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Rashba-Edelstein effect in epitaxial Pt/Co bilayers grown on Al_2O_3(0001) substrates

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Abstract

We report the observation of magnetoresistance (MR) stemming from the Rashba-Edelstein effect in epitaxial (epi-) Pt/Co bilayers grown on Al_2O_3(0001) substrates. A large inverse Edelstein length λ_{IEE} of a few nanometers is extracted from the MR measurement, suggesting efficient charge-to-spin conversion at Pt/Co interface. A temperature-independent Rashba parameter with the lower bound of 10^{-10} eV m is evaluated from a detailed MR analysis. By performing the spin torque ferromagnetic resonance (ST-FMR) measurement, a 10-fold increase in the field-like spin torque efficiency for epi- samples is obtained compared to that of the polycrystalline samples, suggesting significantly enhanced Rashba spin orbit coupling, which is qualitatively consistent with the observed large λ_{IEE}. Additionally, a two-fold enhancement in the damping-like spin torque efficiency is obtained in epi- samples, which is very likely attributed to the large Rashba SOC instead of conventionally considered bulk spin Hall effect.

1. Introduction

The recent discovery of the giant spin Hall effect (SHE)[1] in heavy metals (HMs) with strong spin orbit coupling (SOC) has made it possible to control the magnetizations via electrical means: the flow of a SHE-induced transverse spin current into the neighboring ferromagnetic layer exerts spin orbit torques (SOTs) on it and realizes potential magnetization reversal. The origin of the SHE in HMs lies in the predicted large spin Hall conductivity from band structure calculations.[2] While the SHE enables the charge-to-spin conversion in the bulk of the SO materials, the Rashba-Edelstein effect (REE)[3,4] realizes it at interfaces: the shift of the Fermi contours creates spin accumulations at interfaces, consequently contributing to the generation of a spin current with an electric field.

Although the mechanism of the SHE and REE is intrinsically different, both effects are expected to induce SOTs. In this work, we observed the magnetoresistance (MR) originated from the REE[5] in epitaxial (epi-) Pt/Co samples: a large inverse Edelstein length λ_{IEE} of a few nanometers is extracted from a detailed MR measurement, suggesting efficient charge-to-spin conversion at Pt/Co interface. By performing the spin torque ferromagnetic resonance measurement, we discuss the enhancement of the SOTs in epi- samples compared to the polycrystalline (poly-) ones.

2. Experimental methods

Pt(t_N)/Co(t_F) bilayers are sputter-deposited onto Al_2O_3(0001) substrates to fabricate epi- samples. As a control set, poly- Pt/Co bilayers are deposited onto thermally oxidized Si substrate for comparison. The average roughness at Pt/Co interface is measured to be below 0.1 nm and about 0.3 nm for epi- and poly- samples, respectively. To make ST-FMR devices, thin films are patterned into rectangular shapes using electron beam lithography. Hall bars for MR measurement are fabricated using conventional photolithography. The definition of the MR in this work is the same as the spin Hall MR (SMR),[6,7] *i.e.* $MR = (R_{xx}(H_y)\text{-}R_{xx}(H_z))/R_{xx}(H_z)$, but the origin is from a combination of both SHE and REE.[5]

3. Results and discussions

Fig. 1 shows the MR ratio as a function of t_N for poly- and epi- samples at RT. The experimental data can be well fitted by the conventional SMR theory shown as follows:

$$\frac{\Delta R_{xx}^{SMR}}{R_{xx}^{0}} \approx -\xi_{DL}^{2} \frac{\lambda_{sf}}{t_N} \frac{\tanh\left(t_N/2\lambda_{sf}\right)}{1+\eta}\left[1-\frac{1}{\cosh\left(t_N/\lambda_{sf}\right)}\right] \quad (1)$$

in which $\eta = \rho_N t_F/\rho_F t_N$ is the current shunting coefficient. The poly- samples yield a ξ_{DL} of 0.19 with λ_{sf} of 0.93 nm, showing consistency with earlier reports (*e.g.* ξ_{DL} of 0.12-0.16 and λ_{sf} of 1.0-3.0 nm). But for epi- samples, a large ξ_{DL} of 0.33 with an unphysically short λ_{sf} of 0.35 nm is obtained. Therefore, the SMR model is no longer valid for the analysis of epi- samples. With the extremely short λ_{sf}, we consider the REE instead of the SHE to be the *main* source of spin current generation.

