17th RIEC International Workshop on Spintronics

and

10th JSPS Core-to-Core Workshop on "New-Concept Spintronic Devices"

Agenda & Abstracts

Date: December 3(Tue.) -6(Fri.)

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

17th RIEC International Workshop on Spintronics
and
10th 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 Science and Innovation in Spintronics (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 (GP-Spin), Tohoku University

Committee and Secretariat

- RIEC Workshop -

Chair: S. Fukami, H. Ohno
Local staff: S. Kanai, J. Llandro, B. Jinnai, S. DuttaGupta, C. Zhang
Secretariat: N. Sato

- Core-to-Core Workshop -

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

Timetable for
17th RIEC International Workshop on Spintronics
and
10th JSPS Core-to-Core Workshop on "New-Concept Spintronic Devices"

Date: December 3 (Tue.) – 6 (Fri.), 2019
Venue: Laboratory for Nanoelectronics and Spintronics, Conference Room (4F),
Research Institute of Electrical Communication (RIEC), Tohoku University

Dec. 3 (Tue.)

	Registration	
13:15-13:25	Opening	
13:25-14:05	Tu-1	M. Stiles
14:05-14:45	Tu-2	Y. Suzuki
14:45-15:05	Break	
15:05-15:35	Tu-3	S. Woo
15:35-16:05	Tu-4	A. Kurenkov
16:05-16:55	Tu-5	I. Kataeva

Dec. 4 (Wed.)

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9:30-10:00	We-2	P. Pirro
10:00-10:30	We-3	K. Oyanagi
10:30-10:50	Break	
10:50-11:20	We-4	S. Mangin
11:20-11:50	We-5	S. Mizukami
11:50-12:20	We-6	M. Aeschelimann
	Group Photo	
	Lunch	
14:00-14:30	We-7	Y. Ando
14:30-15:00	We-8	K. McKenna
15:00-15:30	We-9	G. Reiss
15:30-15:50	Break	
15:50-16:20	We-10	W. Borders
16:20-17:10	We-11	M. Ohzeki
	Transfer	
18:20-19:50	Banquet	

Dec. 5 (Thu.)

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9:40-10:10	Th-2	R. Umetsu
10:10-10:40	Th-3	M. Shirai
10:40-11:00	Break	
11:00-11:30	Th-4	J. Chen
11:30-12:00	Th-5	T. Seki
	Lunch	
13:50-14:30	Th-6	T. Ono
14:30-15:00	Th-7	A. Hrabec
15:00-15:30	Th-8	D. Pinna
15:30-17:00	Poster	

Dec. 6 (Fri.)

9:10-9:50	Fr-1	Y. Otani
9:50-10:20	Fr-2	Y. Mokrousov
10:20-10:40	Break	
10:40-11:10	Fr-3	J. Wunderlich
11:10-11:40	Fr-4	T. Dietl
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17th RIEC International Workshop on Spintronics

and

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Program

● December 4 (Tuesday)

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Opening

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Spintronics for neuromorphic computing

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Unconventional computations using magnetic nano-dots and skyrmions

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15:05-15:35

Tu-3 **S. Woo (IBM)** 18

New materials and devices in skyrmionics

15:35-16:05

Tu-4 **A. Kurenkov (Tohoku University)** 19

Uniform artificial synapse and neuron based on spintronic devices

16:05-16:55

Tu-5 **I. Kataeva (DENSO)** 20

Neuromorphic computing using analog memristive crossbars for automotive applications

● December 4 (Wednesday)

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2D mutually synchronized spin Hall nano-oscillator arrays for highly coherent microwave signal generation and neuromorphic computing

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Magnonics for neuromorphic applications

10:00-10:30

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Paramagnetic spintronics

10:30-10:50

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We-4 **S. Mangin (Universite de Lorraine)** 24

All-optical helicity dependent switching in ferromagnetic layers

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We-5 **S. Mizukami (Tohoku University)** 25

Laser-induced magnetization dynamics in synthetic antiferromagnets

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We-6 **M. Aeschelimann (University of Kaiserslautern)** 26

Laser-Induced intersite spin transfer

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We-9	**G. Reiss (Bielefeld University)**	29
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SX-RIXS measurements under magnetic field for Heusler alloys with half-metallic electronic state

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Th-5 **T. Seki (Tohoku University)** 36

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17th RIEC International Workshop on Spintronics
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Poster Program

Oral presentation

Spintronics for neuromorphic computing

Mark D. Stiles[1]
[1]National Institute of Standards and Technology, Gaithersburg, Maryland, 20899-6202, USA

Human brains can solve many problems with orders of magnitude more energy efficiency than traditional computers. As the importance of such problems, like image, voice, and video recognition increases, so does the drive to develop computers that approach the energy efficiency of the brain to solve them. Magnetic devices have several properties that make them attractive for such applications. I give a brief overview of the variety of devices and approaches that are under consideration [1,2] and then focus on magnetic tunnel junctions. Based on the ability to read the magnetic state of a tunnel junction through the tunneling magnetoresistance and the ability to electrically control it through spin-transfer and spin-orbit torques, magnetic tunnel junctions are actively being developed for integration into CMOS integrated circuits to provide non-volatile memory. This development makes it feasible to consider other geometries that have different properties. I describe computing schemes based on two such alternative configurations, spin-torque nano-oscillators, which can be excited into an oscillatory state and used in analogy with oscillatory processes in the brain and superparamagnetic tunnel junctions, which thermally fluctuate between states and can be used in analogy to the stochastic process in the brain. Finally, I focus on representative projects for each of these structures from work by collaborators. The first [3] uses spin-torque nano-oscillators in a reservoir computing scheme and the second [4] uses superparamagnetic tunnel junction for stochastic computing.

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[3] Neuromorphic computing with nanoscale spintronic oscillators, J. Torrejon, M. Riou, F. Abreu Araujo, S. Tsunegi, G. Khalsa, D. Querlioz, P. Bortolotti, V. Cros, K. Yakushiji, A. Fukushima, H. Kubota, S. Yuasa, M. D. Stiles and J. Grollier, Nature 547, 428 (2017).
[4] Energy-efficient stochastic computing with superparamagnetic tunnel junctions, M. W. Daniels, A. Madhavan, P. Talatchian, A. Mizrahi, and M. D. Stiles (to be published).

Unconventional computations using magnetic nano-dots and skyrmions

Yoshishige SUZUKI[1]

[1]Graduate School of Engineering Science, Osaka Uni., Toyonaka, Osaka, Japan

[2]National Institute of Advanced Industrial Science and Technology (AIST), Spintronics Research Center, Ibaraki, Japan

[3]Center for Spintronics Research Network (CSRN), Osaka University, Japan

Recent successes in deep neural network (DNN) were obtained by simplifying the Boltzmann machine. Therefore, we may expect a possibility to realize a machine that is superior to the DNN. Trials to make such machine have already shown some successes in the spintronics [1, 2]. Those examples encourage us to explore non-von Neumann architectures. In this talk, two of such trials will be presented.

The first is a “Natural computing” using a magnetic nano-dot system. Since we use natural dynamics of the system, after input of the information, the calculation process does not need energy, in principle. In practice, however, voltage control of anisotropy is used to control a flow of information. In addition, a frame work of the reservoir computing [3] is used to perform machine learning. Preliminary results proved the non-linear calculation availability of the dipole-coupled nano-dot array [4].

In the second, Brownian motion of skyrmions under a control of Maxwell’s demon was employed to proceed a computation. The concept is known as “Brownian computation” [5, 6]. By fabricating skyrmion babbles in amorphous CoFeB films, skyrmion bubbles with high diffusion constant were obtained. Channels for the skyrmions were formed by using fine control of passivation layer thickness [7]. The method provided free motion of skyrmions through a blanch of the channels that is one of the essential ingredients of the Brownian computer.

Acknowledgement This research and development work was supported by the Ministry of Internal Affairs and Communications.

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New materials and devices in skyrmionics

Seonghoon Woo[1]
[1]IBM TJ Watson Research Center, Yorktown Heights, NY 10598, USA

The field of skyrmion-electronics (called *skyrmionics*) has been actively investigated across a wide range of topics, mainly inspired by the fascinating physical properties of magnetic skyrmions [1-2]. In this talk, I will present our recent experimental achievements on the new material platform and device scheme where magnetic skyrmions can be stabilized and harnessed to realize non-conventional energy efficient future spintronics applications [3-4]. For the first part of this talk, I will present the demonstration of all-electrical fully functional skyrmion-based neuromorphic computing device, using metallic ferrimagnetic multilayers [3]. In this work, we demonstrate an electrically-operating skyrmion device, where electric current-controlled generation, motion, detection and deletion are realized in a Pt|GeFeCo|MgO ferrimagnetic heterostructure-based single device at room temperature. Moreover, utilizing the unique topological characteristics of skyrmions, we present a highly efficient skyrmion-based artificial synaptic device designed for bio-inspired neuromorphic computing and thus artificial neural network (ANN), which could be used in broader technology fields in the future. In the second part of the talk, I will present a new novel material platform, van der Waals (vdW) ferromagnetic crystals, where magnetic skyrmions and their lattice structure can be stabilized [4]. Very recently, it has been reported that 2D vdW crystals can also have long-range intrinsic ferromagnetism in few materials with strong magnetic anisotropy. Due to the broken inversion symmetry and expected large spin-orbit coupling of vdW magnets, vdW magnets could permit the presence of Dzyaloshinskii-Moriya (DM) interaction that could stabilize magnetic skyrmions. We present such demonstration of magnetic skyrmions and their crystal formation in ferromagnetic vdW crystals, Fe_3GeTe_2 (FGT), where the experimental findings are supported by ab-initio calculation study using DFT, envisioning the possible physical origins of DMI in vdW Fe_3GeTe_2 flakes.

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Uniform artificial synapse and neuron based on spintronic devices

Aleksandr Kurenkov[1,2,3], Samik DuttaGupta[1,2,3], Chaoliang Zhang[3,4], Shunsuke Fukami[1,2,3,5,6], Yoshihiko Horio[3] and Hideo Ohno[1,2,3,5,6]

[1]CSIS, Tohoku University, Sendai 980-8577, Japan

[2]CSRN, Tohoku University, Sendai 980-8577, Japan

[3]RIEC, Tohoku University, Sendai 980-8577, Japan

[4]FRIS, Tohoku University, Sendai 980-0845, Japan

[5]CIES, Tohoku University, Sendai 980-8577, Japan

[6]WPI-AIMR, Tohoku University, Sendai 980-8577, Japan

The human brain performs complex cognitive tasks with an unprecedented efficiency which is far superior to von Neumann machines. To achieve such complexity and efficiency in artificial systems, one needs to reproduce its architecture in hardware. A major obstacle here is that functionalities of the unit elements—synapses and neurons—are complex and very different. The functional complexity requires an inefficiently large number of CMOS components per device, and thus forces realization of synapses and neurons in new material systems and based on new approaches. At the same time, the differences force these materials and approaches to be incompatible. This incompatibility impedes development of functional neuronal networks from the artificial synapses and neurons because of the very large number of unit-to-unit interconnections. This long-standing issue has resulted in the absence of very large-scale efficient spiking neural networks required for advanced cognition.

Here we will show how spintronics can help to reconcile the contradictory requirements of synapses and neurons and to realize them in a lean and biologically plausible way by considering an antiferromagnet/ferromagnet heterostructure with field-free spin-orbit torque switching [1,2]. First, control of its switching mode from binary to analog-like [3] will be discussed. This is an essential requirement to realize binary firing/nonfiring states of the neuron and analogue weight memorization of the synapse in the same material stack. Next, we will show that a uniform mechanism of “local time” can drive the functionalities of synapses and neurons despite their differences. To realize such a mechanism in the considered spintronic devices, their dynamical properties under current pulses down to 1 ns will be analyzed. After identifying a suitable dynamical process, it will be used as a timer and thereby as a basis for artificial synapses and neurons.

Finally, all the discussed physical properties will be combined to demonstrate units with inherent synapse- and neuron-like properties, made from the same material and driven by a uniform principle [4]. We will show that the devices respond like their biological counterparts, which makes them promising candidates for future artificial spiking neural networks, and discuss their operation.

A portion of this work was supported by JSPS KAKENHI 17H06093, 18KK0143 and 19K15428, JST-OPERA, JSPS Core-to-Core Program and Cooperative Research Projects of RIEC.

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Neuromorphic Computing Using Analog Memristive Crossbars for Automotive Applications

Irina Kataeva[1]
[1]DENSO CORPORATION, Nisshin 470-0111, Japan

For the past several years, a field of artificial intelligence has been experiencing a boom with Deep Learning (DL) algorithms becoming state-of-the-art approach in a wide variety of fields like computer vision, speech recognition, automatic translation, and robotics [1], [2]. The superior performance of DL makes it an attractive technology to apply to automotive applications such as advanced driver assistance systems (ADAS) and self-driving cars. However, DL is a computationally expensive approach and requires power-hungry parallel hardware such as GPUs. It becomes especially challenging to use for automotive applications that require real-time processing at a limited power budget.

To alleviate the problem of high power consumption, significant effort is currently devoted to developing Deep Learning accelerators. The majority of those efforts focus on digital accelerators, but mixed signal neuromorphic circuits using emerging memory devices, such as phase change memories, magnetic tunnel junctions, ferroelectric memories, solid state electrolyte or metal oxide resistive switching devices, offer further improvement of performance [3], [4].

Our research focuses on analog neuromorphic circuits using metal oxide memristive devices. Our results include small-scale single- and multilayer perceptron prototypes using Al_2O_3/TiO_{2-x} passive crossbars developed in collaboration with University of California Santa Barbara [4], [5]. Recently, we have also been working on a large-scale prototype with 2.4M analog memristors integrated on top of CMOS circuits [6]. Furthermore, we have proposed effective training algorithms that take into account device characteristics and crossbar structure [7]. I will present these results in my talk.

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2D mutually synchronized spin Hall nano-oscillator arrays for highly coherent microwave signal generation and neuromorphic computing

M. Zahedinejad[1], Ahmad A. Awad[1], S. Muralidhar[1], R. Khymyn[1], H. Fulara[1], H. Mazraati[1], M. Dvornik[1], and J. Åkerman[1]

[1]Department of Physics, University of Gothenburg, 412 96 Gothenburg, Sweden

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

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

Given their high operating frequency (~10 GHz), easy fabrication, and highly robust synchronization properties, nano-constriction SHNO arrays are likely the most promising candidates for neuromorphic computing based on oscillator networks.

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Magnonics for neuromorphic applications

Philipp Pirro
Technische Universität Kaiserslautern and Landesforschungszentrum OPTIMAS
Kaiserslautern, Germany

Today's computational technology based on CMOS has experienced enormous scaling of data processing capability as well as of price and energy consumption per logic element. However, new ways to process and analyze data like brain-inspired computing can profit from novel hardware which implements the structure of logical concepts as directly as possible into a physical realization. In this context, spintronic systems are promising because of their intrinsic nonlinearity and the ability to store information.
I will discuss how the field of magnon spintronics can contribute to this development. Building blocks for magnonic devices which make use of the intrinsic nonlinearity of the spin-wave system will be presented. In addition, the ability to reconfigure these devices will be discussed. The basis for these devices is the recent development of nanoscaled magnonic systems with ultralow damping [1,2]. These systems could be used in the future to create magnonic nano-resonators which enhance the intrinsic nonlinearity. Using interference effects, such a resonator could serve as a magnonic activation function like it is used in neuromorphic computing. I will compare this building block of a magnonic neuron to the recently demonstrated optical neurosynaptic networks [3] and discuss the advantages and disadvantages of the magnonic realization. For the device to be able to learn, it needs the ability to have reconfigurable weights for its inputs. Thus, I will demonstrate how adjacent nanomagnets and the ground state of the resonator itself can be used to control the flow of spin waves and to change the functionality of the device in a non-volatile manner.

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Paramagnetic spintronics

Koichi Oyanagi[1], Takashi Kikkawa[1,2], and Eiji Saitoh[1-5]
[1]Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
[2]Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
[3]Department of Applied Physics, The University of Tokyo, Tokyo 113-8656, Japan
[4]Center for Spintronics Research Network, Tohoku University, Sendai 980-8577, Japan
[5]Advanced Science Research Center, Japan Atomic Energy Agency, Tokai 319-1195, Japan

The discoveries of new materials which show spintronic functions have stimulated progress in spintronics. After the demonstration of the injection/propagation/detection of spin currents in Pt/$Y_3Fe_5O_{12}$ junctions [1], a magnetic ordering insulator becomes an important player in spintronics. However, a paramagnetic insulator without magnetic ordering, has not attracted much attention so far, since it seems to be unlikely carrier of spin currents, and only few papers address fundamental spintronic functions [2,3].

