Control of magnetic skyrmion: Theoretical design of skyrmion device

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The key to develop the magnetic memory devices is nothing more than the control technique of the magnetic texture by external fields. The recent studies reveal that skyrmion,[1)] the nano-sized magnetic texture, is driven by a much smaller electric current density than that for the magnetic domain wall motion, and hence, the potential application of the skyrmion has attracted much attention. To utilize the skyrmion for device applications, the control technique for creation (write), annihilation (erase) and motion (transport) must be established. We theoretically study the creation, annihilation and current-driven motion of skyrmion in the chiral and dipolar magnets in two dimensions, by numerically solving Landau-Lifshitz-Gilbert equation. By the numerical study, we explore the optimal condition to control the skyrmion in the ferromagnetic background.[2)]

Figure 1 shows the schematic figure of the magnetic skyrmion in the thin-film system. In Fig.1 (a), the vortex like structure is in the ferromagnetic background and the magnetic moments wind perpendicular to the radial direction of the circular magnetic texture. This is the Bloch skyrmion and is often observed in the chiral magnets. In Fig.1 (b), on the other hand, the winding plane includes the radial direction. This is the Néel skyrmion and is often found in the artificially composed super-lattice magnet. The Bloch and the Néel skyrmions are in the same topological class: The topology of the skyrmion is characterized by the skyrmion number which is defined by the wrapping number of a sphere by the magnetic moments. The skyrmion number of the perfect ferromagnetic state is zero but it is -1 for the skyrmion in the ferromagnetic background. Because of the difference in topology, the skyrmion cannot be reached from the perfect ferromagnetic state within the continuous deformation of the magnetic texture. As a result, the skyrmion carries a (meta-) stability and is protected by a potential barrier. To overcome this barrier, a large energy enough to destroy the magnetic ordering is needed. However, the spatial discontinuity gives a favorable environment to change the topology of magnetic texture and the stability is reduced. For example, the skyrmion is created rather easily at the edge of a magnet in comparison to the deep inside of the system. Also the local heating provides the hot spot where the skyrmions are nucleated.

The topology of the skyrmion is of crucial importance for the current driven motion: Because of the vorticity of the swirling magnetic texture, a Magnus effect occurs along with the motion of the skyrmion. By utilizing this effect, the large spin-transfer-torque effect appears and moving velocity of the skyrmion is enhanced compared to the domain wall motion.

We show the numerical results of the real-time dynamics of the magnetic textures induced by external stimuli and discuss the creation, annihilation and current-driven motion of skyrmion(s) for the theoretical design of the skyrmion memory devices.

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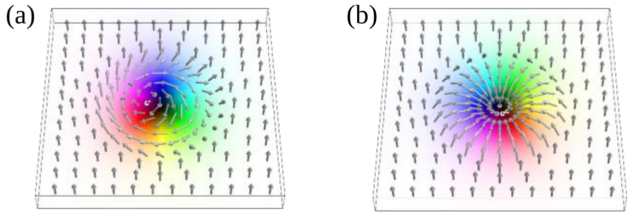

Fig. 1 Shematic figure of the magnetic skyrmion.
(a) Bloch skyrmion. (b) Néel skyrmion. (see text)

Elucidation and application of current-induced domain wall motion

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Current-induced magentic domain wall motion has been attracted much attention both from scientific and technological points of view[1). When a magnetic DW is driven by electric current via adiabatic spin torque, theory predicts a finite threshold current even for a perfect wire without any extrinsic pinning[2). We have shown that this intrinsic pinning determines the threshold current, and thus that the adiabatic spin torque dominates the DW motion resulting in DW motion along electron flow direction, in a perpendicularly magnetized Co/Ni system sandwiched by a symmetric capping and seed layers[3-7). On the other hand, current-induced DW motion against electron flow direction has been observed in ultrathin magnetic films in which the structural inversion symmetry (SIA) was broken[8, 9). Recently, this DW motion against electron flow direction has been explained by the combination of a chiral DW stabilized by Dzyaloshinskii–Moriya interaction (DMI) and spin Hall torque[10-12). Effect of DMI on the field-induced DW motion is also discussed[13).

