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Effect of heavy metal layer thickness on spin-orbit torque and current-induced switching in Hf|CoFeB|MgO structures

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We study the heavy metal layer thickness dependence of the current-induced spin-orbit torque (SOT) in perpendicularly magnetized Hf|CoFeB|MgO multilayer structures. The damping-like (DL) current-induced SOT is determined by vector anomalous Hall effect measurements. A non-monotonic behavior in the DL-SOT is found as a function of the thickness of the heavy-metal layer. The sign of the DL-SOT changes with increasing the thickness of the Hf layer in the trilayer structure. As a result, in the current-driven magnetization switching, the preferred direction of switching for a given current direction changes when the Hf thickness is increased above ~7 nm. Although there might be a couple of reasons for this unexpected behavior in DL-SOT, such as the roughness in the interfaces and/or impurity based electric potential in the heavy metal, one can deduce a roughness dependence sign reversal in DL-SOT in our trilayer structure. *Published by AIP Publishing.*
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In a class of emerging spintronic devices, the magnetization is controlled by spin-orbit torque (SOT), where a current-induced torque on the magnetization is generated in the presence of large spin-orbit coupling (SOC). Due to the low energy dissipation, high speed, and high endurance in SOT-based devices, they have attracted much interest for applications in nonvolatile memory and logic devices.[1–10] The spin-polarized current, generated from an in-plane electric current due to the interaction between spin and angular momentum of the electrons, enables the SOT on the magnetization, e.g., giving rise to switching in memory elements. To generate current-induced field-like (FL) and/or damping-like (DL) SOTs, it is necessary to break the inversion symmetry along the growth direction, such as in heavy-metal(HM)|ferromagnet(FM)|oxide(OX) tri-layer structures. The origin of the current-induced DL-SOTs is often attributed to the bulk spin-Hall effect (SHE) in the heavy metal, as well as to the interfacial Rashba effect. In addition, extrinsic factors, such as interfacial oxidation, surface roughness, and/or other mechanisms, indirectly affect the SOTs on the magnetization.[1,2,6,11–13] Here, we report experimental results on the SOT-induced effective field, as a function of a Hf heavy-metal layer thickness. It

