Spin-orbit torques in Ta/TbxCox ferrimagnetic alloy films with bulk perpendicular magnetic anisotropy

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Spin-orbit torque (SOT) from the spin Hall effect (SHE)\textsuperscript{1,2} has generated considerable interest for manipulating the magnetization in spintronic devices with ultra-low dissipation.\textsuperscript{3–20} Recent research has demonstrated highly efficient magnetization switching\textsuperscript{21–23} and magnetic domain wall (DW) motion\textsuperscript{21–30} by current-induced SOT in ferromagnet (FM)/heavy metal (HM) bilayer films. In order to ensure scalability and thermal stability in device applications, the FM layer in such structures must exhibit perpendicular magnetic anisotropy (PMA). Thus far, most work on SOT in PMA films has focused on FM layers with interfacial PMA generated by adjacent HM or oxide layers. However, the interfacial anisotropy energy density in such films is insufficient to maintain thermal stability for bits scaled below ~20 nm.\textsuperscript{31,32} Bulk PMA materials, such as L10-ordered alloys (FePt, FePd, CoPt, etc.),\textsuperscript{32–35} Heusler alloys,\textsuperscript{36,37} and rare earth-transition metal (RE-TM) alloys,\textsuperscript{14,29–31,38–44} are potential candidates for devices since these materials provide a considerably larger volume anisotropy energy barrier. Furthermore, since the PMA of these materials is less sensitive to the nature of the interfaces, the adjacent layer materials can be optimized to maximize the SOTs without impacting the PMA. However, so far, there have been only a few studies of current-induced torques in bulk PMA materials, focusing mainly on current-induced domain wall motion by spin-transfer torques\textsuperscript{33} or SOT.\textsuperscript{29,30}

Ferrimagnetic RE-TM alloys are of particular interest because in addition to exhibiting bulk PMA, the saturation magnetization ($M_s$) is generally smaller than that in ferromagnetic metals due to partial compensation of the magnetization in opposing sublattices. Since the magnitude of SHE-induced SOTs scales inversely with $M_s$,\textsuperscript{4,20} the switching efficiency in relatively thick ferromagnet/HM bilayer films might therefore be anticipated to be comparable to or even higher than in ultra-thin FM/HM stacks, despite the larger anisotropy energy barrier that must be overcome in the former.

In this paper, we characterize SOTs in ferrimagnetic Tb$_x$Co$_{100-x}$ alloy films generated by the SHE in a Ta underlayer. We examine two alloy compositions corresponding to both RE-dominant and TM-dominant net magnetizations, in order to determine the influence on spin transport and SOTs. We show that strong out-of-plane (OOP) anisotropy can be maintained for film thicknesses up to at least 16 nm, indicating a substantial bulk contribution to the PMA in these films. We then quantify the Slonczewski-like SOT in 8 nm thick Ta/Tb$_x$Co$_{100-x}$ bilayers through current-induced hysteresis loop shift measurements.\textsuperscript{19} Measurements show current-induced effective fields corresponding to an effective spin Hall angle of ~0.11 to 0.17, which compares well to prior results for Ta. Interestingly, we find that the sign of the anomalous Hall voltage is different for RE and TM dominated compositions, whereas the sign of the SOT effective field remains the same, suggesting that the former is related to the TM sublattice magnetization whereas the latter is related to the net magnetization. Our results suggest that Ta/Tb$_x$Co$_{100-x}$ is a potential candidate for spin-orbitonic device applications and give insight into spin transport and SOTs in rare-earth/transition-metal alloys. Published by AIP Publishing.

