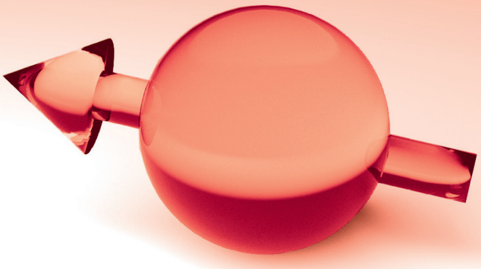
Grant-in-Aid for Scientific Research on Innovative Areas, MEXT, Japan

Nano-Spin Conversion Science

Research Highlights

Nano spin conversion



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Preface

Spintronics research emerged in the 1990s, has evolved throughout two decades, and still continues to grow. Japanese researchers have historically led this field, and the major participants in this innovative research area have made significant contributions in terms ofintriguing physical phenomena such as the spin Hall effect, inverse Faraday effect and spinSeebeck effect. Another outcome of spintronics research has been the concept of spin current,which has been established among the community of solid-state research. The concept of spincurrent has since been extended and is recognized as an angular momentum flow includingspin waves, circularly polarized light and mechanical vibration.

In this innovative research area, we focus on the itinerant and localized electron spins, phonons, and photons to explore and establish the principles of novel conversion mechanisms. Moreover, we aim to propose novel concepts and methods that are based on well-established physics, and finally to develop a spin conversion physics theory that can meet requests from industry. Ideally, we will present research outcomes that can contribute to building new paradigms for the development of practical devices and energy harvesting.

To maintain the future activity of this field, the education and securing of young talented researchers is considered to be an important and high priority. In addition to the securing ofhuman resources in Japan and improvement of research performance, the fostering of top-levelresearchers that will contribute to innovative progress will be promoted. From a long-termperspective, we consider that educating talented young researchers in this research area, notonly from Japan where we endure an aging society and science phobia, but also from overseas,and their promotion worldwide would offer a route to make Japan the world-leading country inthe fields of advanced basic science and technologies, which are related to this innovativeresearch area. Finally, I sincerely hope that this research area will create outcomes that will make significant contributions to society and will stimulate further growth.

大谷義近

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Otani group (A01: Magnetic Spin Conversion)

Electric field excitation of coherent propagating spin waves

Bivas Rana and YoshiChika Otani

Bivas Rana, Yasuhiro Fukuma, Katsuya Miura, Hiromasa Takahashi, and YoshiChika Otani
"Excitation of coherent propagating spin waves in ultrathin CoFeB film by voltage-controlled magnetic anisotropy",
Appl. Phys. Lett. **111**, 052404 (2017). [https://doi.org/10.1063/1.4990724]

Spin waves (SWs) i.e. collective precessional motion of electrons' spins may be used as potential information carrier in next generation low-power microwaves pintronics devices instead of dissipative translational motion of electronic charges. Conventionally, SWs are excited either by current-induced Oersted fields, which are spatially distributed, or by spin-transfer-torques, which are incoherent in nature. Moreover, other excitation methods like femto-second laser or thermally induced SWs are difficult to implement in future technology. In contrast, electric field controlled magnetic anisotropy promises coherent excitation of magnetization dynamics in a spatially localized area with ultralow power consumption. Here, we perform an experimental study on the excitation of propagating magnetostatic surface SWs by electric field. We choose a 2 nm thick $Co_{20}Fe_{60}B_{20}$ film as the SW waveguide for our study. The SWs are excited by periodically modulating perpendicular magnetic anisotropy of $Co_{20}Fe_{60}B_{20}$ film by rf electric field (Fig.1). The SWs are locally and stroboscopically detected by a pico-second time-resolved longitudinal Kerr microscope with 600 nm spatial resolution. We find linear increment of SW amplitude with the applied rf voltage (Fig.2a), which confirms coherent nature of SWs. Experimental results show that in this ultrathin film the electric field excited SWs can propagate up to micrometer distances, which decreases with the increase of bias magnetic field value (Fig.2b). Furthermore, we demonstrate that electric field excitations are spatially localized as opposed to conventional microstrip antenna induced Oersted field excitations. Thus electric field excitation of SWs promises to be more suitable and useful for the development of all-electric-field controlled nanoscale spintronics devices with high density of integration.

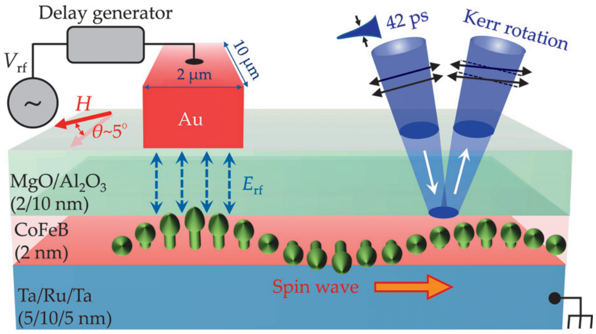

Fig. 1: Schematic illustration of SW device and measurement procedure

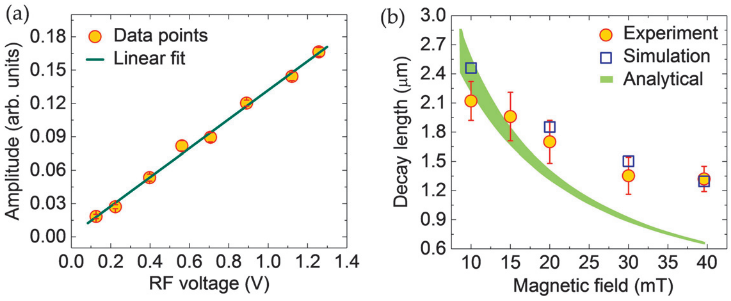

Fig. 2: (a) SW amplitude versusrf voltage (b) SW decay length versus bias magnetic field

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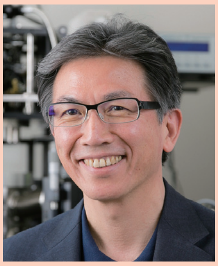

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Miwa group (A01: Magnetic Spin Conversion)

The origin of electric-field-induced change of magnetic anisotropy in ferromagnetic metals

Shinji Miwa and Takeshi Kawabe

S. Miwa, M. Suzuki, M. Tsujikawa, K. Matsuda, T. Nozaki, K. Tanaka, T. Tsukahara, K. Nawaoka, M. Goto, Y. Kotani, T. Ohkubo, F. Bonell, E. Tamura, K. Hono, T. Nakamura, M. Shirai, S. Yuasa, and Y. Suzuki, "Voltage controlled interfacial magnetism through platinum orbits", Nat. Commun. **8**, 15848 (2017). [https://doi.org/10.1038/ncomms15848]

T. Kawabe, K. Yoshikawa, M. Tsujikawa, T. Tsukahara, K. Nawaoka, Y. Kotani, K. Toyoki, M. Goto, M. Suzuki, T. Nakamura, M. Shirai, Y. Suzuki, and S. Miwa, "Electric-field-induced changes of magnetic moments and magnetocrystalline anisotropy in ultrathin cobalt films", Phys. Rev. B **96**, 220412(R) (2017). [https://doi.org/10.1103/PhysRevB.96.220412]

An electric-field control of magnetic properties at room temperature attracts much attention because of its great potential for enabling the construction of ultralow-power-consumption electric devices. Voltage-controlled magnetic anisotropy (VCMA) in ultrathin ferromagnetic metals can be an ultimate technology for the operation of spintronics devices, such as nonvolatile random access memory, where high-speed operation with high writing endurance is indispensable.