Here we show key spintronic functions of paramagnetic insulators such as the injection/propagation/detection of spin currents [4] and spin Hall magnetoresistance (SMR) [5]. Our results unveil unique advantage of paramagnets and open a new research field: Paramagnetic spintronics.

This research is collaboration with Dr. S. Takahashi, Prof. G. E. W. Bauer, Prof. B. J. van Wees, Prof. F. Casanova, Prof. L. E. Hueso, and Prof. F. S. Bergeret.

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All-optical helicity dependent switching in ferromagnetic layers

Stéphane Mangin [1]

[1] Institute Jean Lamour, UMR CNRS 7198, Universite de Lorraine, Nancy, France

All-optical helicity dependent switching in ferromagnetic layers has revealed an unprecedented way to manipulate magnetic configurations by circularly polarized femtosecond pulse laser,[1,2]. It has been investigated using magneto-optical microscopy and anomalous Hall effect measurements. A state diagram is built by studying the effect of pulse duration, fluence, and spot size. We use numerical solutions of the three-temperature model to explain that the all-optical helicity-dependent switching mechanism relies on the spin bath reaching temperatures close to the Curie point. Further insights into the reversal process are provided by the experimental demonstration of significant helicity-dependent reversal after a single laser pulse that reveals the involvement of direct angular momentum transfer. Moreover, based on the observation that longer pulse durations and larger spot sizes lead to enhanced reversal efficiency, we identify experimental conditions that lead to saturated magnetization reversal after just a few tens of laser pulses.
We have also studied rare-earth free synthetic ferrimagnetic heterostructures made of two antiferromagnetically exchange coupled ferromagnetic layers are studied. Experiment results, supported by numerical simulation, show that the designed structures enable all optical switching controlled not only by light helicity but also by the relative Curie temperature of each ferromagnetic layer.

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Laser-induced magnetization dynamics in synthetic antiferromagnets

Shigemi Mizukami[1,2,3]
[1]WPI AIMR, Tohoku Univ., Sendai 980-8577, Japan
[2]CSRN, Tohoku Univ., Sendai 980-8577, Japan
[2]CSIS (CRC), Tohoku Univ., Sendai 980-8577, Japan

There are renewed interests in antiferromagnets [1-4]. One fundamental issue is to understand how we can manipulate and utilize Neel vector of antiferromagnets. Another interest is to explore rich physics originating from antiferromagnetic dynamics, such as antiferromagnetic magnon with left-right-handed symmetry [5]. Here we focuses synthethic antiferromagnets (SyAFs). SyAFs are layered structures of ferromagnet/ nonmagnet/ ferromagnets with interlayer antiferromagnetic coupling. One can easily tune properties of SyAFs with selecting materials and designing stacking, so that SyAFs are well suited to explore spin physics unique to antiferromagnetism [2]. In this talk, we will discuss magnon dynamics in SyAFs observed by an all-optical means [6]. We demonstrated that two eigen modes, namely acoustic ferromagnetic-like and optical antiferromagnetic-like magnon modes, are easily excited and probed by ultrashort laser pulses [6], which enabled us to observe the damping enhanced by the mutual spin pumping [6-8]. We will also discuss some nonlinear effect of magnons in SyAF.

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Laser-Induced Intersite Spin Transfer

Martin Aeschlimann
Department of Physics and Research Center OPTIMAS,
University of Kaiserslautern, Germany

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. Ultimately, light represents the fastest means to alter the state of a material since laser pulses can now be generated with extremely short temporal duration down to a few tens of attoseconds. One particularly interesting and novel scheme for the ultrafast manipulation of spins using light takes advantage of the optically-induced spin transfer (OISTR), which was recently introduced by Dewhurst et al. [1]. This microscopic mechanism is driven by a spin-selective direct optical excitation from one magnetic sublattice to another. Guided by time dependent density functional theory calculations, we are able to monitor the optically induced transient changes in different model systems, FePtMn, FeNi, and Heusler alloys in real time by time-resolved magneto-optical Kerr spectroscopy using high-harmonic generation. Exploiting the spectral sensitivity of this measurement technique we are able to follow the ultrafast spin transfer from Fe to Ni and Mn, respectively, during the optical excitation. OISTR, therefore, opens up a new avenue towards manipulating solids on timescales only limited by the duration of the exciting light pulse, which forecasts a control of the spin dynamics on the attosecond time scale.

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Application of Highly Sensitive Magnetic Field sensors with ferromagnetic tunnel junctions

Yasuo Ando[1,2,3]

[1]Department of Applied Physics, Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan
[2]Center for Science and Innovation in Spintronics (Core Research Cluster) Organization for Advanced Studies, Tohoku University, Sendai 980-8577, Japan
[3]Center for Spintronics Research Network, Tohoku University, Sendai 980-8577, Japan

The discovery of large tunnel magneto-resistance (TMR) effect at room temperature (RT) in magnetic tunnel junctions (MTJs) spurred intensive investigation of MTJ applications for spintronics devices. For sensor application, high sensitivity (or wide field range), low power consumption, small device size and low cost make it prime candidate of the next generation magnetic field sensor [1,2]. Here, sensitivity is defined as TMR-ratio/2H_k, where H_k is anisotropy field of the free layer. SQUID is currently the most sensitive of the magnetic sensor and is used for the measurement of biological fields. The sensor with MTJs has much advantage, in particular, the device can operate without liq. He, that is, the sensor can be used at room temperature. Therefore, we expect that the device can have wide application. We prepared the highly sensitive magnetic field measurement sensor with a magnetic tunnel junction (MTJ) microfabricated in series and parallel in order to reduce device noise and a magnetic field sensor module incorporating various circuits such as a bridge, an amplifier, a filter, etc., for improving the S / N ratio was fabricated. Using this module, a cardiac magnetic field was successfully measured. In addition, by canceling the environmental noise using two sensor probes, it was shown that a signal can be detected even outside the magnetic shield. In this presentation, we show the detailed characteristics of this sensor. The necessary technical challenges toward its realization and the feasibility in the future are discussed

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Understanding the role of extended defects in magnetic and resistive switching memory materials

J. Bean[1], A. C. M. Padilha[1], G. Bersuker[2], M. Nafría[3], M. Lanza[3], L. Molina-Luna[4], L. Alff[4], H. Ohno[5], Y. Ikuhara[6] and K. P. McKenna[1]
[1]Department of Physics, University of York, York, UK
[2]The Aerospace Corporation, El Segundo, California 90245, USA
[3]Dept. Enginyeria Electrònica, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain
[4]Technische Universität Darmstadt, 64287 Darmstadt, Germany
[5]Research Institute of Electrical Communication, Tohoku University, Sendai 980-8577, Japan
[6]Institute of Engineering Innovation, University of Tokyo, Tokyo 113-8656, Japan

Extended defects such as grain boundaries, heterointerfaces and surfaces are ubiquitous in memory devices. Often extended defects are deliberately introduced to realise particular functionalities (for example to inject spin polarized currents across an interface). In many other cases they are present simply as a result of the growth technique employed or the device architecture. In either case a proper understanding of the structure, magnetic, electronic and transport properties of extended defects is essential to realise high performance. In this talk, I will present some of our recent work combining predictive first principles modelling with experimental transmission electron microscopy to unravel the structure and properties of extended defects with relevance to applications in non-volatile memory technology. This will include grain boundaries and dislocations in MgO with relevance to MTJs [1-5] and grain boundaries in HfO_2 for ReRAM devices [6-8].

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Tuning superparamagnetism in perpendicular magnetic tunnel junctions

Günter Reiss, Karsten Rott and Jana Ludwig
Center for Spinelectronic Materials and Devices, Department of Physics, Bielefeld University, Universitaetsstrasse 25, 33615 Bielefeld, Germany

Magnetic tunnel junctions (MTJs) with magnetically perpendicular CoFeB electrodes [1] are key components for novel sensors and memory cells. For such MTJs with CoFeB electrodes thinner than ≈1.5nm, an unexpectedly low critical current density for spin-transfer-torque switching (≈10^4A/cm^2) has been found [2], and recent reports demonstrated a superparamagnetic behavior [3].

Such superparamagnetic MTJs (sp-MTJs) can serve to study superparamagnetism life and be useful for applications. Recently, we proposed a true random number generator based on sp-MTJs [4]. Moreover, they can serve in noisy neural- like computing. One precondition is a pronounced maximum of the sp-MTJ's thermal switching rate in dependence of an external input and a shift of these tuning curves by another external parameter. Mizrahi et al. [5] demonstrated this by varying the current through sp-MTJs.

We analyzed the thermally induced switching of exchange biased sp-MTJs with a stack sequence Ta(5)/Ru(30)/Ta(10)/Pd(2)/MnIr(8)/CoFe(1)/Ta(0.4)/$Co_4Fe_4B_2$(0.8)/ MgO(X)/$Co_4Fe_4B_2$(1.1)/ Ta(3)/ Ru(3) (units in nm), and the thickness X of the MgO was 1.2 nm, 1.4 nm or 1.6 nm. Dwell times have been taken for varying temperature, magnetic and electric field. Although the dwell times follow an Arrhenius law, they are orders of magnitude too small compared to a model of single domain activation. Including entropic effects removes this inconsistency and leads to a magnetic activation volume much smaller than that of the electrode. Comparing data for varying barrier thickness then allows to separate the impact of Zeeman energy, spin-transfer-torque and voltage induced anisotropy change on the dwell times. Based on these results, we demonstrate a tuning of the switching rates by combining magnetic and electric fields, which opens a path for their application in noisy neural networks.

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Probabilistic Computing with Stochastic Magnetic Tunnel Junctions

William A. Borders[1], Ahmed Z. Pervaiz[2], Kerem Y. Camsari[2], Shunsuke Fukami[1,3,4,5,6], Hideo Ohno[1, 3,4,5,6], and Supriyo Datta[2]

[1]RIEC/ [2]School of Electrical and Computer Engineering, Purdue University/ [3]CIES/ [4]CSRN/ [5]CSIS/ [6]WPI-AIMR (1, 3-6 Tohoku University)

Optimization problems are a class of complex problems that conventional computers struggle to solve. This struggle stems from the fact that optimization problems search for the most efficient solution out of a multitude of possible answers. For a while now, quantum computing has shown promise in solving these problems, but is currently limited by technological barriers including decoherence, the number of implementable many-body interactions, and a current requirement of cryogenic temperatures for operation.

In this work we demonstrate use of a probabilistic computer to solve integer factorization, which can be cast as an optimization problem [1]. We borrow an algorithm from the field of adiabatic quantum computing but implement it with probabilistic bits, or p-bits connected electrically at room temperature and composed of stochastic magnetic tunnel junctions (s-MTJs) fluctuating in time between 0 and 1. We first describe the characterization of s-MTJs where we modify a typical magneto-resistive random-access memory (MRAM) stack structure. We then connect the s-MTJ to conventional CMOS circuit components to create a three-terminal p-bit. By connecting eight p-bits we then demonstrate integer factorization up to 945. These result show that probabilistic computing with p-bits can provide a classical analogous to quantum computing and offer a scalable hardware for solving optimization problems.

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Quantum annealing and its practical applications

Masayuki Ohzeki[1,2,3]
[1]Graduate School of Information Sciences, Tohoku University, Sendai 980-8579, Japan
[2] Institute of Innovative Research, Tokyo Institute of Technology, Kanagawa, 226-8503, Japan
[3] Sigma-i Co. Ltd., Shinagawa, 108-0075, Japan

Quantum annealing is a generic solver of combinatorial optimization problem and is implemented by a hardware known as the D-Wave quantum annealer.

On the other hand, the neural network, which is a big success in developing the artificial intelligence and data science, is also attained via solving optimization problem.

In this talk, by taking the quantum annealer as an optimizer, we introduce several directions of its application.

One of the main topics would be an application of the quantum annealer to the deep neural network although the standard one only deal with the binary variables.

In addition, we will report a new type of the applications with machine learning.

Development of Antiferromagnetic and Spin Gapless Semiconducting Heusler Alloy Films

Yuki Yoshihara,[1] Kelvin Elphick,[2] M. Samiepour,[2] Kazumasa Yamada,[3] Hironaga Uchida,[1] Mitsuteru Inoue,[1] Takashi Kimura [3] and Atsufumi Hirohata [2]

[1] Department of Electrical and Electronic Information Engineering, Toyohashi University of Technology, Toyohashi 441-8122, Japan

[2] Department of Electronic Engineering, University of York, York YO10 5DD, United Kingdom

[3] Department of Physics, Kyushu University, Fukuoka 819-0395, Japan

Antiferromagnetic (AF) spintronics has attracted significant attention from the viewpoints of low magnetic susceptibility, zero net magnetisation and high frequency magnetisation dynamics [2]. 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 [3-5], which minimises the use of critical raw materials. 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.

We also investigated the structural and magnetic properties of a spin gapless semiconducting CoFeMnSi Heusler alloy film. We confirmed semiconducting behaviour in the film by measuring the conventional Hall effect. Angular dependence of transverse magnetoresistance was detected, which can be useful for magnetic sensor applications.

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SX-RIXS measurements under magnetic field for Heusler alloys with half-metallic electronic state

Rie Y. Umetsu
Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan

Soft x-ray resonant inelastic x-ray scattering (SX-RIXS) experiments were performed under magnetic field for bulk single crystals in some Heusler alloys. The SX-RIXS is thought to be powerful tool to prove the spin-polarized electronic structures because it is bulk-sensitive, site-selective and not affected by any external perturbation such as magnetic field. Thus, it gives selected information connected directly with a specific intermediate state to which the incident photon energy is tuned [1].

Single crystals of Mn_2VAl, Co_2MnSi and Co_2FeSi Heulser alloys were made by Bridgeman method with the size of 12 mm diameter and about 25 mm length. SX-RIXS was measured at room temperature at the ultra-high resolution soft x-ray emission spectroscopy station (HORNET) at the end of the long undulator beam line BL07LSU of SPring-8, Japan.

SX-RIXS for V and Mn 2*p* core excitation was measured for Mn_2VAl alloy. The *d*-*d* excitation due to the t_{2g}-e_g splitting is clearly observed for V under the L_3-edge excitation. The loss energy of the V *d*-*d* RIXS maximum is found to be about 2 eV, being comparable to the splitting energy between the theoretically predicted e_g and t_{2g} states. Magnetic circular dichroism (MCD) for the RIXS spectra is clearly observed for the Mn L_3-edge excitation. The sign and the shape of the RIXS-MCD are qualitatively reproduced in consistence with the DFT calculations [2,3]. SX-RIXS for Fe 2*p* core excitation for Co_2FeSi alloy was also investigated. The spectra were simulated theoretically by both of GGA and LDA+U. The characteristic feature of weak components observed around the elastic peak for the Fe L_3-edge excitation is well reproduced by the simulated spectra obtained by GGA.

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Computational design of half-metallic quaternary Heusler alloys for magnetic tunnel junctions

Masafumi Shirai[1, 2, 3]
[1]Research Institute of Electrical Communication (RIEC), Tohoku University, Sendai 980-8577, Japan
[2]Center for Spintronics Research Network (CSRN), Tohoku University, Sendai 980-8577, Japan
[3]Center for Science and Innovation in Spintronics (Core Research Cluster), Tohoku University, Sendai 980-8577, Japan

Half-metallic Heusler alloys are promising candidates for electrode materials of magnetic tunnel junctions (MTJ). The crucial problem of the MTJ using half-metallic Heusler alloys is steep reduction of tunneling magnetoresistance (TMR) with increasing temperature. Recently, we carried out comprehensive exploration of quaternary Heusler alloys with high Curie temperature and high spin polarization by means of *ab initio* calculation with the aid of machine learning.

First, we calculated various physical properties such as equilibrium lattice parameters, total energy, spin polarization, Curie temperature, magnetization and magnetic moment of each constituent atom for more than 4,000 sorts of quaternary Heusler alloys. Using these data obtained by *ab initio* calculation, we developed a predictor based on Random Forest for the stability and the Curie temperature of quaternary Heusler alloys. We confirmed relatively high precision of the predictor by feasibility studies. The predictor revealed about 500 candidates which are energetically stable and possess the Curie temperature higher than 800 K from among about 100,000 sorts of quaternary Heusler alloys. After assessment of the candidates, we successfully predicted several half-metallic Heusler alloys with high Curie temperature which had not been reported so far. For an example, the electronic and magnetic properties of CoIrMnZ (Z = Al, Si, Ga, Ge) obtained by *ab initio* calculation [1] will be presented.

