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Enhancement of spin-orbit torques in Ta/Co\textsubscript{20}Fe\textsubscript{60}B\textsubscript{20}/MgO structures induced by annealing

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Spin-orbit torques (SOTs) in Ta/CoFeB/MgO structures are studied by harmonic voltage method. The results indicate that both Slonczewski-like ($H_{SL}$) and field-like ($H_{FL}$) effective field are enhanced by annealing in the film stacks with various Ta thicknesses. Investigation of the crystallographic phase of the Ta layers and resistance of Hall bar devices suggest that annealing may induce a phase transformation in the Ta layers from the $\alpha$ to the $\beta$ phase, which results in the enhanced $H_{SL}$ of the annealed samples. Current-induced magnetization switching experiments revealed a corresponding decrease of the switching current in the annealed samples because of their enhanced SOTs. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

Recently, spin-orbit torques (SOTs) and related effects in heavy metal (HM)/ferromagnetic layer (FM)/insulator (I) heterostructures have drawn much attention because of their potential applications in magnetic memory\textsuperscript{1–4} and logic devices.\textsuperscript{5} In these structures with broken inversion symmetry, an in-plane current may results in SOTs with both Slonczewski-like \textsuperscript{6–9} and field-like \textsuperscript{10} terms, due to the spin Hall\textsuperscript{1,11–13} and Rashba\textsuperscript{14–17} effects. Experimental and theoretical works have already demonstrated that the SOTs are capable of facilitating magnetization switching.\textsuperscript{1,2,4,11–13} Domain wall motion,\textsuperscript{14,18–21} and magnetic moment precession\textsuperscript{22} in these structures. In the spin-Hall effect (SHE) regime, the spin current originating from the spin dependent scattering in the HM layer can exert a torque on the adjacent FM layer and induce deterministic magnetization switching.\textsuperscript{11} The critical current for SOT-induced magnetization switching depends on the anisotropy of the magnetic layer, the volume of the magnetic unit, and the transformation efficiency (e.g. spin hall angle) from charge current to spin current.\textsuperscript{23} Therefore, for low power operation of spintronic memory and logic devices, a nonmagnetic layer with large spin Hall angle has been exploited by many groups.\textsuperscript{24} The SHE of Pt,\textsuperscript{11,14} CuBi alloy,\textsuperscript{25} $\beta$-Ta,\textsuperscript{1} and $\beta$-W\textsuperscript{12} were focused on initially, and recently topological insulators,\textsuperscript{26} which have a large spin Hall angle, have been considered.

Magnetization switching induced by SOTs has been investigated mainly in HM/FM/O\textsubscript{x} heterostructures, such as Pt/Co/AlO\textsubscript{x},\textsuperscript{11,14} Pt/Co/MgO\textsuperscript{27} Ta/CoFeB/MgO\textsuperscript{1,28} W/CoFeB/MgO.\textsuperscript{12} Among these heterostructures, Ta(W)/CoFeB/MgO ones are the most appealing from the application viewpoint, due to their compatibility with existing MgO-based magnetic tunnel junctions structures, which show high magnetoresistance ratio up to 600% at room temperature.\textsuperscript{29} The measurement, optimization, and manipulation of SOTs in these structures are extremely important for the design of SOT-based memory devices. Current-induced SOTs are represented by the so-called effective magnetic fields, which can be measured by the harmonic voltage method.\textsuperscript{30} Kim et al.\textsuperscript{31} measured the...
layer thickness dependence of the current-induced effective fields in Ta/CoFeB/MgO structures and found that the magnitudes of both Slonczewski-like ($H_{SL}$) and field-like ($H_{FL}$) terms increased with Ta layer thickness ($t_{Ta}$) in very thin Ta layers. However, for thicker Ta layers, the thickness dependence of the SOTs in Ta/CoFeB/MgO structures has seldom been reported. In addition, Avci et al.\textsuperscript{32} reported that both $H_{SL}$ and $H_{FL}$ varied strongly with annealing in Ta (3 nm)/CoFeB (0.9 nm)/MgO (2.5 nm) structures. Therefore, a systematic study of SOT effective fields and their relationship with $t_{Ta}$ and annealing conditions of Ta/CoFeB/MgO structures is necessary.

In this work, we examine SOT in Ta/CoFeB/MgO structures with various $t_{Ta}$ by performing harmonic measurements of the current-induced effective fields, and examine current-induced switching in the structures in both as-deposited and annealed states. We find that both effective fields and switching efficiency increase markedly after annealing, which is attributed to the increase of the concentration of the $\beta$ phase of Ta in the annealed structures.

