Observation of Spin-orbit Magnetoresistance in CoFeB/HM/MgO

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Abstract
Spin-orbit magnetoresistance (SOMR) was recently predicted theoretically in Heavy metal (HM) / ferromagnetic insulator system, but the experimental observation is rare. Here, we report the observation of SOMR effect in Ferromagnetic Metal/HM/MgO system. We measure the Spin Hall Magnetoresistance as the function of the thickness of HM for CoFeB/HM/MgO and CoFeB/HM films where HM = Pt and Ta. The evidence of the SOMR is indicated by a peak of the MR ratio when the thickness of HM is around 1 ~ 2 nm for CoFeB/HM/MgO films, which is absent for CoFeB/HM films. Based on published theoretical results, we give the spin diffusion length $\lambda$ and spin Hall angle $\theta_{SH}$ of Ta and Pt, and estimate the spin-orbit coupling parameter $\eta$ at the interface between Pt/MgO and Ta/MgO.

Introduction
Magnetoresistance (MR) effect has long been studied, and their tunable property may provide potential application for future memory devices. In recent years, there have been a lot of reports about new unconventional magnetoresistances. The Spin Hall Magnetoresistance (SMR), which is the result of the interaction between Spin Hall Effect (SHE) and Inverse Spin Hall Effect (ISHE) [1], depends on the direction between magnetization and spin polarization, and it has been reported in several heterostructure systems, e. g. HM/FI samples [2] and HM/FC samples [3]; The recently reported Hanle Magnetoresistance (HMR) depends on the direction and strength of external
magnetic field, and it appears in thin metal film which has a strong spin-orbit coupling [4,5]; The Rashba-Edelstein Magnetoresistance (REMR) is reported in Bi/Ag/CoFeB trilayer, and this magnetoresistance is the result of interfacial spin-orbit coupling and spin-current reflection in the metallic heterostructure [6]. Those unconventional MR effect can help us understand the spin-charge conversion by either bulk or interfacial spin-orbit coupling better.

Recently, a new type of magnetoresistance was predicted [7], called spin orbit magnetoresistance (SOMR). It originates from the Rashba type spin-orbit coupling at the interface, usually enhanced by scattered heavy metal islands. Its angular dependence on $\mathbf{M}$ is identical to SMR, see the following equations. Though having identical angular dependence, it is proposed that we can differentiate SOMR from SMR by their thickness dependence.

\[
J_{\text{SMR}} = \left( 1 + \theta_{SH}^2 \right) \left[ \cosh \frac{2z - d_N}{2\lambda} + \left( 1 - m^2_y \right) Re \frac{2\lambda G_{11} \tanh \frac{d_N}{2\lambda}}{\sigma + 2\lambda G_{11} \coth \frac{d_N}{2\lambda}} \sinh \frac{z - d_N}{\lambda} \right] J_0 \\
J_{\text{SOMR}} = \left[ \frac{d_N}{d_\eta} + \frac{3}{20} \frac{d_N}{d_\eta} (2 + m^2_y) \right] d_\eta \sigma_0 E_x
\]

In the equations, $\theta_{SH}$ stands for spin Hall angle, $d_N$ stands for the thickness of the metal layer, $m_y$ stands for the projection of $\mathbf{M}$ on the direction perpendicular to the direction of charge current, $G_{11}$ stands for the complex spin-mixing interface conductance, $\lambda$ stands for the spin diffusion length and $d_\eta = \eta k_F$, $\eta$ being spin-orbit coupling parameter. Based on Eq. (2), the magnetoresistance will reach a maximum when $d_N = \sqrt{\frac{9}{20}} d_\eta$, which provides us with a way to estimate the strength of Rashba spin-orbit coupling at the interface using SOMR.

The first experimental observation of SOMR was done by Lifan Zhou et al. They observed SOMR in Cu[Pt]/YIG structure [8]. They confirmed that SOMR does have different thickness dependence from SMR. SOMR brings out another peak other than the conventional SMR peak, and that peak appears when the thickness of HM is very thin, because the Rashba spin-orbit coupling is enhanced by the scattered heavy metal islands according to their explanation.
In our experiments, we conduct MR measurements on CoFeB/Ta/MgO and CoFeB/Pt/MgO samples and observe the same SOMR phenomenon at thin HM layer. We then do MR measurements on CoFeB/Ta and CoFeB/Pt to confirm the MR we observe is SOMR and that it originates from the surface between HM and MgO. Based on existing SMR theory, we determine the spin diffusion length and spin hall angle of Ta and Pt, and then estimate the spin-orbit coupling strength of Ta/MgO and Pt/MgO using SOMR theory. Our finding provides a new example of SOMR in FM/HM/MgO samples.