This work was accomplished in collaboration with Tufan Roy, Takuro Kanemura, and Masahito Tsujikawa, and was partly supported by JST CREST (JPMJCR17J5), JSPS Core-to-Core program “New-Concept Spintronics Devices” and CSRN, Tohoku University.

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Electric induced magnetization switching in all oxide structure and single metallic layer

Liang Liu, Jihang Yu, Jingsheng Chen

Department of Materials Science and Engineering, National University of Singapore

Electrical manipulation of magnetization is essential for the integration of magnetic functionalities such as magnetic memories and magnetic logic devices into electronic circuits. The current induced spin-orbit torque (SOT) in heavy metal/ferromagnet (HM/FM) bilayers via the spin Hall effect and/or the Rashba effect provides an efficient way to switch the magnetization direction. In the meantime, current induced SOT has been used to switch a single magnetic layer such as a ferromagnetic semiconductor (Ga, Mn)As6 and antiferromagnetic metal CuMnAs with broken global/local inversion symmetry. Here we demonstrate the electrical switching of a perpendicular magnetized single ferromagnetic layer, $L1_0$-ordered FePt. Different from previously reported SOTs which either decreases with or does not change with the film thickness, the SOT in FePt increases with the film thickness. The SOT in $L1_0$ FePt single layer is attributed to the composition gradient in the atomically layered structure along the film normal direction which causes a new type of bulk-like inversion symmetry breaking. A linear correlation between the SOT and the composition gradient is observed.[1]

Furthermore, we combine a ferromagnetic transition-metal oxide with an oxide with strong SOC to demonstrate all-oxide SOT devices. We show current-induced magnetization switching in $SrIrO_3/SrRuO_3$ bilayer structures. By controlling the magnetocrystalline anisotropy of $SrRuO_3$ on (001) and (110)-oriented $SrTiO_3$ (STO) substrates, respectively, we design two types of SOT switching schemes. For the bilayer on STO (001) substrate, a magnetic field-free switching is achieved, which remains undisturbed even when the external magnetic field reaches 100 mT. The charge-to-spin conversion efficiency for the bilayer on STO (110) substrate ranges from 0.58 to 0.86, depending on the directionality of the current flow with respect to the crystalline symmetry.[2]

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Spin-Charge Conversion in Ferromagnetic Materials

Takeshi Seki[1,2] and Koki Takanashi [1,2]
[1] Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
[2] Center for Spintronics Research Network, Tohoku University, Sendai 980-8577, Japan

Highly efficient conversion from charge current (J_c) to spin current (J_s) and vice versa is the key for spintronic devices to improve their performance and to provide them with multi-functionalities. A promising way for conversion is to exploit large spin Hall effect (SHE) in nonmagnets (NMs). However, as in the case of SHE in NMs, one can also expect the spin-charge conversion in ferromagnets (FMs). In 2015, we reported the conversion from J_s to J_c in the ferromagnetic $L1_0$-FePt [Ref. 1], which was one of the pioneering studies on the spin-charge conversion in FMs. At the same time, the concept of spin anomalous Hall effect (spin-AHE) was proposed [Ref. 2], theoretically predicting that AHE also generates J_s in FM. The large spin-AHE can be used for the field-free magnetization switching of a perpendicularly magnetized free layer. Thus, the spin-charge conversion in FMs is a recent intriguing research topic.

In this talk, we introduce the large spin-AHE in an $L1_0$-FePt ferromagnet [Ref. 3]. By employing the giant magnetoresistance device consisting of $L1_0$-FePt / Cu / $Ni_{81}Fe_{19}$, we have evaluated the spin anomalous Hall angle (α_{SAH}) to be 0.25 ± 0.03 for the $L1_0$-FePt from the linewidth modulation of ferromagnetic resonance spectra by dc current application. This value is much larger than that for CoFeB reported previously [Ref. 4]. In addition, the evaluation of α_{SAH} at different configurations between J_c and magnetization allows us to discuss the symmetry of spin-AHE and gives the unambiguous evidence that spin-AHE provides a source of J_s. Thanks to the large α_{SAH}, we have successfully demonstrated spin-AHE-induced magnetization switching in $L1_0$-FePt / Cu / $Ni_{81}Fe_{19}$. In addition to the spin-AHE in $L1_0$-FePt, we will introduce our recent studies on the spin-charge conversion in a half-Heusler alloy NiMnSb [Ref. 5].

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Ferrimagnetic spintronics

Teruo Ono[1, 2]
[1] Institute for Chemical Research, Kyoto University, Uji 611-0011, Japan
[2] Center for Spintronics Research Network, Osaka University, Toyonaka, Japan

Rare earth-3d transition metal (RE-TM) ferrimagnetic compounds, in which RE and TM magnetic moments are coupled antiferromagnetically, have two distinct compensation temperatures, namely, the magnetization compensation temperature (T_M) where the magnetizations of RE and TM sub-lattices cancel each other and the angular momentum compensation temperature (T_A) where the net angular momentum vanishes.

We found the fast field-driven domain wall (DW) motion in ferrimagnetic GdFeCo at T_A [1]. The collective coordinate approach generalized for ferrimagnets and atomistic spin model simulations show that this remarkable enhancement of DW velocity is a consequence of antiferromagnetic spin dynamics at at T_A. The antiferromagnetic spin dynamics at T_A results in a peculiar phenomenon; vanishing the skyrmion Hall effect at T_A [2]. We also examined the effect of spin-transfer torque on the motion of DW ferrimagnets and found that adiabatic spin transfer torque changes its sign at T_A and non-adiabatic spin transfer torque shows a peak at T_A [3]. We also found bulk Dzyaloshinskii-Moriya interaction (DMI) in amorphous GdFeCo. This bulk DMI is attributed to an asymmetric distribution of elemental content in the GdFeCo layer, where spatial inversion symmetry is broken throughout the layer. [4].

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Chirally coupled nanomagnets

Aleš Hrabec[1, 2,3]
[1] Laboratory for Mesoscopic Systems, Department of Materials, ETH Zurich, 8093 Zurich, Switzerland
[2] Laboratory for Magnetism and Interface Physics, Department of Materials, ETH Zurich, 8093 Zurich, Switzerland
[3] Paul Scherrer Institut, 5232 Villigen PSI, Switzerland

Magnetically coupled nanomagnets have many potential applications including non-volatile memories, logic gates, sensors or domain wall-based devices [1]. In order to realize functional 2-D networks of coupled nanoscale magnetic elements such as those used for nanomagnet logic [2] and artificial spin ice [3], it is desirable to engineer effective lateral magnetic couplings in a controllable way. Up to now, this has been achieved by exploiting the long-range dipolar interaction. However, the dipolar interaction is non-local and scales inversely with the magnet volume, so limiting its use in applications involving nanometer sized structures and thin films.

In this presentation, I will demonstrate an alternative method to control the lateral coupling between adjacent magnetic nanostructures [4] based on the interfacial Dzyaloshinskii-Moriya interaction (DMI). In particular, we have patterned regions with in-plane (IP) and out-of-plane (OOP) magnetic anisotropy in a magnetic element using selective oxidation of Pt/Co/Al films to show that the magnetization in the OOP and IP parts of the islands can be chirally coupled via DMI arising from the Pt underlayer.

We have exploited this concept for various applications. For example, we have created synthetic lateral antiferromagnets, stable skyrmions with different numbers of IP rings and artificial spin ices based on a square lattice and kagome lattice. In addition, we have demonstrated field-free current-induced switching between multistate magnetic configurations in the chirally coupled thin-film nanomagnets via spin-orbit torques. Our work provides a platform to design tailor-made arrays of correlated nanomagnets with a future perspective to achieve all-electric control of planar logic gates and memory devices.

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Reservoir Computing with Random Magnetic Textures

Daniele Pinna[1], George Bourianoff[2], Karin Everschor-Sitte[1]
[1]Physics Department, Johannes Gutenberg University, Mainz 55188, Germany
[2]Intel Corporation (retired)

In this talk we will discuss how a random magnetic "fabric" composed of skyrmion clusters can be effectively employed to implement a computational technique known as reservoir computing [1]. This is achieved by leveraging the nonlinear resistive response of individual skyrmions to driving currents arising from the anisotropicmagneto-resistance effect (AMR). Time-varying current signals injected via contacts into the magnetic substrate are shown to be modulated by the fabric's AMR due to the current distribution following paths of least resistance as it traverses the geometry. By tracking resistances across multiple input/output contacts, we show how the instantaneous current distribution effectively carries temporally correlated information about the injected signal. This in turn allows us to numerically demonstrate simple pattern recognition.

We argue that the fundamental ingredients for such a device to work are threefold [2]: i) Concurrent probing of the magnetic state; ii) stable ground state; iii) nonlinear response to input forcing. Whereas this talk will only consider the use of skyrmion fabrics, the basic ingredients or reservoir computing will be argued to be general enough to spur the interest of the greater complex materials community to explore novel reservoir computing systems.

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Novel functions observed in a topological antiferromagnet

Y. Otani

Institute for Solid State Physics, The University of Tokyo, Kashiwa 277-8581, Japan

Center for Emergent Matter Science, Wako, Saitama 351-0198, RIKEN

CREST, JST, Saitama 332-0012, Japan

A chiral antiferromagnet Mn_3Sn has exhibited a large anomalous Hall effect (AHE) at room temperature, the magnitude of which reaches almost the same order of magnitude as in ferromagnetic metals irrespective of a tiny spontaneous magnetization of about 1 mT [1]. The first principle calculation revealed that this large AHE originates from a significantly enhanced Berry curvature associated with the formation of Weyl points near Fermi energy [2,3]. Even more recently, a detailed comparison between angle-resolved photoemission spectroscopy (ARPES) measurements and density functional theory (DFT) calculations revealed significant bandwidth renormalization and damping effects due to the strong correlation among Mn 3d electrons. Magnetotransport measurements also provide strong evidence for the chiral anomaly of Weyl fermions, i.e. the emergence of positive magnetoconductance only in the presence of parallel electric and magnetic fields [4]. In this way all the electronic properties of Mn_3Sn imply that spin Hall effect (SHE) could also take place in the Mn_3Sn.

In this study, we set up our device that consists of ferromagnetic NiFe and nonmagnetic Cu electrodes formed on the top surface of a micro-fabricated single crystal of Mn_3Sn. We found that antiferromagnets have richer spin Hall properties than non-magnetic materials, that is, in the non-collinear antiferromagnet Mn_3Sn, the SHE has an anomalous sign change when its triangularly ordered moments switch orientation. Our observations demonstrate that a novel type of contribution to the SHE (magnetic SHE, MSHE) and the inverse SHE (MISHE) that is absent in nonmagnetic materials can be dominant in some magnetic materials, including antiferromagnets. We attribute the dominance of this magnetic mechanism in Mn_3Sn to the momentum-dependent spin splitting produced by the noncollinear magnetic order. [5].

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Spin “Chirotronics”: From antiferromagnets to 3D chiral particles

Yuriy Mokrousov[1,2]
[1]Peter Grünberg Institut, Forschungszentrum Jülich, 52428 Jülich, Germany
[2]Institute of Physics, University of Mainz, 55128 Mainz, Germany

In the field of spintronics antiferromagnetic (AFM) materials steadily move to the center of attention owing to their unique properties which range from utter sensitivity to electrical currents, to a whole world of possible topological effects rooting in complex real- and reciprocal-space behavior [1]. In my talk I will show that the so-called scalar spin chirality (SSC), which is inherent to many AFM materials, can serve as a new type of emergent variable in magnetic materials, getting a handle on which can provide a way to material realization of novel phenomena. I will demonstrate that the SSC is ultimately responsible not only for the “topological” Hall effect of chiral AFMs, but it also mediates chiral light-matter interaction in magnets, and it is the ultimate source of the topological magneto-optical effects [2], which can provide a unique tool to access the degree of chirality of AFMs. Further, I will show that the SSC in AFMs gives rise to a “hidden” orbital order which manifests in what we refer to as topological orbital magnetization [3]. We uncover that the topological orbital magnetism originates in the Berry phase properties of electrons hopping on a non-collinear lattice, and it mediates novel exchange interactions among spins – the topological chiral interactions – which are able to stabilize an AFM order of given chirality without the need for Dzyaloshinskii-Moriya interaction or an external magnetic field, and which provide a clear way towards the realization of novel three-dimensional spin textures such as hopfions [4]. Finally, I will make it clear that the discussed phenomena are not limited only to systems which exhibit a finite SSC in their ground state, but are inherent to a wide class of ferromagnets and coplanar AFMs subject to thermal fluctuations [5]. I will also briefly discuss possible applications of uncovered effects in the realm of spin “chirotronics” – i.e. the part of spintronics which deals with creation, control and manipulation of the SSC as the key variable.

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Electrically and thermally detected Néel vector switching in a collinear antiferromagnet

Joerg Wunderlich[1,2,3]

[1] Institute of Physics, Academy of Sciences of the Czech Republic, Cukrovarnicka 10, 162 00 Praha 6, Czech Republic

[2] Institut for Experimental and Applied Physics, University of Regensburg, 93040 Regensburg, Germany

[3] Hitachi Cambridge Laboratory, JJ Thomson Avenue, Cambridge CB3 0HE, United Kingdom

Antiferromagnets are enriching spintronics research by many beneficial properties, including insensitivity to magnetic fields, neuromorphic storage characteristics, and ultrafast spin dynamics. Designing memory devices with electrical writing and reading is one of the central topics of antiferromagnetic spintronics. So far, such combined functionality has been demonstrated by 90° reorientations of the Néel vector, generated by the current-induced spin-orbit torque and detected by the linear response anisotropic magnetoresistance. [1, 2]
In my presentation, I will show that it is possible to also electrically control also 180° Néel vector reversal and propose a method how the two stable states with opposite Néel vector orientations can be electrically distinguished in the collinear antiferromagnet CuMnAs with broken time reversal and spatial inversion symmetries. [3] I will confirm our electrical detection approach by monitoring the antiferromagnetic domain structure using local thermal gradient and anisotropic magnetothermal power measurements to map domain structures in CuMnAs devices. This new technique is compared with synchrotron x-ray dichroism microscopy on biaxial CuMnAs, in which we map a reversible 90-switching domain in micrometer size. In uniaxial CuMnAs, we use a high-resolution near-field technique to map a polarity-dependent 180-degree domain switching. [4]

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Electric field effects in ferromagnetic (Ga,Mn)N and anitferromagnetic CuMnAs

Tomasz Dietl[1,2]

[1]International Research Centre MagTop, Institute of Physics, Polish Academy of Sciences, PL-02668 Warsaw, Poland

[2]WPI-Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan

Magnetization manipulation by an electric field has been demonstrated for many *hybrid* structures consisting of piezoelectric and ferromagnetic materials. We have found experimentally and described theoretically a sizable piezoelectromagnetic effect in eplilayers of piezoelectric magnetic insulator (Ga,Mn)N in paramagnetic [1] and ferromagnetic [2] phases.

Both the electric current and the electric field are considered as tools suitable to control the properties and the Néel vector direction of antiferromagnets (AFs). Among AFs, CuMnAs has been shown to exhibit specific properties that result in the existence of the current-induced spin-orbit torques commensurate with the alternating directions of staggered magnetization and, thus, allowing for Néel vector switching [3]. Recently, a reversible effect of an *electric field* on the resistivity of CuMnAs thin films have been observed employing an ionic liquid as a gate insulator [4]. The data have allowed us to determine the carrier type, concentration, and mobility independent of the Hall effect that may be affected by an anomalous component.

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Poster presentation

Spin-orbit field driven by Rashba-Edelstein effect at W/Pt interface

Shutaro Karube[1,2], Nobuki Tezuka[1,2], Makoto Kohda[1,2,3] and Junsaku Nitta[1,2,3]

[1] Department of Materials Science, Tohoku Univ.,

[2] Center for Spintronics Research Network, Tohoku Univ.,

[3] Center for Science and Innovation in Spintronics (Core Research Cluster) Organization for Advanced Studies, Tohoku University

Spin-orbit (SO) field generated via spin Hall effect (SHE) or Rashba-Edelstein effect (REE) is one of the most important topics in spintronics for both fundamental physics and practical applications. Therefore a lot of SO materials such as heavy metals or topological insulators have been intensively studied so far for high conversion efficiency or functionality. But the SO torque efficiency is a material specific value in any case. It is ideal for us to synthesize the SO materials which have variable efficiency on our purposes.