In this study, we find that VCMA in $3d$-transition metals such as Fe(Co)/MgO systems is explained by electric-field-induced change in orbital magnetic moment (m_L, Fig. 1(a)). As has been reported, orbital magnetic moment influences the magnetic anisotropy through spin-orbit interactions. The VCMA in $3d$-ferromagnetic metals is also explained by the orbital magnetic moment mechanism (Fig. 2). When multilayered ferromagnetic films with $3d$/$5d$-trasition metals are employed, magnetic anisotropy and VCMA can be dominated in the $5d$-metals. For instance, in an $L1_0$-FePt/MgO system, Pt has proximity-induced magnetic moments and the impacts of magnetic anisotropy and VCMA in Pt are greater than those of Fe. Moreover, VCMA in the Pt originates not only from the aforementioned orbital magnetic moment mechanism but also from the electric quadrupole mechanism (Fig. 2). VCMA with the electric quadrupole mechanism is correlated to the electric-field-induced changes in the magnetic dipole T_z term in Pt atom (m_T, Fig. 1(b)). The induced mT term in Pt atom is related to the magnetic anisotropy change through spin-flip excitation process. The electric quadrupole induction can be feasible due to nonlinear electric field potential in metals because of the strong electrostatic screening effect.

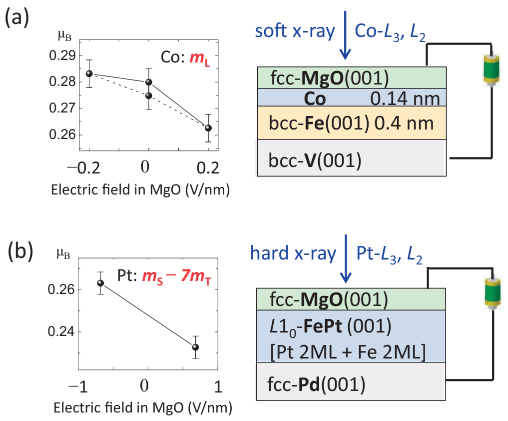

Fig. 1: Schematic of experiments

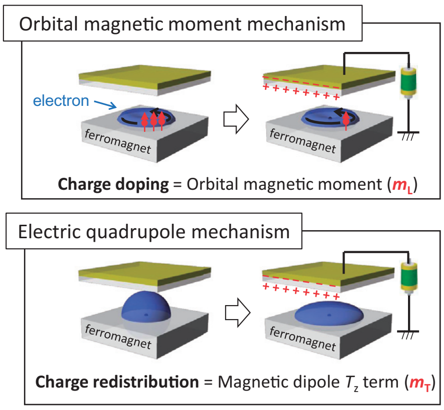

Fig. 2: Origins of magnetic anisotropy change

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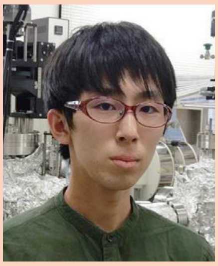

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Jansen group (A02: Electric Spin Conversion)

Giant spin accumulation in Si nonlocal devices using Fe/Mg Omagnetic tunnel contacts

Aurelie Spiesser

AurelieSpiesser, Hidekazu Saito, Yuichi Fujita, Shinya Yamada, KoheiHamaya, Shinji Yuasa, and Ron Jansen,
"Giant spin accumulation in silicon nonlocal spin-transport devices," Phys. Rev. Appl. **8**, 064023 (2017).
［https://link.aps.org/doi/10.1103/PhysRevApplied.8.064023 ］

The design of low-power spintronic devices and circuits requires the creation of a large magnetic response, for which the efficient generation of a substantial spin accumulation is indispensable. To date, the difficulty to induce a large spin accumulation in Si has seriously hampered any potential impact of Si-based spintronic devices. In this communication, we demonstrate that it is possible to create a giant spin accumulation in Si by using nonlocal spin-transport devices with an n-type Si channel and Fe/MgO magnetic tunnel contacts (Fig. 1(a)). We show that the spin splitting reaches 13 meV at 10 K (Fig. 1(b-c)) and 3.5 meV at room temperature, which is indeed very large. To explain the origin of these large spin signals, we carry out a numerical evaluation using a spin-transport model that explicitly takes the width of the injector contact into account. We demonstrate that this model provides an adequate and consistent description of all the nonlocal spin-transport data with reasonable values of the extracted parameters, such as a spin lifetime of 18 ns, a spin-diffusion length of 2.2 μm and a tunnel spin polarization of 53 % at 10 K. From this analysis, we ascribe the giant spin accumulation to i) the large tunnel spin polarization of the Fe/MgO contacts and ii) the spin-density enhancement that is achieved by using a spin injector with a size comparable to the spin-diffusion length of the Si. This result opens the way towards the development of Si spintronic devices with a large magnetic response.

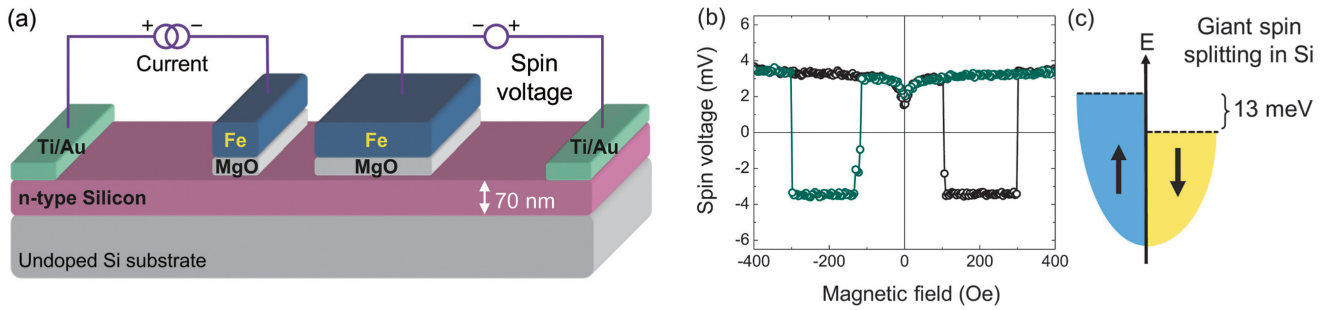

Fig. 1: (a) Schematic diagram of the Si nonlocal device with Fe/MgO magnetic tunnel contacts. (b) Nonlocal spin-valve signal measured at 10 K using a 1.2 μm-width ferromagnetic (FM) contact as the injector and 0.4 μm-width FM contact as the nonlocal detector. The current density is 12.5 kA/cm^2 with the electrons flowing from the FM into the Si. (c) Schematic illustration of the large spin splitting obtained in our Si nonlocal device.

