Poster Presentations New Perspective in Spin Conversion Science (NPSCS2020)

01 Gen Tatara

SPINTRONICS THEORY WITHOUT SPIN CURRENT

02 Yutaka Yamamoto

Antiferromagnetic spin Seebeck effect near the Neel point

03 Koichi Oyanagi

Paramagnetic Spintronics

04 Mori Watanabe

Hall and butterfly-shaped magnetoresistance effects in atomically thin $CeTe_3$ films

05 Yusei Fujimoto

Spin pumping into a spin glass materia

06 Tomoharu Ohta

Measurements of anomalous Hall Effect in van der Waals ferromagnet Fe_5GeTe_2

07 Jorge Puebla

Photoinduced Rashba Spin-to-Charge Conversion via an Interfacial Unoccupied Stat

08 Bivas Rana

Nonlinear variation of damping constant with electric field in ultrathin ferromagnetic films

09 Kouta Kondou

Observation of magnetic spin Hall effect in chiral antiferromagnet

10 Takuya Taira

Spin diffusion equation in superconductors: Analysis near Tc

11 Motomi Aoki

Detection of in-plane magnetization switching using ferromagnetic resonance

12 Shota Suzuki

Spin transport measurement in noncollinear antiferromagnet $Mn_3Ni_{1-x}Cu_xN$

13 Masashi Tokuda

Upper critical field measurements in Bi/Ni superconducting bilayer film

14 Kazushi Aoyama

Anomalous spin transport associated with KT-type topological transitions in magnetic insulators

15	Sachio	Komori
Superconducting spin transport in magnetic Josephson junctions		
16	Kohei	Ohnishi
Transport properties in submicron Nb superconducting wire with ferromagnetic electrode		
17	Junyeon	Kim
Orbital torque in ferromagnetic metal/Cu/Al2O3		
18	Zheng	Zhu
Gigantic Hanle Magnetoresistance in Epitaxial Platinum Single Layer		
19	Tomoyuki	Yokouchi
Creation of skyrmions and control of domain wall velocity by surface acoustic waves in Pt/Co/Ir trilayer films		
20	Yunyoung	Hwang
Enhancement of spin current generation via magnon-phonon coupling by using acoustic cavities		
21	Yuichiro	Ando
Fabrication of nonmagnetic metal/exfoliated topological insulator interface without air exposure for highly efficient spin charge interconversion		
22	Mingran	Xu
Acoustic waves rectification in anisotropic magnets		
23	Yosuke	Sato
Tomonaga–Luttinger liquid behavior in wires on an InAs Quantum well holding strong spin-orbit interaction		
24	Keita	Matsumoto
Optical excitations in multiferroic bismuth ferrite		
25	Akihiro	Okamoto
Topological edge modes for coupled waves between magnons and electromagnetic waves		
26	Rafael	Ramos
Room temperature and low-field spin Seebeck enhancemement by magnon-phonon resonance		
27	Yuichi	Kasatani
Electrical detection and modulation of All-Optical magnetization Switching in GdFeCo ferrimagnetic alloy		

28	Masao	Ono
Development of an apparatus for observation of the Einstein-de Haas effect		
29	Tomohiro	Otsuka
Spin and Charge Dynamics in Nanostructures Probed by Quantum Dot Sensors		
30	Hideki	Narita
Electrical transport properties in a microfabricated Mott insulator		
31	Maki	Umeda
Probe of spin dynamics in superconductor using thermal spin injection and spin-to-charge conversion		
32	Takafumi	Fujita
Spin-orbit interaction induced electron spin resonance enhanced by charge tunneling between quantum dots		
33	Satoshi	Iihama
Charge-spin conversion in metallic glass detected via spin-torque ferromagnetic resonance		
34	Genki	Okano
Nonreciprocal conversion between charge and spin currents in naturally oxidized copper films		
35	Akira	Kamimaki
Laser induced non-linear magnon dynamics in synthetic antiferromagnets		
36	Ei	Shigematsu
Investigation of spin-to-charge conversion in Si/Cu/Py multilayer systems by using the ac inductive measurement technique		
37	Yuta	Yahagi
Theoretical Study of the Spin-current Induced by s-d scattering in Ferromagnetic Metals		
38	Shoya	Sakamoto
Anisotropic distribution of the Mn 3d spins in the ferromagnetic semiconductor (Ba,K)(Zn,Mn)2As2 revealed by angle-dependent XMCD		
39	Hironari	Isshiki
Spin-to-charge current conversion at a molecule/metal interface		
40	Hikaru	SAWAHATA
Computational high throughput screening of two-dimensional magnetic thermoelectric materials		

41 Takahide Kubota

Crystal Structure and Perpendicular Magnetization of MnGaGe Films

42 Takamasa Usami

Temperature dependence of Gilbert damping constant of FeRh thin films

43 Taro Nagahama

Voltage effect on Anomalous Hall Effect of Pt/CoFe2O4 bilayers

44 Taisuke Horaguchi

Improvement of Spin Torque Efficiency of Al/Si Bilayer with Quasi-Graded Interface

45 Mingxing Wu

Magneto-optical Kerr effect in a non-collinear antiferromagnet Mn3Ge

46 Naoya Yamaguchi

First-principles Study of Spin Splitting in Ferroelectric Oxides and Bismuth Surface Alloys

47 Hiroki Yoshikawa

Thickness dependency of GdFeCo films and All-optical magnetization switching phenomena

48 Haruki Kiyama

Measurement of multielectron high-spin states and its spin relaxation in a GaAs quantum dot

49 Kenta Matsumoto

Observation of inverse spin Hall effect in Pd-doped FeRh films

50 Ayuko Kobayashi

Topological transport properties in the noncollinear antiferromagnet Mn3Sn thin film

P01

SPINTRONICS THEORY WITHOUT SPIN CURRENT

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Linear response theory of spin-charge conversion effects [1] in spintronics is presented in terms of correlation functions of physical observables, spin and electric current. Direct and inverse spin Hall effects and spin pumping effect are studied considering metallic systems with random spin-orbit interaction and spatially nonuniform Rashba interaction[2]. The theory is free from ambiguity associated with spin current, and provides a clear physical picture of the spin-charge conversion effects. In the present approach, the spin current transmission efficiency is essentially the nonuniform component of ferromagnetic susceptibility. Spin transport though an antiferromagnetic insulator is studied in detail [3]. Transport efficiency is calculated by evaluating correlation function of ferromagnetic component of antiferromagnet (susceptibility) in the magnon representation taking account of an auxiliary field imposing a constraint of a constant Néel vector.

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P02

Antiferromagnetic spin Seebeck effect near the Neel point

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Spin Seebeck effect (SSE) refers to the magnonic spin injection by a temperature gradient in a magnet/nonmagnetic metal bilayer system. Since its discovery in 2008, this phenomenon has been drawing great interest as a simple method for generating spin currents [1]. Recently, not only the *ferrimagnetic* SSE which has been investigated extensively, but also the *antiferromagnetic* SSE has been attracting increasing attention [2,3,4].

In Ref. [4], the antiferromagnetic SSE was measured in a uniaxial antiferromagnetic insulator (AFI) FeF_2 over a wide range of temperatures including the Neel point. On theory side, existing publications [5,6,7] are based on either the Holstein-Primakoff bosons or the Landau-Lifshitz-Gilbert phenomenology, which are justified at low enough temperatures. Therefore, in order to deal with the SSE near the Neel point, an alternative theoretical framework is needed. Here we develop a theory of the antiferromagnetic SSE near the Neel point on the basis of the Ginzburg-Landau model, where a uniaxial anisotropy and thermal noise fields satisfying the fluctuation-dissipation theorem are included.

As a consequence, we find that the antiferromagnetic SSE is proportional to the applied magnetic field as well as the spin susceptibility in AFI. The latter means that the cusp structure appears in the antiferromagnetic SSE near the Neel point. In fact, Li *et al.* [4] recently reported that the SSE in a uniaxial antiferromagnet FeF_2 shows a cusp structure near the Neel point, which supports our theoretical result [8].

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P03

Paramagnetic Spintronics

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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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P04

Hall and butterfly-shaped magnetoresistance effects in atomically thin $CeTe_3$ films

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$CeTe_3$ is an atomically layered material in the family of rare earth tritellurides. Its crystal structure consists of a CeTe slab which is responsible for its magnetic properties, separated by two Te sheets which are responsible for its highly two dimensional electric transport. $CeTe_3$ is known mainly for its formation of incommensurate charge density waves, which has been studied extensively [1]. It also possesses interesting magnetic properties. According to heat capacity and magnetization measurements, the material shows two magnetic phase transitions at around 3 K and 1.2 K [2,3]. These transitions are suggested to be antiferromagnetic, but the details of these magnetic structures are largely unknown. Moreover, despite its layered structure, most studies focus on bulk properties, and there are no reports on thin film measurements.

In order to gain a better understanding of its magnetic properties, we have performed transport measurements in bulk and 40 nm thick $CeTe_3$ films (see the inset of Fig. 1). In the presentation, we will discuss Hall and magnetoresistance measurements near the first magnetic phase transition T_{N1} (≈ 3 K).

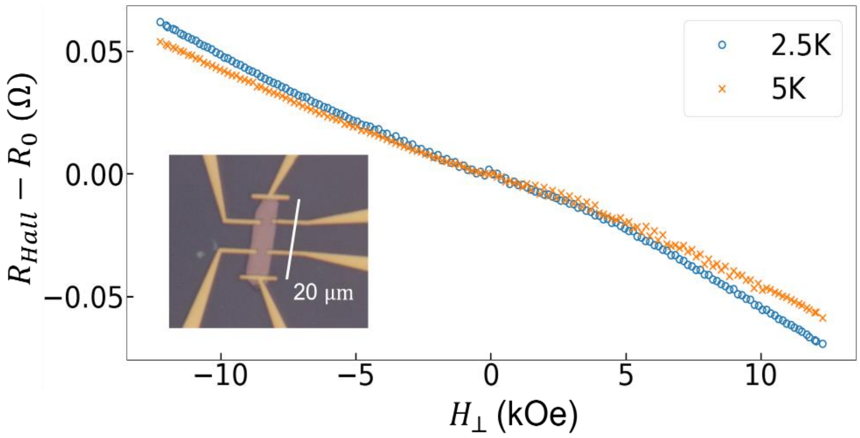

Figure 1: Hall measurement of $CeTe_3$ thin film near the transition temperature T_{N1} ~ 3 K. R_0 is the resistance at zero magnetic field. The Hall resistance is enhanced at H > 5000 Oe below T_{N1}. The inset shows the optical microscope image of the device.

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P05

Spin pumping into a spin glass material

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In recent years, spin transport in spin glass materials has been focused from a variety of perspectives [1-3]. In Ref. [1], for example, the spin pumping into a spin glass material ($Ag_{90}Mn_{10}$) was experimentally examined. Nevertheless, the corresponding theoretical work cannot be found in the literature. Therefore, it is of great interest to develop a theory of spin pumping into spin glasses.

Here, we theoretically investigate the spin pumping into spin glass materials. According to the linear-response formulation of the spin pumping [4], the additional Gilbert damping constant $\delta\alpha$, which is proportional to the spin pumping signal, is associated with the dynamic spin susceptibility $\chi(\omega, T)$ of the target material through the relation:

$$\delta\alpha(T) \propto \frac{1}{\omega}\mathrm{Im}[\chi(\omega, T)]$$

A dynamic theory of spin glasses [5], which reproduces the mean-field solution of Sherrington-Kirkpatrick model [6], is capable of calculating the dynamic susceptibility of the spin glass material, $\chi(\omega, T)$, that appears on the right-hand side of the above relation.

Using the dynamic theory of spin glasses [5], we calculate temperature dependence of the spin pumping near the spin glass transition. We show that a characteristic peak structure appears at the spin glass transition, reflecting the slowing down of spin fluctuations concomitant with the spin freezing of the system.

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P06

Measurements of anomalous Hall Effect in van der Waals ferromagnet Fe_5GeTe_2

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Since the discovery of graphene in 2004, there have been many reports on two-dimensional (2D) materials. In particular, 2D materials showing some phase transition have attracted much attention in terms of the Mermin-Wagner theorem. Recently, two independent groups reported 2D ferromagnetic metals [1,2], which could be useful for future atomic-layer spintronic devices.

The purpose of this study is to fabricate a spintronic device by stacking 2D materials. We have focused on Fe_5GeTe_2 which is one of the 2D ferromagnets with a perpendicular magnetization respect to the 2D plane. Its Curie temperature T_C is higher than room temperature. Thus, atomically thin Fe_5GeTe_2 films are expected for future 2D spintronic devices.

In this work, we have fabricated a thin film device of Fe_5GeTe_2 and measured the electrical resistivity in order to investigate its physical properties. The inset of Fig. 1 shows the optical microscope image of our Fe_5GeTe_2 thin film device fabricated by the scotch tape method. We have then performed Hall measurements at several temperatures. Typical anomalous Hall effect (AHE) curves measured with the Fe_5GeTe_2 thin film device are shown in Fig. 1. Interestingly, the AHE becomes larger with increasing temperature, while the coercive filed decreases with temperature. From the results of the AHE, we estimated the contribution of remnant magnetization R_A and estimated T_C of the Fe_5GeTe_2 film to be about 320 K.

In this presentation, we will discuss the details of these results and show the latest experimental results.

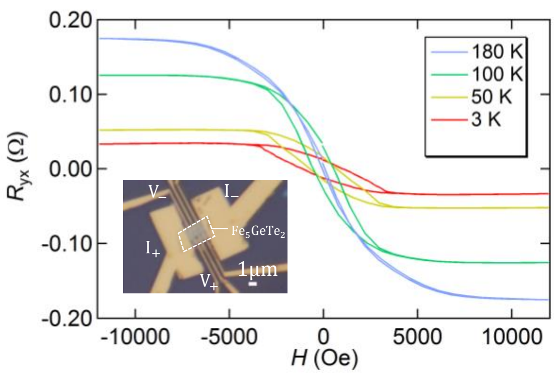

Fig. 1: AHE of Fe_5GeTe_2 thin film device measured below T = 200 K. The inset shows the optical microscope image of the Fe_5GeTe_2 device.

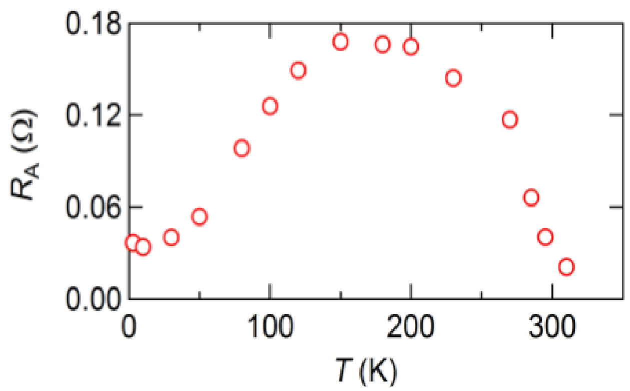

Fig. 2: The temperature dependence of remnant magnetization R_A. R_A is obtained from the y-intercept of a linear fit of the normal Hall term.

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Photoinduced Rashba Spin-to-Charge Conversion via an Interfacial Unoccupied State

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At the interfaces with inversion symmetry breaking, the Rashba effect couples the motion of the electrons to their spin; as a result, a spin charge interconversion mechanism can occur. These interconversion mechanisms commonly exploit Rashba spin splitting at the Fermi level by spin pumping or spin torque ferromagnetic resonance. Here, we report evidence of significant photoinduced spin-to-charge conversion via Rashba spin splitting in an unoccupied state above the Fermi level at the Cu(111)/α-Bi_2O_3 interface. We predict an average Rashba coefficient of 1.72×10^{-10} eV.m at 1.98 eV above the Fermi level, by a fully relativistic first principles analysis of the interfacial electronic structure with spin orbit interaction. We find agreement with our observation of helicity dependent photoinduced spin-to-charge conversion excited at 1.96 eV at room temperature, with a spin current generation of $J_s = 10^6$ A/m^2. The present letter shows evidence of efficient spin charge conversion exploiting Rashba spin splitting at excited states, harvesting light energy without magnetic materials or external magnetic fields.

