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Spin Orbit Torques in Heavy-Metal/Ferromagnet/Normal-Metal Trilayers

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Abstract

We have studied the spin orbit torques in heavy-metal/ferromagnetic-metal/normal-metal (HM/FM/NM) trilayers using spin Hall magnetoresistance (SMR) measurements. We find that a NM (Ru) layer placed on top of a FM (Co) layer considerably influences the spin orbit torques. The effect of spin current absorption into the NM layer is discussed as a function of varying NM layer thickness.

1. Introduction

Electrical manipulation of magnetic moments in spintronic devices has been a central subject for decades to achieve various functionalities at the nanoscale. While conventional methods to controlling the magnetization utilize spin transfer torques (STTs) that require a flow of charge current through an additional ferromagnetic spin polarizer, recent studies have demonstrated an alternative way to manipulate the magnetic moments, i.e. utilizing the spin orbit torques (SOTs) induced by the spin current generated from the HM layer in HM/FM bilayers with a current-in-plane geometry.

For quantitative evaluation of the SOTs, whose two orthogonal components are typically referred to as the damping-like (DL) and field-like (FL) torques, the harmonic Hall voltage measurement[1-3] is often used. Recently, it has been reported that the spin Hall magnetoresistance (SMR) provides a simple method to study the SOTs[4-7]. Specifically, the magnitude of the DL SOTs is directly linked to the SMR ratio, while the FL torques contribute to the anomalous Hall resistance (AHR) in the HM/FM system [4,8,9].

Most SOTs studies either involve a thickness variation of the HM, in which the spin current is generated, or the FM layer, in which the SOTs take place. In this work, we study SOTs in a system where an additional non-magnetic normal metal (NM) layer is placed on top of the FM layer. Recently, it has been reported that an additional NM layer (Ru) fosters the spin absorption in such a HM/FM/NM system and subsequently increases the SOTs[10]. By systematically varying the NM layer thickness, we evaluate the SOTs through the measurement of SMR and AHR.

2. Experimental methods

Thin films of Si-sub./HM/FM/NM/cap (thickness in nm) are deposited using magnetron sputtering onto Si substrates at room temperature (Fig. 1). We use Pt(3) or W(3) for the HM layer, Co(1) for the FM layer and Ru(t_{Ru}) for the NM layer. Hall bar devices are fabricated using photo-lithography and Ar ion-milling. The length and width of the Hall bars are 25 μm and 10 μm, respectively. The SMR and AHR are measured by sweeping the magnetic field in different directions under application of a dc current of 10 μA. The SMR ratio is obtained experimentally as follows:

$$SMR = \frac{R_{xx}(H_y = 3T) - R_{xx}(H_z = 3T)}{\xi * R_{xx}(H_z = 3T)}$$

Here R_{xx} refers to the longitudinal device resistance when external magnetic field is applied along the y or z axis (Fig. 2). $\xi = \frac{t_{HM}}{r_{HM}} / \left(\frac{t_{HM}}{r_{HM}} + \frac{t_{FM}}{r_{FM}} + \frac{t_{NM}}{r_{NM}} \right)$ is a normalized coefficient to take into account current shunting into the FM and NM layers; t_{HM}, t_{FM}, t_{NM} (r_{HM}, r_{FM}, r_{NM}) are the thickness (resistivity) of the HM, FM, NM layer, respectively. The details of the SMR and AHR measurements and their corrections due to the current shunting are provided in Ref. [7,9].

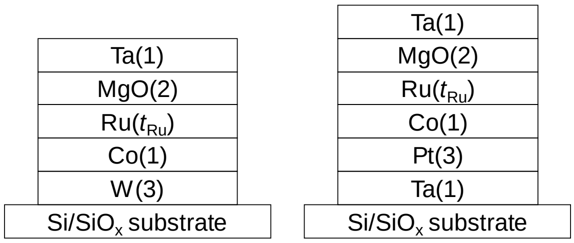

Fig. 1 Schematic illustration of the film stacks in this study.

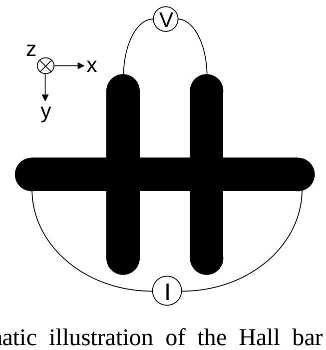

Fig. 2 Schematic illustration of the Hall bar for the SMR measurement in this study.