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Shiraishi group (A02: Electric Spin Conversion)

Strong evidence for *d*-electron spin transport at room temperature at a $LaAlO_3/SrTiO_3$ interface

Ryo Ohshima, Yuichiro Ando, and Masashi Shiraishi

R. Ohshima, Y. Ando, K. Matsuzaki, T. Susaki, M. Weiler, S. Klingler, H. Huebl, E. Shikoh, T. Shinjo, S. T. B. Goennenwein, and M. Shiraishi, "Strong evidence for d-electron spin transport at room temperature at a $LaAlO_3/SrTiO_3$ interface", Nature Materials **16**, 609 (2017). [http://dx.doi.org/10.1038/NMAT4857]

A two-dimensional electron gas demonstrates the ability to enable a material platform for the study of a lot of spintronics applications in a solid-state physics such as a long-range spin transport due to their high mobility and highly efficient spin-charge conversion by the Rashba spin-orbit interaction. $LaAlO_3/SrTiO_3$(LAO/STO) interfaces are one of the promising oxide heterointerfaces with the gate-tunable spin-charge conversion and predicted long spin lifetime. Here, we demonstrated room-temperature spin transport at LAO/STO interfaces. We defined two parallel strips made from NiFe (Py) and Pt (or Ta), respectively, on the surface of a conductive LAO/STO substrate, separated by a distance L (Fig. 1). The sample with Ta electrode was prepared for control experiments by changing the polarity of the spin Hall angle. Spin current generated by means of spin pumping from the Py electrode was detected by the non-local nonmagnetic strip as an electromotive force by the inverse spin Hall effect (ISHE), indicating spin transport through the LAO/STO interface. We successfully observed the electromotive forces by the ISHE from the nonmagnetic electrodes at room temperature, which indicated spin transport through the LAO/STO interface on the micron scale, and the dependence of the normalized electromotive forces on L allowed us to estimate the spin diffusion length of the LAO/STO interface to be 340 nm (Fig. 2).

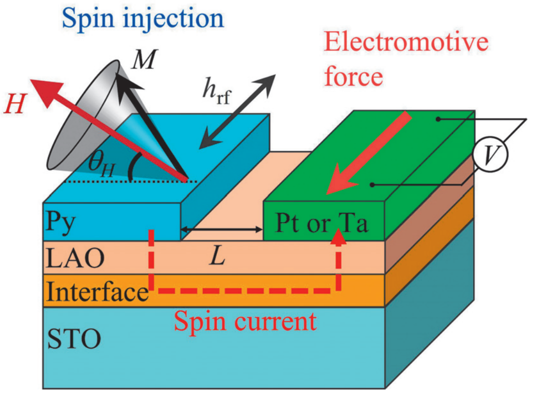

Fig. 1: Schematic illustration of the spin transport device.

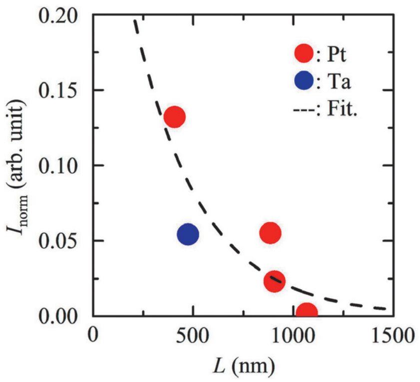

Fig. 2: Dependence of the normalized electromotive forces (I_{norm}) on the transport length (L). Break line is an exponential decay as a function of L.)

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Katsumoto group (A02: Electric Spin Conversion)

New type of conductance fluctuation driven by Zitterbewegung

Taketomo Nakamura and Shingo Katsumoto

Yu Iwasaki, Yoshiaki Hashimoto, Taketomo Nakamura, and Shingo Katsumoto, "Conductance fluctuations in InAs quantum wells possibly driven by Zitterbewegung", Scientific Reports, **7**, 7909 (2017).
[https://doi.org/10.1038/s41598-017-06818-4]

When an electron is injected into a two-dimensional system with the Rashba-type spin-orbit interaction (SOI) with a spin not parallel to the spin-orbit field, the spin begins a precession around the field. The precession, on the other hand gives a back reaction to the orbital motion through the SOI resulting in a meandering orbit as illustrated in Fig.1. This meandering motion corresponds to so called "Zitterbewegung" (trembling motion, ZB) in relativistic electrons, which does not have well-defined velocity because of the intermixing with positrons by the Higgs mode. Though the ZB amplitude in an SOI system, is still very small to be detected directly, it can be amplified with moderate impurity scatterings. The sample used here is a strip of InAs quantum well with the size of twice the mean free path to accommodate a few scatterings in traveling across it. The injection of spin-polarized electrons is achieved by using quantum point contacts with a quantized conductance of $2e^2/h$. The spin precession due to the non-adiabatic spin-injection process can be tuned through the in-plane external magnetic field. Figure 2 shows reproducible conductance fluctuation against the in-plane field, the cut-off frequency of which obeys the prediction of theory based on the ZB manifesting that the SOI-ZB really has appeared as the conductance fluctuation.

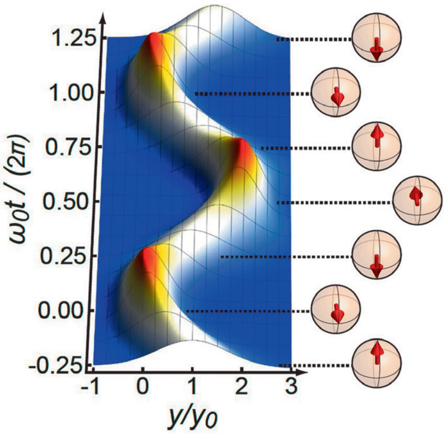

Fig. 1: Meandering of orbit due to the back action of spin precession.

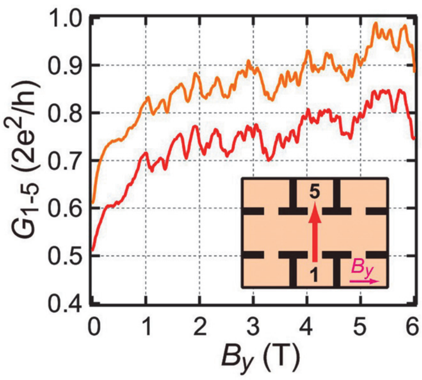

Fig. 2: Reproducible fluctuation in the conductance between two quantum point contacts against in-plane magnetic field.

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Hamaya group (A02: Electric Spin Conversion)

Spin transport and relaxation in *n*-type germanium

Michihiro Yamada, Yuichi Fujita, and Kohei Hamaya

Y. Fujita, M. Yamada, M. Tsukahara, T. Oka, S. Yamada, T. Kanashima, K. Sawano, and K. Hamaya, "Spin Transport and Relaxation up to 250 K in Heavily Doped n-Type Ge Detected Using Co$_2$FeAl$_{0.5}$Si$_{0.5}$ Electrodes"
Phys. Rev. Appl. **8**, 014007 (2017). [https://doi.org/10.1103/PhysRevApplied.8.014007]

Because of the compatibility with next-generation CMOS transistors, spintronic technologies for germanium (Ge) should be developed. However, it is not enough to show highly efficient electrical spin injection/detection and to understand the spin relaxation mechanism in Ge. In the present study, we developeda method for highly efficient spin-injection/detection techniques using a Heusler-alloy, Co$_2$FeAl$_{0.5}$Si$_{0.5}$ (CFAS), grown on Ge by using room-temperature molecular beam epitaxy (MBE) [Fig.1(a)]. We can obtain a flat CFAS/Ge heterointerface with no reaction layer for electrical spin injection/detection. Using the CFAS/Ge Schottky-tunnel junctions, we fabricated the lateral spin valves and measured nonlocal four-terminal magnetoresistance at various temperatures. From nonlocal Hanle-effect curves [see upper inset in (b)], we evaluated temperature dependence of spin lifetime, as shown in Fig. 1(b). Considering the recent theories by Dery and co-workers, we can conclude that the spin relaxation in *n*-Ge is governed by the impurity- and phonon-induced intervalley scattering in the conduction band [see lower inset in (b)], To suppress this spin relaxation mechanism, one should induce the lift of the valley degeneracy by applying the lattice strain.