**Fabrications**

We fabricated six sets of samples: (i) CoFeB(5 nm)/Ta(d_{Ta})/MgO(3 nm); (ii) CoFeB(5 nm)/Ta(d_{Ta}); (iii) CoFeB(5 nm)/Pt(d_{Pt})/MgO(3 nm); (iv) CoFeB(5 nm)/Pt(d_{Pt}); (v) CoFeB(d_{CoFeB})/Ta(10 nm)/MgO(3 nm); (vi) CoFeB(d_{CoFeB})/Pt(10 nm)/MgO(3 nm). All of them were fabricated on Si (100) substrates using magneton sputtering under room temperature, the background pressure of which was controlled to be $2 \times 10^{-7}$ Torr, and the pressure of Argon gas was controlled to be 5 mTorr.

**Experimental results**

The thickness of the layers are determined by X-ray reflectivity (XRR), a typical data for CoFeB(5 nm)/Pt(10 nm) is shown in FIG. 1[a]. From the number and the intensity of the peaks we can determine the roughness. The angle where fluctuation disappears also gives us information about the roughness. Then we ideally fit the curve to determine the thickness of each layer.

We perform angular-dependent MR measurements in two planes, one is called $\beta$ and one is called $\gamma$, which are shown in FIG. 1[b]. The definition of the angles are shown in the picture, and the external magnetic field is controlled to be $\sim 1.35 \, T$. Because those two directions are both out-of-plane directions, the saturated magnetic field under that circumstance will be very high, therefore the original SMR plots we get are not ideal sinusoidal curves. In order to get the sinusoidal curve predicted by Eq. (1) and Eq. (2), the misalignment of $H$ and $M$ has to be considered. We use the equation derived from static equilibrium condition of magnetization:
$$2H \sin(\beta - \beta_M) + \mu_0 M_{\text{eff}} \sin(2\beta_M) = 0$$

to determine the angle of $\mathbf{M}$, where $\mu_0 M_{\text{eff}}$ is the effective demagnetization field which is determined using Magneto-optical Kerr effect.

A typical data for Magneto-optical Kerr effect is shown in FIG. 1[c], and the sample used here is CoFeB(5 nm)/Ta(1.5 nm)/MgO(3 nm). The magnetic field is applied perpendicular to the surface of the sample to measure its Kerr signal as a function of external magnetic field. From FIG. 1[c] we can see that there is no magnetic hysteresis in this system, which implies there is no vertical magnetic anisotropy in this sample, and it is saturated under a magnetic field higher than 1.3 T, therefore we can safely take the saturated magnetic field as the demagnetization field.

FIG. 1. [a] XRR measurements. [b] MR measurements set up. The black line (SMR) corresponds to $\gamma$ measurement, and the red line (AMR) corresponds to $\beta$ measurement. [c] Magneto-optical Kerr effect measurement (300K).
We observed both SMR and AMR in our MR measurements. SMR looks quite similar to AMR, but their dependence on angle differ, which provides a way to distinguish them. AMR depends on the angle between magnetization and charge current, while SMR depends on the angle between magnetization and spin polarization, namely the angle between the external field and spin polarization. And the reason why we did not perform a MR measurement in \(x-y\) plane is that, SMR and AMR will mix in \(x-y\) plane measurements, making it difficult to analyze the SMR effect that we are focusing on. In \(\beta\) measurements, only the angle between external field and charge current is changing, therefore the MR can only originate from AMR. In \(\gamma\) measurements, only the angle between external field and spin polarization is changing, therefore the MR can only originate from SMR. The difference of these two effects is shown in FIG. 1[b]. We will focus on \(\gamma\) measurements, because another MR is detected other than SMR in our samples under \(\gamma\) MR measurement.

In the paper of Lifan Zhou et al.’s work[8], they discovered that SOMR appears as another peak before the peak of SMR. We observed the same effect in our measurements. See FIG. 2 [c]. When the HM layer is thin, the MR effect is very small. As the thickness increases, 2nm for CoFeB(10 nm)/Ta(\(d_{\text{Ta}}\))/MgO(3 nm) and 1.25nm for CoFeB(10 nm)/Pt(\(d_{\text{Pt}}\))/MgO(3 nm), the MR effect reaches a maximum, which is the SOMR effect we observe. Then it decreases for \(d_{\text{Ta}} = 3\)nm and \(d_{\text{Pt}} = 2\)nm. The MR effect reaches a maximum again for \(d_{\text{Ta}} = 5\)nm and \(d_{\text{Pt}} = 2.5\)nm, which is the sign of the conventional SMR effect. When \(d_{\text{Ta}}\) is thicker than 5nm and \(d_{\text{Pt}}\) is thicker than 2.5nm, the MR effect decreases again. The change of MR ratio as the function of HM thickness is shown in FIG. 2[a] and FIG. 2[b].

