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Spin-independent transparency of pure spin current at normal/ferromagnetic metal interface*

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The spin transparency at the normal/ferromagnetic metal (NM/FM) interface was studied in Pt/YIG/Cu/FM multilayers. The spin current generated by the spin Hall effect (SHE) in Pt flows into Cu/FM due to magnetic insulator YIG blocking charge current and transmitting spin current via the magnon current. Therefore, the nonlocal voltage induced by an inverse spin Hall effect (ISHE) in FM can be detected. With the magnetization of FM parallel or antiparallel to the spin polarization of pure spin currents ($\boldsymbol{\sigma}_{sc}$), the spin-independent nonlocal voltage is induced. This indicates that the spin transparency at the Cu/FM interface is spin-independent, which demonstrates that the influence of spin-dependent electrochemical potential due to spin accumulation on the interfacial spin transparency is negligible. Furthermore, a larger spin Hall angle of $Fe_{20}Ni_{80}$ (Py) than that of Ni is obtained from the nonlocal voltage measurements.

Keywords: spin transparency, spin current, magnetic insulator, inverse Hall effect

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1. Introduction

In recent years, a great deal of attention has been focused on the generation, transfer, and detection of pure spin current, which is fundamentally important and central to the development of the next generation of spintronics devices.[1,2] The interfacial spin transparency plays an important role on the transfer of spin current, and its research has attracted a lot of attention since the discovery of giant magnetoresistance (GMR).[3,4] In conventional methods of spin injection, such as spin pumping and the spin Seebeck effect (SSE), the polarization of spin current ($\boldsymbol{\sigma}_{sc}$) is always parallel to the magnetization of the ferromagnetic mental ($\boldsymbol{M}_{FM}$).[5,6] In the spin valve structure,[7] the nonlocal voltage induced by spin-dependent electrochemical potentials due to interfacial spin accumulation can be observed. However, it is hard to directly observe the influence of the spin accumulation on the interfacial spin-dependent transparency at the interface of normal/ferromagnetic metal (NM/FM). As for the spin Hall magnetoresistance (SMR) measurement,[8,9] although the variation of local resistance induced by the inverse spin Hall effect (ISHE) related to the spin accumulation at the interface can be obtained with $\boldsymbol{M}_{FM}$ parallel and antiparallel to $\boldsymbol{\sigma}_{sc}$, there is no information about spin-dependent transparency. Recently, Avci *et al.*[10] found unidirectional spin Hall magnetoresistance via second-harmonic resistance measurement, and they claimed that this was induced by the difference of spin-dependent electrochemical potential due to spin accumulation at the interface. However, the quantitative influence of this spin accumulation on the interfacial spin transparency is still unclear. Generally, it is difficult to obtain the interfacial spin-dependent transparency of pure spin current with the conventional methods mentioned above. In the spin-valve-like trilayer structure with two thin Pt layers sandwiched by a thick yttrium iron garnet (YIG-$Y_3Fe_5O_{12}$) layer, $\boldsymbol{\sigma}_{sc}$ is no long dependent on the applied magnetic field. If we replace the detector Pt layer with an FM layer, exploring the spin-dependent transparency of a pure spin current at the interface of NM/FM becomes possible.

In this paper, we study the transparency of a pure spin current at the Cu/FM interface in Pt/YIG/Cu/FM multilayers. Our nonlocal measurement is illustrated in Fig. 1(a). Via the spin Hall effect, an injected current ($\boldsymbol{I}_{in}$) in the Pt layer generates a spin accumulation at the interface of Pt/YIG with $\boldsymbol{\sigma}_{sc}$ aligned with the x axis. The s–d exchange interaction at the interface creates a non-equilibrium magnon population and spin accumulation in the YIG layer which drives magnon diffusion. The magnons are then converted to a spin current in the Cu layer by the reverse process. This spin current is further converted to a charge current again via the inverse spin Hall effect after flowing into the FM layer. For $\boldsymbol{I}_{in}$ along the $-y$ axis in the Pt layer, $\boldsymbol{\sigma}_{sc}$ can be parallel or antiparallel to $\boldsymbol{M}_{FM}$ with $\alpha = 0^\circ$ or 180°, respectively, and vice versa for $\boldsymbol{I}_{in}$ along the $+y$ axis. By comparing the nonlocal voltages in the FM layer with $\boldsymbol{\sigma}_{sc}$ parallel and antiparallel to $\boldsymbol{M}_{FM}$, we can obtain some

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information about spin-dependent transparency at the Cu/FM interface.

