Interplay of Rashba effect and spin Hall effect in perpendicular Pt/Co/MgO magnetic multilayers*

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The interplay of the Rashba effect and the spin Hall effect originating from current induced spin–orbit coupling was investigated in the as-deposited and annealed Pt/Co/MgO stacks with perpendicular magnetic anisotropy. The above two effects were analyzed based on Hall measurements under external magnetic fields longitudinal and vertical to dc current, respectively. The coercive field as a function of dc current in vertical mode with only the Rashba effect involved decreases due to thermal annealing. Meanwhile, spin orbit torques calculated from Hall resistance with only the spin Hall effect involved in the longitudinal mode decrease in the annealed sample. The experimental results prove that the bottom Pt/Co interface rather than the Co/MgO top one plays a more critical role in both Rashba effect and spin Hall effect.

Keywords: spin Hall effect, Rashba effect, perpendicular multilayers

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1. Introduction

Spin transfer torque generated by spin-polarized current provides another powerful method to manipulate the magnetization direction compared with the traditional way due to Oersted fields.[1–8] More recently, torque related to the Rashba effect and spin Hall effect (SHE), so called spin–orbit torque herein, originating from the spin–orbit coupling (SOC) induced by dc electric current has been demonstrated to realize the magnetization switch.[9–14] It offers for the current-in-plane device more advantages in applications with lower power consumption and higher reliability such as the three-terminal magnetic tunnel junctions with the separated read/write wires.[12] The entangled correlation due to the Rashba effect and SHE is not fully understood although much progress has been made in heavy metal (HM)/ferromagnetic (FM)/oxide heterostructures with structural inversion asymmetry (SIA), such as Pt/Co/MgO,[15] Pt/Co/AlOx,[9,10,13] Ta/CoFeB/MgO,[16–18] and W/CoFeB/MgO.[19] The realization including the experimental setup and novel multilayers to separate the measured parameters from the Rashba effect and the SHE is considerably critical. In this letter, several methods have been carried out to solve this issue, including direction-variable Hall measurements, tunable interfacial structures, together with thermal annealing. With respect to the Pt/Co/MgO sample in vertical mode with only the Rashba effect involved, the coercivity (H_c) as a function of dc current decreases after it is annealed. For the longitudinal mode with only the spin Hall effect involved, calculated SHE torques from the Hall resistance curve show a clear drop after annealing as well. The results from samples with tunable Pt/Co structures prove that the bottom Pt/Co interface rather than the Co/MgO top one has a critical influence here, which can give a reasonable explanation of the reduced effect due to annealing.

2. Experimental details

Three multilayered structures consisting of (from substrate) Pt(3)/Co(0.9)/MgO(2) (labeled as S-1), Pt(2)/Co(0.45)/Pt(1)/Co(0.45)/MgO(2) (S-2), and Pt(2)/[Co(0.3)/Pt(0.5)]$_2$/Co(0.3)/MgO(2) (S-3) (all thickness in nm) were prepared on Si wafer by magnetron sputtering. A 2-nm-thick Pt layer was deposited on the top as the capping layer to avoid degradation. The films were patterned into 10-μm-wide Hall bars using photolithography and Ar-ion etching for the transport measurements. Thermal annealing of the patterned samples were carried out in a vacuum furnace (less than 5×10^{-7} Torr) for 40 minutes at 150 °C and 300 °C, respectively.

A Keithley 2400 SourceMeter as dc current injection and a 2182A NanovoltMeter for Hall voltage were used for transport measurement. The temperature dependence of resistance was measured by a Quantum Design Physical Property Measurement System (PPMS). The details about the sample

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preparation, microfabrication, annealing process, and transport measurements can be found in our previous work.[20,21]

