Thickness dependence of spin torque ferromagnetic resonance in Co$_{75}$Fe$_{25}$/Pt bilayer films

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The spin Hall angle of Pt in Co$_{75}$Fe$_{25}$/Pt bilayer films was experimentally investigated by means of the spin-torque ferromagnetic resonance and the modulation of damping measurements. By comparing the present results with the Ni$_{80}$Fe$_{20}$/Pt system, we found that the ferromagnetic layer underneath the Pt one greatly affects the estimation of the spin Hall angle. We also discuss the spin diffusion length of Pt and the ferromagnetic thickness dependence of the Gilbert damping coefficient. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4865425]

Existing technology of electronic data storage or data transfer devices driven by charge current may be replaced by a technology that solely deals with the spin degree of freedom of an electron, known as spintronics.¹ For a pure spin current there are many advantages like no net flow of charge and hence no stray Oersted field, minimum power dissipation, tunable magnetic damping,³⁻⁶ by which one can achieve loss-less propagation of electromagnetic waves in magnetic media,³ or reduction of noise due to thermal fluctuation⁴ in nanomagnetic devices. Hence, a great deal of research is going on to increase the conversion efficiency between charge current and spin current known as spin Hall angle⁴,⁷⁻⁸ ($\theta_{\text{SH}}$) for applications in spintronic devices. Spin current can be generated by different techniques including nonlocal electrical injection from ferromagnetic contacts in multi-terminal structures, optical injection using circularly polarized light, spin pumping from a precessing ferromagnet and also by spin Hall effect⁴,⁶,⁷⁻¹² (SHE). The SHE does not require any ferromagnet (FM) or external bias field to generate the spin current. However, injected spin current can affect the magnetization dynamics of an adjacent FM layer, from which one can quantify $\theta_{\text{SH}}$. Hence, in case of FM and nonmagnetic metal (NM) bilayer structures, the magnetic properties of the FM layer, thickness of the FM and NM layers, and interface properties can play crucial roles in determining $\theta_{\text{SH}}$. As a matter of fact, there is a large inconsistency in the estimated $\theta_{\text{SH}}$⁴,⁸,¹³,¹⁴ of a standard SHE material Pt. The values reported by several groups differ even by an order of magnitude. Thus, it is very important to investigate the origin of this inconsistency, for which a systematic study of $\theta_{\text{SH}}$ for different materials and thicknesses are required. In this work, we have studied the SHE of Co$_{75}$Fe$_{25}$/Pt bilayer films using the spin torque induced ferromagnetic resonance (ST-FMR)⁴,⁷ and modulation of damping (MOD) measurements.⁴ The later is done by applying a dc current in the bi layer system. This dc current produces an additional torque in FM layer either parallel or anti parallel to the Gilbert damping thereby modifying the effective damping. Here, Co$_{75}$Fe$_{25}$ is chosen as the FM layer as it has a smaller anisotropic magnetoresistance (AMR) effect than Ni$_{80}$Fe$_{20}$. Consequently, for this sample, contributions from other effects to $\theta_{\text{SH}}$ are expected to become more prominent compared to the AMR effect.

Thin films of Co$_{75}$Fe$_{25}$($t = 0$–$17$ nm)/Pt($d = 0$–$20$ nm)/Al$_2$O$_3$(2 nm) are grown on a non-doped Si substrate by dc rf magnetron sputtering in a wedge shape using a linear motion at the base pressure of $4 \times 10^{-7}$ Pa and Ar gas pressure of 0.13 Pa. Al$_2$O$_3$ is used as an insulating capping layer. The resistivities of Pt and Co$_{75}$Fe$_{25}$ are measured to be 28.0 and 15.2 $\mu \Omega$cm while the measured AMR is about 1.0% for the 10 nm CoFe sample, which is smaller than that of Ni$_{80}$Fe$_{20}$ (about 1.6%). The bilayer films are patterned into rectangular shaped elements ($20 \times 60 \mu m^2$) using optical lithography and Ar-ion etching technique. A co-planar Ti(5 nm)/Au(150 nm) waveguide is deposited on top of each sample element so that the sample can act as a part of the waveguide. The schematic of a sample and the circuit diagram of the experimental setup are shown in Fig. 1(a).