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Dzyaloshinskii-Moriya interaction at metallic bilayer interfaces

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In ferromagnetic and heavy metal interfaces, the Dzyaloshinskii-Moriya interaction (DMI), which arises from an asymmetric interface stacking and the strong SOC, plays a key role that may give rise to particular magnetic textures. More specifically, the DMI is essential to stabilize the domain walls in a Néel configuration with a given chirality. Recent measurements and theory for the interfacial DMI have opened new possibilities to obtain understanding on the origin of the DMI and its relation with the details of the electronic and atomic structures of materials.

Here, we present the systematic investigation on the interfacial DMI between 3d transition-metals (TM=Co, Fe) thin films and heavy-metals (X=Ta, W, Re, Os, Ir, P) from first principles.[1)] Calculations were performed within the generalized gradient approximation using the full-potential linearized augmented plane-wave method in a slab geometry, where the spin-spiral structures of a wave vector, *q*, without the spin-orbit coupling (SOC) were first treated in the generalized Bloch theorem and then the SOC was introduced by the second variational method, in which large unit cells (supercells) with lattice constants corresponding to wavelengths of commensurate spin-spiral structures were employed. The 2400 special k-points (in the chemical BZ) were used to reduce the numerical errors. The DMI parameters were estimated from the total energy with respect to the spin-spiral wavevectors.

The results predict that the DMI parameters depend significantly on the species of both the 3d and heavy metals; typical examples are shown in Fig.1, where the DMI parameter in the Co/Pt has a positive value while that in the Co/Ir has a negative one. We confirmed that for both interfaces, when the Co thickness increases the DMI parameters roughly converge to constant values although the absolute values decrease, and thus the signs of the DMI parameters do not alter with the increase of layer thickness. The results of the Co/Pt agree with experiments and suggest that the DMI originates mainly at the interfaces. We have further checked the interfacial structural dependence by comparing the obtained DMI parameters for both fcc and hcp stackings at the TM/X interfaces, and find that the DMI parameters depend on the stacking structures but the sign does not change. Our results further show that the DMI parameters are related to the orbital magnetic moments of the heavy metal elements. In the talk, we will present/discuss systematically the details of the DMI at the 3d and heavy-metal interfaces.

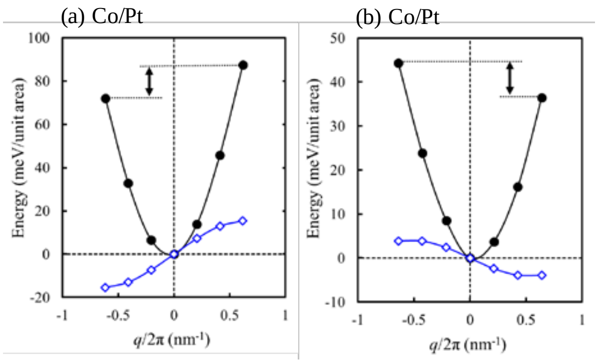

Fig.1. Formation energies of spin-spiral structures, E_{spiral}, as a function of wave number, *q*, for (a) Co/Pt and (b) Co/Ir interfaces. Open diamonds indicate the difference in the E_{spiral} between *q* states, where the gradient corresponds to the DMI parameter.

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Co/Ni-nanowire based magnetic shift registers

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World-wide expansion of ICT infrastructures has demanded the rapid development of the markets for information storage devices. Especially, the CAGR of 40% is expected in next 5-years for the solid-solid data-storage devices which are used in various applications from smart-phones to servers in data-centers. To cover such a huge demand in the next decade however, it is needed to create novel technologies which can realize the nonvolatile memory chip having much larger bit-area-density than that of the state-of-art NAND-flash memory with the fabrication cost as same as that of the current technology.

We are interested in magnetic shift register (MSR), so called “race-track memory”,[1] as one of the candidates for the Tera-bit class nonvolatile memory fitting to the data-storage. We believe that the concept of the MSR, in which the magnetic nanowires acts as shift-register without gating elements and wires to identify spatial positions of stored data, has unique and great advantage for the purpose. The simple structure of MSR as a memory cell storing multi-bits will allow us to fabricate the memory chip with ultra-high bit-densities through the processes with acceptable costs.

From this point of view, we have been carrying out researches related to MSR which are from studies of current-induced domain wall motion (CIDWM) in nanowires to the examination of chemical vapor deposition of magnetic thin-layers as the magnetic device fabrication technique.[2-5] In this presentation we are going to show our recent experimental results on Co/Ni-nanowire based MSR’s.