Film stacks consisting of Ta (x nm)/Co$_{20}$Fe$_{60}$B$_{20}$ (1.3 nm) (hereafter denoted as CoFeB)/MgO (1 nm)/Ta (1 nm) layers with x varying from 3 to 15 nm were deposited at room temperature on thermally oxidized Si substrates by a magnetron sputtering system with a base pressure below $1.0 \times 10^{-7}$ Torr. The Ta and CoFeB layers were grown by direct-current sputtering and the MgO layer was grown by radio-frequency sputtering using an MgO target. The film stack was subsequently patterned into 10 $\mu$m-wide eight-terminal Hall bar devices by standard photolithography and ion milling techniques. Al(300 nm)/TiWN(10 nm) electrodes were formed at the ends of the channel and Hall probes. Some of the processed devices were annealed at 240°C for 1 h in a vacuum furnace at a base pressure of $2.0 \times 10^{-6}$ Torr. The devices were characterized by anomalous Hall effect (AHE) measurements at room temperature. The Hall resistance ($R_H$), which is proportional to the perpendicular magnetization of CoFeB of the structures, was measured using a constant 100-μA bias current. A top view photomicrograph of a typical device and AHE curves of the as-deposited samples are shown in Fig. 1.

For the AHE curves in the Fig. 1(b), constant $R_H$ values were subtracted from the original data to remove the offset of $R_H$ caused by the misalignment of the welding spot of voltage terminals. The square $R_H$ vs. $H$ loops indicate that the CoFeB layers in the as-deposited film stacks with various $t_{Ta}$ exhibit strong perpendicular magnetic anisotropy (PMA).\textsuperscript{32,33} $R_H$ decreases with increasing $t_{Ta}$ because of the shunting effect of the Ta layers.

We quantified SOTs in the structures by detecting current-driven magnetization tilting using harmonic Hall voltage measurements. In this measurement scheme, the variations of the first and second harmonics of the anomalous Hall voltage with in-plane fields are used to quantify the longitudinal and transverse effective fields generated, respectively, by the Slonczewski-like ($H_{SL}$) and field-like ($H_{FL}$) SOTs. Figure 2(a) and (b) depict schematics of the measurement geometry for both cases. The measurements were carried out at room temperature under an alternating current, which generates periodic torques on the uniformly magnetized CoFeB films, causing the $z$-component of the magnetization ($M_z$), and Hall voltage ($V_H$) to vary at the driving frequency. $V_H(t)$ was recorded by a high-accuracy data acquisition (DAQ) card (NI-4461) during sweeps of the external magnetic field for 2 s at each field step. Finally, the first and second harmonics of the anomalous Hall voltage,
FIG. 2. Schematics of experimental geometry used for (a) Slonczewski-like and (b) field-like torque measurements by the alternating-current harmonic technique. Representative data for a sample annealed at 240 °C with $t_{Ta}=5$ nm showing the (c) first and (e) second harmonic signals versus longitudinal swept field, and (d) first and (f) second harmonic signals versus transverse swept field. Measurements for both the “up” and “down” magnetized states are shown.

$V_{\omega}$ and $V_{2\omega}$, respectively, were obtained by fast Fourier transformation (FFT) of $V_H(t)$. Measurements were performed at an excitation frequency of 13 Hz, with the in-plane field swept quasi-statically over 9 kOe. The measurements were repeated more than 50 times to improve the precision of the acquired data. It should be noted that, different from the harmonic voltage measured directly by the lock-in amplifier technique, only the absolute value of $V_{\omega}$ and $V_{2\omega}$ can be obtained by this method, as well as $H_{SL}$ and $H_{FL}$.

