Research articles

Tuning the spin-orbit torque effective fields by varying Pt insertion layer thickness in perpendicularly magnetized Pt/Co/Pt(t)/Ta structures

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ABSTRACT

We experimentally determine that a Pt layer insertion between the Co/Ta interface can effectively negate the field-like spin-orbit torque (SOT) in perpendicularly magnetized Pt/Co/Pt(t)/Ta structures, as the Rashba effects at the Pt/Co and Co/Pt interfaces counteract each other. The damping-like term can be tuned by varying the thickness of the Pt insertion layer to change both the sign and magnitude of the SOT effective fields. An asymmetric SOT contribution from the Pt/Co and Co/Pt interfaces was found, leading to zero damping-like SOT being obtained at different inserted Pt and bottom Pt layer thickness. The ability to change the sign of damping-like SOT allows control over the magnetic switching direction in SOT devices.

1. Introduction

The manipulation of magnetization using local electric currents has been widely studied because of its prospects in non-volatile magnetic memory and logic devices [1–4]. For instance, spin transfer torque (STT) technique has been used to excite oscillations or even switch the magnetic moments of magnetic materials in magnetic nanodevices [5–7]. Recently, current-induced spin-orbit torque (SOT) in ultrathin heavy metal (HM)/ferromagnet (FM) heterostructure has gained prominence as a more efficient alternative for magnetization switching [8–11], as well as faster domain wall propagation [12–15]. SOT is proposed to arise mainly from two spin-orbit effects: the spin Hall effect (SHE) [9,10] and the Rashba effect [8,16]. By injecting a charge current into the HM layer, a perpendicular spin current is generated via SHE which then diffuses into the FM layer. The spin component perpendicular to the local magnetization is absorbed when the polarized spins traverse the HM/FM interface. Therefore, a longitudinal effective field, known as the damping-like term, is generated and exerts a torque on the magnetic moments. For the Rashba effect, the s-d exchange interaction at the HM/FM interface directly creates a transverse field, defined as the field-like term, which also acts on the local magnetic moments.

Enhanced SOT with both damping-like and field-like terms has been observed in Pt/Co/Ta structure [17]. The enhancement of the damping-like term is attributed to the sum of the large SHE from both Pt and Ta layers, as they have opposite spin Hall angles. The modulated Rashba effect at the Pt/Co and Co/Ta interfaces can enhance the effective spin accumulation, resulting in an enhanced field-like SOT. In most work, the SOT-driven magnetization switching has been investigated via the modulation of the damping-like SOT and the Dzyaloshinskii-Moriya interaction (DMI) effect [14,18,19]. As the field-like torque does not add on to the efficiency of SOT switching, the Rashba effect should be kept to a minimum.

In this work, we studied the effect of inserting a Pt layer at the interface between Co/Ta on SOT. Using the AC harmonic Hall voltage measurement technique, large SOT effective fields in perpendicularly magnetized Pt/Co/Ta structure were firstly obtained. The inserted Pt layer between the Co/Ta interface results in negligibly small field-like SOT, due to counteracting Rashba effects at the interfaces of Pt/Co and Co/Pt. The damping-like term was found to be tuned by the thickness of the Pt insertion layer, which changes both sign and magnitude of the SOT effective fields. The contribution from the Ta layer diminishes with increasing Pt insertion layer thickness. The sign reversal of the damping-like SOT effective field also leads to opposite magnetic switching direction.

2. Experimental results and discussion

Control sample comprising of sub./Ta (3 nm)/Pt (3 nm)/Co (0.9 nm)/Ta (3 nm) stack was prepared using DC magnetron sputtering deposition technique with a base pressure of lower than 10−8 Torr. The stack was patterned into Hall cross structures using electron beam lithography and Ar⁺ ion milling techniques. Fig. 1(a) shows schematic illustration of the coordinate system used on the fabricated Hall cross structure. θ (θH) and φ (φH) are the polar and azimuthal angles of the
magnetization $\mathbf{M}$ (external magnetic field $\mathbf{H}$) vector, respectively. Fig. 1(b) shows scanning electron microscopy image of the fabricated device with illustrated electrical measurement configuration. Hall bar structures of 80 µm × 50 µm with a uniform width of 5 µm were added to the patterned stack. Contact pads of Ta (5 nm)/Cu (120 nm)/Au (5 nm) were deposited following a second electron beam lithography step to connect the Hall cross structure for electrical measurements. A DC or AC current was applied through the wire along $x$-direction and the voltage across the Hall bar along $y$-direction was detected for all performed measurements at room temperature.

