Perspective of spin-orbitronics

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Spins of electrons had been so far manipulated by magnetic field since the magnetic moments of spins is strongly coupled with magnetic field. Spin-orbit interaction (SOI) originated from electric field is a relativistic effect, i.e. electrons feel an effective magnetic field when they move in an electric field. Much attention is now focused on spintronics based on SOI, the so-called *spin-orbitronics*, since generation, manipulation and detection of spins are realized by all electrical means via SOI[1)].

Electrical control over the magnetization direction of small magnets is currently among the most active areas in *spin-orbitronics*, due to its interest for memory, logic and data-storage applications. This magnetization control has been achieved by transferring spin angular momentum working as a torque due to the SOI from heavy metals, antiferromagnets, oxide materials and topological insulators. Now, we call it spin-orbit torque (SOT), which is expected to be an innovative way towards energy-efficient applications such as fast domain wall motion and magnetization switching. The charge-spin conversion efficiency (or spin Hall angle) in these hetero-structures is the most crucial parameter for the SOT performance.

However, a major difficulty is clearly identifying the physical origin of the SOT. The spin Hall effect is believed to play a major role when the adjacent layer to magnet is dirty heavy metal[2)]. An intrinsic (Berry phase-induced) SOT mechanism is proposed if the bulk inversion symmetry is broken in the adjacent layer[3)]. It is also pointed out that the Rashba-Edelstein effect at the interface is not negligible[4)]. It is required to enhance the charge-spin conversion efficiency by clarifying the origins and mechanisms.

When the spin Hall effect was discovered in bulk GaAs[5)], no one could imagine that the spin Hall effect can be utilized for magnetization switching since the spin polarization accumulated at the edge of GaAs was extremely small, moreover, it was performed at low temperature. The tremendous progress in *spin-orbitronics* has been achieved and the concept has been extended to variety of systems in the last decade. In this symposium, I hope we can witness the recent progress of *spin-orbitronics* in different systems and discuss future perspective.

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Spin-charge interconversion in topological surface states

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A surface state of the three dimensional topological insulator (TI) has been expected to realize a highly efficient spin-charge interconversion.[1)] Much effort has been paid for quantitative investigation of spin-charge interconversion phenomena by using various ways such as potentiometric measurements[2, 3)], spin pumping,[4)] spin transfer torque ferromagnetic resonance[5, 6)] and so on. However, reciprocal interconversion between spin current and charge current in the same topological surface state has not been achieved so far. In this study, we investigated reciprocal spin-charge interconversion in topological surface state using a copper (Cu) based lateral spin valve with a TI middle wire.

A SEM image of the fabricated lateral spin valves is shown in Fig. 1(a). The single crystalline topological insulator $Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$ were grown by a Bridgeman method in evacuated quartz tubes. Mechanically exfoliated topological insulator flakes, with the thickness of several tens of nanometers, were put on a thermally oxidized SiO_2 layer formed on a Si substrate. The thickness and position of the topological insulator flakes were measured by a laser microscope. $Ni_{80}Fe_{20}$ (Py) ferromagnetic electrodes were fabricated by lift-off process with electron beam lithography and electron beam evaporation. After cleaning of the Py surface with Ar^+ ion milling, Cu/Titanium (Ti) spin transport channel was fabricated by the lift-off process. 2 nm thick Ti layer was deposited by EB evaporation to realize good connection of the Cu layer with the TI. The Cu layer was deposited by thermal evaporation. Nonlocal magnetoresistances measurements were carried out by using Physical Properties Measurement System (PPMS).

Nonlocal magnetoresistances measured at 10 K of Cu based lateral spin valves with and without TI are shown in Fig. 1(b). Although the same spin injector, detector and Cu/Ti spin channel were employed, magnitude of ΔR_S for W/TI device is obviously smaller than those of the Ref. 1 or Ref. 2. This result indicates that spin current transported to the spin detector was reduced because of the spin absorption of the TI. Reciprocal interconversion between spin current and charge current was also demonstrated. In the presentation, we will discuss a quantitative estimation of efficiency of spin-charge interconversion in the topological surface state.