Here using a combination of heavy metals (HMs), we demonstrate to create extra SO fields such as damping-like (DL) and field-like (FL) fields on a $Ni_{80}Fe_{20}$(Py) layer via REE at a W/Pt interface away from the Py layer through spin diffusion in the heavy metal layer as shown in Figs. (a) and (b). This means that we can manipulate the effective SO fields via the interface generated by a combination of materials apart from SHE contribution, and synthesize a designable SO material. Moreover we found opposite sign of the extra FL field in an inverse stacking structure like Py/Pt/W compared with in the Py/W/Pt shown in Fig. (c). This implies that the extra field is coming from the HMs interface which has Rashba effect due to the change of the effective field direction at the interfaces.

This leads us to a new concept of “synthetic SO materials” which paves a way for seeking high efficiency or superior functionalities in SO torque.

Compositional Dependence of Exchange Anisotropy in $Pt_xMn_{100-x}/Co_yFe_{100-y}$

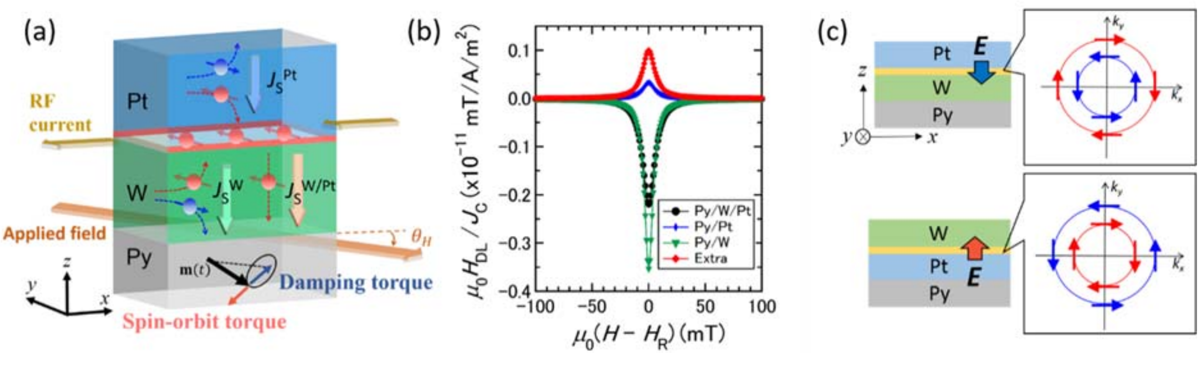

Fig. (a) Schematic image showing each spin current J_S generation via spin Hall effect from the W and Pt layers and Rashba-Edelstein effect from the W/Pt interface, (b)The generated damping-like field divided by charge current density J_C for Py(5nm)/W(2nm) (green triangles), Py(5nm)/Pt(1nm) (blue diamonds), and Py(5nm)/W(2nm)/Pt(1nm) (black circles). Red squares correspond to the extra component of the DL field, (c) Cross sectional views of the structures with effective electric field E at the HMs interface and expected Rashba spin polarization in cases of the normal stacking (Py/W/Pt) and the inverse stacking (Py/Pt/W).

Films and use its potential for Magnetic devices

Sina Ranjbar[1*], Muftah Al-Mahdawi[2], Masakiyo Tsunoda[3], Mikihiko Oogane[1,2], Yasuo Ando[1,2]

[1] Department of Applied Physics, Tohoku University, Sendai 980-8579, Japan

[2] Center for Science and Innovation in Spintronics (Core Research Cluster), Organization for Advanced Studies, Tohoku University, Sendai 980-8577, Japan

[3] Department of Electronic Engineering, Tohoku University, Sendai 980-8579, Japan

Bilayer films consisting of a 15-nm-thick Pt_xMn_{100-x} (x = 48 or 15) layer and a 2-nm-thick Co_yFe_{100-y} (0<y<90) layer were fabricated by ultra-high-vacuum magnetron sputtering. The $Pt_{48}Mn_{52}$ and $Pt_{15}Mn_{85}$ films consisted of face-centered-tetragonal (FCT) and face-centered-cubic (FCC) structures, respectively[1]. The effect of composition of Co-Fe films on the unidirectional anisotropy constant (J_k) in the Pt_xMn_{100-x} /Co_yFe_{100-y} bilayer films and the optimum conditions for producing large J_k were determined. The FCT and FCC PtMn films annealed at 370°C for six hours both exhibited maximum J_k when the film composition was $Co_{70}Fe_{30}$. Blocking temperatures of the FCT and FCC PtMn films were 410°C and 160°C, respectively[2]. Also we investigated the magnetic domain formation and fluctuations in the sensing layer which can be a major source of low-frequency noise in magnetic tunnel junction sensors. We studied the effect of exchange bias on the domain structure in micro-patterned Permalloy (Py: $Ni_{80}Fe_{20}$) sensing layer. We deposited single Py films, and $Pt_{48}Mn_{52}$/Py films, where the latter showed exchange bias. By controlling the thickness of Py, $Pt_{48}Mn_{52}$ (15nm)/Py (t=235 nm) showed a small coercivity and exchange bias of 7 Oe. After micro-fabrication into circular pillars 50 µm in diameter, we measured the domain structure by Magneto Optical Kerr Effect (MOKE) microscopy. MOKE images showed that single Py pillars have a simple closure domain, where the domain wall at the center moved with the applied field. The exchange-biased Py pillars exhibited a more complicated structure, but with fixed domains at the center region due to the exchange bias overcoming the magnetostatic energy. The uniform rotation of magnetization at the center of the sample is promising for decreasing the domain hopping magnetic noise.

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Composition dependence of spin-orbit torques in antiferromagnetic $Pt_{1-x}Mn_x$ ($0 \leq x \leq 1$)/CoFeB heterostructures

K.V. De Zoysa[1], R. Itoh [1], Y. Takeuchi[1], S. DuttaGupta[1-3], S. Fukami[1-5] and H. Ohno[1-5]

[1]RIEC, Tohoku University, Sendai 980-8577, Japan

[2]CSIS, Tohoku University, Sendai 980-8577, Japan

[3]CSRN, Tohoku University, Sendai 980-8577, Japan

[4] CIES, Tohoku University, Sendai 980-8577, Japan

[5] WPI-AIMR, Tohoku University, Sendai 980-8577, Japan

Spin-orbit torque (SOT) in antiferromagnet (AFM)/ ferromagnet (FM) heterostructures is a key ingredient for digital and analogue spintronic devices [1-4]. The co-existence of a large effective spin-Hall angle [5] and significant exchange-bias field [1] are required for a number of applications. These requirements are satisfied in Mn-Y (Y = 4*d* or 5*d* transition metal) metallic AFMs, making them promising for AFM-based spintronic devices. Previous experimental results on polycrystalline Mn-Y/FMs suggested a dominant contribution of Y towards SOT strength [6], while subsequent results indicated a different scenario [7]. Thus, systematic studies of composition dependence of SOTs in metallic Mn-Y/FMs are of necessity for better comprehension of SOT generation mechanism. Here, we evaluate SOTs in AFM/FM PtMn/CoFeB heterostructures as a function of Mn composition (*x* at.%) to obtain insights into the origin of SOT generation.

We utilize sub./Ta(3)/Ru(1.5)/$Pt_{1-x}Mn_x$(10)/$(Co_{0.25}Fe_{0.75})_{75}B_{25}$(1.8)/MgO/Ru(1) (in nm) structure, with various Mn-composition. We use extended harmonic Hall measurement technique for quantification of SOTs [8]. Slonczewski-like (H_{SL}) and field-like (H_{FL}) components of SOT effective fields are determined from fitting analysis of external magnetic field H dependence of 1st and 2nd harmonic signals. Our results show a non-monotonic variation for both H_{SL} and H_{FL} with x. We will discuss possible scenario that can account for the observed composition dependence of SOT. The present results show the possibility for tuning SOTs in Mn-based AFMs for next generation AFM/FM structures.

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Disentanglement of Spin-Orbit Torques in Pt/Co Bilayers with the

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Presence of Spin Hall Effect and Rashba-Edelstein Effect

Y. Du[1], H. Gamou[1], S. Takahashi[2], S. Karube[1,3], M. Kohda[1,3,4] and J. Nitta[1,3,4]

[1]Department of Materials Science, Tohoku University, Sendai 980-8579, Japan

[2]Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan

[3]Center for Spintronics Research Network, Tohoku University, Sendai 980-8577, Japan

[4]Center for Science and Innovation in Spintronics (Core Research Cluster), Tohoku University, Sendai 980-8577, Japan

The current-induced spin-orbit torques (SOTs) [1] provide a way to control local magnetizations electrically by utilizing strong spin-orbit coupling. In heavy metal/ferromagnet bilayers, the main effects accounting for the generation of SOT are the spin Hall effect (SHE) and the Rashba-Edelstein effect (REE), where the former is a bulk effect and the latter is an interface effect. While the origin of the SOT remains controversial, it can be decomposed into two orthogonal components, a (anti-)damping-like (DL) term and a field-like (FL) term. Conventionally, the SHE and REE are considered to be the origin of the DL-SOT and FL-SOT, respectively. However, theoretical studies have suggested an entanglement of SOT in such heavy metal/ferromagnet bilayers, *e.g.* the REE can produce a DL-SOT *via* a combined action of Rashba spin splitting and the exchange interaction between the Rashba spin accumulation and the local magnetization [2]; also, the SHE is able to produce a small FL-SOT [3]. Up to now, a quantitative, experimental evaluation of the SOT efficiency and the corresponding spin transport characteristic length by taking into account both effects, is lacking.

In this work, we present a SOT disentanglement in platinum/cobalt (Pt/Co) bilayers, a prototypical heavy metal/ferromagnet hetero-layer system where both SHE and REE are present. With a detailed Pt thickness and temperature dependent in-plane harmonic Hall measurement [4], the SOTs originated from the SHE in bulk Pt and from the REE at substrate/Pt and Pt/Co interfaces are successfully disentangled and quantified.

As a result, the saturated DL-SOT efficiency scales with Pt resistivity, suggesting an intrinsic (or perhaps side-jump) contribution to the SHE in Pt. The FL-SOT in our samples is originated from the REE, while both SHE and REE contribute to the DL-SOT. The extracted REE-induced FL-SOT (and also DL-SOT) efficiencies at sub./Pt and Pt/Co interfaces are in the same order of magnitude, but of opposite signs, consistent with the REE scenario. The characteristic lengths of SHE and REE are in the order of nanometers and angstroms, respectively. This work provides a unified picture of SOT in heavy metal/ferromagnet where SHE and REE are present.

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Large spin orbit torque in W/CoFeB/MgO with high W resistivity

[1]Laboratory for Nanoelectronics and Spintronics, RIEC, Tohoku Univ. [2]FRIS, Tohoku Univ. [3]CSIS, Tohoku Univ. [4]CIES, Tohoku Univ. [5]CSRN, Tohoku Univ. [6]CSIS (CRC), Tohoku Univ. [7]WPI-AIMR, Tohoku Univ.

K. Furuya[1], **Y. Takeuchi**[1], **B. Jinnai**[3], **S. Fukami**[1,3-7] **and H. Ohno**[1,3-7]

E-mail: kaitof@riec.tohoku.ac.jp

Spin-orbit torques (SOT) allows an electrical control of a magnetization orientation in magnetic heterostructures[1-3]. SOT has two components with different symmetries: the Slonczewski-like (SL) and field-like (FL) torques, whose magnitudes are characterized as spin-orbit torque efficiency parameters (ξ_{SL}, ξ_{FL})[4], where ξ_{SL} is equivalent to the effective spin Hall angle. To achieve the efficient control of the magnetization orientation, a material system that exhibits large ξ_{SL} is desirable. W is a promising material exhibiting large ξ_{SL}[5-8] and a recent study showed a variation of ξ_{SL} by a factor of 2-3 with W resistivity ρ_W in the range of 100-240 μΩcm[7]. Here we study the SOT of the W/CoFeB/MgO heterostructures by controlling ρ_W over a wide range (180-730 μΩcm) and discuss the mechanism for SOT generation in the heterostructures.

All stacks, consisting of W(5)/CoFeB(t_{CoFeB})/MgO(1.3)/Ta(1) (thickness in nm), are deposited on Si substrates by sputtering. Here t_{CoFeB} is the thickness of the CoFeB layer. Ar gas pressure to deposit W is controlled to change ρ_W. As shown in Fig. 1(a), ρ_W increases with Ar gas pressure by a factor of 4. SOT effective fields are evaluated using microfabricated devices by an extended harmonic Hall measurement[9,10]. Figure 2 shows the obtained ρ_W dependence of ξ_{SL} in the W/CoFeB/MgO structures, together with the reported values[5-7]. The results before and after annealing at 300°C are shown. Our results show that ξ_{SL} increases with the increasing ρ_W, following the trend of previous studies[5,7,8]. The highest ξ_{SL} of -1.2 is the largest magnitude which has ever been reported. It is also found that $\xi_{SL(FL)}$ decreases (increases) by annealing. From a relation between transverse and longitudinal resistivity, we will discuss the mechanism accounting for the generation of SOT in this system.

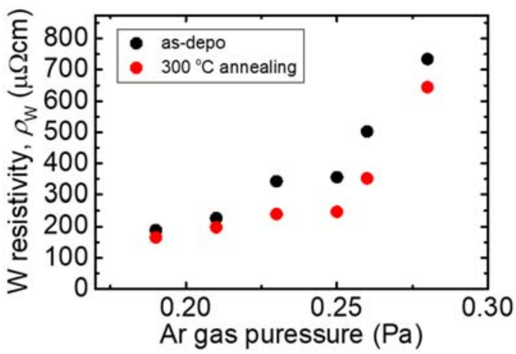

Fig. 1. ρ_W vs Ar gas pressure.

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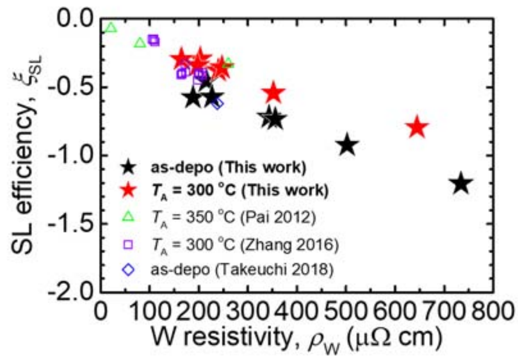

Fig. 2. ρ_W dependence of ξ_{SL}.

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Spin Polarization Characterization by Spin Hall Magnetoresistance in Ferrimagnetic Co1-xTbx/Pt bilayers

Yahan Xu[1], Jianhua Zhao[1] and Dahai Wei[1,*]

[1] State Key Laboratory of Superlattices and Microstructures, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China.

Antiferromagnet and ferrimagnet show a lot of merits of the utilities for spintronic devices. Moreover, it was reported that the SOT efficiency in the ferrimagnetic systems is greatly larger than that of traditional ferromagnetic ones and it can be attributed to an extra damping-like torque in the compensation point of ferromagnetic layers [1]. However, the detailed mechanism of spin-dependent transport has not been fully understood yet. Here we considered a representative $Co_{1-x}Tb_x$ /Pt bilayer system, in which the ferrimagnetic $Co_{1-x}Tb_x$ could has its magnetization compensated with either a proper composition or temperature, makes it an idea system for exploring the spin-dependent transport behaviours and their correlations in such a ferrimagnetic bilayers.

The ultrathin $Co_{1-x}Tb_x$ /Pt bilayers were deposited on a thermally oxidized Si substrate by an UHV sputtering system. The magnetic properties were first measured by anomalous Hall effect to verify the compensation behaviour of the magnetization. The AMR and SMR were systematically studied as a function of temperature and composition. A relatively large SMR up to 0.3% was observed in our experiments, and it has a distinct difference with the AMR for both the temperature and composition dependence. At the critical point the SMR only shows a minimum, while the AMR vanishes. Our discoveries indicating their different response to the magnetization compensation, would be useful to understand the mechanism of the spin-dependent transport in the ferrimagnetic systems.

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Antiferromagnet layer thickness dependence of spin-Hall magnetoresistance in PtMn/Pt metallic heterostructures

°S. DuttaGupta [1-3], R. Itoh [3], S. Fukami [1-5] and H. Ohno [1-5]
[1]CSIS, Tohoku University, Sendai 980-8577, Japan
[2]CSRN, Tohoku University, Sendai 980-8577, Japan
[3]RIEC, Tohoku University, Sendai 980-8577, Japan
[4]CIES, Tohoku University, Sendai 980-0845, Japan
[5]WPI-AIMR, Tohoku University, Sendai 980-8577, Japan

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 roadblocks concerning the realization of sole-antiferromagnetic spintronics is an electrical detection of antiferromagnetic moments having zero net magnetization. Recent results have revealed that the interaction of AFM 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 metallic AFM/NM 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. Mechanism of the various MR effects in PtMn/Pt and reference sub./Pt structures are investigated 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 a spin-Hall magnetoresistive electrical detection scheme in AFM/NM metallic structures offering an unexplored pathway for antiferromagnetic spintronics.