Hall resistance $R_H$ is composed of the anomalous Hall resistance $R_{\text{AHE}}$ and the planar Hall resistance $R_{\text{PHE}}$, given by [20–22]

$$R_H = \frac{V_H}{I} = \frac{1}{2} R_{\text{AHE}} \cos \phi + \frac{1}{2} R_{\text{PHE}} \sin^2 \phi \sin 2\phi$$

(1)

Firstly, the $R_H$ measurement was carried out by passing 100 µA DC current across the patterned structure with sweeping in-plane and out-of-plane magnetic fields, as shown in Fig. 1(c). The obtained square out-of-plane AHE loop, as shown in the inset of Fig. 1(c), indicates that the device has a strong PMA. The measured anomalous Hall resistance was $R_{\text{AHE}} \approx 1.02 \Omega$. The effective out-of-plane and in-plane magnetic anisotropy fields were calculated by fitting to the $x$-axis and $y$-axis magnetic field dependence of $R_H$ and found to be around 8.3 kOe and 500 Oe, respectively. To measure the planar Hall resistance, a constant external magnetic field of $\sim 8$ kOe was applied to the sample in the $y$-direction ($\theta_H = \pi/2$). The external field is comparable to the magnetic anisotropy fields and is therefore large enough to tilt the magnetization in the in-plane direction ($\theta = \pi/2$). The magnetization tilt angle ($\theta$) was assumed to be independent of the azimuthal angle of the external magnetic field. The sample stage was rotated between 0 and $2\pi$, which means that the azimuthal angle of external magnetic field also varies between 0 and $2\pi$, while the Hall resistance was measured. The Hall resistance $R_H$ becomes a sinusoidal function of the azimuthal angle of external magnetic field, as shown in Fig. 1(d). $R_{\text{PHE}}$ was quantified to be $R_{\text{PHE}} \approx 0.25 \Omega$, as the amplitude of the expected sinusoidal fitting. The ratio of $R_{\text{PHE}}$ and $R_{\text{AHE}}$ was calculated to be $\xi = R_{\text{PHE}}/R_{\text{AHE}} \approx 0.25$.

Harmonic Hall voltage measurement technique was used to obtain the SOT effective fields using swept in-plane fields $H_x$ and $H_y$ ($\phi = 90^\circ$) [22,23]. The effective fields, damping-like term $H_{\text{DL}}$ and field-like term $H_{\text{FL}}$ terms are given by [20–23]

$$H_{\text{DL}} = H_x \pm 2H_y/1 - 4\xi^2$$

(2)

and

$$H_{\text{FL}} = H_x \pm 2H_y/1 - 4\xi^2$$

(3)

where the ± sign corresponds to the up and down magnetized states, respectively. $H_x$ and $H_y$ terms were measured separately via swept in-plane field $H_x$ along $x$-direction ($\phi = 0^\circ$) and $H_y$ along $y$-direction ($\phi = 90^\circ$). Without considering the PHE contribution, $H_x$ and $H_y$ can be obtained by [22,23]

$$H_{\text{DL}}(T) = -2 \left( \frac{dV_{\text{oa}}}{dH_x(T)} \right) \left( \frac{d^2V_{\text{oa}}}{d^2H_x(T)} \right)$$

$$V_{\text{oa}}$$ and $V_{\text{oa}}$ are the first and second harmonic voltages detected by the lock-in amplifier, respectively.

The harmonic Hall voltage measurements were performed on Pt/Co/Ta structure using an AC current density $J$ that varies from $1 \times 10^{10}$ A/m² to $1 \times 10^{11}$ A/m², with $H_x$ or $H_y$ quasi-statically swept.
between ± 700 Oe. Fig. 2(a) and (c) show the typical first and second harmonic Hall voltage signals versus \( H_x \) at AC current density \( J = 5 \times 10^{10} \) A/m² for both up (\( M_z > 0 \)) and down (\( M_z < 0 \)) magnetized states. Fig. 2(b) and (d) show the corresponding data for \( H_y \). \( V_\omega \) shows the same parabolic variation with \( H_x \) and \( H_y \), and for up and down magnetized states, the variation tendency is inverted in the range. \( V_\omega \) varies linearly with both \( H_x \) and \( H_y \). While the slope sign for \( H_x \) is dependent on the magnetization states, it is independent on the magnetization states for \( H_y \), as expected for \( H_L \) and \( H_T \), respectively.

Combining Eqs. (2), (3) and (4), the effective fields of Pt/Co/Ta sample were computed and plotted as a function of AC current density \( J \) in Fig. 3(a) and (b) for up and down magnetized states, including both \( H_{DL(L)} \) and \( H_{LT(L)} \). Both \( H_{DL(L)} \) and \( H_{LT(L)} \) increase linearly with \( J \). \( H_{DL} \) and \( H_{LT} \) have opposite signs for up and down magnetized states, while the sign is the same for \( H_{DL} \) and \( H_{LT} \).

