16th RIEC International Workshop on Spintronics

and

8th JSPS Core-to-Core Workshop on "New-Concept Spintronic Devices"

Agenda & Abstracts

Date: January 9(Wed.) -12(Sat.)

Venue: Laboratory for Nanoelectronics and Spintronics,
Conference Room (4F),
Research Institute of Electrical Communication,
Tohoku University

16th RIEC International Workshop on Spintronics
and
8th JSPS Core-to -Core Workshop on “New -Concept Spintronic Devices”

● Organized by

Laboratory for Nanoelectronics and Spintronics,
Research Institute of Electrical Communication (RIEC), Tohoku University
Center for Spintronics Integrated Systems (CSIS), Tohoku University
Center for Spintronics Research Network (CSRN), Tohoku University
WPI-Advanced Institute for Materials Research (WPI-AIMR), Tohoku University
Graduate Program in Spintronics, Tohoku University

● Committee and Secretariat

- RIEC Workshop -

Chair: S. Fukami
Local staff: S. Kanai, J. Llandro, B. Jinnai, S. DuttaGupta, C. Zhang
Secretariat: N. Sato, Y. Jidai, M. Abe, Y. Takahashi
Advisor: H. Ohno

- Core-to-Core Workshop -

Committee: M. Shirai, K. Takanashi, K. O’Grady, A. Hirohata, B. Hillebrands
Local Staff: M. Tsujikawa, S. Fukami, S. Kanai
Advisor: H. Ohno

Timetable for
16th RIEC International Workshop on Spintronics
and
8th JSPS Core-to-Core Workshop on “New-Concept Spintronic Devices”

Date: January 9 (Wed.) – 12 (Sat.), 2019
Venue: Laboratory for Nanoelectronics and Spintronics, Conference Room (4F),
Research Institute of Electrical Communication (RIEC), Tohoku University

Jan. 9 (Wed)

RIEC International Workshop on Spintronics

9:10-9:15		Opening
9:15-10:00	We-1	T. Jungwirth
10:00-10:30	We-2	T. Moriyama
10:30-10:50		Break
10:50-11:20	We-3	C. Song
11:20-11:50	We-4	M. Meinert
11:50-13:50		Lunch
13:50-14:00		Group Photo
14:00-14:45	We-5	P. Gambardella
14:45-15:15	We-6	K. Ando
15:15-15:40		Break
15:40-16:10	We-7	J. Åkerman
16:10-16:40	We-8	E. Sagasta
16:40-17:10	We-9	J. Nitta

Jan. 10 (Thu)

RIEC International Workshop on Spintronics

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9:55-10:25	Th-2	J. Matsuno
10:25-10:45		Break
10:45-11:15	Th-4	D. Querlioz
11:15-11:45	Th-5	K. Camsari
11:45-14:00		Lunch
14:00-15:30		Poster
15:30-16:00	Th-3	C. Back
16:00-16:30	Th-7	H.-W. Lee
16:30-17:00	Th-8	S. Fukami
17:00-17:05		Closing
17:05-18:00		Transfer
18:00-19:30		Banquet

Jan. 11 (Fri)

Tohoku-York-Kaiserslautern Core-to-Core

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9:45-10:15	Fr-2	A. Hirohata
10:15-10:45	Fr-3	T. Kubota
10:45-11:00		Break
11:00-11:30	Fr-4	M. Aeschlimann
11:30-12:00	Fr-5	A. Pratt
12:00-12:30	Fr-6	S. Mitani
12:30-12:35		Group Photo
12:35-14:00		Lunch
14:00-14:30	Fr-7	J. Ieda
14:30-14:50	Fr-8	M. Samiepour
14:50-15:10	Fr-9	L. Scheuer
15:10-15:30	Fr-10	M. A-Mahdawi
15:30-15:45		Free time
15:45-17:15		Poster

Jan. 12 (Sat)

Tohoku-York-Kaiserslautern Core-to-Core

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9:55-10:10		Break
10:10-10:55	Sa-2	G. von Freymann
10:55-11:10		Break
11:10-11:55	Sa-3	K. O'Grady
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16th RIEC International Workshop on Spintronics

● January 9 (Wednesday)

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[Invited Lecture] *Crystal symmetries and transport phenomena in antiferromagnets*

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We-2 **T. Moriyama (Kyoto University)** 16
Spin torque control of antiferromagnetic NiO

10:30-10:50
Break

10:50-11:20
We-3 **C. Song (Tsinghua University)** 17
Electrical switching of antiferromagnetic moments

11:20-11:50
We-4 **M. Meinert (Bielefeld University)** 18
Key role of thermal activation in the electrical switching of antiferromagnetic Mn_2Au and CuMnAs

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13:50-14:00
Group Photo

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[Invited Lecture] *Magnetic Skyrmions: From Topology to Technology*

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Th-2 **J. Matsuno (Osaka University)** 25

Spin-orbitronics at transition-metal oxide interfaces

10:25-10:45

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10:45-11:15

Th-4 **D. Querlioz (Univ. Paris-Sud)** 26

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Th-5 **K. Camsari (Purdue University)** 27

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Th -7 **H.-W. Lee (POSTECH)** 29

Intrinsic spin and orbital Hall effects from orbital texture

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Closing

17:05-18:00

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8th JSPS Core-to-Core Workshop on

“New-Concept Spintornic Devices”

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Fr-2 **A. Hirohata (University of York)** 34

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Fr-3 **T. Kubota (Tohoku University)** 35

Half-metallic Heusler alloys for giant magnetoresistance effects

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11:00-11:30

Fr-4 **A. Aeschlimann (University of Kaiserslautern)** 36

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Fr-5 **A. Pratt (University of York)** 37

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Lunch

14:00-14:30

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Fr-8 **M. Samiepour (University of York)** 41

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Fr-9 **L. Scheuer (Technische Universität Kaiserslautern)** 42

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Fr-10 **M. A-Mahdawi (Tohoku University)** 43

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Sa-2 **G. von Freymann (Technische Universität Kaiserslautern)** 46

Topological protection and time-periodic driving in model systems

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11:10-11:55

Sa-3 **K. O'Grady (University of York)** 47

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11:55-12:00

Closing

16th RIEC International Workshop on Spintronics
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Poster Program

16th RIEC International Workshop on Spintronics

Oral presentation

Crystal symmetries and transport phenomena in antiferromagnets

Tomas Jungwirth[1,2]

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The suppression of dipolar fields in antiferromagnets is favorable for high density integration of memory elements and makes them robust against magnetic field perturbations. Other unique merits of antiferromagnetic spintronics include the multi-level switching, suitable for integrating memory with logic or neuromorphic functionalities, and the ultra-fast THz spin dynamics. In the lecture we will first give a brief overview of the multiple directions in current research of antiferromagnetic spintronics [1]. We will then outline the rich symmetry and topology landscape of antiferromagnets which allows for a range of transport phenomena suitable for manipulating and detecting antiferromagnetic spins. Our main focus will be on electrical readout of 180° spin-reversal in collinear antiferromagnets [2]. Apart from microscopic imaging of a domain wall motion, this can be facilitated by a second-order magnetoresistance effect in antiferromagnets with broken time and space-inversion symmetries. In the linear response, the magnetic structure alone cannot generate a spontaneous Hall effect collinear antiferromagnets. However, we introduce a mechanism and corresponding candidate collinear antiferromagnets, in which the breaking of time-reversal and other symmetries required by the Hall effect is caused by the arrangement of non-magnetic atoms in the lattice. Hall conductivities as large as 1000 S/cm are obtained in our first-principles calculations which originate from spin-orbit coupled bands with topological signatures linked to the remaining crystal symmetries in the considered collinear antiferromagnets.

Reference

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Spin torque control of antiferromagnetic NiO

Takahiro Moriyama
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For a long time, there have been no efficient ways of controlling antiferromagnets. Quite a strong magnetic field was required to manipulate the magnetic moments because of a high molecular field and a small magnetic susceptibility [1]. It was also difficult to detect the orientation of the magnetic moments since the net magnetic moment is effectively zero. Nevertheless, the microscopic magnetic moments should in principle exhibit a similar spintronic effect, such as various magnetoresistance effects and the spin torque effect, as seen in ferromagnets [2,3]. In this talk, we show our recent results of the spin torque switching and magnetoresistive detection of the magnetic moments in antiferromagnets [4], leading to novel antiferromagnetic spintronic applications.

Pt 4 nm/ NiO t_{NiO} nm/ Pt 4 nm multilayers were formed by magnetron sputtering. Figure 1 (a) shows the basic principle of the spin torque rotation of the antiferromagnetic moments in a Pt/ NiO/ Pt multilayer structure where the bipartite magnetic moments rotate without a cost to increasing the exchange energy. To experimentally demonstrate, we used the Hall bar structure with the measurement procedure described in Fig. 1 (b). A writing current I_w flowing from the electrode 2 and 3 to the electrodes 1 and 4, as represented by write "1", rotates the magnetic moments and stabilizes them orthogonal to the direction of I_w. In the same manner, the other current flow of I_w writes "0". The orientation of the magnetic moments is read, after each write, by the transverse resistance (R_{Hall}). We took advantage of the spin Hall magnetoresistance (SMR) to read out the orientation of the magnetic moments. Figure 1 (c) shows representative results of the sequential write-read operation in Pt/ NiO /Pt as well as Pt/ SiO / Pt with I_w = 38 mA. The operation of write "1" results in a high resistance state and "0" in a low state, which is coherently explained by the spin torque rotation of the magnetic moments and the change of R_{Hall} due to SMR. We demonstrated that the spin torque rotation of the Nėel vector with the critical current of ~ 4 x 10^7 A/cm^2 and the spin Hall magnetoresistive detection of its orientation with the magnetoresistance ratio of ~7 x 10^{-4}. The change in the Nėel order upon the spin torque was also imaged by the X-ray magnetic linear dichroism – photoemission electron microscopy (XMLD-PEEM).

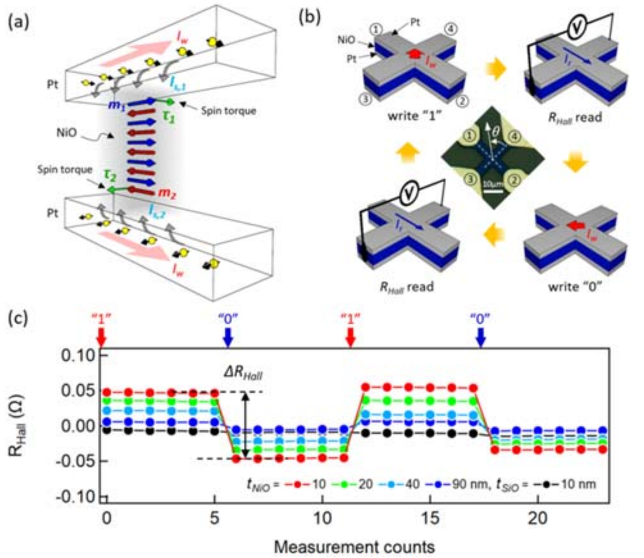

Fig. 1 The spin torque writing scheme and the sequential write-read memory operation.