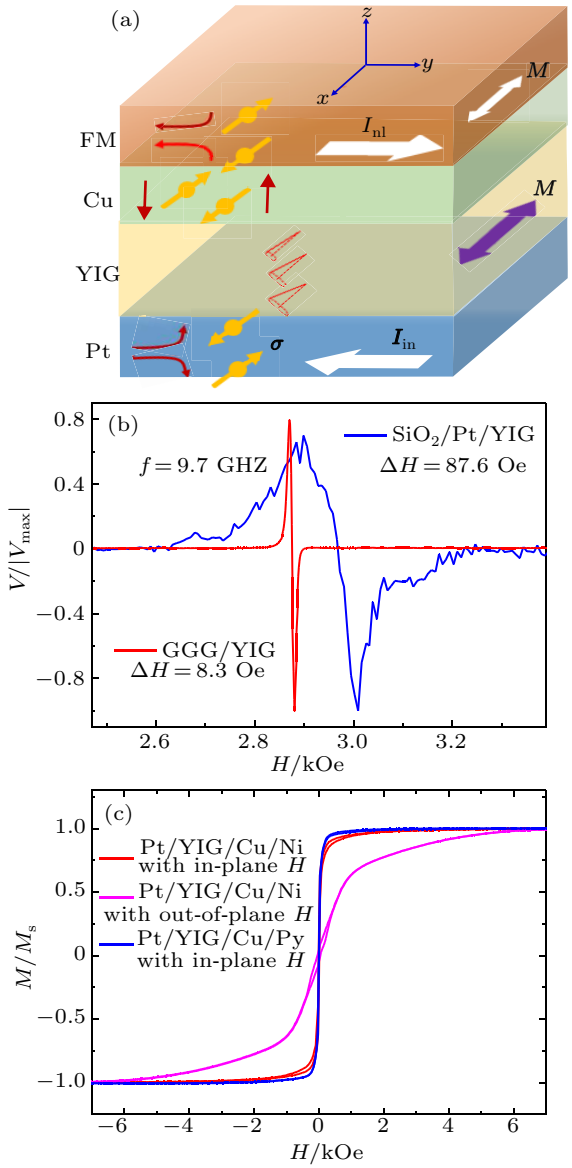


Fig. 1. (color online) (a) The proposed spin transport processes in the Pt/YIG/Cu/FM structure. Via the spin Hall effect, a charge current ($\boldsymbol{I}_{in}$) in the Pt layer generates a spin accumulation at the interface of Pt/YIG. The s–d exchange interaction at the interface creates a non-equilibrium magnon population and spin accumulation in the YIG layer which drives magnon diffusion. The magnon current excited converts into the spin current in the Cu layer, and then flows into the FM layer. Finally, the spin current in the FM layer is detected by the voltage via the inverse spin Hall effect (ISHE). The $\boldsymbol{M}_{FM}$ can be parallel and antiparallel to the polarization of spin current ($\boldsymbol{\sigma}_{sc}$) by rotating the magnetic field. We define the polarized direction of the spin current parallel to that of the spin accumulation at the Cu/FM interface. (b) The ferromagnetic resonance (FMR) absorption spectrum measured in SiO_2/Pt/YIG and GGG/YIG samples. (c) The magnetic hysteresis loops measured by AGM for Pt/YIG/Cu/Ni with in-plane and out-of-plane magnetic fields, and for Pt/YIG/Cu/Py with in-plane magnetic field.