The effective fields are enhanced by ~1.6 times for the damping-like term and ~4 times for the field-like term after PHE correction, indicating that the PHE has a stronger influence on field-like SOT. SOT efficiency is defined as the effective field per unit AC current density \( dH_{DL(L)}/dJ \), characterized by the slope of the line. The sign for \( H_{DL} \) is dependent on the magnetization states, while \( H_{LT} \) is independent on the magnetization states. The SOT efficiencies for the damping-like term and field-like term are evaluated as 160 Oe per \( 10^{11} \) A/m² and 108 Oe per \( 10^{11} \) A/m², respectively. The damping-like term originates from the large SHE from both Pt and Ta layers, as they have opposite spin Hall angles. The field-like term is attributed to the Rashba effects at the Pt/Co interface and Co/Ta interface.

Using similar experimental procedure, the set of samples with Pt inserted between Co/Ta interface were investigated. The thin film stacks comprising of sub./Ta (3 nm)/Pt (3 nm)/Co (0.9 nm)/Pt (t)/Ta (3 nm) were deposited by DC magnetron sputtering system, where \( t \) varies from 0.9 nm to 4 nm. The same fabrication process and electrical measurements were performed on the new set of samples. Fig. 4 shows the harmonic Hall voltage signals for the \( t = 0.9 \) nm sample: first harmonic Hall voltage signals with (a) longitudinal magnetic field \( H_x \) and (b) transverse magnetic field \( H_y \) for up and down magnetization; second harmonic Hall voltage signals with (c) longitudinal magnetic field \( H_x \) and (d) transverse magnetic field \( H_y \) for up and down magnetization. The sign difference is observed from the second harmonic Hall voltage signals with \( H_x \) and \( H_y \). The zero slope indicates that the Rashba effect is cancelled.
out, which is attributed to the counteractive effects at the Pt/Co interface and Co/Pt interface [24]. As a result, the field-like effective field is negligible. Similar results were obtained for varying thickness of Pt insertion layer up to 4 nm.

The damping-like SOT efficiencies of the set of samples were calculated and plotted as a function of the inserted Pt layer thickness $t$ in Fig. 5, including the result for $t = 0$ nm sample. The damping-like SOT has the largest value at $t = 0$ nm, and it decreases once the Pt layer is inserted. As the Pt insertion layer thickness $t$ increases, the damping-like SOT gradually decreases to zero up to approximately 2 nm, and then subsequently increases towards opposite sign. Finally, the damping-like SOT saturates for $t \geq 3$ nm. When the Pt insertion layer thickness is thinner than 0.9 nm, both the Pt and Ta layers contribute to the damping-like term. At the thicknesses above 0.9 nm, the contribution from Ta layer becomes insignificant. In contrast with Pt/Co/Ta structure, opposite spin currents from the inserted Pt and bottom Pt layers flow toward the Co layer, resulting in the reduction of the overall torque. For $t = 3$ nm, the spin current from the inserted Pt layer is the same as that from bottom Pt layer, leading to a cancelled bulk SHE. Therefore, the symmetric Pt (3 nm)/Co (0.9 nm)/Pt (3 nm) structure should have no SOT. While our result is not the case. Bandiera et al. reported that the inter-diffusion at the top Co/Pt interface contributes a lower perpendicular magnetic anisotropy than the bottom Pt/Co interface [25]. The result implies that more Pt atoms are mixed with Co atoms at the top Co/Pt interface than the bottom Co/Pt interface. The side-jump scattering occurs when the spin dependent acceleration and deceleration in the Pt layers are different during the scattering of electrons, resulting in an effective transverse displacement of the electron. It contributes a spin Hall conductivity and a spin Hall angle that are proportional to the impurity concentration [26]. Therefore, the SHE from the side-jump scattering can be asymmetric at the top Co/Pt and the bottom Pt/Co interfaces [25,26]. The top Co/Pt interface can provide higher interfacial SHE than the bottom Pt/Co interface, due to the greater impurity concentration at the top Co/Pt interface. The SHE difference determines a net interfacial SHE, which contributes the damping-like SOT from the top Co/Pt interface. The interfacial SHE contribution can be transferred to that from an extra thin Pt inserting layer with thickness of $\Delta t$, which means that the effective thickness of the Pt inserting layer is $t + \Delta t$. As a result, the zero damping-like SOT is obtained at $t \approx 2.2$ nm, which is thinner than the bottom Pt layer of 3 nm. $\Delta t$ is estimated to be $\Delta t \approx 0.8$ nm. The result shows that the damping-like SOT can be continuously tuned by the inserted Pt layer, including both the sign and magnitude of the SOT effective fields.