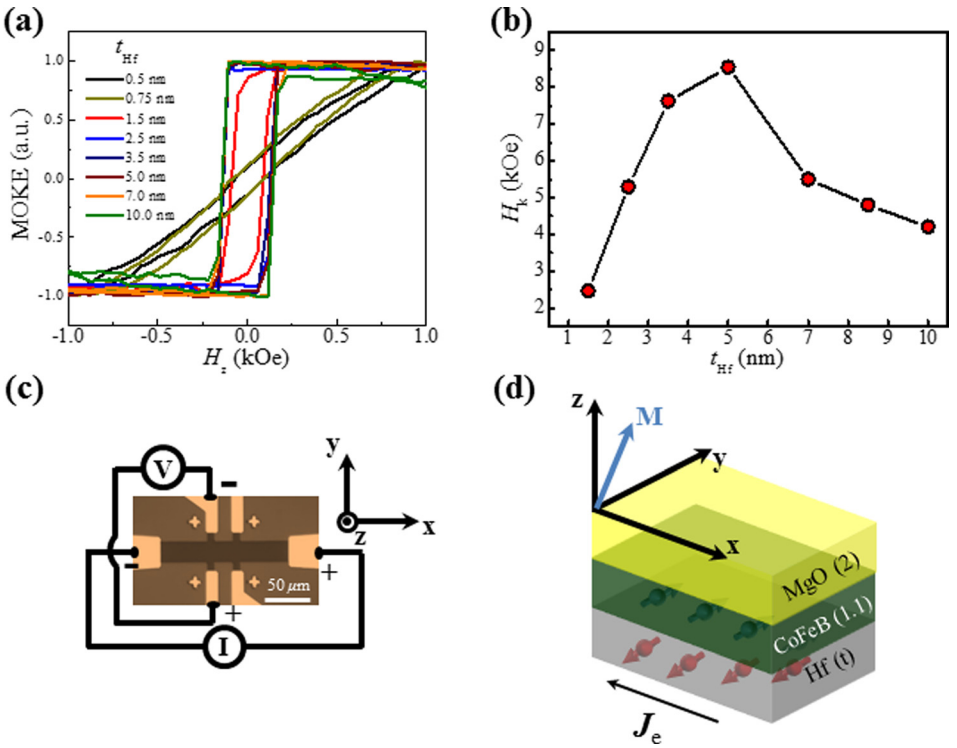

FIG. 1. (a) Magneto-optical-Kerr effect (MOKE) signal as a function of out-of-plane external magnetic field in Hf(t)|CoFeB(1.1)|MgO(2)|Ta(2) (t = 0.5, 0.75, 1.5, 2.5, 3.5, 5.0, 7.0, 8.5, and 10.0). (b) Perpendicular magnetic anisotropy field, H_k, as a function of the Hf layer thickness in Hf|CoFeB|MgO|Ta structures. (c) Optical graph of one device and dc experimental configuration. (d) The multilayer film structure of Hf(t)|CoFeB(1.1)|MgO(2). M and J_e represent the magnetization direction of the CoFeB layer and electric current density, respectively.

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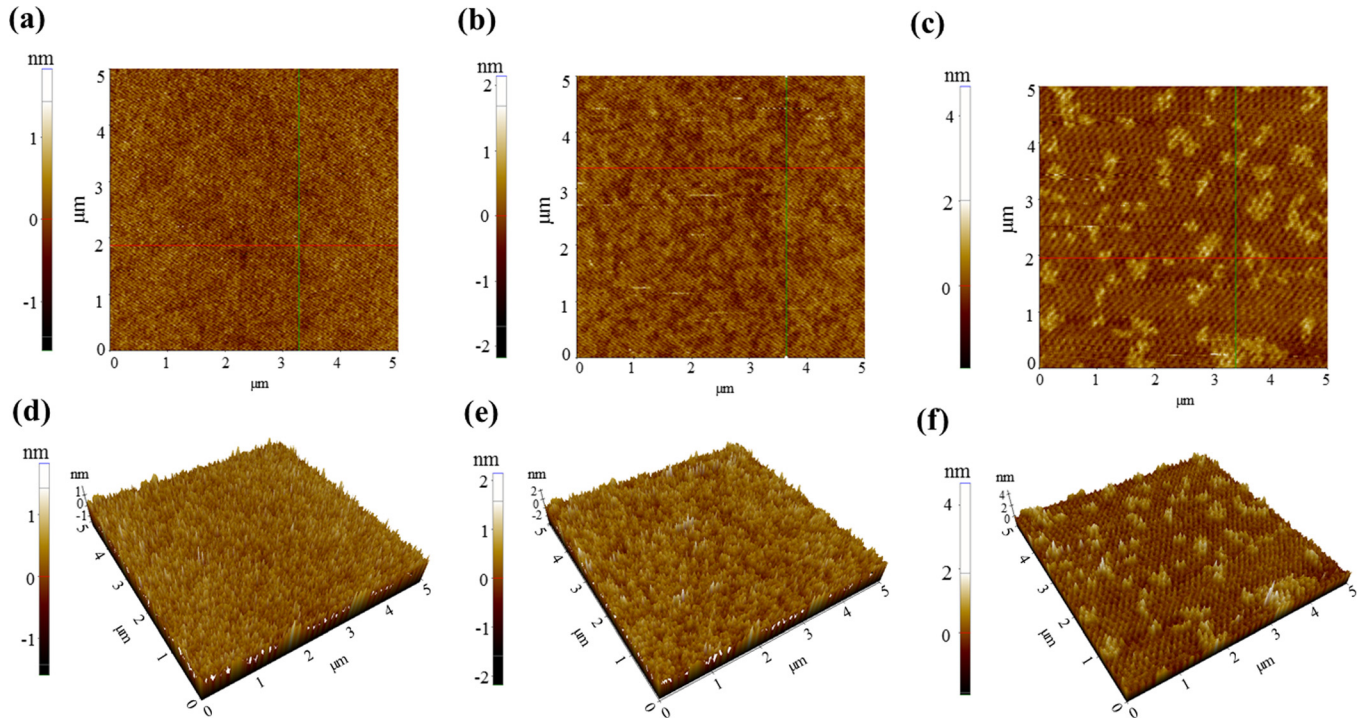