2. Experiment

First, (111)-oriented $Gd_3Ga_5O_{12}$(GGG)/YIG (20) bilayers, Pt (5)/YIG (120) bilayer templates and Pt (5)/SiO_2 (5)/YIG (120) trilayer templates (the numbers are the layer thicknesses in nm and below is the same) were deposited on naturally oxidized Si substrates. These templates were annealed at 800 °C in a tube furnace flowing oxygen gas for 1 hour. Finally, a series of Cu, Ni, and $Fe_{20}Ni_{80}$ (Py) were deposited on these annealed templates as follows:

(i) Pt (5)/YIG (120)/Cu (3)/Ni (10),
(ii) Pt (5)/YIG (120)/Cu (3)/Py (10),
(iii) Pt (5)/YIG (120)/Cu (10),
(iv) Pt (5)/YIG (120)/Py (20),
(v) Pt (5)/YIG (120)/Ni (20),
(vi) Pt (5)/SiO_2 (5)/YIG (120)/Cu (3)/Ni (10).

All films were prepared with a magnetron sputtering system at room temperature, and the base pressure was better than 3×10^{-6} Pa. Shadow masks were used to pattern the films into devices. The width and length are 0.8 mm and 5 mm, respectively. To check the leakage current in the Pt/YIG/Cu/Ni sample, the charge current was applied between the Pt and Ni directly and the resistance was calculated to be larger than 30 MΩ between the Pt and Ni. The ferromagnetic resonance linewidth of the YIG in the SiO_2/Pt/YIG is 87.6 Oe, which is much larger than that in the (111)-oriented GGG/YIG (8.3 Oe) (Fig. 1(b)). This is expected because the crystal quality of the YIG epitaxially grown on the (111)-oriented GGG single crystal is usually much better. Therefore, the YIG on SiO_2/Pt can block charge current and transmit spin current via the magnon current. During different nonlocal measurements, different $\boldsymbol{I}_{in}$ were injected in the Pt and FM layer for Pt/YIG/Cu/FM and Pt/YIG/FM, respectively, and we applied a magnetic field of 7 kOe which was large enough to saturate $\boldsymbol{M}_{YIG}$ and $\boldsymbol{M}_{FM}$ of the magnetic hysteresis loops measured by an alternating gradient magnetometer (AGM) (see Fig. 1(c)).

3. Results and discussion

Figure 2(b) presents nonlocal voltage V_{nl} in Pt/YIG/Cu/Ni with $\boldsymbol{I}_{in} = +8$ mA as a function of α, β, and γ. It is clear that, for $\boldsymbol{I}_{in}$ along the $-y$ axis, $|V_{nl}|$ exhibits maxima at α, $\beta = 0°$ and 180° ($\boldsymbol{M}_{YIG}$ collinear with $\boldsymbol{\sigma}_{sc}$), and minima at α, $\beta = 90°$, 270° and for the applied field along the γ direction ($\boldsymbol{M}_{YIG}$ perpendicular to $\boldsymbol{\sigma}_{sc}$). For the Pt/YIG/Cu/Ni samples, the angular dependence of $V_{nl} \propto m_x^2$ fits excellently with the data. Figure 2(c) presents nonlocal voltage V_{nl} at $\alpha = 180°$ in the Ni layer for Pt/YIG/Cu/Ni with injected currents $\boldsymbol{I}_{in} = -8$ mA, -4 mA, 0, $+4$ mA, and $+8$ mA in the Pt layer. As illustrated in Fig. 2(b), the magnitude of the nonlocal voltage almost scales linearly with the injected current, that is, $V_{nl} \propto \boldsymbol{I}_{in}$, which is consistent with the spin accumulation density induced by the SHE at the Pt/YIG interface. Once $\boldsymbol{I}_{in}$ is reversed, the measured V_{nl} changes the sign. This is because the sign of $\boldsymbol{\sigma}_{sc}$ changes when $\boldsymbol{I}_{in}$ is reversed. The angular dependence of the nonlocal voltages in the Ni layer for

Pt/YIG/Cu/Ni is consistent with that of the nonlocal voltages in the Pt layer for Pt/YIG/Pt.[11,12]

