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Magnetization switching via charge current induced spin-orbit torques (SOTs) in heavy metal/ferromagnetic metal/heavy metal heterostructures has become an important issue due to its potential applications in high stability and low energy dissipation spintronic devices. In this work, based on a Pt/Co/Ta structure with perpendicular magnetic anisotropy (PMA), we report the effect of inserting a non-metal C interlayer between Co and Ta on the current-induced magnetization switching. A series of measurements based on the extraordinary Hall effect were carried out to investigate the difference of the anisotropy field, switching field, and damping-like and field-like SOT-induced effective fields as well as the current-induced spin Hall effect (SHE) torque after C decoration. The results show that PMA can be reduced by C decoration and the ratio of the effective SHE torque per unit current density and anisotropy field plays an essential role in the switching efficiency. In addition, the obtained switching current density has a quite low value around the order of $10^6$ A/cm$^2$. Our study could provide a way for achieving the low switching current density by manipulating PMA in SOT-based spintronic devices through interface decoration. Published by AIP Publishing. [http://dx.doi.org/10.1063/1.4979468]

Current-induced spin orbit torques (SOTs) in heavy metals (HMs) with strong spin-orbit coupling (SOC) have become an intriguing issue in recent years due to their essential role in highly efficient magnetization switching and fast domain wall motion. The SOTs from the bulk spin Hall effect (SHE) and/or the interfacial Rashba effect which can generate the damping-like (DL) and field-like (FL) effective fields have been studied to manipulate the magnetization in ultra-thin ferromagnetic (FM) layers with perpendicular magnetic anisotropy (PMA) in different structures and systems. In particular, the HM/FM/oxide system including Ta/CoFeB/MgO, W/CoFeAl/MgO, W/CoFeB/MgO, Hf/CoFeB/MgO, and Hf/Co/MgO system with two HMs which show opposite signs of spin Hall angle ($\theta_{\text{SH}}$) including Pt/Co/Ta, Pt/Co-Ni/W, and Pt/Co/Gd have been investigated to enhance the effective SOTs and reduce the switching current density ($J_c$). Most of the above investigations mainly focus on choosing HMs with large $\theta_{\text{SH}}$ or the structures with large effective $\theta_{\text{SH}}$ to improve the SOT’s efficiency. Recent reports on manipulating the SOTs and even the magnetic anisotropy through the interfacial non-magnetic metal Cu decoration have attracted attention. In the SHE picture, $J_c$ is not only related to the strength of the effective SHE torque ($\tau_{\text{SH}}$), but also associated with the perpendicular magnetic anisotropy field ($H_{\text{an}}^{\text{perp}}$). Both the enhanced $\tau_{\text{SH}}$ and reduced $H_{\text{an}}^{\text{perp}}$ can reduce $J_c$.

Graphite (C) composed of light-weight element carbon with weak SOC has a weak spin scattering and long spin relaxation time. It makes C a viable candidate for spin-transport materials. In this work, we investigate the effect of inserting a non-metal C interlayer between Co and Ta on the current-induced magnetization switching (CIMS) in Pt/Co/Ta with PMA. The changes of the effective SHE torque per unit current density ($\beta_{\text{SH}} H_{\text{an}}^{\text{perp}}$) and $H_{\text{an}}^{\text{perp}}$ reveal that the ratio ($\beta_{\text{SH}} H_{\text{an}}^{\text{perp}}$) plays a key role in the switching efficiency. A relatively low $J_c$ threshold can be obtained by means of C decoration through reducing PMA. Furthermore, we demonstrate the CIMS for the current density of the order of $10^6$ A/cm$^2$ in Ta/Pt/Co/Ta and Ta/Pt/Co/C/Ta.

Two film stacks Ta(3)/Pt(5)/Co(0.6)/Ta(5) and Ta(3)/Pt(5)/Co(0.6)/C(2)/Ta(5) (thickness in nm) were deposited on corning glass substrates at room temperature (RT) by direct current (DC) magnetron sputtering with a base pressure below 4.0 × 10$^{-5}$ Pa. Among them, the bottom 3 nm Ta is used as the seed layer and the top Ta layer has an around 1.5 nm TaOx capping layer due to the air exposure. Afterwards, the stacks were patterned into 8.5 μm wide Hall bars using standard lithography and Ar-ion milling techniques. The PMA was obtained by annealing the devices at 400 °C for 1 h with a base pressure 3.0 × 10$^{-4}$ Pa for Ta/Pt/Co/Ta structures. The Hall resistances were measured using standard DC and AC analysis techniques. All the measurements were made at RT.