FIG. 2. (a)–(c) (d)–(f). 2D (3D)-atomic force microscopy images for $t_{Hf} = 2.5$, 5.0, and 10 nm in the Hf|CoFeB|MgO multilayer. The images were taken in an area of $5 \times 5\ \mu m^2$. The roughness of the films increases with the increasing Hf thickness in Hf(t)|CoFeB|MgO multilayers. The roughness is found to be ~0.13, 0.27, and 0.45 nm for $t_{Hf} = 2.5$, 5.0, and 10 nm, respectively.

is observed that the sign of the SOT reverses with increasing the Hf layer thickness. Given that the thickness of the heavy metal alone cannot account for the sign change of the bulk spin-Hall contribution to the SOT, the results indicate that the combination of bulk spin-Hall effect with interfacial SOT mechanisms can change the effective spin-orbit torque's sign and magnitude in such structures.

Multilayer films with a structure of Hf(t)|CoFeB(1.1)|MgO(2)|Ta(2), as shown in Fig. 1(d) (thickness in nanometers, where $t = 0.5$, 0.75, 1.5, 2.5, 3.5, 5.0, 7.0, 8.5, and 10.0), were deposited on Si substrates covered with a thermally oxidized SiO_2 (100 nm) layer using a magnetron sputtering system. The top Ta was deposited for protection. MgO was deposited by rf-sputtering from an MgO target, and the metal layers (Hf, CoFeB, and Ta) were deposited by using a dc power source. All samples were annealed at 250 °C for 30 min to improve crystallinity and enhance the perpendicular magnetic anisotropy (PMA). The multilayer films were patterned into $20\ \mu m \times 130\ \mu m$ Hall bar structures (see Fig. 1(c)) by photo-lithography and dry-etching techniques.

To determine the magnetic anisotropy, we used magneto-optical-Kerr effect (MOKE) and vibrating sample

