Spin-Orbit Torque Efficiency in Compensated Ferrimagnetic Cobalt-Terbium Alloys

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Despite the potential advantages of information storage in antiferromagnetically coupled materials, it remains unclear whether one can control the magnetic moment orientation efficiently because of the cancelled magnetic moment. Here, we report spin-orbit torque induced magnetization switching of ferrimagnetic $Co_{1-x}Tb_x$ films with perpendicular magnetic anisotropy. Current induced switching is demonstrated in all of the studied film compositions, including those near the magnetization compensation point. The spin-orbit torque induced effective field is further quantified in the domain wall motion regime. A divergent behavior that scales with the inverse of magnetization is confirmed close to the compensation point, which is consistent with angular momentum conservation. Moreover, we also quantified the Dzyaloshinskii-Moriya interaction energy at the $Ta/Co_{1-x}Tb_x$ interface and we found that the energy density increases as a function of the Tb concentration. The demonstrated spin-orbit torque switching, in combination with the fast magnetic dynamics and minimal net magnetization of ferrimagnetic alloys, promises spintronic devices that are faster and with higher density than traditional ferromagnetic systems.

There has been great interest recently in using antiferromagnetically coupled materials as opposed to ferromagnetic materials (FM) to store information. Compared with FM, antiferromagnetically coupled systems exhibit fast dynamics, as well as immunities against perturbations from external magnetic fields, potentially enabling spintronic devices with higher speed and density^{1,2}. Rare earth (RE)– transition metal (TM) ferrimagnetic alloys are one potential candidate material for realizing such devices. Inside RE-TM alloys, the moments of TM elements (such as Fe, Co, Ni) and the RE elements (e.g., Gd, Co, Ho, etc) can be aligned with anti-parallel orientations due to the exchange interaction between the f and d electrons³. By varying the relative concentrations of the two species, one can reach compensation points where the net magnetic moment or angular momentum goes to zero^{4–7}. In this work, we show that by utilizing the current induced spin-orbit torque, one can switch magnetic moments in Ta/Co_{1-x}Tb_x bilayer films. Particularly, we found that effective fields generated from the spin-orbit torque scaled with the inverse of magnetization and reached maximum when the composition approaches to the magnetic compensation point. The large effective spin-orbit torque and the previously demonstrated fast dynamics^{8,9} in these ferrimagnetic systems provide a promising platform for high speed spintronic applications.

Spin-orbit torque (SOT) originates from spin-orbit interaction (SOI) induced spin generation in the bulk (i.e., the spin Hall effect)^{10,11} or the surface (i.e., the Rashba-Edelstein effect)^{12,13} of solid materials. So far, SOTs have proven to be an efficient method of controlling the ferromagnetic state of nanoscale devices^{14–17}. Recently, it was demonstrated that one can utilize SOT to switch TM-dominant CoFeTb ferrimagnets with perpendicular magnetic anisotropy (PMA)¹⁸. It is therefore interesting to ask what the relationship is between the chemical composition of RE-TM alloys and the SOT efficiency, and whether or not one can switch compensated ferrimagnets using SOT. To answer these questions, we grew a series of Ta(5)/Co_{1-x}Tb_x(t)/Ru(2) (thickness in nm) films using magnetron sputtering. The Co_{1-x}Tb_x alloys were deposited by co-sputtering Co and Tb sources with different sputtering powers. The concentration of Tb *x* was varied between 0.1 and 0.3 and the layer thickness *t* ranges from 1.7 nm to 2.6 nm. The magnetic properties of the deposited films were examined using vibrating sample magnetometer (VSM), and PMA was observed for all samples [Fig. 1 (a)]. Furthermore, the magnetic moment goes through zero and the coercive fields reach their maximum around $x \approx 0.22$, which is consistent with the room temperature magnetic moment compensation point x_{cM} reported earlier^{6,7}. The dependence of the magnetic moment on the Tb concentration is summarized in Fig. 1(c), which agrees well with the trend line calculated by assuming an anti-parallel alignment between the Co and Tb moment (dashed lines). The samples were then patterned into Hall bars with dimensions 4 x 44 μ m² [Fig. 1(d)]. The anomalous Hall resistance (R_{AH}) vs magnetic field H curves measured from these samples are plotted in Fig. 1 (b) and summarized in Fig. 1(e). The polarity of the hysteresis loops changes sign across x_{cM} , consistent with previous studies where R_{AH} is shown to be dominated by the momentum of the Co sublattice^{19,20}.

