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# Time-domain detection of current controlled magnetization damping in Pt/Ni<sub>81</sub>Fe<sub>19</sub> bilayer and determination of Pt spin Hall angle

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The effect of spin torque from the spin Hall effect in Pt/Ni<sub>81</sub>Fe<sub>19</sub> rectangular bilayer film was investigated using time-resolved magneto-optical Kerr microscopy. Current flow through the stack resulted in a linear variation of effective damping up to  $\pm 7\%$ , attributed to spin current injection from the Pt into the Ni<sub>81</sub>Fe<sub>19</sub>. The spin Hall angle of Pt was estimated as  $0.11 \pm 0.03$ . The modulation of the damping depended on the angle between the current and the bias magnetic field. These results demonstrate the importance of optical detection of precessional magnetization dynamics for studying spin transfer torque due to spin Hall effect. © 2014 AIP Publishing LLC.

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Utilizing spin current<sup>1</sup> for manipulating magnetization in non-magnetic (NM)/ferromagnetic (FM) bilayer films is of considerable interest for low power consumption in spintronic devices. Spin current generated via the spin Hall effect<sup>1–3</sup> (SHE) in large spin-orbit coupling NM materials has drawn significant attention due to its technological potential and fundamental interest. To understand the effect of spin current due to SHE, it is important to estimate the conversion efficiency between charge current and spin current which is referred as spin Hall angle (SHA).<sup>4–8</sup> The accuracy of the SHA determined for various materials is still debated due to the large variation in the values reported by different groups for the same material. For example, the estimated value of the SHA for Pt<sup>5,8–10</sup> varies over a wide range (0.0037 to 0.16) as mentioned in other reports.<sup>4–6,11,12</sup>

In general, the spin-torque-induced ferromagnetic resonance technique<sup>4,7</sup> (ST-FMR) has been used to estimate the value of SHA. With the ST-FMR technique, a NM/FM bilayer film is excited using rf current and a response is detected in the form of a dc voltage from the magnetic layer using the spin torque diode effect.<sup>13,14</sup> However, it is known that the ST-FMR spectrum shape can be modified<sup>7</sup> by inverse spin Hall effect<sup>15–17</sup> (ISHE) and line-width broadening can also result from thermal spin waves. These effects may contribute to a significant error in the estimation of the SHA. As an alternative to the ST-FMR technique, optical excitation and detection method for determining SHA looks very promising, which has not been explored so far. Here, time-resolved magneto-optical Kerr effect (TR-MOKE) microscopy<sup>18</sup> was used to investigate the magnetic damping and its modulation due to spin Hall spin torque in Pt/Ni<sub>81</sub>Fe<sub>19</sub> bilayer stack. The advantage of implementing TR-MOKE was that the damping was measured directly in time domain within the highly localized probe area ( $\sim 1 \mu\text{m}^2$ ) due to focused laser spot.<sup>19</sup> It excluded any inhomogeneities or

variation due to larger area averaging and provided better estimates of damping.<sup>19</sup> A further advantage is that the modal composition of the magnetization oscillations can be observed in the time domain and the damping for each mode can be assessed. Another benefit of using TR-MOKE was it did not require any additional fabrication of waveguide on the sample and only dc current was passed through the sample. Estimates of the value of the spin Hall angle for the Pt layer were obtained from the experiment which are comparable with those found in some of the existing literature.<sup>4–6,8</sup>

Thin film stacks of Pt(6.8 nm)/Ni<sub>81</sub>Fe<sub>19</sub>(12.7 nm)/MgO(2.4 nm) were grown on a thermally oxidized Si [100] substrate by dc/rf magnetron sputtering. The base pressure of the chamber was  $\sim 1.0 \times 10^{-7}$  Torr, and the deposition used Ar gas at  $1.14 \times 10^{-3}$  Torr. The MgO layer was an insulating protective capping layer. The sample dimensions of  $5 \times 1.5 \text{ mm}^2$  were obtained by deposition through a rectangular shadow mask. Pt contact pads (15 nm thick) were deposited at the two ends along the length of the sample for electrical connections. The resistivities of the Pt and Ni<sub>81</sub>Fe<sub>19</sub> were measured to be 15.0 and 36.0  $\mu\Omega \text{ cm}$ , respectively. A dc charge current ( $I_{dc}$ ) was applied along the length of the sample using a variable dc current source. An in-plane bias magnetic field  $H$  was applied at an angle  $\theta$  with respect to the long axis of the sample. Due to negligibly small magneto-crystalline anisotropy of Ni<sub>81</sub>Fe<sub>19</sub> thin film, the magnetization  $M$  was uniformly aligned along the direction of the bias magnetic field. Figure 1 shows a schematic of the sample and measurement arrangement. A 400 nm laser with 17.0 mJ/cm<sup>2</sup> of fluence and  $\sim 100$  fs pulse-width was used to excite the magnetization dynamics in the sample while a 800 nm laser with 2.1 mJ/cm<sup>2</sup> of fluence and  $\sim 80$  fs pulse-width probed the sample at different time delays with respect to excitation. The experiments were performed at room temperature.