3. Results and discussion

The experimental setup is illustrated in Fig. 1(a). The anomalous Hall resistance ($R_{\rm Hall}$) was measured under external magnetic fields ($H_{\rm ext}$) applied along the z axis. The value of $R_{\rm Hall}$ is proportional to the average vertical component of Co magnetic moments. This setup is called vertical mode, where the direction of $H_{\rm ext}$ is perpendicular to the dc current. The Hall hysteresis loops shown in Fig. 1(b) prove the good perpendicular magnetic anisotropy (PMA) behavior of the as-deposited S-1: Pt(3)/Co(0.9)/MgO(2) (in nm) stack. The coercivity is found to decrease with increasing dc current. For example, the value of $H_{\rm c}$ is 182 Oe, but only 155 Oe for current of 0.5 mA to 3.5 mA, respectively. The obvious decrease of $H_{\rm c}$ is characteristic of the Rashba effect in multilayers, which was reported by Ohno's group in Ta/CoFeB/MgO structure with SIA.[22] It is well known that Oersted fields from Ampere's law and temperature rise due to Joule heating could also cause the coercivity reduction, so their influence needs to be excluded for further discussion. Figure 1(c) shows the longitudinal resistivity of the sample S-1: Pt(3)/Co(0.9)/MgO(2) (in nm) as a function of applied currents (red scale at bottom) and temperatures (black scale at top), respectively. The resistivity is 33.4 μΩ·cm with a current of 0.5 mA, but only increases to 33.5 μΩ·cm with a 3.5 mA current. The resistivity variation due to currents is estimated to be 0.3%. The temperature dependence of resistivity in the range from 300 K to 355 K is also presented in Fig. 1(c). A linear behavior for resistivity versus temperature was clearly observed. Based on the comparison of the resistivity as a function of current and temperature, the temperature rise due to Joule heating by dc current increasing from 0.5 mA to 3.5 mA is only 5 K. Furthermore, Oersted fields induced by current with a 10 μm wide Hall bar is calculated to be less than 0.63 Oe/mA. So the influence of these two effects can be ignored. Based on the above results, it is reasonable to neglect the temperature variation and Oersted fields due to dc current for our measurements.

We focus on the current dependence of coercivity under vertical mode for deeper understanding. Figure 2(a) presents the coercivity as a function of dc current for sample S-1: Pt(3)/Co(0.9)/MgO(2) (in nm) at various annealing temperatures, such as 150 °C and 300 °C. For the as-deposited sample, the slope was 16 Oe/mA, indicating the Rashba effect as stated above. For sample S-1 annealed at 150 °C and 300 °C, it decreases by 8 Oe/mA and 6 Oe/mA, respectively. The value of $R_{\rm Hall}$ increases for the annealed sample. For example, it is about 0.4 Ω for the as-deposited sample, but increases to 1.1 Ω for the sample annealed at 300 °C, shown in the inset of Fig. 2(a). This will be discussed later in detail. The square shape confirms that the PMA can be maintained after annealing.