Fig. 2(a) illustrates the current-induced magnetic switching for the series of samples. During these measurements, in-plane magnetic fields of ± 2000 Oe were applied in the current flowing direction [y axis in Fig. 1 (d)]. Previous studies showed that an in-plane field is necessary to ensure deterministic magnetic switching of PMA films, as it can break the symmetry between two equivalent final states²¹⁻²⁶. As shown in Fig. 2(a), the current-induced switching shows opposite polarities under the positive and negative applied fields, consistent with the model of SOT induced switching²⁶. Furthermore, under the same in-plane field, the switching polarity changes sign as the samples go from being Co-rich to Tb-rich. This phenomenon can be explained by considering a macrospin model as shown in Fig. 2(b). In SOT switching, the Slonczewski torque²⁷ is proportional to $\hat{\boldsymbol{m}} \times (\hat{\boldsymbol{\sigma}} \times \hat{\boldsymbol{m}})$, where $\hat{\boldsymbol{m}}$ is the unit vector along the magnetic moment direction and $\hat{\sigma}$ is the orientation of electron spins generated from SOI [along the \hat{x} direction in Fig. 1(d)]. Because the torque is an even function of the local magnetic moment \hat{m} , effects from both sublattices in the RE-TM alloy add constructively^{1,28}. At equilibrium positions, \hat{m} and $\hat{\sigma}$ are perpendicular to each other, and it is usually convenient to use an effective field²² $H_{ST} \propto \hat{\sigma} \times \hat{m}$ to analyze the SOT effect on magnetic switching. The equilibrium position of \hat{m} can then be determined by balancing the anisotropy field H_{an} , the applied in-plane field H_y , and H_{ST} . As shown in Fig. 2(b), when H_{v} and $\hat{\sigma}$ are given by the illustrated directions, the final orientation of the Co sublattice magnetic moment will be close to the $+\hat{z}$ direction for the Co dominant sample and close to the $-\hat{z}$ direction for the Tb dominant sample, giving rise to opposite Hall voltages. Based upon this analysis, the current induced switching should exhibit the same polarity change across the compensation point as the magnetic field induced switching. We note that all of the samples follow this rule except for the $Co_{0.77}Tb_{0.23}$ sample, where the field switching data had determined it to be Tb-rich but the current induced switching corresponds to a Co-rich sample. A careful study on this sample reveals that this change simply arises from Joule heating induced temperature change. In RE-TM alloys, the magnetic moments of the RE atoms have stronger temperature dependence compared with TM atoms. Consequently, when the temperature increases, a higher RE concentration is necessary to achieve the same magnetic moment compensation point^{4–9,29}. By measuring the R_{AH} vs H curves of the $Co_{0.77}Tb_{0.23}$ sample under different applied currents, we found that the polarity of the field induced switching did change sign when the current density is higher than 2×10^7 A·cm⁻², suggesting that the sample underwent a (reversible) transition from Tb-rich to Co-rich.

The critical current of SOT induced switching in a multi-domain sample is influenced by defectrelated factors such as domain nucleation and domain wall (DW) pinning²⁴. Therefore, the SOT efficiency *cannot* be simply extracted using the switching current values determined in Fig. 2 (b). To quantify the SOT in our samples, we measured the SOT induced effective field in the DW motion regime by comparing it with the applied perpendicular field, using the approach developed by C. F. Pai et al.²⁵. It has been shown that in PMA films with Néel DWs, the Slonczewski term acts on the DW as an effective perpendicular magnetic field and induces DW motion [Fig. 3(g)]^{21–25}. Therefore, by measuring the current induced shift in the R_{AH} vs H_z curves, one can determine the magnitude of the SOT. Fig. 3 (a) and (b) show typical field induced switching curves for a Co-rich sample $Co_{0.82}Tb_{0.18}$ and a Tb-rich sample $Co_{0.75}Tb_{0.25}$. Under the applied current of ±3 mA and in-plane field of 2000 Oe, the center of hysteresis loops are offset from zero, with opposite values for opposite current directions. The current dependence of the offset fields are summarized in Fig. 3 (c) and (d) for $H_y = 0$ and ±2000 Oe, where a linear relationship between the offset field and the applied current is obtained. In these plots, the ratio between the offset field H_z^{eff} and current density J_e curve represents the efficiency of the SOT at the Ta/RE-TM interface, defined as $\chi \equiv \frac{H_z^{eff}}{J_e}$. χ as a function of applied H_y for Co_{0.82}Tb_{0.18} and Co_{0.75}Tb_{0.25} samples are plotted in Fig. 3 (e) and (f), respectively. χ grows linearly in magnitude for small values of H_y , until reaching the saturation efficiency χ_{sat} at a large in-plane field H_y^{sat} . The evolution of χ as a function of H_y comes from the chirality change of the DWs in the sample. It is known that because of the Dzyaloshinskii-Moriya interaction (DMI) mechanism³⁰, stable Néel DWs are formed at the heavy metal/magnetic metal interface, which exhibit spontaneous chiralities. Under zero H_y , the DWs do not favor either switching polarities, leading to a zero offset field. As H_y increases, the DMI induced effective field H_{DMI} is partially canceled, and DWs start to move in directions that facilitate magnetic switching. H_y^{sat} therefore represents the minimum field that is required to completely overcome H_{DMI} and χ_{sat} represents the maximum efficiency of the SOT.

