Spin Hall magnetoresistance in an ultrathin Co₂FeAl system

Yan-qing Zhang^a, Hua-rui Fu^b, Niu-yi Sun^a, Wen-ru Che^a, Ding Ding^c, Juan Qin^c, Cai-yin You^b, Rong Shan^a, Zhen-gang Zhu^d

^a*Shanghai Key Laboratory of Special Artificial Microstructure and Pohl Institute of Solid State Physics and School of Physics Science and Engineering, Tongji University, Shanghai 200092, China*

^b*School of Materials Science and Engineering, Xi'an University of Technology, Xi'an 710048, China*

^c*School of Materials Science and Engineering, Shanghai University, Shanghai 20044, China*

^d*School of Electronic, Electrical and Communication Engineering, University of Chinese Academy of Sciences, Beijing 100049, China*

Abstract

Spin Hall magnetoresistance (SMR) is observed in an ultrathin Co₂FeAl layer covered by a thin Pt film. The Co₂FeAl layer grown on MgO substrate should be too thin to be continuous. The result reveals that the magnetic insulator layer, such as yttrium iron garnet (YIG) substrate which is frequently used so far, is actually not a requisite for the observation of SMR. This work may greatly help to understand the true nature of SMR effect.

Keywords:

ultrathin Pt/Co₂FeAl bilayer, spin Hall magnetoresistance, magnetic proximity effect

1. Introduction

Since the magnetic transport property of Pt grown on yttrium iron garnet (YIG) was reported several years ago [1], the drastic controversy on the understanding of its origin continues today. On the beginning, the strong ferromag-

*Corresponding author

**Corresponding author

Corresponding author

Email addresses: juan_qin@staff.shu.edu.cn (Juan Qin), caiyinyou@xaut.edu.cn (Cai-yin You), shan.rong@hotmail.com (Rong Shan)

netic characteristics in Pt films on YIG are considered as a consequence of static magnetic proximity effect (MPE) [1, 2, 3, 4]. Soon, Nakayama *et al.* excluded the contribution of static magnetic proximity effect through an inserted 6-nm-thick Cu layer between Pt and YIG, where the magnetic transport property of YIG/Cu/Pt film persists although it turns much weaker [5]. They pointed out that the magnetic transport property of Pt/YIG is actually induced by spin Hall effect (SHE) and meanwhile suggested a new magnetoresistance (MR) phenomenon, i.e. spin Hall magnetoresistance (SMR). Next, Lu Y. M. *et al.* insist on the MPE by a series of experiments on YIG/Pt and Pt/Permalloy/Pt films [6]. They found $\rho_{\parallel} \approx \rho_{\perp} > \rho_T$, where $\rho_{\perp}$, $\rho_{\parallel}$ and ρ_T are longitudinal resistivities with applied magnetic field ($\mathbf{H}$) direction perpendicular to the current direction out of plane (as z-direction), parallel with and perpendicular to it in plane (as x- and y-direction), respectively. This behavior was distinctly different from all other known MR effects including the SMR, and the new MR was termed as the hybrid MR. Immediately, the proposal of hybrid MR caused a more intense argument [7, 8, 9, 10, 11, 12, 13]. To understand the nature of MR in YIG/Pt films, Lin T. *et al.* [7] and Miao B. F. *et al.* [8] suggested two compromised solutions. The former regards that the SMR plays a main role at high temperature and MPE gradually manifests itself with decreasing temperature. The latter believes that the SMR dominates at low magnetic fields, while MPE at high fields. In review all these arguments, we found all viewpoints, to some degree, have their reasonable and unreasonable aspects. However, all these mentioned results about the SMR, or named hybrid MR in different references, were realized on magnetic insulator (MI) substrates only. The reported SMR mechanism are also strongly depended on the MI/(Pt, Pd) system. That is to say, if SMR could be observed in a system without MI substrates, all discussions about SMR are quite limited up to now.