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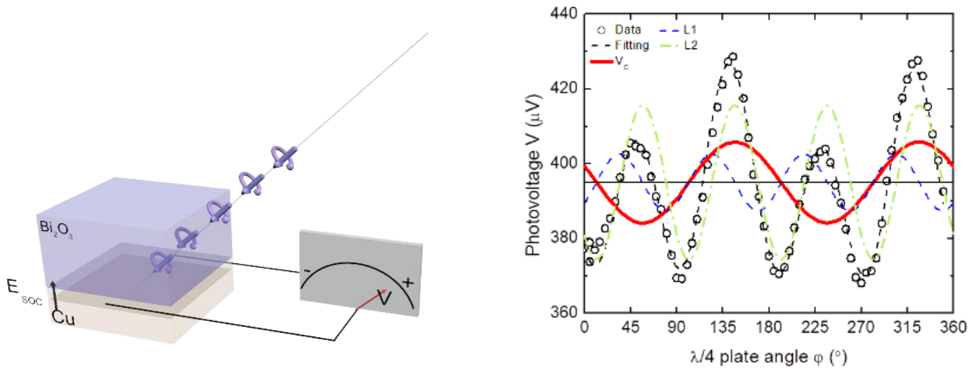

Fig. 1. Schematic of photovoltage modulation by helicity of light (left), and photovoltage modulation data and fittings in Cu(111)/α-Bi_2O_3 interface (right).

P08

Nonlinear variation of damping constant with electric field in ultrathin ferromagnetic films

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Magnetic anisotropy and damping constants are two key parameters that determine the performance of spintronics devices. Since both physical parameters originate from spin-orbit coupling (SOC), it is expected that the materials with higher magnetic anisotropy are generally associated with higher damping constant. Recently, it has been reported that the damping constant of ultrathin CoFeB films can be tuned by electric field and change of damping constant is proportional to the electric field [1]. However, any linear relationship between the change in interfacial magnetic anisotropy (IMA) and the damping constant was not found. Following this another report came out, where the authors did not observe any change in damping constant in spite of observing a huge change in IMA [2]. All these reports open up a question that what is the mechanism of the electric field modulation of damping constant in ferromagnetic metal/insulator heterostructures and how is it different from the electric field modulation of IMA.

Here, we try to clarify these questions by performing ferromagnetic resonance (FMR) experiment of Ta(10)/CoFeB(*t*)/MgO(2)/Al_2O_3(10) heterostructures. We demonstrate a nonlinear dependence of damping constant with gate voltage, i.e., electric field in spite of linear dependence of IMA, especially, for ultrathin ferromagnetic films. By theoretical analysis, we explicitly show that the presence of Rashba spin-orbit interaction at ferromagnet/insulator interface and electric field dependence of Rashba coefficient [3] are the origins behind the observed nonlinear behavior of damping constant. This is further confirmed by studying a reference sample, where the spins are mostly allowed to relax through spin memory loss at ferromagnetic/insulator interface by suppressing the relaxation through spin flip scattering by bulk spin-orbit coupling.

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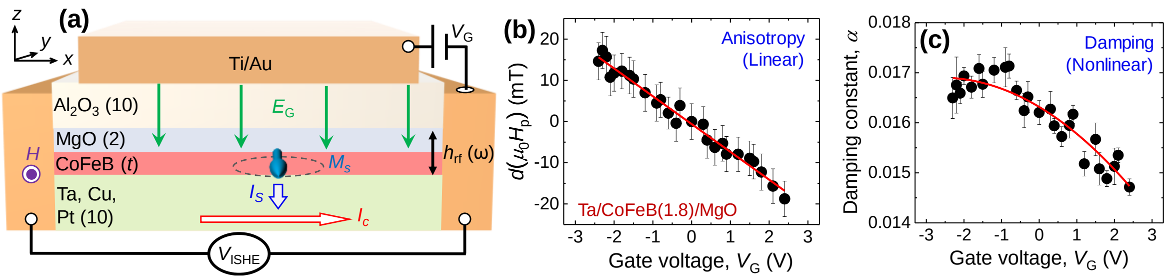

Fig. 1. (a) Schematic diagram of a device and measurement principle. Variation of IMA field (b) and damping constant (c) are plotted as a function of gate voltage V_G. Solid lines are the fittings with a linear and quadratic function, respectively.

P09

Observation of magnetic spin Hall effect in chiral antiferromagnet

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Spin Hall effect (SHE) provides the spin-charge interconversion in non-magnetic materials, which has drawn much attention because of its potential application for efficient magnetization switching via the spin torque [1].

Here we focus on the non-collinear antiferromagnet Mn3Sn to realize the new functionality in spin-charge conversion. Mn_3Sn exhibits the large anomalous Hall effect comparable with ferromagnet at room temperature [2]. Figure 1 shows a devise structure for spin accumulation detection. By applying the charge current on a Mn3Sn strip, spin accumulation can be detected electrically by the ferromagnetic electrode. This technique enables us to observe the SHE in Mn3Sn, exhibiting an anomalous sign change when its small magnetic moment switches orientation. Additionally, we succeeded in observation of the sign change in the inverse effect by means of spin pumping method. By comparison with theoretical toy-model, we found that such unique functionality in Mn3Sn is caused by the momentum-dependent spin splitting produced by non-collinear magnetic order [3].

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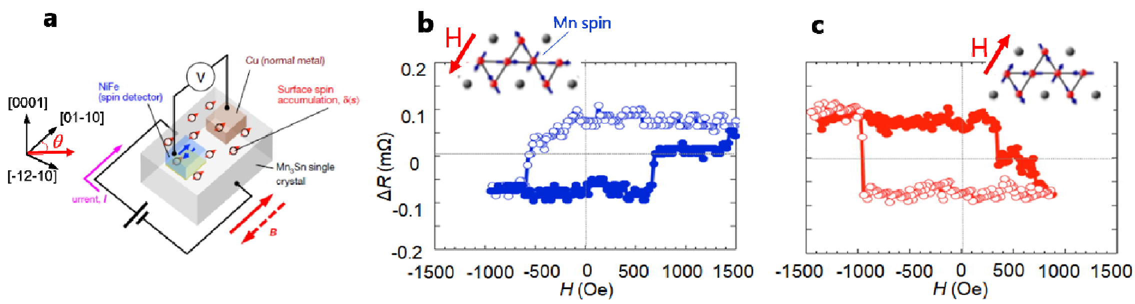

Figure 1 Device structure for spin accumulation detection
a, Measurement setup of spin accumulation. The electrical current was applied along [-12-10] direction. The external magnetic field was rotated within the device basal plane and the field angle θ was measured from the [01-10] axis. **b, c** Spin accumulation signals ΔR. Magnetic field dependence of the resistance measured between NiFe-Cu electrodes at room temperature.

P10

Spin diffusion equation in superconductors: Analysis near Tc

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Much attention is now focused on the interplay of the spin current and superconductivity, and a new research field of superconducting spintronics has been rapidly growing [1]. In discussing the spin transport phenomena in metals and superconductors, the most basic theoretical apparatus is the spin diffusion equation [2]. Indeed, the real space profile of the spin current is described by the spin diffusion equation, which can now be experimentally measured using the lateral spin valve technique [3]. Despite its importance, however, only a little is known about the spin diffusion equation in the superconducting state [2,4].

Here, we microscopically derive the spin diffusion equation in he superconducting state near the transition temperature Tc on the basis of the weak-coupling BCS model with s-wave pairing and with impurity spin-orbit scattering. Applying the general relation between the relaxation function and the response function [5], which in the present context is translated into the relation between the spin diffusion equation and the dynamic spin susceptibility, we examine how the spin diffusion equation is renormalized in the superconducting state. We find that both the spin relaxation time and the spin diffusion coefficient are increased below Tc, resulting in an enhancement of spin diffusion length in the superconducting state [6].

The present result may provide an explanation, in terms of the conventional singlet Cooper pairs, for the recent observation of an enhanced spin pumping signal below Tc in a Py/Nb/Pt system, which would otherwise be attributed to the spin transport mediated by triplet Cooper pairs [7].

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Detection of in-plane magnetization switching using ferromagnetic resonance

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Magnetization switching using spin orbit torque (SOT) [1] have been investigated intensively, because it enables a low power consumption and high endurance magnetoresistive random access memory. For the in-plane magnetization materials, fabrication of spin valves such as a magnetic tunnel junction is generally required. Such additional and complicated fabrication procedures impede a wide variety of material search for spin orbit materials. In this study, we demonstrated in-plane magnetization switching of a single $Ni_{80}Fe_{20}$ (Py) layer on platinum (Pt) layer by using the spin rectification effect under ferromagnetic resonance (FMR) condition [2]. Under irradiation of microwave with a frequency of several GHz, two FMR spectra are obtained when the magnetic field is swept from large negative field to positive one. The absolute value of resonance field is decreased with decreasing the microwave frequency, and finally, the field range of two FMR spectra are superimposed on each other. In this case, we can distinguish between two different magnetization directions from difference in voltage at specific magnetic field, corresponding to the two FMR spectra.

Figure 1 shows a schematic of the fabricated device. Pt/Py/MgO/Cu layers and a Au/Ti coplanar wave guide was fabricated on the MgO substrate. In the measurements, a large magnetic field at $\theta = 5^{o}$ was applied to initialize the magnetization direction. After removing the magnetic field, a low frequency microwave (0.5 GHz) was applied and a dc voltage induced by FMR was measured. After stopping the microwave irradiation, a pulse current (pulse width: 1 ms) was applied into the Pt layer. Magnetization switches to -*y* direction when the SOT generated by the spin Hall effect in Pt and/or Oersted field generated by the charge current in Pt are sufficient. Then, dc voltage induced by FMR was measured again. When the magnetization is successfully switched, a clear difference in dc voltage between before and after application of the pulse current is detected. Figure 2 shows the normalized voltage difference between before and after application of the pulse current as a function of dc charge current. A successful magnetization switching was confirmed above 1.5×10^{7} A/cm^{2}. In the presentation, we will also report relationship between detection sensitivity of the magnetization switching and size of the ferromagnetic layer.

[1] H. W. Tseng et al., Science **336**, 555 (2012). [2] L. Liu et al. , Phys. Rev. Lett. **106**, 036601 (2011).

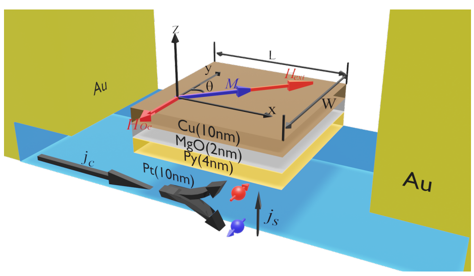

Fig.1. A schematic of device structure for demonstration of current induced magnetization switching.

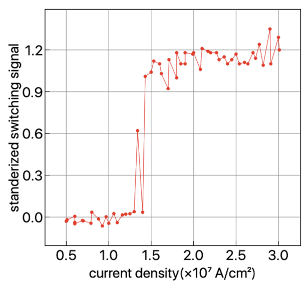

Fig. 2. Normalized voltage difference between before and after application of the pulse current as a function of dc charge current.

Spin transport measurement in noncollinear antiferromagnet $Mn_3Ni_{1-x}Cu_xN$

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Recently, noncollinear antiferromagnets (AFM) have attracted much attention because of many interesting physical properties. For example, Mn_3Sn has a two-dimensional triangular lattice and shows a 120° structure AFM order. Thus, the total magnetization is extremely small, but it shows a large anomalous Hall effect (AHE) [1]. Furthermore, a peculiar spin Hall effect has also been reported in this material [2].

Mn_3NiN is also a noncollinear AFM which has the similar 120° structure to Mn_3Sn, and shows a weak AHE near the Néel temperature T_N. However, when some of Ni atoms are replaced by Cu, the AHE is enhanced, preserving the noncollinear AFM order [3]. On the other hand, Mn_3CuN shows a ferrimagnetic order. These results indicate that the magnetic order can be controlled by Cu doping. Because of these unique properties, $Mn_3Ni_{1-x}Cu_xN$ systems are promising candidates for future spintronic devices.

In this work, we have fabricated $Mn_3Ni_{0.5}Cu_{0.5}N$ nanowires and performed electrical transport measurements. Figure 1 shows the temperature dependence of the resistivity of a $Mn_3Ni_{0.5}Cu_{0.5}N$ nanowire. A kink structure due to the magnetic phase transition was observed at 250 K (= T_N). We next measured Hall resistances and observed the AHE below T_N (Fig. 2). These behaviors are consistent with the previous results measured with the 100 nm thick films [3]. We are now working on fabricating spin transport devices with $Mn_3Ni_{0.5}Cu_{0.5}N$ nanowires. The details will be shown in this presentation.

[1] S. Nakatsuji *et al.*, Nature **527**, 212 (2015). [2] M. Kimata *et al.*, Nature **565**, 627 (2019).
[3] K. Zhao *et al.*, Phys. Rev. B **100**, 045109 (2019)

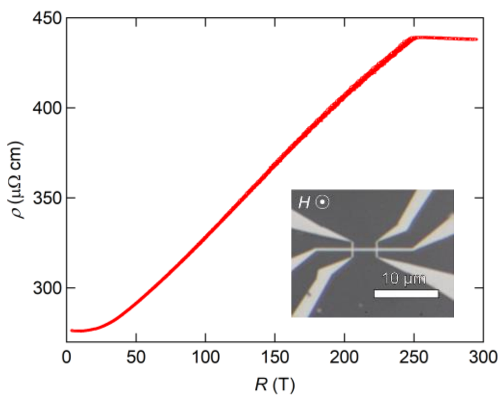

Fig. 1. Temperature dependence of resistivity of a $Mn_3Ni_{0.5}Cu_{0.5}N$ nanowire. The inset shows an optical microscope image of the $Mn_3Ni_{0.5}Cu_{0.5}N$ nanowire.

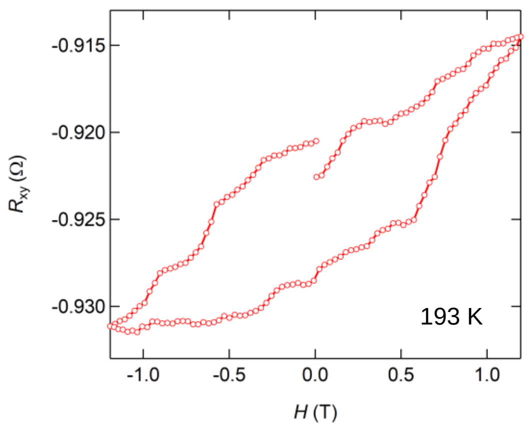

Fig. 2. Hall resistance of the $Mn_3Ni_{0.5}Cu_{0.5}N$ nanowire at 193 K.

Upper critical field measurements in Bi/Ni superconducting bilayer film

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Bismuth has very atractive proparties because of its unique electrical band structure and large spin-orbit interaction. Thus, Bi-related materials have been actively studied in the field of spintronics, superconductors and topological physics. The Bi/Ni bilayer system can meet these resarch topics simultaneously. The bilayer is composed of a few tens nanometor thick Bi film and a few nanometor thick ferromagnetic nickel film. Although the Bi thin film used in this sample shows a semimetallic transport property and does not show a superconductoring behavior, the Bi/Ni bilayer does a metallic transport property and also a superconducting transition at $T_C \approx 4$ K [1]. According to magnetization measurements in the Bi/Ni thin films, the Ni layer keeps ferromagnetism even below T_C [2]. Moreover, recent Andreev reflection measurements pointed out that the *p*-wave spin triplet Cooper pair is realized in this system [1,3]. These results indicate that the bilayer could be a candidate of topological superconductor and a fascinating platform to study spin transport in nomal and superconducting states.

