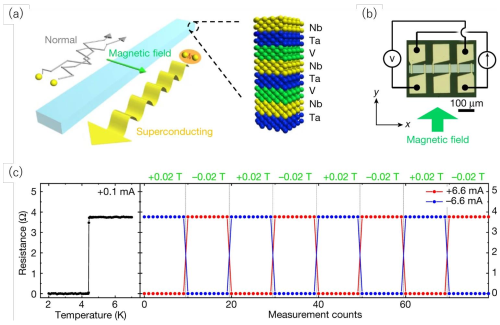
ナノスピントロニクス領域の最近の研究活動・成果

ナノスピントロニクス

Observation of super conducting diode effect

Nonlinear optical and electrical effects associated with a lack of spatial inversion symmetry allow direction-selective propagation and transport of quantum particles, such as photons1 and electrons. The most common example of such nonreciprocal phenomena is a semiconductor diode with a p–n junction, with a low resistance in one direction and a high resistance in the other. Although the diode effect forms the basis of numerous electronic components, such as rectifiers, alternating–direct-current converters and photodetectors, it introduces an inevitable energy loss due to the finite resistance. Therefore, a worthwhile goal is to realize a superconducting diode that has zero resistance in only one direction. Here we demonstrate a magnetically controllable superconducting diode in an artificial superlattice $[Nb/V/Ta]_n$ without a centre of inversion. The nonreciprocal resistance versus current curve at the superconducting-to-normal transition was clearly observed by a direct-current measurement, and the difference of the critical current is considered to be related to the magnetochiral anisotropy caused by breaking of the spatial-inversion and time-reversal symmetries.

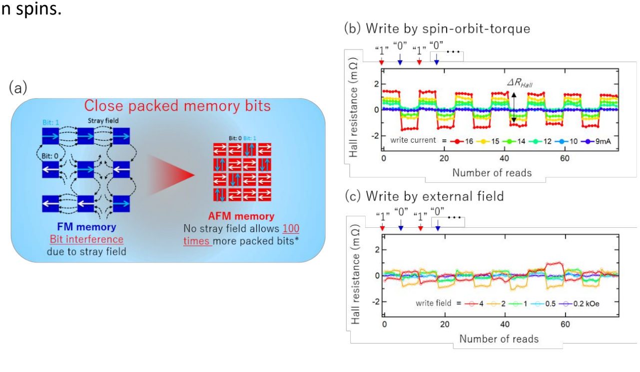


Owing to the nonreciprocal critical current, the $[Nb/V/Ta]_n$ superlattice exhibits zero resistance in only one direction. This superconducting diode effect enables phase-coherent and direction-selective charge transport, paving the way for the construction of non-dissipative electronic circuits.

Figures:(a) Schematic images of the superconducting diode controlled by an external magnetic field and the artificial $[Nb/V/Ta]_n$ superlattice, in which the global inversion symmetry is broken along the direction of stacking. When the directions of the current, the magnetic field and inversion symmetry breaking are orthogonal to one other, the Cooper pairs can flow in only one direction. (b) Photomicrograph of the processed device and the measurement setup with the definitions of electric current and magnetic field. (c) Temperature dependence of the sheet resistance of the $[Nb(1.0\ nm)/V(1.0\ nm)/Ta(1.0\ nm)]_{40}$ film and alternating switching between the superconducting and normal conducting states by changing the sign of the applied current or magnetic field at 4.2 K.

Antiferromagnetic memory that cannot be written by a magnetic field but by a flow of electron spins

Conventional magnetic data storages, such as Hard disk drives (HDDs) and Magnetic random access memory (MRAM), traditionally use ferromagnets to record the information by flipping the macroscopic magnetic moments. However, as shown in Figure (a), a dipole field (or stray field) from the ferromagnets ultimately invokes the bit interference and prevents the information bit from packing closely. Antiferromagnets are another class of magnetic materials which have microscopic magnetic moments but they are coupled in opposite directions. Therefore, antiferromagnets have no net magnetic moment and do not produce any stray field or respond to an external magnetic field. By making use of these properties of antiferromagnets, one could make an extremely dense magnetic memory, which can be an important breakthrough for information storages. In this work, we showed the demonstration of a sequential antiferromagnetic memory operation with a spin-orbit-torque write, by the spin Hall effect, and a resistive read in the CoGd synthetic antiferromagnetic bits, in which we reveal the distinct differences in the spin-orbit-torque- and field-induced switching mechanisms of the antiferromagnetic moment. As shown in Figures (b)(c), the memory states (the Hall resistances) are altered by spin-orbit-torque but are not influenced by the external field. We, therefore, succeeded in demonstrating the antiferromagnetic memory that cannot be written by a magnetic field but by a flow of electron spins.



Figures: (a) Comparison between ferromagnetic bits and antiferromagnetic bits in terms of memory bit density. (b) After each write ("0", "1") by a spin-orbit-torque, the memory states were read by the Hall resistance. (c) After each write ("0", "1") by an external field, the memory states were read by the Hall resistance.

