Influence of damping constant on inverse spin hall voltage of $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3(\text{x})/\text{platinum}$ bilayers

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Pure spin transport via spin pumping in the condition of ferromagnetic resonance can be transformed to charge current in the ferromagnetic/paramagnetic bilayer systems, based on inverse spin Hall effect (ISHE). Here, we explore $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}(\text{x})/\text{Pt}(5.5 \text{ nm})$ [$\text{x} = 10$ to 65 nm] bilayers to investigate the influence of damping constant on spin pumping efficiency. The results show that the ISHE voltage depend on the damping constant of magnetic moment, suggesting that the precession energy transferred to lattice/electron of normal metal is a key parameter to control the magnitude of spin current. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4863485>]

I. INTRODUCTION

The additional degree of freedom “spin” of electron serves the base for information storage and manipulation apart from the “charge” of electron. The spin current generated by spin Hall effect (SHE) was observed by using optical and electrical methods in semiconductor systems.^{1–5} When current pass through a normal metal (NM) layer, the spin-up and -down electrons move in the opposite directions in order to balance the difference in electrochemical potential (μ), thus, accumulating charge on the same side due to spin orbital interaction and creating a potential difference. The metals like Pt, W, Ta, etc., are often used as NM due to their large spin-orbit coupling. In addition, the inverse process of SHE can also occur which transform the spin current into charge current. This phenomenon is known as the inverse spin Hall effect (ISHE).^{6–8} There are plenty of studies that concentrate on the generation, detection, and manipulation of pure spin current.^{3,9–14} Among several existing methods, spin pumping is one of the easy ways to generate spin current, which does not require complicated experimental setups.^{15–19} The process of spin pumping in bilayer structures is mainly activated by ferromagnetic resonance (FMR),^{20–22} causing a spin moment conveyed from the ferromagnetic (FM) layer into the NM layer. The relation of spin current density ($\mathbf{J}_s$), electric current density ($\mathbf{J}_c$), and spin polarization vector ($\boldsymbol{\sigma}$)¹⁵ for ISHE is given as follows:

$$\mathbf{J}_c \propto \mathbf{J}_s \times \boldsymbol{\sigma}. \quad (1)$$

The ISHE generated by spin pumping mechanism has been extensively studied in permalloy/platinum (Py/Pt) bilayer films. Two types of experimental techniques are used to produce FMR. One is the cavity method in which the anomalous Hall effect (AHE) is generated from the electric field of the microwave. The coplanar waveguide method is another one used to excite FMR, which could yield large

ISHE signal but required additional patterned fabrication.^{18,19,23,24} An anisotropic magnetoresistance (AMR) with antisymmetric voltage signal was observed by using the later technique, which arises from the strong capacitive coupling of the sample with the patterned waveguide.

ISHE has been systemically studied for the Py/Pt bilayer systems with varying the microwave power, external magnetic field, and the thicknesses of both constituent layers. Several important physical parameters, such as spin diffusion length, spin mixing conductance, and spin Hall angle, can be acquired by fitting the data with models proposed by several research groups.^{18,19,25–29} However, many factors affecting the spin pumping efficiency, such as interface properties, crystal structure of the FM layer, strain of the substrate, etc., are still less explored. Here, we use highly spin polarized $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ (LSMO)³⁰ as the FM layer capped with Pt to evaluate the spin pumping efficiency by using cavity FMR technique. The damping constant and g-factor are determined by fitting the angular dependence FMR spectra.

II. EXPERIMENT

Seven samples of $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}(\text{x})/\text{Pt}(5.5 \text{ nm})$ [$\text{x} = 10, 20, 26, 30, 43, 50$, and 65 nm] bilayers were deposited by pulsed laser deposition (PLD) and sputtering techniques for LSMO and Pt, respectively. Epitaxial LSMO were grown on $\text{SrTiO}_3(\text{STO})(001)$ substrates at 800°C and 100 mTorr of oxygen pressure. It was then annealed *in situ* at 400°C , with atmospheric oxygen pressure to improve the crystalline quality. The top Pt layer was deposited using commercial sputtering coater (Quorum Q150TS) to a fixed thickness of 5.5 nm at ambient temperature to optimise the ISHE voltage. All the samples were cut into rectangular shape of lateral dimension $1.5 \times 3.0 \text{ mm}^2$. Two electrodes were fixed on the longer side of the Pt layer. The samples were mounted at the centre of a TE_{102} microwave cavity where the magnetic component ($\mathbf{h}_{ac}$) of the microwave is a maximum and its electrical component ($\mathbf{e}_{ac}$) is a minimum. The microwave source is provided by Bruker EMX system ($f = 9.8 \text{ GHz}$) with $\mathbf{h}_{ac}$ parallel to the longer axis of the sample. The external magnetic field ($\mathbf{H}_{dc}$) was

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FIG. 1. Magnetic field dependence of first derivative of FMR spectra (a) and voltage (b) at various microwave power for LSMO(10 nm)/Pt(5.5 nm). (c) is the schematic diagram of ISHE voltage measurements, and the H_{ex} and $h(t)$ are the external magnetic field and magnetic component of microwave, respectively.

varied from parallel to perpendicular ($\theta_H = 0^\circ - 180^\circ$) to the thin film's plane. The induced ISHE voltage is measured by using a nano-voltmeter (Keithley Model 2182A).