Since the Bi/Ni bilayer is a thin film superconductor, it is suitable for fabricating nanoscale devices like SQUID or lateral spin valves [4]. However, the fundamental parameters rerated to the superconductivity like the upper critical field (H_{c2}) have hardly been reported yet because it is difficult to fabricate the high quality Bi/Ni bilayer. In this work, we measured the temperature dependence of resistivity of the Bi/Ni bilayer film at various perpendicular magnetic fields (Fig. 1.). From the Ginzburg-Landau (GL) theory, we estimated the H_{c2} and the GL coherence length at 0 K (Fig. 2.). We will also report the prospect of fabricating nanoscale devices with the Bi/Ni bilayer film.

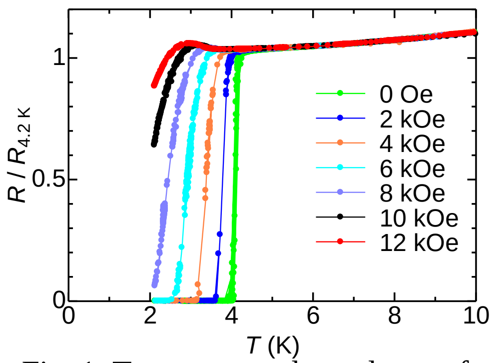

Fig. 1. Temperature dependence of resistance of Bi/Ni bilayer film. The external magnetic field is perpendicular to the film.

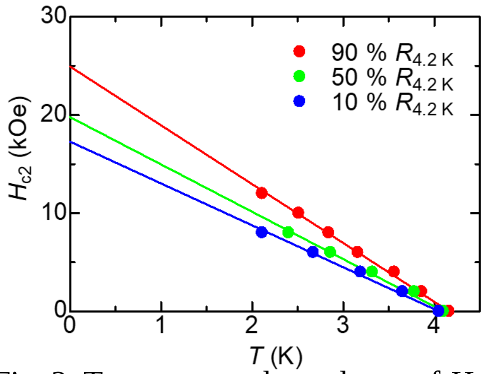

Fig. 2. Temperature dependence of H_{c2}. Data points are 90 %, 50 % and 10 % of the resistance shown in Fig. 1. The solid lines are the fittings with the GL theory.

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[3] G. J. Zhao *et al.*, arXiv: 1810.10403.
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P14

Anomalous spin transport associated with KT-type topological transitions in magnetic insulators

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Heisenberg antiferromagnets on the triangular lattice are prime examples of frustrated magnets. With the nearest-neighbor (NN) antiferromagnetic interaction alone, the ground-state spin configuration is the non-collinear 120°structure. For classical spins, the short-range spin correlation of the non-collinear structure yields the so-called Z_2 vortex, and the existence of a Kosterlitz-Thouless (KT)-type topological transition associated with binding-unbinding of the Z_2 vortices is predicted [1]. Since static physical quantities such as the specific heat C and the magnetic susceptibility χ exhibit only a weak essential singularity at the Z_2-vortex transition temperature T_v [2], high-precision measurements have been required to detect the Z_2-vortex transition.

In this work, to seek signatures of the Z_2-vortex transition in dynamical physical quantities, we theoretically investigate spin and thermal transports of the NN classical Heisenberg model on the triangular lattice. It will be shown by means of the hybrid Monte-Carlo and spin-dynamics simulations that the longitudinal spin-current conductivity σ^s_{xx} exhibits a divergence at T_v, while the thermal conductivity does not show any clear anomaly at T_v [3]. We emphasize that only σ^s_{xx} diverges at T_v, while the static quantities C and χ do not (see Fig.1). Such a characteristic spin-transport phenomenon may be observed in the candidate antiferromagnets $NiGa_2S_4$, $FeGa_2S_4$, $NaCrO_2$, and $KCrO_2$ as a distinct experimental evidence for the so far elusive Z_2-vortex transition.

In the presentation, we will also demonstrate that such a strong association between the spin transport and the vortex binding-unbinding transition can be seen in two-dimensional *XY* magnets exhibiting the ordinary KT topological transition[4].

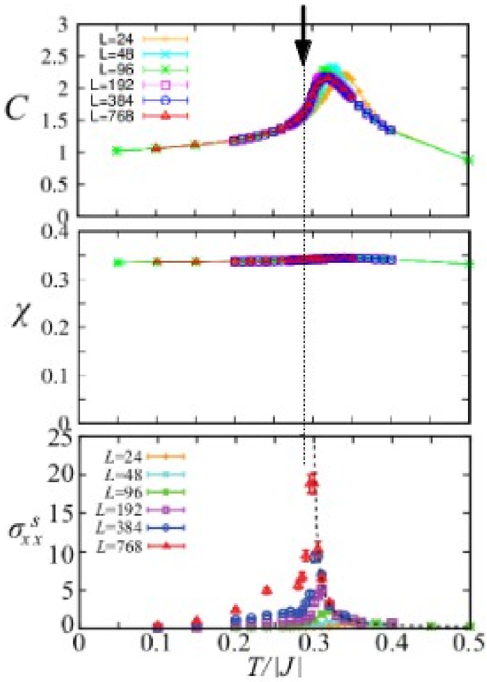

Fig. 1. Temperature dependence of the specific heat C (top), the magnetic susceptibility χ (middle), and the spin-current conductivity σ^s_{xx} (bottom) in the triangular-lattice antiferromagnet. A black arrow indicates the Z_2-vortex transition temperature T_v.

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Superconducting spin transport in magnetic Josephson junctions

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Electron pairing at a superconductor / ferromagnet (S/F) interface is controllable through the alignment of the magnetic exchange field. Over the past decade, it has been established that a non-uniform magnetic exchange field at a S/F interface converts spin-singlet pairs (antiparallel spins) to a triplet state in which the spins are parallel and triplet supercurrents are long-ranged in Fs[1-3]. We demonstrate that spin-polarised triplet supercurrents can transfer spin angular moment from one F to another without dissipation in Nb/Cr/Fe/Cu/Fe/Cr/Nb Josepshon junctions. The triplet supercurrents are generated via Cr/Fe spin-glass interfaces and are controlled through a spin-filtering effect through a Fe/Cu/Fe pseudo spin-valve barrier: an antiparallel alignment of the Fe moments suppresses the triplet Josephson current (10%) with respect to the parallel state, analogues to giant magnetoresistance. Furthermore, we demonstrate a blocking of triplet Josephson currents by a singlet superconducting Nb in equivalent junctions in which the central layer of Cu is substituted for a 10-40 nm-thick layer of superconducting Nb. The results are promising for the development of superconducting spintronic devices in which read and write operations are achieved via spin-polarized triplet states.

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Transport properties in submicron Nb superconducting wire with ferromagnetic electrode

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Spin dependent transport in superconductor is carried by quasi-particles, which can be excited electrically by charge current through superconductor/normal metal interface. Since the possibilities of the phenomena at the interface such as (crossed) Andreev reflection and elastic co-tunneling depend on the spin polarization of the excitation current, the efficiency of quasi-particle injection into a superconductor and the decay in the superconductor may be controlled by utilizing the spin current as an excitation current. However, these spin-dependent phenomenon are still under discussion especially at the vicinity of a transition temperature. To clarify these experimentally, we investigate the spin-polarized quasi-particles injection and transport in superconductor by using normal and ferromagnetic metal electrodes.

First, we explored the influence of electrodes on the superconducting Nb wire. Figure 1 shows a SEM image of the fabricated multi-electrodes lateral structures consisting of a superconducting Nb wire and normal Cu electrodes. In this structure, the injected quasi-particles by the excitation current through the Nb/Cu interface flow diffusively in Nb with relaxation. Since the amount of the quasi-particles transport can be estimated as the non-local resistance by using another normal metal electrode as a detector, the relaxation length can be measured by the distance dependence of the non-local resistances. According to the non-local resistances with changing the number of electrodes and probe configurations, the injection efficiency and the effective relaxation length of quasi-particles at the transition temperature is strongly affected by the contact size of the electrodes. This result indicates that the formation of Cooper pairs from quasi-particles may be disturbed by additional normal metal contacts.

Figure 2 shows a SEM image of the device to investigate the spin relaxation time of quasi-particles. Here, to estimate the spin relaxation length correctly, we optimized the contact size of the electrodes to reduce the influence of the electrode. This structure can effectively induce the spin-polarized quasi-particles by using the ferromagnetic CoFeAl electrode, which needs the additional relaxation time to form Cooper pairs due to the spin polarization. In the presentation, we will also discuss the spin relaxation time of the quasi-particles by comparing the relaxation lengths measured by the excitation current with and without spin polarization.

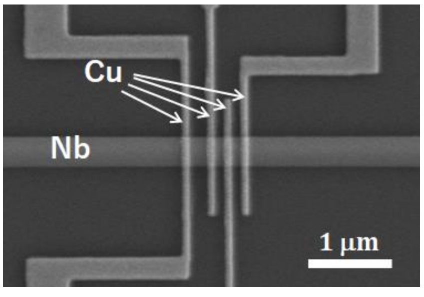

Fig. 1. SEM image of a device to explore the influence of the electrodes.

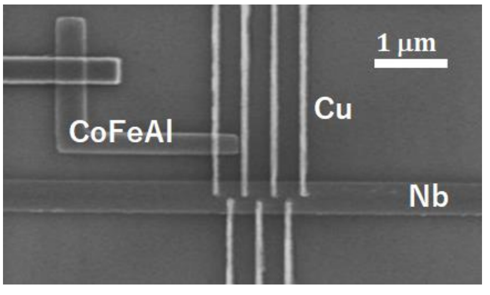

Fig. 2. SEM image of a device to investigate the spin relaxation length.

P17

Orbital torque in ferromagnetic metal/Cu/Al_2O_3

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Nowadays, exploration to a novel spin conversion mechanism to overcome the material restriction to the heavy elements is strongly requested for further broad applications. The confinement of the material selection offers a difficulty on compatibility for the mass production, and/or the high resistivity of a system. Orbital-mediated magnetization manipulation gives an alternative way for the Spintronics development. The orbital generation from the charge current can be achieved even the system does not contain a heavy element. If the generated orbitals are inserted into the ferromagnetic metal (FM), they generate a torque with same form of the spin torque via the spin-orbit coupling. It is called orbital torque (OT) [1].

Here we present a large OT in CoFe/Cu/Al_2O_3 system. And we adopt a spin torque ferromagnetic resonance (ST-FMR) technique to investigate the OT. Although there is no heavy element in this system, we obtain ~0.13 spin torque (ST) efficiency, which is comparable to the conventional spin Hall materials (e.g. Pt or Ta). Moreover the ST efficiency increases with increasing the annealing temperature, and it becomes ~0.3 which is close to ST efficiency of W. These properties feature that the origin of the large torque in this system is OT. Further discussions will be given during the conference.

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P18

Gigantic Hanle Magnetoresistance in Epitaxial Platinum Single Layer

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Recently, a theoretical work predicted the Hanle magnetoresistance (HMR) effect in metallic films with strong spin-orbit coupling (SOC)[1]. A spin current is generated along the thickness direction of the film via spin Hall effect (SHE) when an electric current is applied. The spin current produces an additional electric same direction to the initial current by inverse spin Hall effect (ISHE). If a magnetic field is applied in the direction perpendicular to the spin polarized direction, one can force them to precess via the Hanle effect, and then lead to a decrease of the electric current produced by ISHE, thereby generating a modulation in the resistivity of the material. This effect is small since it is due to a second-order spin Hall angle (θ_{SH}^2) correction. S. Vélez et al. [2] reported an experimental work of HMR in polycrystalline Pt on Pyrex substrates at 100 K and HMR ratio $\Delta\rho_L/\rho_L$ at magnetic field B=9 T is 3×10^{-5}. The same value order room temperature HMR ratio of 7×10^{-5} at B=9 T was reported in polycrystalline Pt on Si/SiO$_x$ substrates[3]. Our purpose is to estimate SHE in epitaxial platinum from HMR measurement and to check if there is a significant difference in epitaxial platinum and polycrystalline platinum.

In Our study, Pt thin films on both sapphire and Si/SiO$_x$ substrates were fabricated using the magnetron sputtering at a substrate temperature of 550°C. The crystallographic structure of Pt thin films was measured by x-ray diffraction (XRD). These films were patterned in the form of a Hall bar with 30 μm × 100 μm by using photolithography and milling process. The HMR measurements were carried out in Quantum Design physical properties measurements system (PPMS) with rotator puck. Figure 1(a) shows the angular-dependent magnetoresistance (ADMR) measurement setup. Under a constant magnetic field B=8 T, the ADMR curves in sapphire/Pt(5 nm) sample at different temperature are shown in Fig. 1(b), $\cos^2\theta$ was observed which are in accordance with the HMR theory[1]. The HMR ratio value is more than one order of magnitude larger than previous reports. The maximal HMR ratio $\Delta\rho_L/\rho_L$ can reach 3×10^{-3} at 4 K. We will show our quantitative analysis in this poster presentation.

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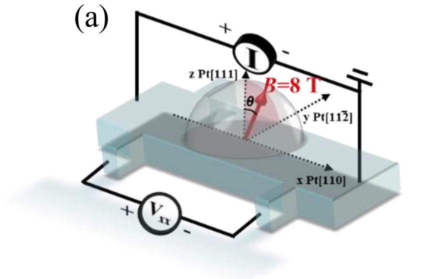
(a)



(b)

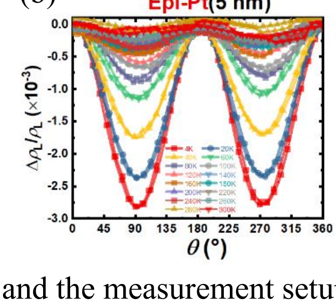


Fig. 1.(a) The schematic of the Hall bar geometry and the measurement setup. (b) ADMR measurement with B=8 T at different temperature in sapphire/Pt(5 nm).

Creation of skyrmions and control of domain wall velocity by surface acoustic waves in Pt/Co/Ir trilayer films

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A magnetic skyrmion (Fig. 1), a particle-like noncoplanar topological spin structure characterized by a nonzero topological integer called the skyrmion number, has great potential for various spintronic applications [1,2]. In particular, efficient and practical means to create skyrmions is an important technological issue. However, creation of skyrmions has been achieved by only using currents so far, and moreover, in these methods, the skyrmions are only created at a specific position in the films [3,4].

In this presentation, we demonstrate a novel approach for skyrmion creation by employing surface acoustic waves (SAWs); in asymmetric multilayers of Pt/Co/Ir, we experimentally observed at room temperature that skyrmions can be created by propagating SAWs in a wide area of the magnetic film due to the long propagation length of SAWs. Micromagnetic simulation reveals inhomogeneous torque arising from both SAWs and thermal fluctuations creates a pair of Néel and antiskyrmion-like structure, which subsequently transforms to Néel skyrmion due to the instability of antiskyrmion-like structure in systems with interfacial Dzyaloshinskii-Moriya interaction. We also demonstrate control of ferromagnetic domain wall velocity by using propagating SAWs. Our finding provides a novel guiding principle for efficient manipulation of topological spin objects without Joule heating dissipation.

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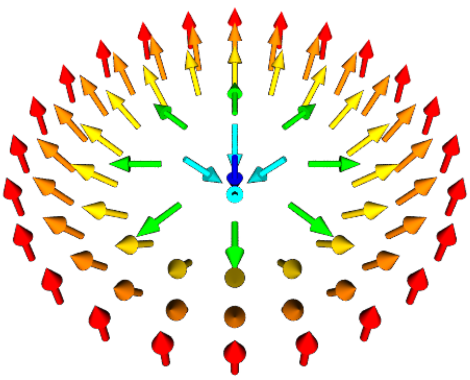

Figure 1 Neel-type skyrmion

Enhancement of spin current generation via magnon-phonon coupling by using acoustic cavities

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In the last few decades, spintronics, which is the field studying the spin of electrons, has been quickly rising because nanotechnology has advanced a lot. The critical concept of spintronics, spin conversion, lies on generation, manipulation, and detection of spin polarization, which is based on various phenomena taking place at nanoscale between electricity, light, sound, vibration, heat, etc. [1]. However, despite the continuous progress in the understanding of spin conversion, few studies have systematically demonstrated the interaction between spin and sound-vibration.