The direct current flowing in the bilayer sample was expected to be distributed between Ni<sub>81</sub>Fe<sub>19</sub> and Pt layers as determined by the resistivity of each layer. Due to strong spin-orbit interaction and impurity scattering within the Pt, electrons with opposite spin polarity would be deflected in opposite

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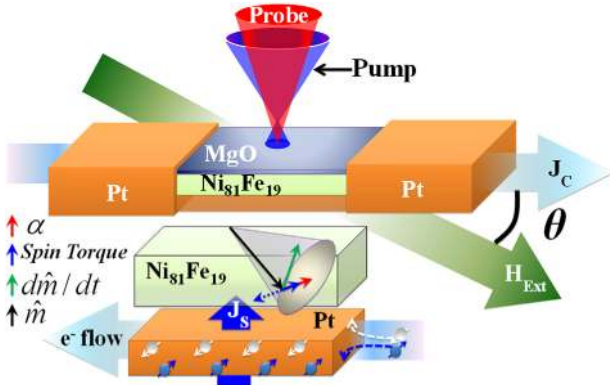


FIG. 1. Schematic diagram of the sample and the experimental geometry.

directions, leading to spin accumulation at the interfaces and giving rise to a spin current due to the SHE. Spin current injected<sup>1</sup> from the Pt into the adjacent Ni<sub>81</sub>Fe<sub>19</sub> layer can exert a torque upon the magnetization which is referred to as the spin transfer torque (STT). This transfer of angular momentum to the magnetization modifies the magnetization relaxation,  $\tau$ , and can thereby modify the effective magnetic damping  $\alpha$ . The polarization of spin current,  $\hat{\sigma}$ , is determined by  $\hat{J}_C \times \hat{n}$ , where  $\hat{J}_C$  is the applied charge current density and  $\hat{n}$  is the normal vector to the interface plane. The interaction between spin current and magnetization has been described by the modified Landau Lifshitz Gilbert equation<sup>7</sup> (LLG equation)

$$\frac{d\hat{m}}{dt} = -\gamma(\hat{m} \times H_{eff}) + \alpha \left( \hat{m} \times \frac{d\hat{m}}{dt} \right) + \frac{\hbar}{2e\mu_0 M_S t} J_S (\hat{m} \times \hat{\sigma} \times \hat{m}), \quad (1)$$

where the last term incorporates the STT.<sup>20–22</sup> The direction of STT is determined by  $(\hat{m} \times \hat{\sigma} \times \hat{m})$  and acts collinearly with the effective damping,  $\alpha$ , and can increase or decrease the effective value of  $\alpha$  depending on the polarity of  $\hat{\sigma}$ . This modulation of the damping can be related to the injected spin current density and the relative orientation of magnetic moment with respect to current by the following equation:<sup>5</sup>

$$\Delta\alpha = (\alpha - \alpha_0) = \hbar\gamma J_S \sin\theta / 2eM_S t 2\pi f, \quad (2)$$

where  $\alpha_0$  is the original damping with zero dc current,  $\Delta\alpha$  is the change in the damping (MOD), and  $J_S$  is the spin current density. The spin Hall angle,  $\theta_{SH}$ , is given by  $J_S/J_C$ , defined as

$$J_S/J_C = 4\pi f e t M_S \Delta\alpha / \hbar\gamma J_C \sin\theta. \quad (3)$$

Hence, by estimating the rate of MOD ( $\Delta\alpha/J_C$ ) experimentally, we can evaluate  $J_S/J_C$  using Eq. (3).