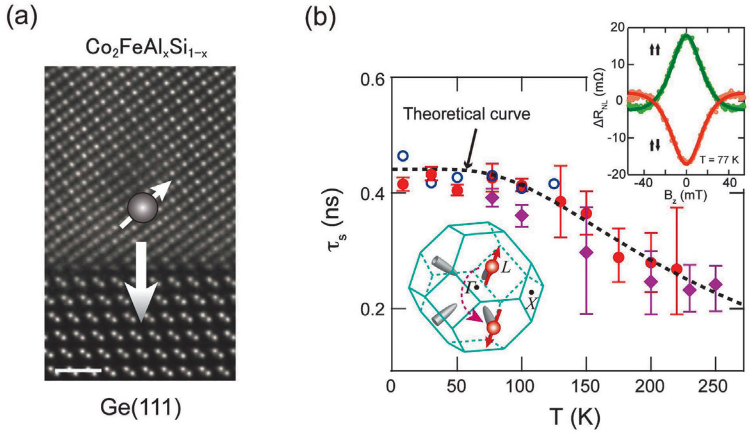

Fig. 1: (a) HAADF-STEM image of a Co$_2$FeAl$_{0.5}$Si$_{0.5}$/Ge interface grown by MBE. (b) Temperature-dependent spin lifetime in *n*-Ge. The dashed line is a theoretical curve considering the theories by Dery and co-workers. The upper and lower insets show Hanle-effect curves and the schematic of intervalley spin-flip scattering in the conduction band of Ge.

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Otsuka group (A02: Electric Spin Conversion)

Probing dynamics of local spin states in nanostructures utilizing quantum dot probes

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Nanostructures are attractive materials in spintronics because of their interesting electronic and spin properties. To explore spin phenomena inside nanostructures, local spin probes which can directly access the local spin states are useful. We can realize such local spin probes utilizing semiconductor quantum dots (QDs). By monitoring electron tunneling into the spin-dependent levels of the QD, we can get information of the local spin states. We can also access the dynamics utilizing high-speed electric measurements. We explore the dynamics of a local spin state in a nanostructure utilizing fast QD probes.The target nanostructure is a simple open quantum system, which consists of a single QD and an open electric reservoir. A QD is coupled to an open electric reservoir through a tunneling barrier, and the charge state is monitored by a nearby fast QD charge sensor. Another ancillary QD is used to detect the target spin state by utilizing the spin-dependent charge transition. We initialize the spin state by utilizing singlet formation in the ancillary QD and transfer the initialized electron into the target QD coupled to the reservoir. We monitor the change of the spin state in the target QD. We measure the change of the spin state around the charge transition. The observed dynamics of the spin state are consistent with the charge relaxation signal and considered as a result of the first order tunneling process, in which the electron escapes and the spin information is lost. When we increase the coupling between the target QD and the reservoir, we observe spin relaxation signals even in a deep Coulomb blockade region. The observed dynamics properties are different for the charge state signal, indicating the second order process through intermediate states, in which only the spin information is lost. These results are important in exploration and understanding of spin dynamics in nanostructure hybrid systems.

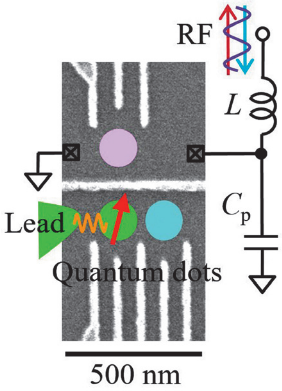

Fig. 1: Scanning electron micrograph of the device

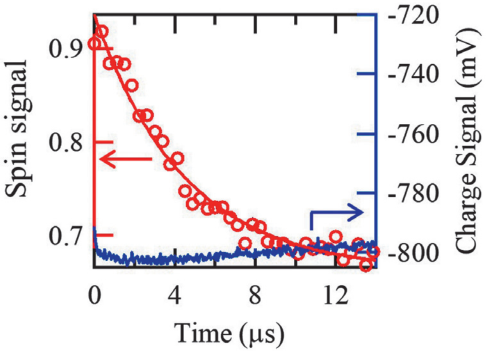

Fig. 2: Spin and charge states dynamics

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Matsuo group (A03: Optical Spin Conversion)

Single electron-photon creation from a single polarization entangled photon pair

Kazuyuki Kuroyama and Sadashige Matsuo

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"Single electron-photon creation from a single polarization entangled photon pair",
Journal: Scientific Reports **7**, 16968 (2017). [http://dx.doi.org/10.1038/s41598-017-16899-w]

Quantum entanglement is non-local correlation which does not appear in classical physics and is a central concept of quantum information and quantum communication. Entanglement between different kinds of qubits like photon and spinis important not only for the fundamental physics but also regarded essential for future photonic quantum communication. However, transfer of entanglement between photon and spin is still technically challenging in any forms of qubits.

In order to verify the entanglement transfer, we designed an experimental approach using a gate defined GaAs quantum dot (QD) and a polarization-entangled photon pair generated in spontaneous parametric down conversion (SPDC) of a type-II BBO crystal. We experimentally performed paired generation of a single electron in a GaAs QD and a single photon from a single polarization-entangled photon pair (Fig.1). As the experiment procedure, first one ofpaired photons is irradiated and excites an electron onto a QD, and the electron is measured by a nearby charge sensor in real-time. Then the other paired photon is simultaneously detected by a photon counter located at a separated place. Since, as characteristic of SPDC, paired photons are generated at same time, we measure temporal coincidence between the single photo-electron detection and the single photon detection (Fig.2). Considering a single photon polarization is coherently converted to an electron spin via a GaAs optical selection rule, the present result indicates the capability of photon to spin entanglement transfer. This may be useful to explore the physics of entanglement transfer and also for applications to quantum teleportation based quantum communication.

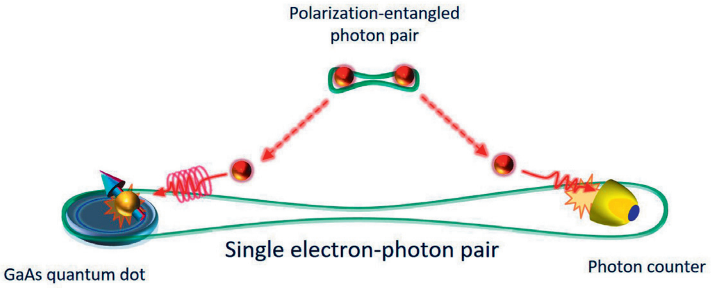

Fig. 1: A schematic figure of single electron-photon creation using a polarization-entangled photon pair.

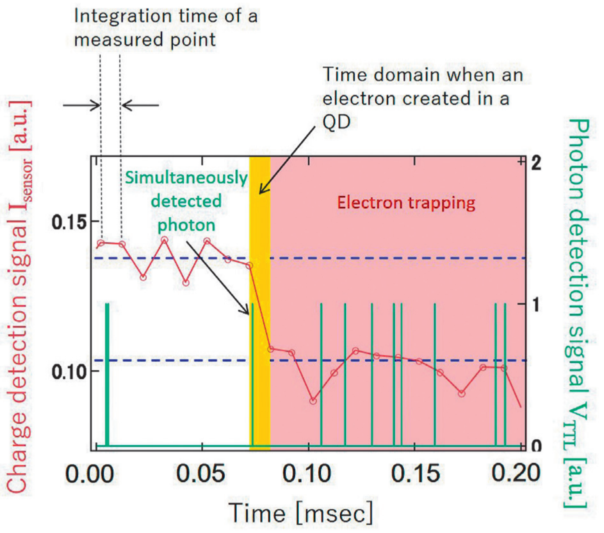

Fig. 2: Real-time trace in which an electron and a photon is simultaneously observed.