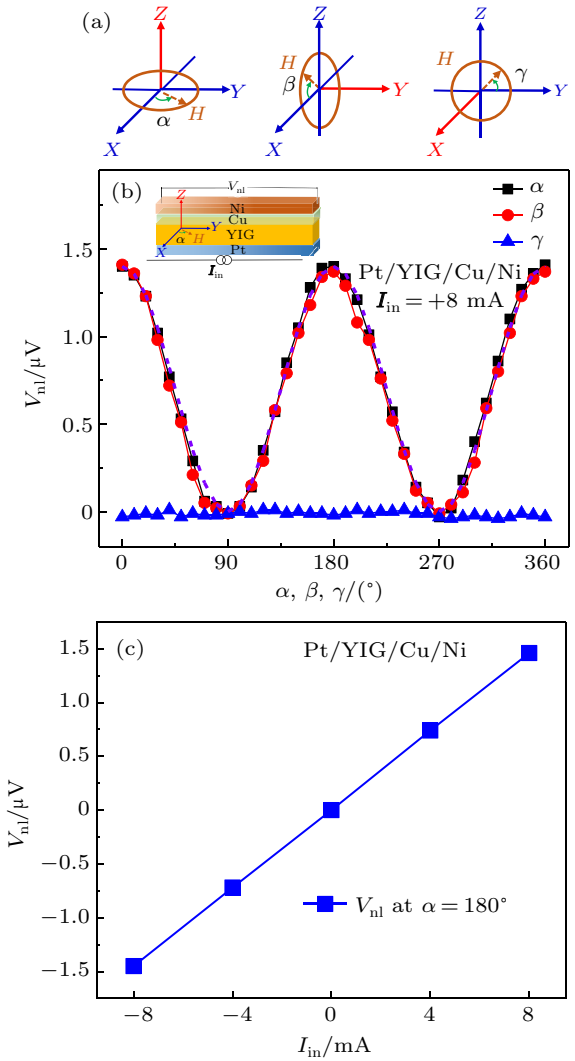


Fig. 2. (a) The definition of the angular α, β, and γ in this figure. A 7 kOe rotatable magnetic field is applied. (b) The angular (α, β, γ) dependence of the nonlocal voltage in Pt/YIG/Cu/Ni. The inset shows the schematic illustration of the sample structure and the measurement method. An injected current $\boldsymbol{I}_{in} = +8$ mA is applied along the $\boldsymbol{y}$ axis in the Pt layer, and the nonlocal voltage V_{nl} is measured along the y axis in the Ni layer. (b) The nonlocal voltages at $\alpha = 180°$ in the Ni layer for Pt/YIG/Cu/Ni with injected currents $\boldsymbol{I}_{in} = -8$ mA, -4 mA, 0, $+4$ mA, and $+8$ mA in the Pt layer.

Compared to the V_{nl} in Pt/YIG/Cu/Ni, there is no measureable V_{nl} with $\boldsymbol{I}_{in} = +8$ mA in Pt/YIG/Cu and Pt/SiO_2/YIG/Cu/Ni samples as shown in Fig. 3(a). Obviously, the large ISHE voltage is not from the Cu layer in the Pt/YIG/Cu/Ni sample. In order to identify the possible influence of thermal gradients and related thermoelectric effects, a 5-nm SiO_2 layer was inserted at the interface of Pt/YIG in the Pt/YIG/Cu/Ni sample to block the spin current induced by the spin accumulation at the Pt/YIG interface. Nevertheless, both SSE and ANE in our samples can be ruled out, since there is a negligible voltage obtained with the insertion of SiO_2. Furthermore, the thermal voltages induced by anomalous Nernst effect (ANE)[13] and spin Seebeck effect (SSE) are proportional to I_m, and exhibit different angular dependence of $V_{nl} \propto m_x$.[14] Hence, the nonlocal voltage is almost induced by the ISHE in the Ni layer where the spin current is converted from the magnons current in YIG due to the spin accumulation at the Pt/YIG interface.