In the previous research of our group, we succeeded to generate spin currents by acoustic ferromagnetic resonance via the magnon-phonon coupling. Surface acoustic wave (SAW) is used in this experiment for exciting magnon. The density of the generated spin current was about 10^8 A/m^2 [2]. However, there is a lot of energy losses of SAW in the structure of the previous research. Enhancement of magnon-phonon interaction would deliver improvements in the generation of spin current by minimizing energy losses by using acoustic wave reflectors. As shown in Fig.1, an acoustic cavity is a pair of Bragg reflector gratings (resonator). In the acoustic cavity, the acoustic energy is confined entirely to one surface of the substrate [3]. In this work, we present the generation of spin currents by acoustic ferromagnetic resonance in the presence of acoustic cavities.

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[2] M. Xu, J. Puebla, F. Auvray, B. Rana, K. Kondou, and Y. Otani, Phys. Rev. B. **97**, 180301(R) (2018).
[3] D.L.T. Bell, R.C.M. Li, Proceedings of the IEEE, **64**, 5, May 1976

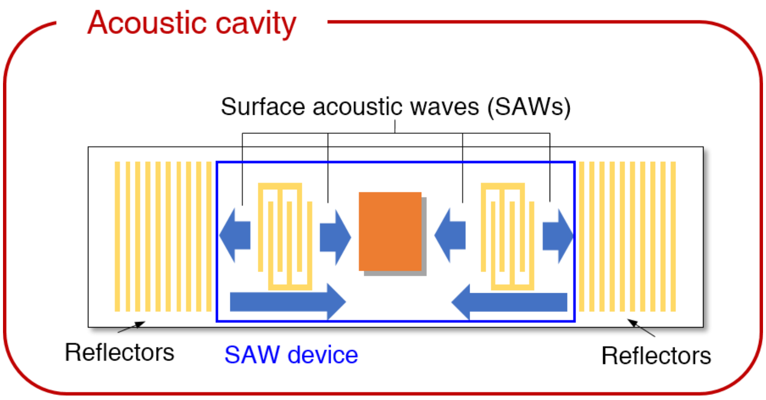

Fig. 1. Schematic of the acoustic cavity structure which is used in this study.

P21

Fabrication of nonmagnetic metal/exfoliated topological insulator interface without air exposure for highly efficient spin charge interconversion

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A surface state of the three dimensional topological insulator has been expected to realize a highly efficient spin-charge interconversion.[1)] Much effort has been paid for quantitative investigation of spin-charge interconversion phenomena by using various ways such as potentiometric measurements[2, 3)], spin pumping,[4)] spin transfer torque ferromagnetic resonance[5, 6)] and so on. Recently, we reported reciprocal spin-charge interconversion in topological surface state using a copper (Cu) based lateral spin valve with a topological insulator middle wire. Clear spin to charge and charge to spin conversion signals were obtained at 10 K as shown in Fig. 1. These conversion signals were obtained even at room temperature. The Rashba length was estimated to be around 18 nm. Because the exfoliated topological insulator materials have atomically flat surface and their composition are precisely controlled due to the well-established growth method, the topological properties is expected to become obvious. In the previous study, however, a Cu/Ti layer was deposited on the exfoliated $Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$ (BSTS) after air exposure, which might induce oxidation of the topological insulator. To remove the oxidized layer, we employed Ar^+ ion miller with low accelerating voltage before the deposition of nonmagnetic layer. Due to the milling process, non-negligible damage might be induced in the topological insulators.

In this study, we established fabrication procedures of copper-based lateral spin valves with topological insulator free from the damages by Ar^+ ion milling and oxidization. Because a non-negligible oxygen gas exists even in the glovebox with a pure N_2 gas, we employed exfoliation procedure in the vacuum chamber with base pressure of 10^{-6} Pa. After exfoliation, nonmagnetic materials were deposited on the topological insulators without air exposure. In the presentation we will discuss the spin-charge interconversion study in the topological insulator with Cu lateral spin valves fabricated by the modified procedures.

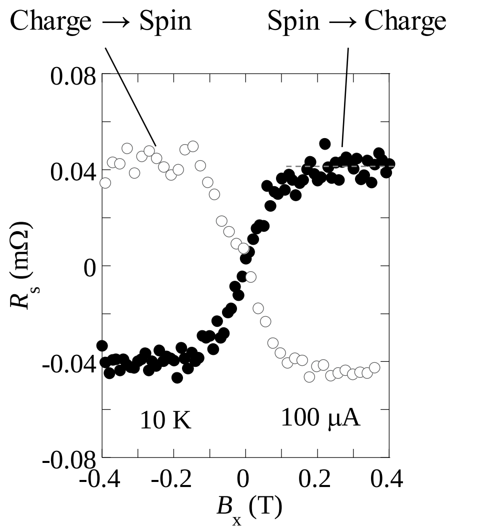

Figure 1 Spin-charge interconversion signals in topological insulator at 10 K.

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Acoustic waves rectification in anisotropic magnets

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As one of the most fundamental properties of magnetic materials, magnetoelastic effect has been discovered and deeply investigated for more than one century. This particular effect has been utilized in various strain related applications where mechanical stress induces the change of the magnetic susceptibility. Different from this conventional form, more than 40 years ago, it was proposed [1] that surface acoustic waves may induce magnons excitation via rotational motion to the lattice in anisotropic magnets, named as magneto-rotation coupling. However, this magnon-phonon coupling mechanism has been elusive and been ignored for a long time. Here, we show the first observation of this coupling mechanism in high perpendicular anisotropic ultra-thin film Ta/CoFeB(2 nm)/MgO. Interestingly, as a consequence of the effect, we observed giant nonreciprocal acoustic wave attenuation. Besides, since the nonreciprocal attenuation highly depends on the magnetic anisotropy, it can be further modulated by external electric field, as has been reported for the CoFeB/MgO interface [2]. Considering the wide application of the general acoustic device in sensing, filtering and information transportation, utilization of acoustic-magneto rectifier would not only provide highly accurate methods for sensing magnetic properties, but also further advances present acoustic technology, and eventually pushes the development of acoustomagnetic logic devices as an attractive alternative to their magnonic counterparts [3, 4].

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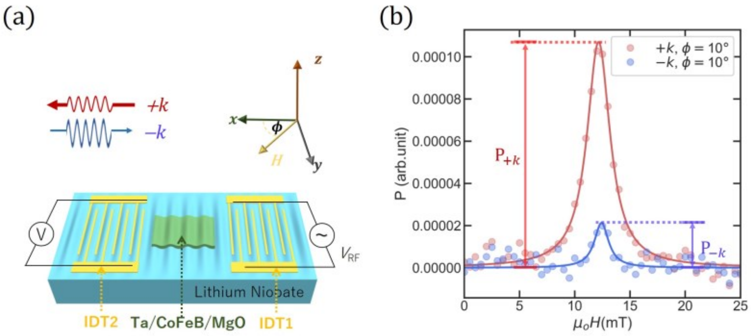

Fig. 1. Nonreciprocal propagation of acousto-magnetic waves in Ta/CoFeB/MgO. (a) Device schematics of surface acoustic waves coupling to a ferromagnetic layer at GHz frequencies. (b) Attenuation of acoustic waves at resonance condition for surface acoustic wave vectors +k and -k.

Tomonaga–Luttinger liquid behavior in wires on an InAs Quantum well holding strong spin-orbit interaction

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Tomonaga–Luttinger liquid (TLL) offers a universal physics of interacting 1D electron systems and has been studied extensively. Accordingly, interesting phenomena, such as scaling behavior and spin-charge separation, are predicted and observed[1]. The phenomena are characterized by the Luttinger liquid parameter, which indicates the strength of the electron-electron (e-e) interaction. In particular, TLL with strong spin-orbit interaction (SOI) attracts theoretical interests in virtue of a prediction that TLL may be a platform for Kramers pairs of Majorana fermions or parafermions [2]. For the realization, the small Luttinger liquid parameter is preferred. However, despite active discussion in theory, only a few TLL experiments are done for systems holding strong SOI as in Ref.[3]. However, discussion on the effect of SOI in this paper is still controversial.

Here, we report on observation of TLL behavior in electron transport of InAs wires. The wires are chemically etched out from an InAs quantum well. The width and length of the wires are 100 nm and 20 µm, respectively. We fabricated parallel 10 wires and top-gate structure to control the electron density. We measured the current vs. voltage in a fridge at various temperatures. As a result, we observed universal scaling behavior, which is a signature of TLL. From fitting with a theoretical model [4], we acquired a significantly small Luttinger liquid parameter, which indicates strong e-e interaction. In addition, we repeated the same measurement at different top-gate voltages and observed an enhancement of the interaction, namely the smaller Luttinger parameter as the wires get depleted. The parameter reached below 0.3, whereas similar GaAs devices give values ~0.6, typically.

We also theoretically investigate the SOI effects on the scaling behavior and find the influence is negligible in the strongly interacting regime. Therefore, the observed small value of the parameter cannot be attributed to an artifact of the strong SOI of InAs wires, allowing us to conclude that our device indeed reaches the strongly interacting regime, and thus can serve as a platform for the realization of Majorana Kramers pairs or parafermions [5,6].

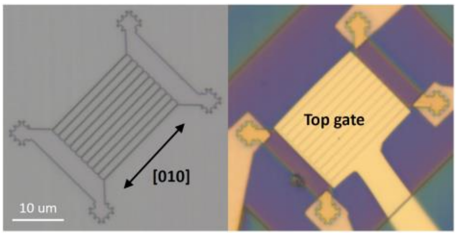

Fig. 1. Photographs of the device.

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Optical excitations in multiferroic bismuth ferrite

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Bismuth ferrite ($BiFeO_3$) is a well-known multiferroic material which exhibits both antiferromagnetism and ferroelectricity at room temperature. Therefore, it can be used for fabricating storage device and communication owning to the coexistence of magnetic and ferroelectric order [1]. Likewise, many studies have been devoted to reveal the fundamental physics, e.g. phonon, magnon, and their coupling in the bismuth ferrite [2].

In the study, we performed femtosecond pump-probe measurements. Linearly polarized pump of wavelength 1300 nm excites localized phonon, magnon, and propagating phonon-polariton mainly via impulsive stimulated Raman scattering, whereas circularly polarized probe light of wavelength 800 nm is used to detect the ellipticity change.

In the experiment, the observed ellipticity changes are shown in Fig. 1. After the decay of 2.4 THz phonon around 20 ps, 530, 560 and 740 GHz magnon modes appear. According to Raman spectroscopy measurements [2], the 2.4 THz phonon mode is identified as the transverse optical phonon with *E*-symmetry, whereas the three magnon modes are $\Psi_1^{(2)}$, $\Psi_1^{(1)}$, and $\Phi_2^{(1,2)}$, respectively.

In the poster we will also show the propagation profiles of phonon, magnons, and observed phonon-polariton mode.

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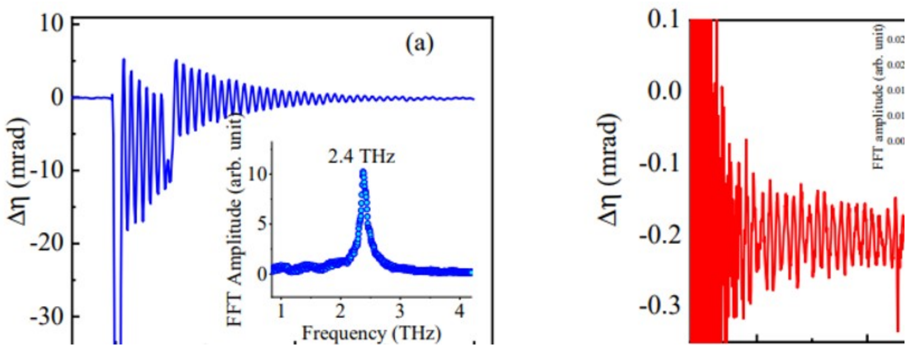

Fig. 1. Time-resolved ellipticity change (Δη) of transmitted probe polarization at different probe delays of (a) 20 and (b) 60 ps. The insets show the FFT amplitude spectra of the signal at the respective delays which reveal the central frequency of (a) 2.4 THz phonon and (b) 530, 560 and 740 GHz magnons.

Topological edge modes for coupled waves between magnons and electromagnetic waves

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The Chern number characterizes existence of the chiral topological edge modes inside the gap. The chiral topological edge modes are well studied in electronic systems, and besides they can be realized in photonic crystals and magnonic crystals, in which the time-reversal symmetry is broken. In addition to systems with a single kind of particles, systems consisting of more than two kinds of particles or quasiparticles attract much attention recently, in the context of topological phases.

In this poster, we consider coupled waves between magnons and electromagnetic waves in a ferromagnet. In order to calculate the Berry curvature, we formulate a Hermitian eigenvalue equation derived from the equation of motions. The resulting Berry curvature is enhanced at the crossing point of dispersions, as is the case for other coupled waves such as magnons with the dipolar hybridization and magnetoelastic waves [1,2]. The Chern number, i.e. the integral of the Berry curvature for the coupled waves between the magnon and the electromagnetic wave is quantized (Fig.1.(a)). We find that the hybridization gap in this case is topological. There exist topological chiral edge modes inside this gap. We calculated edge modes at an interface between two topologically different regions. Two kind of edge modes appear dependent on symmetry of electromagnetic waves at the interface (Fig.1. (b)).

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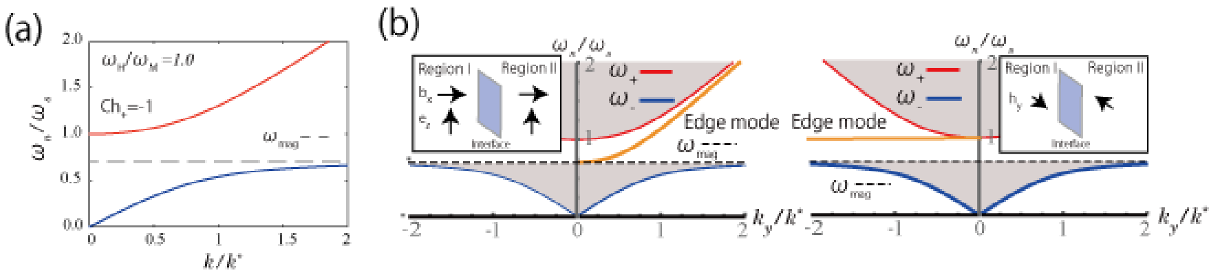

Fig. 1. (a) Dispersions of the magnon and electromagnetic wave and the corresponding Chern number
(b) Dispersions for the edge modes and schematic pictures of electromagnetic waves near the interface

Room temperature and low-field spin Seebeck enhancemement by magnon-phonon resonance

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The spin Seebeck effect (SSE) has attracted a lot of attention in spintronics due to its capability to generate spin currents by heat excitation, and the possibility to achieve heat-to-electricity conversion using insulating materials and lower dissipation losses. Recently, it has been shown that the magneto-elastic coupling can improve the thermoelectric conversion efficiency of the SSE: manifested as the appearance of voltage peaks at magnetic field values where the magnon and phonon dispersions just touch, resulting in larger magnon-phonon hybridizations over the k-space [1,2].

Here, I will introduce recent progress on the SSE in a nearly compensated ferrimagnetic insulator. I will show recent observations of the enhancement of SSE by magnon-phonon resonant coupling in a Ga-doped iron garnet film, where peak structures in the magnetic field-dependent SSE response have been observed at room temperature and low magnetic fields [3]. These findings can be explained by the effect of the magnetic compensation on the magnon dispersion and the effect of doping on the magnon-lifetime of the magnetic system.