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Mizukami group (A03: Optical Spin Conversion)

Reciprocity and Dispersion relation for magnon generated by a laser pulse in magnetic metals

Akira Kamimaki and Shigemi Mizukami

A. Kamimaki, S. Iihama, Y. Sasaki, Y. Ando, and S. Mizukami, "Reciprocal excitation of propagating spin waves by a laser pulse and their reciprocal mapping in magnetic films", Phys. Rev. B. **96**, 014438 (2017). [https://doi.org/10.1103/PhysRevB.96.014438]

The magnon propagation in magnetic metals have been mostly studied by a microwave technique with electrical antennas. Recently we have demonstrated all-opticalgeneration and detections of magnons under the microscope [S. Iihama *et al*., Phys. Rev. B. **94**, 020401(R) 2016]. We further developed this microscopic technique and confirmed the reciprocity of the laser-induced magnons for 80NiFe thin films [Fig. 1(a)]. The laser-induced magnon packets show symmetric propagations in the positive and negative directions[Fig. 1(b)]. This indicates that the magnons generated from the focused laser light via the torque with the inversion symmetry in space. Meanwhile, we succeeded to visualize the dispersion relation of magnons by transforming the data obtained in real space to the reciprocal Fourier space. The dispersion relation was clearly seenwithin the wavenumber of about 3 rad/μm and the frequency of about 10 GHz, which was in good agreement with the theoretical dispersion relations. [Fig. 1(c) and1(d)]. These results indicate that this optical technique will be a powerful tool to investigate the magnon spectra in a small area for various metallic films.

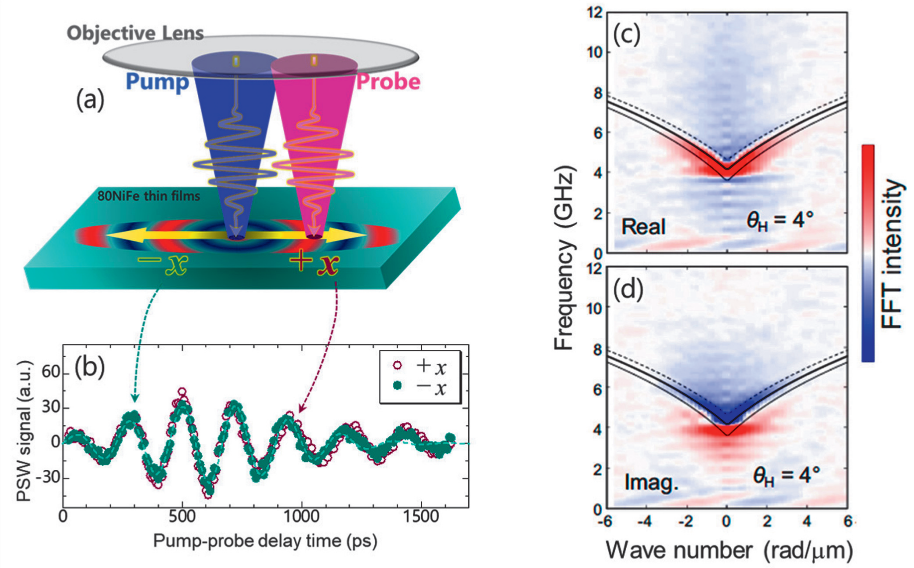

Fig. 1: (a) Schematic illustration of the all-optical technique to detect the magnon propagation. (b) Magnon packets detected at $x = \pm 2.1$ μm. (c) The real and(d) imaginary part of the Fourier transform of the magnon propagation. Curves are the theoretical magnon dispersion relation.

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Ono group (A04: Thermodynamic Spin Conversion)

Barnett effect in rare earth metals

Yudai Ogata

Y. Ogata, H. Chudo, M. Ono, K. Harii, S. Okayasu, M. Matsuo, S. Maekawa,and E. Saitoh,
"Gyroscopic g factor of rare earth metals", Appl. Phys. Lett. **110**, 072409 (2017). [http://dx.doi.org/10.1063/1.4976998]

A magnetic moment consists of spin and orbital magnetic moments. To reveal the spin and orbital contributions, the gyroscopic g factor, g', and the spectroscopic g factor, g, are measured. The g' factor is the ratio between the angular momentum J and the magnetic moment μ and is determined by the gyromagnetic effects known as the Barnett effect and Einstein-de Haas effect. The g factor is defined as $\hbar_\omega = g\,\mu_B H$ and is determined by the ESR methodwith ω , μ Band H being the resonance frequency, Bohr magneton and magnetic field, respectively. However, the short relaxation time of electron prevents from ESR measurements. In the 4*f* rare earth metals, both measurements have not been experimentally reported.

We developed the apparatus for observing the Barnett effect(Fig.1). A sample is introduced into the rotation system and is rotated by the bearing and the driving air. To measure the stray field ΔB from the rotating sample, the fluxgate sensor is mounted next to the rotation system. A static magnetic shield and a thermal isolation chamber with air controller suppressed the magnetic and the temperature fluctuations, respectively. We confirmed that our apparatus works well down to a few pT by applying an electric current to a solenoid coil.

Fig. 2 shows the rotational frequency dependence of the effective magnetic fields (the Barnett fields B_Ω). The Barnett field was estimated from the magnetization caused by rotation and the magnetic susceptibility of sample. The Barnett field of samples linearly depends on the rotational frequency. From slopes of the lines, we estimated the g' factors to be 2.00±0.08, 1.53±0.17, 1.15±0.32, for Gd, Tb, and Dy, respectively. These values coincide with the Lande g factor.

Recently, we succeeded in observing the Barnett effect in FeCo nanogranules [Y. Ogata *et al*., JMMM, **442**, 329 (2017)]. The experimental result indicates that the orbital contribution is enhanced by symmetry breaking at the surface. Furthermore, the present technique expects to experimentally extract the orbital contributions to the magnetism in the 5*f*-electron state of actinide compounds, which are described as the intermediate state between the *LS* coupling and *j-j* coupling schemes.

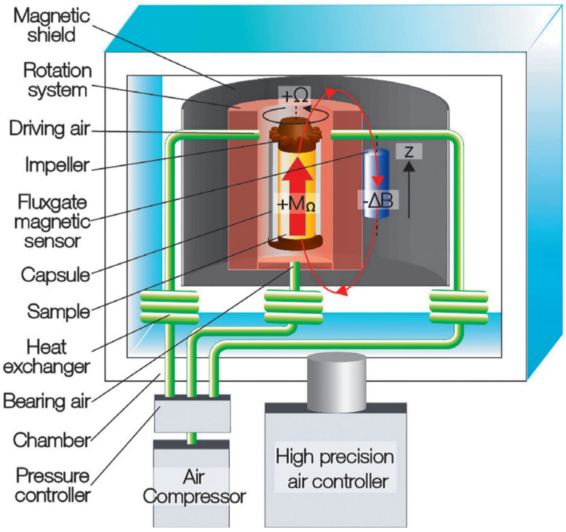

Fig. 1: Schematic illustration of the apparatus for observing the Barnett effect.

