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Disentanglement of Spin Orbit Torques Originated from Spin Hall Effect and Rashba-Edelstein Effect Using Harmonic Hall Measurements

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Abstract

We report on the quantitative separation of the spin orbit torques (SOTs) originated from the spin Hall effect (SHE) and the Rashba-Edelstein effect (REE), by performing the Harmonic Hall measurements for epitaxial platinum/cobalt (Pt/Co) bilayers. The damping-like (DL-) and field-like (FL-)SOT efficiencies (ξ_{DL} and ξ_{FL}) are quantified respectively by fitting the SOT data with corresponding spin-diffusion equation. As a result, the ξ_{DL} originated from the Pt bulk region (ξ_{DL0}) decreases significantly with decreasing temperature, while the ξ_{FL} from the substrate (sub.)/Pt (ξ_{FL1}) and Pt/Co (ξ_{FL2}) interface barely change, suggesting that the origin of FL-SOT is the REE instead of the SHE; the sign of ξ_{FL1} is opposite to ξ_{FL2}, which is consistent with the REE where the direction of the spin accumulation depends on the interfacial electric field induced by broken inversion symmetry. Moreover, the ξ_{DL} induced by sub./Pt (ξ_{DL1}) and Pt/Co (ξ_{DL2}) interfaces are found to be about 1 order of magnitude smaller than maximum ξ_{DL0}, while their sign are consistent with respective ξ_{FL} (ξ_{FL1} and ξ_{FL2}). Our work presents a thorough disentanglement of the SOTs in heavy metal/ferromagnet bilayers in which both SHE and REE are present, and provides deterministic answers to the fundamental question on their physical origin.

1. Introduction

The recent advances in the spin Hall effect (SHE) have made it possible to manipulate the local magnetizations via electrical means.[1,2] A longitudinal charge current flowing in SH materials such as heavy metals (HMs) generates a transverse pure spin current that exerts a spin orbit torque (SOT) on the neighboring ferromagnetic (FM) layer. Although the origin of the SOT remains controversial, it can be decomposed into two orthogonal components, a (anti-)damping-like (DL) term $m \times (m \times \sigma)$ and a field-like (FL) term $m \times \sigma$, where the m denotes the magnetization of the FM layer, and σ is the spin polarization. Generally, the SHE is considered to be the dominant origin of the DL-SOT,[3] and the Rashba-Edelstein effect (REE) is considered to be the main origin of the FL-SOT.[4] However, theoretical studies have shown that the REE can produce a non-trivial DL-SOT,[5–7] *e.g.* by means of the giant Rashba spin splitting[8] at HM/normal metal interfaces; moreover, the SHE can produce a small FL-SOT as well.[7] Therefore, the interface-generated SOT have up to now remained unclear due to the difficulty in the separation of DL- and FL-SOT because of the presence of both SHE and REE. Here in this work, by performing a detailed harmonic Hall measurement for epitaxial Pt/Co bilayers, we are able to present a thorough, quantitative separation of the SOTs originated from these two effects.

2. Experimental methods

Multilayer thin films of Pt(t_{Pt})/Co(1.95)/AlO_x(2) were sputter-deposited onto Al_2O_3(0001) and Si/SiO_2 substrates at room temperature (T) to make epitaxial (epi-) and polycrystalline (poly-) samples respectively, where the former is the main focus of this study and the latter is the control set. The saturation magnetization (M_s) of Co was measured via Vibrating Sample Magnetometer and found to be T independent. The harmonic Hall measurements[9,10] were carried out for Hall bar devices that have in-plane magnetic anisotropy.