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Electrical switching of antiferromagnetic moments

Cheng Song[1], Xianzhe Chen[1], Feng Pan[1]
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Antiferromagnets with zero net magnetic moment, strong anti-interference and ultrafast switching speed have potential competitiveness in high-density data storage. Electrical switching of antiferromagnets is at the heart of their device application [1,2]. The antidamping torque-induced switching of Néel order is attained in a biaxial antiferromagnetic insulator NiO, which is manifested electrically via spin Hall magnetoresistance in NiO (100)/Pt bilayers [3]. The antiferromagnetic moments are switched towards the current direction, different from the vertical configuration in the fieldlike torque scenario (e.g., CuMnAs and Mn_2Au) [4,5]. On the other hand, electric field is used to switch the magnetic moment of Mn_2Au films grown on piezoelectric $Pb(Mg_{1/3}Nb_{2/3})_{0.7}Ti_{0.3}O_3$ (PMN-PT) (011) substrates. When the electric field is swept, the easy axis of Mn_2Au is switched between [100] and $[01\bar{1}]$ directions of PMN-PT (011) at room temperature, exhibiting a butterfly-like swithing feature. This feature indicates that the underlying mechanism is the electric field-induced ferroelastic strain. Such a transition of the easy axis leads to the change of threshold current for the field-like torque switching of Mn_2Au, based on which an antiferromagnetic ratchet is proposed [6]. Electrical switching of antiferromagnetic moments paves the way for all-electrical writing and readout in antiferromagnetic spintronics.

We are grateful to the theoretical contribution by Prof. Yaroslav Tserkovnyak, Dr. Ricardo Zarzuela, Dr. Jia Zhang, and Dr. Ran Cheng.

[1] C. Song, et al. Nanotechnology 29, 112001 (2018)
[2] C. Song, et al. Prog. Mater. Sci. 87, 33 (2017)
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[4] P. Wadley, et al. Science 351, 587 (2016).
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[6] X. Z. Chen, et al. To be submitted.

Key role of thermal activation in the electrical switching of antiferromagnetic Mn_2Au and CuMnAs

Markus Meinert
Center for Spinelectronic Materials and Devices, Department of Physics, Bielefeld University, Germany

Electrical manipulation of antiferromagnets with specific symmetries offers the prospect of creating novel, antiferromagnetic spintronic devices [1]. Such devices aim to make use of the insensitivity to external magnetic fields and the ultrafast dynamics at the picosecond timescale intrinsic to antiferromagnets. The possibility to electrically switch antiferromagnets was first predicted for Mn_2Au [2] and then experimentally observed in tetragonal CuMnAs [3].

In this talk, I will report on the electrical switching of epitaxial films of Mn_2Au. Exponential dependences of the switching amplitude on the current density and on the temperature are observed and a saturating behaviour with pulse widths approaching 1ms is seen. We analyze the switching by constructing a macroscopic stochastic switching model, which is solved with a Monte Carlo technique and describes the observed data well when the Joule heating of the current is taken into account. The model analysis further shows that the electrically set magnetization state is long-term stable at room temperature, paving the way for practical applications in memory devices [4].

In the second part of the talk, I will discuss our experiments on the electrical switching of magnetron-sputtered CuMnAs thin films. Most notably, the switching is observed even in films with rather poor crystalline quality and does not seem to rely on excellent crystal quality. Similar switching behaviour as compared to Mn_2Au is observed, however at much smaller current densities and in agreement with the previously reported switching in epitaxial CuMnAs.

[1] O. Gomonay et al., Phys. Status Solidi RRL RRL **11**, 1700022 (2017)
[2] J. Zelezny et al., Phys. Rev. Lett. **113**, 157201 (2014)
[3] P. Wadley et al., Science **351**, 587 (2016)
[4] M. Meinert et al., Phys. Rev. Applied **9**, 064040 (2018)

Spatially-resolved magnetization dynamics induced by spin-orbit torques

Pietro Gambardella
Department of Materials, ETH Zurich, Switzerland

Although small, the spin-orbit interaction determines the equilibrium properties of magnets as well as the possibility to excite the magnetization out of equilibrium while ensuring the conservation of angular momentum. In this talk, I will review prominent mechanisms due to spin-orbit coupling that give rise to spin currents in ferromagnetic and antiferromagnetic heterostructures, showing how unusual magnetoresistance and spin torque phenomena emerge from charge-spin conversion in these materials. Finally, I will present recent results based on pump-probe x-ray experiments that allow us to image current-induced magnetization switching of ferromagnetic layers coupled to either nonmagnetic or antiferromagnetic heavy metal layers.

Spin-orbit torques in metal-oxide heterostructures

Kazuya Ando
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Spin-orbit coupling (SOC) in solids plays a crucial role in modern spintronics. When a charge current passes through a heavy metal with strong SOC, electrons with opposite spins are deflected in opposite directions, resulting in the generation of a transverse spin current, which is known as the spin Hall effect. Another source of the charge-spin conversion is the Rashba-Edelstein effect, where a charge flow in a Rashba two-dimensional electron gas results in the creation of a non-zero spin accumulation. The charge-spin conversion enables the generation of spin-orbit torques, offering a route to the electrical manipulation of magnetization through SOC.

Here, we report the generation of the spin-orbit torques in metal-oxide heterostructures. We show that the spin-orbit torques can be significantly enhanced by oxidation engineering. The oxidation engineering of the spin-torque generation allows efficient spin-torque generation using Cu, a light metal with weak SOC [1]. Furthermore, we show that oxygen incorporation into the most widely used spintronic material, Pt, turns the heavy metal into an electrically insulating generator of the spin-orbit torques, enabling the electrical switching of perpendicular magnetization in a ferrimagnet sandwiched by insulating oxides [2]. Our results also show that the damping-like spin-orbit torque generated by metal oxides can be attributed to the intrinsic mechanism [3]. These findings open a route toward energy-efficient spin-orbit devices based on metal oxides.

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Spin transfer torque driven higher-order propagating spin waves in nano-contact magnetic tunnel junctions

Afshin Houshang[1], Roman Khymyn[1], Himanshu Fulara[1], Ajay Gangwar[1], Mohammad Haidar[1], Seyyed Etesami[1], Riccardo Ferreira[2], Paolo Freitas[2], Mykola Dvornik[1], Johan Åkerman[1]

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Short wave-length exchange-dominated propagating spin waves will enable magnonic devices to operate at higher frequencies and higher data transmission rates. While GMR based magnetic nano-contacts are highly efficient injectors of propagating spin waves, the generated wave lengths are 2.6 times the nano-contact diameter [1], and the electrical signal strength remains much too weak for practical applications. Here we demonstrate nano-contact (diameter of 150 nm) spin torque nano-oscillators (STNOs) based on ultra-low-RA CoFeB/MgO/CoFeB magnetic tunnel junction stacks. Lateral current shunting in the free and cap layers is suppressed by gradually thinning the layers away from the nano-contact. The fabricated STNOs show a tunneling magnetoresistance (TMR) of 36%, confirming that a substantial fraction of the total current indeed flows through the tunneling barrier. The STNOs show a number of different auto-oscillating modes consistent with both propagating and self-localized spin waves. At high out-of-plane fields of about 1.3 T we observe large discrete frequency steps consistent with the hitherto ignored possibility of second and third order propagating spin waves corresponding to wave lengths of 120 and 74 nm, i.e. much smaller than the 150 nm nano-contact. The observed spin wave modes can be well fitted with Slonczewski's prediction for propagating spin wave modes [1] allowing for the possibility of higher-order modes. We also demonstrate mutual synchronization on all three propagating mode orders, further corroborating the propagating character of all modes. These higher-order propagating spin waves will not only enable magnonic devices to operate at much higher frequencies, but also greatly increase their transmission rates and spin wave propagating lengths, both proportional to the much higher group velocity. [1].

[1] John Slonczewski, J. Magn. Magn. Mater. **195**, 261 (1999).

Tuning the spin Hall effect in heavy metals

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The discovery of new spin-to-charge conversion effects (spin Hall effect (SHE), Rashba-Edelstein effect, spin-momentum locking) is expanding the potential of applications such as the magnetization switching of ferromagnetic elements for memories [1] or the recent proposal of a spin-orbit logic [2] which can have a strong technological impact. Finding routes to maximize the SHE is not possible as long as it remains unclear which is the dominant mechanism in a material. I will show a systematic study in Pt, the prototypical SHE material, using the spin absorption method in lateral spin valve devices. We find a single intrinsic spin Hall conductivity in a wide range of conductivities, in good agreement with theory. By tuning the conductivity, we observe for the first time the crossover between the moderately dirty and the superclean scaling regimes of the SHE, equivalent to that obtained for the anomalous Hall effect. Our results explain the dispersion of values of spin-to-charge conversion efficiency in the literature and find a route to maximize this important effect [3]. We also study the mechanisms in Ta, a material with a claimed giant SHE. We experimentally demonstrate the dominance of the intrinsic mechanism in Ta and the observation of a record value of the spin Hall angle (-35 %) [4]. Finally, I will show how to optimize the spin-to-charge current conversion at room temperature by combining Pt with a graphene channel [5], opening up exciting opportunities towards the implementation of spin-orbit-based logic circuits.

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[5] W. Yan, E. Sagasta *et al.*, Nat. Commun. **8**, 661 (2017).

Spin-orbit torque efficiency in epitaxial Pt/Co bilayer systems

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The Rashba spin orbit coupling (SOC) induced by structural inversion asymmetry is now at the heart of condensed matter physics and its applications for spin-orbitronics [1]. The spin-orbit torque (SOT) is expected to be an innovative way towards fast domain wall motion and magnetization switching. There are two possible origins for the SOT in heavy metal/ferromagnet (HM/FM) bilayer systems, namely, the Rashba-Edelstein effect (REE) at the interface and the bulk spin Hall effect. Although a large spin splitting due to the Rashba SOC is observed at the surfaces of HMs [2], the contribution of the Rashba SOC in the HM/FM systems is still controversial. It is required to enhance the SOT efficiency by clarifying the origins.