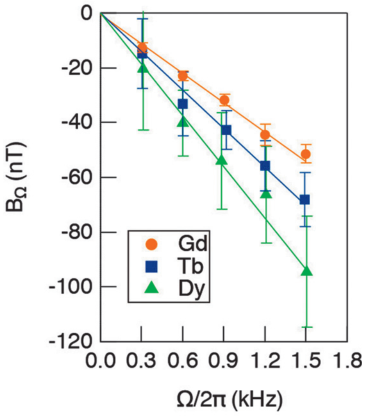

Fig. 2: Rotational frequency dependence of the Barnett field B_Ω .

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Saitoh group (A04: Thermodynamic Spin Conversion)

Spin-wave tomography

Yusuke Hashimoto and Eiji Saitoh

Y. Hashimoto, S. Daimon, R. Iguchi, Y. Oikawa, K. Shen, K. Sato, D. Bossini, Y. Tabuchi, T. Satoh, B. Hillebrands, G. E. W. Bauer, T. H. Johansen, A. Kirilyuk, T. Rasing, and E. Saitoh, "All-optical observation and reconstruction of spin wave dispersion", Nat. Commun. **8**, 15859 (2017). [https://www.nature.com/articles/ncomms15859]

In a magnet, wave motion of atomic spins serves as an elementary excitation, called a spin wave. To know the properties of a spin wave, one should measure how its frequency changes with its wavenumber vector. The relation between them is called the dispersion relation, which represents essential information of the kinetics. Spin waves whose dispersions are dominated by a dipole-diploe interaction are called pure-magnetostatic waves. The pure-magnetostatic spin waves are characterized by complicated and anisotropic dispersion relations; for instance, their slope may even become negative for the so-called backward volume magnetostatic waves. Although magnetostatic waves are employed in spintronic and magnonic devices, the observation of dispersion relations of pure-magnetostatic waves was one of the challenges. Recently, we reported the direct observation of the dispersion relation of pure-magnetostatic waves by developing a table-top all-optical spectroscopy; we named spin-wave tomography. Spin waves are excited by the illumination of an ultrashort light pulse focused on a very small surface area of a magnet. When the pulse duration and the excitation area are infinitesimally small, the pulse includes all temporal and spatial wave components according to the Fourier theorem. Then, spin waves of all frequency and wavenumber vector can be created simultaneously and propagate radially from the excitation point. The created spin waves are detected using a time-resolved magneto-optical imaging technique. By Fourier transformation of the observed waveform with respect to time and spatial coordinates, we obtain the power spectra of spin waves as a function of the frequency and the wavenumber vector. The dispersion relation of spin waves is read from the spectra (Fig. 1).This is the basicconcept of spin-wave tomography. Spin-wave tomography gives access to the spin-wave dispersion with wavelengths typically larger than a micrometer, which has been difficult with conventional methods of spin-wave spectroscopy.

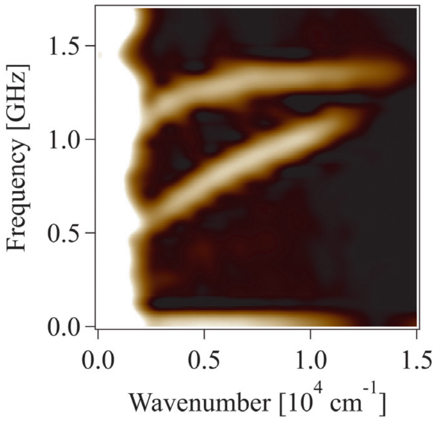

Fig. 1: Dispersion relations of spin waves observed by spin-wave tomography

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Saitoh group (A04: Thermodynamic Spin Conversion)

Tunable sign change of spin Hall magnetoresistance in Pt/NiO/YIG structures

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"Tunable Sign Change of Spin Hall Magnetoresistance in Pt/NiO/YIG Structures",
Phys. Rev. Lett. **118,** 147202 (2017). [https://doi.org/10.1103/PhysRevLett.118.147202]

Recent studies of thin film bilayer systems comprised of a normal metal (NM) and a ferromagnetic insulator (FI) revealed a new type of magnetoresistance called spin Hall magnetoresistance (SMR), originating from the interplay between the spin accumulation at the NM/FI interface and the magnetization of the FI layer. SMR should always be positive according to the present understanding, however, the sign change of SMR has been found in Pt/NiO/YIG structures.

In this study,SMR has been investigated in Pt/NiO/YIG structures in a wide range of temperature and NiO thickness, as shown in Figure 1a. The SMR shows a negative sign below a temperature that increases with the NiO thickness. The negative SMR is found to persist even when NiO blocks the spin transmission between Pt and YIG, indicating it is governed by the spin current response of the NiO layer. We explain the negative SMR by the NiO "spin flop" coupled with YIG as illustrated in Fig. 1b, which can be overridden at higher temperature by positive SMR contribution from YIG. This highlights the role of magnetic structure in antiferromagnets for transport of pure spin current in multilayers.

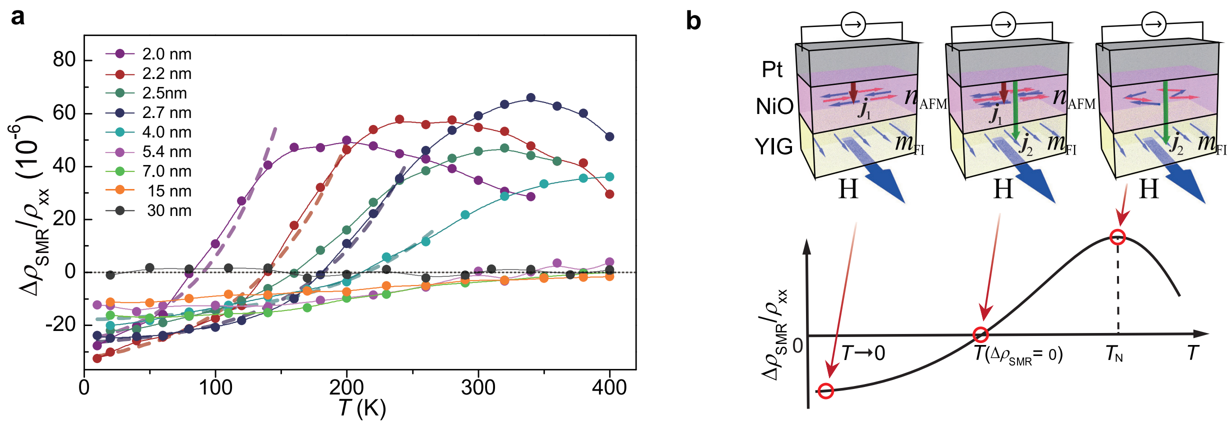

Fig. 1: a. Sign change of SMR observed in Pt/NiO/YIG devices. The sign change temperature depends on the NiO thickness. b. Illustrations for the magnetic structure and spin transportin Pt/NiO/YIG at different temperatures.

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Maekawa group (A05: Functional Design of Spin Conversion)

Scaling law of spin-current generation by fluid motion

Mamoru Matsuo, Yuichi Ohnuma, and Sadamichi Maekawa

M. Matsuo, Y. Ohnuma, and S. Maekawa, "Theory of spin hydrodynamic generation", Phys. Rev. B **96**, 020401(R)(2017).
[https://doi.org/10.1103/PhysRevB.96.020401]

Very recently, spin-current generation by elastic [D.Kobayashi et al., Phys. Rev. Lett. **119**, 077202 (2017)]and fluid motion [R.Takahashi et al., Nat. Phys. **12**, 52 (2016)] has been demonstrated, wherein the spin-rotation coupling is exploited. The spin-rotation coupling refers to the fundamental coupling between spin and mechanical rotational motion and emerges universally in moving materials, such as ferromagnetic and paramagnetic metals as well as nuclear spin systems. This coupling allows the interconversion of spin and mechanical angular momentum.

