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# Current Direction-dependent Spin Hall Magnetoresistance in Epitaxial Pt/Co Bilayers on MgO (110)

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**Abstract**

**We demonstrate that large anisotropy in the spin Hall magnetoresistance (SMR) of epitaxial Pt/Co bilayers on MgO (110) depends on the applied current direction with respect to the two primary in-plane crystal directions, $[001]$ and $[1\bar{1}0]$, in the Pt layer. At sufficient Pt thickness, there is a greater than 2 times increase in ΔSMR when current flows in the $[001]$ direction as compared to current in $[1\bar{1}0]$. The observed anisotropic SMR suggests anisotropic spin-orbit torque.**

## 1. Introduction

Experiments regarding spin-orbit torques have primarily been performed using polycrystalline metal/ferromagnet systems [1]. However, an enhanced Rashba-Edelstein (RE) effect is expected in epitaxial Pt/Co bilayers since the D'yakonov-Perel (DP) spin relaxation mechanism is dominant, for example in epitaxial Pt thin films grown on MgO (111) substrates [2]. Further, an anisotropic spin Hall effect has been predicted in hexagonal and tetragonal systems [3]. In this work, strong anisotropic spin Hall magnetoresistance (SMR) is observed at room temperature in epitaxial Pt/Co bilayers on MgO (110), the magnitude of which depends greatly on the crystal lattice direction along which current is applied, along $[001]$ or $[1\bar{1}0]$ (see Fig. 1c inset).

## 2. Experimental Methods

*Fabrication*

The Pt/Co films were grown using magnetron sputtering, with Pt grown at 200°C in order to achieve good epitaxy on the MgO substrate, and Co and the $Al_2O_3$ capping layer grown at room temperature. For thickness dependent measurements, the Pt layer was grown as a gradient in thickness, while flat reference samples were used to calibrate thickness. Finally, Hall bars were patterned using photolithography along $[001]$ and $[1\bar{1}0]$, as seen in the Fig. 1c inset.

*Measurement Techniques*

Epitaxy of the films was confirmed using RHEED during growth to qualitatively monitor the growth, and also via in-plane XRD through phi scans, in which the 2-fold rotational symmetry of the 110 surface was seen.

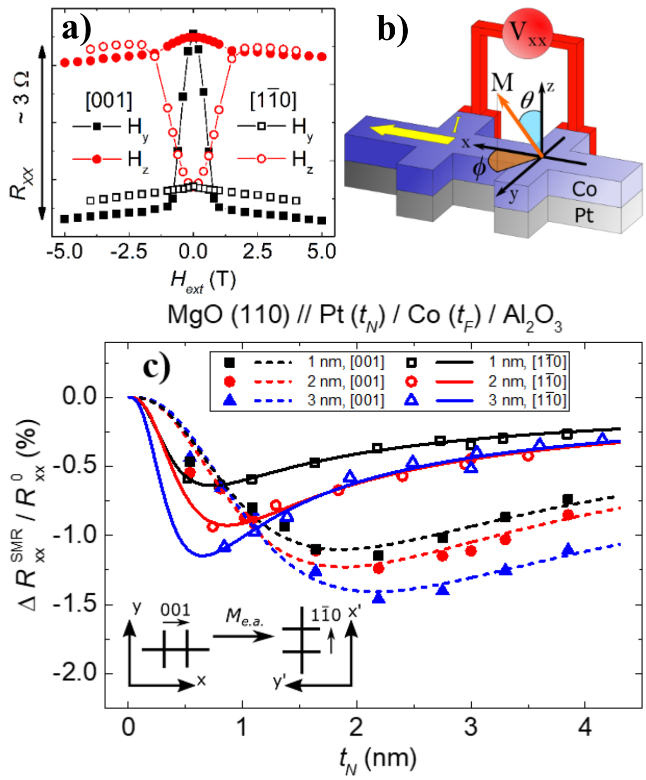


Fig 1. a) Example $R_{XX}$ measurements for $[001]$ and $[1\bar{1}0]$. b) Diagram of Hall bar defining theta and phi directions. c) Pt thickness $t_N$ dependence of SMR signal for various Co thicknesses. $[001]$ and $[1\bar{1}0]$ define the current direction in the Pt layer. Open/filled symbols are SMR data; solid/dotted lines are fits by standard SMR model. Inset defines Hall bar orientations; $\hat{x}$ is defined by applied current direction.

For the magnetoresistance (MR) measurements, a Quantum Design PPMS was used for both thickness and angular dependent MR measurements. During measurements, a field of at least 4 T was applied to fully saturate the magnetization of the samples.

## 3. Results and Discussion

*Magnetization Direction*

From the shape of the raw $H_y$ and $H_z$ field scans (as seen in Fig. 1a), it was found that due to magnetocrystalline anisotropy in the Co that is much larger than the shape anisotropy due to Hall bar patterning, the magnetic easy axis is always aligned along the [001] direction, regardless of Hall bar orientation. This is compensated for by applying an external magnetic field of more than 4 T.

*Thickness Dependent MR*

Thickness dependent measurements were performed by measuring the difference in longitudinal resistance when magnetization is fully saturated in the $\hat{y}$ (in-plane perpendicular to current direction) or $\hat{z}$ (out-of-plane) directions (see Fig. 1b), and $\Delta R_{xx}^{SMR} = R_{xx}(H_y) - R_{xx}(H_z)$ [4]. These measurements allow for extraction of the spin Hall angle ($\theta_{SH}$) and the spin diffusion length ($\lambda_{sf}$).