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Anomalous Hall effect of sputter-deposited non-collinear antiferromagnetic Mn_3Sn thin films with controlled crystal orientation

Juyoung Yoon[1], Yutaro Takeuchi[1], Ryuichi Itoh[1], Shun Kanai[1,2], Shunsuke Fukami[1-5], and Hideo Ohno[1-5]

[1]Lab. for Nanoelectronics and Spintronics, RIEC, Tohoku Univ., Sendai 980-8577, Japan

[2]CSRN, Tohoku Univ., Sendai 980-8577, Japan

[3]CSIS, Tohoku Univ., Sendai 980-8577, Japan

[4]CIES, Tohoku Univ., Sendai 980-0845, Japan

[5]WPI-AIMR, Tohoku Univ., Sendai 980-8577, Japan

Antiferromagnetic spintronics, where new physical properties and functionalities of antiferromagnetic materials are explored, is one of the most active fields in recent spintronics [1,2]. Non-collinear antiferromagnetic materials with Kagome lattice such as Mn_3Sn and Mn_3Ge have recently attracted much attention as they exhibit large anomalous Hall effect (AHE) originating in the Berry curvature mediated by the non-collinear spin structures [3,4].

Here we study the growth technique, crystalline structure, and magnetic/transport properties of Mn_3Sn thin films deposited by sputtering on various substrates and underlayers. 50-nm-thick Mn_3Sn films with various underlayers are deposited onto Si/SiO_2 or MgO substrates, and subsequently annealed at 500°C. Crystal structure, magnetic and transport properties are characterized by X-ray diffraction, vibrating sample magnetometry, and physical property measurement system, respectively.

We achieve a formation of epitaxial Mn_3Sn films with both C-plane (0001) and M-plane $(1\bar{1}00)$ orientations, whose Kagome lattices are parallel and perpendicular to the film plane, respectively. Transverse resistivity originating from the anomalous Hall effect shows different trends reflecting the Kagome lattice orientations of each stack. The established technique and findings offer a platform to study functional devices utilizing unconventional physical properties of non-collinear antiferromagnets with controlled Kagome lattice orientation.

The authors thank B. Jinnai for technical support. This work is partly supported by JSPS Kakenhi 19H05622 and 19J13405. J. Yoon and Y. Takeuchi acknowledge GP-Spin and JST-OPERA for financial support.

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Spin relaxation mechanism in Cu/Bi bilayers

Masaki Abe[1], Hiromu Gamou[1], Makoto Kohda[1,2,3] and Junsaku Nitta[1,2,3]

[1]Department of materials science, Tohoku University, Sendai 980-8579, Japan

[2]Center for Spintronics Research Network, Tohoku University, 980-8577, Japan

[3]Center for Science and Innovation in Spintronics (Core Research Cluster) Organization for Advanced Studies, Tohoku University, Japan

The Rashba-Edelstein effect (REE) is known as the way to generate spin current, and a Cu/Bi system is one of the candidates to observe the strong REE. Until now, the ways to evaluate the spin-orbit effects at the interface are mainly performed by the measurements which require a ferromagnet layer [1]. In this study, we have investigated the strength of the spin-orbit coupling of Cu/Bi system by focusing on weak antilocalization (WAL) effect which does not require any ferromagnet layer. There are two possible spin relaxation mechanisms in Cu/Bi system, the Elliot-Yafet [2] and the D'yakonov-Perel (DP) mechanisms [3]. Cu (0.2-7 nm)/Bi (5 nm)/AlO_x (2 nm) thin films were sputtered on sapphire (0001) substrates. Magneto-conductance and Hall resistance were measured in a ^{4}He cryostat at 2 K.

The result of the magneto-conductance measurement is shown in Fig. 1(a). All Cu/Bi bilayer samples with different Cu thickness show WAL. Spin relaxation time τ_{so} was evaluated by fitting the Hikami-Larkin-Nagaoka formula [4], and momentum scattering time τ_p was calculated by using the carrier density estimated by the Hall resistance measurement. As a result, the obtained τ_{so} as a function of τ_p is shown in Fig. 1(b), and it indicates the DP mechanism is dominant over the EY mechanism in Cu/Bi because the τ_{so} is inversely proportional to the τ_p.

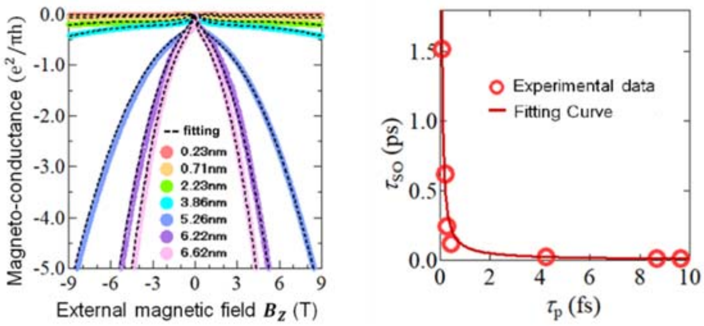

Fig 1. (a) Magneto-conductance of Cu/Bi(5 nm) with different Cu thickness at 2 K. (b) The relationship between spin relaxation time τ_{so} and momentum scattering time τ_p .

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Magnetization reversal via the combination of spin-orbit torque and spin-transfer torque in sub-ns region

C. Zhang[1,2], Y. Takeuchi[2], S. Fukami[2,3,4,5,6,7], and H. Ohno[2,3,4,5,6]
[1]FRIS, Tohoku University, Sendai 980-0845, Japan
[2]RIEC, Tohoku University, Sendai 980-8577, Japan
[3]CSIS, Tohoku University, Sendai 980-8577, Japan
[4]CIES, Tohoku University, Sendai 980-8572, Japan
[5]CSRN, Tohoku University, Sendai 980-8577, Japan
[6]WPI-AIMR, Tohoku University, Sendai 980-8577, Japan

Magnetization reversal via spin-transfer torque (STT)[1,2] or spin-orbit torque (SOT)[3-5] has been studied in two or three-terminal magnetic tunnel junctions (MTJs), respectively. Recently, the reversal under both STT and SOT has been predicted to be faster with lower power consumption compared to the conventional schemes in calculation studies.[6,7] We here experimentally study the combinational effect of SOT and STT on magnetization reversal in two and three-terminal MTJs.

Devices in this work have elliptic and in-plane magnetized CoFeB/MgO-based MTJs with Ta/W channels. STT and SOT are induced by vertical and horizontal components of current, respectively. The resistance-area product of MgO tunneling barrier is 31 $\Omega\mu m^2$ and the channel resistance is 2.6 kΩ, with which STT and SOT become comparable in magnitude under a single input current. We prepare devices with various angles (ϕ) between the major axis of elliptic MTJs and channels, allowing us to control mutual directions between SOT and STT.

We first check the combinational effects of SOT and STT on magnetization reversal in devices with ϕ = 90^o using two different measurement setups; anti-parallel ("STT−SOT" hereafter) or parallel ("STT+SOT" hereafter) relation between SOT and STT depending on the channel current direction. The threshold reversal current for "STT+SOT" configuration is smaller than "STT−SOT" configuration, evidencing an additive effect of STT and SOT. We then study the threshold current of magnetization reversal for various pulse widths τ_p and find a strong dependence on ϕ especially at $\tau_p < 1$ ns. Thanks to the combination effect of SOT and STT, we achieve magnetization reversal by sub-ns pulses down to 0.2 ns for a device with $\phi = 0^o$ in the absence of magnetic field. This work demonstrates a field-free switching scheme to enhance speed at reduced voltage/current in the two and three-terminal MTJ devices.

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Tuning the Skyrmion Hall Effect via Engineering of Spin-Orbit Interaction.

Collins Ashu Akosa[1], Hang Li[2], Gen Tatara[1], and Oleg A. Tretiakov[3]

[1]RIKEN Center for Emergent Matter Science (CEMS), 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
[2]Institute for Computational Materials Science, School of Physics and Electronics, Henan University, Kaifeng 475004, China
[3]School of Physics, The University of New South Wales, Sydney 2052, Australia

Ferromagnetic skyrmions are promising information carriers for nonvolatile, energy-efficient, ultradense memory and logic devices of the future. However, their integration in these applications is hampered by the undesirable skyrmion Hall effect (SkHE), a motion transverse to the direction of current flow. In this study we demonstrate that the Magnus force acting on magnetic skyrmions can be efficiently tuned via modulation of the strength of spin-orbit interactions. We show that the skyrmion Hall effect, which is a direct consequence of the nonvanishing Magnus force on the magnetic structure, can be suppressed in certain limits. Our calculations show that the emergent magnetic fields in the presence of spin-orbit coupling (SOC) renormalize the Lorentz force on itinerant electrons, and thus, influence topological transport. In particular, we show that, for a Néel-type skyrmion and Bloch-type antiskyrmion, the skyrmion Hall effect (SkHE) can vanish by tuning appropriately the strength of Rashba and Dresselhaus SOCs, respectively. Our results open up alternative directions to explore in a bid to overcome the parasitic and undesirable SkHE for spintronic applications.

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Current-induced motion of synthetic antiferromagnetic skyrmion bubbles free from the skyrmion Hall effect

Takaaki Dohi[1], Samik DuttaGupta[1-3], Shunsuke Fukami[1-5], and Hideo Ohno[1-5]
[1]RIEC, Tohoku University, Sendai 980-8577, Japan
[2]CSIS, Tohoku University, 2-1-1 Katahira, Aoba, Sendai 980-8577, Japan
[3]CSRN, Tohoku University, 2-1-1 Katahira, Aoba, Sendai 980-8577, Japan
[4]CIES, Tohoku University, Sendai 980-0845, Japan
[5]WPI-AIMR, Tohoku University, Sendai 980-8577, Japan

Magnetic skyrmion has attracted much attention because of a variety of emergent exotic spin-dependent phenomena owing to its topology in real space [1]. Room-temperature magnetic skyrmion has been demonstrated in heavy metal/ ferromagnet systems due to an interfacial Dzyaloshinskii-Moriya interaction (DMI) induced by strong spin-orbit coupling. The spin-orbit coupling also gives rise a spin-orbit torque (SOT) under in-plane current, allowing efficient control of the skyrmion [2]. However, there still remain some fundamental issues for applications [3]. For instance, skyrmion Hall effect (SkHE), a diagonal motion of skyrmion with respect to the current direction owing to the Magnus force, limits the velocity when one moves skyrmions on a track [4]. Theoretical studies predicted a SkHE-free motion for antiferromagnetic skyrmions [5,6], and formation [7,8] and SkHE-free motion at a specific temperature [9] has been demonstrated in ferrimagnetic [7,9] and synthetic antiferromagnetic (SyAF) [8] systems. Here we show a SkHE-free motion of skyrmion bubbles at room temperature in a SyAF system. We show that the SyAF skyrmion can be driven with much smaller current density than conventional ferromagnetic skyrmion bubbles. The achieved favorable properties are attributed to the employed stack structure which is engineered so that the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction, DMI, and SOT act in a concerted way [10].

This work was supported in part by JSPS KAKENHI 17H06511/18KK0143/19H05622, Core-to-Core Program of JSPS, and Cooperative Research Projects of RIEC. T.D. acknowledges financial support from GP-Spin, JST-OPERA, and DIARE of Tohoku University.

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Controlling the transmission of spin waves in a directional-coupler via domain walls

Milan Ender, Philipp Pirro and Burkard Hillebrands
AG Magnetismus, TU Kaiserslautern, 67663 Kaiserslautern , Germany

In the field of magnonics, the exploitation of manipulated spin waves in logic devices has gained substantial interest.
The excitation of these spin waves in waveguides via a current-induced dynamic field has been subjected to extensive studies. As such, it is apparent to utilize spin wave waveguides as a basis for such a logic device.

Especially, with the advent of neuromorphic computing, the interest for finely tunable, hardware-implemented transmission functions has risen significantly.

In this work, a potential implementation of such a device is presented. Recently, the mechanism of directional coupling, where two adjacent spin wave waveguides are coupled via dipolar interaction, revealed itself to be a versatile building block for spin wave computing[1]. Henceforth, this work investigates a design where a directional-coupler is modified by a configurable domain wall in one of the waveguides, which controls the effective coupling area. This in turn, will influence the transmission of a spin wave, which travels from one to the other waveguide. As such, it would represent an analogous to a weighted signal transport like it is needed in artifical neural networks. As the position of the domain wall can be potentially permanently moved via a temporary magnetic field, this weight is also tunable, fullfilling another requirement for more complex hardware-implemented learning algorithms.

Utilizing finite-difference base micromagnetic simulations in MuMax3, a numerical proof-of-concept of the device and potential transmission functions in dependence of the domain wall position are presented.

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Importance of Transport Phenomena in Ultrafast Switching of Magnetic Multilayer Thin films

Q. C. J.-M. Remy[1], J. Hohlfeld[1], J. Gorchon[1], M. Hehn[1], G. Malinowski[1] and S. Mangin[1]

[1]Institut Jean Lamour, CNRS UMR 7198, Université de Lorraine, Nancy F-54000, France

All Optical Helicity Independent Switching (AO-HIS) in ferrimagnets, a purely thermal mechanism [1], is generally understood through transfer of energy and angular momentum between electrons, their spin and the lattice. The Microscopic Three Temperature Model (M3TM) is one way of considering these transfers in order to successfully reproduce AO-HIS [2]. However, some aspects of AO-HIS are still not clear. Especially the role of spin orbit coupling (appearing through anisotropy, spin diffusion length, magnetization relaxation time, etc.) and transport phenomena (spin currents and hot electrons). In this work, we try to shed light on the possible influence of transport phenomena by reproducing the work of Iihama [3] with two layers of GdFeCo. Layer 1 of GdFeCo exhibits AO-HIS above a certain fluence threshold while layer 2 is too far from the compensation point to exhibit it at any fluence. We show that all four possible magnetic configurations are reachable by sending single femtosecond light pulses with two different fluences (Figure 1). Starting from a parallel configuration P+ (for the total magnetization), one obtains an antiparallel configuration with a single light pulse because of AO-HIS in layer 1. More pulses allow toggle switching between the two antiparallel configurations (meaning both layers now switch simultaneously). Starting from an antiparallel configuration (AP+) and using a fluence lower than the AO-HIS threshold, one obtains the opposite parallel (P-) configuration because of the switching of layer 2. More pulses with the same fluence do not change the magnetic configuration. This suggests that layer 2 is switched due to an electron current polarized by the other magnetic layer. Moreover, it is also possible to switch the magnetization of layer 2 without having AO-HIS of layer 1. The nature and the origin of this current is still unclear.

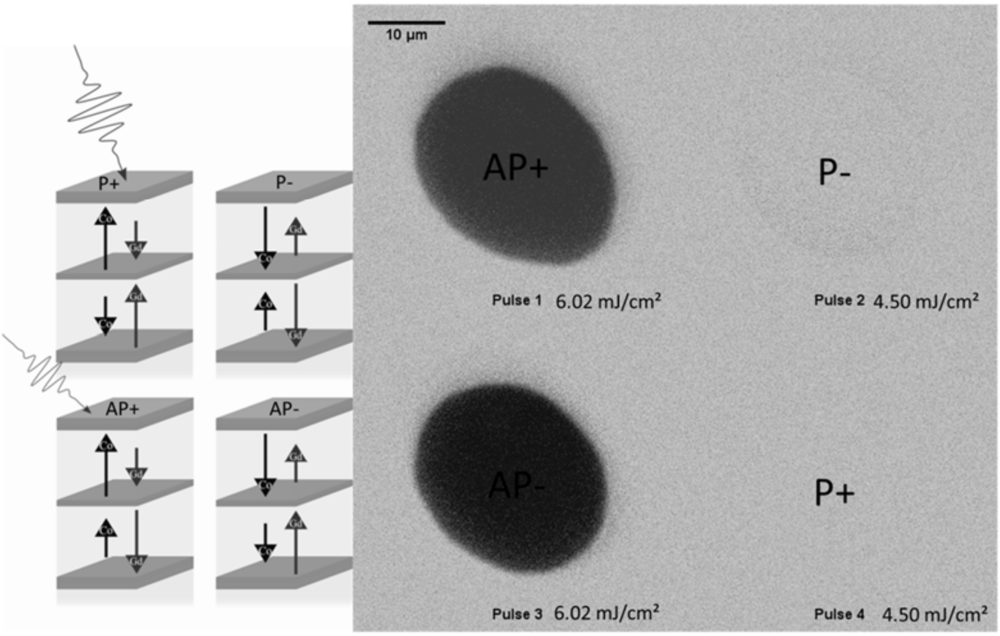

Figure 1: On the left, all four possible magnetic configuration in the stack are shown. On the right, all configurations are successively obtained by shining single pulses with different fluences.

