Interfacial current-induced torques in Pt/Co/GdOx

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Current-driven domain wall (DW) motion is investigated in Pt/Co/GdOx nanostrips with perpendicular magnetic anisotropy (PMA) exhibit lower critical currents for displacement than in-plane-magnetized materials, and can be driven at velocities of up to several hundred m/s by electric current alone. Together with the narrow width and thermal stability of DWs in high-PMA materials, the enhanced efficiency of current-driven DW motion makes out-of-plane magnetized thin films well suited to achieving competitive device performance.

In thicker ferromagnetic films in which interfacial effects can be neglected, current-driven DW motion is well described by adiabatic and nonadiabatic spin-transfer torques (STTs) exerted by the conduction electron spins on the DW magnetization. However, out-of-plane magnetization is usually achieved by sandwiching ultrathin ferromagnetic films between nonmagnetic high-Z metals such as Pt, Au, or Pd that generate PMA in the adjacent ferromagnet via interfacial spin-orbit coupling (SOC). As the ferromagnet is typically only a few monolayers thick, SOC at these interfaces can lead to additional current-induced torques qualitatively distinct from the usual STTs. Miron et al. reported current-driven DW velocities approaching 400 m/s in Pt/Co/AlOx stacks, much larger than expected from STT alone and in a direction opposite to the electron flow. They attributed these results to a large out-of-plane effective field of ~80 Oe per 10^11 A/m^2, augmented by a SOC-mediated transverse Rashba field thought to stabilize the Bloch DWs such that they moved rigidly rather than by precession. Evidence for a large current-induced transverse field has been independently confirmed in Pt/Co/AlOx (Refs. 16 and 18) and Ta/CoFeB/MgO, but highly efficient current-driven DW motion has not yet been reported in any metal/oxide structure beyond Pt/Co/AlOx.

It was recently argued that in addition to a transverse effective field, Rashba SOC in asymmetric structures should generate a Slonczewski-like torque similar to that induced by perpendicular current injection in magnetic multilayers. Together, these Rashba spin-orbit torques could account for the direction and high-efficiency of current-driven DW motion reported in Pt/Co/AlOx. However, a Slonczewski-like torque can also arise through spin pumping from the adjacent high-Z metal via the spin Hall effect (SHE), which was invoked to explain observations of magnetization switching by in-plane current injection. Very recent theoretical analyses suggest that when dissipative corrections are taken into account, the torques generated by Rashba-SOC and SHE-induced spin-pumping yield phenomenologically equivalent current-driven dynamics. It is therefore essential to isolate interfacial contributions to the current-induced torques to identify the dominant mechanisms in real materials systems.

In this letter, we examine current-driven DW motion in out-of-plane magnetized Pt/Co/GdOx films with strong PMA. We have recently shown that an electric field applied across the GdOx can control DW propagation by modulating the interfacial PMA, implying that significant SOC exists at the metal/oxide interface. Strong Rashba splitting has previously been observed at the surface of oxidized Gd, suggesting that Rashba-SOC might likewise manifest at the Co/GdOx interface. Here we show that an in-plane current generates a large effective out-of-plane field of ~60 Oe per 10^11 A/m^2 that drives DWs against the electron flow direction. Decorating the Co/GdOx interface with just 4 Å of Pt diminishes the efficiency of the current-induced torque significantly, and when the GdOx is replaced by a symmetric Pt overlayer the torque vanishes entirely. These results suggest that the metal/oxide interface plays a direct role in generating this large current-induced torque.

The thin-film stack had the form Si/thermal-SiO_2(50)/Ta(4)/Pt(3)/Co(0.9)/GdOx(3) (numbers in parentheses indicate thicknesses in nm). The metal layers were deposited by DC magnetron sputtering under 3 mTorr of Ar at a background pressure of ~1 × 10^{-7} Torr. The GdOx films were grown by DC reactive sputtering of a metal Gd target in an oxygen partial pressure of ~5 × 10^{-5} Torr. The as-grown Pt/Co/GdOx films had a saturation magnetization of ~1300 emu/cm^3 and strong PMA with an in-plane saturation field of ~8 kOe, measured using vibrating sample magnetometry.

To examine DW dynamics in these structures, 500 nm wide Pt/Co/GdOx strips with Ta(3)/Cu(100) electrodes were...
The substrate temperature was controlled using a ther-
mostat, and was maintained at 308 K unless otherwise noted.