A constant rf (8–12 GHz) signal with an output power of 10 dBm is applied along the length of the sample using a microwave analog signal generator [model No. MXG N5183A]. An external bias magnetic field ($H_{\text{ext}} = 0$–$1.8$ kOe) is also applied at an angle of 45° within the plane of the sample. In this power range the output signal amplitude is linear with power, and hence the spin precession in the ferromagnetic layer is in the small angle regime. All the experiments are performed at room temperature.

The current applied in the bilayer film is divided in two parts flowing into the two adjacent layers depending on their resistances. The stray Oersted field generated due to the current in the Pt layer induces a FMR, which is antisymmetric with respect to the resonant magnetic field. On the other hand, due to the spin orbit interaction and impurity scattering charge carriers with opposite spin polarities are...
where, $J_S$ and $J_C$ is the half width at half maximum, the Lorenzian function, which is symmetric at resonant field, $\Delta$ is the half width at half maximum, $H_0$ is the resonant field, $S$ and $A$ are the weight factors for the symmetric and anti-symmetric FMR, $\theta$ is the angle between current and magnetization, $R$ is the resistance, $f$ is the frequency, and $\gamma$ is the gyromagnetic ratio. The effective damping coefficient $\alpha_{\text{eff}, 4,7}$ of the sample is related to the linewidth by $\Delta = 2\pi \alpha_{\text{eff}} / \gamma$ while $S$ and $A$ are proportional to the spin current density $J_S$ and charge current density $J_C$, respectively, in the Pt layer as given by Eq. (2)

$$S = \frac{\hbar J_S}{2e\mu_0 M_{\text{eff}}},$$

$$A = H_{\text{eff}} \left[ 1 + \left( M_{\text{eff}} / H_{\text{ext}} \right) \right]^{1/2},$$

$$\approx \frac{J_C d}{2} \left[ 1 + \left( M_{\text{eff}} / H_{\text{ext}} \right) \right]^{1/2},$$

where $e$ is the charge of electron, $\mu_0$ is the free space permeability, $M_s$ is the saturation magnetization, $H_{\text{eff}}$ is the field due to rf current and $M_{\text{eff}}$ is the effective magnetization including magnetic anisotropy. Since the magnetic anisotropy is small for ferromagnetic thin films, we can approximate $M_{\text{eff}}$ as $M_s$. Hence, the ratio between spin current and charge current densities $(J_S/J_C)$ can be summarized from Eq. (2) as given in Eq. (3)

$$\frac{J_S}{J_C} = \frac{td}{A} \frac{S e\mu_0 M_s}{\hbar} \sqrt{1 + \left( M_{\text{eff}} / H_{\text{ext}} \right)}. \tag{3}$$

We have processed the measured FMR spectra to isolate the symmetric and asymmetric contributions and thereby estimated the $J_S/J_C$ value, which we termed as the ST-FMR results in this paper.

On the other hand, if a dc charge current is applied to the sample in addition to the rf charge current, a dc spin current is generated in the NM layer perpendicular to the charge current. This produces a spin transfer torque $^{4,12,15}$ (STT) in the FM layer, acting along the $(\hat{m} \times \hat{\sigma} \times \hat{m})$ direction, where $\hat{m}$ is the magnetization vector and $\hat{\sigma}$ is the injected spin moment. The STT is collinear with the damping torque and either increases or decreases the effective value of damping depending on the polarity of $\hat{\sigma}$. The STT is incorporated as the last term in the Landau–Lifshitz–Gilbert equation as given by Eq. (4) below

$$\frac{d\hat{m}}{dt} = -\gamma [\hat{m} \times (H_{\text{eff}} + H_{\text{ext}})] + \alpha [\hat{m} \times \left( \hat{m} \times \frac{d\hat{m}}{dt} \right)]$$

$$+ \frac{\hbar}{2e\mu_0 M_{\text{eff}}} J_S (\hat{m} \times \hat{\sigma} \times \hat{m}), \tag{4}$$