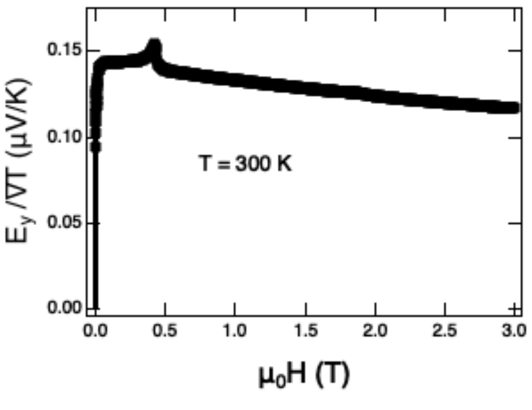

Figure 1. SSE measured at 300 K in a Ga-doped garnet film, showing the peak in the voltage at low magnetic field.

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Electrical detection and modulation of All-Optical magnetization Switching in GdFeCo ferrimagnetic alloy

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All-Optical magnetization Switching (AOS) via ultra-short pulse laser catches a lot of attention because of its low energy consumption and sub-ps switching speed [1]. There are few approaches to understand AOS quantitatively, only for example, the relationship among film thickness, laser power, and created domain size [2]. In this study, we experimentally demonstrate the electrical detection of the single pulse AOS in ferrimagnetic GdFeCo alloy.

Hall-bar shaped sample composed of SiN(10 nm)/GdFeCo(20 nm)/SiN(100 nm)/Si substrate was prepared. The width and length of the Hall-bar is 50 μm and 800 μm, respectively. Sample was fixed to the optical sample mount and electric current was applied along x-axis. Pulse laser (pulse width: 35 fs and repetition rate: 0.25 Hz) was irradiated on the sample, and voltage caused by anomalous Hall effect (AHE) was measured along y-axis.

Figure 1 shows the result of time variation of AHE voltage measurement during irradiation. When a single laser pulse was irradiated on the center of Hall-bar, direction of magnetization changed (from initially light gray (+z) to deep gray (-z); see MO images) and V_H simultaneously changed. After the next single laser pulse irradiation, magnetization reversed to initial direction (from deep gray to light gray) and V_H returned. Rapid change of AHE voltage is considered to occur due to single pulse AOS without external magnetic field in GdFeCo.

Furthermore, we found the magnetization reversal due to AOS was suppressed with increasing the intensity of charge current.

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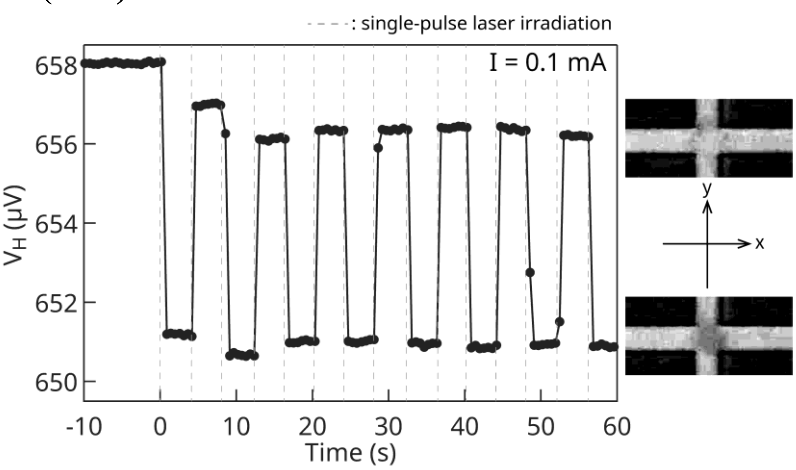

Fig. 1 Time variation of anomalous Hall voltage and typical MOKE images of samples before/after irradiation.

Development of an apparatus for observation of the Einstein-de Haas effect

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The Einstein−de Haas effect, rotation by magnetization of a magnetic body, was first reported in 1915 [1]. The effect is categorized together with the Barnett effect [2] as a gyromagnetic effect. We are developing an apparatus to observe the effect.

Figure 1-a) is a conceptual diagram of the apparatus. A ball shaped specimen hanging by a string is set in the center position of a solenoid coil. When magnetizing the specimen, it will rotate around the string as an axis of rotation. The rotation will be observed by projection of a laser spot on a wall reflected by a mirror that is placed upper side of the specimen. The magnitude of the rotation angle is known by the migration length of the laser spot on the wall and the distance between the wall and the miller.

Figure 1-b) is a photograph of the apparatus. Tungsten wire with a diameter of 20 μm is used for the string. The actual apparatus is covered with a magnetic shield film to suppress the fluctuation of the environmental magnetic field. Moreover, the rest environmental magnetic field in the shield is offset by Helmholtz coils that are placed inside of the shield to suppress a phenomenon that the specimen act as a compass to the horizontal environmental magnetic field. The numerical data of time-dependent migration length of the laser spot on the wall is obtained by the image analysis of the video. The frequency of the Einstein−de Haas effect and the others are distinguished by means of frequency analysis.

The details of the apparatus and some experimental results will be shown in the session.

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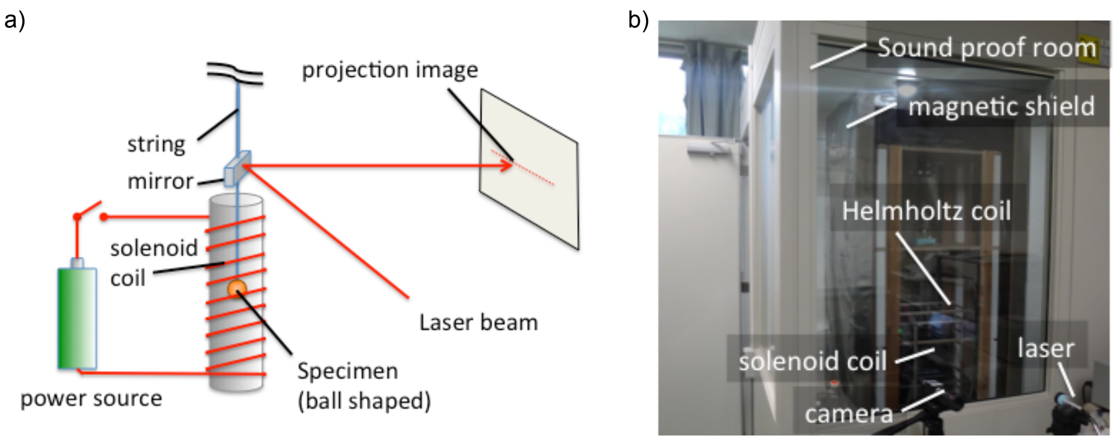

Fig. 1. a) a conceptual diagram of the apparatus, b) a photograph of the apparatus.

Spin and Charge Dynamics in Nanostructures Probed by Quantum Dot Sensors

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Spin states in nanostructures are interesting targets in science and important in spintronics applications. Local spin sensors that can directly access the local spin states are useful in the measurement. We can realize such local spin sensors by utilizing semiconductor quantum dots (QDs). Electron tunneling into the spin-selective levels in QDs depends on the spin states in the nanostructures to which the QDs are connected. We can get information on the local spin states by analyzing the electron tunneling. We can also measure the dynamics of the states by high-speed electric measurements realized by high-frequency techniques.

We measure the local spin and charge states in a semiconductor nanostructure: a hybrid quantum system including a QD and an open electronic reservoir. The target QD is coupled to the electronic reservoir through a tunneling barrier. The local spin and charge states inside of the target QD are modified by the interaction between the QD and the reservoir.

The measured spin and charge signals show relaxation with a typical timescale of microseconds. The timescale depends on the tunnel coupling between the target QD and the reservoir. The origin of this change of the states is the first-order electron tunneling between the target QD and the reservoir. An electron leaves and enters into the QD in a sequential way. There is a difference in the decay time between the spin and charge states. The decay of the charge state is faster than the spin relaxation. The difference also depends on the energy level of the QD. This can be reproduced by solving a theoretical model treating the first-order tunneling process [1]. When we increase the coupling between the target QD and the reservoir, there is finite spin relaxation even in a deep Coulomb blockade region. On the other hand, there is no charge relaxation in this condition. This relaxation is induced by the higher-order tunneling process, in which only the spin information is lost [2]. These results are important in the understanding of spin dynamics in semiconductor nanostructures and spin device applications.

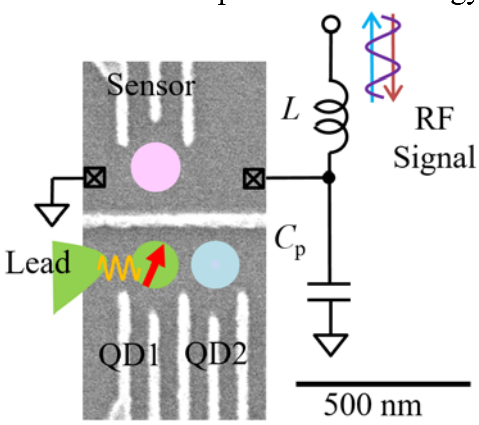

Fig. Scanning electron micrograph and measurement setup of the quantum dot sensor.

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Electrical transport properties in a microfabricated Mott insulator

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Current-induced phenomena [1-4] in Mott insulators have been the subjects of much attention recently. The origin of the current-induced nonlinear transport phenomena has been attributed to current-induced gap suppression [3]. The layered perovskite Ca_2RuO_4 provides an ideal platform to study such non-equilibrium steady states (NESS) under a simple non-equilibrium stimulus *i.e.*, the application of direct electric current. It is a 4*d*-electron Mott insulator in which the metal-insulator transition coincides with a structural transition at 360 K and antiferromagnetic ordering occurs below 110 K. For the characterization of such NESS phenomena, however, it is crucial to evaluate the accurate sample temperature in the presence of unavoidable Joule heating. Microfabricated sample may allow us to investigate the NESS phenomena to much higher direct electric current density without a serious overheating.

In this work, we investigated the nonlinear transport properties of a Ca_2RuO_4 device with the aim of extending its nonequilibrium phase diagram to a wider range of temperatures and direct electric current densities. Focused ion beam (FIB) lithography was employed to microfabricate single-strip devices comprising a single crystal Ca_2RuO_4 flake, insulating amorphous Al_2O_3 layer underneath, and a Ta layer as a resistive temperature sensor below it. Figure 1 shows a SEM image of such microfabricated device.

We will present transport properties Ca_2RuO_4 in this device. The resistivity of a Ca_2RuO_4 flake indeed exhibits strongly-nonlinear behavior under direct electric current. According to the Ta temperature sensor, the Joule heat in the Ca_2RuO_4 flake diffuses more rapidly into the substrate at a much faster rate than what observed than in bulk single crystals, allowing to accurately measure the intrinsic properties of the material. This technique is a promising approach to extend the phase diagram of NESS to lower temperature and higher current-density region.

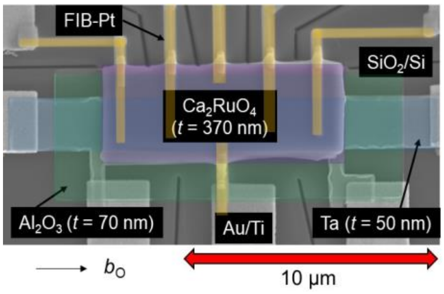

Fig.1: False-colored SEM image of the device made of Ca_2RuO_4. Thickness is represented by *t*.

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P31

Probe of spin dynamics in superconductor using thermal spin injection and spin-to-charge conversion

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Since spin current generated at the interface of ferromagnetic | paramagnetic thin film junction by spin pumping is proportional to the imaginary component of the dynamic spin susceptibility χ, its electrical detection by the inverse spin Hall effect (ISHE) is a good probe of magnetization dynamics. On the other hand, in superconductors, the dynamic spin susceptibility shows an anomaly due to the coherence effect of superconductivity in the region where a frequency is much lower than the superconducting energy gap. Experimentally, it is known that the signal of Ni80Fe20|Nb spin pumping decreases below Tc [1]. But recently, it has been pointed out by the theoretical calculation that in ferromagnetic|superconductor junctions, the temperature dependence of the χ and the magnetic relaxation constant α indicate the coherence peak in the vicinity of Tc [2].

In this study, we have investigated the ISHE induced by longitudinal spin Seebeck effects (SSE) in a superconductor/ferrimagnet (S/F) bilayer comprising an 20nm s-wave superconductor NbN thin film and a ferrimagnetic insulator Y3Fe5O12 (YIG) for thermal spin injection. First of all, in the normal state, we found the normal SSE signals corresponding to the spin Hall angle of Nb. Also, in the superconducting state where the temperature is sufficiently low compared to Tc, the signal disappeared. However, just below the Tc, we show that the generated ISHE voltage exhibits an anomalous enhancement. On the day, we will discuss the origin of this anomaly in relation to the coherence peak using the theoretical calculation based on the linear response theory.

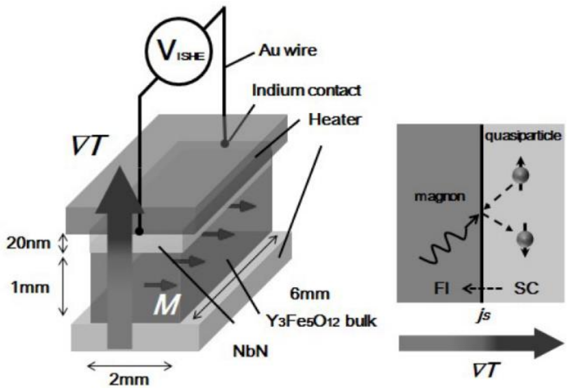

Fig. 1. A schematic illustration of the longitudinal SSE measurement (left) and Spin-flip scattering of QPs at the NbN/YIG interface (right)

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Spin-orbit interaction induced electron spin resonance enhanced by charge tunneling between quantum dots

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We apply the so-called coherent spin shuttle in a 1-dimensionally aligned multiple quantum dot (QD) array so that the charge experiences multiple inter-dot tunnelings during an electric dipole spin resonance (EDSR) drive, which speeds up the spin rotation an order of magnitude.

Spin qubit operations are now achieved by driving the electronic charge inside a single QD under an artificial magnetic field gradient, producing an oscillating effective magnetic field and realizing spin rotations faster than its coherence time [1]. Meanwhile, quantum technology leads to easier control over multiply tunnel coupled QD systems. In such system, we utilize single spin shuttling, which is a gate voltage ramping technique to move the single charge via charge adiabatic tunneling while maintaining the coherence of its spin [2], and here we combine it with EDSR. In this regime, the driven modulation on the electron wavefunction spans across the length of the multiple QDs, rather than residing in a single QD. Ideally, the internal spin-orbit interaction produces orders of magnitude larger effective magnetic field associated with the speed of charge during the resonant electrical drive. This technique will provide faster spin rotation without depositing extra magnetic structures on the device [1].

We fabricated a GaAs based quadruple quantum dot device and confined a single electron spin. The individual dot potentials were tuned so that the charge oscillates within a single dot, between two dots, and across three dots during the drive. Fig.1 shows the resulting Rabi oscillations reaching above 200 MHz in the triple QD configuration. Our shuttling induced EDSR may generalize to other semiconductor materials and integrated qubit architectures to reduce the complexity of achieving moderate spin manipulations in proof-of-principle experiments or may provide flexible effective field tuning for higher fidelity qubit operations.

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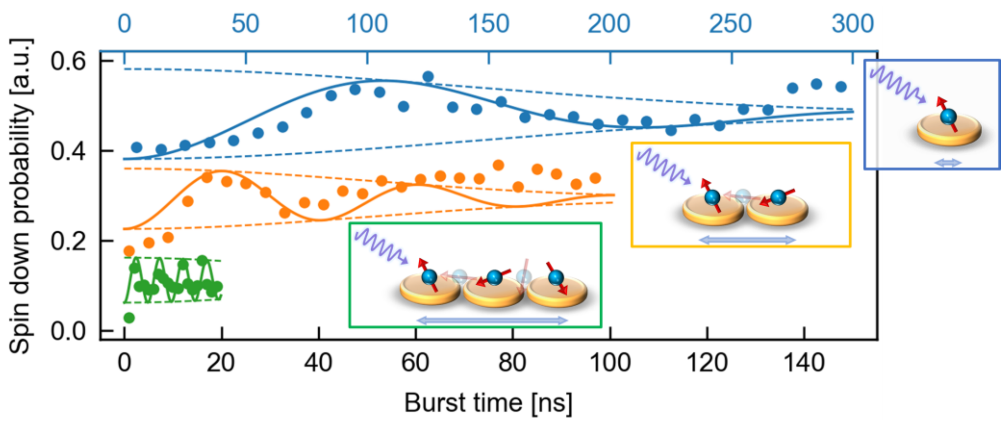

Fig. 1. Time-resolved Rabi oscillations presenting x40 increased spin rotation speed up to 200 MHz for a single electron spin oscillated inside a triple-dot.