Ultrafast domain wall motion in ferrimagnetic materials

Antiferromagnetic spintronics is an emerging research field which aims to utilize antiferromagnets as core elements in spintronic devices. A central motivation towards this direction is that antiferromagnetic spin dynamics is expected to be much faster than its ferromagnetic counterpart. Recent theories indeed predicted faster dynamics of antiferromagnetic domain walls (DWs) than ferromagnetic DWs. However, experimental investigations of antiferromagnetic spin dynamics have remained unexplored, mainly because of the magnetic field immunity of antiferromagnets. Here we show that fast field-driven antiferromagnetic spin dynamics is realized in ferrimagnets at the angular momentum compensation point T_A.

Using rare earth–3d-transition metal ferrimagnetic compounds where net magnetic moment is nonzero at T_A, the field-driven DW mobility is remarkably enhanced up to $20\ \mathrm{km\ s^{-1}\ T^{-1}}$. The collective coordinate approach generalized for ferrimagnets and atomistic spin model simulations show that this remarkable enhancement is a consequence of antiferromagnetic spin dynamics at T_A. Our finding allows us to investigate the physics of antiferromagnetic spin dynamics and highlights the importance of tuning of the angular momentum compensation point of ferrimagnets, which could be a key towards ferrimagnetic spintronics.

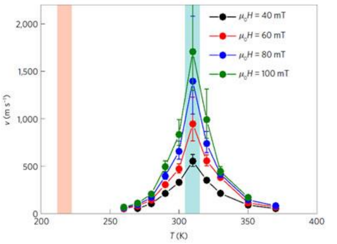
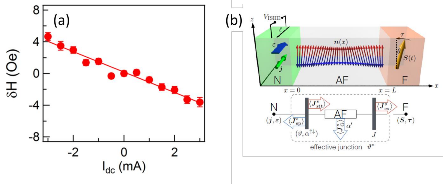


Figure: DW speed v as a function of temperature T for several driving fields. v diverges at T_A.

Anti-damping spin transfer toque though antiferromagnetic material

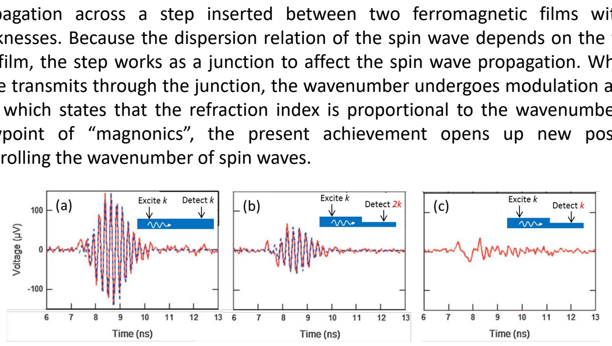
Spin transfer torque (STT) has been an efficient and promising technique to control magnetizations of ferromagnetic materials in modern spintronic devices. This novel technique is based on an interaction between electron spin and local magnetic moments. The same interaction should be conserved in antiferromagnets (AFMs), in which there are microscopic local magnetic moments that compensate each other to exhibit no net magnetization. In this work, we prepared MgO(001) substrate/Pt 5nm/NiO 10nm/FeNi 3nm/SiO2 5nm multilayers, in which the films are epitaxially grown until the NiO layer, and performed a spin torque ferromagnetic resonance (ST-FMR) measurement to quantify the anti-damping spin torque transported between the Pt and the FeNi through the antiferromagnetic NiO layer. A pure spin current is created by the spin Hall effect of the Pt and injected into the NiO. As shown in Fig (a), it is found that the FMR linewidth monotonously varies with the spin current injection. As the ST-FMR measurement is only sensitive to the linewidth (i.e. magnetic damping) of the FeNi layer, this change in the linewidth in Pt/NiO/FeNi can be interpreted in a way that the spin current is transferred through the NiO and interacts with the FeNi. This intriguing spin current transport can be explained by the angular momentum transfer mediated by the antiferromagnetic magnons as shown in Fig. (b). Our results assure that the spin current exerts a spin torque on the NiO magnetic moments and excites their dynamics. The results open up a new field of "antiferromagnetic" spintronics.



Figures: (a) FMR linewidth δH as a function of the dc current. Due to the spin Hall effect of Pt, the spin current injection is proportional to the dc current. (b) Schematic illustration of the N (Pt)/AF (NiO)/F (FeNi) structure in which the anti-damping spin transfer torque takes place. N (Pt) layer injects the spin current J^s_{stt} toward AF (NiO). The antiferromagnetic magnon in AF (NiO) carries the spin current J^s_{ex} toward F (FeNi).

Observation of Snell's law for spin waves in thin ferromagnetic films

Magnon, a quasiparticle of the spin wave, can potentially be used for information processing and storage technology. We report the real-time observation of spin-wave propagation across a step inserted between two ferromagnetic films with different thicknesses. Because the dispersion relation of the spin wave depends on the thickness of the film, the step works as a junction to affect the spin wave propagation. When the spin wave transmits through the junction, the wavenumber undergoes modulation as per Snell's law, which states that the refraction index is proportional to the wavenumber. From the viewpoint of "magnonics", the present achievement opens up new possibilities of controlling the wavenumber of spin waves.



Figures: Time-domain wave packet transmission measurements for (a) film with no thickness difference (b) and (c) film with a thickness step at which the film thickness becomes a half. One can see the wavevector k is doubled when the wave is transmitted through the step.