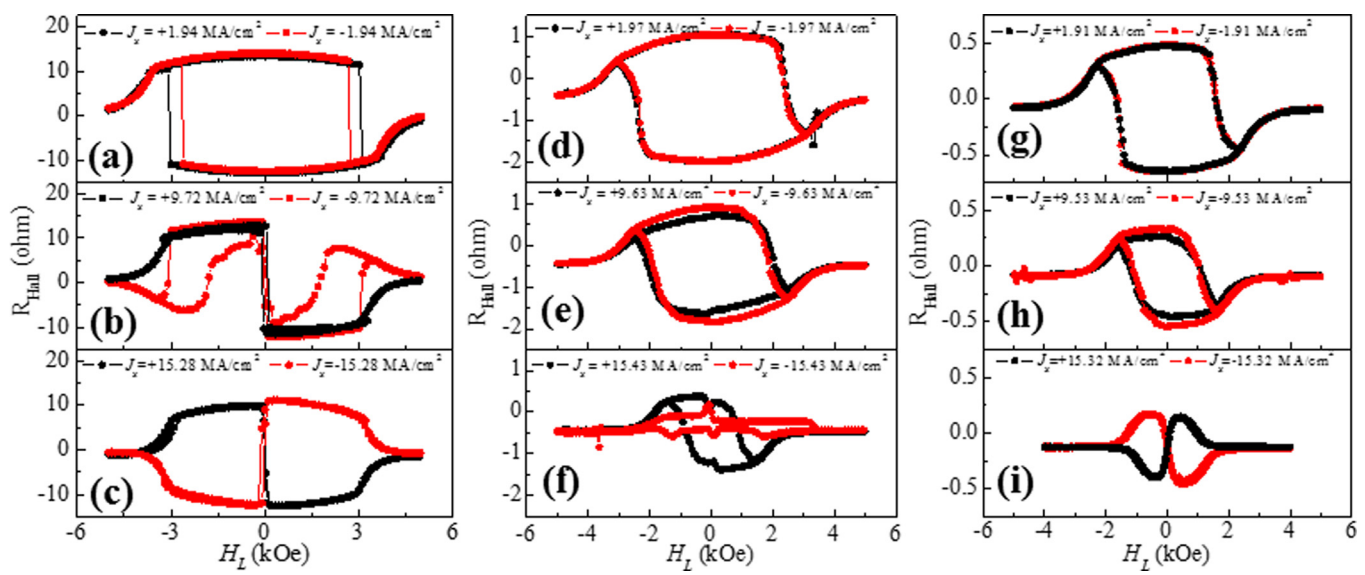

FIG. 3. The Hall resistance, R_{Hall}, as a function of the longitudinal magnetic field, H_L, at $J_x \approx \pm 1.9$ MA/cm^2 (a), (d), and (g), ± 9.6 MA/cm^2 (b), (e), and (h), and ± 15.3 MA/cm^2 (c), (f), and (i). The red (black) curves represent the negative (positive) current direction. The left (a), (b), and (c), center (d), (e), and (f), and right (g), (h), and (i) figures show the structures of Hf(t)|CoFeB(1.1)|MgO(2)|Ta(2) for t = 2.5, 7.0, and 10.0 nm, respectively.

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magnetometry (VSM) measurements. First, MOKE was performed under an out-of-plane magnetic field, H_z. Fig. 1(a) shows hysteresis loops of the MOKE signal versus H_z for the films with different Hf thicknesses. Perpendicular magnetic anisotropy (PMA) is observed in the range of 1.5 to 10.0 nm of the Hf layer thickness. Below the thickness of $t_{Hf} < 1.5$ nm, the magnetic anisotropy changes from perpendicular to in-plane. The perpendicular magnetic anisotropy field, H_k, was quantified from hard-axis magnetization measurements by performing VSM with an in-plane field. A non-monotonic PMA behavior as a function of t_{Hf} was observed in a range of 1.5 to 10.0 nm, as shown in Fig. 1(b). Here, there are two regions of PMA behavior: (i) the PMA increases with t_{Hf} up to 5.0 nm, and then (ii) once the thickness of Hf goes above 5.0 nm, it gets weaker up to 10.0 nm in this work. The origin of PMA is partly attributed to the Fe-O and Co-O hybridization at the interface between CoFeB|MgO and partly to the interface between buffer-layer|CoFeB, as observed in previous works.[14–17] The reason for observing a weaker PMA at thicker Hf layers may be attributed to the surface roughness. To investigate this, we performed atomic force microscopy (AFM) imaging of samples. Figures 2(a)–2(c) (2(d)–2(f)) show the AFM 2D (3D) images of $t_{\mathrm{Hf}} = 2.5$, 5.0, and 10 nm samples, respectively. As seen from Fig. 2, the surface roughness increases with the Hf layer thickness. In addition to the roughness, we observed some island formation above $t_{\mathrm{Hf}} = 5.0$ nm. As a result, it can be expected that the crystal quality of the CoFe layer is reduced as the thickness of Hf is increased, and the effective perpendicular magnetic anisotropy is reduced as well.