In the present study, we formulated a microscopic theory of spin-current generation by fluid motion based on the quantum kinetic theory, and derived the spin-diffusion equation in a liquid metal flow.

The derived spin-diffusion equation has a source term, which is responsible for the angular momentum conversion from the liquid metal vorticity to the electron spins. By combining the Navier-Stokes equation, we show that spin current is generated along the vorticity gradient of the fluid (Fig.1).

Moreover, we have evaluated the spin current generated under both laminar- and turbulent-flow conditions, such as the Poiseuille(the parallel flow between the two parallel planes; Fig. 1) and Hage-Poiseuille flow (a steady viscous flow in a pipe of circular cross-section; Fig. 2) scenarios and the turbulent flow in a fine pipe. The generated inverse spin Hall voltage is linearly proportional to the flow velocity, whereas that in a turbulent-flow environment is proportional to the square of the velocity. Our theory proposed here will bridge the gap between spintronics and fluid physics, and pave the way to fluid spintronics.

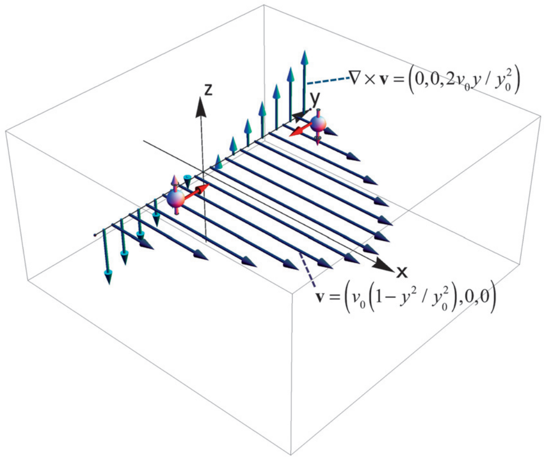

Fig. 1: Representation of the spin current in the two-dimensional Poiseuille flow. The parallel Laminar flow along the x-direction creates the vorticity gradient and the spin current in the y-direction.

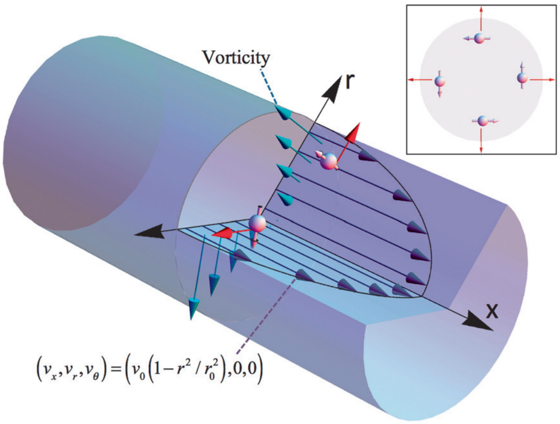

Fig. 2: Representation of the spin current for the Hagen-Poiseuille flow. The vorticity gradient generates the spin current in the radial direction.

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Effective Hamiltonian theory for nonreciprocal light propagation in magnetic Rashba conductor

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H. Kawaguchi and G. Tatara, "Effective Hamiltonian theory for nonrecipro-cal light propagation in magnetic Rashba conductor", Phys Rev B, **94**, 235148 (2016). ［https://doi.org/10.1103/PhysRevB.94.235148 ］

Spin-orbit interaction attracts the interest of researchers in the context of mixing of electric and magnetic degrees of freedom. Of particular current interest is Rashba spin-orbit interaction which arises from breaking of spatial inversion symmetry. The Rashba interaction leads to electromagnetic cross-correlation effects such as Rashba-Edelstein effect and inverse Edelstein effect. It was pointed out that those cross-correlation effects induce anomalous optical responses. Moreover, when a Rashba conductor is magnetic or under a magnetic field, an anisotropic light propagation, directional dichroism, is induced as was recently shown theoretically. In present study, we explored the mechanism of the directional dichroism in a magnetic Rashba conductor by studying an effective Hamiltonian for electromagnetic fields based on an imaginary-times path-integral formalism. We found that the directional dichroism is induced by a coupling between electric and magnetic fields ($\boldsymbol{E}$ and $\boldsymbol{B}$, respectively), which reads

$$\boldsymbol{H}_{\mathrm{eff}} = g\boldsymbol{A}_{\mathrm{R}}\cdot(\boldsymbol{E}\times\boldsymbol{B}),$$

where g is a coupling constant, $\boldsymbol{A}_{\mathrm{R}} \equiv \alpha_{\mathrm{R}} \times \boldsymbol{M}$ is a Rashba-induced gauge field for an electron spin, α_{R} is Rashba field, and $\boldsymbol{M}$ is a magnetization. Since $\boldsymbol{E}\times\boldsymbol{B}$ represents the Poynting vector, the Hamiltonian is a gauge coupling between a photon current and the Rashba-induced gauge field. Moreover, the effective coupling clearly indicates that the dichroism is induced by the Doppler shift due to an intrinsic flow in medium induced by the Rashba-induced gauge field (Fig. 1). The Rashba-induced gauge field, $\boldsymbol{A}_{\mathrm{R}}$, has the same symmetry as so called the toroidal moment discussed in multiferroics. Our analysis thus gives a microscopic ground for the directional dichroism due to the toroidal moment discussed phenomenologically in multiferroics. It is intriguing and nontrivial that the Rashba-induced gauge field, originally introduced as an effective vector potential (gauge field) acting on the electron spin, acts as a vector potential for light or photons at the same time.

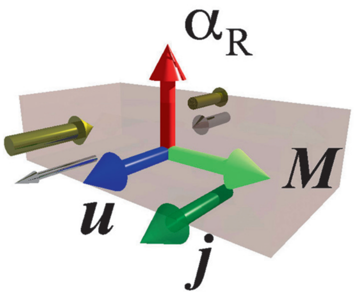

Fig. 1: Schematic illustration of the directional dichroism in the magnetic Rashba conductor. When the Rashba field (α_{R}) and the magnetization ($\boldsymbol{M}$) are noncollinear, the Rashba-induced gauge .eld, a metallic counterpart of the toroidal moment, induces the intrinsic flow ($\boldsymbol{u}$), which induces the directional dichroism of light as a result of the Doppler shift. The intrinsic flow generates a current ($\boldsymbol{j}$) as a result of spin-charge conversion ('Rashba-Edelstein') effect.