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Optical Investigation of the Magnon Chemical Potential in YIG/Pt Systems

D. Breitbach[1] and M. Schneider[1], T. Brächer[1], A. M. Friedel[1], P. Pirro[1], V. S. Tiberkevich[2], A. N. Slavin[2], C. Dubs[3], B. Hillebrands[1] and A. V. Chumak[1]

[1]Fachbereich Physik and Landesforschungszentrum OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany

[2]Department of Physics, Oakland University, Rochester, MI 48309, USA

[3]INNOVENT e.V., Technologieentwicklung Jena, 07745 Jena, Germany

The influences of the Spin-Seebeck-Effect (SSE) as well as Spin-Transfer-Torques (STT) on the spin system of magnetically ordered insulators have been extensively studied in the field of magnon spintronics [1,2]. These influences can be interpreted using a description of the magnonic system outside its state of equilibrium by means of the magnon chemical potential [3,4].

The most widely used approach to investigate these phenomena is to use currents in an adjacent metallic injector structure to excite spin waves through SSE by Joule Heating induced thermal gradients and by STT via the Spin Hall Effect (SHE). Subsequent detection of the spin waves is commonly done nonlocally by taking advantage of Spin Pumping and the Inverse Spin Hall Effect (ISHE) in a metallic detector structure in a certain distance to the injector. This method is very sensitive to the overall magnon population in the system, but it cannot distinguish between different magnon modes. Nevertheless, the direct access to the spectral magnon distribution is crucial for the direct measurement of the chemical potential.

In this work, we studied the influence of SSE on the spatial distribution of the magnon chemical potential of YIG/Pt thin film systems by Micro-focused Brillouin Light Scattering (μBLS) Spectroscopy. By using this technique, we are able to extract the intensities of different spin wave modes in the GHz regime, which are compared to the Bose-Einstein distribution in the Rayleigh-Jeans limit. The magnon distribution is probed in dependence of the applied current and the direction of the resulting temperature gradient. It is observed to be strongly affected by the applied heating. The extracted chemical potential shows a decreasing trend due to the SSE, with values down to -0.4 GHz at injector temperatures of around 100 °C. However, the results show, that the dominant influence on the magnon distribution is the temperature change itself, which allows for determination of the magnon gas temperature. This approach is of special interest for the possible generation of magnon Bose-Einstein-Condensates (BEC) as well as the investigation of spin transport phenomena.

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

Afshin Houshang[1], R. Khymyn[1], H. Fulara[1], A. Gangwar[1], M. Haidar[1], S. R. Etesami[1], R. Ferreira[2], P. P. Freitas[2], M. Dvornik[1], R. K. Dumas[1], and J. Åkerman[2,3]

[1] University of Gothenburg, Gothenburg, Sweden

[2]International Iberian Nanotechnology Laboratory, Braga, Portugal

[3]Material Physics, Royal Institute of Technology, Kista, Sweden

In order to enable magnonic devices to operate at much higher data transmission rates and higher frequencies, exchange dominated spin waves (SWs) with a short wavelength is a key ingredient. While magnetic nano-contacts based on giant magnetoresistance are effective injectors of propagating SWs, their signal strength is too weak for applications. Here we demonstrate nano-contact magnetic tunnel junctions (NC-MTJs) [1], and for the first time the possibility of exciting not only first- but also second- and third-order propagating SWs [2]. Furthermore, mutual synchronization is observed on all the three SW modes.

The power spectral density (PSD) generated by auto-oscillations vs. the field strength is shown in Fig 1(a-c). At currents above a certain threshold (i.e. Idc= -8 mA), strong modes with a frequency higher than the ferromagnetic resonance frequency (fFMR) are excited. Increasing the current to -9 and -10 mA, these modes dominate the high field region. As can be seen in Fig. 1 (a-c), these modes can be well fitted with the higher-order propagating SW modes put forward by Slonczewski [2] but otherwise overlooked in literature until now. It is noteworthy that higher currents needed to excite these higher mode numbers are also in agreement with Slonczewski's original proposals.

Furthermore, we experimentally show in Fig.1 (d-f) that it is possible to achieve spin-wave-mediated mutual synchronization on all three modes, corroborating the

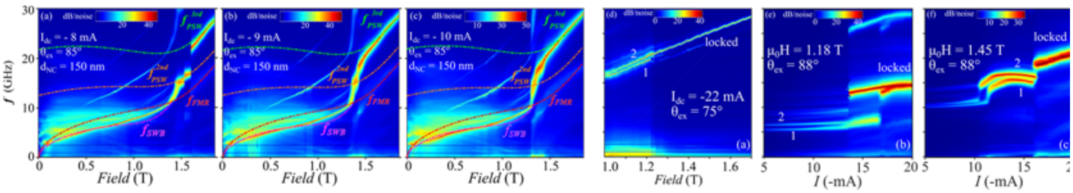

Figure 1: a-c: PSD vs. applied field (θ_{ex} =85°), for the (a) I_{dc} = -8 mA, (b) I_{dc} = -9 mA, and (c) I_{dc} = -10 mA. The pink, red, brown, and green dashed lines represent the calculated frequencies for the SW bullet (f_{SWB}), the FMR (f_{FMR}), the second-order Slonczewski mode, and the third-order Slonczewski mode, respectively. d-f: Mutual

propagating nature of the modes. As can be seen in Fig. 1d, at low fields two distinct modes can be detected together with substantial noise below 2.5 GHz. Increasing the field above 1.22 T, the two modes merge into one and the noise disappears. Fig 1(e) and (f) show the PSD vs. current for nano-contacts optimized to sustain higher currents. Mutual synchronization of the second-order mode is observed at 1.18 T at about -18 mA; for the third-order mode, it is observed at a higher field, 1.45 T, and -17 mA, while the second order mode does not show synchronization at these specific conditions.

In conclusion, for the first time, we observed higher order propagating SW modes in NC-MTJs, and robust mutual synchronization of all the modes.

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Antiferromagnetic cavity optomagnonics

Tahereh Parvini[1], Victor Bittencourt[1] and Silvia Kusminskiy[1,2]
[1]Max PlanckInstitute for the Science of Light, Staudtstr. 2, PLZ 91058, Erlangen, Germany

2Institute for Theoretical Physics, University Erlangen-Nürnberg, Staudtstr. 7, 91058 Erlangen, Germany

We propose a cavity optomagnonic system based on antiferromagnetic insulators. We derive the Hamiltonian of the system and obtain the coupling of the antiferromagnetic magnon modes to the optical cavity field as a function of magnetic field and material properties. We show that, in the presence of hard-axis anisotropy, the optomagnonic coupling can be tuned by a magnetic field applied along the easy axis, allowing to bring a selected magnon mode into and out of a dark mode. For easy-axis antiferromagnets the coupling is instead independent of the magnetic field. We study the dynamic features of the driven system including optically induced magnon amplification and cooling, Purcell enhancement of transmission, and induced transparency, and discuss their experimental feasibility.

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Enhancement of the spin pumping effect by magnon confluence process

Timo B. Noack[1], Vitaliy I. Vasyuchka[1], Dmytro A. Bozhko[1], Björn Heinz[1], Pascal Frey[1], Denys V. Slobodianiuk[2], Oleksandr V. Prokopenko[2], Gennadii A. Melkov[2], Peter Kopietz[3], Burkard Hillebrands[1] and Alexander A. Serga[1],

[1] Fachbereich Physik and Landesforschungszentrum OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany

[2] Faculty of Radiophysics, Electronics and Computer Systems, Taras Shevchenko National University of Kyiv, 01601 Kyiv, Ukraine

[3] Institut für Theoretische Physik, Universität Frankfurt, 60438 Frankfurt, Germany

[4] School of Engineering, University of Glasgow, Glasgow G12 8LT, United Kingdom

The electrical detection of magnon dynamics by means of the spin pumping (SP) and the inverse spin Hall effect (ISHE) is a widely utilized method in the field of magnon spintronics for investigations of magnetization dynamics. Besides its simple realization, one of the main advantages of this approach is the sensitivity to all excited magnons independent from their frequencies and wavevectors. Therefore, the electrical detection of magnons can be efficiently utilized for studies of magnon–magnon scattering processes, when magnons with different wavevectors are involved.

The experimental investigation of the spin pumping process by dipolar-exchange magnons parametrically excited in in-plane magnetized yttrium iron garnet/platinum bilayers is presented [1]. In the field-dependent measurements of the spin pumping-induced component of the ISHE-voltage, a clearly visible sharp peak is detected at high pumping powers. It is found that the peak position is determined by the process of confluence of two parametrically excited magnons into one magnon possessing twice the frequency and the sum of the wavevectors of the initial magnons. Measurements of the peak position at different pumping frequencies clearly show this relation. The three-magnon confluence process constitutes an additional damping mechanism for the group of parametrically pumped magnons. Thus, for low pumping powers the confluence will decrease the total number of magnons in the system. Nevertheless, for high pumping powers the pumping source can compensate this additional damping and the number of magnons is even increasing around the point of confluence.

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Ab initio studies on Equiatomic Quaternary Heusler Alloys CoIrMn*Z* (*Z* = Al, Ga, Si, Ge)

Tufan Roy[1], Masahito Tsujikawa[1, 2], Takuro Kanemura[1] and Masafumi Shirai[1,2,3]
[1]Research Institute of Electrical Communication, Tohoku University,
[2]Center for Spintronics Research Network, Tohoku University,
[3]Center for Science and Innovation in Spintronics, Core Research Cluster, Tohoku University, Sendai, Japan

Many of the Co-based full Heusler alloys are known for potential candidates in the field of spintronics application, because of their high spin polarization at Fermi level and high Curie temperature. Indeed, Co_2MnSi/MgO and other related heterojunctions have been extensively studied during last few decades [1]. Ir being isoelectronic to Co, CoIrMnSi could also be a promising candidate. As the number of valence electrons also plays a crucial role in determining the physical properties, so it is worth while investigating CoIrMn*Z* (*Z* = Al, Ga, Si, Ge) systems.

Based on first-principles calculations, we study the electronic and magnetic properties of the CoIrMn*Z* (*Z* = Al, Ga, Si, Ge) equiatomic quaternary Heusler alloys [2]. Ferromagnetic ground state has been observed for all these alloys with their Curie temperatures much higher than room temperature. The electronic structure of CoIrMnAl has resemblance with spin-gapless semiconductor, which shows a gapless majority-spin channel and a nearly semiconducting minority-spin channel. We predicted that CoIrMnSi and CoIrMnGe are half-metallic with fully spin-polarized Δ_1 band crossing the Fermi level. We also confirmed that the spin-orbit coupling causes negligible effects on the electronic structures of these alloys.

Furthermore, we investigated the electronic and transport properties of the CoIrMn*Z*/MgO (001) heterojunctions and found that the Mn*Z*-terminated interface is energetically more favorable over CoIr-terminated case for every system. Analyzing the spin-dependent tunneling conductance, we concluded that CoIrMnSi/MgO/CoIrMnSi (001) junction could be a promising candidate for magnetic tunnel junctions showing high tunneling magnetoresistance.

This work was partially supported by JST CREST and JSPS Core-to-Core program "New-Concept Spintronics Devices".

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Spin-torque ferromagnetic resonance in Co_xFe_{1-x} / Ti / NiFe trilayers

Yuya Koike[1,2] , Satoshi Iihama[2,3] and Shigemi Mizukami[2,3,4]

[1]Department of Applied Physics, Tohoku Univ., Sendai 980-8579, Japan

[2]WPI-AIMR, Tohoku Univ., Sendai 980-8577, Japan

[3]CSRN, Tohoku Univ., Sendai 980-8577, Japan

[4]CSIS, Tohoku Univ., Sendai 980-8577, Japan

Magnetization switching using spin-orbit torque (SOT) has attracted much attention as writing technique for magnetoresistive random access memory (MRAM). Conventionally, an in-plane external or effective magnetic field is applied for SOT switching of the out-of-plane magnetization. However, a field-free switching is more desirable and physically possible when an injected spin current has a spin direction perpendicular to a film plane. One of the promising ways is to use ferromagnet (FM) as a spin current source [1]. It was recently reported that spin current generation from FMs such as CoFeB and FePt and its efficiency is comparable to nonmagnetic heavy metals (HMs) [2,3]. In particular, CoFeB shows high spin current generation efficiency even though it does not contain nonmagnetic HMs, however, its origin is not yet clear. Here, we performed spin-torque ferromagnetic resonance (ST-FMR) measurements in Co-Fe binary alloys to gain insights into the spin current generation from FMs which does not contain nonmagnetic HMs.

Film stacking was thermally-oxidized Si substrate/Co_xFe_{1-x}(5)/Ti(3)/NiFe(4)/ MgO(3)/Ta(2) (thickness is in nm, x=0, 0.5, 1.0). Ti layer is inserted to prevent interlayer coupling between FM layers and MgO/Ta is capping layer. We confirmed whether there is interlayer coupling by frequency dependence of the resonance field of ST-FMR. The experimental data was well fitted to the data calculated with Kittel's formula using reasonable parameter sets. This indicates negligible interlayer coupling between the CoFe and NiFe lyers. The evaluation of the spin current generation from the ST-FMR curves is also discussed.

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Engineering the Emission of Spintronic Terahertz Emitters based on Defect Densities

Laura Scheuer[1], Dennis Nenno[1], Garik Torosyan[2], Alexander Brodyanski[3], Rolf H. Binder[4], Hans C. Schneider[1], René Beigang[1] and Evangelos Th. Papaioannou[1]

[1] Fachbereich Physik and Landesforschungszentrum OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany

[2] Photonic Center Kaiserslautern, Kaiserslautern 67663, Germany

[3] Institut für Oberflächen- und Schichtanalytik (IFOS) and Landesforschungszentrum OPTIMAS, 67663 Kaiserslautern, Germany

[4]College of Optical Sciences, University of Arizona, Tucson, AZ 85721, USA

The field of THz spintronics aims to control ultrafast spin currents and spin waves that could enable novel applications and devices operating in the THz range. In particular, we demonstrated the generation of pulsed broadband terahertz radiation utilizing the inverse spin Hall effect in ferromagnetic / nonmagnetic metallic heterostructures. Recent studies have nicely shown the effect in different FM/NM systems considering the influence of the layer thicknesses, substrates, geometrical arrangement and excitation energy [1, 2]. However, in these former studies the significance of the crystal structure of the metallic layers was not yet investigated. Here, we reveal the defect density of the crystal structure as a major factor to engineer the THz generation regarding electric field amplitude and bandwidth of the spectrum [3].

We experimentally show the role of the defect density by studying relaxed epitaxial, deformed epitaxial and fully non-epitaxial Fe/Pt bilayers. We control the emitted THz spectra by modifying the defect density that results in changing the elastic electron-defect scattering lifetime in Fe and Pt and the interface transmission for spin-polarized, non-equilibrium electrons.

To support the experimental findings, we employ a theoretical model based on the Boltzmann transport equation that accounts for the differences in elastic electron scattering lifetime in the layers and for the transmission of spin-polarized hot carriers at the FM/NM interface.

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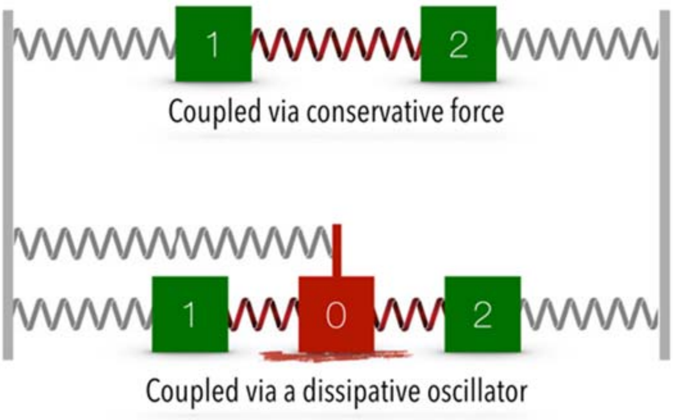
Prediction of Attractive Level Crossing via a Dissipative Mode

Weichao Yu[1,2], Jiongjie Wang[1], H. Y. Yuan[3] and Jiang Xiao[1,4]
[1]Department of Physics and State Key Laboratory of Surface Physics, Fudan University, Shanghai 200433, China
[2]Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
[3]Department of Physics, Southern University of Science and Technology, Shenzhen 518055, Guangdong, China
[4]Institute for Nanoelectronics Devices and Quantum Computing, Fudan University, Shanghai 200433, China

The new field of spin cavitronics focuses on the interaction between the magnon excitation of a magnetic element and the electromagnetic wave in a microwave cavity. In the strong interaction regime, such an interaction usually gives rise to the level anticrossing for the magnonic and the electromagnetic mode. Recently, the attractive level crossing has been observed, and it is explained by a non-Hermitian model Hamiltonian. However, the mechanism of such attractive coupling is still unclear. We reveal the secret by using a simple model with two harmonic oscillators coupled to a third oscillator with large dissipation. We further identify this dissipative third party as the invisible cavity mode with large leakage in cavity-magnon experiments. This understanding enables one to design dissipative coupling in all sorts of coupled systems.