Figure 2(a) shows the time-resolved Kerr rotation data obtained from Pt/Ni<sub>81</sub>Fe<sub>19</sub> bilayer film at  $H \sim 1.4$  kOe,  $\theta = 0^\circ$ , and  $I_{dc} = 0$ . The data can be divided into three different temporal regions. Region I ( $t < 0$ ) shows negative time delay where the sample is probed before excitation and the sample shows steady magnetization due to external bias magnetic field. Region II (up to few tens of ps) shows a sharp demagnetization (500 fs) and a subsequent fast relaxation due to spin lattice relaxation. This is followed by a slower relaxation in region III and precession of magnetization

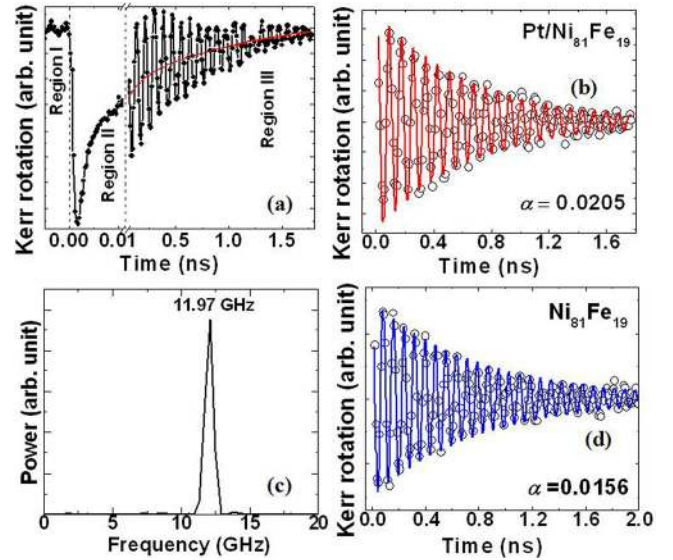


FIG. 2. (a) Time-resolved Kerr rotation data for Pt/Ni<sub>81</sub>Fe<sub>19</sub> bilayer film at  $H \sim 1.4$  kOe,  $I_{dc} = 0$ , and at  $\theta = 0^\circ$ . (b) Precessional part of the time-resolved data. (c) Fast Fourier transform (FFT) spectrum of Fig. 2(b). (d) Time-resolved Kerr rotation data from a single Ni<sub>81</sub>Fe<sub>19</sub> layer of equal dimensions as that in the bilayer film.

around its new equilibrium. In Region III, heat is diffused to the substrate and to the surrounding, and the precession was slowly damped. The analysis here mainly concentrates on region III, which is the region of interest for estimating  $\alpha$ . The solid line in Fig. 2(a) is the bi-exponential background of the damped oscillation shown in region III from which relaxation times of 1.4 ps and 1.43 ns were obtained. Figure 2(b) shows the precessional data with the background subtracted. A single mode oscillation decaying with time was typically observed. The time-resolved data were fitted with a damped harmonic function from which  $\alpha$  was estimated as  $\alpha = 1/2\pi f\tau$ , where  $f$  is the frequency of oscillation and  $\tau$  is the relaxation time corresponding to oscillation of magnetization. Figure 2(c) shows the fast Fourier transform (FFT) spectrum of the data in Fig. 2(b) from which  $f$  was determined to be about 12.0 GHz. From Fig. 2(b),  $\alpha$  was found to be about 0.021. Figure 2(d) shows the time evolution of magnetization dynamics of Ni<sub>81</sub>Fe<sub>19</sub> film of same dimensions. From this, we found  $\alpha$  to be about 0.016. The enhanced value of  $\alpha$  for Pt/Ni<sub>81</sub>Fe<sub>19</sub> bilayer stack in comparison to a single Ni<sub>81</sub>Fe<sub>19</sub> layer may be explained by considering additional loss due to spin pumping into the Pt layer, as well as due to the  $d-d$  hybridization<sup>23</sup> at the Pt/Ni<sub>81</sub>Fe<sub>19</sub> interface.

The effect of the magnetic field on the magnetization dynamics of the Pt/Ni<sub>81</sub>Fe<sub>19</sub> bilayer is shown in Fig. 3. Figure 3(a) shows the TR-MOKE data at various  $H$  values, and Fig. 3(b) shows the corresponding FFT power spectra. The precessional frequency  $f$  values obtained from Fig. 3(a) are plotted as function of  $H$  in Fig. 3(c). The experimental data points can be fitted using the Kittel formula

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

A value for  $M_S$  of 770 emu/cc was obtained from fitting and a value for the gyromagnetic ratio  $\gamma \sim 0.0185 \times 10^{11}$  Hz/T. Figure 3(d) shows a plot of  $\alpha$  as a function of frequency  $f$ . It



