Tohoku-Lorraine Joint Conference 2021

March, 3 2021

Spintronic

Tohoku-Lorraine Joint Conference 2021

March 3: Scientific session « Spintronic »

PROGRAM

8:30 – 11:30 (Nancy) / 16:30 – 19:30 (Sendai)

8:20 – 8:30 / 16:20 – 16:30	Welcome
8:30 – 9:45 / 16:30 – 17:45	Invited Talks #1 (5)
9:45 – 9:55 / 17:45 – 17:55	One-Slide Presentation #1 (5)
9:55 – 10:05 / 17:55 – 18:05	coffee break
10:05 – 11:20 / 18:05 – 19:20	Invited Talks #2 (5)
11:20 – 11:30 / 19:20 – 19:30	One-Slide Presentation #2 (5)

INVITED TALKS # 1

- Kaushalya Jhuria: **Picosecond spin-orbit torque switching in ferromagets**
- Takeshi Seki: **Origin and Optical Switching of Perpendicular Magnetization for Co-Gd/Pt Multilayers**
- Heloise Damas: **Self-Spin-Orbit Torque in GdFeCo ferrimagnet**
- Satoshi Iihama: **Optical spin torque in ferromagnet/heavy metal thin films**
- Maryam Massoura: **Artificial spin systems: potential device for random number generation**

INVITED TALKS # 2

- Makoto Kohda: **Spatiotemporal dynamics of helical spin wave under persistent spin helix state**
- Claudia De Melo Sanchez : **Transport properties of Co2MnSi Heusler compounds**
- Tufan Roy: **A combined study of computational prediction and experimental fabrication of quaternary Heusler alloy CoIrMnZ (Z = Al, Ga, Si, Ge)**
- Quentin Remy: **Control of Single Pulse All Optical Magnetization Switching of Ferromagnets**
- Shunsuke Fukami: **Spin-orbit torque-induced sub-nanosecond magnetization switching in in-plane magnetic tunnel junctions**

ONE-SLIDE PRESENTATION

- Hiroto Masuda: **Large spin Hall effect in a non-equilibrium Iridium-doped Copper binary alloy**
- Alberto Anadon: **Disentangling the anomalous Nernst and spin Seebeck effect in epitaxial Graphene/Cobalt heterostructures**
- Junta Igarashi: **Shape-anisotropy magnetic tunnel junctions with multilayered ferromagnets**
- Xiaofei Fan: **Magnetization control and all-optical switching mediated by phase transition of VO_2**
- Takashi Kimura: **Valley dynamics of charged exciton in monolayer WS_2 treated by organic acid**
- Wei Zhang: **All optical helicity-independent switching in GdTbCo alloys**
- Kazuaki Ishibashi: **All-optical probe of magnetization precession frequency shift due to spin-orbit torque**
- Kosseila Ait-Oukaci: **Stripe domains in thin magnetic films for spin waves channeling**
- Junpei Sonehara: **Anisotropic spin relaxation and precession frequency depending on in-plane magnetic field orientation in GaAs-based wire structures**
- Jean LoÏs Bello: **Zero field current induced switching of GdFeCo**

Picosecond spin-orbit torque switching in ferromagets

Kaushalya Jhuria[1], Julius Hohlfeld[1], Akshay Pattabi[2], Elodie Martin[1], Aldo Ygnacio Arriola Córdova[1,3], Xinping Shi[4], Roberto Lo Conte[3], Sebastien Petit-Watelot[1], Juan Carlos Rojas-Sanchez[1], Gregory Malinowski[1], Stéphane Mangin[1], Aristide Lemaître[5], Michel Hehn[1], Jeffrey Bokor[2,6], Richard B. Wilson[4], Jon Gorchon[1,*]

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Reducing energy dissipation while increasing speed in computation and memory is a long-standing challenge for spintronics research1. In the last 20 years, femtosecond lasers have emerged as a tool to control the magnetization in specific magnetic materials at the picosecond timescale2–4. However, the use of ultra-fast optics in integrated circuits and memories would require a major paradigm shift. An ultrafast *electrical* control of the magnetization is far preferable for integrated systems. Here we demonstrate reliable and deterministic control of the out-of-plane magnetization of a 1 nm-thick Co layer with single 6 ps-wide electrical pulses that induce spin orbit torques on the magnetization. We can monitor the ultrafast magnetization dynamics due to the spin orbit torques on sub-picosecond timescales, thus far accessible only by numerical simulations. Due to the short duration of our pulses, we enter a counter-intuitive regime of switching where heat dissipation assists the reversal. Moreover, we estimate a low energy cost to switch the magnetization, projecting to below 1fJ for a (20 nm)3 cell. These experiments prove that spintronic phenomena can be exploited on picosecond time-scales for full magnetic control and should launch a new regime of ultrafast spin torque studies and applications.

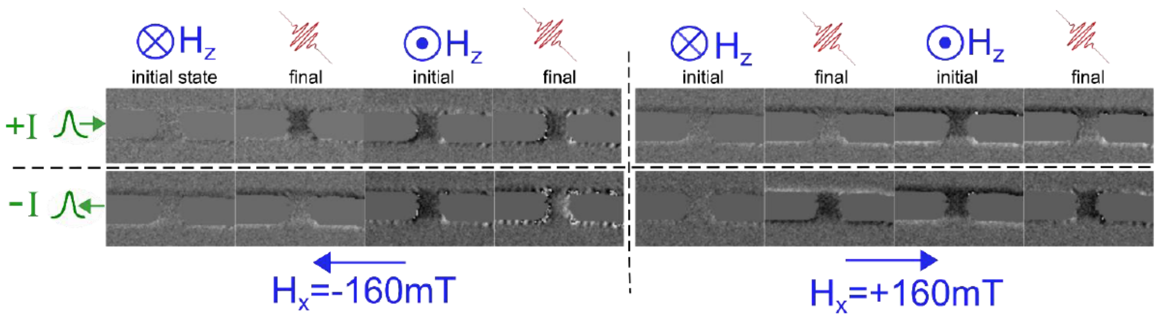

Figure 1: MOKE micrographs of single 6 ps electrical pulses switching the magnetization via SOT. The four quadrants show 2 before and 2 after-pulse images under different in-plane field and current directions. The inversion of the final state with current or in-plane field is a clear signature of SOT switching. Bias voltages used for switching were slightly above the critical threshold ($\Delta V \sim 40$ V).