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Size-dependent spatial magnetization profile of Manganese-Zinc ferrite nanoparticles

M. Bersweiler[1], P. Bender[1], L.G. Vivas[1], M. Albino[2], M. Petrecca[2,3], S. Mühlbauer[4], S. Erokhin[5], D. Berkov[5], C. Sangregorio[2,3] and A. Michels[1]

[1]Physics and Materials Science Research Unit, University of Luxembourg, 162A Avenue de la Faïencerie, L-1511 Luxembourg, Grand Duchy of Luxembourg
[2]Università degli Studi di Firenze, Dipartimento di Chimica "U. Schiff", Via della Lastruccia 3, 50019 Sesto Fiorentino, Italy
[3]ICCOM-CNR via Madonna del Piano 10, 50019 Sesto Fiorentino, Italy
[4]Heinz Maier-Leibnitz Zentrum (MLZ), Technische Universität München, D-85748 Garching, Germany
[5]General Numerics Research Lab, An der Leite 3B, D-07749 Jena, Germany

Manganese–Zinc Ferrite oxide (MZFO) systems have raised a great interest in recent years, because they are very promising candidates for various technological, biological, and clinical applications. However, such potential applications are one of the most challenging research areas, since the magnetic properties of MZFO are strongly related to their chemical composition [1], synthesis methods [2], distribution of cations between interstitial tetrahedral and octahedral sites [3], and their particle size [1]. Moreover, precise knowledge about the magnetization profile of MZFO nanoparticles is of utmost importance, since it can affect drastically their magnetization behavior. In the present work, we report the results of an unpolarized small-angle neutron scattering (SANS) study on MZFO nanoparticles with the aim to elucidate the interplay between their particle size and the magnetization profile. SANS provides information about variations of the magnetization vector on a nanometer length scale of about 1 – 100 nm (see Ref. [4,5] for a review) and was already used in several other studies to investigate intra- and inter-particle moment correlations [6]. Here, $Mn_{0.2}Zn_{0.2}Fe_{2.6}O_4$ nanoparticles covered with a thin layer of oleic acid (capping agent) were synthesized by co-precipitation or thermal decomposition. The chemical composition of the nanoparticles was determined using X-Ray Fluorescence (XRF). The studied MZFO nanoparticle samples have average diameters ranging from 8 to 80 nm according to TEM; XRD confirms in each case their single crystallinity. By taking advantage of the SANS technique, we demonstrate that the smallest nanoparticle are homogeneously magnetized. However, with increasing particle size we observe the transition from uniform to nonuniform magnetization states. Field-dependent results for the pair-distance distribution function $p(r)$ on a 38-nm-sized specimen reveal that the internal spin disorder can be suppressed by an increasing field. The experimental SANS data are supported by the results of micromagnetic simulations, which confirm an increasing inhomogeneity of the magnetization profile of the particle with increasing size.

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Anisotropic transport of spontaneously accumulated magneto-elastic bosons in Yittrium Iron Garnet films

Pascal Frey[1] and D.A. Bhozko[2], V. Vasyuchka[1], A. A. Serga[1] and B. Hillebrands [1]

[1] Fachbereich Physik and Landesforschungszentrum OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany
[2] Department of Physics and Energy Science, University of Colorado at Colorado Springs, Colorado Springs CO 80918, USA

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: an accumulation of hybrid magneto-elastic bosons [2]. 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 observed behavior can be explained trough precise modeling of the avoided crossing region in wavevector space.
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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Influence of temperature on in-plane effective damping constant of amorphous Co-Fe-B thin films

T. V. A. Nguyen,[1,2,3] H. Sato,[1,2,3] S. Ikeda,[1,2,3] T. Endoh[1,2,3,4,5], Y. Endo,[1,2,5]
[1]CSIS, Tohoku Univ., [2]CSRN, Tohoku Univ., [3]CIES, Tohoku Univ., [4]RIEC, Tohoku Univ., [5]Grad. School of Eng., Tohoku Univ.,

Amorphous Co-Fe-B thin films have been widely used in spintronics devices such as MRAM, spin-torque oscillator, and the spin-based logic systems because of their low Gilbert damping constant (α) and high spin polarization. For these devices, a detailed understanding of behavior of α in Co-Fe-B thin films with external environments such as magnetic field, temperature and so on are important. Herein we evaluate α at various temperatures of amorphous Co-Fe-B thin films with various thicknesses using a broadband ferromagnetic resonance (FMR) measurement technique, and discuss the influence of temperature on α in these films in detail.

Figs. 1 (a) shows typical FMR spectra for a 15-nm-thick Co-Fe-B thin film at 100 K and 300 K. As the frequency increased, the resonance peak clearly shifted to a higher magnetic field at all measured temperatures. In addition, the peak intensity decreased and the peak width increased as the temperature decreased. The same behaviors were also observed for other samples with the thickness of 5 nm and 10 nm. By analyzing these spectra in detail, α and the effective saturation magnetization, the inhomogeneous field were evaluated.

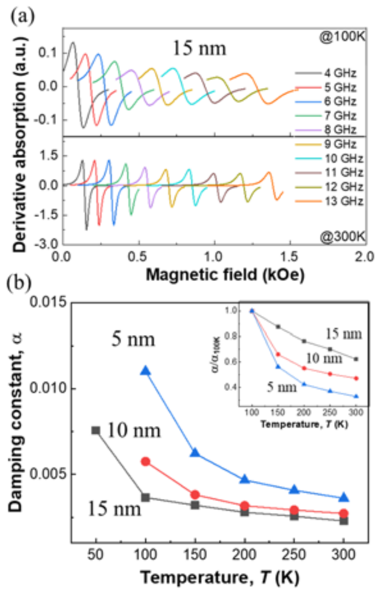

Fig. 1. (a) FMR spectra at 100 K and 300 K (b) temperature dependence of α.

Fig. 1 (b) shows the temperature dependence of α for Co-Fe-B films with various thickness. For all samples, α slightly increased as the temperature decreased down to 150 K followed by a significant increase at temperature lower than 150 K. This behavior is close to that of the electrical conductivity [1]. Moreover, the increment of α with the temperature in the 5-nm-thick film becomes larger (inset of Fig. 1 (b)), which might be ascribed to the magnetic inhomogeneity such as the anisotropy dispersion. On the basis of these results, it can be suggested that the tendency of damping in each Co-Fe-B film with temperature is mainly consistent with the behavior of damping expected by intra-band transition.

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Ferromagnetic resonance and current induced magnetization switching in nanoscale CoFeB/MgO magnetic tunnel junctions

Motoya Shinozaki[1], Junta Igarashi[1], Justin Llandro[1,3,4], Hideo Sato[1-4], Shunsuke Fukami[1-5], and Hideo Ohno[1-5]

[1]Laboratory for Nanoelectronics and Spintronics, Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577 Japan.

[2]Center for Innovative Integrated Electronic Systems, Tohoku University, 468-1 Aramaki Aza Aoba, Aoba-ku, Sendai 980-0845 Japan.

[3]Center for Spintronics Research Network, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577 Japan.

[4]Center for Science and Innovation in Spintronics (Core Research Cluster), Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577 Japan.

[5]WPI-Advanced Institute for Materials Research, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577 Japan.

CoFeB/MgO-based perpendicular magnetic tunnel junctions (MTJs) are attracting much attention for future low power-consumption and high-performance memories. In actual applications, it is very important to understand magnetic properties and magnetization switching behavior for nanoscale MTJs. 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 size 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. 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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From nonlinear interacting magnon gas to magnon Bose-Einstein condensate and supercurrents

Halyna Musiienko-Shmarova[1], Vasyl S. Tyberkevych[2], Andrei N. Slavin[2], Alexander A. Serga[1], and Burkard Hillebrands[1],
[1]Fachbereich Physik and Landesforschungszentrum OPTIMAS, Technische Universität Kaiserslauten, 67663 Kaiserslautern, Germany
[2]Department of Physics, Oakland University, Rochester, Michigan 48309, USA

Bose-Einstein condensate (BEC) is a fascinating quantum phenomenon that manifests itself in the formation of a coherent macroscopic state from chaotic motions in a thermalized many-particle system. BEC can also occur in such a nonequilibrium system as an overpopulated gas of interacting quasiparticles – excitons, polaritons, photons and magnons. The dynamics of incoherent quasiparticle cloud – magnon gas, its thermalization via four-magnon scattering processes leading to the formation of a magnon BEC as well as the behavior of the condensed magnon phase strongly depend on the peculiarities of magnon-magnon interaction processes, which can be described using corresponding nonlinear coefficients [1, 2]. Besides, the values of these coefficients crucially influence the formation of such nonlinear spin-wave objects as solitons, bullets and droplets [3], and determine the specific scenarios of a phase induced macroscopic quantum collective motion of a magnon condensate — supercurrent [4]. Thus, determination of such coefficients is an important task for the understanding of dynamics of the coherent macroscopic quantum state.

In the presented research, we present a completely new theoretical approach, which allows directly determine real values of magnon-magnon interaction coefficients in yttrium iron garnet films of different thicknesses magnetized under different angles. The obtained data are used to investigate the behavior of interacting magnon condensates formed in two magnon spectrum minima at opposite wavenumbers. Particularly, we predict the conditions for the formation and stability of the magnon BEC and analyze a supercurrent-like BEC motion in such a system under different initial conditions.

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Investigation of junction-size dependence of TMR-sensor detectivity

Zhenhu Jin[1], Yupeng Wang[1], Mikihiko Oogane[1,2,3], and Yasuo Ando[1,2,3]
[1]Department of Applied Physics, Tohoku University, Sendai 980-8577, Japan
[2]Center for Science and Innovation in Spintronics (Core Research Cluster), Tohoku University, Sendai 980-8577, Japan
[3]Center for Spintronics Research Network, Tohoku University, Sendai 980-8579, Japan

Measurement of weak low-frequency magnetic fields is extremely important for medical diagnosis and nondestructive testing [1]. Owing to high magnetoresistance at room temperature and miniaturization capability, magnetic tunnel junction (MTJ) based tunnel magnetoresistance (TMR) sensors have been widely used for detecting small variations in magnetic fields. To date, many studies focus on enhancement of tunnel magnetoresistance for improvement of sensitivity. However, the reduction of low-frequency noise is still a critical issue for achieving high signal to noise ratio (S/N) of TMR sensors. The previous study theoretically indicated that the junction area the sensitivity and noise property of MTJ devices [2]. It is necessary to investigate the relationship between junction size and low-frequency noise power for optimizing of TMR sensor. In this study, the various junction-sizes MTJs were fabricated and their noise properties were investigated. Furthermore, their S/N ratio of low-frequency magnetic field was investigated for determining suitable dimension characteristics of MTJ

The magnetic films were prepared by magnetron sputtering system and their stacking structure was SiO_2 sub./Ta(5)/Ru(10)/Ta(5)/$Ni_{80}Fe_{20}$(70)/Ru(0.9)/$Co_{40}Fe_{40}B_{20}$(3)/MgO (1.6)/$Co_{40}Fe_{40}B_{20}$(3)/Ru(0.9)/$Co_{75}Fe_{25}$(5)/$Ir_{22}Mn_{78}$(10)/Ta(8) (in nm). The bottom free layers have different junction area *A* (590 μm^2 ~4492 μm^2). After fabrication, the magneto-resistance and noise spectral density of sensors were investigated. Moreover, their outputs were obtained for sensing a small alternating magnetic field (about 0.35 Oe), and their detectivities can be experimentally differentiated.

Figure 1(a) shows noise power spectral densities of serial MTJs with various junction areas, at a bias voltage of 100 mV and zero magnetic field. The experimental result indicated that the low-frequency noise can be reduced by increasing the junction area. Furthermore, Fig. 1(b) shows the dependence of S/N ($V_{peak}/V_{background}$) on the junction area. Owing to low noise power, the highest S/R ratio was obtained in the serial MTJs with a junction area of 4492 μm^2. Therefore, this study indicated the choice of junction area is significantly for reduction of noise power and enhancement of the TMR sensor detectivity.

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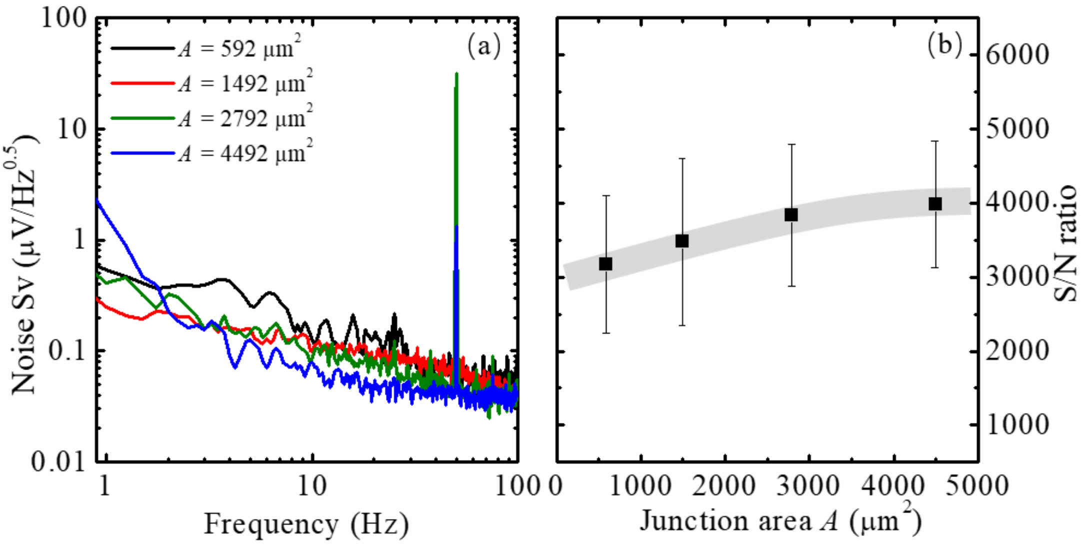

Figure 1. (a) Noise power spectral density as a function of the frequency of the various serial-MTJ devices. (b)The S/N ratio of MTJ output signal at an applied AC magnetic field (0.3 Oe, 23 Hz).

Electric field modulation of magnetic anisotropy in Fe/Mn/MgO/Fe Magnetic tunnel junction

Tsubasa Watakabe[1], Minori Goto[1,2], Hikaru Nomura[1,2], Yoshishige Suzuki[1,2]
[1]Graduate school of Engineering Science, Osaka University, Osaka 560-8531, Japan
[2]Center for Spintronics Research Network (CSRN), Osaka University, Osaka 560-8531, Japan

Modulating magnetic anisotropy with electric field is attracting attention because it doesn't produce joule-heating when magnetization is switched [1][2]. Recently, it was reported that Cr insertion between Fe and MgO enhances voltage induced magnetic anisotropy change [3]. This result suggests that Cr can be playing a role of hole-doping at Fe and MgO interface. Mn also has less electron than Fe does, so similar effect can be expected for Mn. In this research, the magnetic tunnel junction (MTJ) including Mn layer at Fe/MgO interface was fabricated, and the electric field induced magnetic anisotropy change was evaluated.

An epitaxially grown multilayer MgO (5 nm)/V (30 nm)/Fe (0.4, 0.5 nm)/Mn (0 - 0.15 nm)/MgO (1.4 nm)/Fe (10 nm) was fabricated on MgO (001) substrate. Multilayer was patterned to MTJ by using photolithography and Ar ion milling. The voltage controlled magnetic anisotropy (VCMA) coefficient was characterized by spin-torque ferromagnetic resonance under the bias voltage with the value of saturation magnetization of Fe (M_s = 2.16 T). For both 0.4 and 0.5 nm Fe samples, Mn thickness dependence of VCMA exhibit V-shaped behaviors (Fig.).