III. RESULTS AND DISCUSSION

The FMR spectra are detected by sweeping the external magnetic field (H) from 0 to 12 kOe. Figures 1(a) and 1(b) show the spectra of first derivative FMR and ISHE voltage with microwave power varying from 20 to 125 mW for LSMO(10 nm)/Pt(5.5 nm), and the schematic diagram of the measurement is shown in Fig. 1(c). The resonance field (H_R) of the film is found to shift slightly toward higher magnetic field, which may be due to the microwave heating effect. Two types of mechanisms contribute to the observed voltage signal, one from spin pumping mechanism induced by FMR and the other is AHE due to the interaction of e_{ac} and the magnetization of the FM layer. The V-H behaviour consists symmetric and anti-symmetric Lorentzian functions given by the relation¹⁶

$$V(H) = V_{ISHE} \frac{\Gamma^2}{(H - H_R)^2 + \Gamma^2} + V_{AHE} \frac{-2\Gamma(H - H_R)}{(H - H_R)^2 + \Gamma^2}, \quad (2)$$

where $V_{ISHE}(H)$ and $V_{AHE}(H)$ represent the voltage contributed from ISHE and AHE, respectively. Γ and H_R are the line width and resonant field, respectively.

FIG. 2. Microwave power dependent ISHE voltage for LSMO(x)/Pt(5.5 nm) bilayers with different LSMO thickness.

Figure 2 shows the microwave power dependence of ISHE voltage (V_{ISHE}) extracted from Eq. (2) for LSMO(x)/Pt(5.5 nm) and all of curves saturate at high microwave power. Spin voltage is linearly depending on the microwave power below 60 mW, thus we chose 40 mW for the purpose of comparison. In order to obtain the damping constant, H_R is measured at 40 mW with angle θ_H varying from 0° to 180° . The angular dependent H_R are shown in Figures 3(a) and 3(b) as open symbols for LSMO(10)/Pt(5.5) and LSMO(26)/Pt(5.5), respectively. The red solid lines indicate the fitting results as demonstrated in Ref. 16 with H and M being the external magnetic field and magnetization vector, respectively.³¹ From Ref. 16, the total free energy of magnetization of the system is given by

$$E = -M_s H [\sin \theta_H \sin \theta_M \cos(\varphi_H - \varphi_M) + \cos \theta_H \cos \theta_M] + 2\pi M_s^2 \cos^2 \theta_M - K_\perp \cos^2 \theta_M. \quad (3)$$

Equation (3) includes the Zeeman energy, demagnetization energy, and perpendicular anisotropy energy, which relate to the saturation magnetization M_s , polar angle $\theta_{H(M)}$ and azimuthal angle $\varphi_{H(M)}$ of external magnetic field (magnetization). The H_R of the FMR are determined by the resonance condition³²

FIG. 3. Out of plane angular dependent FMR resonance field (open circle) and the fitting results (solid lines) for (a) LSMO(10 nm)/Pt(5.5 nm) and (b) LSMO(26 nm)/Pt(5.5 nm).

FIG. 4. Thickness dependent ISHE voltage (solid circles) and damping constant acquired from numerical fitting with FMR model (open squares).

$$\left(\frac{\omega}{\gamma}\right) = \frac{1}{(M_s \sin \theta_M)} \left(E_{\theta_M \theta_M} E_{\varphi_M \varphi_M} - E_{\theta_M \varphi_M}^2 \right)^{1/2}. \quad (4)$$

Here, M_s and ω are saturation magnetization and microwave frequency. The g-factor is given by gyromagnetic ratio ($\gamma = g\mu_B/\hbar$), where μ_B and $\hbar$ are Bohr magneton and Plank constant, respectively. E_{ij} ($i, j = \theta_M$ or φ_M) denotes the partial derivative indexes of E . The equilibrium state of magnetization obtained from $\partial E/\partial \theta_M = 0$ and $\partial E/\partial \varphi_M = 0$, are expressed as follows:³³

$$2H_R \sin(\theta_M - \theta_H) = 4\pi M_{\text{eff}} \sin(2\theta_M). \quad (5)$$

Here, $4\pi M_{\text{eff}}$ is the effective magnetization defined as $4\pi M_{\text{eff}} = 4\pi M_s - 2K_{\perp}/M_s$. By using Eq. (3), the resonance condition is deduced as³³

$$\begin{aligned} (\omega/\gamma)^2 &= H_1 \times H_2 \\ H_1 &= (H_R \cos(\theta_H - \theta_M) - 4\pi M_{\text{eff}} \cos^2 \theta_M) \\ H_2 &= (H_R \cos(\theta_H - \theta_M) - 4\pi M_{\text{eff}} \cos 2\theta_M). \end{aligned} \quad (6)$$

The angular dependent resonance field can be acquired by combining Eqs. (5) and (6) with numerical calculation. The damping constant ($\alpha = \gamma \Delta H/\omega$) is calculated with the gyromagnetic ratio γ obtained from the numerical results of line width of FMR spectra and microwave frequency. The FM layer thickness dependent ISHE voltage and their damping constant at 40 mW microwave power are shown in Figure 4. It is observed that the spin pumping efficiency has close relation with the damping constant of the system, meaning a high V_{ISHE} is related to a low α . The results show that LSMO (26 nm)/Pt(5.5 nm) has the lowest damping constant which could be due to the strain relief in LSMO.³⁴ Therefore, our results suggest that the more the precession magnetization releases their energy to lattice/conduction-electrons in the FM metal, the less the spin angular momentum is transferred to the neighbouring NM layer and induce lower ISHE voltage. Thus, the spin current can be controlled by damping rate, which is an important message for designing the spintronics devices.

IV. CONCLUSION

We have measured the ISHE voltage for a series of LSMO(x)/Pt(5.5 nm) bilayer systems by changing the LSMO

thickness from 10 nm to 65 nm. The angular dependent FMR measurements are carried out to obtain the damping constant of each bilayer sample. Our results show that the spin pumping efficiency is significantly influenced by the damping constant of LSMO layer.

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