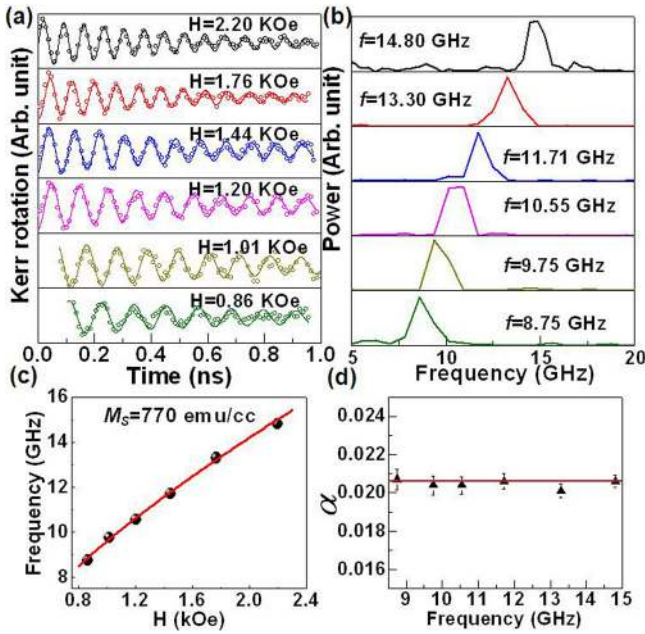


FIG. 3. (a) Time-resolved Kerr rotation for Pt/Ni<sub>81</sub>Fe<sub>19</sub> bilayer film at different bias field values (H) at  $I_{dc}=0$  and  $\theta=0^\circ$ . (b) The corresponding FFT spectra. (c) Variation of experimental precession frequency ( $f$ ) with H (symbol) and fit to the Kittel formula (solid line). (d) Variation of  $\alpha$  as a function of  $f$ .

is observed that  $\alpha$  remains almost constant over a range of frequency between 8.5 to 15 GHz, from which it is inferred that in this sample, extrinsic phenomena,<sup>24</sup> such as two magnon scattering, do not contribute to the effective damping.

In order to investigate the effect of spin torque on damping, a dc current was passed through the stack. Figure 4(a) shows the time-resolved magnetization precession at different current densities ( $J_c$ ) varying from  $-1.11 \times 10^{10}$  A/m<sup>2</sup> to  $+1.11 \times 10^{10}$  A/m<sup>2</sup> with a magnetic field,  $H \approx 1.2$  kOe applied at an angle of  $\theta=90^\circ$  to the current flow. A variation in  $\alpha$  of up to  $\pm 7\%$  as compared to its intrinsic value was observed for positive and negative values of  $J_c$  up to

$1.11 \times 10^{10}$  A/m<sup>2</sup>. Significantly, for positive  $J_c$ , the damping,  $\alpha$  decreases whereas for negative  $J_c$ ,  $\alpha$  increases. The observed sensitivity of MOD on the sign of  $J_c$  suggests that the origin is related to the injected spin current due to SHE from the Pt layer, which depends on the current polarity. Joule heating produced by the application of a dc current would only induce an increase in  $\alpha$  with respect to its zero current value and show no polarity dependence. Thus, the results suggest that Joule heating has a negligible influence on the magnetization dynamics in the Pt/Ni<sub>81</sub>Fe<sub>19</sub> bilayer. In Fig. 4(b), the variation of effective value of  $\alpha$  with  $J_c$  is shown for  $H \approx 1.2$  kOe where the field is orientated at  $\theta=0^\circ$ ,  $45^\circ$ , and  $90^\circ$  with respect to the current axis. At  $\theta=0^\circ$ ,  $\alpha$  remains almost constant for all  $J_c$ , indicating that there is no net torque on the magnetization. More interestingly, for  $\theta=45^\circ$  and  $90^\circ$ , a clear linear MOD is observed. The slopes of the linear fit to the current density dependence of MOD determined for  $\theta=90^\circ$  and  $45^\circ$  are  $1.24 \times 10^{-13}$  m<sup>2</sup>/A and  $8.14 \times 10^{-14}$  m<sup>2</sup>/A, indicate that the MOD depends not only on the polarity of  $J_c$  but also on magnetization orientation with respect to the current. The above observations further support the notion of spin torque acting on the Ni<sub>81</sub>Fe<sub>19</sub> layer due to SHE from Pt layer leads to MOD. By extracting the values of  $\Delta\alpha/J_c$  obtained from Fig. 4(b) for  $\theta=45^\circ$  and  $90^\circ$  and using in Eq. (3), we estimate spin Hall angle,  $\theta_{SH}$ , to be  $0.11 \pm 0.02$  and  $0.11 \pm 0.03$ , respectively. From these values, an average value for  $\theta_{SH}$   $0.11 \pm 0.03$  is calculated which is within the upper bound ( $<0.16$ ) of the values reported in the literature.<sup>4-6,8</sup> Here, the observed value of  $\theta_{SH}$  is on the higher side which may be related to some aspect specific to the sample (transparency of the Pt/NiFe interface, Pt microstructure, substrate, etc.) as well as the different methodology (TR-MOKE) used to estimate the same. Figure 4(c) shows the variation of frequency as a function of  $J_c$ . A decrease (red shift) in the precessional frequency,  $f$ , with increasing magnitude of  $J_c$  was observed and was more or less symmetric with respect to zero current. Previously, a red shift in frequency with  $J_c$  was explained by considering the reduction in effective magnetization of the material because of magnetic