Origin and Optical Switching of Perpendicular Magnetization for Co-Gd/Pt Multilayers

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All-optical switching (AOS) of magnetization by femtosecond laser pulses has attracted much attention as a route for ultrafast magnetization manipulation. The Gd-based alloys such as Gd-Fe-Co are representative ferrimagnetic materials exhibiting the all-optical helicity independent switching (AO-HIS). However, the detailed process of AO-HIS has not been elucidated yet. The perpendicularly magnetized Gd-based alloys are key materials not only in the AOS experiment, but also in the field of antiferromagnetic spintronics. Although the combinations of Gd-based alloys and Pt have widely been exploited for a variety of studies [1,2], the origin of perpendicular magnetic anisotropy (PMA) has been rarely addressed. These facts make the Gd-based alloys a unique platform to investigate the correlation between the fundamental magnetic properties and the AOS behavior, which will provide knowledge to gain insight into the AOS.
In this study, we paid attention to the combination of Co-Gd and Pt. The origin of PMA and the role of interface magnetic moment were first investigated for the Co-Gd/Pt multilayers with various Co-Gd layer thicknesses (t) and alloy compositions ($Co_{100-x}Gd_x$). Then, the AOS experiments were carried out in order to find the composition dependence of AOS probability. Thin films with the stacking structure of [Pt (2.0)/$Co_{100-x}Gd_x$ (t)]$_{\times 3}$/Pt (2.0) (in nanometer) were prepared on sapphire (11-20) substrates at room temperature using an ultrahigh vacuum compatible magnetron sputtering system.
We found that the PMA mainly comes from the Co-Gd/Pt interface while the contribution from the bulk properties of Co-Gd is negligibly small. The proximity-induced magnetic moment in Pt remarkably appeared for the thin Co-Gd layers, which coupled with the Co moment in parallel. It is noted that the proximity-induced Pt moment largely affected the condition for the magnetization compensation of Co-Gd. The Co-Gd/Pt multilayers exhibited the single laser pulse AO-HIS in the wide Co-Gd composition range, and the maximum AOS probability was obtained around the compensation composition of Co-Gd. The above findings are useful to improve the performance of AOS-based device [3].

This work was done in collaboration with J. Wang, Y.-C. Lau, Y. K. Takahashi, and K. Takanashi, and was partly supported by JSPS KAKENHI Grant-in-Aid for Scientific Research (S) (JP18H05246), Grant-in-Aid for Scientific Research (A) (JP20H00299), and Grant-in-Aid for Scientific Research (A) (JP18H03787).

[1] W. Zhou, **TS** *et al.*, Phys. Rev. Mater. **2**, 094404 (2018).
[2] T. Moriyama, **TS** *et al.*, Phys. Rev. Lett. **121**, 167202 (2018).
[3] J. Wang, **TS** *et al.* (Submitted).

Self-Spin-Orbit Torque in GdFeCo ferrimagnet

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Spin-orbit torque has been widely studied in ferromagnet/heavy metal bilayers due to their high application potential regarding modern electronic devices [1,2]. The heavy metal is presented as a primordial element of the structure since it is the source of spin current. However, magnetic materials with large spin-orbit coupling, like GdFeCo ferrimagnetic alloys, can be a source of spin currents as well. A distinction can be drawn between the SAHE-like spin current [3,4] with the Spin Anomalous Hall Effect symmetry and the SHE-like spin current [5] with the Spin Hall Effect symmetry. In the SAHE symmetry, the spin current Js emitted from the magnetic material has the spin polarization aligned with the magnetization while in the SHE symmetry the spin polarization is perpendicular to Js and the injected charge current Jc [3-6]. Only the SHE-like symmetry emission could produce damping-like *self-torque*.

In this talk, we present the study of the *self-torque* performed by means of harmonic Hall voltage measurements in bi- or tri- layers where the GdFeCo layer displays out-of-plane magnetization. We first focus on the temperature dependance of the effective fields associated to the *self-torque.* We show that the effective fields are magnified near the magnetic compensation temperature T_M and reverse sign across it (see Fig). In a second part, we compare the *self-torque* in GdFeCo/Cu with torques induced by an additional heavy metal in GdFeCo/Cu/Pt and GdFeCo/Cu/Ta structures. We show that the addition of a spin-sink can improve the damping-like *self-torque*. Thus, in our work [6], we estimate the global efficiency of GdFeCo spin emission as $\theta_{SAHE+SHE} = 0.78$. Moreover, the SHE-like spin emission results $\theta_{SHE} = 0.16$. The latter is of the same order of magnitude as heavy metals efficiencies [1]. Our results pave the way to exploit spin-orbit torque generated in single magnetic layer, which we coined *self-torque*.

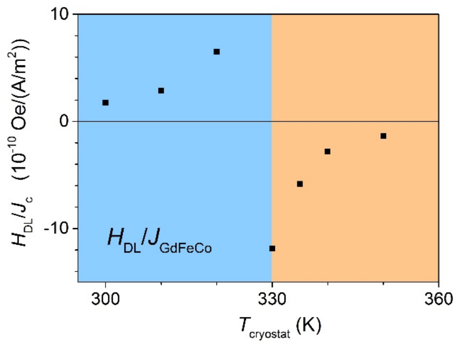

Fig: Temperature dependance of the damping-like efficiency in $Gd_{27}Fe_{50.9}Co_{10.2}$(10nm)/Cu(2nm)/AlOx(2.5nm). The magnetization compensation temperature T_M = 330°K is depicted by the background change of color. The DL effective field changes sign when crossing T_M.

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[3] T. Taniguchi et al., Phys. Rev. Appl. 3, 044001 (2015).
[4] S. Iihama et al., Nat. Elecron. 1, 120 (2018).
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[6] David Céspedes-Berrocal, H. Damas et al. Adv. Materials (2021). https://doi.org/10.1002/adma.202007047 ArXiv: 2010.09137

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TOHOKU UNIVERSITY

Optical spin torque in ferromagnet/heavy metal thin films

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An efficient electrical switching of thin film metallic nanomagnets has been demonstrated by using spin-orbit torques in ferromagnet/heavy metal heterostructures. The spin-Hall effect in the heavy metal layer and the Rashba-Edelstein effect at the interface have been widely studied. Light-induced switching of nanomagnets is expected to be utilized for fast and low-power consumption opto-spintronic memory device, in which nanomagnets are integrated with photonic circuits [1,2]. A strong coupling between electron spin and light polarization/helicity is crucial for such applications. Recently, optical-helicity induced magnetization precession, which we term *optical spin torque*, in ferromagnet/heavy metal heterostructures were reported [3,4]. Figure 1 shows magnetization precession induced by the optical spin torque in a 2-nm-thick FeCo/3-nm-thick Pt heterostructure. The optical spin torque vector in the heterostructure was analyzed in detail. We found that the optical spin torque was induced not only by non-equilibrium spin generated in the bulk Pt layer via the optical orientation effect but also by the optical Rashba-Edelstein effect at the interface of the heterostructure. In this talk, details of the experimental results and the mechanism of the optical spin torque induced by the optical Rashba-Edelstein effect will be discussed.