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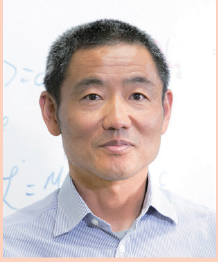

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Sato group (A05: Functional Design of Spin Conversion)

Novel applications of twisted laser for ultrafast control of magnetism

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H. Fujita and M. Sato, "Ultrafast generation of skyrmionic defects with vortex beams: Printing laser profiles on magnets", Physical Review B **95**, 054421 (2017). [https://doi.org/10.1103/PhysRevB.95.054421]

H. Fujita and M. Sato, "Encoding orbital angular momentum of light in magnets", Physical Review B **96**, 060407(R) (2017). [https://doi.org/10.1103/PhysRevB.96.060407]

Optical vortex (vortex beam), the laser carrying an orbital angular momentum (OAM), is being one of the hot topics in the field of optics. Various sorts of application of vortex beams have been argued, and particularly many studies have explored the transfer of the OAM from the laser to materials. However, most of the researches for vortex beams have focused only on macroscopic degrees of freedom, typically objectslarger than micrometers, while the control of more microscopic degrees of freedom such as electron charges and spins has not been argued well. Recently, we have given some theoretical proposals for the application of vortex beams to nano-scale magnetism. Based on the numerical calculation with Landau-Lifshitz-Gilbert (LLG) equation, we analyze electron-spin dynamics in magnets under vortex beams. We show that topological magnetic defects such as skyrmions and skyrmioniums can be created by applying focusing high-frequency (X-ray, ultraviolet, visible) or low-frequency (Tera Hz) vortex beams to a class of chiral magnets in an ultrafast way (Figs. 1 and 2). Moreover, we show that Tera Hz beam driven magnetic resonance induces a scalar spin chirality and it means that the vortex beam can generate a transient topological Hall effect in itinerant magnets, in principle. Our results are expected to open a novel research field of the spintronic application of spatially structural laser beams including vortex beams.

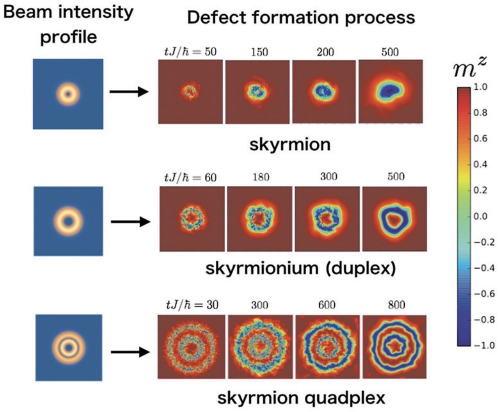


Fig. 1: Typical time evolutions of electron spins in chiral ferromagnets after applying high-frequency vortex beams. The time unit t=1 corresponds to about 0.1-1.0 [pico sec], and the color bar stands for the value of S^z component of the local magnetization. These are our numerical result based on LLG equation, and the spin dynamics is generated by heating effect of the beams. Skyrmion, skyrmionium (skyrmion duplex), and skyrmion quadplex are respectively created by applying small-size vortex beam, proper-size beam, and double-ring beam.

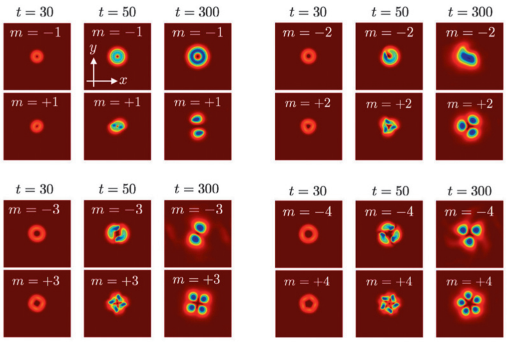
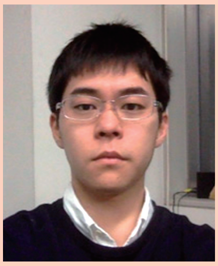


Fig. 2: Typical time evolutions of electron spins in chiral ferromagnets after applying half-cycle pulses of Tera Hz vortex beams with different OAMs $\hbar m$ ($m=\pm 1$, ± 2, ± 3, and ± 4). The magnetic field of the beams is coupled tospins via the Zeeman interaction. Each small circle corresponds to a skyrmion. The number of created skyrmions are given by sign(m)($m+1$).



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Ultrasonic elastic responses in a Skyrmion/monopole lattice

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X. Zhang and N. Nagaosa, "Ultrasonic elastic responses in a monopole lattice",
New Journal of Physics, **19**, 043012, 2017. [https://doi.org/10.1088/1367-2630/aa6322]

The latest experimental advances have extended the scenario of coupling mechanical degrees of freedom in chiral magnets (e.g., MnSi/MnGe) to the topologically nontrivial Skyrmion lattice and even the simultaneous lattice of Skyrmions and monopoles. This is based on the fact that sound wave modulated lattice bond in turn modifies the magnetic interactions such as the Heisenberg exchange interaction J and the Dzyaloshinskii−Moriya interaction D (Fig. 1), which are the typical constituents of a chiral magnet Hamiltonian. Equipped with a spin-wave theory highlighting the topological features, we devise an interacting model for acoustic phonons and magnons to explain the experimental findings in a monopole lattice with a topological phase transition, i.e. annihilation of monopole−antimonopole pairs. We reproduce the anisotropic magnetoelastic modulations of elastic moduli: drastic ultrasonic softening around the phase transition and a multi-peak-and-trench fine structure for sound waves parallel and perpendicular to the magnetic field, respectively (Fig. 2). Comparison with experiments indicates that the magnetoelastic coupling induced by Dzyaloshinskii−Moriya interaction is comparable to that induced by the exchange interaction. Other possibilities such as elastic hardening are also predicted. The study implies that the monopole defects and their motion in MnGe play a crucial role.

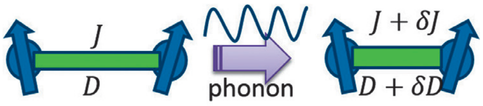

Fig. 1: Cartoon for the mechanism of the magnetoelastic couplings.

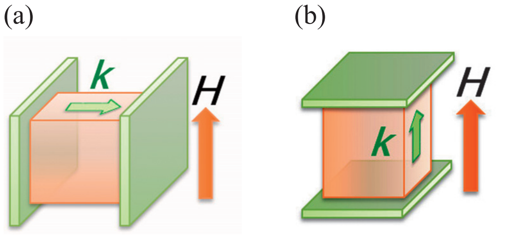

Fig. 2: Illustration of experimental settings for the parallel and perpendicular cases. k and H stand for the sound wave and the external magnetic field, respectively.

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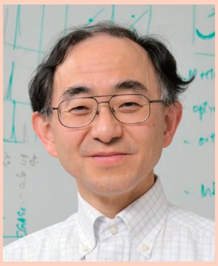

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Research group A04：Thermodynamic Spin Conversion

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Co-Investigator Masao Ono Advanced Science Reserch Center, Japan Atomic Energy Agency, Senior Scientist
Co-Investigator Koki Takanashi Institute for Materials Research, Tohoku University, Professor (Director)

Selected Projects

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Principal Investigator Yukio Nozaki Department of Physics, Keio University, Professor

Research Group A05：Functional Design of Spin Conversion

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Co-Investigator Sadamichi Maekawa Advanced Science Research Center, Japan Atomic Energy Agency, Director General
Co-Investigator Gen Tatara RIKEN Center for Emergent Matter Science, Team Leader
Co-Investigator Naoto Nagaosa Department of Applied Physics, The University of Tokyo, Professor/ RIKEN Center for Emergent Matter Science, Group Director
Co-Investigator Gerrit E. W. Bauer Institute for Materials Research, Tohoku University, Professor

Selected Projects

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Principal Investigator Fumiyuki Ishii Faculty of Mathematics and Physics, Kanazawa University, Associate Professor
Principal Investigator Masahiro Sato Department of Physics, Ibaraki University, Associate Professor
Principle Investigator Takehiko Yokoyama Department of Physics, Tokyo Institute of technology, Assistant Professor