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with a Ta(3 nm) layer, which is expected to be largely oxidized under ambient conditions so that its contribution to current-induced SOTs is small. Magnetic properties were characterized with a vibrating sample magnetometer (VSM) in the out-of-plane (OOP) and in-plane (IP) configurations, as summarized in Fig. 1. Figures 1(a) and 1(b) show coercivity $\mu_0 H_c$ and saturation magnetization $M_s$, respectively, as a function of $t_{\text{TbCo}}$. $\mu_0 H_c$ increases monotonically with $t_{\text{TbCo}}$ and is significantly enhanced by the Ta underlayer. $M_s$ also depends on the presence of the underlayer and is larger for films grown directly on the thermally-oxidized substrate. Similar effects have been reported elsewhere and attributed to preferential oxidation of the rare-earth metal by reduction of the substrate thermal oxide layer, which changes the surface roughness and alloy content. The anisotropy field $\mu_0 H_k$ and effective magnetic anisotropy energy density $K_u = \mu_0 H_k^2/2$ with $H_k = H_{\text{sat}} + 4\pi M_s$ are plotted versus $t_{\text{TbCo}}$ for the cases with a Ta underlayer (Fig. 1(c)) and without (Fig. 1(d)), where a positive sign indicates the out-of-plane anisotropy. Both $H_k$ and $K_u$ show a similar trend with $t_{\text{TbCo}}$ for both series of samples. We find a threshold thickness (dotted lines in Figs. 1(c) and 1(d)) for generating PMA, suggesting that the film structure at low thicknesses is different from bulk. At larger thicknesses, the PMA energy density varies weakly with film thickness, consistent with a dominantly bulk contribution to the PMA. We find that the Ta underlayer promotes films with higher $\mu_0 H_c$ and PMA at lower threshold thicknesses.

Next, we characterize the Slonczewski-like SOT generated by the SHE in the Ta underlayer, by means of current-assisted hysteresis loop shift measurements, following a technique developed earlier. Out-of-plane (OOP) hysteresis loops are measured as a function of in-plane bias field for various injected currents $I_{\text{DC}}$. In this configuration, with the bias field along the current-flow direction, the Slonczewski-like effective field possesses an out-of-plane component $\mu_0 H_z$ that leads to a current-induced shift of the OOP hysteresis loop. Due to the limited field range for the out-of-plane magnet in our setup, we focus on thinner (8 nm) TbCo films to examine SOTs. We first studied Tb$_2$Co$_7$ films in which the Ta underlayer thickness $t_{\text{Ta}}$ was varied from 4 to 8 nm in 2 nm increments to examine the effect of the SHE. Fig. 2(a) shows VSM OOP and IP hysteresis loops for $t_{\text{Ta}} = 6$ nm, indicating PMA with $\mu_0 H_c = 0.1$ T. As shown in Fig. 2(b), $\mu_0 H_c$ and $M_s$ are relatively independent of $t_{\text{Ta}}$ in this range.
To perform hysteresis loop shift measurements, we patterned 5 μm wide by 12 μm long Hall bars by photolithography and lift-off and used the anomalous Hall effect (AHE) to monitor the OOP magnetization electrically using a standard lock-in technique. Fig. 2(c) illustrates the measurement configuration. The DC current flows in the direction labeled $I_{\text{DC}}$. Applied fields are labeled $H_{\text{x}}$, $H_{\text{y}}$, and $H_{\text{z}}$ for OOP, longitudinal, and transverse to $I_{\text{DC}}$, respectively. Fig. 2(d) shows a typical AHE hysteresis loop under $\mu_0H_{\text{z}}$ for $t_{\text{Ta}} = 6$ nm.

Figures 3(a)–3(c) show AHE hysteresis loops for the same sample under $I_{\text{DC}}$ without and with a longitudinal in-plane bias field of $\mu_0H_{\text{x}} = \pm 60$ mT. As can be seen, no current-induced loop shift occurs for $I_{\text{DC}} = 0$ mA, whereas a current-polarity-dependent loop shift is evident for $I_{\text{DC}} = \pm 6$ mA. The direction of the loop shift reverses when the direction of $\mu_0H_{\text{x}}$ reverses. These characteristics are consistent with the OOP effective field expected from the Slonczewski-like SOT. Figs. 3(d)–3(f) show the switching fields $H_{\text{SW}}$ for up-to-down and down-to-up transitions, and the OOP loop centers as a function of $I_{\text{DC}}$ for the indicated bias field conditions. The switching fields uniformly decrease with increasing $|I_{\text{DC}}|$, which is indicative of Joule-heating induced coercivity reduction. In addition, a shift of the loop center, proportional to $I_{\text{DC}}$, is observed for finite $\mu_0H_{\text{x}}$, corresponding to the current-induced effective field $\mu_0H_{\text{eff}}$.