Fig. 1(a) schematically shows the device structure and measurement configuration. Figs. 1(c) and 1(d) illustrate the Hall resistance ($R_{\text{Hall}}$) as a function of $H_z$ under +1 mA (the current direction is shown in Fig. 1(a)) in Ta/Pt/Co/Ta and Ta/Pt/Co/C/Ta, respectively. The square shaped loops confirm the presence of PMA. Moreover, $R_{\text{Hall}}$ is proportional to the perpendicular component of magnetization ($M_2$) of the...
in Fig. 2(b), we summarize the SHE when the current increases (Joule heating effect can be negligible, which will be discussed below). Furthermore, the switching field ($H_{sw}$) extracted from the $R_{Hall}$-$H_z$ loops with different currents ($I$) is shown in Fig. 2(a). It can be seen that $H_{sw}$ decreases remarkably as the current increases for Ta/Pt/Co/C/Ta, while the $H_{sw}$ changes little for Ta/Pt/Co/Ta. It may be ascribed to the decreased PMA in Ta/Pt/Co/C/Ta due to C decoration, which makes $H_{sw}$ readily affected by the increased current-induced torque related to the SHE when the current increases (Joule heating effect can be negligible, which will be discussed below). Furthermore, in Fig. 2(b), we summarize $H_{sw}$ against the angle θ obtained from the angle dependent $R_{Hall}$-$H_z$ loops which are measured at $I = 0.5$ mA to reduce the spin Hall torque. From Fig. 2(b), one can see that the $H_{sw}$ follows an inverse cosθ curve shown in solid lines at small angles. This kind of relationship indicates that the magnetization reversal is dominated by depinning of domain walls in the large anisotropic systems ($H_{sw} \ll H_{an}^{\perp}$) when the magnetic field deviates from out-of-plane in a small angle range. However, for Ta/Pt/Co/C/Ta, the $H_{sw}$ remarkably deviates from the 1/cosθ dependence in the large angle ranges in comparison with Ta/Pt/Co/Ta, indicating the reduced anisotropy field in Ta/Pt/Co/C/Ta. It can be explained by that the coherent rotation process plays a dominant role in the magnetization reversal at large angles, which reduces the $H_{sw}$ in total. Thus, we conclude that PMA is reduced by C decoration. In addition, the increased $H_{sw}$ for the device with a C interlayer may be explained by a relatively large pinning field existing due to some interdiffusion between the Co and C layers. Figs. 2(c) and 2(d) show the CIMS curves under in-plane assisted magnetic field $H_x = \pm 200$ Oe along the current direction for Ta/Pt/Co/Ta and Ta/Pt/Co/C/Ta, respectively. Due to $M_{Z_{down}}^{up}$ corresponding to $R_{Hall} < 0$ ($R_{Hall} > 0$) in our experiment, the direction of current and $H_x$ determines the polarity of the switching, which is consistent with the model of the SHE switching. In addition, the $J_c$ for the assisted field $H_x = 200$ Oe is around $2.82 \times 10^6$ and $3.39 \times 10^6$ A/cm² for Ta/Pt/Co/Ta and Ta/Pt/Co/C/Ta, respectively, if we assume the uniform current flows across metallic layers and the C interlayer. Although the approximate and relatively low $J_c$ of the order of $10^6$ A/cm² is obtained for the two devices, $J_c$ is not further reduced due to the reduced PMA when inserting a C layer. It can be ascribed to the decreased current-induced SHE torque for Ta/Pt/Co/C/Ta. The further investigations will be shown in the next part.

