Optical detection of spin–orbit torque and current-induced heating

Yukihiro Marui1, Masashi Kawaguchi1, and Masamitsu Hayashi1,2

1Department of Physics, The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan
2National Institute for Materials Science, Tsukuba, Ibaraki 305-0047, Japan

Received May 8, 2018; accepted July 26, 2018; published online August 20, 2018

We studied the spin–orbit torque in heavy metal/ferromagnetic metal bilayers using the magneto-optical Kerr effect. A double-modulation technique is developed to separate signals from the spin–orbit torque and Joule heating. At a current density of $1 \times 10^{10}$ A/m$^2$, we observe optical signals that scale linearly and quadratically with the current density, both in similar magnitude. The spin–orbit torque estimated using this technique is consistent with that evaluated using spin-transport measurements. We find that changes in the refractive index of the film with temperature are the main source of the heating-induced signal.

© 2018 The Japan Society of Applied Physics

Generation of spin current via the spin Hall effect in heavy metals (HMs) and spin accumulation via the Rashba–Edelstein effect at interfaces are attracting considerable interest owing to their potential application towards magnetic random-access memory technologies. The spin current and/or spin accumulation can diffuse into adjacent magnetic layer(s) to exert spin–orbit torque on magnetic moments and allow current-induced control of magnetization. Advances in the understanding of the mechanism whereby spin–orbit torque arises at interfaces have been made owing to the development of electrical and optical measurement techniques. The accuracy of the torque evaluated using different techniques, however, appears to differ depending on the system studied, and its improvement remains as a subject to be addressed.

Recent experiments have demonstrated that it is possible to optically detect spin accumulation at sample edges or surfaces generated by the spin Hall effect in semiconductors and metals. Direct measurements of the spin accumulation allow straightforward characterization of the efficiency of spin current generation in various materials. However, it has been reported that the optical signal used to study spin accumulation can be contaminated by current-induced heating (Joule heating) effects. To resolve signals originating from current-induced spin accumulation, one needs the current density reduced for minimizing the Joule heating effects and simultaneously improve the signal-to-noise ratio of the optical detection setup.

Here, we show that it is possible to separate magnetic and heating-induced signals in optical measurements. In model systems consisting of a HM/ferromagnetic metal (FM) bilayer, we study the spin–orbit torque using a double-modulation magneto-optical detection technique. We find signals that scale linearly and quadratically with the current density. The former is due to current-induced changes of the magnetization, which reflects the size of spin–orbit torque. The estimated torque agrees well with transport measurements of the same sample. The signal that scales quadratically with the current density is larger than the signal associated with the spin–orbit torque even at a current density of $1 \times 10^{10}$ A/m$^2$. We find the changes in the refractive index of the film (and/or the silicon oxide layer of the substrate) with temperature cause the spurious heating-induced signal. The detection scheme developed here may be applied to study current-induced spin accumulation at surfaces and interfaces using higher current density, providing easier access to study such effects.

Samples are grown on thermally oxidized silicon substrates using RF magnetron sputtering. Two representative films are made for this study. A: sub./0.5 Ta/3 Pt/1 Co$_{20}$Fe$_{60}$B$_{20}$/2 MgO/1 Ta and B: sub./3 W/1 Co$_{20}$Fe$_{60}$B$_{20}$/2 MgO/1 Ta (thickness in nanometers). Films are deposited through a metal shadow mask to create Hall bars. The width and length (i.e., distance between the voltage probes) of the Hall bars are 0.4 and 1.2 mm respectively. All films are deposited and measured at room temperature. The magnetization easy axis points along the film plane (we find little perpendicular magnetic anisotropy at the CoFeB/MgO interface without any post-annealing).

The experimental setup and the coordinate axis are schematically illustrated in Fig. 1. The film normal points along the z-axis, and the current is passed along the y-axis. A positive current is defined as current flow to $+y$. The magneto-optical Kerr effect is used to probe the magnetization direction of the films. A continuous-wave (CW) He–Ne laser (wavelength: 633 nm, power: 5 mW) is used as the light source. The light is polarized along the x-axis and is irradiated to the sample (at the center of the wire) from the film normal. The light reflected from the sample passes through a photoelastic modulator (PEM) and a polarization filter before entering a silicon avalanche photodetector. The modulation frequency $f$ of the PEM is $50$ kHz.