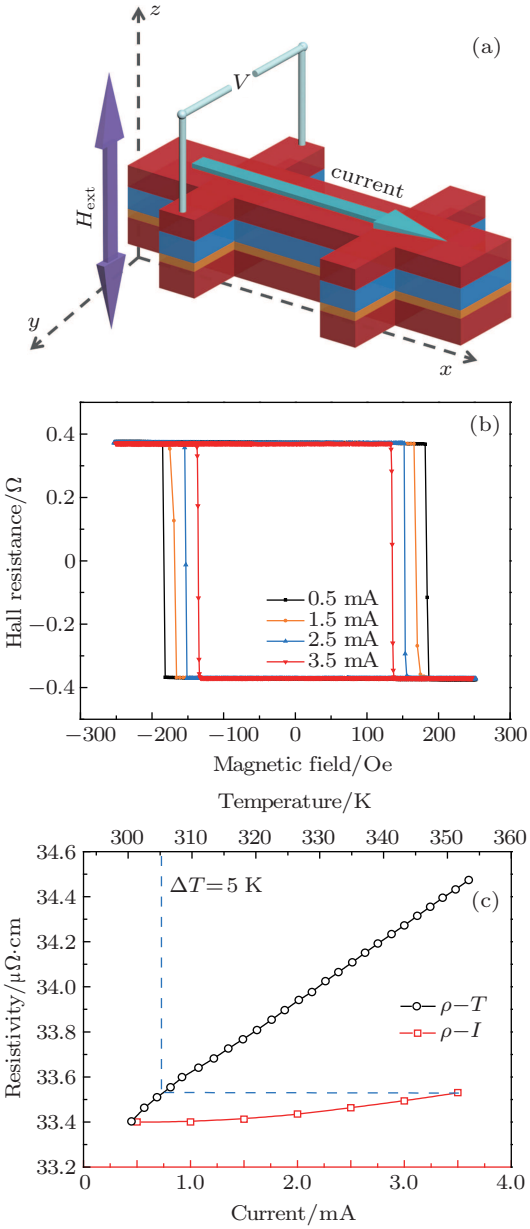


Fig. 1. (color online) (a) Schematic illustration for vertical measurement. (b) Hall hysteresis loops for Pt(3)/Co(0.9)/MgO(2) (in nm) (sample S-1) under various applied dc currents. (c) The longitudinal resistivity for S-1 as a function of current (red scale at bottom) and temperature (black scale at top), respectively.

The HM/FM interfacial structures have been proven to be considerably critical for the Rashba effect in multilayers in former studies.[23–25] In order to manipulate the interfacial structures, two samples were deposited, S-2: Pt(2)/Co(0.45)/Pt(1)/Co(0.45)/MgO(2), and S-3: Pt(2)/[Co(0.3)/Pt(0.5)]$_2$/Co(0.3)/MgO(2) (in nm). It is necessary to emphasize that the total thickness of Pt and Co is the same for three samples with different layer structures. In other words, the repeat number of Pt/Co is one, two, and three, respectively. Figure 2(b) shows the current dependence of coercivity for the above three samples. The slope is 16, 4, and

2 Oe/mA for sample S-1, S-2, and S-3, respectively. This obvious decrease is in good agreement with the behavior due to thermal annealing.

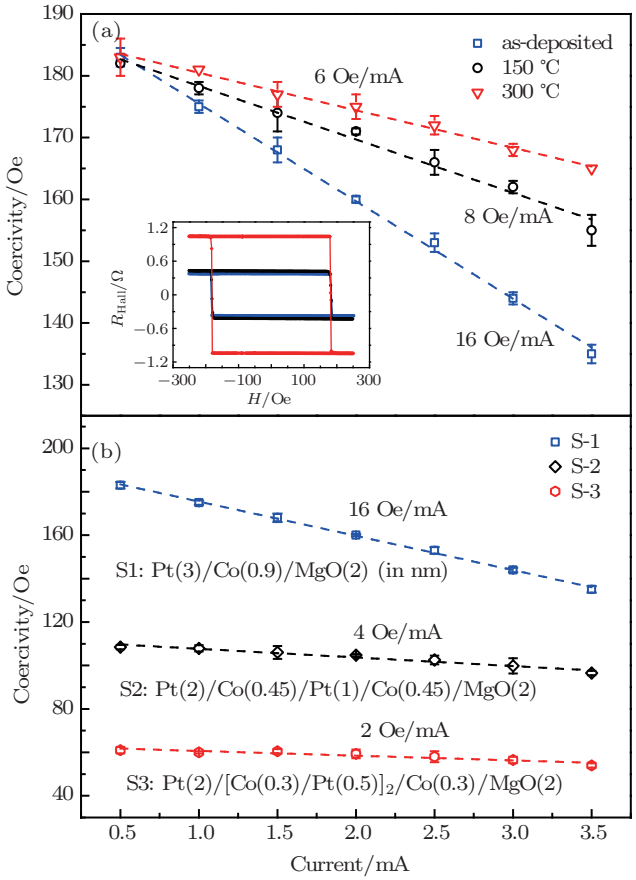


Fig. 2. (color online) (a) Coercivity as a function of current for Pt(3)/Co(0.9)/MgO(2) (S-1) stack annealed at different temperatures. (b) Coercivity as a function of current for as-deposited S-1, S-2, and S-3 stacks.

