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Citation: Applied Physics Letters 103, 262407 (2013); doi: 10.1063/1.4859656
View online: http://dx.doi.org/10.1063/1.4859656
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/103/26?ver=pdfcov
Published by the AIP Publishing
Magnetotransport measurements of current induced effective fields in Ta/CoFeB/MgO

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(Received 25 October 2013; accepted 15 December 2013; published online 31 December 2013)

We evaluate current-induced effective magnetic fields in perpendicularly magnetized Ta/CoFeB/MgO structures from the external magnetic field angle dependence of the Hall resistance. We confirm the presence of two components of effective fields. The dependence of their magnitudes on Ta thickness implies that both components are related to the spin current in Ta layer generated by the spin Hall effect. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4859656]

Recently, it has been found that effective magnetic fields can be induced by an in-plane electrical current in a thin ferromagnetic metal layer sandwiched with a heavy metal and oxide, which give rise to torque acting on magnetization in the ferromagnetic layer.1–9 For a perpendicularly magnetized ferromagnetic layer, which give rise to torque acting on magnetization in the plane, can be induced by an in-plane electrical current in a thin ferromagnetic layer.1–9 The origin of the two effective fields is under discussion; the Rashba effect due to the structural inversion asymmetry as well as the spin Hall effect (SHE) in the adjacent heavy metal layer are involved.10–15 To evaluate the effective magnetic fields, three methods have been proposed and employed; one measures the dependence of coercivity on in-plane dc current,1,2 another measures the equilibrium magnetization direction under in-plane dc current as a function of magnitude or direction of external magnetic fields,3–5,9 and the third utilizes first- and second-harmonic magnetotransport response to an external magnetic field with the application of an in-plane ac current.6–8 By using these methods, effective fields more than 0.2 T at a current density of 108 A/cm2 have been reported in a number of material systems. Magnetization reversal using the effective fields has also been demonstrated,3,5,7 offering a new route to magnetization switching in three-terminal spintronics devices.3,16,17 In-plane current-induced magnetization reversal in Ta/CoFeB/MgO structure with perpendicular easy axis is of great interest, because the structure is an important building block for spintronics devices, such as magnetic tunnel junction exhibiting a large tunnel magnetoresistance ratio18 and is expected to be utilized in future very large scale integrated circuits.18–20 The effective fields in Ta/CoFeB/MgO structures with perpendicular easy axis have been investigated by using the methods mentioned above. The presence of Ta thickness dependent $H_T$ and $H_L$ was confirmed in these structures with Ta thickness less than 2 nm,6 and $H_T$ was found to be a few times larger than $H_L$.8,9 Dependence of magnitude of the effective fields on the angle between magnetization and current direction had also been investigated.8 Here, we present a method to measure $H_T$ and $H_L$ that can be applied to a Hall bar structure as shown in Fig. 1(a) and use it to investigate the dependence of the fields on Ta thickness in the technologically relevant thickness range (1–5 nm) in Ta/CoFeB/MgO structures. Stack structure of, from the substrate side, Ta ($t = 1, 1.5, 2.5, 4, 5$)/CoFeB($1$)/MgO($1.3$)/Ta(1) is deposited on thermally oxidized Si substrate by using dc and rf-magnetron sputtering. The numbers in parentheses are nominal thicknesses in nm. The stacks are patterned into Hall bar devices with a 10-$\mu$m wide channel and a pair of Hall probes. Then, Cr(5)/Au(100) electrodes are formed at the ends of the channel and probes. The devices are annealed at 300°C under an out-of-plane magnetic field of 0.4 T for 1 h. The experimental configuration and the definition of the Cartesian coordinate system in the present work are presented in Fig. 1(a). The direction of an external magnetic field $H_{\text{ext}}$ is described by polar angle $\theta_H$ and azimuth angle $\phi_H$. We measure the Hall resistance $R_{\text{Hall}}$ to determine the direction of magnetization $M$ as a function of $\theta_H$. The Hall resistance is given by the sum of the anomalous Hall resistance $R_{\text{AHIE}}$ proportional to the perpendicular component of magnetization, and the planar Hall resistance $R_{\text{PHE}}$, which is the transverse component of anistotropic magnetoresistance reflecting the in-plane component of magnetization. Therefore, by analyzing data on $R_{\text{Hall}}$, one can determine the magnetization direction in the CoFeB layer.