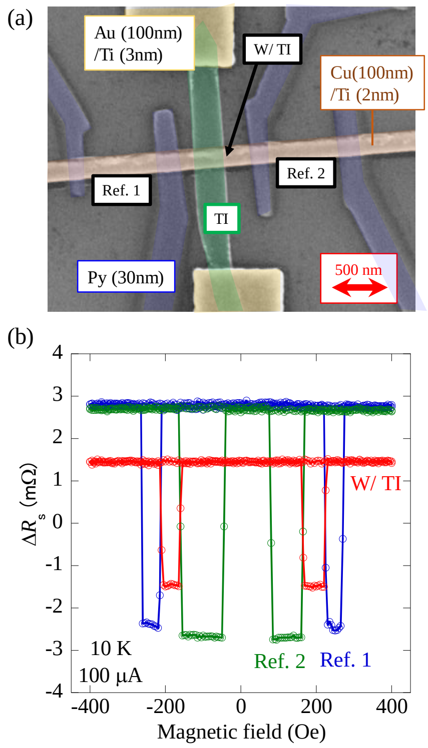

Figure 1 (a) A SEM image of fabricated Cu-based lateral spin valve with TI. (b) Nonlocal magnetoresistance for Ref.1, Ref.2 and W/ TI device at 10 K.

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スピン軌道材料における電流誘起トルク

Current induced torque in spin orbit materials

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スピン軌道相互作用が大きい物質や界面に電流を流すと、スピン流やスピン蓄積が生じることが近年明らかになった。これらの物質と薄い強磁性層を組み合わせたヘテロ構造では、電流印加によって生成されたスピン流、スピン蓄積が強磁性層の磁化にトルクを作用する。従来のスピン分極電流によるスピン移行トルクと識別して、スピン軌道相互作用が関与するトルクを「スピン軌道トルク」と呼ぶことが多い。ヘテロ構造におけるスピン軌道トルクは、三端子磁気ランダムアクセスメモリ（MRAM）などへの利用が期待されている。

本講演では、ヘテロ構造を構成する材料や膜厚、強磁性層内の磁気構造がスピン軌道トルクに及ぼす影響について報告する。スピン軌道相互作用が大きい 5*d* 遷移金属や、Sb, Bi などの *p* 軌道材料などにおけるスピン流、スピン蓄積の生成とその評価、スピン軌道トルクへの寄与に関して議論する。

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Oxide spin-orbitronics

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To date, extensive studies on *oxide* spintronics have been devoted for 3*d* transition-metal oxides mainly due to its unique magnetic properties such as half-metallicity. Here we suggest that 5*d* electron systems are promising class of spintronic materials because of its strong spin-orbit coupling (SOC). This type of spintronics utilizing strong SOC can be called as “spin-orbitronics”; a strong SOC inherent to 5*d* Ir oxides recently emerged as a new paradigm for oxide spin-orbitronics. For example, we investigated novel physics of spin-orbital Mott insulators [1] and possible topological insulators [2] by tuning the electronic phases through superlattice technique. We also demonstrated a large spin Hall effect of IrO_2, one of the simplest 5*d* oxides, indicating that Ir oxides are promising class of spin-orbitronic materials [3].