With respect to SHE in Pt/Co/MgO, the longitudinal mode is used for the investigation, where $R_{\rm Hall}$ is measured by applying a positive or negative current. The setup is shown by the inset of Fig. 3(a) with an external magnetic field ($H_{\rm ext}$) in the z–x plane, together with the β angle to the x axis. The direction of Co magnetization vector $\boldsymbol{M}$ will rotate towards $H_{\rm ext}$, and the angle between $\boldsymbol{M}$ and the x axis is defined as θ. Figure 3(a) shows the Hall resistance curves of S-1: Pt(3)/Co(0.9)/MgO(2) with currents of $\pm$3.5 mA in the field range from 4000 Oe to 11500 Oe. The data in the whole range is shown in the top inset of Fig. 3(a). For one $R_{\rm Hall}$, two $H_{\rm ext}$ values ($H_+(\theta)$ and $H_-(\theta)$) correspond to the positive and negative current, respectively. According to the macrospin model and the equilibrium conditions for $\boldsymbol{M}$,[13,16,19] the spin orbit torque due to SHE, $\tau_{\rm SHE}$, can be calculated by

$$\tau_{\rm SHE}=\frac{|H_+(\theta)-H_-(\theta)|}{2}\sin(\theta-\beta),$$

where $\theta=\arcsin(R_{\rm Hall}/R_0)$ according to Hall curves, and R_0 is the Hall resistance when $\theta=90°$. β is decided to be 4° by measurement apparatus. According to the above equation, the value of $H_+(\theta)-H_-(\theta)$ is proportional to $1/\sin(\theta-\beta)$, and the linear relationships under various currents are shown in Fig. 3(b). Figure 3(c) presents the $\tau_{\rm SHE}$ as a function of current for sample S-1 at as-deposited and annealed conditions. The slope for the as-deposited sample is 35 Oe/mA, but decreases to 22 Oe/mA and 5 Oe/mA with an annealing temperature of 150 °C and 300 °C, respectively.