The MSR’s shown in this presentation were fabricated from Co/Ni-multilayer-based stack structures prepared by using a magnetron sputtering system. We have been focusing the studies using the MSR’s on DW-position control and multi-bit read out operations. The position control of DW’s has realized by utilizing periodic width modulation for Co/Ni-nanowires.[2] The experimental results reveal that the combination of built-in potential energy valley and current-pulse-DW-driving effectively compensates DW-position fluctuation induced by CIDWM. We have also demonstrated the multi-bit read out operation utilizing a magnetic tunnel junction (MTJ) integrated on the nanowire.[3] Thanks to the Co/Pt-based synthetic antiferromagnetic structure for the reference layer of MTJ, no magnetic field was needed to achieve the data readout from the MTJ-integrated MSR.

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The numerical analysis of standing spin wave configurations controlled with a domain wall in nanowires

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1. Introduction

Spin dynamics in nanostructured magnetic system have attracting intense research interests from view point of fundamental physics and practical applications. The geometrically confined standing spin wave resonance (SSWR) is one of the most power efficient excitation modes. Various kinds of SSWR modes have been observed in wires [1], squares [2] and rectangular dots [3], made of in-plane magnetization films. In the present study, the SSWR properties of nanowires with perpendicular anisotropy have been numerically investigated. Especially, the effect of the domain wall (DW) on the SSWR is focused, aiming at the application to a novel memory and logic applications.

2. Numerical model

Fig. 1 (a) presents a designed device structure, consists of a nanowire and inductively coupled conductors for the SWs generators (GE1, GE2) and detector (DE). Material parameters of large perpendicular and low damping ferromagnets, such as MnGa, MnAl, were assumed in the micromagnetic simulations: M_s = 1000 emu/cm^3, H_k = 13 kOe, α = 0.01. Pulsed microwave currents with phase lag $\Delta\phi = \pi$ and the duration of 930 ps (37.2 ps (=1/(26.9 GHz)) × 25 periods) were assumed to be applied through GE1 and GE2, which excite the 2nd mode SSW along the nanowire. The inductive output waveform when the DW located at the nanowire center is shown as Fig. 1(b).

3. Results and discussions

The maximum amplitude Vout computed for various locations of the DW (x_{DW}) is shown in Fig. 2(a). The significant dependence of the Vout reflects the modification of the SSW configuration due to the DW location, as shown in Fig. 2(b), (c). The DW located under the GE locally suppresses the magnetization precession, reflecting lower Vout, while the influence from the DW located at the nanowire center (node of the SSW) is subtle, reflecting higher Vout. The obtained numerical results demonstrate feasibility of the domain wall location as a state variable of nanowires.

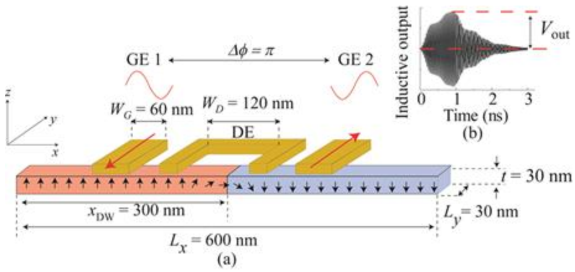

Fig. 1. Schematic of a designed nanowire with DW (a) and the V_{out} waveform (b).

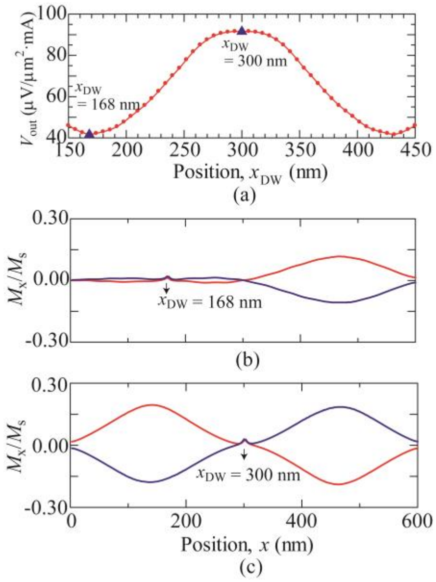

Fig. 2. Dependence of the Vout on the x_{DW} (a), and the comparison of the SSW profile for different DW position; x_{DW} = 168 nm (b) and = 300 nm (c).