As the incident light is polarized along the x-axis, we express its polarization as $E_0 = E_0 (1e_1 + 0e_2)$, where $e_1$ represents a unit vector along the i direction and $E_0$ is the...
amplitude of the light. The polarization of the reflected light that enters the silicon photodetector takes the following form:

$$E_{PD} = H_{PAS}H_{PEM}H_{K}E_{IN}$$ (1)

where $H_{K}$ represents the magneto-optical Kerr effect of the sample. $H_{PAS}$ and $H_{PEM}$ are the operations of the polarization filter and the PEM, both placed in a position where the reflected light from the sample passes through. The matrix forms of these operations are

$$H_{K} = r_{K} \left[ \begin{array}{cc} \cos \theta \cos \eta - i \sin \theta \sin \eta & -\sin \theta \cos \eta - i \cos \theta \sin \eta \\ \sin \theta \cos \eta + i \cos \theta \sin \eta & \cos \theta \cos \eta - i \sin \theta \sin \eta \end{array} \right],$$

$$H_{PEM} = \left[ \begin{array}{cc} 1 & 0 \\ 0 & e^{-i\delta \sin(2\pi t)} \end{array} \right],$$

$$H_{PAS} = \frac{1}{2} \left[ \begin{array}{cc} 1 & 1 \\ 1 & 1 \end{array} \right].$$ (2, 3, 4)

Here, $r_{K}$ represents the reflectivity, and $\theta$ and $\eta$ are the Kerr rotation angle and the ellipticity of the sample. $\delta$ is the phase delay at the PEM.

The intensity of the light ($I_{PD} = |E_{PD}|^2$) that arrives at the silicon photodetector is

$$I_{PD} = \frac{(r_{K}E_{0})^2}{4} \left[ 1 + \sin(2\theta) \cos(2\eta) \cos(\delta \sin(2\pi t)) + \sin(2\eta) \sin(\delta \sin(2\pi t)) \right].$$ (5)

According to Eq. (5), $I_{PD}$ oscillates with frequency $\omega$. We Fourier expand $I_{PD}$ in series of the PEM frequency $\omega$:

$$I_{PD} = \frac{(r_{K}E_{0})^2}{2} \sum_{n} \left[ I_{n} \cos(2\pi n t) + i_{n} \sin(2\pi n t) \right].$$ (6)

The first three components ($n = 0, 1, 2$) are expressed as

$$I_{0} = \frac{1}{2} (1 + J_{0}(\delta) \sin(2\theta) \cos(2\eta)), \quad \tilde{I}_{0} = 0,$$ (7)

$$I_{1} = 0, \quad \tilde{I}_{1} = J_{1}(\delta) \sin(2\eta),$$ (8)

$$I_{2} = J_{2}(\delta) \sin(2\theta) \cos(2\eta), \quad \tilde{I}_{2} = 0.$$ (9)

Here, $J_n(x)$ is the Bessel function of the first kind. The PEM phase delay $\delta$ is set as $\sim 2.4 \text{ rad}$ to obtain $J_{0}(\delta) \sim 0$, which results in $I_{0} \sim 1/2$. With $\theta \ll 1$ and $\eta \ll 1$, we obtain $\tilde{I}_{1} \sim 2n_{t} J_{1}(\delta)$ and $I_{2} \sim 2n_{t} J_{2}(\delta)$.

The light is converted into an electrical voltage at the photodetector, and the conversion process is linear. The output voltage from the photodetector is fed into a lock-in amplifier to pick up the two frequency components $I_{1}$ and $I_{2}$. The direct-current component $I_{0}$ is measured using a digital multimeter. A representative trace of the voltage that enters the lock-in amplifier, which shows the modulation by the PEM, is shown in the lower panel of Fig. 1(b). From the Fourier transform of the data, the Kerr rotation angle and the ellipticity are obtained using the following identities:

$$\theta \sim \frac{1}{4J_{2}(\delta)} I_{2},$$ (10)

$$\eta \sim \frac{1}{4J_{1}(\delta)} I_{1},$$ (11)

with $J_{1}(\delta) \sim 0.52$ and $J_{2}(\delta) \sim 0.43$ for $\delta \sim 2.4 \text{ rad}$. $\theta$ and $\eta$ reflect the magnetic state of the sample. Since both $\theta$ and $\eta$ provide the same information, we focus on $\eta$, which is larger in magnitude than $\theta$ here (the relative size of $\theta$ and $\eta$ is mostly determined by the light wavelength and the thickness of the silicon oxide layer of the substrate$^{22}$).