We have found that the D'yakonov-Perel' spin relaxation mechanism due to the Rashba SOC in *epitaxial* Pt thin films is dominant over the Elliot-Yafet mechanism [3]. Here in this work, we compared the SOT efficiencies between *epitaxial* and *polycrystalline* Pt/Co bilayers from spin Hall magnetoresistance (SMR) and spin torque ferromagnetic resonance (ST-FMR) measurements [4]. The average roughness of the Pt/Co interface for *epi*-samples is determined to be below 0.1 nm from the X-ray reflectivity measurement, demonstrating interfacial flatness at the atomic scale. In contrast, the roughness for *poly*-Pt/Co interface is above 0.3 nm. The SMR and ST-FMR measurements demonstrate enhancement of SOT efficiency in *epi*- samples with Pt films having lower resistivity than *poly*- samples. This result is different from the previous reports and suggests that the REE at the Pt/Co interface plays a role for the enhancement. Our study provides experimental evidence that SOT can be significantly modulated with hetero-interface control.

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[4] Y. Du, *et al.*, ArXiv:1807.10867

Magnetic Skyrmions: From Topology to Technology

Geoffrey S. D. Beach[1]
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Magnetic skyrmions [1] are particle-like spin textures that are topologically protected from being continuously ‘unwound’. Skyrmions exhibit rich behaviors including ordered lattice formation, emergent electrodynamics and robust current-driven displacement at remarkably low current densities, but in most materials they manifest only at low temperature. This talk focuses on skyrmions in ferromagnetic and ferrimagnetic multilayers in which an interfacial Dzyaloshinskii-Moriya interaction (DMI) [2] stabilizes chiral magnetic skyrmions at room temperature [3]. Using high-resolution x-ray microscopy, we reveal isolated skyrmions and skyrmion lattices in engineered heterostructures, and provide key insights into their formation, stability and dynamics. We show pure spin currents can drive skyrmions at speeds >100 m/s [3], and that current pulses can be used to write and delete them electrically [4] or thermally [5] at sub-ns timescales. We find that current-induced shifting is repeatable over billions of cycles, and we discover an analogue to the conventional Hall effect [6] in which current-driven skyrmions deflect similarly to electrons in a magnetic field. We present an analytical framework [7,8] for computing the energy and structure of any skyrmion in any material, providing the tools to engineer skyrmions with desired properties through informed materials selection. We show that whereas ferromagnets possess fundamental limits for skyrmion speed and size [7,8], ferri- and antiferromagnets provide a path toward ultrasmall and ultrafast skyrmions at room temperature. We verify these predictions experimentally in a compensated ferrimagnet [9], demonstrating soliton speeds >1300 m/s and room-temperature skyrmions with minimum sizes close to 10 nm. These results demonstrate the promise of using skyrmions as topological bit carriers in spin-based devices for low-power memory and logic.

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Spin-orbitronics at transition-metal oxide interfaces

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Spintronics utilizing strong spin-orbit coupling (SOC) can be called as "spin-orbitronics". Here we suggest that promising are 5*d* electron systems such as Ir *oxides*, which recently emerged as a new paradigm for oxide spin-orbitronics. For example, we investigated novel physics of spin-orbital Mott insulators [1] and possible topological insulators [2] by tuning the electronic phases through superlattice technique. We also demonstrated a large spin Hall effect of IrO_2, indicating that Ir oxides are promising class of spin-orbitronic materials [3].

In this talk, we focus on yet another topic on spin-orbitronics – magnetic skyrmion as a topological spin texture. We have studied transport properties of bilayers consisting of *m* unit cells of ferromagnetic $SrRuO_3$ and 2 unit cells of $SrIrO_3$. We observed an anomaly in the Hall resistivity in addition to anomalous Hall effect (AHE); this is attributed to topological Hall effect (THE) [4]. The result suggests that magnetic skyrmions of 10–20 nm are generated by Dzyaloshinskii-Moriya interaction, which might be caused by both broken inversion symmetry at the interface and strong SOC of $SrIrO_3$. Even more surprising is that we can control both AHE and THE by electric field in the $SrRuO_3$-$SrIrO_3$ bilayers [5]. We observed the clear electric-field dependence only when $SrIrO_3$ is inserted between $SrRuO_3$ and a gate dielectric. The results established that strong SOC of nonmagnetic materials such as $SrIrO_3$ is essential in electrical tuning of these Hall effects. Considering that AHE and THE are governed by momentum-space and real-space topology, respectively, we may have a chance to approach a triple point for topology, correlation, and spin-orbit coupling through Ir oxides.

We are also searching for spin-current-driven thermoelectric conversion through spin Seebeck effect [6]. We will report on the latest results of spin Seebeck effect at interfaces between magnetic oxides and nonmagnetic Ir oxides.

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Bioinspired Computing Leveraging the Physics of Magnetic Nano-Oscillators

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Brains display many features typical of non-linear dynamical networks, such as synchronization or chaotic behavior. These observations have inspired a whole class of models that harness the power of complex non-linear dynamical networks for computing. In this framework, neurons are modeled as non-linear oscillators, and synapses as the coupling between oscillators. However, there are few hardware implementations of these systems, because large numbers of interacting non-linear oscillators are necessary. In this talk, we will see why coupled magnetic nano-oscillators are very promising for realizing cognitive computing at the nanometer scale. Then, we will present our experimental and theoretical results. We will show how speech recognition can be performed using the transient dynamics and the synchronization of a few harmonic spin torque oscillators [1]. These results highlight key opportunities and requirements for harnessing spintronic physics for bioinspired computing. We will also show how superparamagnetic oscillators can code and transform information in a robust population-type scheme [2]. These results highlight that some apparently undesirable phenomena like superparamagnetism can become compelling for bioinspired schemes. We will finally discuss how this line of research can take inspiration from both neuroscience and machine learning, and finish by open questions raised by our research.

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p-bits for Probabilistic Spin Logic

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Deterministic bits that represent "0" or "1" form the basis of all digital computing. At the other end of the spectrum, quantum bits that represent a superposition of "0" and "1" form the basis of the emerging field of quantum computing. In this talk, I will introduce probabilistic or p-bits that fluctuate between "0" and "1" and argue that correlated p-bits (p-circuits) can address some of the challenging problems tackled by quantum computers. Importantly, p-circuits can operate robustly at room temperature unlike q-bits whose delicate entanglement requires cryogenic temperatures. I will show that existing embedded MRAM technology could lead to a natural and scaled implementation of hardware p-bits by minimal modifications. In addition to its relevance to Quantum Computing, I will also discuss applications of p-circuits as hardware accelerators in the context of Machine Learning. Finally, I will review our experimental and theoretical efforts towards implementing p-circuits in hardware.

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Magnetization dynamics driven by spin-orbit torques

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Interfacial spin-orbit fields (iSOFs) enable the manipulation of the magnetization through in-plane charge currents. We use high frequency currents and current pulses to excite magnetization dynamics in nanostructured elements of thin ferromagetic layers. Two examples are shown.

Fe/GaAs(001) is a well-studied material system that shows efficient and voltage-controllable iSOFs [1-3]. Here we demonstrate magnetization dynamics launched by iSOTs and probed by time resolved magneto-optic Kerr microscopy.

We use the same experimental technique to follow the trajectory of the dynamic magnetization of nanostructured Pt/Co/Al_2O_3 elements during SOF induced magnetization switching [4].

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Intrinsic spin and orbital Hall effects from orbital texture

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We show theoretically [1,2] that both the intrinsic spin Hall effect (SHE) and orbital Hall effect (OHE) can arise in centrosymmetric systems through momentum-space orbital texture, which is ubiquitous even in centrosymmetric systems unlike spin texture. The OHE occurs even without spin-orbit coupling (SOC) and is converted into the SHE through SOC. The resulting spin Hall conductivity is large (comparable to that of Pt) but depends on the SOC strength in a nonmonotonic way. This mechanism is stable against orbital quenching. This work suggests a path for an ongoing search for materials with stronger SHE. It also calls for experimental efforts to probe orbital degrees of freedom in the OHE and SHE. Possible ways for experimental detection are briefly discussed.

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Spin-Orbit Torque Switching in Nanoscale Devices: Material and Device Engineering

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Utilization of spin-orbit interaction to manipulate magnetization offers various opportunities in fundamental research and integrate-circuit technologies. Magnetization switching induced by the spin-orbit torque (SOT) [1-3] has a potential for the write operation of three-terminal nonvolatile memory devices in digital integrated circuits [4] and artificial neural networks [5,6]. In this presentation, we will review our studies on the SOT-induced magnetization switching. The following topics will be discussed: the device size dependence of the switching current density in nonmagnet (Ta or W)/ ferromagnet (CoFeB) [7] and antiferromagnet (PtMn)/ ferromagnet ([Co/Ni]) [8] systems, and relation between the SOT switching efficiency and longitudinal resistivity of W in W/CoFeB/MgO [9,10], and so on.

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8th JSPS Core-to-Core Workshop on "New-Concept Spintornic Devices"

Oral presentation

Implementation of the Stimulated-Raman-Adiabatic-Passage mechanism in magnonics

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Magnonics is the field of spin waves, the dynamic excitations of a magnetically ordered body, and magnons are the quanta of spin waves. Being wave-based, magnonics bears the advantage of the ease of implementation of computation schemes developed in other areas of wave-based phenomena. One example is the concept of “quantum-classical analogy”, which was created in the field of waveguide optics [1]. It was shown, that the use of classical light in optical waveguides allows for the physical realization of quantum phenomena in atom physics, such as the population transfer between two states via a third, intermediate, dark state, where direct transitions between the two states are dipole forbidden. This process is referred to as STImulated Raman Adiabatic Passage (STIRAP) and has found various applications in many fields of physics [2].

We present first results of the magnonic realization of the STIRAP process (m-STIRAP). Our demonstrator consists of three, partially curved magnonic waveguides, which are locally coupled to each other via the dipolar stray fields of magnons in well-defined regions of small separation between two neighboring waveguides. This design is equivalent to two magnonic directional coupler devices [3] arranged in series and with coherent coupling between them. Using micromagnetic simulations, we show that the population of magnons can be transferred between the outer waveguides via the intermediate waveguide. If the “counterintuitive” coupling scheme is used, the intermediate waveguide is not excited during the transfer, thus resembling the quantum-classical analogy of a dark state.

Our results bear high potential for future magnonic device functionalities and designs by bringing together the wealth of quantum-classical analogy phenomena with the wealth of means to control wave propagation in magnonic systems.

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Development of Antiferromagnetic Mn-Based Heusler Alloy Films

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Recently, antiferromagnetic (AF) spintronics has attracted significant attention from the viewpoints of low magnetic susceptibility, zero net magnetization and high frequency magnetisation dynamics. However, the main obstacle in AF spintronics is their small output signals. In order to solve this essential problem, we have developed a new AF Mn-based Heusler alloy film.