This research and development work was supported by Bilateral Programs (MEXT), and ImPACT program of the Council for Science, Technology, and Innovation (Cabinet Office, Government of Japan), and the MIC.

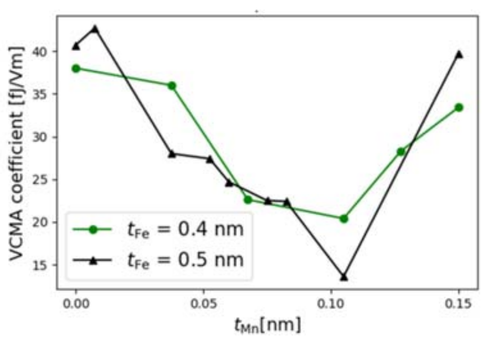

Fig. Mn thickness dependence of VCMA coefficient

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Gilbert damping constant of metastable bcc CoMn thin films

Yuma Ogasawara[1,2], Kazuma Kunimatsu[1,2], Tomoki Tsuchiya[4,3], Satoshi Iihama[2,3], and Shigemi Mizukami[2,3,4]

[1] Dept. Appl. Phys., Graduate School of Eng., Tohoku Univ., Sendai, Japan, [2] WPI AIMR, Tohoku Univ., Sendai, Japan, [3] CSRN, Tohoku Univ., Sendai, Japan, [4] CSIS (CRC), Tohoku Univ., Sendai, Japan

Gilbert damping is a key parameter for spintronics devices, such as spin-transfer-torque and spin-orbit torque devices, because lowering Gilbert damping reduces a threshold current of magnetization switching. Thus it is a longstanding issue to clarify its physics. The ultralow damping constant, $\alpha \sim 10^{-4}$, was recently reported in Fe_xCo_{1-x} binary at $x \sim 0.3$, which was explained by a low electron density of states at the Fermi level at this composition [1]. A Co rich Co-Mn binary alloy forms a hcp or fcc phase as a thermodynamically stable phase. Recently it has been reported that a metastable bcc Co-Mn alloys were obtained in thin film grown on GaAs(001) and MgO(001) single crystalline substrates using a molecular beam epitaxy (MBE) [2,3] and a sputtering [4]. Here, we report a relatively low damping constant observed in bcc Co-Mn thin films. The sample structure was MgO (100) substrate / Cr(40)/ Co_xMn_{100-x}(10) (x = 100, 90, 80, 75, 70)/ MgO(2)/ Ta(3) (thickness in nm). The damping constant was evaluated by a broadband ferromagnetic resonance (FMR) technique. The typical FMR spectrum and the least square fitting are shown in Fig. 1. Figure 2 shows the composition dependence of the damping. We obtained the minimum damping constant of approximately 3.2×10^{-3} at x = 80. This result could be interpreted by a small density of states at the Fermi level at this composition for the bcc Co-Mn alloys. This work was partially supported by JST CREST (No. JPMJCR17J5).

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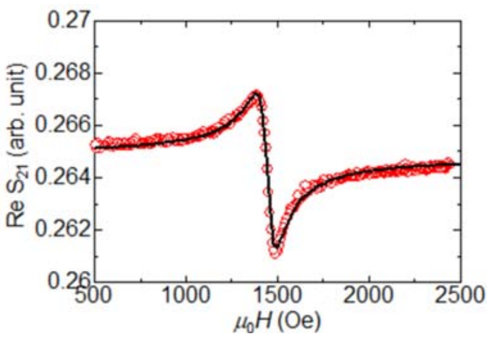

Fig. 1. Typical FMR spectrum for the Co-Mn alloy film. Curve is a fitting.

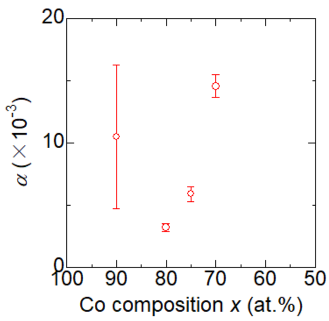

Fig. 2. Co composition x dependence of damping constant α.

Magnon Condensation in the Presence of Magnetoelastic Interaction

Vitaliy I. Vasyuchka[1], Pascal Frey[1], Mio Ishibashi[2], Alexander A. Serga[1], and Burkard Hillebrands[1]

[1]Fachbereich Physik and Landesforschungszentrum OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany

[2]Institute for Chemical Research, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan

Interactions between bosonic quasiparticles of different nature, for example between magnons and phonons in a magnetic medium, can significantly alter the properties of corresponding quasiparticle gases. In particular, this can notably modify the scenario of the Bose-Einstein condensation (BEC) of magnons in the overpopulated magnon-phonon gas.

One example is our recently reported discovery of a novel condensation phenomenon mediated by the magnon-phonon interaction: A bottleneck accumulation of magnetoelastic bosons–excitations formed by hybridization between magnons and phonons [1]. We have found that the transfer of magnon quasiparticles toward a BEC state is almost fully suppressed near the intersection point between the magnon and phonon spectral branches. Such a bottleneck leads to a strong spontaneous accumulation of the magnetoelastic quasiparticles trapped near the semi-linear part of the magnon-phonon hybridization area [1].

Here, we report on the investigation of the magnon condensation in the presence of the magnetoelastic interaction in different areas of the magnon phase space. For this, the energy spectra of an overpopulated magnon-phonon gas were studied at room temperature in an yttrium iron garnet (YIG, $Y_3Fe_5O_{12}$) film by frequency-, time- and wave-vector-resolved Brillouin light scattering (BLS) spectroscopy under different pumping and bias field conditions. The population of magnon-phonon spectra and its time evolution demonstrate a strong interaction between condensed magnons and accumulated magnetoelastic quasiparticles, when they are located close to each other in the phase space.

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Approach to Low-Noise Magnetic Field TMR Sensors by Hybrid Sensing Layers and Deep-Learning Denoising

Muftah Al-Mahdawi[1], Mikihiko Oogane[1,2], Yasuo Ando[1,2]
[1]Center for Science and Innovation in Spintronics (Core Research Cluster), Tohoku University, Sendai, Japan
[2]Department of Applied Physics, Graduate School of Engineering, Tohoku University, Sendai, Japan

Magnetic field sensing is still a small segment of sensors market. Among the magnetic sensor technologies, Tunneling Magnetoresistance (TMR) based sensors are still not widely employed. A shifting landscape of Internet-of-Things (IoT) application demands in automotive, healthcare, infrastructure, and power-grid sectors will require specifications found only in TMR technology. One major challenge in magnetic sensing is environmental and sensor noise. Especially, the frequency band of the aforementioned applications lies at 1–100 Hz range, where the noise with $1/f$ character dominates.

In this presentation, we will introduce our multilevel approach for dealing with noise. For understanding the origin of magnetic in high-sensitivity TMR sensing layers, we used Magneto-Optical Kerr Effect (MOKE) domain imaging. From the spectral analysis on images time series, we found dominant $1/f$ noise of the multi-domain state [Fig. 1]. The likely noise origin is the domain wall fluctuations, due to soft-magnetic property required for high sensitivity. A common method for domain control is field biasing at the orthogonal direction to sensing field [1]. We designed an exchange-biased sensing layer based on $L1_0$-PtMn antiferromagnet/NiFe, with low coercivity and high sensitivity. We show that sensing response of mnicrofabricated mesa is by uniform rotation of magnetic domains, which is in contrast to domain wall movement of closure domains without the PtMn AFM [2].

Furthermore, we investigated building a deep-learning Denoising Auto-Encoder (DAE) [3] for overcoming low-frequency noise in single-channel magnetocardiography (MCG) signals [4]. We could demonstrate a novel DAE based on a combination of a convolutional neural network and a gated-recurrent unit. The trained deep-learning model could decrease noise more than 10 times compared to an averaging filter, without degrading the signal feature [Fig. 2]. The research on DAE has been an active area recently, and our addition will be very promising for integrating logic and sensing on the same integrated circuits for Logic-in-Sensor IoT applications.

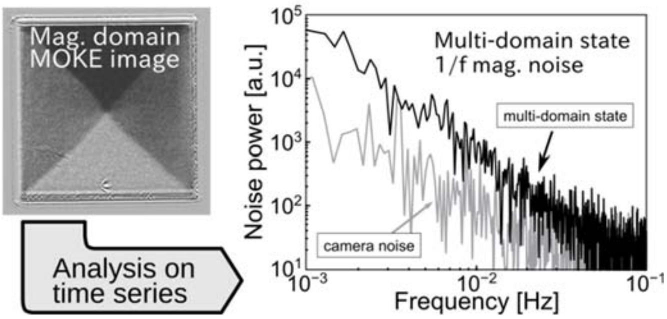

Fig. 1: The multi-domain fluctuations show a 1/f magnetic noise.

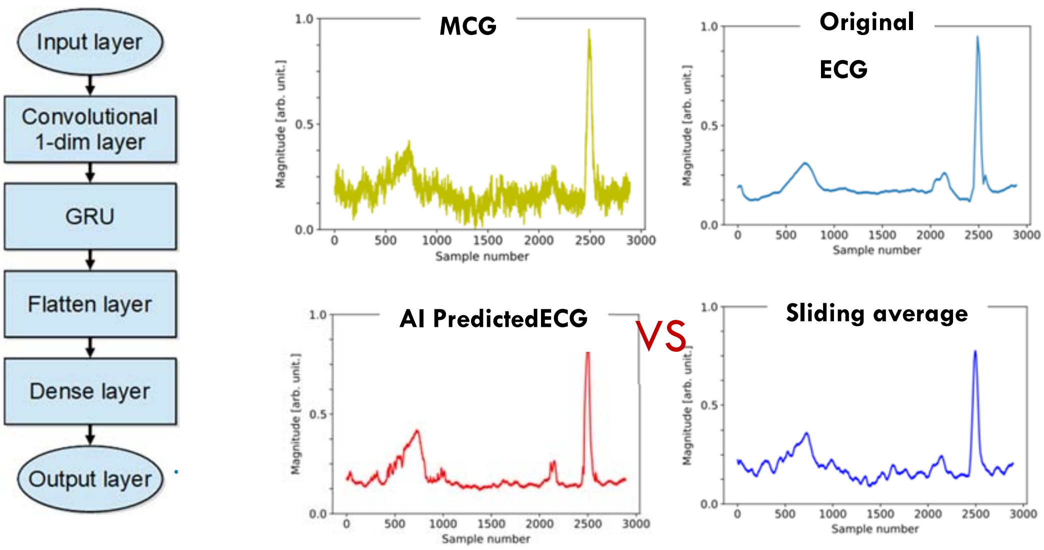

Fig. 2: The deep learning denoising model and prediction demonstration.

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Thermal torque in double barrier tunnel junctions with magnetic insulators

C. Ortiz-Pauyac, [1] C. Akosa, [1] G. Tatara, [1] and A. Kalitsov [2]

[1]RIKEN, Saitama, Japan

[2]Western Digital, San Jose, California 95131, USA

The thermal spin torque induced by the spin dependent Seebeck effect [1] in double barrier tunnel junctions is derived considering free electron and tight binding calculations. We show that in systems comprising ferromagnetic electrodes and non-magnetic barriers the in-plane component of the thermal spin torque is the dominant term, whereas in junctions comprising non-magnetic electrodes and ferromagnetic barriers the dominant term is the out-of-plane. Moreover, larger torque amplitudes are obtained in the second system as a result of spin filtering effect; consequently, double barrier tunnel junctions in the presence of magnetic insulators offer an enhanced thermal spin torque mechanism for reliable applications. We propose that taking advantage of quantum resonant tunneling through resonance states below the Fermi level in these structures can be a route towards achieving larger spin torque efficiencies compared to the voltage induced case. Furthermore, we identify the parameters needed to tune efficiently these resonant states.

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Dynamics of a magnon Bose-Einstein condensate in inhomogeneous magnetic fields

Alexander J. E. Kreil, Alexander A. Serga and Burkard Hillebrands

Fachbereich Physik and Landesforschungszentrum OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany

A supercurrent is a macroscopic quantum phenomenon, which appears when many bosons are being self-assembled in one quantum state with minimum energy and zero group velocity—a Bose-Einstein condensate (BEC)—and move as a whole due to a phase gradient imposed on their joint wave function. This phenomenon is commonly associated with resistant-free electric currents of Cooper pairs in superconductors, and superfluidity of liquid Helium. For example, in in-plane magnetized Yttrium Iron Garnet (YIG) ferrimagnetic films a Bose-Einstein condensate (BEC) of spin-wave quasiparticles, magnons, can be formed even at room temperature if the quasiparticle density exceeds a critical value [1]. The possibility of supercurrents in such a BEC has been recently reported: a phase gradient, being induced in the BEC wave function by local optical heating of the YIG-film sample [2,3], propels the long-distance supercurrent transport of the magnon condensate density over the distance of several hundred micrometres [3].

Here we present another approach to induce magnon supercurrents and to control the transport properties of a magnon BEC. By applying a direct electric current, which flows through a microstrip line placed near the surface of the parametrically pumped YIG film, the bias magnetic field is locally modified. Depending on the current direction, a potential wall or well can be formed in the BEC along the direction of the external magnetic field $\mathbf{H}_{ext}$. By means of time- and space-resolved Brillouin light scattering spectroscopy, we investigate the influence of this inhomogeneous magnetic field on the temporal and two-dimensional spatial dynamics of the magnon BEC with emphasis on the behaviour of a freely evolving BEC, formed after the termination of the external microwave pumping. The stability of the magnon condensate in magnetically formed potential wells and the excitation of two-dimensional supercurrents is discussed.

Financial support by the European Research Council within the Advanced Grant 694709 “SuperMagnonics” is gratefully acknowledged.

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New ferromagnetic semiconductor: rare-earth monoxide GdO

Taku Yamamoto[1], Kenichi Kaminaga[2], Daichi Saito[1], Daichi Oka[1] and Tomoteru Fukumura[1–3]
[1]Department of Chemistry, Graduate School of Science, Tohoku University, Sendai 980-8578, Japan
[2]Advanced Institute for Materials Research and Core Research Cluster, Tohoku University, Sendai 980-8577, Japan
[3]CSIS･CSRN, Tohoku University, Sendai 980-8577, Japan

Ferromagnetic semiconductors (FMSs) constitute an important class of spintronic materials owing to interplay between charge and spin degrees of freedom. New FMS is strongly required to resolve the demerits of existing FMSs such as small magnetization and low Curie temperature (T_C). Gadolinium monoxide GdO ($4f^7 5d^1$) is one of the candidates because of the localized $4f^7$ electrons reminiscent of EuO and the $5d^1$ electron yielding narrow gap in the electron correlation. However, GdO has never been synthesized because of thermodynamically unstable divalent Gd ion [1]. In this study, we report thin film growth and ferromagnetism of GdO with T_C of 279 K.

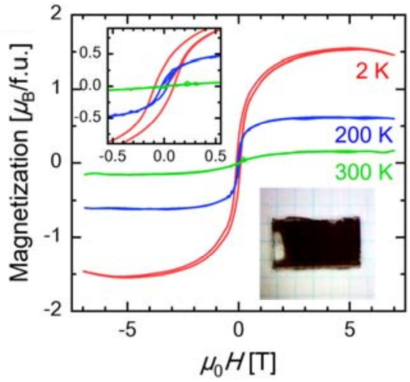

Fig. 1 *M-H* curves for electron-doped GdO epitaxial thin film at various temperatures under in-plane magnetic field. Insets show magnified view (upper left) and sample photo (bottom right).

The GdO (001) epitaxial thin films were deposited on CaF_2 (100) substrates by pulse laser deposition method at 375 °C from a Gd_2O_3 (99.999%) target. The epitaxial thin film growth and the inclusion of paramagnetic Gd_2O_3 phase were confirmed by x-ray diffraction and the films were blackish opaque (inset of Fig. 1). While stoichiometric GdO was insulating, GdO doped with electron by oxygen deficiency was electrically conductive with a relatively high conductivity of 10 S cm^{-1}.

Figure 1 shows magnetization curves at several temperatures for the electron-doped GdO, where the full sample volume was assumed to be GdO phase. The ferromagnetic hysteresis with coercive field of 920 Oe and the saturation magnetization of 1.5 μ_B/f.u. were observed at 2 K. T_C of the electron-doped GdO was as high as 279 K, which was slightly higher than T_C = 274 K of the stoichiometric GdO. The electron-doped GdO showed anomalous Hall effect below T_C, indicating the intrinsic ferromagnetism of GdO.

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