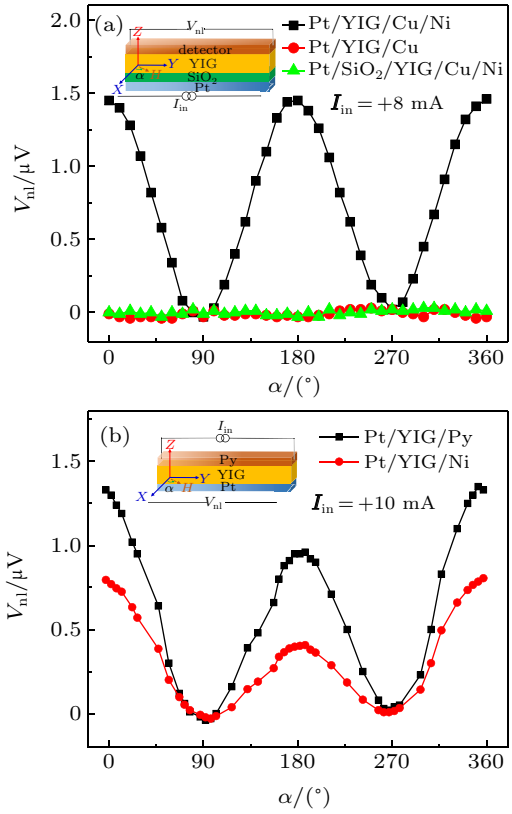


Fig. 3. (color online) (a) The angular dependence of the nonlocal voltage with $\boldsymbol{I}_{in} = +8$ mA for Pt/YIG/Cu/Ni, Pt/SiO_2/YIG/Cu/Ni and Pt/YIG/Cu. (b) The angular dependence of the nonlocal voltage measured in the Pt layer with $\boldsymbol{I}_{in} = +10$ mA in the Py and Ni layer for Pt/YIG/Py and Pt/YIG/Ni.

More interestingly, for the angular dependence of V_{nl} in the Pt/YIG/Cu/Ni sample illustrated in Fig. 2, there is almost no difference for $\boldsymbol{M}_{FM}$ parallel and antiparallel to $\boldsymbol{\sigma}_{sc}$. When we pass a current in FM and measure the V_{nl} in NM for Pt/YIG/FM (see Fig. 3(b)), we can clearly see the asymmetry with a maximum value when $\boldsymbol{M}_{FM}$ is antiparallel to $\boldsymbol{\sigma}_{sc}$. The magnitude of the nonlocal voltage scales linearly with the spin accumulation density at the YIG/FM interface, and therefore the interfacial spin accumulation is different for $\alpha = 0°$ and 180°. This is because the spin electrons are spin-polarized in FM. When we pass a current in Pt which is not spin-polarized, the spin accumulation at the Pt/YIG interface induced by SHE is the same for $\alpha = 0°$ and 180°. Pure spin currents will be induced in the Cu layer via the magnon current in YIG, and flow across the Cu/FM interface into the FM layer. Unlike NM metal, there should be a strong spin-dependent transparency at the Cu/Ni interface due to the spin polarization in the FM layer. At the Cu/FM interface, there will be a spin accumulation whose spin polarization is consistent with that of the spin current. With the spin accumulation at the interface, a

conductivity mismatch of majority and minority electrons in the two materials will be induced. With $\boldsymbol{\sigma}_{sc}$ parallel to $\boldsymbol{M}_{FM}$, the transparency of majority or minority electrons at the interface is enhanced or reduced, respectively, and vice versa with $\boldsymbol{\sigma}_{sc}$ antiparallel to $\boldsymbol{M}_{FM}$. Therefore, different interfacial spin transparency of spin current should be obtained with $\boldsymbol{\sigma}_{sc}$ parallel and antiparallel to $\boldsymbol{M}_{FM}$.

However, our experimental results show that almost the same nonlocal voltage is obtained for $\boldsymbol{\sigma}_{sc}$ parallel and antiparallel to $\boldsymbol{M}_{FM}$, indicating a spin-independent transparency of pure spin current at the NM/FM interface and flowing into the FM layer. This means that the transparency of majority or minority electrons at the Cu/FM interface is almost the same for $\boldsymbol{\sigma}_{sc}$ parallel and antiparallel to $\boldsymbol{M}_{FM}$. Furthermore, our results demonstrate that the influence of the conductivity mismatch induced by spin accumulation at the interface on the interfacial spin transparency observed in an early experiment[10] may be very weak and could be negligible. Therefore, there is a spin-independent transparency of spin current at the Cu/FM interface.