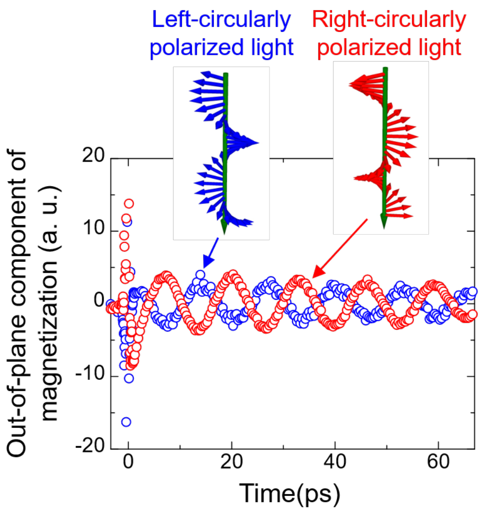

Figure 1 Circularly polarized laser pulse induced magnetization precession observed in a 2-nm-thick FeCo/3-nm-thick Pt film.

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[2] H. Becker et al., IEEE J. Sel. Top. Quant. **26**, 8300408 (2020)
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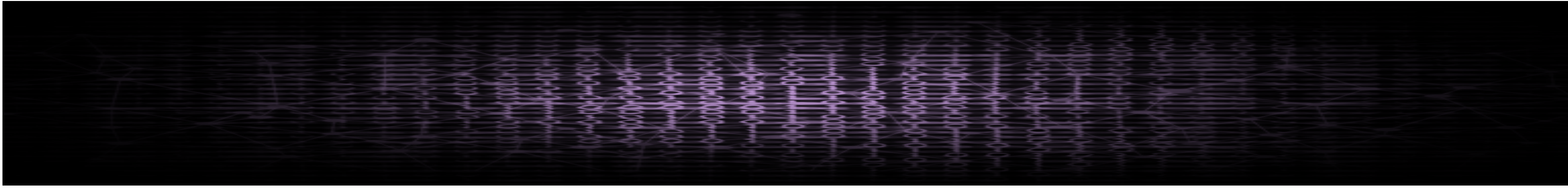

Artificial spin systems: potential device for random number generation

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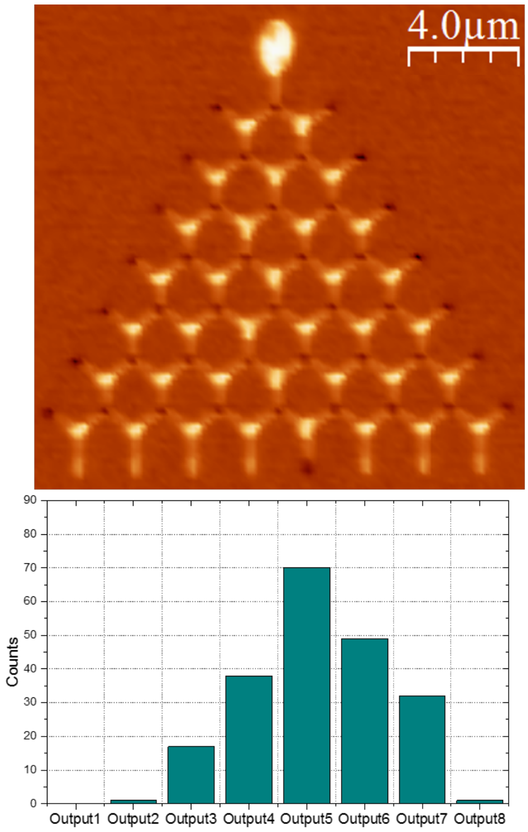
A wide range of devices based on domain wall (DW) propagation has been proposed and investigated. Magnetic storage is obviously the key application either in the form of single bit or multi-level devices or in "racetrack" devices. But other applications are also targeted like magnetic logic devices, multiturn position sensors, memresistors... Reproducible and controllable domain wall propagation is therefore a challenge for most of the evocated devices that require a precise control of the DW propagation. On the other hand, other devices might benefit from random or pseudo-random propagation for random number generation[1], cryptography or neuromorphic structures. This aspect will be investigated in this presentation with the demonstration of the magnetic analog to the Galton board (also called bean machine or quincunx). We have developed an artificial spin system arranged in honeycomb lattice optimised to observe one-dimensional propagation of a DW[2] injected by an elliptic pad. We will show the characteristic features of the DW propagations (reversals, propagation scenario, pinning) along with its intrinsic stochasticity. Our artificial spin system can be compared to macroscopic Galton board in terms of individual weights and output distribution consistent with a binomial distribution. We will also show that there is only negligible correlation between successive choices at the intersections emphasising its analogy to the Galton board.



MFM image of our 8-output nanoscale magnetic Galton board with a DW propagation from the pad to output 5 and output distribution oif the field protocol is performed 197 times (all experiments taken into account are unidimensional DW propagations).

[1] K. Zeissler *et al.*, Sci Rep 3, (2013). [2] E. Mengotti *et al.*, Nature Phys- ics 7, 68 (2011).

Helical spin wave under persistent spin helix state

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In a semiconductor heterostructure, collective exciation of spin texture usually decay rather fast due to D'yakonov-Perel' spin relaxation. However, when two kinds of spin-orbit (SO) induced magnetic fields are equal to each other, namely Rashba and Dresselhaus SO interactions, spin relxation is completely suppressed due to spin SU(2) symmetry. In addition, the persisntent rotation of spatially developed spins generates a helical spin wave. This electron spin wave holds long spin lifetime as well as spin precessional motion, being an ideal platform to manipulate and transfer spin information in semiconductors. In this talk, I will show the theoretical prediction of the longest spin lifetime in helical spin waves among all crytal orientations in III-V semiconductor heterostructures [1,2]. While the persistent spin helix state has been demonstrated in a [001]-oriented quantum well [3], an ideal crystal orientation for the heical spin wave is revealed to be a [225] oriention. I will also discuss the origin of suppressed spin relaxation in a [225] quantm well by considering the cubic Dresselhaus contribution to the spin orbit effective magnetic field.