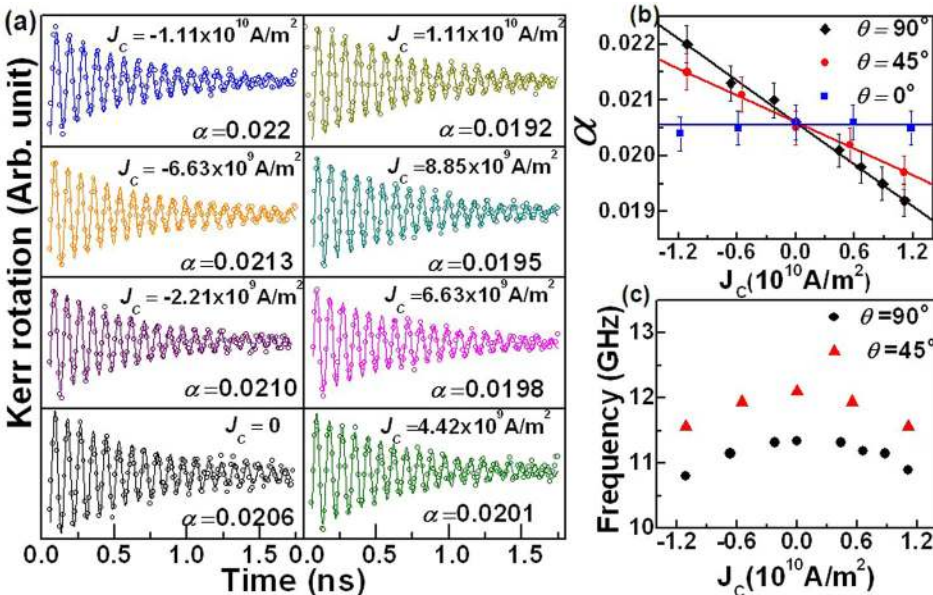


FIG. 4. (a) Time-resolved magnetization precession at different dc charge current densities,  $J_c$ , for  $\theta=90^\circ$  obtained from the TR-MOKE experiment. Symbols represent the experimental data points, and solid lines are the theoretical fits. (b) The variation of  $\alpha$  with  $J_c$  for magnetic fields oriented at angle  $\theta=0^\circ$ ,  $45^\circ$ , and  $90^\circ$  with respect to the current direction. (c) Variation of the precessional frequency  $f$  with  $J_c$  for  $\theta=45^\circ$  and  $90^\circ$ .

fluctuation<sup>25</sup> due to Joule heating. However, the change in  $f$  with current should not affect  $\alpha$  as is shown in Fig. 3(c) or the estimation of  $\theta_{SH}$ .

In summary, using an all-optical excitation and detection technique, the magnetization dynamics in a Pt/Ni<sub>81</sub>Fe<sub>19</sub> bilayer was studied. A spin transfer torque was indicated in Ni<sub>81</sub>Fe<sub>19</sub> via a current dependent modulation of the effective damping which is attributed to the spin Hall effect from the Pt underlayer. A linear modulation of the damping up to  $\pm 7\%$  was observed as a function of current density, to an experimental limit of  $1.11 \times 10^{10}$  A/m<sup>2</sup>. An average spin Hall angle for Pt was estimated from analysis of the data to be about  $0.11 \pm 0.03$ . A larger modulation of damping may be observed by increasing the current density, allowing the determination of  $\theta_{SH}$  with greater precision. These results will help in understanding the role of spin Hall effect in affecting magnetization dynamics.

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