Figure 4(a) shows the slope of $\mu_0H_{\text{eff}}$ per unit current density flowing in the Ta layer, estimated from a parallel resistor model using the measured resistivities of individual Ta (370 $\mu$Ω-cm) and Tb$_2$Co$_7$ (290 $\mu$Ω-cm) layers. This slope, corresponding to the SOT efficiency $\chi$, was measured as a function of longitudinal and transverse bias field. In the case of a transverse field, no loop shifts are observed and $\mu_0H_{\text{eff}} = 0$, as expected for Slonczewski-like torque. In the case of a longitudinal field, $\chi$ varies linearly with $\mu_0H_{\text{x}}$ and saturates above a threshold. We note that we observe neither a loop shift nor a change in coercivity under application of transverse fields up to at least 100 mT, indicating that the field-like torque, if present, has at most a very small influence on the measured switching fields.

This behavior has been previously observed and described in terms of domain nucleation and propagation during the reversal process. Sweeping the OOP field nucleates reverse domains that expand across the film. For domain wall (DW) propagation-limited reversal, the effect of current can be understood through its effect on DW motion. Slonczewski-like SOT exerts an OOP effective field on DWs when the DW moment aligns along the current-flow direction. In the case of homochiral Néel DWs such as those that occur in PMA thin films with HM interfaces, the effective fields in the DWs on either side of a domain drive the DWs in the same direction rather than causing domain expansion or contraction. However, an in-plane bias field along the current-flow direction tends align DW moments in the same direction, so that the current-induced effective fields in the DWs at either end of a domain orient in the same direction and drive the domain to expand (contract), assisting (impeding) field-driven reversal. In this model, the saturation of $\chi$ at large $\mu_0H_{\text{x}}$ thus corresponds to the threshold field to orient the DWs along the bias field direction, which depends on the DW shape anisotropy field (preferring Bloch DWs over Néel) and the Dzyaloshinskii-Moriya interaction (DMI).

![Figure 3](https://via.placeholder.com/150) **FIG. 3.** (a)–(c) Typical out-of-plane hysteresis loops for (a) $\mu_0H_{\text{x}} = 0$ mT, (b) $\mu_0H_{\text{x}} = +60$ mT, and (c) $\mu_0H_{\text{x}} = -60$ mT. (d)–(f) Switching field ($\mu_0H_{\text{sw}}$) as a function of DC current for various (d) $\mu_0H_{\text{x}} = 0$ mT, (e) $\mu_0H_{\text{x}} = +60$ mT, and (f) $\mu_0H_{\text{x}} = -60$ mT. Red symbol and the fitting line show effective field ($\mu_0H_{\text{eff}}$) and spin-orbit torque efficiency.

![Figure 4](https://via.placeholder.com/150) **FIG. 4.** (a) Spin-orbit-torque efficiency ($\chi$) as a function of $\mu_0H_{\text{x}}$ and $\mu_0H_{\text{y}}$. The line is a guide for the eye. (b) $\chi$ and spin Hall angle as a function of Ta layer thickness.
strength (stabilizing homochiral Néel DWs). Above this threshold, the current-induced effective field is maximized and saturates at a value $\mu_0H_{Dx} = \frac{e\ell_{SW}^0}{2\alpha M_{SW}T_{CO}}j$, where $h$ is the Plank constant, $\theta_{SH}^0$ is the effective spin Hall angle, $e$ is the electron charge, and $j$ is the current density. A transverse field $\mu_0H_y$, by contrast, orients the DW moments orthogonal to the current flow such that the current-induced effective field is expected to vanish, consistent with our observation.