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薄膜ヘテロ構造におけるカイラル磁気構造とその制御

Chiral magnetism in thin film heterostructures

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スピン軌道相互作用が大きい遷移金属層と強磁性層の界面では、ジャロシンスキー・守谷相互作用によってカイラル磁気構造が形成されることが近年明らかになった。また、カイラル磁気構造を有する細線に電流を流すと、電流と同じまたは逆方向に磁区パターン（磁壁）が平行移動できることが実証された。磁区パターンの移動速度は界面ジャロシンスキー・守谷相互作用の大きさに比例するため、その効果を最大化できる積層構造の探索や背後にある物理・材料力学的理解が必要不可欠である。

本講演では、薄膜ヘテロ構造を構成する材料や膜厚が界面ジャロシンスキー・守谷相互作用に及ぼす影響について報告する。また、カイラル磁気構造を自在に制御するために必要となる磁壁の生成と磁壁間相互作用[1]に関する実験について議論する。

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Magnetic nanowire memory for realizing ultra-fast data transfer rate: Magnetic and magneto-optical detection of current-driven domain motion

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To record the video data of 8K ultra-high definition TV, future storage devices require not only a large capacity but an ultra-high data transfer rate. In fact, an enormous transfer rate of more than 144 Gbps is required for recording the uncompressed full-featured 8K video, and of course, an extremely high data transfer rate over 1 Tbps may be required for the future 3D video recording. However, there is no way to treat such terrible “data flood” using conventional memories. For example, even solid-state drives (SSDs), which use semiconductor memory and are currently the fastest commercially available storage devices, have a fundamental data transfer rate of only several Gbps. As a result, SSDs are incapable of recording the uncompressed full-featured 8K video unless multiple devices are used simultaneously.

The racetrack memory[1)] that utilizes the high-speed current-driven domain walls motion[2)] in the magnetic nanowire (NW) has been proposed as a non-volatile random access memory with large capacity. Here, by limiting the direction of current-driven domain motion in one way for the racetrack memory, sequential memory architecture suitable for video recording can be constructed. We have proposed this new sequential “magnetic nanowire memory” consisting of parallel aligned magnetic NWs, as shown in Fig. 1. Each magnetic NW acts as a recording medium, and a pair of write and read head (writer and reader) is attached on. The data are stored along the magnetic NWs direction as the magnetic domains with upward or downward magnetization directions. These troops of domains are shifted quite fast by applying optimum current pulses along the NW direction for data writing and reading purposes. The ultra-high speed storage device will be achieved if the domains in thousands of parallel aligned NWs can be controlled synchronously by applied current pulses.

To demonstrate the operational principle of this NW memory, we adopted a magnetic recording head, in which a pair of write head and read head is equipped, as the writer and the reader in NW memory element. We have succeeded in recording, shifting and detecting the domain motion along the fabricated NW with perpendicular magnetic anisotropy by a magnetic head with current pulses application in our previous work[3)].

In this study, in order to search the artificial lattice NW materials with high domain wall velocity, the multiple magnetic domains motion along an entire NW area was observed by magneto-optical Kerr effect microscopy (MOKE), since a magnetic head can detect only the change in magnetization beneath the reader. As shown in Fig. 2, we could observe the current-driven magnetic domains toward the electron flow along a NW with 1.5 μm-width in real-time. Since an MOKE can detect the multiple domains motion in the entire NW area, it is suitable for investigating the control of synchronous current driven magnetic domains. For realizing parallel aligned magnetic nanowire memory, both magnetic and magneto-optical detection methods are essential to study micron to sub-micron behavior of current driven domain motion.

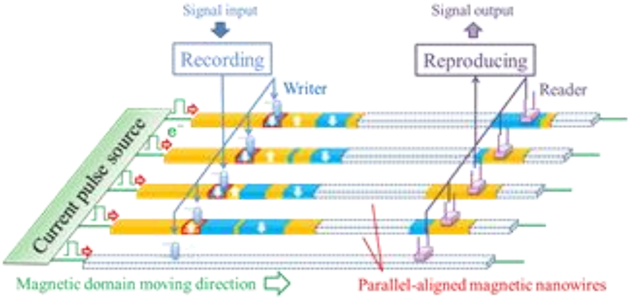

Fig. 1 Schematic illustration of magnetic NW memory consisting of parallel aligned NWs.