We investigated $D0_{19}$ Mn_3Ga and Mn_3Ge films with and without doping of ferromagnetic elements. These films were found to be in a single-phase polycrystalline phase with perpendicular anisotropy. By attaching a ferromagnetic (FM) $Co_{0.6}Fe_{0.4}$ and $[Co/Pt]_3$ layer, both in-plane and perpendicular exchange bias fields were measured to be 299 Oe (446 Oe) at 120 K for a $Mn_{2.8}Ga_{1.2}$ ($Mn_{1.99}Fe_{0.49}Ga$) film and 163 Oe for $Mn_{1.96}Fe_{0.67}Ga$ film at 120 K, respectively. Median blocking temperature of Mn_2FeGa films were estimated to be 235 and 185 K for in-plane and perpendicular cases, respectively. These results are very useful to develop antiferromagnetic materials and implement them into a spintronic device.

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Half-metallic Heusler alloys for giant magnetoresistance effects

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Since the first theoretical prediction of half-metallic electronic structure of NiMnSb [1], the family of Heusler alloys have been attractive materials for spintronics application[2]. Half-metallic materials are an ideal spin source which can realize extremely large magnetoresistance in giant magnetoresistance (GMR) junctions.

Many kinds of Heulser alloys have been studied for GMR in current-perpendicular-to-plane (CPP) geometry, and in recent studies, cobalt (Co) based full Heuelser alloy is the most popular material[3 – 7]. We have also successfully observed CPP-GMR at room temperature using half-Heusler alloys, such as NiMnSb [8] and PtMnSb [9]. In this presentation, a brief overview of the Heusler based CPP-GMR studies will be shown, and recent study on magnetic properties of inverse type Heusler alloy, Mn_2CoGa films will be discussed. The inverse Heusler alloy is of interest for the half-metallic electronic structure, and relatively large resistivity which may be a merit for enhancing device output in CPP-GMR junctions.

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Light Induced Magnetization Dynamics in Ferromagnetic Alloys

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In recent years, magnetism at the ultrafast timescale has been a topic of increasing interest. A thorough understanding of femtosecond magnetism will address the important questions of how fast the magnetization can be reoriented in a material and what physical processes present fundamental limits to this speed. New developments in laser-based femtosecond x-ray and extreme-ultraviolet sources make it possible to probe element-specific spin dynamics in multispecies magnetic systems. These nascent optical tools therefore provide new and detailed information that is mostly not accessible by using visible light, and allow for the design of experiments that can help to identify the microscopic mechanisms of ultrafast spin dynamics. Using femtosecond soft X-ray pulses we were able to investigate the ultrafast breakdown of the magnetic coupling in heterogeneous magnetic materials [1] as well as speed and efficiency of femtosecond spin current injection into a nonmagnetic material [2].

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Surface spin polarisation mapping using spin-polarised metastable emission electron microscopy (SPMEEM)

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The Fermi-level spin polarisation at the surface of a material plays a critical role in determining the efficiency of spin injection in spintronic and organic spintronic devices [1]. Previously, we have investigated the surface spin-polarisation of spintronic materials using the extreme surface-sensitivity associated with the technique of spin-polarised metastable de-excitation spectroscopy (SPMDS) [1,2]. This involves exposing a surface to a beam of helium atoms prepared in the long-lived 2^3S metastable state which has an energy of 19.8 eV, ideal for probing valence-band electronic structure [3]. In this contribution, we present the first results from the development of spin-polarised metastable emission electron microscopy (SPMEEM), the microscopic equivalent of SPMDS. In the same way that photoemission electron microscopy (PEEM) greatly enhances photoelectron spectroscopy, SPMEEM has the potential to extend SPMDS and spatially map the spin-polarisation at the topmost surface of a magnetic material, as we demonstrate using a single crystal of Fe_3O_4(001). We also show a strong coverage dependence in the spin polarisation of the aromatic molecule naphthalene on Fe_3O_4, possibly arising due to a change in molecular orientation. Higher coverages form well-ordered layers with a spin polarisation that is uniform across a much larger region than for the underlying substrate.

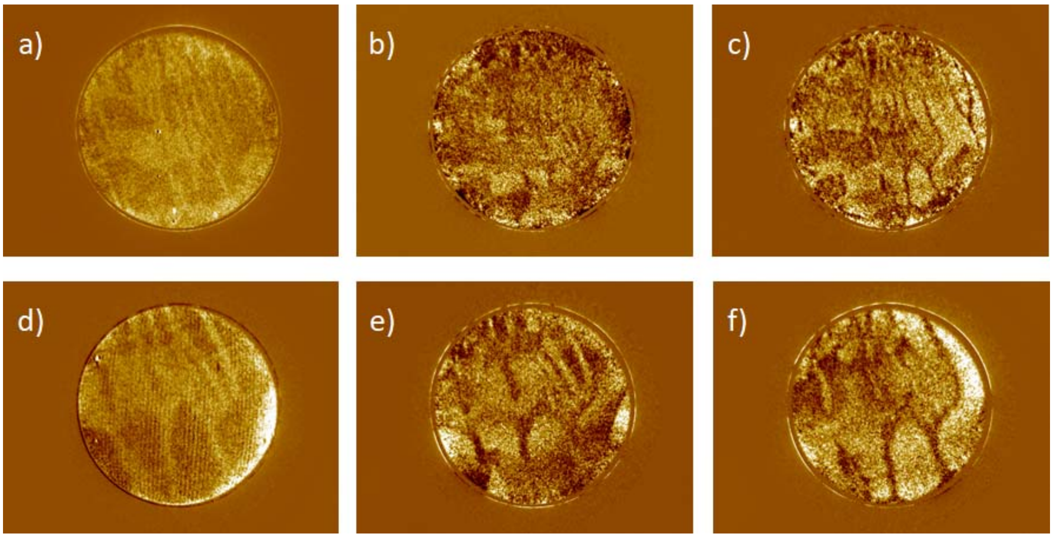

Fig. 1. (a) ultraviolet magnetic circular dichroism (UVMCD), (b) in-plane SPMEEM and (c) out-of-plane SPMEEM images from the surface of an $Fe_3O_4(001)$ single crystal. Field of view is 100 μm. (d), (e), and (f) show equivalent images of the same region but with a field of view of 50 μm.

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Spin polarized quantum well states in atomically controlled $Cr/Fe/MgAl_2O_4$ structures

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By using a wedge layer technique and a lattice matched $Fe/MgAl_2O_4$ interface [1], atomically controlled quantum well structures [2] were prepared on monocrystalline Cr(001) underlayer, which can work as a pseudo barrier potential, for the purpose of modulating spin dependent transport and interface magnetic properties. The $Cr/Fe/MgAl_2O_4$ structures showed quantum well resonance peaks in their full-stacked magnetic tunnel junctions (MTJs). Enhanced tunnel magnetoresistance (TMR) was observed at room temperature, as well as a large interface perpendicular magnetic anisotropy occurring at Fe/oxide interface [3-5]. In addition, characteristic temperature dependence of tunnel conductance was found to appear in the MTJs [6]. In this presentation, voltage controlled magnetic anisotropy in the quantum well structures will also be discussed.

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Theory of spin-transfer torques in antiferromagnetic textures

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We present a theory of spin-transfer torques in textured antiferromagnets considering the small and large limits of the exchange coupling energy relative to the kinetic energy of the inter-sublattice electron dynamics. Our theory suggests a natural definition of the efficiency of spin-transfer torques in antiferromagnets in terms of well-defined material parameters, revealing that the charge current couples predominantly to the antiferromagnetic order parameter and the sublattice-canting moment in, respectively, the limits of large and small exchange coupling [1]. The effect leads to antiferromagnetic domain wall motion and the characteristic Doppler shift in the antiferromagnetic spin-wave dispersions. The same formalism also predicts a cross effect of magnetic field gradient and charge current on a antiferromagnetic domain wall motion [2]. The findings offer a framework for understanding and designing spin-transfer torques in antiferromagnets belonging to different classes of sublattice structures.

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Study of spin-current operation in patterned $IrMn_3$

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Since the discovery of giant magneto-resistance (GMR), the GMR and tunnel magneto-resistance (TMR) have been used in data storage industry such as a read head in a hard disk drive (HDD) and a cell in a magnetic random access memory (MRAM) [1]. The development of magnetic memories significantly demand to make new data storages with more stability. In order to obtain higher thermal and magnetic stability in magnetic storage the magnetisation of a ferromagnetic (F) layer is pinned by using an attached antiferromagnetic (AF) layer.

The AF induces exchange bias at an AF/F interface and causes magnetisation pinning. Even though many different kinds of AFs have been investigated such as IrMn, FeMn, PtMn [2] to achieve stronger AF/F pinning fields and higher efficiency in spintronic devices there is still lack of study on characterisation of a patterned AF layer.

Following our previous studies on non-local lateral spin-valves [3, 4] and some reports on strange behaviour observed in $IrMn_3$ when it is used as a contact [5] we are interested in measuring the spin diffusion length of $IrMn_3$. Therefore we used $IrMn_3$ instead of conventionally used Cu or Ag as a connecting spin channel between injector and detector ferromagnetic (typically Py) bars in lateral spin-valve geometry. We measured spin imbalance detected at the detector while a pulsed electrical current applied to the injector interface. The result shows the spin-diffusion length of $IrMn_3$ can be as long as 100nm at around 200K which is much longer than all previous reports [2]. We will report our systematic study on the $IrMn_3$-based spin-valves with and without setting the AF $IrMn_3$.

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Roadmap of Spintronic THz Emitters

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The use of bilayers composed of a ferromagnetic metal (FM) layer attached to a non-magnetic metal (NM) as sources for THz emission opens a new direction in physics. It combines the field of THz with the field of spintronics since the creation of the THz pulse is based on the generation of spin currents. The spin current is created in the magnetic layer by a fs laser pulse and diffuses into the non-magnetic metal through a super diffusive process. Subsequently, the inverse spin Hall effect (ISHE) transforms the pure spin current into a transient charge current due to spin-orbit coupling. The accelerated electrons of the transient current emit radiation in the THz range. Initially, the metallic layers where optimized with respect to layer thickness and geometrical arrangement and excitation wavelength [1,2].

Further exploring the efficiency of THz spintronic emitters, we find significant differences in the efficiency and bandwidth for emitters using epitaxial or polycrystalline grown layers. We correlate the THz-signal amplitude and its bandwidth with the electron-defect scattering lifetime and the interface transmission for spin-polarized, non-equilibrium electrons. We experimentally and numerically show that epitaxially grown defect-free interfaces contribute to a significant enhancement of the THz-signal amplitude and result in a shift of the spectral maximum towards lower THz frequencies.