The current-induced spin–orbit torque effect on the magnetization is first investigated by measuring Hall resistance, R_{Hall}, as a function of sweeping longitudinal magnetic field, H_L, at various in-plane dc electric currents (see Figs. 3(a)–3(i)). Fig. 1(c) shows the measurement configuration (also showing the Hall-bar device structure) where the bias current is applied along the x-axis and the voltage is measured along the y-axis. Due to the qualitatively similar R_{Hall}-H_{L} behavior for $t_{Hf} = 1.5$, 2.5, 3.5, and 5.0 nm in the Hf(t)|CoFeB(1.1)|MgO(2)|Ta(2) structure, we only present the data for $t_{Hf} = 2.5$ nm in Fig. 3(a)–3(c). Figures 3(d)–3(f) and 3(g)–3(i) show the measurement results for $t_{Hf} = 7.0$ nm and 10.0 nm, respectively. As can be seen from Figs. 3(a), 3(d), and 3(g), there is no clear difference between the R_{Hall}-H_{L} loops at low positive (black) and negative (red) electric currents (here, the current density is $\approx$1.9 MA/cm^2). When $J_{\mathrm{x}} \approx 9.6$ MA/cm^2, the switching field is reduced significantly, and in the negative current curve, the hysteresis behavior for $t_{Hf} = 2.5$ nm is slightly changed (see Fig. 3(b)). For $t_{Hf} = 7.0$ nm and 10.0 nm, however, there is still no clear difference at ± 9.6 MA/cm^2 (see Figs. 3(e) and 3(h)). At higher J_{x} values ($\approx$15.3 MA/cm^2), the direction of current determines the trend of the R_{Hall}-H_{L} loop, which means that the current-induced spin-orbit torque controls the magnetization direction in the Hf(t)|CoFeB(1.1)|MgO(2)|Ta(2) structure for $t_{Hf} = 2.5$ nm (Fig. 3(c)). However, there is no clear difference in the R_{Hall}-H_{L} loop for $t_{Hf} = 7.0$ nm even at a large current value (Fig. 3(f)). Interestingly, a reverse sign R_{Hall}-H_{L} loop compared to $t_{Hf} = 2.5$ nm was observed in $t_{Hf} = 10.0$ nm (Fig. 3(i)). Given that the sign of DL-bulk SOT cannot be changed by just increasing the heavy-metal layer thickness, this may indicate an additional mechanism in the present system to affect the DL-SOT sign.

To quantify the effect of the heavy metal layer thickness on damping-like spin–orbit torque, vector measurements were done, where we used a small amplitude sinusoidal a.c. with a frequency of 154 Hz through the Hall bars (along $\pm x$) of each device. More information on the measurement can be found in the previous work.[11] The current-induced magnetization switching is enabled by the damping-like SOT. The normalized second harmonic voltage, $V^{2\omega}$ as a function of the longitudinal magnetic field (same direction with current), is shown in Fig. 4(a) for different thicknesses of the

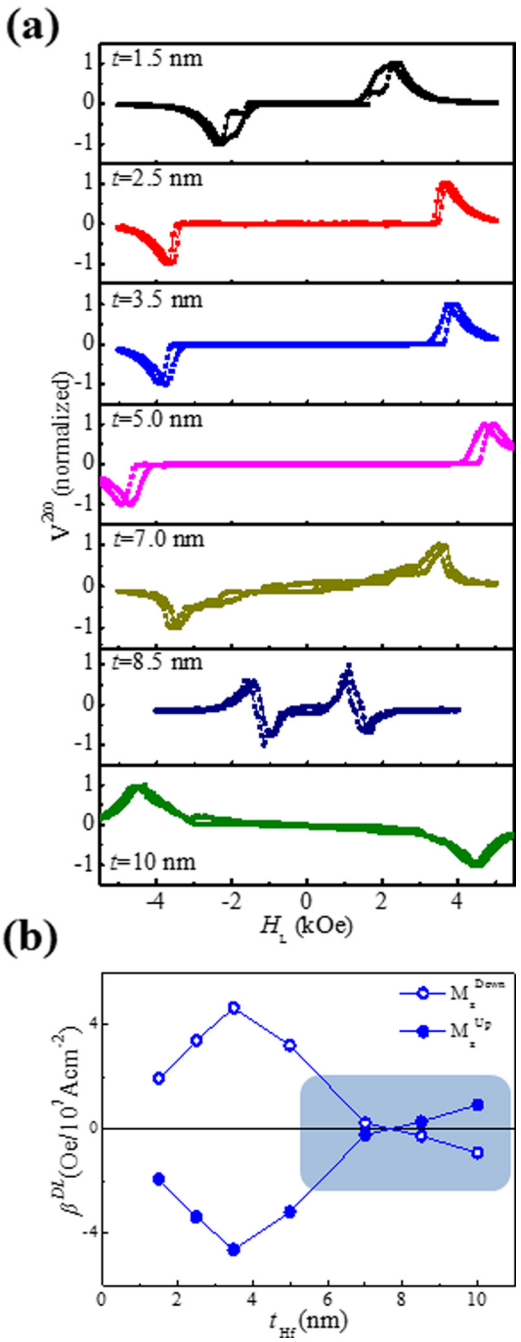

FIG. 4. (a) Second ($V^{2\omega}$) harmonic signal as a function of longitudinal external magnetic field, H_{L}, in the Hf|CoFeB|MgO|Ta structure with various thickness of Hf, (b) an expression of DL-SOT field per current density, $\beta_{DL} = \Delta H^{DL}/J_x$ dependence Hf thickness.