The DW velocity at four different substrate temperatures
was measured by a time-of-flight technique as described in Ref. 26. Starting from the saturated state, a reversed driving magnetic field \( H \) and current density \( J \) were applied, and a reverse domain was then generated by a 25 ns current pulse in the transverse nucleation line. Time-resolved MOKE transients were then acquired as a function of position along the strip. Fig. 2(a) shows time-resolved MOKE transients (magnetization reversals) averaged over 150 cycles at several positions along the strip. The exponential tail of each averaged transient, whose breadth increases with increasing DW displacement, reflects the stochastic nature of thermally activated DW motion. The average DW arrival time, taken as the time \( t_{1/2} \) at which the probability of magnetization switching was 0.5, increases linearly with distance from the DW nucleation line (inset of Fig. 2(a)). These data show that DWs propagate with a uniform average velocity along the strip, governed by motion through a fine-scale disorder potential. The average DW velocity increases exponentially with driving field (Fig. 2(b)), as expected for thermally activated propagation.

The DW velocity at all different substrate temperatures
was measured as a function of \( H \) (at \( J = 0 \)) and \( J \) (at \( H = 169 \text{ Oe} \)) in Figs. 2(c) and 2(d), respectively. The DW velocity increases by nearly an order of magnitude with \( J \) parallel to the field-driven propagation direction and decreases similarly along the field-driven propagation direction (\( J > 0 \)), and decreases when \( J \) is reversed.

The variation of \( H_{\text{prop}} \) with \( J \) was plotted in Fig. 1(c). Measurements were repeated on three nominally identical strips yielding an average field-to-current ratio \( \Delta H_{\text{prop}}/\Delta J = 57 \pm 3 \text{ Oe/}10^{11} \text{ A/m}^2 \). As observed in other Pt/Co systems, \( 5,6,28,29 \) DW propagation is facilitated (hindered) when it is parallel (antiparallel) to the current direction. This behavior is contrary to the typical behavior under STT, which assists DW propagation in the direction of electron flow. Identical results were obtained with the opposite configuration of magnetization across the DW, realized by reversing the polarities of the driving field and initialization pulse. This demonstrates that the Oersted field from the injected current cannot play a significant role.

As shown in Fig. 1(c), when a thin Pt layer of 4 Å was inserted between the Co film and the GdOx overlay, \( \Delta H_{\text{prop}}/\Delta J \) dropped to \( 33 \pm 2 \text{ Oe/}10^{11} \text{ A/m}^2 \). Moreover, no current-induced effects were observed in symmetric Pt(3)/Co(0.9)/Pt(3) strips, which were identical to Pt/Co/GdOx except for the topmost layer. These results suggest that the Co/GdOx interface plays a direct role in generating the observed large current-induced torque.

The DW propagation field depends on temperature and the timescale over which reversal is probed, and is therefore an indirect probe of thermally activated DW motion through the defect potential landscape. The DW velocity in the thermally activated regime follows an Arrhenius behavior \( v = v_0 \exp(-E_A/kT) \), where the thermal activation energy barier \( E_A \) directly reflects the influence of the driving field and/or current on the DW dynamics. To access \( E_A \) directly, we have measured thermally activated DW velocities as a function of field, current, and temperature, and used an Arrhenius analysis to unambiguously assess the influence of current on \( E_A \).\textsuperscript{30}

Average DW velocities were extracted using a time-of-
flight technique as described in Ref. 26. Starting from the saturated state, a reversed driving magnetic field \( H \) and current density \( J \) were applied, and a reverse domain was then generated by a 25 ns current pulse in the transverse nucleation line. Time-resolved MOKE transients were then acquired as a function of position along the strip. Fig. 2(a) shows time-resolved MOKE transients (magnetization reversals) averaged over 150 cycles at several positions along the strip. The exponential tail of each averaged transient, whose breadth increases with increasing DW displacement, reflects the stochastic nature of thermally activated DW motion.\textsuperscript{26} The average DW arrival time, taken as the time \( t_{1/2} \) at which the probability of magnetization switching was 0.5, increases linearly with distance from the DW nucleation line (inset of Fig. 2(a)). These data show that DWs propagate with a uniform average velocity along the strip, governed by motion through a fine-scale disorder potential. The average DW velocity increases exponentially with driving field (Fig. 2(b)), as expected for thermally activated propagation.

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when $J$ is reversed, in agreement with the trend in $H$ versus $J$ (Fig. 1(c)). Notably, a temperature increase of just 24 K also enhances the DW velocity by an order of magnitude, highlighting the importance of accounting for even weak Joule heating in such measurements. In Figs. 2(e) and 2(f), we have extracted $E_A$ at each driving condition, taken as the slope of $\ln(v)$ versus $T_{\text{strip}}/C_0$, where $T_{\text{strip}} = T_{\text{sub}} + D_T$ and $D_T$ is the temperature increase due to Joule heating. $D_T$ was measured by comparing the strip resistance versus $T_{\text{sub}}$ at $J = 0$ to the strip resistance versus $J$ at constant $T_{\text{sub}}$, giving a small correction $\Delta T = hJ^2$ with $h = 0.8 \text{ K}/[10^{11} \text{ A/m}^2]$.