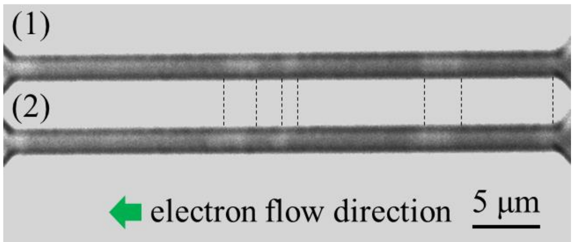

Fig. 2 (1) Initial MOKE image and (2) MOKE image after injection of current pulse. The width of NW is 1.5 μm. Queue of written domains moves along the electron flow direction.

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Recent progresses and future challenges in voltage-controlled magnetic anisotropy effect

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The development of electric-field manipulation of magnetism is strongly demanded for the reduction in operation power of future spintronic devices. The voltage-controlled magnetic anisotropy (VCMA) effect in an ultrathin ferromagnetic metal layer [1, 2] is a promising and practical approach due to its high applicability in an MgO-based magnetic tunnel junction (MTJ) with high-speed response [3,4]. The VCMA effect originates from voltage-induced charge accumulation/depletion and induction of electron redistribution at the interface between ultrathin ferromagnet and dielectric layers [5]. To show the feasibility of MRAM controlled by voltage, called voltage-torque MRAM [6], we need further improvement in VCMA coefficient. For example, for giga-bit class memory applications, VCMA coefficient of more than a few hundreds or even 1000 fJ/Vm is required [7]. However, high speed VCMA effect is limited to be 100 fJ/Vm at present [8].

In this talk, recent progresses in materials research for the enhancement in the VCMA effect, especially focusing on an epitaxial Fe/MgO MTJs, will be reviewed. Large VCMA coefficient of about 300 fJ/Vm has been achieved by interface engineering using a transition metal doping at the ultrathin Fe/MgO interface.

We'll also introduce the evaluation of write error rate (WER) of precessional magnetization switching induced by VCMA effect in perpendicularly magnetized MTJs [9]. By optimizing the thermal stability and VCMA coefficient in the voltage-controlled free layer, lowest WER of 2×10^{-5} has been demonstrated [10]. Future strategy to realize the practical low WER value will also be discussed.

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Perpendicular magnetic anisotropy at $Fe/MgAl_2O_4$ interfaces and its voltage effect

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Voltage-controlled magnetic anisotropy (VCMA) [1] in magnetic heterostructures is expected as a key technology for achieving low-power consumption spintronic devices such as voltage-torque magnetoresistive random access memories (MRAMs). However, increase of both the interface perpendicular magnetic anisotropy (PMA) energy (K_i) and the VCMA coefficient (β), i.e., K_i > 2–3 mJ/m^2 and β > 1000 fJ/(Vm), is necessary for high density memory applications. In order to achieve such a giant VCMA effect, exploring the origin of the VCMA effect using "standard PMA heterostructures" without any interfacial defects can be indispensable. Recently, large PMA energies were reported in lattice-matched $Fe/MgAl_2O_4$ [2] and $Co_2FeAl/MgAl_2O_4$ heterostructures [3]. Therefore, we focused in this study on ultrathin $Fe/MgAl_2O_4$(001) epitaxial interfaces to achieve high K_i and β using an electron-beam evaporation technique. Especially, we precisely investigated the Fe thickness dependence using $Fe/MgAl_2O_4/CoFeB$ orthogonally magnetized MTJs. We report that only a monolayer thickness difference has a significant impact on the PMA energy and VCMA effect.

MTJ stacks of Cr buffer (30)/Fe (t_{Fe} = 0.70, 0.84, 1.0 = 5, 6, 7 monolayers (MLs))/$MgAl_2O_4$ (2)/$Co_{20}Fe_{60}B_{20}$ (5)/Ru (10) (unit in nm) were prepared on an MgO(001) substrate by electron-beam evaporation. The top 5-nm CoFeB is the reference layer with in-plane magnetization for evaluating the VCMA effect of the bottom Fe. The Cr, Fe, $MgAl_2O_4$, and CoFeB layers were post-annealed to improve their crystallinity and flatness. Magnetic properties were investigated using a vibrating sample magnetometer-superconducting quantum interference device. After microfabrication (10 μm scale), magnetotransport properties of MTJs were characterized by a physical property measurement system at room temperature. The positive bias was defined with respect to CoFeB (electron tunneling from the lower to upper electrode).