Figure 1(b) shows the $R_{\text{Hall}}$ versus $H_{\text{ext}}$ curve for the device with $t = 2.5$ nm at $\theta_H = 0$ and a small dc current of 20 $\mu$A. The square hysteresis indicates that the magnetic easy axis is perpendicular to the plane, which is also the case for other devices with different $t$. We measure $R_{\text{Hall}}$ as a function of direction $\theta_H$ of magnetic fields rotating in the $y$-$z$ plane ($\phi_H = -90^\circ$) or $z$-$x$ plane ($\phi_H = 0^\circ$). In order to...
evaluate \( H_T \) and \( H_L \), we measure \( R_{\text{Hall}} - \phi_H \) curves as a function of the magnitude \( I \) of dc current. Error of \( \phi_H \) in the measurement is less than 0.1°, which is due to misalignment. We measure \( R_{\text{Hall}} \) at a constant \( \theta_H \) to avoid the electromagnetic induction effect induced by continuous \( \theta_H \) rotation, and apply a dc current only during the \( R_{\text{Hall}} \) measurement (0.5 s) to minimize the Joule heating. The magnetization is pointing along a composite magnetic field formed by the effective anisotropy field \( H_{\text{Keff}} \), the external magnetic field \( H_{\text{ext}} \), \( H_T \), and \( H_L \). The magnitude of \( \mu_0 H_{\text{Keff}} \sim 0.6 \) T (\( \mu_0 \) the permeability in vacuum) in present devices can be determined by a separate measurement;21 the information of its precise value, however, is not needed for the determination of \( H_T \) and \( H_L \). We focus on the situation with magnetization nearly along \( z \) axis, i.e., \( \cos \theta_M \geq 0.995 \), where \( \theta_H \) is magnetization angle with respect to \( z \) axis. This can be realized even under \( \mu_0 H_{\text{ext}} \) of 0.1 T with \( |\theta_H| \leq 20^\circ \) for the present devices. In this case, \( R_{\text{Hall}} \) is approximated as

\[
R_{\text{Hall}} = A[(\sin \theta_H \cos \phi_H - \delta_L)^2 + (\sin \theta_H \sin \phi_H - \delta_T)^2] + C, \quad \delta_L = -H_L/H_{\text{ext}} - A_P/(2A), \quad \delta_T = H_T/H_{\text{ext}},
\]

\[
A = -R_{\text{AHE}}^0/[2(\cos \theta_H + H_{\text{Keff}}/H_{\text{ext}})^2], \quad A_P = R_{\text{PHE}}^0/(H_{\text{Keff}}/H_{\text{ext}} + \cos \theta_H),
\]

where \( R_{\text{AHE}}^0 \) and \( R_{\text{PHE}}^0 \) are the magnitudes of saturated anomalous Hall and planar Hall resistances, and \( C \) is nearly equal to \( R_{\text{AHE}}^0 \) at \( \theta_H \leq 20^\circ \) because of \( M \) being closely along the \( z \) axis. The values of \( A, A_P, \) and \( C \) are regarded as constants in our measurement (variation <1% for \( \mu_0 H_{\text{ext}} = 0.1 \) T, \( |\theta_H| \leq 20^\circ \), \( \mu_0 H_{\text{Keff}} \sim 0.6 \) T). At \( \phi_H = -90^\circ \) and 0°, \( R_{\text{Hall}} \) becomes a simple quadratic function of \( \sin \theta_H \), and the position of an extremum with respect to \( \sin \theta_H = 0 \) corresponds to the value of \( \delta_T \) at \( \phi_H = -90^\circ \) and that of \( \delta_L \) at \( \phi_H = 0^\circ \). By assuming the linear relationship between the magnitudes of the effective fields and the dc current, effective fields \( H_T \) and \( H_L \) are determined from the dc current dependence of \( \delta_T \) and \( \delta_L \), respectively. The \( R_{\text{Hall}} - \sin \theta_H \) curves are presented in Fig. 2(a) at \( \phi_H = -90^\circ \) and Fig. 2(b) at \( \phi_H = 0^\circ \) for the device with \( t = 2.5 \) nm, obtained at \( \mu_0 H_{\text{ext}} = 100 \) mT and \( I = 2.5 \) mA. The solid lines in Fig. 2 show fitted lines by a quadratic function with \( \delta_T = -0.016 \) and \( \delta_L = 0.099 \). Figure 3 summarizes the dc current dependence of \( \delta_T \) and \( \delta_L \) from the slopes of which \( \mu_0 H_T \) and \( \mu_0 H_L \) per unit current are determined to be \( \mu_0 H_T/I = -0.68 \) T/A and \( \mu_0 H_L/I = -0.36 \) T/A, respectively.