P33

Charge-spin conversion in metallic glass detected via spin-torque ferromagnetic resonance

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Recently, large spin-charge conversion in metallic glass, disordered metallic atomic structure, was observed [1]. The anomalous temperature dependence of inverse spin-Hall effect in metallic glass was explained by phonon skew scattering due to the nature of metastable atomic structure of metallic glass. In this study, charge-spin conversion and spin-orbit torque in metallic glass PdSi / NiFe bilayer is investigated. Here, we focused on Pd-Si binary metallic glass, which is known to show large glass forming ability.

Stacking structure of the film is shown as follows: Si / SiO_2 sub./ $Pd_{80}Si_{20}$ (5-20) / NiFe (4) / Al_2O_3 (3) (thickness is in nm). Spin-torque ferromagnetic resonance (ST-FMR) measurement was performed to evaluate charge-spin conversion efficiency in PdSi.

Figure 1 shows typical ST-FMR spectrum observed for PdSi (5) / NiFe (4) film. The signal was fitted by summation of symmetric and anti-symmetric Lorentzian functions as shown in solid curves in the figure. Figure 2 shows modulation of ST-FMR spectrum linewidth by injecting direct current with different magnetic field directions. Modulation of damping was clearly observed and effective spin-Hall angle was evaluated to be 0.20 ± 0.03 for PdSi (5) / NiFe (4) sample. Electrical resistivity as well as comparison with Pd will be discussed.

This work was partially supported by Fusion research project in AIMR, Tohoku University and KAKENHI (No. 19K15430).

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[2] S. Iihama, Y. Koike, Z. Lu, K. Watanabe, M. W. Chen, and S. Mizukami, submitted

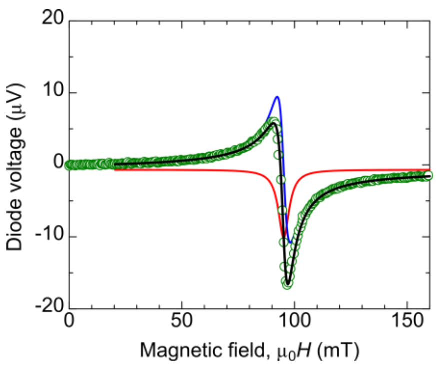

Fig. 1. Typical ST-FMR spectrum observed for PdSi (5) / NiFe (4) bilayer.

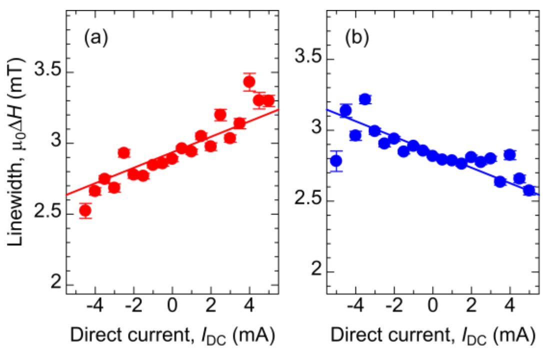

Fig.2. Modulation of ST-FMR linewidth measurement. (a) positive and (b) negative magnetic field is applied.

Nonreciprocal conversion between charge and spin currents in naturally oxidized copper films

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A spin current (J_s) is a flow of spin angular momentum without an accompanying electric charge, and it has been widely used to control various spintronics devices. The spin-Hall and Rashba-Edelstein effects (i.e., SHE and REE, respectively) have been widely investigated for the mutual conversion between charge current (J_c) and J_s. The inverse effects to the SHE and REE—that is, the conversion from J_s to J_c—have been successfully demonstrated, and the efficiencies of the direct ($\theta_{Jc\Rightarrow Js}$) and inverse ($\theta_{Js\Rightarrow Jc}$) conversions have been reported to differ only by a small factor [1,2]. Meanwhile, in 2016, it was found that naturally oxidized Cu film (Cu*) can generate J_s as large as Pt, while non-oxidized Cu has been known as small SOI material. In this work, we examined the reciprocity of J_s generation for Cu* and found that Cu* shows negligibly small spin-to-charge conversion.

We examined the reciprocity of J_s generation for the NiFe(5)/Pt(10) and NiFe(5)/Cu*(10) bilayers, which were patterned in the shapes of Hall bars with a nominal length l = 20 μm and width of w = 8 μm. Here, Cu* denotes surface-oxidized Cu. The charge-to-spin interconvrsion were studied by measuring the unidirectional spin-Hall magnetoresistance (USMR) and by using the spin pumping (SP) effect. In the USMR experiment, surface-oxidized Cu* generated finite J_s, while in the SP experiment, no spin-to-charge conversion was observed.

One possible mechanism for the nonreciprocity is the spin-vorticity coupling (SVC), which enables the conversion of a macroscopic angular momentum due to mechanical rotation into a microscopic spin angular momentum [3]. In the Cu*, a large gradient of the mo bility exists in the thickness direction, which leads to the spatially nonuniform distribution of the drift velocity of the conduction electrons as shown in Fig. 1.

From the viewpoint of applications, J_s generation via angular-momentum transfer from the vorticity of electron flow in an electrical mobility modulated film increases the freedom of material design for spintronics devices, because neither ferromagnets nor large SOI materials are necessary for a J_s generation.

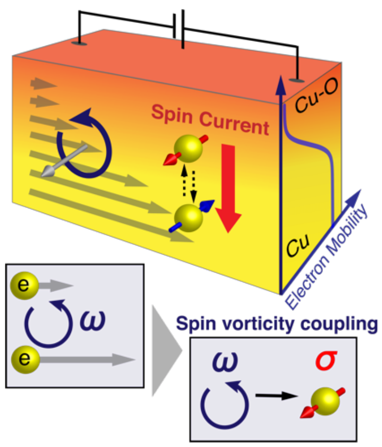

Fig.1 Schematic image for J_s generation via the spin-vorticity coupling.

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P35

Laser induced non-linear magnon dynamics in synthetic antiferromagnets

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Non-linear magnon dynamics are expected to be applied to advanced computing devices [1]. Synthetic antiferromagnets (SAFs) are the candidate materials because they have the acoustic (AC) and optical (OP) mode [2]. However, there are no reports whether the AC and OP mode can interact with each other. Thus, in this study we aimed for observation of non-linear interactions using time-resolved magneto-optical Kerr effect (TRMOKE) technique [3].

SAF films, Si/SiO_2(subs.)/Ta(3)/$Co_{20}Fe_{60}B_{20}$(3)/Ru(0.4)/$Co_{20}Fe_{60}B_{20}$(3)/Ta(3) (thickness is in nm), was prepared by a sputtering. Fig. 1(a) shows the TRMOKE data with various pump laser power P_{pump} at the critical magnetic field angle $\theta_{H,c}$. At this angle, $2f_{AC} = f_{OP}$ is satisfied, where f_{AC} and f_{OP} are the frequency of the AC and OP mode, respectively. $\Delta\theta_K$ and Δt are the change in the Kerr rotation angle and the pump-probe delay time, respectively. In case of P_{pump} > 5 mW, the temporal amplification of the magnon amplitude was observed (dashed curves). Fig. 1(b) shows the θ_H dependence of the peak intensity of the FFT spectrum at the P_{pump} = 10 mW for the AC and OP mode, respectively. At around θ_H = 45° ~ $\theta_{H,c}$, the intensity of the AC mode rapidly enhanced. This indicated the three-magnon interaction between the AC and OP modes is allowed for SAFs. The threshold of the OP mode will be also discussed. This work was partially supported by KAKENHI (Nos. 26103004 and 19K15430). A.K. thanks to the GP-Spin at the Tohoku University.

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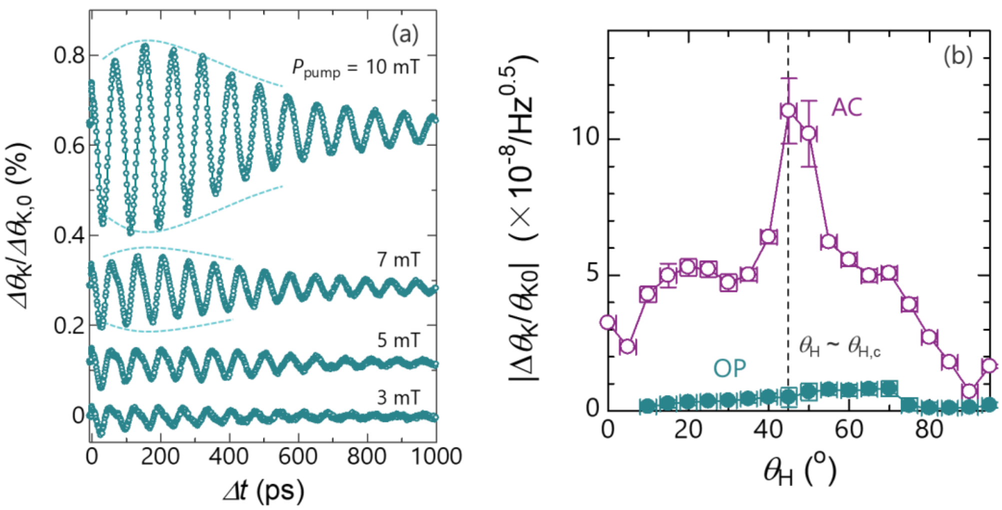

Fig. 1 (a) shows the TRMOKE results at $\theta_{H,c}$, which is the critical magnetic field angle $\theta_{H,c}$, for with different pump power P_{pump} = 3, 5, 7, 10 mW. When At P_{pump} > 5 mW, temporal amplifications of the magnon amplitude were was observed (dashed curves). Fig. 1(b) shows the θ_H dependence of peak FFT power density for acoustic (AC) and optical (OP) mode. doted Dashed line shows the $\theta_{H,c,}$, where the peak of the AC mode remarkably enhanced.

P36

Investigation of spin-to-charge conversion in Si/Cu/Py multilayer systems by using the ac inductive measurement technique

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Precise determination of spin-to-charge conversion effeciency, e.g. spin Hall angle and Rashba-Edelstein length, is necessary for further undenstanding of spin-current-related physics in solid materials. dc spin pumping in ferromagnetic/nonmegnetic bilayer systems has been a prime technique for determination of spin Hall angle. Along with vigorous studies on the spin dynamics and the spin-related rectification effects, superposition of parasitic dc electromotive forces (EMFs) on the spin Hall EMF has been pointed out. In case of measuring spin-to-charge conversion in materials where an expected EMF is small, this problem becomes serious. To cope with this, we tried to apply the phase-sensitive ac measurement of spin-to-charge conversion to semiconductor-based systems. This technique was originally proposed in 2018 [1] and they demonstrated the evaluation of the spin-to-charge conversion effeciency in Pt/$Ni_{80}Fe_{20}$(Permalloy, Py), Cu/Py bilayer systems. For each system, the spin-orbit torque conductivity (σ_0^{SOT}), an inclusive index of spin transmission from the ferromagnet and the spin-to-charge conversion in the nonmagnetic material, was determined.

In this study, we investigated the silicon-based system by using the aforementioned ac technique to by-pass the superposition of the dc EMFs peculiar to the dc spin pumping scheme. Dopant atoms are implanted into the 100-nm-thick Si film on a SOI wafer. The Py ferromagnetic layer and the Cu interlayer was deposited onto the n-type (Phosphorus), p-type (Boron), and non-doped Si layers. The fabricated sample was attached to a coplanar waveguide connected to a vector network analyzer (Fig. 1). By sweeping the dc magnetic field perpendicular to the sample face around the ferromagnetic resonance field, the real and imaginary transmission S_{21} spectra were obtained. By utilizing the protocol in Ref. 1, the spin-orbit torque conductivity for each sample was determined (Fig. 2). The sign inversion relative to the baseline of the non-doped sample between the degenerate n-type and p-type samples was observed. We attributed this to the modulation of the inverse spin Hall effect (ISHE) by carrier change. As for he results for the non-degenerate samples, we discuss the possible origins based on the ISHE and the Rashba-Edelstein effect at the Si/Cu interface.

[1] A. J. Berger *et al*., Phys. Rev. B **97**, 094407 (2018).

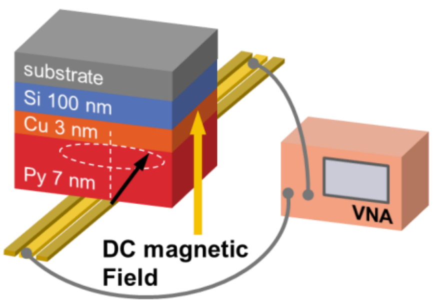

Fig. 1. Illustration of the setups.

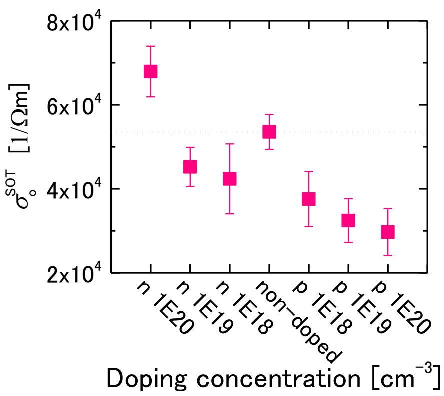

Fig. 2 σ_0^{SOT} observed in each sample.

P37

Theoretical Study of the Spin-current Induced by s-d scattering in Ferromagnetic Metals

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We theoretically investigate the time-reversal odd spin Hall currents due to the s-d impurity scattering in ferromagnetic metals. The charge to spin conversion phenomena like the spin Hall effect (SHE) have been attracted in the field of spintronics in order to realize novel spin current driven devices. The SHE has been mainly studied on nonmagnetic materials so far because it does not rely on broken time-reversal symmetry (TRS), that is, finite magnetic moments are not required. However, recently, some spin Hall-like effects have been experimentally observed in magnetic materials, whose spin currents have opposite TRS to SHE [1, 2]. These effects are considered to have different mechanisms from the ordinal SHE, and further analyses are demanded. In this work, we focus on ferromagnetic 3d metals, which hold a prominent position on application, and describe the behavior of spin current arising from s-d impurity scattering. The model we employ is based on the impurity Anderson model and we assume that the impurities have 3d electron orbitals with an LS-coupling. We describe the spin Hall conductivity (SHC) on the basis of the Kubo formula, and we investigate its odd part by analyzing the magnetization direction dependence of the each spin component.

As the result, we find that the time-reversal odd spin current appears when the direction of transported spin direction lies on the plane containing both the applied field and the spin current (Fig. 1). To inspect the behavior in detail, we rewrite the spin components of the SHC as the transported spin points to the parallel or perpendicular direction to the magnetization (Fig. 2). The parallel part can be understood as the contribution from spin-polarized current driven by the planer Hall effect [3]. On the other hand, the perpendicular part is considered as the magnetic spin Hall effect coming from the LS-coupling in 3d orbitals [4].

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[3] T. Taniguchi, J. Grollier, and M. D. Stiles, Phys. Rev. Appl. **3**, 044001 (2015).
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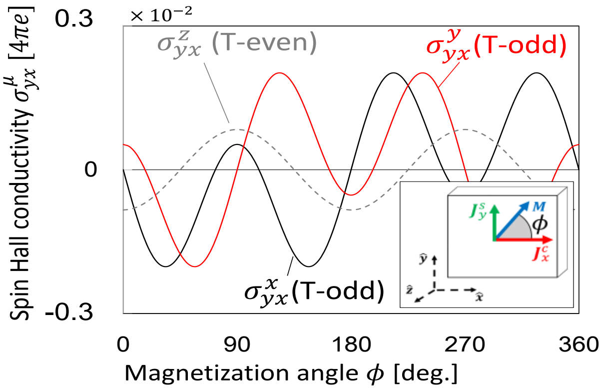

Fig. 1. Spin Hall conductivities as functions of the magnetization direction angle.