Fig. 4 (a) illustrates the dependence of χ_{sat} on x in Co_{1-x}Tb_x samples. It can be seen that χ_{sat} diverges near x_{CM} , with the largest value occurring for the sample with smallest magnetization. This result is consistent with the spin torque theory, where the ratio between the SOT effective field and applied charge current is $\chi_{sat} = (\pi/2)(\xi\hbar/2e\mu_0M_st)^{25,31}$. Here $\xi = \frac{J_s}{J_e}$ represents the effective spin Hall angle, $\frac{\hbar}{2e}J_s$ is the spin current density, \hbar is Planck's constant, μ_0 is the vacuum permeability, and M_s is the saturation magnetization. Note that this model of spin torque is based upon the conservation of total angular momentum. Previously it has been suggested to utilize ferrimagnetic materials with minimized M_s to increase the efficiency of spin torque induced switching³². However, it was not verified if an efficient spin absorption could be achieved at the surface of a ferrimagnet material with antiparallel aligned sublattices. Moreover, because of the mixture between the spin angular momentum and orbital angular momentum in RE-TM alloys, there have been debates over the conservation of total angular momentum in these systems³³. Our experiment results provide clear evidence on the strong efficiency of spin orbit torques in antiferromagnetic coupled materials. Within the experimental accuracy, we found

that the effective field from the SOT does follow the simple trend given by $1/M_S$ [dashed lines in Fig. 4(a)], reflecting total angular momentum conservation. ξ in our samples is determined to be ~0.03, smaller than previously reported values from Ta/magnetic layer devices, possibly due to the relatively smaller spin-mixing conductance at the Ta/CoTb interface³⁴.

In addition to the magnetic moment compensation point x_{cM} , inside RE-TM systems there also exists an angular momentum compensation point x_{cJ} due to the different g factors associated with spin and orbit angular moment. For our $Co_{1-x}Tb_x$ system, using the g factors of Co (~2.2) and Tb (~1.5) atoms^{35,36}, along with the relation $J_{Co(Tb)} = M_{Co(Tb)}/\gamma_{Co(Tb)}$, where $\gamma_{Co(Tb)} = -g_{Co(Tb)}\mu_B/\hbar$ (μ_B being the Bohr magneton, $\gamma_{Co(Tb)}$ the gyromagnetic ratio, and $J_{Co(Tb)}$ the total angular momentum per unit volume), we determine x_{cJ} to be ~17%, which is within the range of the studied samples and lower than x_{cM} . Previously it was demonstrated that ultrafast field-driven magnetic dynamics could be excited around $x_{cJ}^{8,9}$. According to Landau-Lifshiz-Gilbert equation of a ferrimagnetic system^{27,29,37}, the spin torque term leads to $\frac{d\hat{\boldsymbol{m}}}{dt} \sim -\gamma_{eff} \frac{\hbar J_s}{2e\mu_0 M_{St}} (\hat{\boldsymbol{m}} \times \hat{\boldsymbol{\sigma}} \times \hat{\boldsymbol{m}})$, where $\gamma_{eff} = (M_{Co} - M_{Tb})/(J_{Co} - J_{Tb})$ is the effective gyromagnetic ratio and $M_S = M_{Co} - M_{Tb}^{8,9}$. When $J_{Co} - J_{Tb}$ approaches zero, the time evolution of \hat{m} diverges if J_s remains finite at x_{cJ} . As observed in Fig. 4(a), χ_{sat} remains roughly unchanged across x_{cJ} , suggesting that similar to the field-driven experiment, SOT could also be used as an efficient drive force for achieving fast dynamics at this concentration. Finally, we find the switching polarity keeps the same sign across x_{cJ} , differing from the current induced switching of CoGd spin valves studied in Ref. [29], where a switching polarity reversal was observed between x_{cJ} and x_{cM} . This difference is due to the presence of different switching mechanisms: in SOT induced switching of PMA films, the two competing torques are the field torque $\gamma_{eff} M \times H_{eff}$ and the spin torque. Because the two terms have the same prefactor γ_{eff} and are only functions of M, H_{eff} , and $\hat{\sigma}$, under the same applied $\hat{\sigma}$ and H_y , the orientation of \hat{m} will remain the same (Fig. 2b), regardless of the sign of γ_{eff} . In contrast, the anti-damping switching of spin valves changes polarity for regions with $\gamma_{eff} < 0$, as explained in Ref. [29].