where $H_{\text{eff}}$ is the effective magnetic field and $\alpha$ is the Gilbert damping. Hence, by tuning the applied dc charge current we can externally control the effective damping of the FM material (MOD) as estimated from the FMR linewidth. According to the theory of spin torque, this modulation is related to the injected spin current density and relative orientation of magnetic moment with current as given by Eq. (5)

$$\Delta \alpha = (\alpha - \alpha_0) = \frac{\sin \theta}{(H_{\text{ext}} + M_{\text{eff}})\mu_0 M_{\text{eff}}} \frac{\hbar J_S}{2e}, \tag{5}$$

where $\alpha_0$ is the Gilbert damping with zero dc current and $\Delta \alpha$ is the MOD. Hence by calculating the rate of MOD, $\Delta \alpha/J_C$ we can evaluate $J_S/J_C$ from Eq. (5). This, in turn, gives...
another estimate of $\theta_{3SH}$. This measurement technique is referred to as MOD measurement in this paper.

Figure 1(b) shows the typical ST-FMR spectra for a CoFe(6.5 nm)/Pt(5.8 nm) bilayer film excited at different rf frequencies ($f$) from 8 to 12 GHz. The obtained $f$ vs. resonant field curve is well fitted with Kittel formula \(7\) for in-plane magnetized samples given by Eq. (6), as shown in Fig. 1(c)

$$f = \frac{\gamma}{2\pi} \sqrt{H_{ext}(H_{ext} + 4\pi M_S)}.$$

From the fit, we obtained $\gamma = 1.76 \times 10^{11}$ rad/($s\cdot T$) and $4\pi M_S = 2.3$ T, which is more than two times larger compared to commonly used Permalloy (Ni$_{80}$Fe$_{20}$, hereafter Py) ($\sim$1 T).

In Fig. 2(a) we plot $J_S/J_C$ values obtained from the ST-FMR measurement as a function of Pt thickness. $J_S/J_C$ is found to be constant for thick Pt films, while it decreases as we lower the thickness and approaches towards zero at zero thickness limit. This behavior can be well explained by Eq. (7)

$$J_S/J_C = \theta_{3SH} \left[ 1 - \text{sech} \left( \frac{d}{l_S} \right) \right],$$

where $\theta_{3SH}$ is the characteristic spin Hall angle and $l_S$ is the spin diffusion length \(7\) of the nonmagnetic layer, which is Pt in our case. From the fitted curve $l_S$ is found to be $2.1 \pm 0.2$ nm, which is almost independent of CoFe thickness as shown in the inset of Fig. 2(a). We should note here that the spin diffusion length estimated using Eq. (7) is a characteristic length for bilayer films, which is essentially different from the one obtained from nonlocal spin valve measurements \(16\) or from weak anti-localization measurements \(17\) where Pt is not directly in contact to FM. More details about the spin diffusion length will be discussed elsewhere.

On the other hand, in the MOD measurement, the effective value of damping shows a linear variation with the dc charge current density in the Pt layer as shown in Fig. 2(b). When the bias field angle is reversed from 45° to $-135°$ the slope of the curve only changes sign while keeping its magnitude unaffected. This clearly shows that MOD must have a magnetic origin. Moreover, the slope of the graph in Fig. 2(b) is also an important measurable quantity, from which we can calculate $\Delta\alpha/\alpha$ and hence $J_S/J_C$ using Eq. (5), which gives an estimate of $\theta_{3SH}$.