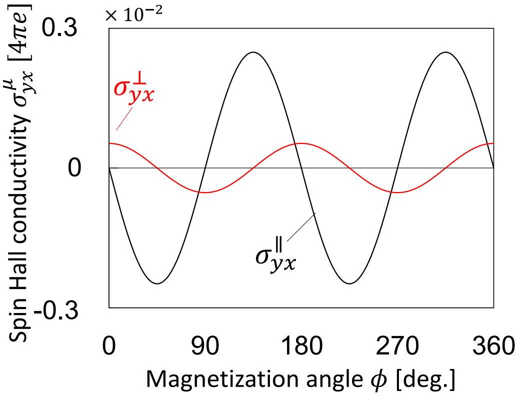

Fig. 2. Parallel and perpendicular components of spin Hall conductivity.

P38

Anisotropic distribution of the Mn 3*d* spins in the ferromagnetic semiconductor (Ba,K)$(Zn,Mn)_2As_2$ revealed by angle-dependent XMCD

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(Ba,K)(Zn,Mn)2As2 is a new p-type diluted ferromagnetic semiconductor, which crystallizes in the tetragonal ThCr2Si2 structure (I4/mmm). Here, Mn and K atoms provide spins and hole carriers, respectively. The Curie temperature (T_C) reaches 230 K exceeding the highest T_C = 200 K of (Ga,Mn)As. This material has a *c*-axis magnetic anisotropy originating from the layered crystal structure.

In this study, in order to reveal the origin of the uniaxial magnetic anisotropy, we have measured the K 9.6%- and Mn 19.5%-doped single crystals using the angle-dependent x-ray magnetic circular dichroism (AD-XMCD) method.

Figure 1 shows the XMCD spectra taken with the transverse geometry (TXMCD), where the spin magnetic moment is aligned perpendicular to the incident x ray. The observed finite dichroic signals indicate the aspherical distribution of 3*d* electrons, and the TXMCD spectra were well reproduced by the configuration-interaction cluster-model calculation incorporating the D_{4h} crystal-field splitting. Since hole carriers resided in the d_{xz} and d_{yz} orbitals in the calculation, we propose that the degeneracy lifting of p-$d_{xz,yz}$ hybridized orbitals at the Fermi level caused by spin-orbit interaction is responsible for the perpendicular magnetic anisotropy of this compound.

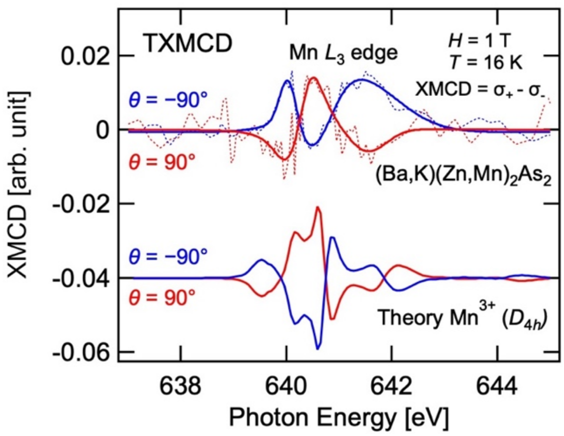

Fig. 1 Transverse XMCD spectra. Calculated spectra are also shown at the bottom. Here, θ represents the angle between the magnetic moment and x rays.

P39

Spin-to-charge current conversion at a molecule/metal interface

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An interface of molecule and metal has attracted much attention in the research field of nanoelectronics because of their high degree of design freedom. The specific properties of molecules such as high permittivity, self-assembly and flexibility, could lead to novel spin functionalities at the molecule/metal interface[1]. Here, we demonstrate an efficient spin-to-charge current (S-C) conversion at the metal surface covered by a single layer of molecules[2].

Here, we focused on lead (II) phthalocyanine (PbPc). We performed spin pumping for the NiFe/Cu/PbPc trilayers. Spin currents are injected into an interface between Cu and PbPc by means of the spin pumping. An observed voltage signal is attributed to the S-C conversion at the Cu/PbPc interface. Interestingly, the amplitude of the signal strongly depends on the thickness of the molecules and takes a maximum value when a single layer of molecules is formed on the Cu surface, as shown in Fig. 1. Comparative analysis between scanning probe microscopy and first-principles calculations reveal that the formation of interface state with Rashba spin splitting causes the S-C conversion, whose magnitude is sensitive to the adsorption configuration of the molecules. Our study provides a guiding principle for the interfacial modification with molecules.

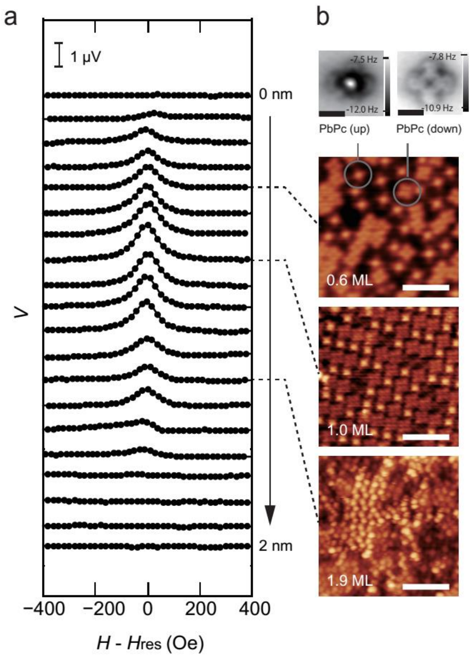

Fig. 1. Molecular thickness dependence of S-C signals. (a) The magnetic field dependence of the output DC voltage for NiFe/Cu/PbPc samples with different PbPc thickness. (b) AFM and STM images of Cu(111)/PbPc with PbPc thickness of 0.6, 1.0, and 1.9 ML. The white bars in the images indicate the length of 5 nm.

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Computational high throughput screening of two-dimensional magnetic thermoelectric materials

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The thermoelectric conversion based on the anomalous Nernst effect (ANE) has attracted attention because the ANE realizes the high-density integration more easily compared to that based on the Seebeck effect [1]. The ANE is the phenomenon that the electric power is created along the direction perpendicular to both the temperature gradient and the magnetization in magnetic materials. This effect is induced by the anomalous Hall conductivity (AHC), and if the AHC changes drastically as a function of the Fermi level, we expect the large ANE [2]. In our previous first-principles study, we predicted that an electron doped EuO skyrmion crystal shows the large ANE induced by the finite Chern number at the Fermi level [3]. For discovery and design of new materials which have the large ANE via computational high throughput screening, we need an efficient computational method to investigate the Fermi level dependence of the AHC.

In this study, we implemented the code of computing the AHC applicable to metallic systems in OpenMX package [4] by improving Fukui-Hatsugai-Suzuki method [5]. Using this code, we computed AHCs $\sigma_{xy}(\varepsilon)$ and transverse thermoelectric conductivities $\alpha_{xy}(\varepsilon)$ in two-dimensional ferromagnetic materials [6]. In this poster session, we introduce how to implement this scheme and calculated results of the AHC and transverse thermoelectric conductivity in two-dimensional ferromagnetic materials. We will discuss necessary conditions of the large Nernst coefficient in two dimensional magnetic materials.

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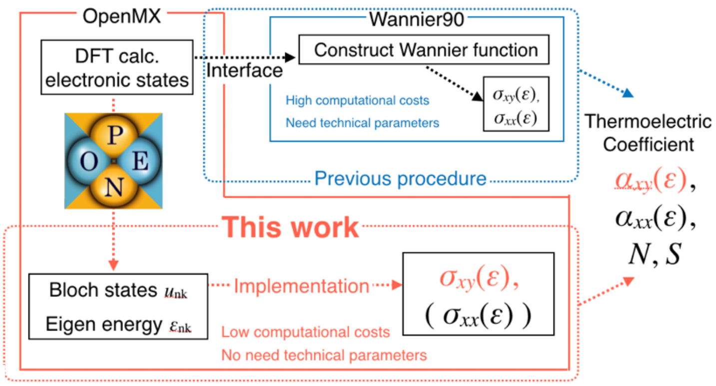

Fig. 1. Computational procedure of anomalous Nernst coefficient in our study.

Crystal Structure and Perpendicular Magnetization of MnGaGe Films

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In the society of Internet of Things, the competition of memory development is becoming more and more serious. Among various memories, magnetoresisitive random access memory (MRAM) attracts great attention for its non-volatile attribute and high-working-speed, recently. From the viewpoint of data retention for longer than 10 years, thermal stability factor Δ defined as $K_u V/k_B T$ must be larger than 60, where K_u, V, k_B, and T are uniaxial magnetic anisotropy energy, cell volume, Boltzmann constant and temperature, respectively. With the further integration of memory devices, Ku must be high enough to ensure the large Δ for the ferromagnetic layers in tunnel junctions of MRAM cells. According to the above reasons, our group has been working on C38-type MnGaGe films. In our previous study, the saturation magnetization of 260 emu/cm^3 and the K_u of 8.1 × 10^6 erg/cm^3 were found in a MnGaGe film deposited on MgO (100) substrate [1]. The Ms is comparatively small and the K_u is larger than that of CoFeB [2]. However, a problem is relatively large crystalline orientation dispersion which resulted in the poor squareness of magnetization curves. To improve the crystalline orientation of MnGaGe films, we have investigated the buffer layer dependence of magnetic properties and crystal structures for C38-type MnGaGe films.

The stacking structure was as follows: MgO (100) substrate/buffer layer(s)/ MnGaGe (t)/MgO (2 nm)/Ta (5 nm). The layer thickness, t was varied from 5 nm to 100 nm. Different types of buffer layers such as Cr (60 nm), Cr (60 nm)/Pt (5 nm), Cr (20 nm)/Ru (40 nm) and Cr (60 nm)/MgO (2 nm) were used. A 100-nm-thick MnGaGe sample using the Cr/MgO hybrid buffer layer exhibited the best squareness of 81% for the magnetization curve and the full-width at half maximum was reduced to 1.1°. In addition, perpendicular magnetization was observed down to the thickness of 5 nm for the MnGaGe sample using the Cr/MgO hybrid buffer layer. Samples using other buffer layers will also be discussed in this presentation.

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Temperature dependence of Gilbert damping constant of FeRh thin films

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B2 ordered FeRh shows a first-order phase transition from the antiferromagnetic (AFM) to ferromagnetic (FM) states around 380 K. The unique phase transition has attracted much attention due to its potential for spintronic applications. In the AFM-FM phase transition process, it is well known that FM and AFM domains coexist in FeRh. However, the effect of the phase coexistence on the magnetization dynamics or magnetization relaxation has not been clear yet, although magnetization dynamics is another key issue from the viewpoint of spintronic applications. In this work, we investigate the ferromagnetic resonance (FMR) of FeRh thin films in the phase transition process to get insight into the origin of the correlation between the phase coexistence and the magnetization dynamics.

A 30-nm thick FeRh thin film was grown on a single-crystalline MgO (001) substrate at 400°C by co-evaporating Fe and Rh in an ultrahigh-vacuum chamber. Magnetic properties of the FeRh film were measured using a vibrating sample magnetometer. The crystal structure was characterized by x-ray diffraction (XRD) in the out-of-plane geometry. FMR measurements were performed by using a vector network analyzer in the frequency range from 1 to 20 GHz, where the sample was placed on a waveguide in a vacuum probe station with temperature variation capability from 300 to 420 K. External static magnetic fields were applied along the in-plane FeRh [100] direction. S_{21} parameters were measured by applying an rf power of 5 dBm.

Clear (001) and (002) peaks are confirmed in XRD, which indicates that the film is epitaxial and it has the B2 (CsCl) ordering. The temperature dependence of the magnetization shows that an AFM-FM phase transition occurs around 360 K. When FMR spectra are recorded in the heating process, a FMR absorption appears around 350 K, and the absorption dip intensity increases with increasing temperature. The increase in the absorption arises from the growth of the FM domains in the FeRh film. The linewidths of the FMR spectra ΔH are plotted as a function of resonance frequency f, from which we obtain the Gilbert damping constant α by fitting the slope of ΔH vs. f. We find that α increases with decreasing temperature, clearly showing that the presence of the AFM domain enhances α.

There are two possible origins of the temperature dependence of α, which is associated with the evolution of AFM domains. One is a direct exchange coupling between the AFM and FM domains. In general, an AFM domain has a resonance frequency much higher than that of FM domains and the magnetic moments of the AFM sublattice are insensitive to the applied rf field. Given that the FM domains are coupled to the AFM domains, the AFM domains efficiently pin the FM moments, suppressing the procession of the FM moments. The other origin arises from the fact that AFM domains work as a spin sink. Frangou *et al.* studied spin pumping effect in FeNi/Cu/IrMn and they found that the damping was enhanced around the magnetic phase transition temperature of IrMn [1]. In case of FeRh, the AFM-FM phase transition is a consequence of a subtle energy balance between the FM and AFM states, and spin fluctuation becomes more remarkable during the transition. Thus, spin pumping from FM into the fluctuating AFM phase may occur similar to the study by Frangou, thereby it enhances the spin damping.

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P43

Voltage effect on Anomalous Hall Effect of Pt/$CoFe_2O_4$ bilayers

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Platinum is the most important element in the spin-orbitoronics because of large spin-orbit interaction. Pt also exhibited a large magnetic proximity effect in bilayer system with ferromagnetic materials due to the large density of states at Fermi level. Therefore, it is considered to show the anomalous Hall effect in Pt/ferromagnetic insulator, which was reported in Pt/$CoFe_2O_4$[1]. On the other hand, the electronic states of Pt could be tuned by voltage significantly. Dushenko et al. succeeded in control of the electric resistance by applying gate voltage using an ionic liquid[2]. These results implied the possibility of tuning of the magnetic proximity effect by the gate voltage, and also tuning of the anomalous Hall effect in Pt magnetized by the proximity effect. In this study, we prepared the $CoFe_2O_4$/Pt bilayers and investigated the anomalous Hall effect with gate voltages.

The films were fabricated by reactive MBE method at a base pressure of 10^{-8} Pa order. A $CoFe_2O_4$ film was deposited in an atmosphere of oxygen radicals ($P_{O*}=4.0\times10^{-4}$ Pa) by co-depositing Co and Fe by electron-beam deposition. The Pt was deposited by using the electron beam at 100 °C, relatively low temperature ensuring that the Pt grow smoothly.

Fig.1 showed the electric resistivity of the $CoFe_2O_4$/Pt as a function of the gate voltages. The resistivity varied about 5 ~ 10% in ±2V at room temperature, indicating that the electronic states in Pt layer were modulated by the gate voltage. In Fig. 2, the anomalous Hall effect of $CoFe_2O_4$/Pt in various gate voltages were shown. The Pt layer exhibited anomalous Hall effect apparently at zero gate voltage, and the effect was modulated by the gate voltages significantly. Since the magnetic moment induced by the proximity effect was estimated to be very small theoretically, it was considered that the anomalous Hall effect could be attributed to the band structure in Pt.

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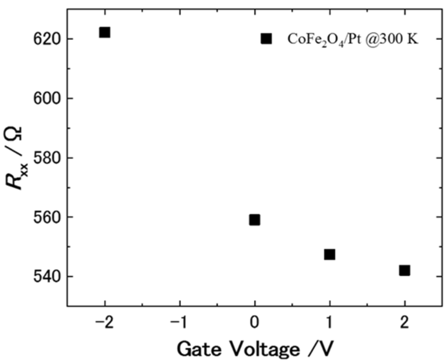

Fig. 1. Electric resistance of the $CoFe_2O_4$ /Pt(2.5nm) as a function of the gate voltage.