Next, the harmonic Hall voltage measurement technique was used to quantify the current-induced SOT effective fields. The measurement diagram is depicted in Fig. 1(b). A sinusoidal current with a frequency of 133 Hz along x axis was passed through the Hall bars and the first ($V^{00}$) and second ($V^{20}$) harmonic voltages along y axis were collected using the Analog-Digital/Digital-Analog card by the frequency-spectra analysis. $H_{Hall}$ was applied along the x (longitudinal-field $H_L$) and y (transverse-field $H_T$) directions to obtain the longitudinal damping-like effective field ($H^{DL}$) and the transverse field-like effective field ($H^{FL}$), which is, respectively, induced by the damping-like and field-like SOTs using the equations: \[ H^{DL/FL} = -2 \frac{\partial V^{20}}{\partial H_L} \frac{\partial^2 V^{00}}{\partial H_T^2}. \] (1)

Figs. 3(a)–3(d) show $V^{00}$ as a function of $H_z$ and $H_T$ for Ta/Pt/Co/Ta and Ta/Pt/Co/C/Ta, respectively. The insets of each figure represent $V^{20}$ as a function of $H_z$ and $H_T$. In addition, in order to obtain $H^{DL}$ and $H^{FL}$ using Eq. (1), the first and second harmonic curves were, respectively, fitted using the quadratic and linear fitting function. The calculated $H^{DL}$ is plotted with respect to the amplitude ($I_0$) of the sinusoidal current for both devices in Figs. 4(a) and 4(c). The effective fields are linear with $I_0$, indicating that the Joule heating and other non-linear effects can be negligible in our experiment. $H^{FL}$ per unit current density ($j_{DL}$) is found to be $-3.98 \pm 0.20$ Oe/(10⁶ A/cm²) ($3.93 \pm 0.12$ Oe/(10⁶ A/cm²)) for the “up” (“down”) magnetized states in Ta/Pt/Co/C/Ta and $-8.11 \pm 0.14$ Oe/(10⁶ A/cm²) ($8.76 \pm 0.12$ Oe/(10⁶ A/cm²)) for the “up” (“down”) magnetized states in Ta/Pt/Co/Ta. It is two times larger for Ta/Pt/
measure \( R_{Hall} \) under a sweeping magnetic field \( H_{ext} \) to compare the difference of the \( R_{Hall} - H_{ext} \) curves under the same magnitude of positive and negative constant charge current. The schematic measurement diagram is shown in the inset of Fig. 5(a) and \( \alpha \) is the angle between the magnetization \( M \) and \( x \) axis, which is determined via measuring \( R_{Hall} \). i.e., 
\[
\sin \alpha = \frac{R_{Hall} R_0}{R_0} \quad \text{is the maximum Hall resistance when the magnetization} \quad M \quad \text{is along the} \quad z \quad \text{axis.}
\]
\[
\delta = \angle H_{ext} \quad \text{and} \quad x \quad \text{axis in the} \quad x-z \quad \text{plane. Therefore,} \quad H_{an} \quad \text{and} \quad \tau_{\alpha ST} \quad \text{can be quantitatively analyzed by the equilibrium equation}^4
\]
\[
\tau_{\alpha ST} = \frac{1}{2} H_{ext} \sin(\alpha - \delta) - H_{an} \sin \alpha \cos \alpha = 0,
\]
where \( \frac{1}{2} H_{ext} \sin(\alpha - \delta) \quad \text{and} \quad H_{an} \sin \alpha \cos \alpha = 0 \),
\[
\tau_{\alpha ST} = \frac{1}{2} H_{ext} \sin(\alpha - \delta) - H_{an} \sin \alpha \cos \alpha = 0,
\]
Using the combination of (3) and (4), one can obtain the equation
\[
[ H_+ (\alpha) - H_- (\alpha) ] = 2 H_{an} \sin \alpha \cos \alpha / \sin(\alpha - \delta),
\]
\[
[ H_+ (\alpha) + H_- (\alpha) ] = 2 H_{an} \sin \alpha \cos \alpha / \sin(\alpha - \delta).
\]
And then using Eqs. (5) and (6), one can fit the experimental data to calculate \( \tau_{\alpha ST} \) and \( H_{an} \). Fig. 5(b) shows the \( [ H_+ (\alpha) - H_- (\alpha) ] \) as a function of \( 1/\sin(\alpha - \delta) \) and Fig. 5(c) shows the \( [ H_+ (\alpha) + H_- (\alpha) ] \) against \( \sin \alpha \cos \alpha / \sin(\alpha - \delta) \) for Ta/Pt/Co/Ta. The insets in Figs. 5(b) and 5(c) show the corresponding

FIG. 3. (a)–(d) First harmonic voltages \( V_{1n} \) versus in-plane longitudinal \( H_L \) and transverse \( H_T \) swept magnetic fields. The inset in each figure shows the second harmonic voltage \( V_{2n} \) as a function of \( H_L \) and \( H_T \). The solid green and blue symbols correspond to “up” and “down” magnetized states, respectively. The red lines stand for the quadratic and linear fitting.