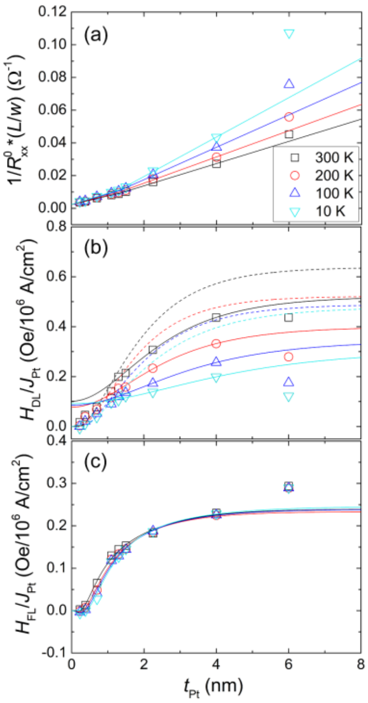

Fig. 1 (a) Inverse of the sheet resistance of epi-Pt(t_{Pt})/Co(1.95)/AlO_x(2) measured at 10-300 K. Solid lines are linear fitting to the experimental data ranging from 0.2-1.1 nm and 1.3-4.0 nm, respectively. (b) Normalized DL-SOT as a function of t_{Pt} measured at 10-300 K. Solid lines are fitting to the data (Eq.1) in the range of 1.3-4.0 nm, broken lines are fitting to the data (Eq. 3) in the range of 0.2-1.1 nm. (c) Normalized FL-SOT as a function of t_{Pt} measured at 10-300 K. Solid lines are fitting to the data (Eq. 2) in the range of 0.2-4.0 nm.

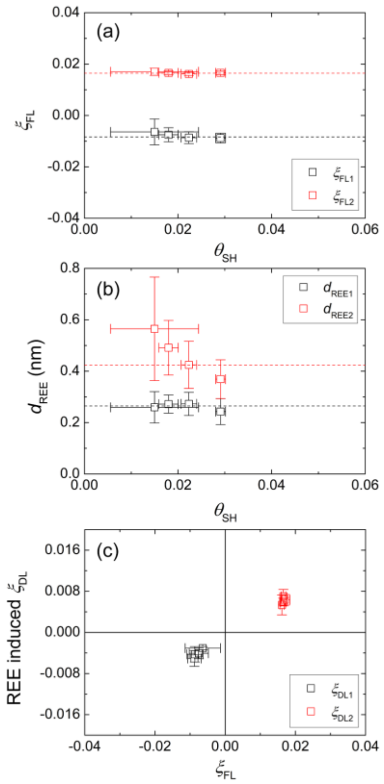

Fig. 2 (a) Bulk θ_{SH} dependence of FL-SOT efficiency at sub./Pt (ξ_{FL1}) and Pt/Co (ξ_{FL2}) interfaces. (b) Bulk θ_{SH} dependence of effective REE thickness at sub./Pt (d_{REE1}) and Pt/Co (d_{REE2}) interfaces. (c) REE induced ξ_{DL} from sub./Pt (ξ_{DL1}) and Pt/Co (ξ_{DL2}) interfaces plotted as a function of respective ξ_{FL}.

3. Results and discussions

Figure 1(a) shows the inverse sheet resistance as a function of t_{Pt}. The data ranging from 0.2-1.1 nm and 1.3-4.0 nm respectively follows a linear relationship, suggesting a constant resistivity in each range. By considering that both SHE and REE contributes to the DL-SOT, the following equation is used to fit the data in Fig. 1(b) with t_{Pt} = 1.3-4.0 nm:

$$H_{DL} \approx H_{DL0}(1 - \mathrm{sech}(t_{Pt}/\lambda_{Pt})) + H_{DL2}, \tag{1}$$

where H_{DL0} is the DL-SOT induced by bulk Pt, λ_{Pt} is the spin diffusion length (SDL) in Pt, and H_{DL2} is the DL-SOT generated at Pt/Co interface due to the REE. Note that the effective REE thickness (*e.g.* ~0.4 nm)[11] is estimated to be several times to one order of magnitude smaller compared to such a t_{Pt} range, therefore it is reasonable to consider H_{DL2} as a constant for the fitting above.