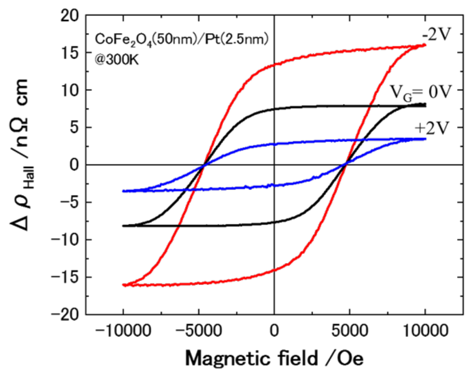

Fig.2. Hall resistivity of the $CoFe_2O_4$ /Pt(2.5nm) with various gate voltages

Improvement of Spin Torque Efficiency of Al/Si Bilayer with Quasi-Graded Interface

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Spin torque is potential tool for low energy consuming spintronics devices such as magnetic random-access memory, spin-torque oscillator, and logic gates. Many researchers have explored an efficient generation of spin current by developing materials with large bulk and/or interfacial spin orbit interactions (SOIs). Generally, heavy metal such as Pt and W have large SOI whose magnitude is characterized by a spin Hall angle which represents the conversion ratio between charge and spin currents. Recently, some studies reported an enhancement of spin Hall angle by alloying metals [1], insertion of ultra-thin layer [2], and oxidization [3,4], which are potential for removal of material choice restriction in spin current generation.

In this study, we conducted spin torque ferromagnetic resonance (ST-FMR)[5] experiments in Sub./Si(10 nm)/Al(*t*)Si(*t*)/Al(10 nm)/$Ni_{95}Cu_5$(10 nm) strip for various insertion layer thickness of *t*. The ST-FMR is the well-established method for evaluating spin torque efficiency ξ_{FMR}, which represent the conversion ratio from charge current to spin torque. ξ_{FMR} can be evaluated from amplitude ratio between symmetric and anti-symmetric components of the ST-FMR spectrum. Figure 1 is our experiment setup. We applied 10 dBm and 5 GHz microwave into the strip. We compared the value of ξ_{FMR} for insertion layer thickness between 0.5 nm and 1.0 nm and succeeded in modulating ξ_{FMR}. The value of ξ_{FMR} decrease with decreasing the thickness of insertion layer.

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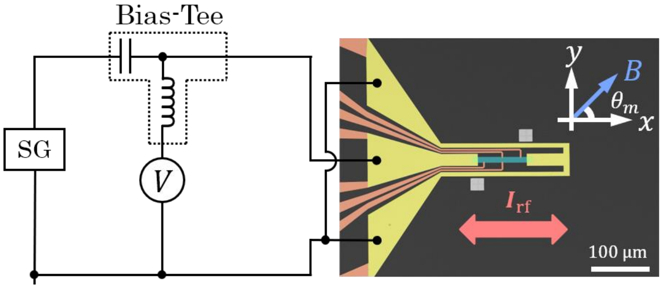

Fig. 1. The SEM image and experiment setup.

Magneto-optical Kerr effect in a non-collinear antiferromagnet Mn_3Ge

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Recently, the novel non-collinear antiferromagnet Mn_3X (X = Sn, Ge) has been reported to exhibit giant anomalous Hall effect (AHE) as large as ferromagnets at room temperature[1],[2]. In this class of triangular lattice system, the tiny finite magnetization originating from the canting of Mn sublattice moments is not large enough to account for such a large AHE. Instead, the nonvanishing Berry curvature arising from the Weyl fermions in the momentum space is considered to be responsible for this nontrivial response[3].

The Mn_3Sn has drawn much attention since the first discovery of its giant AHE. Apart from the AHE, remarkable is that this compound exhibits other intriguing thermomagnetic, magneto-optical, and transport properties such as the anomalous Nernst effect (AHE), the magneto-optical Kerr effect (MOKE), the spin Hall effect (SHE) and the magnetic SHE. Unfortunately, the research effort on the Mn_3Ge has fallen far behind that of the Mn_3Sn. It is noticeable that the thermal response as ANE in Mn_3Ge has been reported very recently. While the optical response such as MOKE and transport responses such as SHEs are still absent.

In fact, Mn_3Ge, isostructural to Mn_3Sn, is also expected to exhibit a similar MOKE but has not been demonstrated yet. In this study, we performed the MOKE measurement in a Mn_3Ge single crystal and succeeded in obtaining a large polar MOKE signal (~ 8.2 mdeg) as shown in Fig 1(a) and a longitudinal MOKE signal (~ 5.6 mdeg) as shown in Fig 1(b). Furthermore, by applying hyperfine polishing and annealing to the surface, we successfully rebuilt a homogenous surface and largely improved the reproducibility of the MOKE signal in Mn_3Ge.

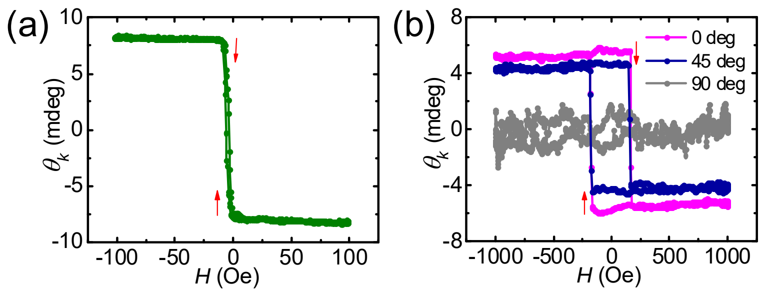

Fig. 1. (a) Polar MOKE with the sweeping magnetic field (b) φ dependence of versus θ_K the magnetic field under the longitudinal set-up.

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P46

First-principles Study of Spin Splitting in Ferroelectric Oxides and Bismuth Surface Alloys

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Spin-to-charge conversion via Rashba spin splitting, that is, the inverse Rashba-Edelstein effect (IREE) [1] has been researched in various interfaces. Two-dimensional electronic systems with large spin splitting can become a candidate of spin-to-charge conversion materials because the efficiency of IREE may become higher, as the Rashba coefficient, the strength of the Rashba effect, α_R is larger [1]. In fact, it was reported that there are giant Rashba spin splitting in such systems as a Bi/Ag surface alloy [2, 3]. Modulation of α_R can be applied to spintronic application such as control of spin-to-charge conversion, and an electric field can enhance α_R in an $LaAlO_3/SrTiO_3$ interface [4], for example. On the other hand, in a Bi/Ag surface alloy, α_R depends on the corrugation parameter *d* [3]. These may depend on how surface or interface states to induce spin splitting behave.

In this study, we have investigated an effect of strain-induced polarization on spin splitting at an $LaAlO_3/SrTiO_3$ interface [5] and $SrTiO_3$ surfaces [6], and the *M* dependence of spin splitting in Bi/*M* surface alloys [7] using fully relativistic density functional calculations. For the oxide systems, we found that strain-induced polarization can make larger spin splitting. For Bi/*M* surface alloys, analyzing the surface Rashba states, we also found that strong localization of Rashba states at surfaces make giant spin splitting. In addition, we will show our contributions to several collaborative researches of spin-to-charge conversion with experimental groups [8-10].

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Thickness dependency of GdFeCo films and All-optical magnetization switching phenomena

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Only tens fs of laser pulse irradiation is sufficient to induce ultrafast dynamics of electrons and spins in metallic magnetic thin films. All–Optical magnetization Switching (AOS) is originated from the non-adiabatic and non-equilibrium energy dissipation process of electron, spin and lattice systems in short time scale after the single laser pulse excitation[1)]. Furthermore, we suggest that AOS strongly depends on the non-local energy dissipation of stacked metallic layers in the depth direction by electrons which occurs in sub-ps time scales[2)]. In this time scale, we're able to consider the strong relation between AOS and the transient quantum statistic state of electrons associated with electronic temperature T_{el} and electronic specific heat C_{el}.

Meanwhile, the magnetic character of ferrimagnetic GdFeCo drastically changes with composition, temperature and film structure[2)- 5)]. This character makes difficult to investigate the relation between AOS to those material parameters.

In this report, we discussed new layered structure for efficient light absorption and stabilizing magnetic character in ultra-thin fime that induces All-optical magnetization switching. We investigated 2 samples' series, the films which have different stacked magnetic structures (single layered GdFeCo or Gd (1 nm) / GdFeCo / Gd (1 nm)). The single GdFeCo (5-30 nm) films has Thickness dependency of net-magnetization. For example, the magnetizations are drastically change from 10 emu/cc to 300 emu/cc. On the other hand, the new layered structure (Gd (1 nm) / GdFeCo (5-30 nm) / Gd (1 nm)) makes almost same magnetic characters (110-130 emu/cc) [3), 4)].

In the study of sample series, the thickness dependency of saturation magnetization and magnetic anisotropy for Gd (1 nm) / GdFeCo (5 nm to 30 nm) / Gd (1 nm) films is significantly different from that for single layered GdFeCo films. However, AOS created domains in the both structures are similar each other and depend on the GdFeCo thickness clearly. The size of AOS domains decrees monotonically, as GdFeCo thickness increase. Furthermore, the created domain sizes are almost same at each GdFeCo thickness and irradiated laser powers. It means that AOS is generally dependent on the thickness, metallic volume, not clearly on the net-magnetization of ferrimagnet system. Additionally, we found AOS in 5 nm ultrathin GdFeCo film.

Acknowledgement
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P48

Measurement of multielectron high-spin states and its spin relaxation in a GaAs quantum dot

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Electron spins in semiconductor quantum dots (QDs) are promising candidate of qubit for thanks to their controllability and scalability. Although one- or two-electron spin qubits have been intensively studied so far, multielectron spin qubits have advantages such as robustness against charge noise.

In this work, we propose the scheme of the single-shot readout of multielectron high-spin states, and experimentally demonstrate it for a three-electron spin-quartet and a four-electron spin-quintet in a GaAs gate-defined QD. The high-spin states are created using spin-filtering by quantum Hall edge channels near the QD. In the readout, the multielectron spin state are first converted to a two-electron spin state. Because of the spin-filtering, only the high-spin states are converted to triplet T_+. Finally, the high-spin states are recognized by the detection of T_+ [1].

Figure 1(a) shows the measured spin relaxation rates of the high-spin states as a function of the excitation energy. The relaxation rates monotonically increase with the excitation energy, which is consistent to the spin-relaxation mechanism by the spin-orbit interaction and the electron-phonon interaction and thus supports the validity of the presented spin readout scheme. Moreover, we find that the relaxation of the high-spin states is one-order-magnitude faster than that of two-electron spin state having $S_z = 0$ (singlet or triplet T_0). We numerically calculate the relaxation rates by exact diagonalization method, which qualitatively agrees with our experimental results [Fig. 1(b)].

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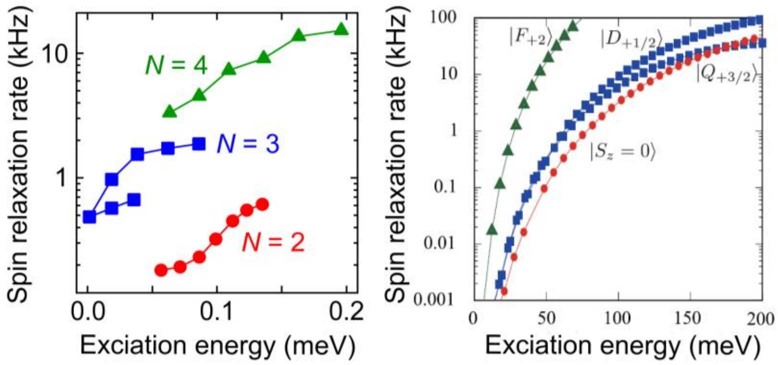

Fig. 1. (a) Spin relaxation rates as a function of excitation energy. (b) Spin relaxation rates calculated by exact diagonalization method.

Observation of inverse spin Hall effect in Pd-doped FeRh films

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Ferromagnetic or antiferromagnetic materials exhibiting large spin fluctuations at around the second order transition temperatures, Curie temperature[1, 2] or Néel temperature[3], have drawn a great deal of attention because of the enhancement of spin pumping and spin torque efficiency. Here we investigate the spin transport properties at the first order phase transition temperature around which the contribution of spin fluctuation might be different than that at the second order phase transition temperature. For this purpose, we chose Pd-doped FeRh which undergoes the first order transition from antiferromagnetic (AFM) to ferromagnetic (FM) phases with increasing temperature. Then we performed spin pumping induced inverse spin Hall effect measurements using a tri-layer $Fe_{47}Rh_{50}Pd_3$ (Fe(Rh, Pd), 60 nm) / Cu (10) / $Ni_{81}Fe_{19}$ (10) sample. Interestingly the effective spin mixing conductance determined from the linewidth analysis of ferromagnetic resonance in the NiFe layer on heating process exhibits a sharp enhancement around the transition temperature as in Fig. 1, meaning that the spin current injection efficiency was dramatically increased. This may be the characteristic behavior of spin susceptibility at the first and second order phase transitions. We also performed inverse spin Hall voltage measurements at the same device. The inverse spin Hall current (I_{ISH}) plotted in Fig. 1 revealed that the sign of spin Hall angle for Fe(Rh, Pd) is negative in both AFM and FM phases. Despite the dramatic increase in the spin current injection efficiency, I_{ISH} was strongly suppressed around the AFM-FM phase transition temperature. We will also discuss temperature dependence of spin-to-charge conversion efficiency of Fe(Rh, Pd).

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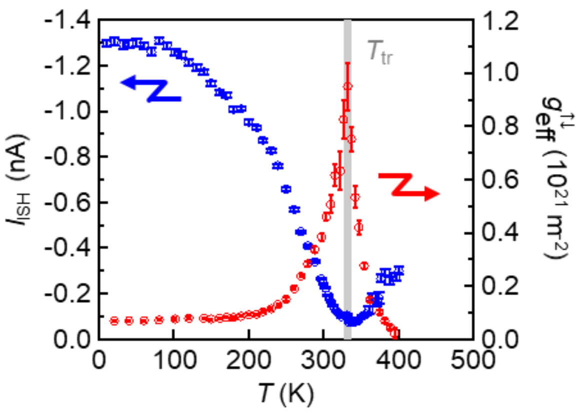

Fig. 1: Temperature dependence of the effective spin mixing conductance (red) and the inverse spin Hall current (blue). A gray line indicates the phase transition temperature from antiferromagnetic to ferromagnetic phase (T_{tr}).

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Topological transport properties in the noncollinear antiferromagnet Mn_3Sn thin film

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Antiferromagnets have recently attracted considerable attention as a key material for next generation spintronic devices due to their advantages such as negligible stray field and high-frequency spin dynamics [1]. However, because of the absence of magnetization, neither electrical detection nor external manipulation of the Néel state is possible, even though these functions are essential for the spintronic devices.

Surprisingly large spontaneous transverse responses have recently been found in the noncollinear kagome-lattice antiferromagnetic hexagonal Mn_3X (X=Sn, Ge, Ga). It exhibits large anomalous Hall [2-5], anomalous Nernst [6], and magneto optical Kerr effects [7] at room temperature. It has also been found that the spin Hall effect has an anomalous sign change when its triangularly ordered spins switch orientation in Mn_3Sn [8]. All these phenomena are related to the macroscopic time reversal symmetry breaking due to the noncollinear spin structure of Mn_3X and large real-space Berry curvature. [9, 10]. In addition to those phenomena, which are derived from the noncollinear spin structure, the characteristics of magnetic phase transition into noncoplanar spin structure at low temperature [2, 5, 11] or spin structures created in domain walls [12] have been considered to lead topological Hall effect. In order to study diverse transport properties of Mn_3X, the measurement of thin film samples with manipulation of the spin structure has been a big focus in recent research.

We measured the magneto-transport properties of polycrystalline Mn_3Sn thin film fabricated onto Si/SiO_2 substrate by sputtering method [13] under several temperatures. In this work, we report the detailed magneto-transport properties derived from the characteristic spin structure of Mn_3Sn.

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