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Non-volatile modulation of surface anisotropy in CoPt by ZnO ferroelectric polarization in magnetic tunnel junctions

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The recent strong interest in the control of magnetism by electric means has been driven by the aspects of fundamental physical understanding of magnetism, and more importantly towards applications in nonvolatile information processing in magnetic memories [1]. The electric field effect on the interfacial electronic states has been reported to control many magnetic properties, both in magnetic semiconductors and transition metals [2–10]. By using the voltage control of magnetic anisotropy energy (VCMA), fast writing by nanosecond electric pulses in magnetic tunnel junctions (MTJs) has been widely demonstrated in MTJs based on rock-salt-type MgO barrier [11–13]. An alternative is the heterostructure of a ferromagnet/ferroelectric (FM/FE) combination [14,15], where a relatively large modulation of anisotropy is achieved by the control of FE polarization (*P*).

In this work, we propose and clarify an FM/FE MTJ system for achieving a large nonvolatile control of magnetic anisotropy, with a different mechanism. We investigated MTJs made from fcc-CoPt FM and wurtzite-ZnO FE, using first-principles calculations and magnetotransport measurements. A large non-volatile change of interfacial anisotropy was found, which is driven by the *P*-modulation of the spin-orbit coupling and the *3d-5d* hybridization.

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Nematicity of spin systems driven by anisotropic chemical phase separation

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The origin of nematicity, i.e., in-plane rotational symmetry breaking, and in particular the relative role played by spontaneous unidirectional ordering of spin, orbital, or charge degrees of freedom, is a challenging issue of magnetism, unconventional superconductivity, and quantum Hall effect systems, discussed in the context of doped semiconductor systems such as $In_{1-x}Fe_xAs$,[1] $Cu_xBi_2Se_3$,[2] and Ga(Al)As/$Al_xGa_{1-x}As$ quantum wells,[3] respectively. After presenting the recent progress in the understanding of cubic magnetic anisotropy in $Ga_{1-x}Mn_xAs$,[4] we will show experimental and theoretical results for $In_{1-x}Fe_xAs$,[5] which visualize spinodal phase separation and demonstrate how quenched nematic order of alloy components governs anisotropic magnetoresistance (AMR) but do not affect magnetic anisotropy. These findings, together with earlier data for $Ga_{1-x}Mn_xAs$, reveal under which conditions the anisotropic chemical phase separation accounts for AMR and the magnitude of transition temperature to a collective phase or merely affects magnetic anisotropy. We address the question to what extent the directional distribution of impurities or alloy components setting in during the growth may account for the observed nematicity in other classes of spin systems.

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Topological protection and time-periodic driving in model systems

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Topological protection and Floquet (time-periodic) driving are hot topics in several research fields. Experimental model systems allow for studying these phenomena under very well controlled conditions.

In this tutorial I will discuss the interplay between topological protection and time-periodic driving for some selected examples: Periodic driving of topologically protected edge modes in the one-dimensional Su-Schrieffer-Heeger-chain leads to depopulation of the edge mode despite topological protection [1], while periodic driving of two-dimensional honey-comb-lattices establishes topological protection in an otherwise topologically trivial model system [2]. Time-periodic driving furthermore allows for introducing artificial gauge-fields in topologically trivial materials, modifying transport properties in unexpected ways [3].

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Anomalous Effects in Exchange Bias Systems

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At a previous Core-to-Core meeting we described measurements of a conventional IrMn/CoFe exchange bias system undertaken to extremely low temperatures (2K). From this data we could see that even at these low temperatures the interface had not become totally magnetically rigid and hence the exchange bias was still increasing. This we attribute to disordered spin clusters and single spins at the interface. We have now further examined this data and discovered another anomaly in that for a system which is thermally annealed (set) in say a positive field there exists a difference in the saturation magnetisation in the positive and negative directions. The magnetisation of the sample in the positive i.e. field setting direction being larger than that in the negative direction. This difference in magnetisation appears to persist even when a large field is applied.

It is difficult to imagine a structure that can lead to this effect but when examined to low temperatures the difference in magnetisation appears to go through a peak at very low temperatures. This is analogous to the situation that is observed in a spin glass when the susceptibility is measured. The only possible explanation for this effect is that the act of setting the antiferromagnet appears to lock in a unidirectional anisotropy to the interface spins in the direction of the setting field. Further evidence for an irreversible alignment within the system can be observed by first setting a sample in say a positive field under a given set of field temperature conditions for a fixed time t_{set}. If subsequently a reverse field of the same magnitude is applied and the sample exposed to the same setting temperature for the same setting time the exchange bias observed is now in a positive field but is not of the same magnitude as from the original setting process. This again indicates that some irreversible and possible unidirectional anisotropy is induced in the interface by the original setting process.

Poster presentation

Electric-field control of interfacial spin-orbit fields

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Current induced spin-orbit magnetic fields (iSOFs), which arise in single-crystalline ferromagnets with broken inversion symmetry [1] and in non-magnetic metal/ferromagnetic metal bilayers [2,3], produce spin-orbit torques that can be used to manipulate the magnetization of a ferromagnet. In single crystalline Fe/GaAs (001) heterostructures, for example, interfacial spin-orbit magnetic fields emerge at the Fe/GaAs (001) interface due to the lack of inversion symmetry [4]. In order to develop low-power spin-orbit torque devices, it is important to have electric-field control over such spin-orbit magnetic fields [5]. Here, we show that the current-induced spin-orbit magnetic fields at the Fe/GaAs (001) interface can be controlled with an electric field. In particular, by applying a gate-voltage across the Fe/GaAs interface, the interfacial spin-orbit field-vector acting on Fe can be robustly modulated via the change of the magnitude of the interfacial spin-orbit interaction. Our results illustrate that the electric-field in a Schottky barrier is capable of modifying spin-orbit magnetic fields, an effect that could be used to develop spin-orbit torque devices with low-power consumption [6].

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Low magnetic damping of ferrimagnetic GdFeCo alloys

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Magnetic damping, commonly described by the Gilbert damping parameter, represents the magnetization relaxation phenomenon, describing how quickly magnetization spins reach equilibrium. Understanding the fundamental origin of the damping as well as searching for low damping materials has been a central theme of magnetism research. Several theoretical models for magnetic damping have been proposed and compared with experiments. However, the majority of these studies have focused only on ferromagnetic systems. We investigate the Gilbert damping parameter α for rare earth (RE)–transition metal (TM) ferrimagnets over a wide temperature range. Extracted from the field-driven magnetic domain-wall mobility, α was as low as 7.2×10^{-3} and was almost constant across the angular momentum compensation temperature T_{A}, starkly contrasting previous predictions that α should diverge at T_{A} due to vanishing total angular momentum. Thus, magnetic damping of RE-TM ferrimagnets is not related to the total angular momentum but is dominated by electron scattering at the Fermi level where the TM has a dominant damping role.

Spin-orbit Toque Switching of a Synthetic Antiferromagnet $Co_2MnSi/MnGa$ bilayer

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Spintronic devices with high frequency and high speed have important potential applications in high density magnetic recording, millimeter wave communication and magnetic random access memory. Several strict demands on the magnetic material are needed to satisfy simultaneously: high magneto-crystalline anisotropy, high spin polarization, low saturation magnetization and low magnetic damping factor. Synthetic antiferromagnet (SAFM) composed of Mn-based ordered alloys with perpendicular magnetic anisotropy and low magnetic damping factors and Co based half metals, such as $Co_2MnSi/MnGa$ bilayers, not only behaves magnetically like an antiferromagnet, but also has a high spin polarization, which make it an ideal candidate for spintronic devices [1, 2]. In 2017, some researchers found anomalous spin-orbit torque switching in Pt/compensated ferrimagnet and Pt/SAFM structures [3, 4]. Comparing with conventional AFMs, SAFMs can be used to overcome the detecting difficulty in AFMs and reveal new mechanisms of SOT effect in SAFMs. Recently, we have epitaxially grown a $Co_2MnSi/MnGa$ SAFM bilayer on GaAs substrate with near zero net magnetic moment (Fig. 1). We realized the spin-orbit-toque switching of the SAFM bilayer with a critical current density of 5.8×10^7 A/cm^2 at different temperatures as shown in Fig. 2.

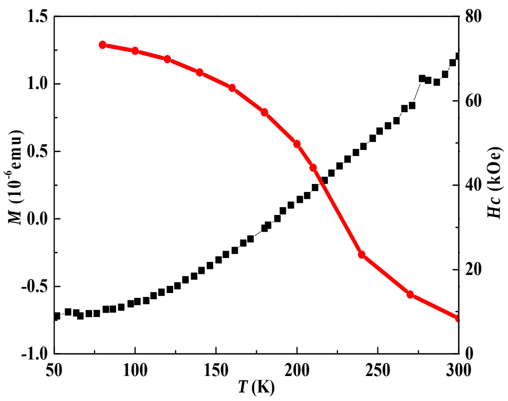

Fig. 1 H_c-T and M-T from SQUID.

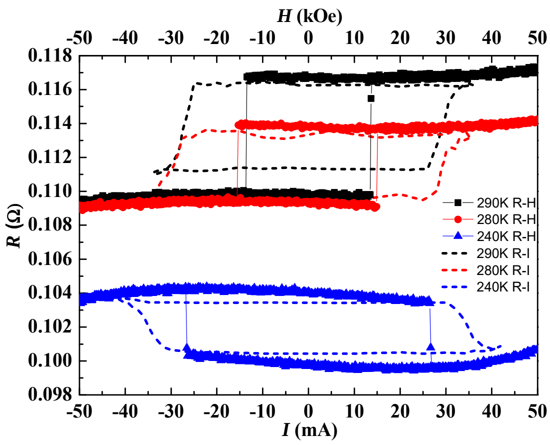

Fig. 2 R-H curve and R-I curves at different T

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Spin-orbit torque induced magnetic switching in ferrimagnetic Heusler alloy $D0_{22}$-Mn_3Ga

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Ferrimagnetic materials combine the advantages of the low magnetic moment of antiferromagnet and the ease of magnetic reading of ferromagnet [1]. Recently, tetragonal ferrimagnetic Heusler alloy $D0_{22}$-Mn_3Ga has attracted much interest for its low Gilbert damping constant, small saturation magnetization, large spin polarization and strong perpendicular magnetic anisotropy (PMA) [2]. Here, we report on the spin-orbit torque induced magnetic switching in $D0_{22}$-Mn_3Ga/Pt bilayers grown on GaAs (001) substrate by molecular-beam epitaxy. The out-of-plane hysteresis loops and anomalous Hall effect measurement have demonstrated the large bulk PMA and low saturation magnetization of ferrimagnetic $D0_{22}$-Mn_3Ga. The spin-orbit torque induced magnetic switching has been realized in $D0_{22}$-Mn_3Ga/Pt bilayer based Hall devices by applying pulsed current under in-plane magnetic field. Notably, the critical switching current density J_c reaches to 1.837×10^7 A/cm^2, which is one order of magnitude smaller than that of $L1_0$-MnGa/Pt system. Besides, both damping-like torque H_D and field-like torque H_F are quantified by performing harmonic Hall voltage measurements in the temperature range of 5 to 300 K. All these results indicate that $D0_{22}$-Mn_3Ga can be a potential candidate for developing high density and energy-efficient spintronic devices

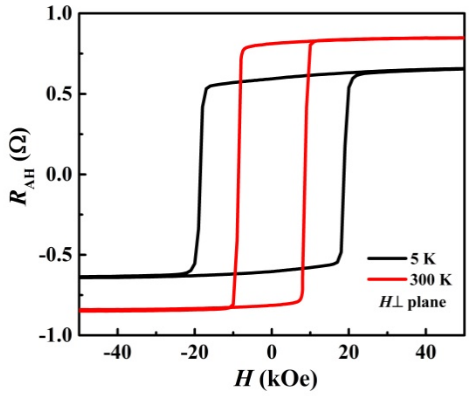

FIG. 1. Anomalous Hall effect of $D0_{22}$-MnGa/Pt bilayer.