The work has been carried out in collaboration with D. Iizasa, M. Kammemeier, J. Nitta, U. Zülicke and S. Karube. These works have been partly supported by the Grant-in-Aid for Scientific Research (Grants No. 15H02099, No. 15H05854, No. 25220604, and No. 15H05699) by the Japan Society for the Promotion of Science and Cooperative Research Projects of RIEC.

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Transport properties of Co_2MnSi Heusler compounds

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Co-based Heusler compounds are promising candidates for many emerging spintronic applications regarding the potential full spin polarization, ultra-low magnetic damping, and high Curie temperatures [1,2]. In this work, we report on the transport properties of Co_2MnSi Heusler compounds grown by molecular beam epitaxy and patterned into Hall bars by standard UV-photolithography. The formation of the chemically-ordered $L2_1$ phase was verified by in-situ reflection high-energy electron diffraction and transmission electron microscopy (Figure 1, left). Ultralow-magnetic damping coefficients were measured for all the Co_2MnSi thickness series. Negative anisotropy magnetoresistance ratios confirm the half-metallicity of Co_2MnSi. The electron mean free path of Co_2MnSi was determined from the study of electrical resistivity of the films versus thickness. Finally, the evolution of film resistivity with temperature gives us access to the distance between the Fermi energy and the minority-spin conduction band minimum (Figure 1, right), and in combination with spin-resolved photoemission spectroscopy allow us to estimate the Co_2MnSi spin gap between 0.55 - 0.7 eV, in agreement with ab initio calculations [3].

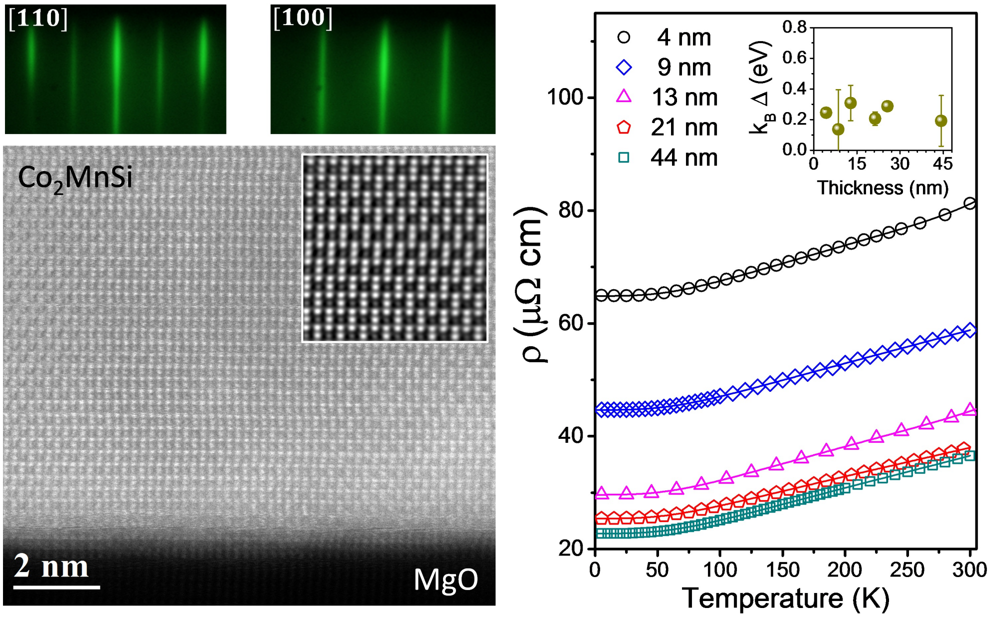

Figure. 1. Reflection high-energy electron diffraction patterns and high-angle annular dark-field scanning transmission electron microscopy micrograph of the Co_2MnSi film (left). Electrical resistivity of Co_2MnSi versus temperature from 300 to 5 K (right). Distance between the Fermi energy and the bottom of the minority spin band versus film thickness (inset).

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A combined study of computational prediction and experimental fabrication of quaternary Heusler alloys CoIrMnZ (Z=Al, Ga, Si, Ge)

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Co-based Heusler alloys are potential candidates in the field of spintronics applications because of their high Curie temperatures and high spin polarization at the Fermi level. In this family, Co_2MnSi/MgO is the heterojunction studied most extensively. However, the lattice mismatch between Co_2MnSi and MgO is about 5% [1]. Ir being an isoelectronic element with Co, CoIrMnSi could effectively reduce the lattice mismatch, maintaining resemblance of electronic structure of Co_2MnSi. As the number of valence electrons plays a crucial role in determining the physical properties, so it is worth investigating CoIrMnZ systems (Z=Al, Ga, Si, Ge) [2].

Based on first-principles calculations we show that these materials have ferromagnetic ground state with Curie temperatures moderately higher than the room temperature. CoIrMnSi and CoIrMnGe are found to have the spin polarized Δ_1 band across the Fermi level. Furthermore, we predict CoIrMnAl as a spin gapless semiconductor (left panel of Fig. 1). In the case CoIrMnZ/MgO (001) heterojunctions, the MnZ-terminated interface is found to be energetically favourable over the CoIr-terminated interface. We show that CoIrMnAl/MgO preserves its half-metallicity even at the interface (right panel of Fig. 1).

Recently, CoIrMnAl thin films have been fabricated by using magnetron sputtering on single crystal MgO (001) substrate. Structural analysis by X-ray diffraction confirms that single-phase B2-ordered epitaxial films were obtained. The saturation magnetization and the Curie temperature are about 70% of the values theoretically obtained for the XA-ordered CoIrMnAl. The difference between the theoretically obtained value and experimental result can be explained by taking the Co-Mn antisite-disorder into account [3].

This work is partially supported by CREST (No. JPMJCR17J5).