In order to analyze the observed MR which is induced by both REE and SHE, a model is derived in which a Rashba potential $\lambda_{IEE}\hat{\boldsymbol{z}} \times \langle \boldsymbol{k} \rangle$ is added to the boundary condition in the original SMR theory:

$$\begin{aligned}
\frac{\Delta R_{xx}}{R_0} &\approx -\frac{\lambda_{sf}/\rho_N}{t_N/\rho_N + t_F/\rho_F}\mathrm{Re}\left[\frac{2\rho_N\lambda_{sf}G_{\uparrow\downarrow}}{1+2\rho_N\lambda_{sf}G_{\uparrow\downarrow}\coth(t_N/\lambda_{sf})}\right] \\
&\times\left\{\left[\theta_{SH}\tanh\frac{t_N}{2\lambda_{sf}}+\left(\frac{\lambda_{IEE}}{2\lambda_{sf}}\right)\right]^2\right. \\
&-2\left(\frac{\lambda_{IEE}}{2\lambda_{sf}}\right)\left[\theta_{SH}\tanh\frac{t_N}{2\lambda_{sf}}+\left(\frac{\lambda_{IEE}}{2\lambda_{sf}}\right)\right]\frac{\langle\sinh\left[(t_N-d_2)/\lambda_{sf}\right]\rangle}{\sinh(t_N/\lambda_{sf})} \\
&\left.+\left(\frac{\lambda_{IEE}}{2\lambda_{sf}}\right)^2\frac{\langle\sinh^2\left[(t_N-d_2)/\lambda_{sf}\right]\rangle}{\sinh^2(t_N/\lambda_{sf})}\right\} \quad (2)
\end{aligned}$$

in which $\rho_{N(F)}$ and $t_{N(F)}$ are the resistivity and thickness

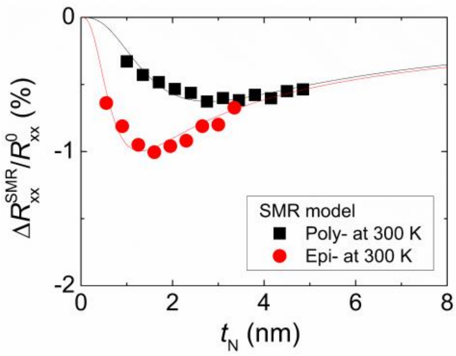

Fig. 1 SMR ratio as a function of t_N for poly- and epi- Pt(t_N)/Co(3) at RT.

of Pt(Co) layer, respectively; θ_{SH} and λ_{sf} are the bulk spin Hall angle and spin diffusion length in Pt; $G_{\uparrow\downarrow}$ is the spin mixing conductance at Pt/Co interface, λ_{IEE} and d_2 are the inverse Edelstein length and effective thickness of the RE region.

In order to fit our results with Eq. (2), we consider the Elliot-Yafet (EY) spin relaxation mechanism for bulk Pt[8] with $\lambda_{sf} \cdot \rho_N$ ranging from (0.36-0.69)×10^{-15} Ω m^2 and a fix the value of $\lambda_{sf} \cdot \theta_{SH}$ = 0.2 nm, corresponding to a θ_{SH} ranging from 0.06-0.12, consistent with previous reports. As a result, we found that d_2 is averaged to be about 0.6 nm, independent of *T*; a large λ_{IEE} of a few nanometers (*e.g.* 2.5 nm at 300 K and 5.3 nm at 4.2 K) is obtained, which is comparable to that in the $LaAlO_3/SrTiO_3$ 2 dimensional electron gas,[9] demonstrating efficient interfacial charge-to-spin conversion. From the *T* dependent of λ_{IEE} (*e.g.* from Fig. 2) we obtain a reasonable Rashba parameter in the order of 10^{-10} *e*V m which is *T* independent.