The data in Figs. 2(e) and 2(f) show that $E_A$ is lowered with increasing $H$ and with increasing $J$ parallel to DW motion. This strong variation of $E_A$ with $J$ in the Pt/Co/GdOx strip is in contrast with our previous results on symmetric Co/Pt multilayer strips, in which $E_A$ was insensitive to current. The linear scaling of $E_A$ with field and current is consistent with the depinning regime of thermally activated DW motion, corresponding to the intermediate regime separating DW creep and viscous flow dynamics previously identified in this velocity range. By comparing the slope of $E_A$ versus $H$ to that of $E_A$ versus $J$, we arrive at a field-to-current ratio of $67 \pm 8 \text{ Oe}/10^{11} \text{ A/m}^2$, in reasonable agreement with the ratio derived above from the change in $H_{\text{prop}}$ with $J$. This analysis indicates that the slope $\Delta H_{\text{prop}}/\Delta J$ provides an accurate assessment of the efficiency of current-driven DW motion.

In Fig. 3, we use the same time-of-flight technique to investigate high-speed DW motion as DW dynamics approaches the flow regime, driven by combinations of field and current. Following the procedure in Ref. 26, the DW velocity was extracted by measuring the DW arrival time at multiple positions along the strip (Fig. 3(a)). Fig. 3(b) shows a series of DW mobility curves at several injected current densities. With current parallel to DW motion ($J < 0$), the DW mobility curves are lifted to higher velocities, approaching 200 m/s in the fastest cases. When $J$ is incorporated as part of an effective out-of-plane field $H_{\text{eff}} = H + eJ$, where $e = -63 \text{ Oe}/10^{11} \text{ A/m}^2$, the mobility curves converge to the same dynamic scaling as shown in Fig. 3(c). Therefore, even at these high DW velocities, the influence of current can be entirely accounted for by an effective out-of-plane field with the same field-to-current ratio found from slower DW motion.

In the present experiment, random nucleation in the strip limited the maximum driving field that could be employed, preventing access to the linear flow regime of DW dynamics. The exponential increase of DW velocity with $H_{\text{eff}}$ in Fig. 3(b), together with a weak temperature dependence observed in separate measurements, indicates that DW motion at these high velocities (though approaching the viscous flow regime)
is still governed by thermal activation. According to a recent finite-temperature micromagnetics study by Martinez, thermally activated DW propagation at $v > 1 \text{ m/s}$ in a PMA nanostrip with defects occurs by DW precession. The results indicated that a DW can more readily overcome the pinning potential energy barrier by exploiting both the translational and precessional degrees of freedom. In a related study, Martinez showed that a large current-induced transverse Rashba field raises the threshold driving force required for sustained DW motion by suppressing the precessional mode. Comparing Fig. 5 in Ref. 17 and Fig. 9 in Ref. 32, the current density required to move the DW at $\sim 10 \text{ m/s}$ increases by a factor of 4 in the presence of the Rashba field compared to the zero-Rashba field case. With the strong transverse field increasing the energy barrier for transformation between the Bloch and Néel configurations, the low-energy precessional mode is disabled and the DW can propagate only by rigid translation at higher driving currents.

If a large current-induced transverse field were present in the experiments at hand, the velocity of thermally activated DW motion at a given effective driving field $H_{\text{eff}}$ would be expected to decrease at large current densities. However, as shown in Fig. 3(c), DW dynamics remain unchanged for a fixed $H_{\text{eff}}$ even at large currents and vanishingly small applied fields. The convergence of the mobility curves to one common dynamic behavior (Fig. 3(c)) suggests that this interface plays a direct role in the current-driven DW motion. The high efficiency of current-driven DW motion in Pt/Co/Gdx interface diminishes the current-induced torque, suggesting that this interface plays a direct role in the current-driven DW motion. The high efficiency of current-driven DW motion in Pt/Co/GdOx is similar to what has been observed in Pt/Co/Oxide structures. However, we did not observe any evidence of an effective Rashba transverse field strong enough to suppress precessional DW motion. This work was supported under NSF-ECCS 1128439. S.E. acknowledges support by the NSF Graduate Research Fellowship Program. The authors thank Eduardo Martinez for additional insights into Refs. 17 and 32. Technical assistance from Chad Kohler is gratefully acknowledged. Work was performed using instruments in the MIT Nanostructures Laboratory, the Scanning-Electron-Beam Lithography facility at the Research Laboratory of Electronics, and the Center for Materials Science and Engineering at MIT.

27. The reported current density is the average value through the Pt and Co layers, assuming a current distribution in the Ta/Pt/Co stack based on the bulk resistivities of the individual layers.