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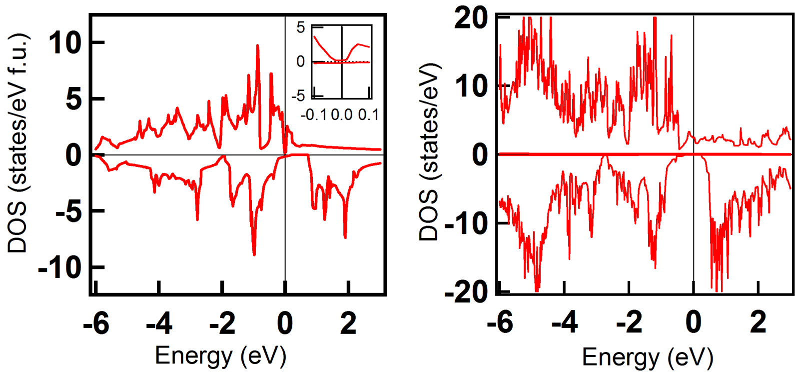

Fig. 1. Left and right panels depict the spin polarized density of states (DOS) of bulk CoIrMnAl and CoIrMnAl/MgO (001) heterojunction with the MnAl termination, respectively. The inset of the left panel shows the DOS in the vicinity of the Fermi level, which is set at 0 eV.

Control of Single Pulse All Optical Magnetization Switching of Ferromagnets

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All Optical Helicity Independent Switching (AO-HIS) of magnetization, using single femtosecond laser pulses, has been demonstrated in GdFeCo ferrimagnetic alloys for various concentrations [1] as well as in other structures with antiferromagnetic coupling, Gd/Co, Tb/Co multilayers and Mn_2Ru_xGa [2,3,4]. Up to now, AO-HIS has never been observed for ferromagnetic layers. However, it was shown that a single pulse magnetization reversal of a ferromagnet could be observed in a spin-valve structure [5]. The switching is then achieved by the ultrashort spin current pulse generated from the ultrafast demagnetization of GdFeCo [5,6].

In this work, we study $Gd_x(FeCo)_{1-x}$/Cu/FM spin-valve structures, where FM can be different ferromagnetic layers [7] and the composition x of the GdFeCo alloy is also changed [8]. By increasing the Gadolinium concentration x, we aim at increasing the spin current injected in the copper layer [6]. We show that this can reduce the laser fluence threshold required to observe the FM magnetization reversal. In particular, no AO-HIS of the GdFeCo layer is required and the threshold fluence for the FM layer is around 1.6 mJ/cm² i.e. comparable to GdFeCo and Gd/Co multilayers [1,2] and smaller than what is achieved for Tb/Co [2] and Mn_2Ru_xGa [3]. We also show that by changing the Curie temperature and the Cu/FM interface, one can control the interaction between the spin current and the FM layer and so the laser fluence threshold. Finally, we change the laser pulse duration and show that this not only changes the laser fluence threshold but also the entire laser fluence range where the single pulse FM switching can be observed without having any multidomain state.

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Spin-orbit torque-induced sub-nanosecond magnetization switching in in-plane magnetic tunnel junctions

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High-speed magnetization switching scheme in magnetic tunnel junction (MTJ) is highly demanded for the progress of magnetoresistive random access memory (MRAM) technology, whose commercialization has been started from the replacement of NOR-Flash memory. Spin-orbit torque (SOT)-induced magnetization switching is a prime candidate for this purpose. In this talk, I will present a material and device engineering [1,2] for the demonstration of SOT-MRAM with 55-nm CMOS circuits fabricated through an industry-compatible 300-mm wafer process [3,4]. Using three-terminal MTJ with in-plane magnetic easy axis and Ta/W channel, field-free switching is achieved down to the pulse width of 0.35 ns. I will also show our latest studies, in which 0.2-ns magnetization switching in MTJ with the same material system is achieved at zero magnetic field by a combinatorial effect of spin-transfer torque and spin-orbit torque [5].

The work has been carried out in collaboration with H. Ohno, C. Zhang, Y. Takeuchi, T. Endoh, T. Hanyu, H. Honjo, M. Natsui, H. Sato, and S. Ikeda. These works have been partly supported by the ImPACT Program of CSTI, JSPS KAKENHI 19H05622, and Cooperative Research Projects of RIEC.

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Large spin Hall effect in a non-equilibrium Iridium-doped Copper binary alloy

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The spin Hall effect (SHE) is one of the phenomena converting a charge current ($\mathbf{J}_c$) into a spin current ($\mathbf{J}_s$). In order to improve the performance of spintronic devices, large conversion efficiency of SHE called spin Hall angle (α_{SH}) is indispensable. Large α_{SH} has been observed in simple nonmagnets with strong spin-orbit interaction such as Pt, Ta, and W. Element doping and alloying are also effective ways to enhance α_{SH}. The Iridium-doped Copper (Cu-Ir) [1-4] is an intriguing material because α_{SH} of ~2.1 % was observed in the Ir concentration range from 1 at.% to 12 at.% [1], in spite of the fact that neither Cu nor Ir exhibits remarkable SHE. Cu-based alloys are also advantageous from the perspective of practical applications because of its compatibility to the standard integrated circuit interconnection technology. However, the comprehensive study on SHE in Cu-based binary alloys in a wide range of concentration is very limited.

In this study, the SHE in a non-equilibrium Cu-Ir binary alloy was investigated by exploiting a combinatorial technique based on the thermal imaging for a composition-spread film [5]. The composition-spread Cu-Ir film was fabricated on the yttrium-iron garnet (YIG) substrate at room temperature using magnetron sputtering. Repeating the process of deposition of wedge-shaped Cu, rotation of substrate by 180 degree, and deposition of wedge-shaped Ir led to the Cu-Ir film of which the composition is varied along the film position. The spin Peltier effect (SPE), which is the phenomenon of heat current generation in a linear response to $\mathbf{J}_s$ injection, was utilized as a probe of the spin-charge current conversion. The spatial distribution of the temperature modulation due to the SPE (ΔT^{SPE}) in the composition-spread film was visualized using the active infrared emission microscopy called the lock-in thermography. From the thermal images, we have found that the optimum Ir concentration for enhancing SHE of Cu-Ir is around 25 at.%, which corresponds to the region beyond the solubility limit and is not thermodynamically stable in the bulk phase diagram. We also evaluated α_{SH} of the $Cu_{76}Ir_{24}$ alloy using a $Cu_{76}Ir_{24}$/CoFeB bilayer. We obtained $\alpha_{SH} = 6.29 \pm 0.19$ % using the harmonic Hall voltage measurements. This remarkable α_{SH} suggests that the non-equilibrium Cu-Ir alloy is a candidate of spin Hall material [6]. Furthermore, the temperature dependence of spin Hall conductance revealed that the mechanism of SHE in $Cu_{76}Ir_{24}$ is the side jump or the Berry curvature-induced intrinsic process.