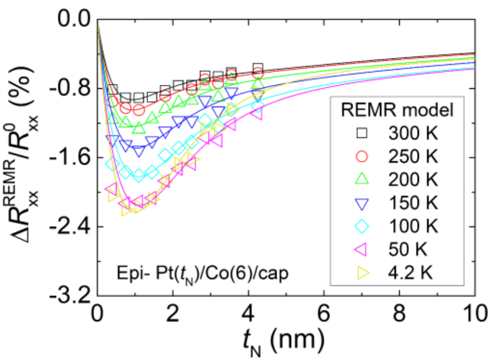

Fig. 2 *T* dependent of REMR for epi- Pt(t_N)/Co(6) fitted by Equation (1).

The ST-FMR results are analyzed by fitting the ST-FMR spectra (Fig. 3) using a combination of a symmetric (*S*) and anti-symmetric (*A*) Lorentzian function. The spin torque efficiency is obtained via

$$\xi_{ST} = \frac{S}{A}\frac{e\mu_0 M_s t_F t_N}{\hbar}\left(1 + \mu_0 M_{eff}/\mu_0 H_R\right)^{1/2} \quad (3)$$

in which *e* is the electron charge, $\mu_0 M_s$ is the saturation magnetization, $\mu_0 H_R$ is the resonance field, $\mu_0 M_{eff}$ is the effective demagnetization field, obtained by fitting the frequency as a function of the H_R using the Kittel formula $f_R = (\gamma/2\pi)\left[\mu_0 H_R\left(\mu_0 H_R + \mu_0 M_{eff}\right)\right]^{1/2}$.

As a result, we found the damping-like and field-like spin torque efficiency (ξ_{DL} and ξ_{FL}) for the poly- control samples to be 0.16 and 0.016; while for epi- samples, a 10-fold increase in the ξ_{FL} of 0.2 is found, suggesting a substantially enhanced Rashba SOC at Pt/Co, which is consistent with the large λ_{IEE} found through the MR measurement. Additionally, a 2-fold increase in the ξ_{DL} is found for the epi- samples, though the resistivity for both layers is lower compared to poly- samples. We will further discuss that such enhancement probably does not come from the bulk SHE in Pt, but has its origin in the Rashba SOC.

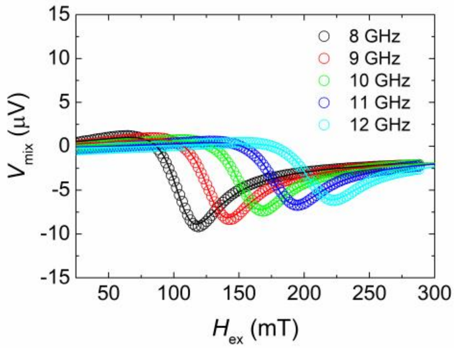

Fig. 3 ST-FMR spectra at different frequency for poly- sample with structure of Pt(10)/Co(3).

4. Summary

We observe MR stemming from the REE in epi- Pt/Co bilayers. A large λ_{IEE} of a few nanometers is extracted from a detailed MR measurement, suggesting efficient charge-to-spin conversion at Pt/Co interface. By performing the ST-FMR measurement, a 10-fold increase in the ξ_{FL} for epi- samples is obtained compared to that of the poly- samples, suggesting significantly enhanced Rashba SOC, which is qualitatively consistent with the observed large λ_{IEE}. Moreover, a two-fold enhancement in the ξ_{DL} is obtained in epi- samples, which is very likely attributed to the large Rashba SOC instead of bulk spin Hall effect in Pt layer.

5. References

[1] L. Liu *et al.*, Science **336**, 555 (2012).

[2] J. Sinova *et al.*, Reviews of Modern Physics **87**, 1213 (2015).

[3] Y.A. Bychkov and E.I. Rashba, JETP Letters **39**, 78 (1984).

[4] V.M. Edelstein, Solid State Communications **73**, 233 (1990).

[5] H. Nakayama *et al.*, Physical Review Letters **117**, 116602 (2016).

[6] H. Nakayama *et al.*, Physical Review Letters **110**, 206601 (2013).

[7] J. Kim *et al.*, Physical Review Letters **116**, 097201 (2016).

[8] E. Sagasta *et al.*, Physical Review B **94**, 060412(R) (2016).

[9] E. Lesne *et al.*, Nature Materials **15**, 1261 (2016).