The in-plane field needed for saturating the SOT, H_y^{sat} , is plotted against the Tb concentration in Fig. 4(b). First of all, we notice that H_y^{sat} is largest near x_{cM} . This result is consistent with fact that the effective DMI field³¹ $H_{DMI} = D/M_s t \mu_0 \Delta$, where D is the interfacial DMI energy density and Δ is the DW width, would become divergent when M_s approaches zero. Secondly, H_y^{sat} is generally larger for the Tbrich samples than the Co-rich ones. For example, the sample with the highest Co concentration, $Co_{0.87}Tb_{0.13}$, shows $H_y^{sat} \sim 100$ Oe, which is close to the reported saturation field of Ta/FM stacks²⁵. However, in the Tb rich sample $Co_{0.71}Tb_{0.29}$, which has similar magnetic moment, H_y^{sat} is found to be ~ 1500 Oe. In the inset of Fig. 4(b) we plot $H_y^{sat}M_st$, which increases roughly linearly as a function of x. By calculating the DW width $\Delta = \sqrt{\frac{A}{K_u}}$ using the determined anisotropy energy $K_u = 6.4 \times 10^4 \text{ J} \cdot \text{m}^{-2}$ and reported exchange stiffness³⁸ A $\sim 1.4 \times 10^{-11}$ J/m, we get D in the range of 0.05~0.66 pJ/m. The increasing DMI energy with increasing Tb concentration can be explained by the strong spin-orbit coupling and large deviation from the free electron g factor³⁰ in the Tb atoms. The generation of magnetic textures such as chiral DWs and magnetic skymirons³⁹ relies on the competition between the DMI energy and other magnetostatic energies. Therefore, the tunable DMI through chemical composition provides a useful a knob for controlling magnetic phases.

To summarize, we demonstrated SOT induced switching in $Co_{1-x}Tb_x$ thin films with a wide range of chemical compositions. The effective field from the SOT was found to scale with the inverse of magnetization, consistent with the conservation of angular momentum. The high efficiency of SOT at the compensation points as well as the previously demonstrated fast dynamics in these systems makes them highly attractive for high speed spintronic applications. Moreover, we found that the DMI energy density is much larger in samples with high rare earth concentrations, which could provide useful applications in spintronic devices that employ stable magnetic textures.

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Fig. 1 (a) Out of plane magnetization curves of $Co_{1-x}Tb_x$ films. (b) R_{AH} as a function of perpendicular magnetic field. (c) Magnetic moments of $Co_{1-x}Tb_x$ alloys as a function of Tb concentration. (d) Schematic of the device geometry for R_{AH} measurement. (e) R_{AH} as a function of Tb concentration.



Fig. 2 (a) Current induced SOT switching of $Co_{1-x}Tb_x$ for in-plane fields of \pm 2000 Oe. (b) Schematic of effective fields in a ferrimagnetic system. Fields acting on the moment consist of the in-plane field H_y, the anisotropy field H_{an}, and the SOT field H_{ST}.



Fig. 3 (a),(c),(e) Measurements on Co-rich sample $Co_{0.82}Tb_{0.18}$. (b),(d),(f) Measurements on Tb-rich sample $Co_{0.75}Tb_{0.25}$. (a),(b) R_{AH} vs. applied perpendicular field under a DC current of ±3 mA. (c),(d) SOT effective field as a function of applied current density under in-plane fields of ±2000, and 0 Oe. (e),(f) SOT efficiency vs. H_y. Efficiency saturates at the field H^{sat}_y. (g) SOT induced DW motion in the ferrimagnetic system for Tb-rich and Co-rich films, showing that the effective perpendicular field has the same sign in both cases.



Fig. 4 (a) Saturation efficiency and (b) in-plane saturation field for different $Co_{1-x}Tb_x$ films. Both the saturation efficiency and in-plane saturation field are largest near the magnetic moment compensation point. Inset of (b) plots the product of the in-plane saturation field and magnetic moment M_st , indicating an increase in DMI energy density D with increasing Tb concentration.