Recently, we found that when conduction electrons are travelling in an ultra-thin nonmagnetic/ferromagnetic (NM/FM) bilayer, quantized states extending through the layers along the z direction may be formed, and thus conduction electrons feel like travelling in an inhomogeneous media, which suggests that

Figure 1: (Color online) Diagrammatic sketches of spin Hall effect in different structures. (a) and (b) show spin Hall effect in a continuous nonmagnetic metal layer grown on a magnetic insulator layer (MI) ; (c) and (d) display spin Hall effect in a discontinuous magnetic layer grown on a nonmagnetic insulator (NMI) layer covered by a nonmagnetic metal layer. Blue and red arrows indicate spins. The long yellow arrow represents an electron flow ($\mathbf{J}_e$). $\mathbf{M}$ indicates magnetic moments of MI in (a) and (b) or discontinuous magnetic layer in (c) and (d), respectively. Here spin accumulations only occur at top, bottom, left and right interfaces.

electrons from the FM layer can be affected by electronic properties of NM layer such as spin orbit coupling [14]. This discovery inspired us to realize SMR in an unexplored structure.

Figure 1 shows classic diagrammatic sketches of spin Hall effect in different structures. When a nonpolarized electron flow passes through a conductor, a transverse pure spin current will be generated due to the spin orbit coupling (SOC). The spin current density can be read as

$$\mathbf{J}_s = -\theta_{\text{SH}} \frac{\hbar}{2|e|} \mathbf{J}_e \times \boldsymbol{\sigma}, \quad (1)$$

where θ_{SH} is the spin Hall angle, $\boldsymbol{\sigma}$ represents the spin, $\hbar$ is the reduced Planck constant, e is the electronic charge, and $\mathbf{J}_e$ is the electron flow density [15, 16]. In a cylindrical wire the spins wind around the surface. For a wire with rectangular cross-section like the commonest thin film sample, spins are accumulated at opposite interfaces with opposite spin directions, as shown in Fig. 1. On the discussion about YIG/Pt system at present, spin accumulation at top and

bottom interfaces, as shown in Fig. 1(a), is considered as the only reason to trigger the SMR. Hereinto, the magnetization direction of magnetic insulator layer (e.g. YIG) parallel with and perpendicular to accumulated spins at YIG/Pt interface in xy plane, $\mathbf{M} \parallel \boldsymbol{\sigma}$ and $\mathbf{M} \perp \boldsymbol{\sigma}$, are deemed to be two maximum states of spin scattering and spin absorption, respectively. The resistance of Pt film can therefore be tuned by $\mathbf{M}$ under the interaction of inverse SHE, causing the SMR effect. The influence of spin accumulation at left and right interfaces shown in Fig. 1(b) was neglected in the SMR. Being the most important conclusion from this physical image of the SMR, magnetoresistance must remain constant when $\mathbf{M}$ is rotating in xz plane, because $\mathbf{M}$ has no transverse component. On the other hand, the magnetic insulator layer seems to be indispensable for the observation of SMR. This is the reason why so many studies on the SMR have chosen YIG, Fe_3O_4 and CoFe_2O_4 as the bottom layer [17, 18, 19, 20, 21, 22].

2. Experiments

In our work, MI substrate was replaced by a NMI substrate with a very thin magnetic layer, for example, Co_2FeAl (CFA). Two samples, Co_2FeAl (0.3 nm)/Pt (2.5 nm) and Co_2FeAl (0.6 nm)/Pt (2.5 nm), were prepared with Hall bar mask on MgO substrates by DC sputtering at room temperature. The base pressure is 2×10^{-5} Pa. Magnetic transport properties of samples were measured by a physical property measurement system (PPMS). Ultrathin Co_2FeAl film cannot grow on MgO substrate uniformly, and thus it is insulating until the thickness is over 1.1 nm. Unfortunately, the CFA layer is too thin and the surface morphology cannot be detected by atomic force microscopy in our experiment. Here spin Hall behavior should be similar to the conventional situation, as shown in Fig. 1(c) and (d).