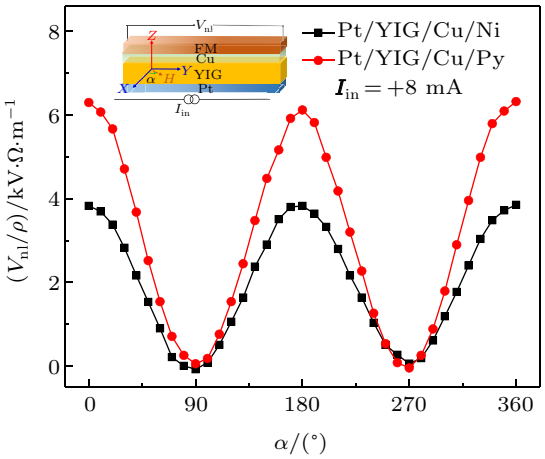


Fig. 4. (color online) The angular dependence of the nonlocal voltage with $\boldsymbol{I}_{in} = +8$ mA for Pt/YIG/Cu/Ni and Pt/YIG/Cu/Py.

We should mention that in the Pt/YIG/Cu/FM samples, the intervening Cu layer provides a shunting effect on the voltage while ISHE occurs in the FM layer. If V_0 and V_{nl} stand for the ISHE voltage generated in the FM layer and the measured voltage, respectively, we will have a relationship $V_{nl} = V_0[R_{Cu}/(R_{FM} + R_{Cu})]$.[15] R_{Cu} and R_{FM} are the resistances of Cu and FM layer, respectively. Since the resistance of 3-nm Cu layer is much larger than that of 10-nm FM layer,[16] the V_{nl} is almost equal to the V generated in the FM layer.

In general the V_{nl} in Pt/YIG/Cu/FM samples can be expressed by

$$V_{nl} = \left(ALJ_{in}\cos^2\varphi\right)\left(\rho\theta_{SH}^{FM}\right)\left[\frac{\lambda_{sf}}{t}\tanh\left(\frac{t}{2\lambda_{sf}}\right)\right], \quad (1)$$

a product of three terms. The first term includes the spin injection coefficient A, the sample dimension L, the injected current density $\boldsymbol{J}_{in}$ in the Pt layer, and the angular dependence $\cos^2\varphi$, where φ is the angle between the applied magnetic field and $\boldsymbol{\sigma}_{sc}$. The second term includes the electrical resistivity ρ and the spin Hall angle of FM. The third term describes the decay of the pure spin current due to spin diffusion length λ_{sf} and layer thickness t of the FM layer. We assume that the spin current injection efficiency remains the same among samples, and there is no significant decay of spin current in the Cu layer. From the V_{nl}/ρ in Fig. 4, with $\lambda_{sf} = 3.2$ nm and 1.7 nm for Ni and Py, respectively,[5] we can obtain $\theta_{SH}^{Ni} : \theta_{SH}^{Py} = 19 : 32$, indicating a relative larger one for Py.

4. Conclusion

In summary, we studied the transparency of pure spin current with $\boldsymbol{M}_{FM}$ parallel and antiparallel to $\boldsymbol{\sigma}_{sc}$ at the Cu/FM interface in Pt/YIG/Cu/FM multilayers, and the spin-independent nonlocal voltage was obtained from nonlocal measurement. Our result indicates a spin-independent transparency at the Cu/FM interface, which demonstrates that the influence of spin-dependent electrochemical potential due to spin accumulation on the interfacial spin transparency is very weak and can be negligible. Furthermore, a larger spin Hall angle of Py than that of Ni was obtained by comparing the nonlocal voltages in Py for Pt/YIG/Cu/Py with that in Ni for Pt/YIG/Cu/Ni.

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