Co/Ta than that for Ta/Pt/Co/C/Ta, revealing that the \( \beta_{DL} \) is reduced after inserting a C layer.

Similarly, the calculated \( H^{FL} \) is displayed in Figs. 4(b) and 4(d). The dependence of \( H^{FL} \) on \( I_0 \) is also linear for the “up” and “down” magnetized states. \( H^{FL} \) per unit current density (\( \beta_{DL} \)) is found to be \( 0.99 \pm 0.06 \mathrm{Oe}/(10^6 \mathrm{A/cm}^2) \) (1.09 \pm 0.06 \mathrm{Oe}/(10^6 \mathrm{A/cm}^2)) for the “up” (“down”) magnetized states in Ta/Pt/Co/C/Ta and 1.13 \pm 0.03 \mathrm{Oe}/(10^6 \mathrm{A/cm}^2) \) (1.03 \pm 0.02 \mathrm{Oe}/(10^6 \mathrm{A/cm}^2)) for the “up” (“down”) magnetized states in Ta/Pt/Co/Ta. It is evident that the \( \beta_{DL} \) is almost equivalent, indicating that the \( J_c \) for both devices is determined by damping-like SOT and \( H_{an} \).

In order to quantitatively evaluate \( H_{an} \) and \( \tau_{\alpha ST} \) and understand the relationship between \( J_c \) and them, we

FIG. 4. (a)–(d) damping-like (field-like) SOT-induced effective field for Ta/Pt/Co/Ta (Ta/Pt/Co/C/Ta) against the amplitude of the sinusoidal current. The slope of the fitted curves gives \( \beta_{DL, FL} = H^{DL, FL}/J_c \). The green and blue symbols represent “up” and “down” magnetized states, respectively.

FIG. 5. (a) \( R_{Hall} \) as a function of \( H_{ext} \) with \( \pm 2 \mathrm{mA} \) DC for Ta/Pt/Co/C/Ta. The inset shows the schematic measurement diagram. (b) The linear fitting between \( [ H_+ (\alpha) - H_- (\alpha) ] \) and \( 1/\sin(\alpha - \delta) \) based on Eq. (5) and the inset is for Ta/Pt/Co/Ta. (c) The linear fitting between \( [ H_+ (\alpha) + H_- (\alpha) ] \) and \( \sin \alpha \cos \alpha / \sin(\alpha - \delta) \) based on Eq. (6) and the inset is for Ta/Pt/Co/Ta. (d) The \( H_{ext} \) versus \( \sin \alpha \cos \alpha / \sin(\alpha - \delta) \) with a linear fitting based on Eq. (8).
results for Ta/Pt/Co/Ta. The obtained $\theta_{ST}^0$ is 12.38 $\pm$ 0.21 Oe and 33.37 $\pm$ 0.38 Oe under the $\pm 2$ mA current corresponding to 7.42 $\pm$ 0.13 Oe/(10$^4$ A/cm$^2$) and 17.16 $\pm$ 0.20 Oe/(10$^4$ A/cm$^2$) for Ta/Pt/Co/C/Ta and Ta/Pt/Co/Ta, respectively. It reveals that the $\beta_{ST}^0$ for Ta/Pt/Co/Ta is also about two times larger than that for Ta/Pt/Co/C/Ta. It is worth to note that both $\beta_{ST}^0$ for Ta/Pt/Co/C/Ta and Ta/Pt/Co/Ta are about two times larger than the $\beta_{PS}^0$ discussed above, which is due to not taking the planar Hall effect (PHE) correction into consideration in the harmonic Hall voltages measurements.\textsuperscript{23} Meanwhile, according to the formula \textsuperscript{36}

$$\theta_{SH} = J_s/J_e = (2|e|M_F t_F/M_s)(e_{ST}^0/J_e),$$

(7)