3. Results and Conclusions

Figure 2 shows diagrammatic sketch of SMR measurement. Figure 2(a) defines the coordinate system. Figure 2(b) exhibits spin accumulations generated

Figure 2: (Color online) Diagrammatic sketches of spin Hall magnetoresistance. (a) Coordinate system of the electron flow (yellow arrow), transverse direction (green arrow) in plane, perpendicular direction (gray arrow), and schematic diagram notations of rotation angles of magnetic field in different planes. (b) spin accumulations generated by the electron flow ($\mathbf{J}_e$), where the black arrow at the center of every image represents $\mathbf{M}$ direction along the applied magnetic field when $\alpha=0^\circ$, $\beta=0^\circ$ and $\gamma=90^\circ$, corresponding to longitudinal resistance $\rho_{\parallel}$, ρ_T and $\rho_{\perp}$. w and t are sample's width and thickness, respectively.

by spin Hall effect of the electron flow ($\mathbf{J}_e$), where the black arrow at the center of every image represents $\mathbf{M}$ direction along the applied magnetic field. Also partial conduction electrons would be polarized along $\mathbf{M}$ direction.

For $\mathbf{M}$ in xy plane, the resistivity tensor can be written as

$$\hat{\rho} = \begin{pmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{pmatrix} = \begin{pmatrix} \rho_{\parallel} & \epsilon \\ \epsilon & \rho_T \end{pmatrix}, \quad (2)$$

Here ρ_{11} and ρ_{22} are longitudinal resistivities, ρ_{12} and ρ_{21} are transverse resistivities, respectively, when $\alpha = 0$ and 90° . We make $\rho_{12} = \rho_{21} = \epsilon$ because they are usually minute. For arbitrary α , using unitary transformation we get $\rho' = R_{-\alpha} \hat{\rho} R_{\alpha}$ [23], where

$$R_{\alpha} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix}, \quad (3)$$

is the rotation matrix. Then the longitudinal resistivity in new coordinate

system can be simply read as,

$$\begin{aligned}
\rho_l(\alpha) &= \begin{pmatrix} \cos \alpha & \sin \alpha \end{pmatrix} \begin{pmatrix} \rho_{\parallel} & \epsilon \\ \epsilon & \rho_T \end{pmatrix} \begin{pmatrix} \cos \alpha \\ \sin \alpha \end{pmatrix} \\
&= \rho_{\parallel} \cos^2 \alpha + 2\epsilon \sin \alpha \cos \alpha + \rho_T \sin^2 \alpha \\
&\approx \rho_{\parallel} - (\rho_{\parallel} - \rho_T) \sin^2 \alpha,
\end{aligned} \tag{4}$$

and

$$\rho_{\text{Trans}} \approx (\rho_T - \rho_{\parallel}) \sin \alpha \cos \alpha. \tag{5}$$

Using a phenomenological model, we get the same expression of the SMR on α as that in reference [5, 9, 10]. Changing α to β and γ , we can also obtain

$$\begin{aligned}
\rho_l(\beta) &\approx \rho_T - (\rho_T - \rho_{\perp}) \sin^2 \beta, \\
\rho_l(\gamma) &\approx \rho_{\parallel} - (\rho_{\parallel} - \rho_{\perp}) \sin^2 \gamma,
\end{aligned} \tag{6}$$

Nevertheless, ρ_{Trans} should be measured in Z direction for β and γ rotation. If the measurement is performed in XY plane, only ordinary Hall effect would be observed [9].