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heavy metal layer. The dip and peak points in the second harmonic signals correspond to the effective fields of the torque on the magnetization. In Fig. 4(a), the peak (dip) points are at the positive (negative) magnetic fields for the thickness of Hf up to 7.0 nm. However, an unexpected behavior is observed in the $t_{Hf} = 8.5$ nm sample, where multiple dip and peak points are seen for both positive and negative fields. Once the thickness of Hf reaches 10.0 nm, the peak (dip) point changes from the positive (negative) to the negative (positive) magnetic field axis. The polarization of $V^{2\omega}$ shows that the sign of the damping-like SOT is changed when the thickness of the Hf layer is increased. This may be understood in terms of a competition between the damping-like SOT and an unknown mechanism with an opposite sign. Based on the experimental data, we calculated the strength of the damping-like SOT-induced effective magnetic field, expressed as $\beta_{DL} = \Delta H^{DL}/J_x$, where J_x is the current density and ΔH^{DL} is the damping-like SOT-induced magnetic field found for both magnetization states (M_z^{Up} and M_z^{Down}). The Hf layer thickness dependence of β_{DL} is shown in Fig. 4(b), where the β_{DL} increases first with the thickness of Hf, as expected. However, at a critical Hf thickness, it starts to reduce with increasing thickness of Hf. Finally, the sign of DL-SOT changes once the thickness of Hf is increased above 7.0 nm. A similar reduction in the DL-SOT was observed by Torrejon *et al*. where the thickness of Hf was increased up to 6.0 nm; however, the change of the torque sign was not observed within the thickness range of that work.[18] It is believed that while the thickness of the heavy metal as a source of creating spin-current by bulk spin-Hall effect contribution cannot change the sign of damping-like SOT due to the linear dependence of spin current on the thickness of the heavy metal, $J_s(t) \approx 1 - \mathrm{sech}\left({}^{t_{HM}}/_{\lambda_{sd}}\right)$, where t_{HM} is the thickness of heavy-metal and λ_{sd} is the spin-diffusion length, the magnitude of SOT can be affected by changing the thickness of the heavy metal, ferromagnets, and insulating layer. There are limited number of studies which show sign reversal behavior in damping-like SOT.[1,19,20] In addition to interfacial and bulk contributions from the HM, recent experimental and theoretical works have shown contributions to SHE from oxygen content in ferromagnetic layer, the oxide layer, ferromagnetic layer thickness, and surface roughness.[1,11,12,19,21] If the interfacial SOC has an opposite sign to the bulk spin-Hall contribution, the effective damping-like SOT can be changed by the interfacial SOC contribution. Therefore, the competition of these two terms in the multilayer system can determine the sign of the effective damping-like SOT. In the light of these possible scenarios, we evaluate each as outlined below.

Among the possible contributions to the SOT, in the present multilayer structures, the oxygen content of the interface, which is one possible reason of sign-reversal,[1] is expected to be the same in all samples. Another possible reason is interface scattering and interfacial spin-orbit coupling previously studied at the surface of a non-heavy metal thin film, such as Cu.[12,22,23] The spin-orbit coupling at a rough interface results in spin-Hall conductivity due to the potential gradient at the interface. Zhou *et al*. theoretically showed that Cu thin films with rough surface can create a spin-Hall effect itself, and the spin-Hall angle (%0.35) is comparable with Au, which is known as a heavy metal.[12] In addition, they showed that the spin-Hall angle can be increased with increasing roughness. In the present case, we observed thickness dependent surface segregation by atomic force microscopy images, where the roughness increases with Hf thickness. This, in turn, can contribute to interface spin-orbit coupling. The interface SOC thus drives a torque on the magnetization which is opposite in sign to the bulk SOC. The spin-Hall angle coming from the interface roughness is larger for rough surfaces. Since the back-scattering electrons from the uniform interface cannot be large as in a rough interface, the bulk-SOT contribution can be dominant in the whole system. The bulk-SOT can be enhanced by the increasing thickness of heavy-metal layer, limited to a couple of nanometers due to the low spin diffusion length of heavy-metals, as explained by the above relation. In a rough or asymmetric structure, the interface-SOT can be emerged because of interfacial effective electric field and back-scattered electrons. The effective SOT of these

