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Anisotropic spin-orbit torques in epitaxial ruthenium oxide

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Abstract

Anisotropic spin-orbit (SO) torques depending on the crystal orientation have been unveiled in an epitaxial ruthenium oxide. Both damping-like (DL) and field-like (FL) SO torques demonstrate the same anisotropy as the in-plane 2-fold crystal symmetry in the epitaxial RuO_2(101), while the FL torque is stronger than the DL torque. Interestingly, 10 times difference in the DL torque can be tuned by the crystal orientation.

1. Introduction

SO torque is necessary to perform an efficient magnetization switching in an adjacent ferromagnet. Therefore, a lot of the SO materials such as heavy metals [1, 2], topological insulators [3, 4], and Weyl semimetals [5] have been intensively studied in order to explore higher charge-spin conversion efficiency and gate-controlling functionality, so far. On the same way, electrically-conductive oxides are also interesting materials which can generate the SO torque (or spin current) via the spin Hall effect. Actually, polycrystalline or amorphous IrO_2 [6] and RuO_2 [7] have experimentally been demonstrated to achieve the conversion by means of spin absorption technique using lateral spin valve, and spin Seebeck measurement. Furthermore, this rutile type oxide has collinear antiferromagnetism which has intrigued us in spintronics interestingly. For this kind of the oxide, there are some theoretical reports concerning the spin Hall conductivity which has an anisotropy due to the specific band structure affected by the Dirac nodal line [8,9]. This implies that we can control the SO torque efficiency depending on in-plane crystal orientation. In this study, we have studied an epitaxial RuO_2 by means of harmonic Hall measurement [10], and found the anisotropic SO torque in the crystallinity.

2.Experiments

First of all, we have prepared the epitaxial RuO_2 by reactive magnetron RF sputtering at 400 ℃ onto Al_2O_3(11-02) substrates. After the deposition, we have also checked the surface crystallinity of the oxide using reflection high energy electron diffraction (RHEED) in-situ, then found a streak pattern showing high crystal orientation as shown in Fig. 1(a). In fact, the crystallinity is unveiled to have RuO_2 (101) single peak in x-ray diffraction (XRD) experiment (Fig. 1 (b)), and around 1:2 as the concentration ratio of the Ru and O atoms by means of x-ray photoelectron spectroscopy (XPS) as shown in Fig. 1 (c). As can be seen in Fig. 1(a), it seems to be dot-like pattern, suggesting the rough surface. So, we have also measured the surface roughness by atomic force microscope (AFM), then found that the averaged roughness is 0.225 nm, whose value ensures the smooth surface.

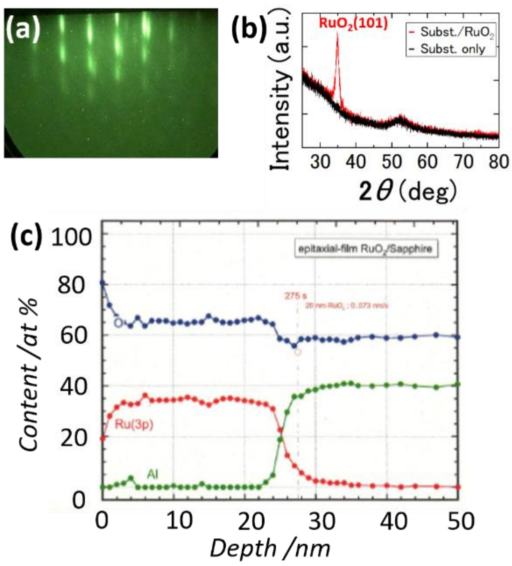

Fig. 1(a) RHEED pattern, (b) XRD patterns (red and black lines are for the RuO_2 with the substrate and only the substrate), and (c) Concentration ratio of the Ru (red) and O (blue) atoms of the prepared epitaxial RuO_2, respectively.

After the evaluation of the crystallinity, we deposited $Ni_{80}Fe_{20}$ (Py, 5 nm) as a spin detector, and AlO_X (2 nm) as a capping layer onto the Py, and fabricated the Hall bar structure which has $10 \times 25\ \mu\mathrm{m}^2$ aspect ratio for the harmonic Hall measurement. Furthermore, the several samples with different crystal angle directions were also fabricated as shown in Fig. 2(a). In the measurement, we applied around $10^{11}\ \mathrm{A/m^2}$ -magnitude ac current density with 13 Hz frequency from the wave factory into the sample strips.