Typical SMR results of Co_2FeAl (0.3 nm)/Pt (2.5 nm) film under 5 T magnetic field at room temperature are shown in Fig. 3. Here, $\Delta\rho = \rho_l - \rho_T$ for α ; $\Delta\rho = \rho_l - \rho_{\perp}$ for β and γ . In this figure, the dependency of γ is almost flat, which is thought as the most important evidence for the SMR based on the theory raised in Ref. [10]. For $\mathbf{M}$ in XZ plane, it is always perpendicular to $\boldsymbol{\sigma}$ (please see the figures in first and third columns of Fig. 2). Therefore, the resistivity should not change in an ideal case according to the present SMR theory, which is regardless of sample's geometry. However, it is still a function of $\cos^2 \gamma$ as $\Delta\rho \approx (\rho_{\parallel} - \rho_{\perp}) \cos^2 \gamma$ in our model. The weak (cosine)² relationship is observed not only in our experiment, but also in Refs. [6-10]. Even in the first report of the SMR, the relationship had appeared in Fig.4(e) of Ref. [5], although they were treated as a constant law. Moreover, the α dependence of transverse magnetoresistance conforms to Eq. 5 very well, as shown in Fig. 3(b).

Figure 3: (Color online) Longitudinal (a) and transverse (b) magnetoresistance in three orthogonal planes for Co₂FeAl (0.3nm)/Pt (2.5 nm) with $H = 5$ T at 300 K. ρ_0 is the resistivity at zero magnetic field. Solid lines are fitted according to Eqs. 4 and 5.

Figure 4: (Color online) Field rotation magnetoresistance data for (a) Co_2FeAl (0.3nm)/Pt (2.5 nm) at 20 K with $H = 5$ T and (b) Co_2FeAl (0.6nm)/Pt (2.5 nm) at 300 K, where $H = 1$ T for α and $H = 2$ T for β and γ . ρ_0 is the resistivity at zero magnetic field. Solid lines are fitted according to Eq. 4.

Noted that, the phenomenological model only gives angle relationships of resistivities. The relationships among resistivities should be sought from magnetic proximity or SMR mechanism [1, 5, 24].

When $\rho_{\parallel}$ deviates from $\rho_{\perp}$, the $\cos^2 \gamma$ dependence would be more distinct. At a low measurement temperature, MPE was considered to dominate the mechanism of magnetoresistance in Ref. [7], and thus γ dependence changes obviously, as shown in Fig. 4(a). However, in our another research, we found spin orbit coupling proximity effect rather than MPE dominates magnetic transport property in Pt/magnetic film [25]. For SMR, two essential conditions are spin polarized current and spin orbit coupling. In Pt/CFA films, the spin polarized current is motivated by CFA clusters directly and strong spin orbit coupling is offered by the Pt layer. MPE should not be important even at a low temperature. When CFA thickness is increased a little, as shown in Fig. 4(b), the similar phenomenon is observed at the room temperature, which may also prove our opinion.

4. Conclusions

SMR is a fascinating conception. It is significant to study the related spin transport behavior and application in spintronics. Up to now, the physical image of the SMR was not clear in previous studies. Someone argued that the film quality would affect SMR effect strongly. However, SMR effect in our experiment is much larger than those in reported results using sputtering growth for the samples. Our results can compare with those in experiments using molecular beam epitaxy in Ref. [9]. The relative larger SMR effect should, we believe, result from the different film system with an ultrathin magnetic layer. This research proved that the magnetic insulator which is frequently used is not necessary for the observation of SMR. Also, it might imply that the present SMR theory should be reconsidered for more situations.

Acknowledgments

We thank the beamline 08U1 at the Shanghai Synchrotron Radiation Facilities (SSRF) for the sample preparation and measurement. This work was supported by the National Science Foundation of China Grant Nos. 51331004, 51171148, 11374228, 11205235, the National Basic Research Program of China under grant No. 2015CB921501 and the Innovation Program of Shanghai Municipal Education Commission No. 14ZZ038. Z. G. Zhu is supported by Hundred Talents Program of The Chinese Academy of Sciences.

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