In general, the spin–orbit torque can be decomposed into two components: the damping-like and field-like components. When current is passed along $+y$ and the initial magnetization is directed along $+z$, the effective field associated with the damping-like ($H_{DL}$) and the field-like ($H_{FL}$) components of the torque point along $\pm z$ and $\pm x$, respectively. Here we study the damping-like component, which is known to predominantly originate from the spin-transfer torque$^{24}$ when spin current is injected into the FM layer via the spin Hall effect of the HM layer. We therefore use the polar geometry, as shown in Fig. 1, to probe the out-of-plane component $m_z$ of the magnetization in response to the current along $y$.

To convert the optical signal ($\eta(t)$) to an effective field, we first study the magnetic-field response of the magnetization as a function of an out-of-plane field $H_z$. Using the relation noted in Eq. (11), the Kerr ellipticity is measured as a function of $H_z$ and the results are plotted in Fig. 2(a). The change of $\eta$ with respect to $H_z$ is almost linear. We fit the data with a linear function to obtain a proportionality constant $\alpha$, which can be used to convert $\eta$ into an effective field. $\alpha$ is listed in Table I for both samples (A and B). The offset in $\eta$ is predominantly due to an intentional tilting of $E_{PD}$ polarization with the $x$-axis (i.e., the PEM polarization plane). Without the tilting, the optical signal becomes distorted and hinders accurate measurements of $\eta$.

Next we study the effect of current on the magnetization. We apply a constant current $i_c$ to the sample for a certain duration $t$ to acquire $\eta$. The size of $i_c$ is varied stepwise to follow a sinusoidal function with frequency $f$ [see Fig. 1(b), upper panel], i.e., $i(t) = i_{c}(t) = i_{c} \cos(2\pi f t)$. Because $\eta$ is evaluated at each $i_{c}$, we denote $\eta$ as $\eta(t)$ hereafter to explicitly show its time dependence through $i_{c}(t)$. This process of varying $i_{c}$ with frequency $f$, i.e., the second modulation (the first one is at the
PEM), is repeated many times (typically 1,000 times) to improve the signal-to-noise ratio. The experiment was conducted for various values of $i_0$. We compute the equivalent current density $j$ that passes through the HM layer with $i_0$. To calculate $j$, the resistivity of the layer is obtained as follows. Ta: $\sim 200 \mu \Omega \text{cm}$, W: $\sim 110 \mu \Omega \text{cm}$, Pt: $\sim 55 \mu \Omega \text{cm}$, and CoFeB: $\sim 160 \mu \Omega \text{cm}$ (Ref. 25). During the measurements with current, a magnetic field directed along the $y$-axis is applied ($H_y \sim \pm 50 \text{mT}$) to avoid causing demagnetization and also to set the initial magnetic state of the wire.

Representative data of $\eta(f)$ are shown in Fig. 2(b). The time-dependent Kerr ellipticity $\eta(f)$ is fitted with a sum of sinusoidal functions with frequency $f$ and $2f$, i.e.,

$$\eta(f) = \eta_1 f \cos(2\pi f t + \varphi_1) + \eta_2 \cos(4\pi f t + \varphi_2) + \eta_0.$$  

(12)

In Eq. (12), $\eta_1 f$ is the term that scales linearly with current and represents contribution from the spin–orbit torque, whereas $\eta_2 f$ is proportional to the square of the current and is likely related to Joule heating-induced effects. $\eta_0$ is the background signal described above. $\varphi_1$ and $\varphi_2$ are the phase delay, which is discussed later. The contribution from each component ($\eta_1 f$ and $\eta_2 f$) is represented by the dashed lines in Fig. 2(b). As evident, the $2f$ component that scales with the square of $j$ dominates the signal.