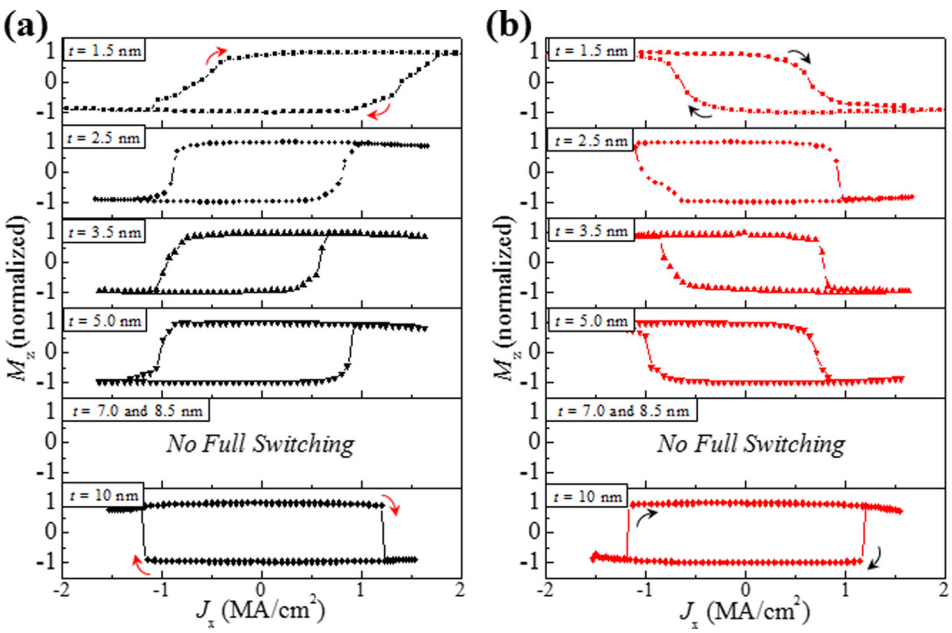

FIG. 5. (a), (b) Current-driven magnetization switching while applying longitudinal external magnetic field at positive (negative) x-direction (see the Fig. 1(c)) in Hf|CoFeB|MgO|Ta structure with various thickness of Hf.

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bulk and interfacial torques can be either enhanced or weakened. One can thus presume that the observation of sign reversal in DL-SOT in thick Hf samples may in part be related to the larger surface roughness in those samples.

We next study the effect of the sign reversal behavior on current-driven magnetization switching in the presence of an in-plane magnetic field to break the symmetry.[2,24–27] The out-of-plane magnetization, M_z normalized from the extraordinary Hall resistance since R_{EHE}, is shown in Figs. 5(a) and 5(b). The magnetic switching direction is in the clockwise (counter-clockwise) direction for the thickness of Hf up to 7.0 nm under positive (negative) external magnetic field. For $t_{Hf} = 7.0$ and 8.5 nm, there is no full magnetization switching observed. However, an opposite switching behavior is observed for $t_{Hf} = 10.0$ nm, as expected.

In conclusion, the presented results indicate that the sign of DL-SOT can change with the thickness of the Hf heavy metal layer. The origin of the sign reversal is possibly related to interface SOC due to scattering at rough interfaces of the Hf and CoFeB layers. The results show that the thickness of the heavy metal layer, in addition to its spin Hall effect, is an important parameter when designing devices for applications in magnetic random access memory (MRAM).

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