In Fig. 2(c) we compare the values of $\theta_{3SH}$ as a function of CoFe thicknesses obtained from ST-FMR as well as the MOD measurement. We should note that the $\theta_{3SH}$ values from ST-FMR measurement shown in Fig. 2(c) are the characteristic value of $\theta_{3SH}$ obtained from the fitted curves of Fig. 2(a). It monotonically increases with the CoFe thickness and the data points are well fitted by a straight line. At zero thickness limit $\theta_{3SH}$ comes out to be $2.2% \pm 0.8%$. In contrary from the MOD measurement we obtain a $\theta_{3SH}$ value of $8.5% \pm 0.9%$, which is almost independent of CoFe thickness. To investigate this behavior we compare the results of ST-FMR and MOD measurements of CoFe/Pt with those from Ni$_{80}$Fe$_{20}$(Py)/Pt system as shown in Figs. 3(a) and 3(b), respectively. In case of ST-FMR measurement, as shown in Fig. 3(a), we again observe a linear increase of $\theta_{3SH}$ with Py layer thickness but with a smaller slope. What is interesting to note is that at zero thickness limit both of the curves converge to the same value (2.2% ± 0.4% in case of Py/Pt (Ref. 7)). These results indicate that for finite values of $t$, $\theta_{3SH}$ has a clear dependence of ferromagnetic material whereas at $t \rightarrow 0$ it no longer depends on the type of ferromagnet. Hence, the $t \rightarrow 0$ limit closes with the actual measure of $\theta_{3SH}$ of the NM layer, which is an intrinsic property of that material.

We have analyzed the reason for the dependence of $\theta_{3SH}$ on the FM material and its thickness as follows. (i) First, we apply an rf current in a single CoFe layer \(18\) and found an ST-FMR like spectrum at the same resonance frequency as observed for the bilayer system as shown in Fig. 3(c). This
behavior is unexpected as the current density inside the CoFe layer should be uniform as the thickness of the CoFe layer is smaller than the microwave skin depth. However, there is a possibility that nucleation and propagation of non-uniform spin waves\textsuperscript{18} around the FM wire edges may give rise to a dc voltage inside the FM layer. In case of a FM/NM bilayer samples similar voltage can also be generated in the FM layer, which further modifies the spectrum shape and thereby the value of $\theta_{\text{SH}}$. This effect is expected to increase with the FM layer thickness as the demagnetization region increases with thickness, which may give rise to a monotonic increase in $\theta_{\text{SH}}$ as shown in Fig. 3(a). However, the contribution of nonuniform spin wave is very small in the CoFe/Pt bilayer film. This is because the output voltage of ST-FMR like spectrum in single CoFe layer is much smaller than the FMR spectrum in CoFe/Pt bilayer film as shown in Fig. 3(c). (ii) The other possibility is the much smaller than the FMR spectrum in CoFe/Pt bilayer film. This is because the output voltage of ST-FMR like spectrum in single CoFe layer is small in the CoFe/Pt bilayer film. However, the contribution of nonuniform spin wave is very small in the CoFe/Pt bilayer film. This is because the output voltage of ST-FMR like spectrum in single CoFe layer is much smaller than the FMR spectrum in CoFe/Pt bilayer film as shown in Fig. 3(c).

Finally, the observed variation in $x_{\text{eff}}$ with the CoFe layer thickness ($t$) shown in Fig. 3(d) may be interpreted as follows. Due to the Co 3d-Pt 5d hybridization\textsuperscript{20} at the interface atoms of the bilayer sample, d-band width for Co reduces, resulting in an increase in the spin-orbit coupling and thereby the damping coefficient $x_{\text{eff}}$. However, the non-linear variation of $x_{\text{eff}}$ with $t$ implies that in addition to the interface hybridization effect, the spin pumping effect may also have an influence in determining the $x_{\text{eff}}$ vs. $t$ variation.

In summary, we presented the thickness dependence of $\theta_{\text{SH}}$ in Co$_{35}$Fe$_{25}$/Pt bilayer using the ST-FMR and MOD measurement and compared the results with those from the
Py/Pt bilayers. From the ST-FMR measurements, we found that the intrinsic value of $\theta_{SH}$ for Pt does not depend on the material and thickness of the adjacent FM layer. However, due to the large influence of some extrinsic effects such as ISHE, the measured $\theta_{SH}$ value strongly depends on the FM material and its layer thickness. The MOD measurement gives higher value of $\theta_{SH}$, which is independent of the FM layer thickness but depends on the FM material and the reason of this inconsistency is not very clear. We also found that the effective value of Gilbert damping sharply decreases with the CoFe thickness probably due to a combination of the Co $3d$-Pt $5d$ hybridization at the interface and the spin pumping effect.

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