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Disentangling the anomalous Nernst and spin Seebeck effect in epitaxial Graphene/Cobalt heterostructures

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Conversion between spin and charge currents is essential in spintronics, since it enables a handful of potentially transformative phenomena such as modifying the magnetization of ultra-thin films by means of spin-orbit torque or generating energy by spin-current-driven thermoelectric generation [1,2]. The inclusion of graphene in spintronics has allowed to unravel new arising spin-orbit effects unique of graphene/metal interfaces [3–5]. However, the thermal magnetotransport properties in Gr-based structures with perpendicular magnetic anisotropy have not been investigated at all.
We have studied the thermal magnetotransport in Pt(Ta)/Gr/Co/Ir and Pt(Ta)/ Co/Ir asymmetric epitaxial heterostructures on Al2O3(0001) single crystal substrates produced by means of a combination of DC sputtering, MBE and CVD techniques (see [3]). By applying a thermal gradient in the out of plane direction a transversal voltage can be observed. This voltage is a combination of several effects arising from the magnetic (anomalous Nernst effect) and spin-orbit (Spin Seebeck effect) properties of the materials and interfaces involved. We have disentangled the origin of these components and observed that the inclusion of a graphene monolayer in the interface between cobalt and a metal can induce a significant interfacial contribution to the observed voltage, reducing the thermo-spin voltage for two different metals on top with different spin Hall angle: Pt and Ta.
In addition there are ongoing measurements in this system using spin pumping and spin-torque ferromagnetic resonance in order to clarify the origin of the observed reduction in the inverse spin Hall effect excited by incoherent thermal excitation.

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Shape-anisotropy magnetic tunnel junctions with multilayered ferromagnets

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The development of STT-MRAM—non-volatile spintronics memory—helps overcome the increasing power consumption in semiconductor device scaling. Crucial to integrating STT-MRAM in advanced integrated circuits is scaling magnetic tunnel junction (MTJ)—a core component of STT-MRAM—while improving its performance in data retention and write operation. Shape-anisotropy MTJ has shown MTJ scaling down to single-digit nanometers while achieving sufficiently high thermal-stability factor [1-3]. In the shape-anisotropy MTJ, thermal stability is enhanced by making the ferromagnetic layer thick. Once the thickness goes beyond a certain point, however, device reliability becomes degraded.

To address the issue in the conventional shape-anisotropy MTJ with a single ferromagnetic structure, we employ a new structure that uses magnetostatically coupled multilayered ferromagnets. The developed MTJs are successfully scaled down to 2.3 nm in diameter—the world's smallest MTJ size. We also achieve high data retention properties up to 200°C and high-speed and low-voltage write operation down to 10 ns below 1 V at a single-digit-nanometer scale [4].

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Magnetization control and all-optical switching mediated by phase transition of VO_2

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Exploring a new method to regulate the magnetization of a ferromagnet has always been the focus of spintronics development. Magnetic switching by femtosecond laser pulse is one of the promising approaches to achieve ultrafast magnetic manipulation. In addition, finding a material, whose electronic properties can be controlled, will assist the magnetization regulation more efficiently. VO_2, a kind of phase transition material, could be a good candidate for this goal. First, with atomically thin VO_2 being the spacer, we realize a reversible switching of interlayer exchange coupling, from antiferromagnetic coupling to ferromagnetic coupling, induced by the metal-insulator transition(MIT) of VO_2. We attribute such an evolution originates from two distinct coupling mechanisms of spin-dependent tunneling and Rudermann-Kittel-Kasuya- Yosida interaction determined by the electronic states of VO_2. Lately, combining with the all-optical switching, we are making efforts to search a method for ultrafast magnetic control affected by MIT, for instance, the influence of MIT on the transport of polarized hot electron. More recently, we have found that the single-pulse switching of a ferromagnet can be mediated by MIT of VO_2. The effect of VO_2-tailored magnetic manipulation highlights the great potential of controllable spinterface as a magic building block in beyond-CMOS electronic devices.

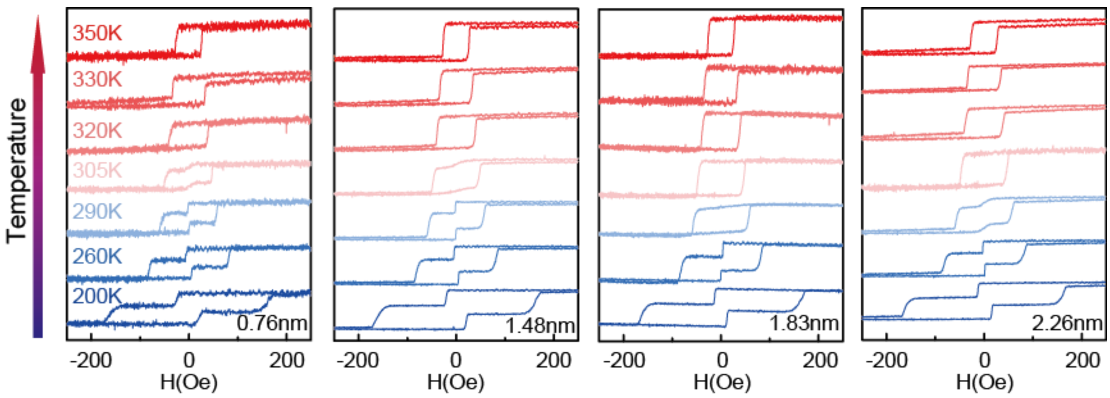

Figure. Interlayer exchange coupling regulation of [Pt/Co(1 nm)]$_2$/VO_2(t nm)/[Co(0.45 nm)/Pt]$_2$ induced by phase transition of VO_2. With temperature rises, the interlayer exchange coupling switches from antiferromagnetic coupling (AFM) to ferromagnetic coupling (FM).