Figure 2(c) and (e) depict representative curves of $V_{\omega}$ and $V_{2\omega}$ versus $H_x$ at a current of 1mA for the annealed samples with $t_{Ta}=5$nm, measured both for $M_z>0$ and $M_z<0$. Figs. 3(d) and (f) show corresponding data for $H_T$. As mentioned previously, because the absolute values of $V_{\omega}$ and $V_{2\omega}$ were obtained by FFT of $V_H(t)$, we observed reversed $V_{\omega}$ vs. $H_{SL(y)}$ curves for down magnetized branches. Due to the existence of an offset voltage of the DAQ card, linear variations of $V_{2\omega}$ vs. $H_x(y)$ are observed at low field range. Additionally, the slopes of $V_{2\omega}$ change sign with $M_z$ for the measurements under $H_y$, but not for $H_x$, as expected for field- and Slonczewski-like SOTs, respectively. We also note that $V_{2\omega}$ deviated from the linear curve when it reached the offset voltage of DAQ card (~0.15 µV). Finally, the transverse ($H_{FL}$) and longitudinal ($H_{SL}$) effective fields...
were obtained by the following equations in which the planar Hall effect (PHE) contribution was included.\(^{34}\)

\[
H_{SL(FL)} = -2 \frac{\Delta H_{x(y)} + 2\xi \Delta H_{x(x)}}{1 - 4\xi^2},
\]

where \(\Delta R_P\) and \(\Delta R_A\) are Hall resistances originating from the PHE and AHE, respectively. \(\xi\) was 0.05–0.08 for the samples in this work, as determined by measuring \(R_H\) versus in-plane applied field \(H\) with different field orientations.\(^{35}\) It should also be noted that the measured Hall voltages includes the contribution from the AHE and PHE in the Ta layer, resulting from the nonlocal AHE\(^{36}\) and the spin Hall Magnetoresistance effect,\(^{37}\) respectively. They were ignored in our calculation because they are at least an order of magnitude smaller than that in the FM layer.

Figure 3(a) displays the amplitudes of \(H_{FL}\) and \(H_{SL}\) for a sample with \(t_{Ta}=5\) nm annealed at 240°C, which scaled linearly with current up density to \(3 \times 10^{10} \text{ A/m}^2\). Above this value, we observed a nonlinear increase of these coefficients, which can be ascribed to the reduction of the AHE and magnetic anisotropy caused by Joule heating.\(^{38}\) To compare the SOT effective field for as-deposited and annealed samples, the \(H_{SL}\) and \(H_{FL}\) per unit current density were plotted as a function of \(t_{Ta}\) in Fig. (3(b)). In these experiments, \(H_{SL}\) and \(H_{FL}\) of all samples were measured with the same current density to avoid influence from the nonlinear effect of the effective field versus current density. \(H_{SL}\) increased with \(t_{Ta}\) until it reached maximum values at \(t_{Ta}=5–10\) nm for both as-deposited and annealed samples, and then decreases at larger \(t_{Ta}\). The thickness dependence of \(H_{SL}\) observed here is quite different from some previous results for Pt/Co multilayers\(^{39}\) and Hf/CoFeB/MgO structures.\(^{40}\) In both of these previous studies, \(H_{SL}\) increased and then became saturated at a certain HM thickness according to the relation \(J_s(t_{HM}) = J_s(\infty)[1 - \text{sec} h(t_{HM}/\lambda_{sf})].\(^{41}\) However, our results are quite similar to those observed recently by Nguyen et al.\(^{42}\) for Pt/Co bilayers. They attributed the decrease of the Slonczewski-like torque observed at larger HM thickness to strong scattering at the FM/HM interface.

We extracted the effective spin Hall angle \(\theta_{SH}\) using the equation \(H_{SL} = \hbar \theta_{SH} |j_e|/2|e|M_s t_{F}\),\(^{43}\) which gave values of 0.07 and 0.11 for as-deposited and annealed 5-nm Ta layers, respectively. These values are lower than that reported by Liu et al.\(^{1}\) (0.12) but higher than that by Zhang et al.\(^{44}\) (0.03). The spread of \(\theta_{SH}\) reported for the Ta/CoFeB/MgO system can be explained by the discrepancy of the crystallographic structure in the HM layers which depends on the deposition conditions. In addition, \(H_{FL}\), which is considered to originate from the Rashba effect, exhibits a different variation trend to \(H_{SL}\). The amplitude of \(H_{FL}\) is much larger than that of \(H_{SL}\). These behaviors are consistent with the previous results reported for systems with structure inversion asymmetry.\(^{31,40}\)
From Fig. 3(b), it should also be noted that both $H_{SL}$ and $H_{FL}$ increased abruptly after annealing for all the samples, which may result in a raise of current switching efficiency. To confirm this effect, pulse current-induced switching experiments were carried for all the samples using the method reported in our previous paper.\textsuperscript{28} The results for as-deposited and annealed samples with 5-nm Ta layers are provided in Fig. 4(a) and (b), respectively. A constant in-plane field of 300 Oe was applied along the current direction during switching. We note that the average critical switching currents ($I_s$) for the as-deposited and annealed samples were 7.8 mA and 6.7 mA, respectively. The variation of the switching current did not scale with $H_{SL}$ because of the increase of PMA in the annealed samples,\textsuperscript{33} as illustrated by the M-H loops in Fig. 4(c) and (d). The effective perpendicular anisotropy fields ($H_k$) for the as-deposited and annealed samples are about 4 kOe and 7 kOe, respectively. The reduction of $I_s/H_k$ indicates that switching efficiency is increased by annealing. In addition, we observe asymmetric switching curves for both as-deposited and annealed samples because a perpendicular component of the applied field may exist in the experiment originating from a slight tilt of the in-plane field.