3. Results and Discussion

In order to extract the SO torque (or the field), we have to know amplitudes of the anisotropy field and the anomalous Hall resistance of the Py layer at first. So, we have measured anomalous Hall effect with applying out-of-plane field, then found the values of the field $\mu_0 H_\mathrm{K}$ and the resistance ΔR_AH

are almost independent of crystal orientation angle ϕ_C (Figs. 2 (b) and (c)). This result confirms that the ferromagnetic Py layer is not affected the epitaxial RuO_2 crystallinity as the spin detector.

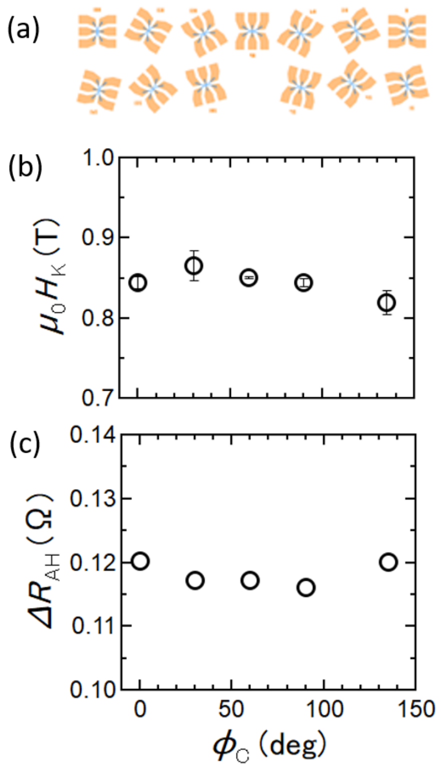

Fig. 2(a) Hall bar structures with different crystal angle ϕ_C, Crystal orientation dependence of (b) Anisotropy field, and (c) Anomalous Hall resistance for the prepared epitaxial RuO_2.

Next, we measured the harmonic Hall resistance for extracting the SO fields for each sample with different crystal orientation of the RuO_2. The extracted DL and FL fields are plotted in Figs. 3 (a) and (b), respectively. It is clear that the two SO fields have the same crystal orientation dependence. This dependence follows $\sin 2\phi_C$, meaning that both DL and FL SO torques have 2-fold crystal symmetry. In fact, the RuO_2(101) has the in-plane crystalline symmetry. Therefore, the generated SO torques are attributed to the RuO_2 crystallinity, as it has already been predicted theoretically [9].

4. Conclusion

We have studied the epitaxial RuO_2(101) deposited by the reactive sputtering onto the sapphire R-plane substrate in order to extract the SO torques. We found that the anisotropy field $\mu_0 H_K$ and the anomalous Hall resistance ΔR_{AH} of the Py layer are independent of the crystal orientation. On the contrary, the generated DL and FL fields from the epitaxial RuO_2 strongly depends on the orientation. This would be originated from the in-plane 2-fold crystal symmetry of RuO_2(101), and is in good agreement with the theoretical prediction [9] in the viewpoint of the anisotropy. In this conference, we discuss further mechanism to generate the SO torques in this electrically-conductive oxide.

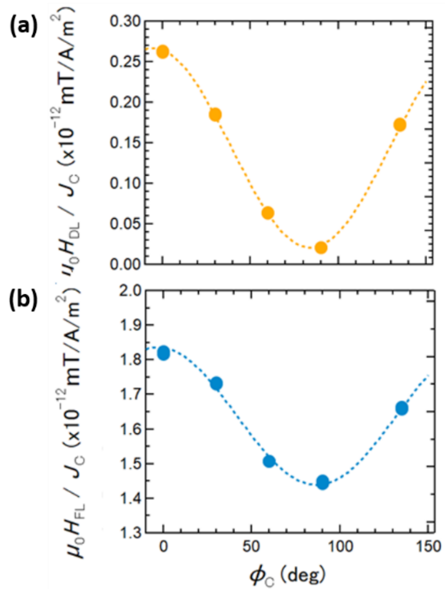

Fig. 3 Crystal orientation dependence of the (a) DL field, (b) FL field of the prepared epitaxial RuO_2.

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