Using the $\alpha$ listed in Table I, we convert $\eta_1 f$ and $\eta_2 f$ into effective fields using the following relation:

$$\eta_1 f = \alpha h_{\text{DL}},$$

$$\eta_2 f = \alpha h_{\text{HE}}.$$  

(13)

where $h_{\text{HE}}$ represents the size of Joule heating-induced effect. Note that $h_{\text{HE}}$ is not a field that appears due to Joule heating; it characterizes the effect so that we may compare its influence on the optical signal with that of current-induced torques.

The effective fields $h_{\text{DL}}$ and $h_{\text{HE}}$ are shown in Fig. 3 with respect to $j$ and $j^2$ for both samples A and B. As evident, $h_{\text{DL}}$ linearly scales with $j$ and changes its sign with $j^2$, whereas $h_{\text{HE}}$ is opposite for samples A and B and reflects the opposite spin Hall angles of W and Pt. These features are consistent with the damping-like component of the current-induced torque. The spin-torque efficiency $\xi$ of samples A and B is estimated from $h_{\text{DL}}$. Assuming a transparent interface, which provides the lower limit of the effective spin Hall angle, we use the following relation for the conversion:

$$\xi = \frac{h_{\text{DL}}/j \times M_s t}{\hbar/2e},$$  

(14)

where $M_s$ and $t$ are the saturation magnetization and thickness of the FM layer, respectively; $\hbar$ is the reduced Planck constant and $e$ is the electric charge. $\xi$ and $M_s$ for samples A and B are summarized in Table I. For comparison, the spin Hall magnetoresistance (SMR) of samples A and B are measured using the Hall bars. These results are included in Table I. We find that both techniques—magneto-optical detection ($\xi_{\text{MOKE}}$) and SMR ($\xi_{\text{SMR}}$)—return $\xi$ values that are comparable in magnitude. $\xi$ is consistently smaller when the former method is used; the reason for this is unclear and requires further investigation.

With regard to $h_{\text{HE}}$, we find that it scales with $j^2$ and its sign is the same regardless of the initial state of the magnetization direction and the HM layer used (i.e., samples A and B possess the same sign for $h_{\text{HE}}$). These results indicate that $h_{\text{HE}}$ is related to current-induced (Joule) heating. The difference in the size of $h_{\text{HE}}$ for samples A and B may partly be explained by the difference in the film resistance. As noted in Table I, the resistivity of the HM layer is nearly two times larger for sample B, giving rise to larger Joule heating (heating scales with the film resistance for a fixed current density; the geometry of the wire is the same for both samples). However, the absolute value of $h_{\text{HE}}$ depends on extrinsic factors, e.g., the thermal contact between the sample and the sample stage, the laser power, and the temperature of the environment. It is thus difficult to compare $h_{\text{HE}}$ between samples, as these effects can vary.

The duration of current application $\tau$ is varied to study the effects of Joule heating on the optical signal and the estimation of the spin–orbit torque. The $\tau$ dependences of $\eta_1 f$ and $\eta_2 f$ are shown in Fig. 4(a). Whereas $\eta_1 f$ shows little change with respect to $\tau$, $\eta_2 f$ significantly increases with increasing of $\tau$. We also plot the phase delay ($\varphi_1 f$ and $\varphi_2 f$) with respect to $\tau$ in Fig. 4(b). The non-zero phase delay for small $\tau$ indicates that the heating process does not saturate in one cycle (within $\tau$). We observe a large change in $|\varphi_2 f|$ with
Increasing $r$, while the change in $|\rho_{12}|$ is small. These results indicate that the optical signal related to the measurements of the spin–orbit torque ($\eta_{11}$) is not significantly influenced by the degree of heating, i.e., by $r$.

We next discuss the origin of $h_{\text{HE}}$. The Joule heating-induced Kerr signal change $\eta_{2}/\eta_{0}$ is, for example, $-2 \times 10^{-3}$ from the results shown by the red dashed line in Fig. 2(b).