As shown in Fig. 1c, there is a striking difference in the SMR signals for Hall bars aligned with the [001] or $[1\bar{1}0]$ directions. At small Pt thicknesses (below ~1 nm), ΔSMR for $[1\bar{1}0]$ is larger than for [001], but after ~2 nm of Pt, the signal for [001] becomes more than 2 times larger than for $[1\bar{1}0]$. $\theta_{SH}$ values obtained from fittings using equation 1 (wherein $\eta = \rho_N t_F / \rho_F t_N$ is the current shunting coefficient), which is based on the standard SMR model [2], are nearly equivalent between the two directions ($\theta_{SH}$ ~ 0.25 ± 0.05), but there is a large difference in the spin diffusion length ($\lambda_{sf}^{[1\bar{1}0]}$~ 0.25 ± 0.05 nm, and $\lambda_{sf}^{[001]}$~ 0.71 ± 0.02 nm).

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

These extremely small $\lambda_{sf}$ values indicate that this standard SMR model may not be entirely valid for these epitaxial samples, and that the RE effect plays a role at the Pt/Co interface [2]. Furthermore, the results of resistivity $\rho_{[1\bar{1}0]}^{\mathrm{Pt}}$~14 μΩ · cm < $\rho_{[001]}^{\mathrm{Pt}}$~21 μΩ · cm and spin diffusion length $\lambda_{sf}^{[1\bar{1}0]} < \lambda_{sf}^{[001]}$ rule out the Elliot-Yafet spin relaxation mechanism (in which $\lambda_{sf} \propto {}^{1}/{\rho_{\mathrm{Pt}}}$) in these bilayers. This result suggests the DP mechanism is dominant, in which spins precess around an effective magnetic field between scattering events, and is consistent with our previous work [2].

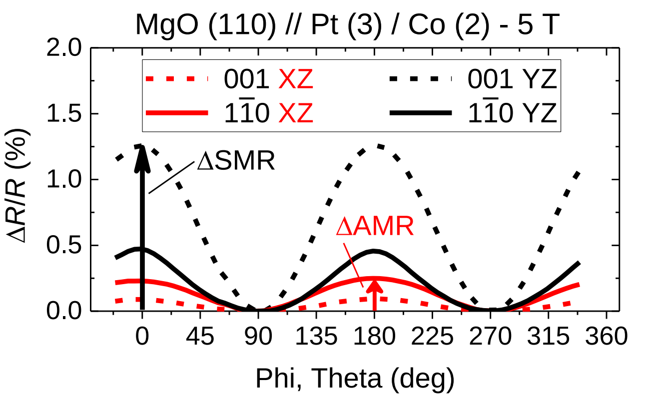


Fig 2. Angular dependent MR measurements taken at 5 T in XZ (AMR, red curves) and YZ planes (SMR, black curves), for Pt (3) / Co (2) samples showing a slight difference in AMR and large difference in SMR between the two primary current directions, [001] (dotted lines) and $[1\bar{1}0]$ (solid lines). ΔSMR (ΔAMR) is seen graphically as the peak value of the black (red) curves.

*Angular Dependent MR*

To further investigate the anisotropy in the MR signal, angular dependent MR measurements were performed. Because the anisotropic magnetoresistance (AMR) and SMR differ in their angular dependence, it is easy to separate their contributions. AMR depends on the angle between the magnetization and the applied current, so during a YZ scan this is a constant at 90°. SMR, on the other hand, depends on the angle between spin accumulation and magnetization [5], which is likewise constant at 90° in an XZ scan.

In Fig. 2, it can be seen that once again there is a striking difference in the MR signal between the [001] or $[1\bar{1}0]$ directions, especially in YZ scans. Measurements were taken at 5 T, and $\Delta R/R = (R - R_{90°})/R_{90°}$, while ΔSMR, $\Delta\mathrm{AMR} = \Delta R^{\max}/R$, which occurs at 0° and 180°. The YZ scans in Fig. 2 correspond to the SMR values at 3 nm $t_N$ in Fig. 1c, and show good agreement in magnitude. Further, the ratio of SMR to AMR is much higher along the [001] direction (ΔSMR/ΔAMR ~ 4.7 for 1 nm Co and ~ 13.8 for 2 nm Co) than the $[1\bar{1}0]$ direction (ΔSMR/ΔAMR ~ 1.6 for 1 nm Co and ~ 2.0 for 2 nm Co).

## 4. Conclusions

Large anisotropy in the SMR signal for epitaxial Pt/Co bilayers on MgO (110) has been discovered. From fitting the SMR data, a large difference in the spin diffusion length is found between the [001] and $[1\bar{1}0]$ directions, which implies the dominance of the DP spin relaxation mechanism and the importance of the interfacial Rashba effect in this system. At a Pt thickness of more than 2 nm, the ΔSMR signal is over 2 times larger for the [001] direction compared to the $[1\bar{1}0]$ direction. Through the angle dependent MR measurements to separate the AMR and SMR effects, the ΔSMR/ΔAMR ratio is 3~7 times larger for the [001] direction than the $[1\bar{1}0]$ direction, depending on Co thickness. The observed anisotropic SMR suggests current direction dependent spin-orbit torque.


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