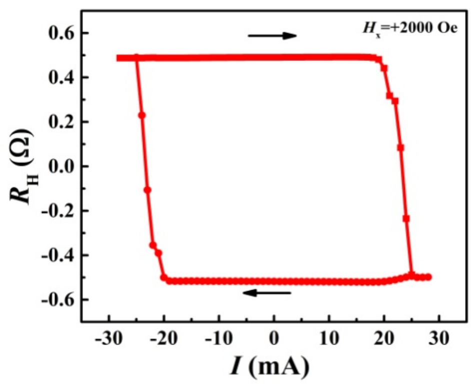

FIG. 2. R_H-I curve of Hall devices.

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Wide-temperature spin-orbit torque switching operation in high-thermal-stability Co/Pt-multilayer nanowire device

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Magnetization switching induced by spin-orbit torques (SOTs) [1-3] is extensively studied because it provides a pathway for ultra-low power and high performance integrated circuits. To use SOT switching devices for versatile applications, including automobile and aerospace, they need to ensure wide-temperature operations in nanoscale dimensions. Thus, it is important to understand temperature dependence of the device performance. We have been studying SOT devices with Co/Pt multilayers having high anisotropy and shown SOT-induced magnetization switching in micrometer-scale Hall-bar devices [4]. In this work, we study SOT switching and thermal stability of Co/Pt-multilayer nanowire devices down to 20 nm in width over a wide range of temperatures. Based on the results, we discuss the feasibility of Co/Pt-multilayer nanowire device for those applications that require wide-temperature operations [5].

This work was partly supported by JST-OPERA, ImPACT Program of CSTI, Core-to-Core Program of JSPS, and Cooperative Research Projects of RIEC.

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magnetic circular dichroism spectroscopy study of layer materials

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The valley Zeeman splitting of monolayer two-dimensional (2D) materials in the magnetic field plays an important role in the valley and spin manipulations. In general, a high magnetic field and low temperature were two key measurement conditions to observe the resolvable valley Zeeman splitting of monolayer 2D materials. We experimentally demonstrate an effective measurement scheme by employing magnetic circular dichroism (MCD) spectroscopy, which enables us to distinguish the valley Zeeman splitting under a relatively low magnetic field even at room temperature.

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Detection of the interfacial exchange field at a ferromagnetic insulator-nonmagnetic metal interface with pure spin currents

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Interfacial spin-orbit and exchange fields at the surface of a ferromagnetic insulator can be studied with the help of a lateral spin valve (LSV) device [1]. We report spin transport measurements in lateral spin valve devices where a Cu spin transport channel is in proximity with ferromagnetic insulator EuS (EuS-LSV) and yttrium iron garnet $Y_3Fe_5O_{12}$ (YIG-LSV). The spin signals in these LSV devices were compared with reference devices fabricated on nonmagnetic Si/SiO_2 substrate with MgO or AlO_x capping. The nonlocal spin valve signal is about 4 and 6 times lower in the EuS-LSV and YIG-LSV, respectively. The suppression in the spin signal has been attributed to enhanced surface spin-flip probability at the Cu-EuS (or Cu-YIG) interface caused by an interfacial spin-orbit and exchange field. Besides spin signal suppression we also found a widely observed low temperature peak in the spin signal at T ~30 K is shifted to higher temperature in the case of devices in contact with EuS or YIG. Temperature dependence of the spin signal for different injector-detector distances reveal fluctuating exchange field at these interfaces cause additional spin decoherence which limit spin relaxation time in addition to conventional sources of spin relaxation. Our results show that temperature-dependent measurement with pure spin current can be used to probe interfacial exchange fields at the ferromagnetic insulator-nonmagnetic metal interface.

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Magneto-optical and optical spectroscopy of perovskites, ferrites, and Heusler compounds to determine features of their electronic structure

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Magneto-optical and optical spectroscopy are broadly applied for determination of the important features of material band structure, such as gap sizes, transition energies and related splitting of *d*-bands due to the crystal field.

We summarize important results of magneto-optical and optical investigations on different kinds of magnetic metals, half-metals, and semiconductors. First the Fe_3O_4, $NiFe_2O_4$, and $CoFe_2O_4$ ferrite films on MgO or glass substrates prepared by MBE and dip-coating. Second, the Heusler compound bulk $Co_2FeAl_{0.5}Si_{0.5}$ and thin films of Co_2FeSi, Rh_2MnAl, and Rh_2MnBi on MgO substrates, which shows larger Kerr effect, e.g. in the case of $Co_2FeAl_{0.5}Si_{0.5}$ large Kerr rotation up to 0.5°. Finally, we investigated bulk perovskites $PrMn_{1-x}Fe_xO_3$ and $NdMn_{1-x}Fe_xO_3$.

We have determined energies of materials bandgaps, if any, its important transition energies, and complete permittivity tensors with induced magneto-optical off-diagonal parts. The goal was to compare the measurements with performed ab-initio calculations and fine tune them to obtain better basis for materials design to specific applications.

Ferromagnet thickness dependence of effective Dzyaloshinskii-Moriya field in W/(Co)FeB/MgO systems

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Spin-orbit torque (SOT)-induced magnetization switching and domain wall (DW) motion by in-plane current in heavy metal (HM)/ferromagnet (FM) heterostructures offer attractive capabilities for future spintronic devices. While the interfacial Dzyaloshinskii-Moriya interaction (DMI) plays a key role, underlying mechanism responsible for the interfacial DMI has remained elusive [1-3]. Here, we systematically investigate effective DMI field (H_{DMI}) in W(Co)FeB/MgO system to shed light on the factors relating to the interfacial DMI.

The stacks consisting of Si sub./(α or β)W(4)/(Co)FeB(t_{eff})/MgO(1.6)(/Ta(2)) (in nm) are prepared by dc/rf sputtering. We investigate field-induced DW motion under simultaneous application of in-plane (H_x) and perpendicular (H_z) fields [4] from creep to flow regime. We find that H_x dependence of DW velocity v_{DW} in creep regime obviously includes large antisymmetric contribution which precludes accurate evaluation of H_{DMI} [5]. Thus, we evaluate H_{DMI} in depinning or flow regime, where antisymmetric contribution is almost vanished as previously pointed out [6].

Interestingly, sign reversal of H_{DMI} and DW chirality is observed with varying ferromagnet thickness t_{eff} regardless of W phase and FM material (CoFeB or FeB). We will discuss possible scenarios to describe this intriguing behavior.

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Enhancement of the Spin Pumping Effect by Magnon Confluence Process in YIG-Pt Bilayers

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We present the experimental investigation of the Spin Pumping process[1] by both long-wavelength dipolar and short-wavelength exchange magnons parametrically excited in in-plane magnetized yttrium iron garnet/platinum bilayers. In our field-dependent measurements of the Inverse Spin Hall Effect[2] voltage, a clearly visible sharp peak is detected. It is found that the peak position is determined by the process of confluence of two parametrically exited magnons into one magnon having twice the frequency and the sum of the wave vectors of the initial magnons. We demonstrate that under the action of a rather strong parametric pumping[3] this confluence process results in the increasing of the total number of magnons in the magnetic sample, and thus leads to the enhancement of the Spin Pumping Effect.

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Long-distance supercurrent transport in a magnon Bose-Einstein condensate

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Currently, supercurrents in a room-temperature magnon Bose-Einstein condensate (BEC) have been reported [1]. The condensate is created by parametric microwave pumping in a tangentially magnetized yttrium-iron-garnet (YIG) film. We study the condensate by means of time-resolved Brillouin light scattering spectroscopy (BLS). By heating the sample, a spatially variation of the saturation magnetization is induced, which leads to a change of the magnon frequencies across the heated film. Because the magnon condensate is coherent across the entire heated area, a spatial varying phase shift is imprinted into its wavefunction. The spatial phase gradient generates a magnon supercurrent flowing out of the probing point. The earlier evidence of these supercurrents was obtained by an observation of the different relaxation behaviors of the magnon BEC under different heating conditions. By heating the sample with an external heat source, we are able to perform spatially resolved measurements. In this work we are showing the one-dimensional supercurrent transport measured over a large distance whereby travelling magnon density wave packets could be observed.

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Antiferromagnet layer thickness dependence of spin-orbit torque in PtMn/CoFeB structures

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The utilization of antiferromagnet (AFM) materials as a source of spin-orbit torques (SOTs) has attracted attention owing to its possibilities for next-generation devices including digital and analogue spintronic applications [1-3]. Understanding of the SOT generation mechanism is a key factor for successful implementation of AFM/ferromagnet (FM) structures for applications. While a previous work has pointed out an intrinsic mechanism of spin Hall effect in metallic AFMs [4], there are few experimental studies evaluating SOTs in AFM/FM systems [4-7]. Here, we quantify SOTs in AFM/FM PtMn/CoFeB heterostructures using an extended harmonic measurement technique [8,9] to obtain clues to understand the mechanism of SOT generation in AFM/FM systems.

We utilize Si/SiO_2 sub./Ta/Pt (or Ru)/$Pt_{38}Mn_{62}$/CoFeB stacks with various PtMn thicknesses (t_{PtMn}). The 1st and 2nd harmonic Hall voltages are simultaneously measured from patterned Hall-bar structures while applying AC current along the wire and magnetic field in the film plane [8,9]. From a fitting analysis of the magnetic field dependence of 2nd harmonic Hall signals using planar Hall resistance evaluated by 1st harmonic Hall signal, we obtain t_{PtMn} dependence of Slonczewski-like and field-like components of SOT, without any thermal effects. The results indicate a large SOT efficiency and an effective spin Hall angle ~ 0.1 of AFM PtMn, comparable to that of nonmagnetic metal Pt.