To study the effect of the sign reversal behaviour on SOT-driven magnetization switching in the presence of an in-plane magnetic field to break the symmetry, an in-plane field of 2 kOe was applied and a quasi-static in-plane current was swept across the wire. By measuring the dependence of Hall resistance on the current, a hysteretic magnetic switching between up and down magnetization states for samples $t = 0$, 0.9, 3 nm, was observed in Fig. 6(a) with the in-plane bias field along (a) $+x$ and (b) $-x$ directions. The positive and negative in-plane magnetic fields result in opposite magnetization switching directions, as shown in Fig. 6(a) and 6(b), respectively. With the same in-plane magnetic field, the $t = 3$ nm sample has an opposite switching behaviour, which is due to the sign reversal of the damping-like SOT. The result shows that the magnetic switching direction can be controlled by both the direction of external in-plane magnetic field and the sign of damping-like SOT.

3. Conclusion

In summary, a Pt layer was inserted between the Co/Ta interface to effectively negate the field-like SOT in perpendicularly magnetized Pt/Co interface and Co/Pt interface [24]. As a result, the field-like effective field is negligible. Similar results were obtained for varying thickness of Pt insertion layer up to 4 nm. The damping-like SOT efficiencies of the set of samples were calculated and plotted as a function of the inserted Pt layer thickness $t$ in Fig. 5, including the result for $t = 0$ nm sample. The damping-like SOT has the largest value at $t = 0$ nm, and it decreases once the Pt layer is inserted. As the Pt insertion layer thickness $t$ increases, the damping-like SOT gradually decreases to zero up to approximately 2 nm, and then subsequently increases towards opposite sign. Finally, the damping-like SOT saturates for $t \geq 3$ nm. When the Pt insertion layer thickness is thinner than 0.9 nm, both the Pt and Ta layers contribute to the damping-like term. At the thicknesses above 0.9 nm, the contribution from Ta layer becomes insignificant. In contrast with Pt/Co/Ta structure, opposite spin currents from the inserted Pt and bottom Pt layers flow toward the Co layer, resulting in the reduction of the overall torque. For $t = 3$ nm, the spin current from the inserted Pt layer is the same as that from bottom Pt layer, leading to a cancelled bulk SHE. Therefore, the symmetric Pt (3 nm)/Co (0.9 nm)/Pt (3 nm) structure should have no SOT. While our result is not the case. Bandiera et al. reported that the inter-diffusion at the top Co/Pt interface contributes a lower perpendicular magnetic anisotropy than the bottom Pt/Co interface [25]. The result implies that more Pt atoms are mixed with Co atoms at the top Co/Pt interface than the bottom Co/Pt interface. The side-jump scattering occurs when the spin dependent acceleration and deceleration in the Pt layers are different during the scattering of electrons, resulting in an effective transverse displacement of the electron. It contributes a spin Hall conductivity and a spin Hall angle that are proportional to the impurity concentration [26]. Therefore, the SHE from the side-jump scattering can be asymmetric at the top Co/Pt and the bottom Pt/Co interfaces [25,26]. The top Co/Pt interface can provide higher interfacial SHE than the bottom Pt/Co interface, due to the greater impurity concentration at the top Co/Pt interface. The SHE difference determines a net interfacial SHE, which contributes the damping-like SOT from the top Co/Pt interface. The interfacial SHE contribution can be transferred to that from an extra thin Pt inserting layer with thickness of $\Delta t$, which means that the effective thickness of the Pt inserting layer is $t + \Delta t$. As a result, the zero damping-like SOT is obtained at $t \approx 2.2$ nm, which is thinner than the bottom Pt layer of 3 nm. $\Delta t$ is estimated to be $\Delta t \approx 0.8$ nm. The result shows that the damping-like SOT can be continuously tuned by the inserted Pt layer, including both the sign and magnitude of the SOT effective fields.

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3. Conclusion

In summary, a Pt layer was inserted between the Co/Ta interface to effectively negate the field-like SOT in perpendicularly magnetized Pt/
Co/Pt(t)/Ta structures using AC harmonic Hall voltage measurement technique, as the Rashba effects at the Pt/Co and Co/Pt interfaces counteract each other. The DMI strength also decreases by the Pt inserting layer as the DMI contribution arising from the upper Co/Pt and lower Pt/Co interfaces compensate each other. The damping-like term is tuned by varying the thickness of the inserted Pt layer to change both sign and magnitude of the SOT effective fields. The damping-like SOT is zero at $t \approx 2.2$ nm, which is thinner than the bottom Pt layer of 3 nm, indicating the asymmetric contribution from the Pt/Co and Co/Pt interfaces to the damping-like SOT. The magnetic switching direction is found to be controlled by both the orientation of external in-plane magnetic field and the sign of damping-like SOT, which offers additional flexibility in the design of SOT-based spintronic devices.

4. Competing financial interests

The authors declare no competing financial interest.