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Valley dynamics of charged exciton in monolayer WS_2 treated by organic acid

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Two-dimensional atomic layer materials have attracted much attention because of both valley and spin degrees of freedom for information carriers. Monolayer transition metal dichalcogenide (TMD) exhibits a direct band gap at K and K' valleys, showing strong optical absorption and exciton / trion formation. In addition, because of crystal inversion symmetry breaking, Zeeman-type spin splitting is induced in conduction and valence band extrema at K and K' points. Recently, it has been reported that charged exciton (trion) has longer lifetime of valley polarization more than that of exciton in monolayer TMD [1]. However, details of relaxation process of trion have not been identified. In addition to that, recent study reveals the stabilization of trion in addition to the exciton with the surface treatment by organic acid (OA) [2,3]. In this presentation, we investigated the valley relaxation process of trion in OA-treated monolayer WS_2 by the circularly polarized photoluminescence (PL), time-resolved Kerr rotation measurement (TRKR) and simulation based on rate equation. TRKR exhibited tri-exponential decay and those time constants could be identified with PL and simulated decay mechanisms.

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All optical helicity-independent switching in GdTbCo alloys

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All optical switching (AOS) of magnetization has been demonstrated experimentally in GdFeCo using a femtosecond laser pulse without the aid of magnetic field[1]. So far, helicity-independent AOS (HI-AOS) is mostly observed in Gd based materials. In order to clarify the essential role of Gd, we deposited the $Gd_{100-R-x}Tb_xCo_R$ alloys with R=78, 80, 84 to study HI-AOS using time-resolved magneto-optical kerr effect (TRMOKE).

Fig.1(a) shows the laser fluence dependent magnetization evolution as a function of time for $Gd_{14.5}Tb_{5.5}Co_{80}$ with $\tau_{pulse} = 60\ fs$. The magnetization shows partial demagnetization、switching and full demagnetization with the laser fluence increasing from 0.82 to 2.47mJ/cm^2. As shown in Fig. 1(b), by changing the pulse duration and laser fluence, we established the state diagram showing HI-AOS or full demagnetization for various GdTbCo thin films with different compositions of Tb. The laser fluence window allowing for HI-AOS narrows for longer pulse duration and larger concentration of Tb. In order to find out the essential parameter determining the HI-AOS in GdTbCo alloys, we present the atomistic simulations to reproduce the spin dynamics obtained in experiment shown as the solid lines in Fig. 1(a). Within the simulations, element-specific Gilbert damping has to be taken into account to reproduce the state diagram in experiment, suggesting the essential role of Gilbert damping in the understanding of HI-AOS in rare-earth transition metal alloys.

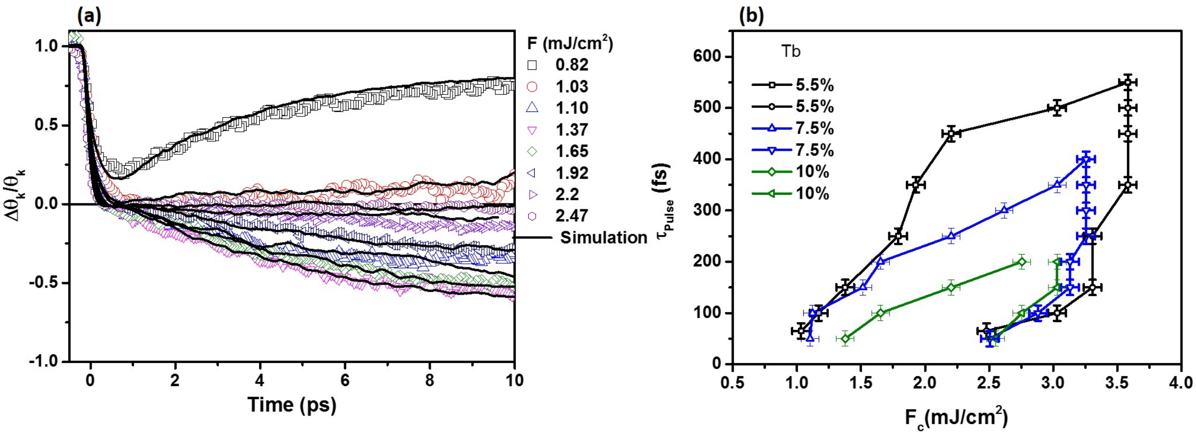

Fig1:(a),laser fluence dependance of the laser induced spin dynamics in Gd14.5Tb5.5Co80. (b), the laser fluence window allowing for HI-AOS in GdTbCo with different composition of Tb as a function of laser pulse duration.

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All-optical probe of magnetization precession frequency shift due to spin-orbit torque

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Spin-orbit torque (SOT) is an attractive technique to manipulate magnetization for magnetic thin films. SOT has been widely studied using the spin-torque-induced ferromagnetic resonance and the second-harmonic-Hall effect measurements, whereas parasitic voltages induced by spin-charge conversion and thermoelectric effect tend to disturb the precise evaluation of SOT in these electrical methods [1, 2]. Here we investigate SOT using an all-optical time-resolved measurement which is free from such parasitic effects. There were a few studies investigating the SOT effect on the decay time of magnetization precession driven by the laser pulse [3, 4]. In this study, we demonstrated the precession frequency can be modulated by SOT as well.

The films were fabricated by a DC/RF magnetron sputtering and the multilayer stacking was Si/SiO_2/W(5)/CoFeB(2.4)/MgO(1.3)/Ta(1) (thickness in nm) [5]. The film was patterned into a rectangular stripe. The magnetization dynamics was investigated by the all-optical time-resolved magneto-optical Kerr effect (AO-TRMOKE) microscope, in which an external field H_{ext} was applied at an out-of-plane angle θ_{H} and a direct current I was applied parallel to y-axis [Fig. 1(a)]. Figure 1(b) shows typical normalized MOKE signals measured with $I = 0, \pm 5$ mA. The modulation of the precession frequency was clearly observed. This can be understood by the change in the equilibrium magnetization angle θ induced by SOT, and the SOT generation efficiency was evaluated as -0.35 [6]. This work was supported by KAKENHI(19K15430, 19H05622) and the ImPACT Program.