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Investigation of the exchange anisotropy in PtxMn1-x/Co70Fe30 Films

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Exchange bias (EB) can be observed by the exchange coupling between the magnetic moments of an antiferromagnet (AFM) and those of a ferromagnet (FM) at an AFM/FM interface [1,2]. There are many reasons to choose AFM materials for instances: the large exchange-biasing field, the high blocking temperature at which the exchange-biasing disappears, good corrosion resistance, minimal critical thickness, and surface flatness [3,4]. In this study We systematically investigated the exchange anisotropy for ferromagnetic $Co_{70}Fe_{30}$ and antiferromagnetic Pt-Mn bilayer films by Co-sputtering method. We focused on the relevance between the exchange bias and the composition of the Pt_xMn_{1-x} ($14 < x < 22$ and $45 < x < 56$ at %) films, and we successfully optimized the composition. The crystal structure of the Pt_xMn_{1-x} films was FCC for $14 < x < 22$ at % and FCT for $45 < x < 56$ at % after annealing at 370 ˚C for 6 hours. The unidirectional anisotropy constant (J_k) for fcc-$Pt_{15}Mn_{85}$ (20 nm) and fct-$Pt_{48}Mn_{52}$ (20 nm) prepared under optimum conditions in composition were 0.16 and 0.20 erg/cm^2, respectively. Both $Pt_{15}Mn_{85}$ and $Pt_{48}Mn_{52}$ films showed a larger unidirectional anisotropy constant (J_k) than in other reports for the bilayer system that uses Pt-Mn antiferromagnetic layer. They also showed a flatter surface than that of other antiferromagnetic/ferromagnetic materials, which is suitable to avoid unexpected interlayer coupling in spin-valve structure. The obtained Pt-Mn films with a large exchange anisotropy and slight roughness are useful as an antiferromagnetic layer in spintronic applications.

Key words: antiferromagnetic material, PtMn thin film, exchange anisotropy

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Effects of free layer size on magnetic properties and current induced magnetization switching in nanoscale CoFeB/MgO magnetic tunnel junctions

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CoFeB/MgO-based perpendicular magnetic tunnel junctions (MTJs) are attracting much attention for future low-power-consumption and high-performance memories. For actual applications, it is very important to understand magnetic properties and magnetization switching behavior for nanoscale MTJs, where their edge effects are expected to play crucial roles. In this study, we investigate magnetic properties (effective magnetic anisotropy field H_K^{eff} and damping constant α) and current induced magnetization switching (CIMS) for MTJs with various free layer sizes D.

We fabricate two types of MTJ to evaluate edge effects on magnetic properties and CIMS[1][2]. We use homodyne-detected ferromagnetic resonance (FMR) to evaluate magnetic properties[2]. To evaluate CIMS, we measure dependence of switching current density J_C on out-of-plane field in the two structures prepared by different processes. From both measurements, we find that the differences of behavior between two types of MTJ are clearly shown for smaller D.

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Spin-orbit torque-induced switching of in-plane magnetized elliptic nanodots detected using planar Hall effect

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Spin-orbit torque (SOT) induced magnetization switching has attracted great attention as a new writing method for magnetoresistive random access memories (MRAMs) [1-3]. SOT-MRAMs with an in-plane easy axis achieve sub-ns and field-free switching whose properties depend on the easy axis direction [4], and it is of high importance to systematically and statistically investigate the dependence of switching properties on the design of nanomagnets towards low-power and reliable operations. Here we develop a scheme to statistically evaluate the SOT switching properties of in-plane nanomagnets, where the planar Hall effect (PHE) is utilized to detect the magnetization direction. Using the scheme, switching properties are systematically evaluated as a function of size, aspect ratio, and easy axis direction of nanomagnets, and current pulse duration.

A stack, Ta/W/CoFeB/MgO/Ta, is deposited by sputtering on a Si substrate and patterned into devices with an array of elliptic CoFeB/MgO nanomagnets with various designs on top of a micrometer-scaled Ta/W Hall cross. This structure allows to provide a short turn-around time, sufficient signal-to-noise ratio (S/N), and statistical information. To detect the magnetization state, a transverse resistance due to PHE is measured under an application of off-axis and bidirectional in-plane fields. The field rotates the magnetization and gives rise to a differential Hall resistance ΔR whose sign depends on the original magnetization direction [5]. We confirm that this scheme works for all the studied nanomagnet designs with arbitrary easy-axis angles by choosing a proper off-axis field direction. We systematically evaluate threshold current density for samples with different easy axis directions using current pulses with various widths. Based on the obtained results, we discuss the favorable design to realize high-speed and low-current SOT-MRAMs.

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Magnetization dynamics in Pt/FM/AFM stack films

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Electric field-induced magnetization switching in perpendicular magnetic anisotropy ferromagnetic/antiferromagnetic (FM/AFM) stack films has been reported by using a conventional electric measurement.[1] To realize the device applications for these systems, the investigation and the control of the magnetization dynamics, such as the Gilbert damping constant (α) are essential. Herein, we chose Pt/Co/Cr_2O_3 as FM/AFM stacks, and then investigated the change in α of these stack films with the thickness of Co (t_{Co}) and Pt (t_{Pt}) layers in detail.

Pt(t_{Pt})/Co(t_{Co})/Cr_2O_3(200 nm)/Pt stack films were deposited on α-Al_2O_3(0001) substrates by DC magnetron sputtering. Their static magnetic properties were studied by a vibrating sample magnetometer at room temperature. The α of these stack films was investigated by a broadband ferromagnetic resonance measurement technique composed of a vector network analyzer and a coplanar waveguide. Fig. 1(a) and (b) show the dependence of α on t_{Co} (with t_{Pt} = 3 nm) and t_{Pt} (with t_{Co} = 1 nm), respectively. α decreases with the increase of t_{Co}, while increases with the increase of t_{Pt}. These behaviors can be explained by the spin pumping at the Pt/Co interface: the spin current generated in the Co layer is pumped to the Pt layer, and the degree for spin pumping depends on the thickness of both Co and Pt layers.[2,3] More details will be discussed in the presentation.

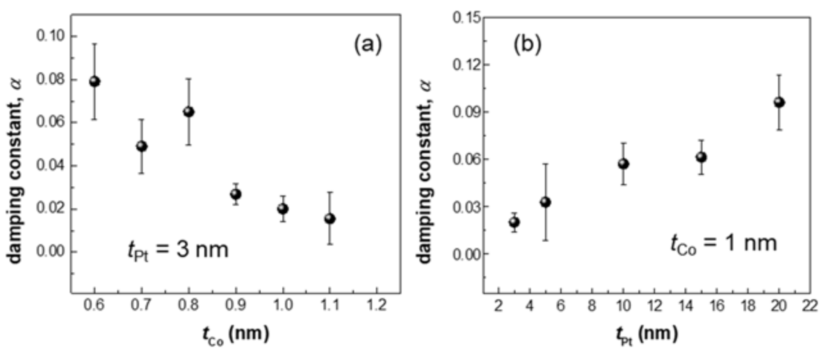

Fig. 1: The dependence of damping constant on (a) t_{Co}, and (b) t_{Pt}.

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Current direction-dependent spin Hall magnetoresistance in epitaxial Pt/Co bilayers on MgO (110)

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Experiments regarding spin-orbit torques have primarily been performed using polycrystalline metal/ferromagnet systems. However, an enhanced Rashba-Edelstein (RE) effect is expected in epitaxial Pt/Co bilayers since the D'yakonov-Perel (DP) spin relaxation mechanism is dominant, for example in epitaxial Pt thin films grown on MgO(111) substrates [1]. In this work, strong anisotropic spin Hall magnetoresistance (SMR) is observed at room temperature in epitaxial Pt/Co bilayers on MgO(110) along two in-plane crystal lattice directions normal to each other, $[001]$ or $[1\bar{1}0]$ (see Fig. 1 right inset).

As shown in Fig. 1, there is a striking difference in the SMR signals for Hall bars aligned with the $[001]$ or $[1\bar{1}0]$ directions. Spin Hall angle (θ_{SH}) values obtained from fittings based on the standard SMR model [2] are nearly equivalent between the two directions (θ_{SH} ~ 0.25 ± 0.05), but there is a large difference in the spin diffusion length ($\lambda_{sf}^{[1\bar{1}0]}$~ 0.25 ± 0.05 nm, and $\lambda_{sf}^{[001]}$~ 0.71 ± 0.02 nm). These extremely small λ_{sf} values indicate that this standard SMR model is not entirely valid for these epitaxial samples, and that the RE effect plays a role at the Pt/Co interface [1]. Furthermore, the results of resistivity $\rho_{[1\bar{1}0]}^{Pt}$~14 μΩ · cm < $\rho_{[001]}^{Pt}$~21 μΩ · cm and spin diffusion length $\lambda_{sf}^{[1\bar{1}0]} < \lambda_{sf}^{[001]}$ rule out the Elliot-Yafet spin relaxation mechanism

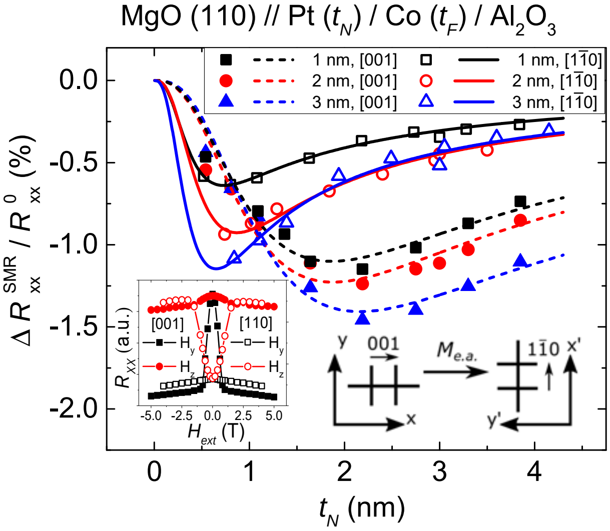

Figure 1. Pt thickness t_N dependence of SMR signal for various Co thicknesses. $[001]$ and $[1\bar{1}0]$ define the current direction in the Pt layer. Open/filled symbols are SMR data; solid/dotted lines are fits by

(in which $\lambda_{sf} \propto {}^{1}/_{\rho_{\mathrm{Pt}}}$) in these bilayers. This result suggests the DP mechanism is dominant, and is consistent with our previous work [1].

The sharp decrease in SMR signal in the $t_N > 1$ nm region seen in $[1\bar{1}0]$ oriented Hall bars could be explained by the higher resistivity in the $[001]$ direction, giving a much larger current shunting effect into the Co than for $[1\bar{1}0]$. Further analysis of the R_{XX} data (example in Fig. 1 left inset) indicates that the strong magnetic anisotropy gives an easy axis ($M_{e.a.}$) along the $[001]$ direction, regardless of Hall bar orientation.