We consider there are two possible sources of $h_{\text{HE}}$: temperature-dependent changes of the film thickness, including the silicon oxide layer of the substrate, and changes in the refractive index of the film and oxide layer. The Kerr signals observed here are enhanced by the optical interference effect that occurs within the oxide layer of the substrate. Upon Joule heating, each layer undergoes thermal expansion and changes its thickness. In addition, the refractive index of each layer changes owing to the temperature change. We use the effective refractive index approach to estimate changes in the Kerr signal. With the thermal expansion coefficients of the silicon oxide, we find $\eta_{2}/\eta_{0} \sim 10^{-6}$ (1/K). (The contribution of the thermal expansion of the film to the Kerr signal is even smaller.) In contrast, changes in the refractive index cause $\eta_{2}/\eta_{0} \sim 5 \times 10^{-4}$ (1/K): the contribution from each layer is nearly the same. As the latter contribution is larger by orders of magnitude, we consider that $h_{\text{HE}}$ is caused by Joule heating-induced changes of the refractive index of the oxide/film. For a current density of $10^{10}$ A/m$^2$, we estimate that it requires the temperature to change by $\sim$4 K for observing the changes in $\eta_{2}/\eta_{0}$ found here.

Finally, it has been recently reported that spin accumulation due to the spin Hall effect in non-magnetic metals can be detected using magneto-optics. To reduce the spurious optical signal from Joule heating, the current density passed along the film must be reduced to $\sim 10^{7}$ A/m$^2$ or smaller. As a consequence, the signal resolution must be better than $10^{-8}$ rad. Using the optical detection scheme developed here, we consider that it is possible to separate optical signals due to spin accumulation and the Joule heating effect, allowing larger current to be passed to the film. Assuming that the optical signal due to spin accumulation scales with the current density, one estimates the Kerr signal of $10^{-5}$ rad at the current density used here ($\sim 10^{10}$ A/m$^2$).

The Kerr resolution of the setup here is $10^{-6}$ rad [see Fig. 2(b)], we consider that it is possible to detect the signal due to spin accumulation.

In summary, we studied magneto-optically detected current-induced spin–orbit torque in HM/FM bilayers (HM = Pt, W, FM = CoFeB). Using a double-modulation technique, optical signals arising from the magnetic system are separated from those due to current-induced (Joule) heating. Although we find a significant contribution from Joule heating to the optical signal at a current density of $\sim 1 \times 10^{10}$ A/m$^2$, the spin-torque efficiency varies little with the current density. The obtained spin-torque efficiency agrees with that estimated using spin-transport measurements of the same sample. We find that the Joule heating-induced optical signal originates from changes in the temperature-dependent refractive index of the film/silicon oxide layer. As the detection scheme developed here can separate magnetic and heating-related optical signals, we consider that this technique can be applied to study spin accumulation in metals and interfaces.

Acknowledgments This work was partly supported by a JSPS Grant-in-Aid for Scientific Research (16H03853), Specially Promoted Research (15H05702), and the Center of Spintronics Research Network of Japan.
G. E. W. Bauer, E. Saitoh, and S. T. B. Goennenwein, Phys. Rev. B 87, 224401 (2013).

28) Y. T. Chen, S. Takahashi, H. Nakayama, M. Althammer, S. T. B. Goennenwein, E. Saitoh, and G. E. W. Bauer, Phys. Rev. B 87, 144411 (2013).

29) J. Kim, P. Sheng, S. Takahashi, S. Mitani, and M. Hayashi, Phys. Rev. Lett. 116, 097201 (2016).

30) H. Nakayama, M. Althammer, Y. T. Chen, K. Uchida, Y. Kajiwara, D. Kikuchi, T. Ohtani, S. Geprags, M. Opel, S. Takahashi, R. Gross, G. E. W. Bauer, S. T. B. Goennenwein, and E. Saitoh, Phys. Rev. Lett. 110, 206601 (2013).

31) Y.-C. Lau and M. Hayashi, Jpn. J. Appl. Phys. 56, 0802B5 (2017).

32) K. Egashira and T. Yamada, J. Appl. Phys. 45, 3643 (1974).

33) Z. Q. Qui and S. D. Bader, Rev. Sci. Instrum. 71, 1243 (2000).

34) H. Tada, A. E. Kumpel, R. E. Lathrop, J. B. Slanina, P. Nieva, P. Zavracky, I. N. Miaoulis, and P. Y. Wong, J. Appl. Phys. 87, 4189 (2000).

35) G. Vuye, S. Fison, V. N. Van, Y. Wang, J. Rivory, and F. Abeles, Thin Solid Films 233, 166 (1993).

36) American Institute of Physics, American Institute of Physics Handbook (McGraw-Hill, New York, 1972) 3rd ed.