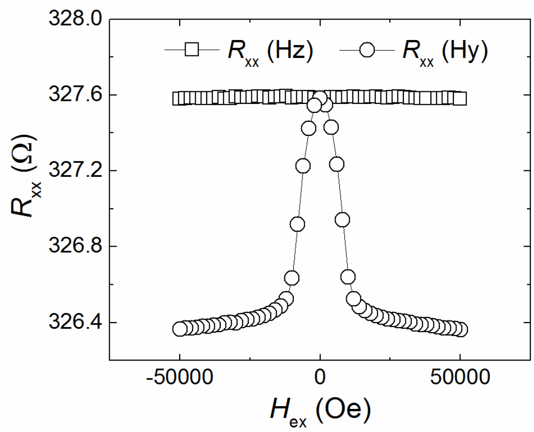

Fig. 3 R_{xx}-H curve of Pt(3)/Co(1)/Ru(0.2)/cap.

3. Results and discussion

Figure 3 shows typical R_{xx}-H curve for a film stack with t_{Ru} = 0.22 nm. The SMR ratio of this film is estimated to be ~-0.5% using the relation described above. Theoretically, the SMR scales[6] with the square of spin Hall angle of the HM layer and reflects the magnitude of the DL torque, which is closely related to the real part of the spin mixing conductance. An NM layer placed above the FM layer significantly influences the SOTs as well as the spin mixing conductance. Figure 4 shows the SMR ratios as a function of Ru thickness t_{Ru} for HM=Pt samples. With increasing t_{Ru},

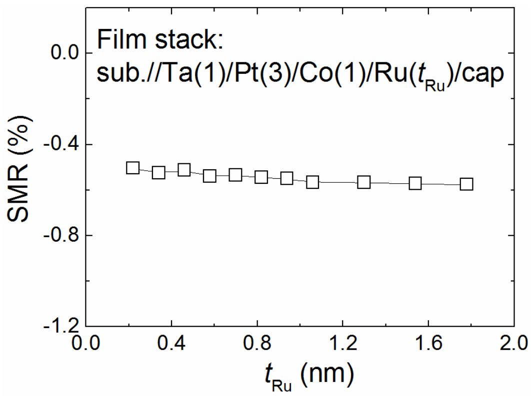

Fig. 4 SMR ratio obtained from film stacks of Pt(3)/Co(1)/Ru(t_{Ru})/cap.

there is a slight increase in the SMR ratio, suggesting a small enhancement of the DL torque. Specifically, the maximum increase is ~14% for the film with the thickest Ru layer compared to that of the thinnest Ru layer film. In contrary, when the Pt layer is replaced by W, as shown in Fig. 5, we observe almost 100% increase in the SMR ratio, suggesting a significant enhancement of DL torque. Although the magnetic anisotropy for the Pt and W-based systems is different, i.e. the magnetic easy axis is along the film normal for the films with HM=Pt whereas it is along the film plane for films with HM=W, its influence on the SMR magnitude was reported to be negligible[7]. These results are qualitatively in agreement with previous work[10] in which the DL torque increases with the Ru layer thickness. Here we have also studied the Ru thickness dependence of the FL torque by measuring the AHR. We model the system by using an effective spin mixing conductance for the trilayers and discuss their change with the Ru layer thickness.

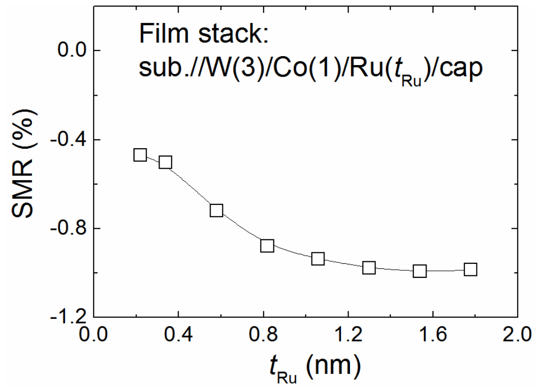

Fig. 5 SMR ratio obtained from film stacks of W(3)/Co(1)/Ru(t_{Ru})/cap.

4. Summary

We have studied the SOTs that develop in HM/FM/NM trilayers using the spin Hall magnetoresistance. We show that the insertion of a NM layer considerably increases the SOT exerted on the FM layer. The increase of the DL SOT is much larger when W is used for the HM layer, compared to the case with HM=Pt. The origin of the significant enhancement of the DL SOT with the Ru insertion layer, together with the change in the FL torque, will be discussed.

5. References

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