By using the present method, we investigate the Ta thickness dependence of \( H_T \) and \( H_L \). The values of \( \mu_0 H_T/I \) and \( \mu_0 H_L/I \) are plotted as a function of Ta thickness in Fig. 4(a). The directions of \( H_T \) and \( H_L \) with respect to current are consistent with the results of previous works, and the magnitudes of \( \mu_0 H_T/I \) and \( \mu_0 H_L/I \) are comparable to those obtained in the structures with a thinner Ta.6,8 Note that the magnitude of Oersted field is less than 10% of \( H_T \) in the studied current range. The magnitude of \( \mu_0 H_L/I \) is about 2 times larger than that of \( \mu_0 H_T/I \) regardless of \( t \), which is also consistent with the previous reports.6,8

Around \( t = 1.5 \) nm, the absolute values of \( \mu_0 H_T/I \) and \( \mu_0 H_L/I \) take a maximum, which is in accordance with the result of in-plane current-induced magnetization reversal measurements in the same device that shows minimum threshold current for the magnetization reversal around \( t = 1.5 \) nm.21

The increase of the magnitudes of the effective fields with the increase of Ta thickness suggests that effective magnetic fields are related to the spin Hall effect in the Ta layer.
We determine the current density $J$ flowing in the Ta layer by measuring the Ta and CoFeB thickness dependence of the sheet resistance on separately prepared samples. The values of $\mu_0 H_T/J$ and $\mu_0 H_L/J$ against Ta thickness are plotted in Fig. 4(b). The magnitudes of $\mu_0 H_T/J$ and $\mu_0 H_L/J$ increase initially with the increase of $t$ and saturate at $t \geq 2.5$ nm. Dependence of the spin current at the interface on Ta layer thickness $t$ is proportional to $1 - \text{sech}(t/t^*)/\lambda_{\text{sf}}$, where $t^*$ is the effective thickness of high resistivity region in Ta layer and $\lambda_{\text{sf}}$ is the spin diffusion length in the Ta layer. The origin of the difference is a subject of future study. The spin Hall angle in the Ta layer is expressed as

$$\theta_{\text{SH}} = M_S t_\text{F}(H_L/J)/h/2e,$$  

where $M_S$ is the saturation magnetization (0.8 T determined from magnetization measurement), $t_\text{F}$ is the thickness of CoFeB layer, $e$ is the elementary charge, and $h$ is the Dirac constant. By substituting the saturation values of $H_L/J$ into Eq. (2), $\theta_{\text{SH}}$ is determined to be 0.02–0.03, which gives the lower bound of $\theta_{\text{SH}}$ and is within the range of previous reports.4,12,23,24

In summary, we use a dc Hall resistance measurement as a function of direction of magnetic fields to evaluate effective magnetic fields induced by in-plane current for perpendicularly magnetized Ta/CoFeB/MgO structures with Ta thickness ($t$) ranging from 1 to 5 nm. The magnitude and directions of transverse $\mu_0 H_T$ and longitudinal $\mu_0 H_L$ effective field as well as their ratio being about 2 are in accordance with the previous reports. The magnitudes of $\mu_0 H_T/J$ and $\mu_0 H_L/J$ increase with increasing $t$ and saturate at $t \geq 2.5$ nm, suggesting that the observed effective fields are related to the spin current generated in the Ta layer by the spin Hall effect, and that the spin diffusion length and the lower bound of the spin Hall angle in Ta are 0.5 nm and 0.02–0.03, respectively.

We thank T. Hirata, N. Ohshima, H. Iwanuma, Y. Kawato, and C. Igarashi for their technical supports. This work was supported by the FIRST program from JSPS, the Research and Development for Next-Generation Information Technology of MEXT, and Grants for Excellent Graduate Schools of MEXT.