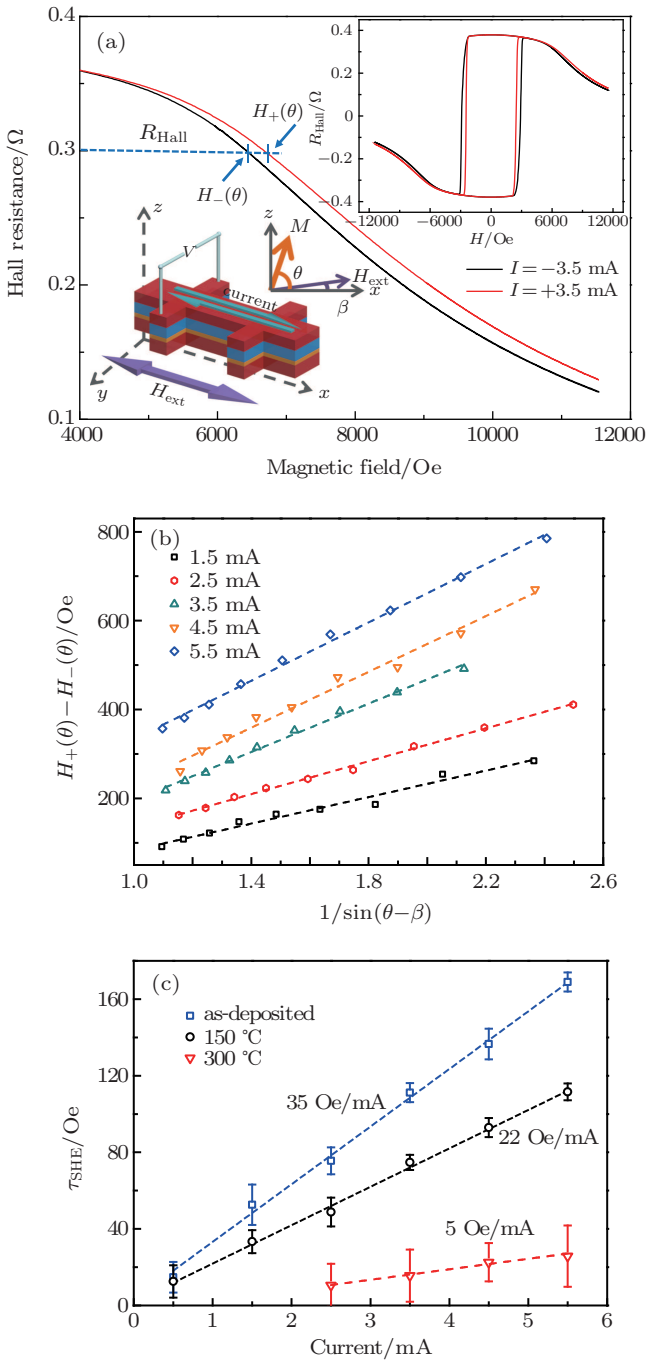


Fig. 3. (color online) (a) Hall resistance as a function of in-plane magnetic fields with the current of $\pm$3.5 mA in S-1: Pt(3)/Co(0.9)/MgO(2) (in nm). (b) Linear relationships between $H_+(\theta)-H_-(\theta)$ and $1/\sin(\theta-\beta)$ under different currents from 1.5 mA to 5.5 mA. (c) The calculated $\tau_{\rm SHE}$ as a function of current of the sample under different annealing temperatures.

As stated above, the Pt/Co interface plays a dominant role

in the transport behavior, where the Rashba effect and SHE are entangled due to spin orbit coupling. However, this interfacial role is quite different for the Rashba effect and SHE, which is investigated for the vertical and longitudinal modes, respectively. More exactly, for the vertical mode with only the Rashba effect involved, the measured AHE Hall resistance is closely related to PMA. It means the magnetic structures at the Pt/Co interface together with the perpendicular Co layer will determine the measured values due to the Rashba effect. Regarding the longitudinal mode with only SHE involved, the Hall resistance is measured. In this case, the Pt/Co interface plays a more critical role in the injection of spin current from Pt layer to Co layer. That is to say, the interfacial states, such as intermixing, roughness, and defects, are quite important for the SHE in longitudinal mode, rather than the magnetic states such as magnetized Pt partial layers for the Rashba effect in vertical mode.

Recently, the experimental evidence for the induced magnetization of HM films adjacent to a magnetic layer due to a strong proximity effect has been provided by x-ray magnetic circular dichroism measurements.[26] For the Pt/Co bilayer, it is reasonable to assume a magnetic interfacial layer consisting of magnetic Pt atoms and their adjacent Co atoms. Therefore, for simplicity, the Pt/Co bilayer can be considered as three stacks, including traditional Pt and layers separated by a magnetic interface. For the vertical mode with only the Rashba effect involved, the value of $R_{\rm Hall}$ shown in Fig. 2(a) increases with the raising annealing temperature, especially at 300 °C mainly because the intermixing at the Pt/Co interface takes place. This increasing behavior agrees with a previous report.[27] For samples with tunable Pt/Co structures, the Rashba effect is reduced due to the degradation of the magnetic interface (see Fig. 2(b)). Finally, for the longitudinal mode with only SHE involved, the value of SHE torque $\tau_{\rm SHE}$ decreases with thermal annealing due to the intermixing, roughness, and defects (see Fig. 3(c)). In longitudinal mode, this interface variation plays a direct effect on the spin current injection from Pt layer to Co layer.

Based on the above discussion about the interplay of the Rashba effect and SHE both due to spin orbit coupling, the Pt/Co interfacial structure plays an important role. However, the roles of the interface take place in different ways. For the vertical mode with only the Rashba effect involved, the magnetic structures at the interface are quite critical. Meanwhile, for the longitudinal mode with only SHE involved, the morphological states such as intermixing, roughness, and defects are more important.

4. Conclusions

In summary, the Rashba effect and SHE originating from current-induced spin orbit coupling were investigated in as-deposited and annealed Pt/Co/MgO with PMA based on transport measurements under direction-variable external magnetic field. According to the results of vertical mode Hall measurement, the coercivity as a function of dc current related to the Rashba effect decreases in annealed sample S-1: Pt(3)/Co(0.9)/MgO(2). This can be attributed to variation of the magnetic structure of the Pt/Co bilayer due to thermal annealing. Meanwhile, the results from samples with tunable interfaces (S-2 and S-3) can also prove the rationality of this interpretation. With respect to the SHE studied in longitudinal-mode Hall measurement, the calculated spin–orbit torque due to the SHE shows a clear drop after annealing, especially at 300 °C. This means that the morphological states such as intermixing, roughness, and defects are more important for the spin current injection.

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