In this talk, we focus on yet another topic on spin-orbitronics – magnetic skyrmion as a topological spin texture. We have studied transport properties of bilayers consisting of m unit cells of ferromagnetic $SrRuO_3$ and 2 unit cells of $SrIrO_3$. We observed an anomaly in the Hall resistivity in addition to anomalous Hall effect (AHE); this is attributed to topological Hall effect (THE) [4]. The topological term rapidly decreases with m, ending up with a complete disappearance at $m = 7$. These results suggest that magnetic skyrmions of 10–20 nm are generated by Dzyaloshinskii-Moriya interaction, which might be caused by both broken inversion symmetry at the interface and strong SOC of $SrIrO_3$. Even more surprising is that we can control both AHE and THE by electric field in the $SrRuO_3$-$SrIrO_3$ bilayers [5]. We observed the clear electric-field dependence only when $SrIrO_3$ is inserted between $SrRuO_3$ and a gate dielectric. The results established that strong SOC of nonmagnetic materials such as $SrIrO_3$ is essential in electrical tuning of these Hall effects. Considering that AHE and THE are governed by momentum-space and real-space topology, respectively, we may have a chance to approach a triple point for topology, correlation, and spin-orbit coupling through Ir oxides.

We are also searching for spin-current applications in oxide systems beyond the spin Hall effect already shown in Ref. 3. Among them, promising is spin-current-driven thermoelectric conversion through spin Seebeck effect; high conversion efficiency is expected by utilizing and controlling SOC in Ir oxides. We will report on the latest results of spin Seebeck effect at interfaces between magnetic oxides and nonmagnetic Ir oxides.

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Magnetization control and detection of antiferromagnetic NiO

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

Pt 4 nm/ NiO t_{NiO} nm/ Pt 4 nm multilayers were formed by magnetron sputtering. Figure 1 (a) shows the basic principle of the spin torque rotation of the antiferromagnetic moments in a Pt/ NiO/ Pt multilayer structure where the bipartite magnetic moments rotate without a cost to increasing the exchange energy. To experimentally demonstrate, we used the Hall bar structure with the measurement procedure described in Fig. 1 (b). A writing current I_w flowing from the electrode 2 and 3 to the electrodes 1 and 4, as represented by write “1”, rotates the magnetic moments and stabilizes them orthogonal to the direction of I_w. In the same manner, the other current flow of I_w writes “0”. The orientation of the magnetic moments is read, after each write, by the transverse resistance (R_{Hall}). We took advantage of the spin Hall magnetoresistance (SMR) to read out the orientation of the magnetic moments. Figure 1 (c) shows representative results of the sequential write-read operation in Pt/ NiO /Pt as well as Pt/ SiO / Pt with I_w = 38 mA. The operation of write “1” results in a high resistance state and “0” in a low state, which is coherently explained by the spin torque rotation of the magnetic moments and the change of R_{Hall} due to SMR.

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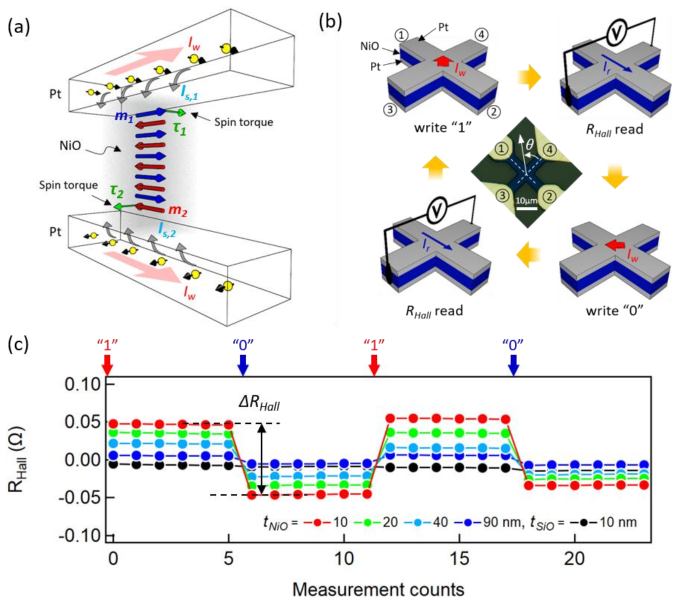

Fig. 1 The spin torque writing scheme and the sequential write-read memory operation.

Analog spin-orbit torque switching for neuromorphic application

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

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