Figure 1 shows the typical in-plane magnetization curves for the MTJ stacks with different Fe thicknesses. It was found that the 5- and 6-ML Fe layers had perpendicular magnetization. Arial PMA energy density E_{pma} (PMA energy density K_{eff} [unit in J/m^3] × t_{Fe}) for the 5-ML (6-ML) Fe sample was determined to be 0.85 mJ/m^2 (0.77 mJ/m^2). We investigated the bias voltage dependence of E_{pma} for the 5- and 6-ML Fe samples using normalized tunnel magnetoresistance ratios as functions of both bias voltage and in-plane magnetic field. As clearly seen in Fig. 2, E_{pma} values for both the samples show complicated bias voltage dependence. Importantly, the E_{pma} curve shape significantly depends on the Fe thickness; a local minimum appears near +0.2 V for the 5-ML Fe sample, whereas a peak appears at the zero-bias voltage for the 6-ML one. We found that the complicated VCMA effect was associated with the formation of quantum well states [4] for the Δ_1 states in the ultrathin Fe layers between Cr and $MgAl_2O_4$. This work was partly supported by the ImPACT Program of Council for Science, Technology and Innovation, Japan, and JSPS KAKENHI Grant No. 16H06332.

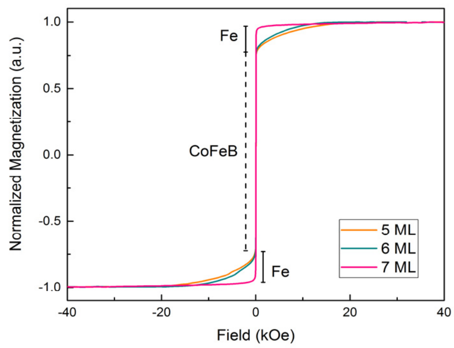

Fig. 1. Magnetizations as a function of in-plane magnetic fields for ultrathin-$Fe/MgAl_2O_4/CoFeB$ MTJs with 5-7 ML thick Fe.

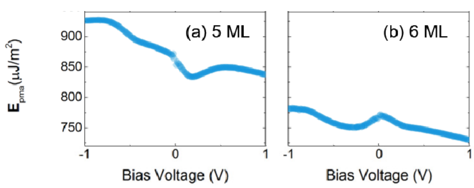

Fig. 2. Bias voltage dependences of $E_{pma} = K_{eff} \times t_{Fe}$ for (a) 5-ML and (b) 6-ML Fe sample.

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The effect of Os or Ir layer insertion into MgO/Fe interface on the electric-field modulation of magnetic anisotropy

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The voltage-torque magnetoresistive random access memory is the ultra-low energy consumption non-volatile memory based on voltage-controlled magnetic anisotropy (VCMA). The VCMA coefficient was reported to be 30-40 fJ/Vm for the MgO/Fe/Au and MgO/CoFeB/Ta films [1, 2]. Recently, large VCMA of 290 fJ/Vm was demonstrated for the MgO/Fe/Cr film [3]. However, VCMA effect larger than 1000 fJ/Vm is required for realizing the voltage-induced magnetization switching in magnetic tunnel junctions below 30nm. The purpose of this work is to design the magnetic film exhibiting larger VCMA. We theoretically investigated the effect of 5*d* transition-metal layer insertion into the MgO/Fe interface on the electric-field modulation of magnetic anisotropy.

We have carried out first-principles electronic-structure calculations employing the projector augmented-wave with plane wave basis set by using the Vienna ab initio simulation package [4]. We estimated magnetic anisotropy energy (MAE) and its electric-field modulation for MgO/Os(Ir)/bcc-Fe/Cu(001) films. The MAE was estimated by using the magnetic force theorem.

Figures 1(a) and (b) show the electric-field modulation of MAE for the Os/Fe and Ir/Fe films, respectively, with and without MgO capping layer. The VCMA coefficient is estimated to be -173, 298 fJ/Vm for the MgO/Os/Fe and MgO/Ir/Fe film, respectively, and these values are one order of magnitude larger than that for the MgO/Fe interface. These VCMA coefficients are comparable with that of Os- and Ir-monolayer on the Fe surface. However, perpendicular MAE is drastically decreased in both Os/Fe and Ir/Fe film by MgO capping. In the case of Ir/Fe film, opposite sign of VCMA is obtained for the film with and without MgO. These results indicate that the bonding between 5*d* transition-metal and oxygen plays an important role for the MAE and its electric-field modulation. At the MgO/Os and MgO/Ir interfaces, the density of states (DOS) projected on the majority-spin 5*d*($3z^2$-r^2) orbital, which contributes to the in-plane MAE, is increased near the Fermi level by the hybridization between 5*d*($3z^2$-r2) and O-2*p*(z) orbitals. This is the origin of the reduction of perpendicular MAE by the MgO capping. In particular, MgO/Ir/Fe film shows the huge in-plane MAE, since the DOS of 5*d*($3z^2$-r^2) orbital is located just at the Fermi level. In the presentation, we also discuss the origin of the sign change of VCMA coefficients for the Ir/Fe and MgO/Ir/Fe films.