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Two-dimensional wave vector resolved transport measurements of magneto-elastic bosons

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Macroscopic quantum states---Bose-Einstein condensates (BECs) can be created in overpopulated gases of bosonic quasiparticles as excitons, polaritons or magnons[1]. However, interactions between quasiparticles of a different nature, for example, between magnons and phonons in a magnetic medium, can significantly alter the properties of these gases and thus modify the condensation scenarios.
Recently, we reported on the discovery of a novel condensation phenomenon mediated by the magnon-phonon interaction[2]: an accumulation of hybrid magneto-elastic bosons. Unlike a BEC, the accumulated magneto-elastic bosons possess a nonzero group velocity, making them promising data carriers in prospective magnon spintronic circuits. Here, we present the results of two-dimensional transport measurements of magneto-elastic bosons in a single-crystal yttrium iron garnet film. Due to the strong magnetically induced anisotropy the curvature of the magnon-phonon spectrum is changed in the hybridization area and therefore we observe several spatially localized beams with different group velocities for the magnon-phonon hybrid states. The nature of the observed beams and their relations with caustic effects is discussed.
This work is supported by the European Research Council within the ERC Advanced Grant "Supercurrents of Magnon Condensates for Advanced Magnonics".

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Time and spatial evolution of spin-orbit torque-induced switching in W/CoFeB/MgO

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Spin-orbit torque (SOT) induced magnetization switching has attracted considerable interest as a writing scheme of information for nonvolatile spintronics devices [1-3]. In order to understand the time and spatial evolution of magnetization during the switching, we systematically investigate SOT-induced magnetization switching in W/CoFeB/MgO structures with various dot diameters D using pulsed current with various widths τ [4]. In the large device with D = 3500 nm, switching mode changes from probabilistic, full/none switching to partial switching with reproducible degree as τ decreases from 500 ns to 5 ns. At τ = 500 ns, the probability of switching reflects the probability of nucleation. Since no partial switching is observed in this case, 500 ns is considered to be long enough for domain wall(s) to sweep and reverse the whole dot. On the other hand, the partial and reproducible switching observed at τ = 5 ns suggests that the domain wall(s) cannot sweep through the whole dot due to a limited speed of domain wall although the pulsed current is large enough to induce the nucleation with 100% probability. As D decreases from 3500 nm to 700 nm, switching behavior does not change significantly, suggesting multiple nucleation taking place and domain walls propagating only in small areas among the nucleation sites. In contrast, devices with further reduced size (D = 120 nm) show only probabilistic, full/none switching, indicating that nucleation governs the switching.

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Magnon Chemical Potential Evolution during the BEC Formation by Rapid Cooling

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In previous studies, the conditions for the formation of a magnon Bose-Einstein Condensate (BEC) are artificially created by parametric pumping [1]. Recently we presented a fundamentally new approach. Fast DC current pulses applied to yttrium-iron-garnet (YIG)/Pt microstructures result in a strong heating. The rapid cooling of the micro-sized system leads to a non-equilibrium of the magnon and the phonon system. The consequent spectral redistribution of magnons leads to a strong increase of the population at the bottom of the spectrum, which, in this work, is observed by using Brillouin light scattering spectroscopy (BLS). At the same time the population of the first thickness mode is found to rise only marginally.
The relative intensities of both modes allow for the direct determination of the chemical potential. The obtained results clearly show that the chemical potential reaches the minimum energy in the magnon spectrum after the heating current is switched off, and, therefore, directly confirm the formation of the magnonic BEC by rapid cooling.
This research has been supported by ERC Starting Grant 678309 MagnonCircuits, ERC Advanced Grant 694709 Super-Magnonics and DFG Grant DU 1427/2-1.

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Anomalous spin-orbit torques on Py layer via Edelstein effect at W/Pt interface

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Magnetization switching induced by spin-orbit (SO) torque is central issue in spintronics for more efficient devices such as storage or logic device. A threshold current density for the switching is proportional to inverse of a spin-torque efficiency. So a lot of materials have been intensively studied so far. Recently there are several challenges for novel SO materials like oxidized metals (CuOx[1], WOx[2]) or artificial SO lattice (Pt/FM/Ta[3], Pt/W/FM[4]), where FM is ferromagnet. Especially, for making novel artificial lattice structures, we could design new materials based on conventional SO materials whose properties are well known. In this study, we investigated $Ni_{80}Fe_{20}$(Py)/W/Pt trilayer system by means of spin-torque ferromagnetic resonance (ST-FMR) measurement. We found that Py(5nm)/W(2nm)/Pt(1nm) has anomalous behavior because the detected signal has opposite sign compared to that for Py(5nm)/W(2nm)/
Al_2O_3(2nm) as a reference and consists of almost Lorentzian spectrum. This implies that there are two effects on it as shown below. At first, an additional damping-like field appears by a contribution of the W/Pt interface because it is not possible for only Pt to overturn the sign. At second, comparable field-like (FL) field to Oersted field emerges and the signs are opposite each other. We concluded that these SO fields are originated from Edelstein effect at W/Pt interface, diffusive spin transport in W layer, and spin accumulation at Py/W interface.

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Solitons in one-dimensional mechanical linkage

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Certain types of classical chains admit topologically protected zero-energy modes that are localized on the boundaries. The static feature of such localized modes was first investigated by linearized equations of motion of the mechanical chain, and a certain topological invariant is used to explain the existence of the boundary modes [1]. It was further observed that the description of the dynamical properties of the localized modes requires the nonlinearity of the system [2]. We investigate quasiperiodic solutions of the nonlinear equations of motion of one-dimensional classical chains. We introduce the description of solitons in such discrete systems as quasiperiodic solutions in the configuration space of the mechanical chain. This allows us to define solitons without relying on a continuum theory. Furthermore, we discuss the dynamics of solitons in inhomogeneous systems by connecting two chains with different parameter sets, where nontrivial transmission and reflection properties of solitons at the boundary of the two chains are exhibited [3].

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Magnetization Reversal of a 1X/X nm Perpendicular Shape-Anisotropy MTJ

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Perpendicular-easy-axis (Co)FeB/MgO [1] is a de-facto material stack system for magnetic tunnel junctions (MTJs) in spin-transfer torque magnetoresistive random access memory (STT-MRAM). This stack allows to miniaturize the MTJ while keeping high performance down to around 20 nm [2], below which a new approach needs to be explored to achieve high enough thermal stability. Recently, to address this issue, we showed a shape-anisotropy MTJ, where the shape anisotropy positively contributes to the perpendicular anisotropy by reducing the free layer diameter D and increasing the thickness t. High thermal stability and STT-induced switching are demonstrated for MTJs even below 10 nm, or the single-digit-nanometer scale [3]. An important question for the shape-anisotropy approach is the coherency/incoherency along the vertical direction of magnetization reversal, because the benefit of this approach presupposes a single-domain model. Here we elaborate the physics of the shape-anisotropy MTJ, the magnetization reversal mechanism and upper limit of the thickness. We firstly measure the magnetic field angle θ_H dependence of the switching field [4] for fabricated MTJs and show that the result is well described by an astroid-like curve derived from the single-domain model, suggesting coherent reversal of the MTJ. We then discuss the thickness dependence of reversal mode during current-induced switching from micromagnetic simulations of shape-anisotropy MTJs with various t. The simulation results indicate that single-domain switching occurs until an upper limit of $t \sim$ 30nm (the domain wall width). These results indicate that our concept of the shape-anisotropy MTJs drawn from predictions of the single-domain analytical model [4] is valid, allowing high performance STT-MRAM to be realized in a single-digit-nanometer scale.

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Analogue Spin-Orbit Torque Devices for Artificial Neural Network Applications

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Development of nonvolatile memories for computers with the von Neumann architecture has been one of the mainstream outlets of spintronics research in the last few decades. Meanwhile, non-von Neumann architectures have attracted great attention in the field of information processing, completing complex tasks at high speeds and at low power consumption levels that conventional computers struggle with. In this work, we introduce a previously reported spin-orbit torque (SOT) induced switching device [1] and show its capability to demonstrate a brain-like associative memory operation [2]. The device's material stack structure, mainly comprised of an antiferromagnet (AFM)-ferromagnet (FM) stack structure, which was found to show analogue-like resistance switching, is first improved upon to characterize an artificial synapse. These characteristics involve improving the dynamic switching range of anomalous Hall resistance in the device, which represents the perpendicular component of magnetization in the FM layer, and increasing the stability of the device to external effects [3]. The fabricated 36-devices' array is then implemented into a demonstration system as synapses to associate several 3×3 block patterns through learning. The system determines a synaptic weight matrix that describes the weight relating one block to the other blocks, then produces a "recalled" vector based on the synaptic weight matrix and compares it to a "memorized" vector stored in the computer memory. If the "recalled" vector and "memorized" vectors differ, an iterative learning process [4] is conducted, where the synaptic weights of the devices are adjusted in an analog manner. The direction cosine of each test, or the agreement between the recalled vectors and memorized vectors (1 being complete agreement), is determined to test the system's learning ability, when one block in the pattern is 'flipped'. Over 100 tests, the neural network 'recovered' from a direction cosine value of 0.601 before learning, to a value of 0.852, demonstrating the improved SOT device's capability, as a synapse, to learn patterns for associative memory [2].

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Angular dependence of longitudinal and transverse magnetoresistance in antiferromagnet/nonmagnet metallic heterostructures

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The possibility for utilization of antiferromagnets (AFMs) as multifunctional components of spintronic devices has opened new directions in the field of spintronics [1-3]. One of the major hurdles concerning the realization of pure antiferromagnetic spintronics is an electrical detection of antiferromagnetic moments which have no net magnetization. Recent results have revealed that the interaction of antiferromagnetic moments with charge/spin currents might serve as a robust electrical probe for detection [4-6]. However, an investigation concerning the magnetoresistance (MR) effects in AFM/NM metallic structures have remained elusive. Here, we study magnetoresistive effects in PtMn/Pt and show the existence of an appreciable MR in this metallic structure.

Multilayer films of sub./Ta/Pt/MgO/$Pt_{0.38}Mn_{0.62}$/Pt/Ru [PtMn/Pt, hereafter] and sub./Ta/Pt/MgO/$Pt_{0.38}Mn_{0.62}$/Ru [sub./PtMn, hereafter] are patterned into μm-sized devices by photolithography and Ar ion milling. We investigate PtMn thickness (t_{PtMn}) dependence of longitudinal and transverse MR for applied magnetic field rotations along x-y, y-z and x-z planes. Quantification of the various MR effects in PtMn/Pt and sub./Pt structures are obtained from t_{PtMn} dependence of MR and their respective functional dependencies. Our experimental results indicate a dominant role played by spin Hall magnetoresistance towards the observed MR behavior in PtMn/Pt [7]. The present study highlights the possibility of electrical detection schemes in AFM/NM metallic structures offering an unexplored pathway for antiferromagnetic spintronics.

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