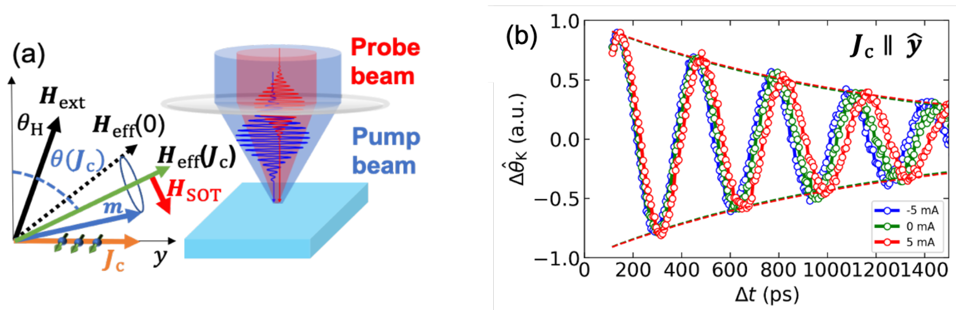

Fig. 1(a) Schematic illustration of the experimental setup of AO-TRMOKE. (b) Normalized MOKE signals $\Delta\hat{\theta}_K$ as a function of the pump-probe delay time Δt with $I = 0, \pm 5$ mA(I // y).

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Stripe domains in thin magnetic films for spin waves channeling

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The possibility to channel spin waves in domain walls has been first shown by numerical calculations in materials with perpendicular to film plane magnetization in 2009 [1]. This concept is particularly interesting since domain walls can reach lateral sizes of several nanometers (so with ultra-high integration capabilities) and are reprogrammable (the channel can be erased and rewritten through an appropriate magnetic field history). The aim this work is the development of new spin-waves guides and devices based on the use of magnetic domain walls to channel spin waves. To achieve a first experimental demonstration in perpendicular to film plane magnetized films materials with low magnetic damping and control magnetic textures have to be synthetized.

I will present in detail the domain structures in two magnetic systems, high (111) textured [Co/Ni] Multilayers of thicknesses varying from 10 nm to 200 nm and amorphous CoFeB with thicknesses varying from 100 nm to 270 nm. The domain sizes and domain shapes have been studied as a function of thickness, magnetic history and annealing temperature. In [Co/Ni], a quality factor around 1 and a damping parameter of 1.5x10-2 could be measured. We observed by magnetic force microscopy (MFM) that the stabilization of straight stripe patterns is more difficult to obtain in comparison to epitaxial Co layers [2]. In the sample with the optimum thickness of 50nm, straight stripe patterns could be stabilized. Amorphous CoFeB shows weak stripes domains and a damping parameter of 7x10-3 could be measured. From the domain pattern and damping point of view, this material appears to be the most promising for spin wave channeling.

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Anisotropic spin relaxation and precession frequency depending on in-plane magnetic field orientation in GaAs-based wire structures

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In III-V semiconductor heterostructures, there exist Rashba and Dresselhaus spin-orbit (SO) interactions, which yield effective magnetic fields for moving electrons. The induced SO field depends on the electron momentum that is randomized by scattering, resulting in D'yakonov-Perel spin relaxation. In order to enhance the spin relaxation time, quantum wire structures are attracted much attention since the geometrical confinement suppresses momentum randomization [1-3]. Application of an external magnetic field to the wire induces spin precession and enhances the spin relaxation time, which depends on the relative angle between the SO field and external magnetic field. Here, we investigated the anisotropic spin dephasing depending on the direction of an external magnetic field in wires based on a 20-nm (001)-oriented GaAs/AlGaAs quantum well (QW). We fabricated 800-nm-width wires parallel to [1-10] (|| x), [110] (|| y), [100] and [010] crystal orientations by electron beam lithography and reactive ion etching. We employed time-resolved Kerr rotation microscopy for measuring the spin dephasing time in the wires. In-plane external magnetic field $\boldsymbol{B}_{\mathbf{ex}}$ was applied with different angles at 30 K. The evaluated spin relaxation time is twice longer when the external magnetic field is perpendicular to the SO field in comparison with the parallel external magnetic field. Contrary, Larmor precession frequency is decreased when the external magnetic field was perpendicular to the SO field. By solving the spin diffusion equation, we obtained the analytical formula to explain such an enhanced spin relaxation time by the lateral confinement of electron momentum.

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Zero applied field current induced switching of GdFeCo

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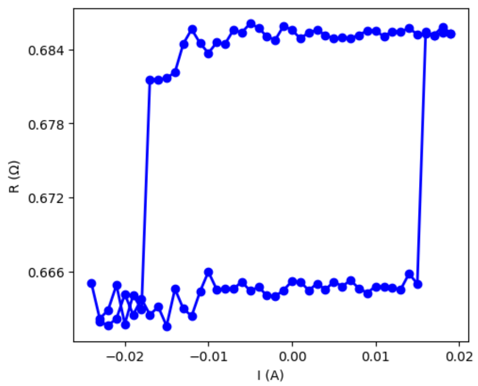
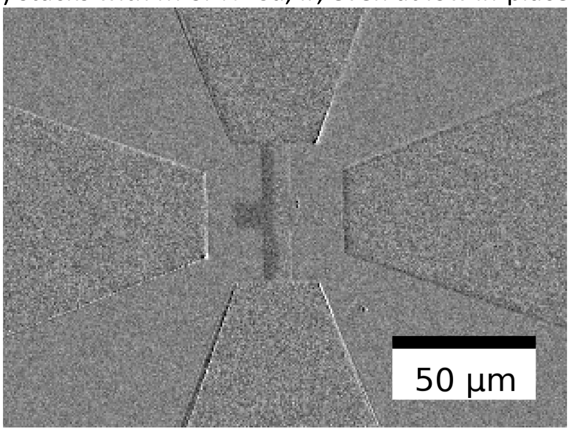
Amorphous rare-earth transition-metal (RE-TM) GdFeCo ferrimagnetic thin films are well-known to exhibit many interesting magnetic properties. Indeed its magnetization can be switched using a magnetic field, but also because of single femtosecond laser pulse [1] or spin orbit torque [2]. Since this material appears to be promising for future spintronics applications, we focused on the combine effect of field, light and current on magnetization reversal.

We observed that GdFeCo could show magnetization reversal by Spin Orbit Torque whithout any applied field (figure 1) . We could then demonstrate that the magnetization switching of $Gd_x(Fe_{90}Co_{10})_{1-x}$ ferrimagnetic alloys single layers was caused by the combined effects of the spin-orbit torque and current-induced Oersted field [3] figure 2. We show switching via spin-orbit torque of low coercive field $M(5nm)/Gd_x(Fe_{90}Co_{10})_{1-x}(5nm)/N(5nm)$ stacks with M or N=Cu, Ir, even at low in-place field.





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