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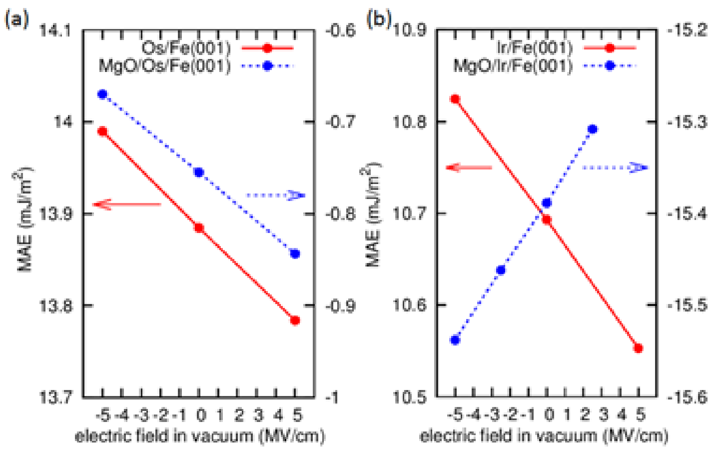

Fig. 1: Magnetic anisotropy energy (MAE) as a function of electric field in vaccum for the Os/Fe (a) and Ir/Fe (b) films with and without MgO capping layer.

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Electric field control of magnetic anisotropy in bilayer contacts with Rashba-type spin-orbit interaction

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Uniaxial magnetic anisotropy (MA) plays an important role in spintronic applications in which ferromagnetic (FM) thin films and heterojunctions are utilized. The MA in such magnetic materials originates from spin-orbit interaction (SOI) expressed by *L-S* coupling and the low dimensionality of the lattice structure. As a result, out-of-plane MA often occurs at surfaces and interfaces of these magnetic heterojunctions. The magnetization direction in ferromagnets is usually controlled by an external magnetic field. Recently, control of magnetic ordering by using spin-transfer torque, the magnetostrictive effect, ferroelectricity, the piezoelectric effect, and electric field has attracted much attention in the field of spintronics.

Quite recently, another type of SOI, the Rashba-type SOI (R-SOI) was proposed to be a source of MA. Theoretical analysis of MA was performed for a two-dimensional layer by using exchange-split free electron and single-orbital TB models with R-SOI.[1-3] The study using TB model[3] predicted that the layer shows in-plane MA for both low and high electron densities, while it shows out-of-plane MA otherwise. The occurrence of MA by the R-SOI may be attributed to a characteristic change in the Rashba-split energy state under an exchange field produced by the FM layer itself or by magnetic ions/atoms in an FM material attached to a non-magnetic (NM) layer. It is interesting to note that the R-SOI may be controlled by an external electric field because of its intrinsic nature.

In this work,[4] we theoretically study the uniaxial MA of a bilayer made of NM and FM layers putting an emphasis of relative role of the R-SOI on NM layer and *L-S* coupling, that is, atomic-SOI (A-SOI) on the FM layer. We construct a simple model for the bilayer based on the first-principle calculation of the Rashba-split bands of the Au(111) surface. In this model, the electronic structure of NM layer is given by a single-orbital TB model, while that of FM layer is presented in the full 3*d*-orbital TB model, in addition to the orbital mixing between NM and FM layers. After numerical calculation, we have shown that the R-SOI of the NM layer produces MA via *p-d* mixing between the NM and FM layers. The MA energy caused by the R-SOI is less than 1 meV, while that caused by the A-SOI is a few meV per unit cell. Both interactions show an oscillatory dependence of the uniaxial MA energy on the electron number. Because the "phases" of these oscillations are different, the uniaxial MA originating from the R-SOI alone could be the same order of magnitude as that produced by A-SOI alone under certain conditions. The result indicates that an external electric field with reasonable magnitude may change the MA from being out-of-plane to in-plane, and vice versa.