From the analysis above we obtain the H_{DL0} and λ_{Pt} depending on *T*. The bulk Pt spin Hall angle (θ_{SH}) (assuming a transparent interface) is calculated via θ_{SH} = $(2eM_s t_F)/\hbar \times H_{DL0}/j_c$, where M_s, t_F and j_c are saturation magnetization, Co layer thickness and current density in Pt. From the plot of θ_{SH}-ρ_{Pt} and λ_{Pt}-σ_{Pt} (not shown due to page limitations) we experimentally obtain an intrinsic and/or side-jump contribution to the SHE and the Elliot-Yafet (EY) spin relaxation in *bulk* Pt, which are consistent with previous study.[12]

Qualitatively, the DL- and FL-SOT have shown a significant difference in *T*-dependence (Fig. 1(b) and(c)): the DL-SOT decreases drastically when $t_{Pt} \geq$ 1.3 nm while the FL-SOT barely changes in all thickness and *T* ranges. Particularly, at $t_{Pt} =$ 6.0 nm, the FL-SOT remains constant while the DL-SOT decreases by a factor of 3 when *T* drops from 300 K to 10 K. This demonstrates that the FL-SOT efficiency (ξ_{FL}) is independent of the DL-SOT efficiency (ξ_{DL}) via $\xi_{D(F)L}$ = $(2eM_s t_F)/\hbar \times H_{D(F)L}/j_c$. Such a result suggests that the SHE-induced FL-SOT is negligible in our samples.

The t_{Pt} dependence of H_{FL} is then quantitatively analyzed and fitted (as shown in Fig. 1(c)) using the equation below based on the spin diffusion model:

$$\begin{aligned} H_{FL} \approx\ & H_{FL1}(1 - \mathrm{sech}(t_{Pt}/d_{REE1}))\,\mathrm{sech}(t_{Pt}/\lambda'_{Pt}) \\ & + H_{FL2}(1 - \mathrm{sech}(t_{Pt}/d_{REE2})), \end{aligned} \tag{2}$$

where H_{FL1} and H_{FL2}, d_{REE1} and d_{REE2} are the FL-SOT, effective REE thickness at sub./Pt and Pt/Co interfaces, respectively. Note that λ'_{Pt}, the SDL with $t_{Pt} =$ 0.2-1.1 nm, is obtained based on the λ_{Pt}-σ_{Pt} plot. The corresponding ξ_{FL1} and ξ_{FL2} (Fig. 2(a)) show comparable magnitude but opposite sign, consistent with the REE; the d_{REE1} and d_{REE2} (Fig. 2(b)) are quantitatively consistent with previous work.[11]

Finally, the REE induced ξ_{DL} from sub./Pt (ξ_{DL1}) and Pt/Co (ξ_{DL2}) interfaces are quantified using the following equation:

$$\begin{aligned} H_{DL} \approx\ & H_{DL1}(1 - \mathrm{sech}(t_{Pt}/d_{REE1}))\,\mathrm{sech}(t_{Pt}/\lambda'_{Pt}) \\ & + H_{DL2}(1 - \mathrm{sech}(t_{Pt}/d_{REE2})) \\ & + H'_{DL0}(1 - \mathrm{sech}(t_{Pt}/\lambda'_{Pt})), \end{aligned} \tag{3}$$

where H_{DL1} and H_{DL2} are the REE induced DL-SOT from sub./Pt and Pt/Co interfaces. H'_{DL0} is the SHE induced DL-SOT with $t_{Pt} =$ 0.2-1.1 nm, estimated based on the θ_{SH}-ρ_{Pt} plot. The obtained ξ_{DL1} and ξ_{DL2} in Fig. 2(c) show opposite sign, consistent with the sign of ξ_{FL1} and ξ_{FL2}.

4. Conclusions

We present a thorough, quantitative disentanglement of the SOTs originated from SHE and REE in Pt/Co bilayers. The FL-SOT is found to originate from the REE. The REE induced ξ_{FL1} and ξ_{FL2} at sub./Pt, Pt/Co interfaces are of comparable magnitude, but opposite sign, which is consistent with the REE. The REE-induced ξ_{DL1} and ξ_{DL2} are also of opposite sign, and are about 1 order of magnitude smaller than the maximum ξ_{DL0}. This work quantifies the SOT in SH systems with the presence of strong Rashba spin splitting.

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