where $e$ is the elementary charge, $t_F$ is the thickness of the ferromagnetic layer, $h$ is the reduced Planck constant, and coalt saturation magnetization $M_s$ is about 1.288 $\times$ 10$^6$ and 1.213 $\times$ 10$^6$ A/m for Ta/Pt/Co/C/Ta and Ta/Pt/Co/Ta, respectively, the calculated effective $\theta_{SH}$ is 0.379 $\pm$ 0.004 for Ta/ Pt/Co/Ta. The value is also similar to that reported in the Pt/ Co/Ta system.\textsuperscript{23} However, it is 0.174 $\pm$ 0.003 for Ta/Pt/Co/ C/Ta, which is ascribed to the decreased $\beta_{ST}$ as discussed above. From Fig. 5(c), the $H_{an}^0$ is 3308 $\pm$ 4 Oe and 6728 $\pm$ 27 Oe for Ta/Pt/Co/C/Ta and Ta/Pt/Co/Ta, respectively. By comparison, the anisotropy field decreases more than half when inserting a C interlayer between Co and Ta layers, which is in agreement with the qualitative discussion above. And then we also estimate $H_{an}^0$ using another method. When reducing the charge current close to zero, the Eq. (3) or (4) can be replaced by $\textsuperscript{36}

$$H_{ex} = H_{an}^0 \sin \alpha \cos \alpha / \sin(\alpha - \delta).$$

(8)

Fig. 5(d) shows the fitting curves and results based on Eq. (8). The obtained $H_{an}^0$ is very similar to the values obtained using the first method. As a result, $H_{an}^0$ indeed has a dramatic decrease by C decoration.

Finally, the relationship between the $J_s$ and $H_{an}^0$ as well as $\beta_{ST}^0$ is quantitatively elaborated. We use $\beta_{ST}^0/H_{an}^0$ to determine $J_s$. If $\beta_{ST}^0/H_{an}^0$ is large, $J_s$ becomes low, and vice versa. Thus, low $J_s$ can be obtained if enhancing $\beta_{PS}^0$ or reducing adequately $H_{an}^0$. In our experiment, $\beta_{ST}^0/H_{an}^0$ is found to be 2.24 $\pm$ 0.04/(10$^4$ A/cm$^2$) for Ta/Pt/Co/C/Ta and 2.55 $\pm$ 0.03 / (10$^4$ A/cm$^2$) for Ta/Pt/Co/Ta. That is, the value of $\beta_{ST}^0/H_{an}^0$ is not raised while inserting a C layer. Therefore, the $J_s$ is also not decreased compared to that for Ta/Pt/Co/Ta. It can be understood by the fact that although the $H_{an}^0$ is dropped by C decoration, the $\beta_{ST}^0$ is also reduced. One possible reason for the reduced effective torque while inserting a C layer is that the C layer in the experiment was deposited by sputtering, which could lead to form some defects in the C layer. Therefore, the spin current resulting from the top Ta layer may be partly scattered when it flows through the C interlayer. And another possibility is that some interdiffusion and chemical reaction from the interface between Co and C as well as the interface between C and Ta may also increase the spin flipping probability.\textsuperscript{37} Moreover, the large pinning field in Ta/Pt/Co/C/Ta due to some interdiffusion between Co and C is also responsible for the not reduced $J_c$. As a consequence, the low $J_c$ can be achieved by reducing the PMA through C decoration on the basis of enhancing and improving the quality of the C layer and the interfacial environment.

In summary, we have investigated the effect of inserting a C interlayer between Co and Ta on the anisotropy field, spin orbit torques, and the associated effective fields in Pt/ Co/Ta structures with perpendicular magnetic anisotropy. The obtained magnetization switching current density is in the order of 10$^6$ A/cm$^2$ in both Ta/Pt/Co/Ta and Ta/Pt/Co/C/ Ta devices. Both the anisotropy field and the effective SHE torque per unit current density are reduced by nearly a half by C decoration due to the change of interfacial magnetic anisotropy and the formation of defects during C sputtering. However, the switching current density changes a little since the ratio between the effective SHE torque per unit current density and anisotropy field plays an important role in the current-induced magnetization switching. Thus, further decreasing the switching current density could be realized by C decoration with a high quality interface for free spin current transport. Our study could provide a way for achieving the low switching current density by manipulating the perpendicular magnetic anisotropy through the non-metal C decoration in SOT-based spintronic devices.

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