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電界による g 因子の変調と磁気異方性の相関

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Correlation between g-factor and magnetic anisotropy under the bias electric field

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はじめに

磁性金属超薄膜に電界を印加し、垂直磁気異方性(PMA)を制御する試みが近年注目を集めている[1]。理論的には、界面での局在電子の軌道磁気モーメントの異方性と、スピン軌道相互作用が、磁性多層膜における PMA の起源であると予想されている（Bruno's model）[2]。軌道磁気モーメントの異方性は、強磁性共鳴(FMR)測定から得られる g 因子の異方性を通してその評価が可能である[3]。今回、我々は Pt/Co 超薄膜にゲート電圧 V_g を印加した状態で FMR 測定を行い、電界による g 因子の異方性の変調と、PMA との相関について調査した。

実験方法

Ta(5)/Pt(3)/Co(0.8)/MgO(4)(単位：nm)層を GaAs 基板上にスパッタ成膜後、細線状に加工し、V_g 印加用の「絶縁層(HfO_2)/ゲート電極(Au)」を作製した（図 1 (a)）。高周波電流 I_{rf} を細線に注入しながら外部磁場 H_{ex} を掃引し、ホモダイン検出による FMR 測定を行った。試料に対する外部磁場 H_{ex} の掃引方向（θ_H = 30, 90°）を変えて FMR 測定することで、g 因子の異方性を見積もった。

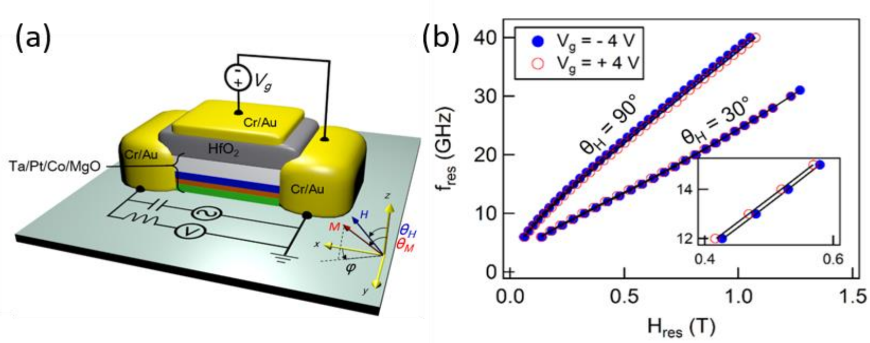

図 1 (a)デバイスの模式図　(b)共鳴磁場と周波数の関係

実験結果

図 1(b)に示したように、共鳴条件のずれから、V_g 印加により磁気特性が変調されていることがわかる。これらの共鳴条件から見積もった g 因子の異方性（$\Delta g = g^{\perp} - g^{\parallel}$）及び、垂直異方性磁場（$H_{k1}$）の電界による変化を図 2 に示す。ここで、$g^{\perp}$ および $g^{\parallel}$ はそれぞれ面直方向および面内方向の g 因子である。Δg、H_{k1} 共に正の電界に対して増加しており、両者に正の相関があることが分かる。本講演では Bruno's model [2]を用いてこれらの相関の詳細について議論する。

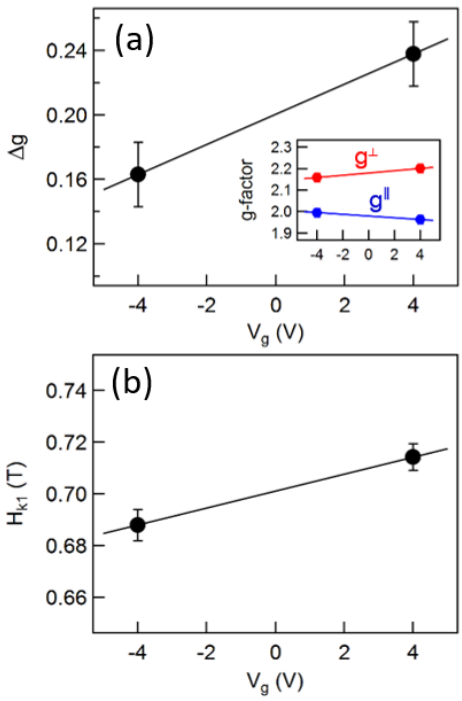

図 2 (a) g 因子の異方性 (Δg) および(b) 垂直異方性磁場（H_{k1}）のゲート電圧依存性

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