It is generally believed that the SOT effective fields, $H_{SL}$ and $H_{FL}$, originate respectively from the bulk spin Hall effect\textsuperscript{11} in the HM layer and from interfacial spin orbit interaction\textsuperscript{14,15,45–47} at both the FM/HM and FM/I interfaces. In the Ta/CoFeB/MgO structures, annealing may induce a change of the crystallographic structure in the Ta and CoFeB layers, as well as diffusion of boron element towards both the MgO and the Ta layers.\textsuperscript{48} The latter changes the internal electric field at the interfaces, which play a key role for $H_{FL}$ generation through Rashba spin-orbit coupling. Therefore, although further studies are required to clarify the reason for the enhancement of $H_{FL}$, we believe that it may result from the change of the interface properties during annealing.

The increase of $H_{SL}$ and switching efficiency induced by annealing can be ascribed to the change of the crystallographic structure of the HM layers. Previous reports state that the $\beta$ phase of Ta has a large spin Hall angle,\textsuperscript{1} therefore, the concentration of the $\beta$ phase in the Ta layers may affect $H_{SL}$ and $\theta_{SH}$. To investigate the crystallographic phase of Ta in the layers, $\theta$-2$\theta$ X-ray diffraction measurement were carried out. However, because of the weak diffraction of the Ta crystallographic plane, obvious diffraction peaks were only observed for the 15 nm-thick Ta layer, as shown in Fig. 5(a). In the diffraction pattern of the as-deposited state, both $\beta$-Ta (002) and $\alpha$-Ta (110) peaks were identified. The existence of the $\alpha$ phase of Ta is the reason why low $\theta_{SH}$ values were obtained for the as-deposited samples. Although its XRD pattern did not obviously change following annealing of the sample, we speculate that the concentration of the $\beta$ phase of Ta increases during annealing because of the observed rise in $\theta_{SH}$, especially for samples with thin Ta layers. To confirm this effect, we measured the device resistance as a function of $t_{Ta}$, as shown in Fig. 5(b). The Ta resistivity of the as-deposited samples was around 110 $\mu\Omega$·cm, indicating a mixture of $\alpha$-Ta (15–60 $\mu\Omega$·cm) and $\beta$-Ta (170–210 $\mu\Omega$·cm) was present in the Ta layers. The resistance of all the samples increased obviously after annealing, and this behavior was more remarkable for thinner Ta layers. Because $\beta$-Ta has higher resistivity than $\alpha$-Ta, the increase of the resistance of the annealed devices suggests that the concentration of $\beta$-Ta is increased by annealing. Annealing may also induce crystallization.

![Figure 4](image_url) FIG. 4. (a) $\theta$-2$\theta$ XRD patterns of Ta (15nm)/CoFeB (1.3 nm)/MgO (1.0 nm)/Ta (1 nm) film stacks and (b) resistance of Hall bar devices with a length of 70 $\mu$m and width of 10 $\mu$m and different Ta thicknesses before and after annealing at 240 °C.
of CoFeB, which lowers the resistance of the FM layer, so the actual increase of the resistance of the Ta layers should have been underestimated.

In summary, the measurement on SOTs in Ta/CoFeB/MgO structures indicates that both $H_{SL}$ and $H_{FL}$ are increased by post-annealing of the film stacks with different $t_{Ta}$. The enhancement of $H_{SL}$ can be ascribed to the increase of the $\beta$-phase concentration in the annealed Ta layers, which was confirmed by measurements of the crystallographic phase of the films and device resistance. Current-induced switching experiments revealed a corresponding increase in the switching efficiency of the annealed samples because of the enhancement of their SOTs.

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