Figure 4(b) shows that the saturation SOT efficiency $\chi \approx [4.6 \pm 0.3] \text{ mT}/[(10^{11} \text{ Am}^{-2})]$ is independent of the Ta underlayer thickness for the range studied, which is to be expected for the SHE since $\tau_S$ in this case exceeds the spin diffusion length of Ta, which is from $\sim 1.4 \text{ nm}$ to $2.7 \text{ nm}$. Using this saturation efficiency, we estimate $\theta_{SH}^0$ through the relation $19$ in the preceding paragraph to be $\sim 0.17 \pm 0.02$ (Fig. 4(b)). This value is consistent with the results of other reports for Ta, indicating that the SHE in the Ta layer is likely responsible for the Slonczewski-like torque in this bulk-PMA film.

Next, we discuss the field at which $\chi$ saturates, as shown in Fig. 4(a). The saturation field is generally expected to occur when the DW moment fully aligns with the applied field, acting against the DW shape anisotropy field and occurring when the DW moment fully aligns with the applied field. We estimated the DW shape anisotropy field, acting against the DW shape anisotropy field and occurring when the DW moment fully aligns with the applied field, to be $\sim 0.17 \pm 0.02$ (Fig. 4(a)). This value is consistent with the results of other reports for Ta, indicating that the SHE in the Ta layer is likely responsible for the Slonczewski-like torque in this bulk-PMA film.

Finally, we examined a substrate/Ta(6 nm)/Tb$_{33}$Co$_{67}$(8 nm)/Ta(3 nm)-cap film with higher Tb content, in which the net magnetization is expected to be dominated by the RE sublattice. Fig. 5(a) shows an AHE hysteresis loop under $\mu_0H_x$. We find an inverted AHE voltage as compared to the Tb$_{50}$Co$_{50}$ film (Fig. 2(d)) in this case, where the Co sublattice is aligned antiparallel to the net magnetization. Since the sign of the anomalous Hall coefficient is the same (opposite) as in ferromagnetic Co PMA films, for the Co-dominated (Tb-dominated) composition, we infer that the AHE reflects the magnetization of the TM sublattice rather than the net magnetization. These results are consistent with other reports on RE-TM alloys.

Figures 5(b) and 5(c) show current-induced hysteresis loop shifts under in-plane bias fields for this sample. From these measurements, we determine $\chi$ versus $\mu_0H_x$ and $\mu_0H_y$, as plotted in Fig. 5(d). Similar to the Co-dominated film, we find no hysteresis loop shift for transverse fields and a linear increase in $\chi$ with $\mu_0H_y$ up to a saturation value corresponding to $\theta_{SH}^0 \approx 0.11 \pm 0.02$. This value is somewhat smaller but reasonably consistent with $\theta_{SH}^0$ obtained for the TM-dominated composition. The measured difference may reflect a difference in the spin-mixing conductance due to the different compositions. Notably, although the sign of the AHE is reversed for this composition, indicating a dominant spin-transport interaction with the TM sublattice, the current-induced effective field is the same sign. Hence, we infer that the SHE-induced SOT is exerted on the net magnetization, rather than the Co sublattice. Finally, we note that a very recent study in Ta/GdFeCo ferrimagnetic films also concluded that the AHE sign follows the TM sublattice magnetization, whereas the SOT acts on the net magnetization, consistent with our observations in Ta/TbCo.

In conclusion, we characterized the magnetic properties of co-sputtered Tb$_x$Co$_{100-x}$ alloy films as a function of thickness, as well as the role of a Ta underlayer on these properties. We find that strong bulk PMA can be realized in films with thickness up to at least 16 nm and that the film properties are improved by a Ta underlayer. The Ta underlayer simultaneously provides a source for SOT via the SHE, generating a Slonczewski-like effective field corresponding to an effective spin Hall angle of $\sim 0.11$ to $0.17$. Hence, SOTs can be used to efficiently manipulate the magnetization in relatively thin bulk anisotropy RE-TM films, with an efficiency similar to that in ultrathin FM/HM systems due to the relatively small $M_s$. Furthermore, we find that although the AHE reflects the magnetization of the TM sublattice, the SHE-induced torque tends to act on the net magnetization, giving further insight into spin transport and SOTs in rare-earth-containing materials. These results may help enable magnetic tunnel junction devices driven by SOT switching based on TM-RE alloy materials.

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