Based on Grigoryan et al.’s theory, SOMR originates from the Rashba-type SOI at the interface, and it will cause a MR maximum when \(d_{N} = \sqrt{9/20} d_{\eta}\). We speculate that SOMR originates from the Rashba spin-orbit interaction at the interface between Pt(Ta) and MgO. In order to make sure that the MR we observed is SOMR and that it is generated at the interface between HM(Pt, Ta) and MgO, we did exact the same measurements on CoFeB(10 nm)/Ta(\(d_{\text{Ta}}\)) and CoFeB(10 nm)/Pt(\(d_{\text{Pt}}\)). The \(\Delta \rho/\rho\) diagrams of those two series are shown in FIG. 2[a] and FIG. 2[b]. As we expected, the
SOMR peak disappears in this case. This result conforms to Grigoryan et al.’s theory that SOMR is the result of Rashba-type SOI and provides a strong evidence that the MR we observed is SOMR and it originates from the interface between the metal layer and MgO layer.

FIG. 2. [a] Ta layer thickness dependence of MR ratio for CoFeB(5 nm)/Ta($d_{Ta}$)/MgO(3 nm) and CoFeB(5 nm)/Ta($d_{Ta}$) respectively. [b] Pt layer thickness dependence of MR ratio for CoFeB(5 nm)/Pt($d_{Pt}$)/MgO(3 nm) and CoFeB(5 nm)/Pt($d_{Pt}$) respectively. [c] Angular dependent MR measurements in $\gamma$ direction for CoFeB(5 nm)/Ta($d_{Ta}$)/MgO(3 nm) and CoFeB(5 nm)/Pt($d_{Pt}$)/MgO(3 nm).

Analysis

In SMR theory developed by Yan-Ting Chen et al., the dependence of ratio $\Delta \rho/\rho$ can be described by the following equation:
\[
\frac{\Delta \rho}{\rho} = \theta_{SH}^2 \frac{\lambda}{d_N} \frac{2 \lambda G_r \tanh \frac{d_N}{2\lambda}}{\sigma + 2 \lambda G_r \coth \frac{d_N}{2\lambda}}
\]

where \(\theta_{SH}\) is the spin Hall angle, \(\lambda\) is spin-diffusion length, \(G_r\) is the real part of spin-mixing conductance, \(\sigma\) is conductivity and \(d_N\) is the thickness of HM layer.

In our results, the series without MgO layer show only SMR, and using Eq. (3) we can ideally fit the curve. We get \(\lambda_{Ta} = 2.83\) nm, and \(\lambda_{Pt} = 1.12\) nm. We also get the spin hall angle from our results, where \(\theta_{Ta} = -5.47 \pm 0.18\%\) and \(\theta_{Pt} = 8.77 \pm 0.27\%\).

FIG. 3. SMR fitting for CoFeB(5 nm)/Ta\((d_{Ta})\) and CoFeB(5 nm)/Pt\((d_{Pt})\).

For SOMR, the resistivity will reach its maximum when \(d/d_\eta = \sqrt{9/20}\), where \(d_\eta = \eta k_F\), with \(\eta\) the spin-orbit coupling parameter[7]. In our results, we can determine the thickness where SOMR causes resistivity to reach its maximum and therefore estimate the value of \(\eta\). We use

\[k_F = (3\pi^2 n)^{\frac{1}{3}}\]

to determine the fermi wave vector. For SOMR(Ta) reaching its maximum at 2nm and SOMR(Pt) reaching its maximum at 1.25nm, we get \(\eta(Ta) = 2.005 \times 10^{-19}\) m\(^2\) and \(\eta(Pt) = 1.4895 \times 10^{-19}\) m\(^2\). Please be noticed that \(\eta\) here is not the conventional Rashba parameter.

**Conclusions**

We report the SOMR effect in CoFeB/Ta/MgO and CoFeB/Pt/MgO system, and confirm that SOMR originates from the interface between HM and MgO. Yet the amplitude of SOMR in CoFeB/Ta/MgO
is small compared to its SMR amplitude, the relation between the heavy metal and the amplitude of SOMR is still not obvious and needs more research. In the end we calculate the spin diffusion length and spin hall angle of Ta and Pt, and then estimate the spin-orbit coupling parameter $\eta$ at the interface between Pt/MgO and Ta/MgO. This paper is a new report of SOMR in FM/HM/MgO samples, which may provide more details about SOMR effect.

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