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Magnetization switching of an MgO/Co/Pt layer by in-plane current injection

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We demonstrate magnetization switching of a perpendicularly magnetized MgO/Co/Pt trilayer by application of an in-plane current and a constant in-plane magnetic field of small amplitude. Switching occurs due to an effective torque generated by spin-orbit coupling intrinsic to the trilayer structure. We investigate the dependence of the critical switching current on the current pulse width, showing that magnetization reversal in the dc limit is assisted by thermal fluctuations.
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Current-induced *spin-orbit* torques (SOT) provide an appealing solution to manipulate the magnetization of thin films and nanostructures,[1,2] which is alternative to magnetic fields and pure spin transfer torques. In ferromagnetic layers lacking structure inversion symmetry, two types of SOTs can arise: one from an effective field of constant direction, consequence of the Rashba and exchange interactions[3–9] and one from an effective field whose direction is always perpendicular to the magnetization, consequence of more complex mechanisms including the Rashba interaction and/or the spin Hall effect.[2,10–12] Recently, magnetization switching of a single ferromagnetic layer induced by current injection has been demonstrated in AlO_x/Co/Pt heterostructures possessing strong spin-orbit coupling and perpendicular magnetic anisotropy.[2] Switching was found to occur due to the second type of SOT, perpendicular to both the current and instantaneous magnetization directions and equivalent to an effective field that rotates with the magnetization in the plane defined by the current and the z axis of the stack [Fig. 1(a)].

Although the origin of this effect is not yet fully understood, in particular with respect to the relative weight of interfacial effects and the spin Hall contribution from the Pt layer,[2,12] this discovery may be crucial for the development of spintronic devices based on magnetic tunnel junctions (MTJs).[13] SOT induced by lateral current injection allow the decoupling of the read and write current paths in MTJs, which avoids electrical stress of the tunnel barrier during the write process, a major problem of the spin transfer approach.[14,15] However, the relatively low magnetoresistance ratio of MTJs with AlO_x as tunnel barrier[16,17] constitutes a restriction for such applications. Advances in this field require to realize in-plane current induced switching in material systems more adapted to MTJ applications and in particular to replace the top AlO_x oxide layer by MgO.

In this letter, we demonstrate deterministic magnetization switching of a perpendicularly magnetized MgO/Co/Pt layer by application of an in-plane current. To realize bipolar magnetization reversal, positive and negative current pulses are employed in combination with a constant in-plane magnetic field collinear with the current direction. The final magnetization state of the Co layer is determined by the sign of the product I_pB_{ext}, where I_p represents the amplitude of the current pulse and B_{ext} the external field. Switching by a dc current is found to require about four times less current density compared to 10 ns long pulses, indicating that magnetization reversal is assisted by joule heating.

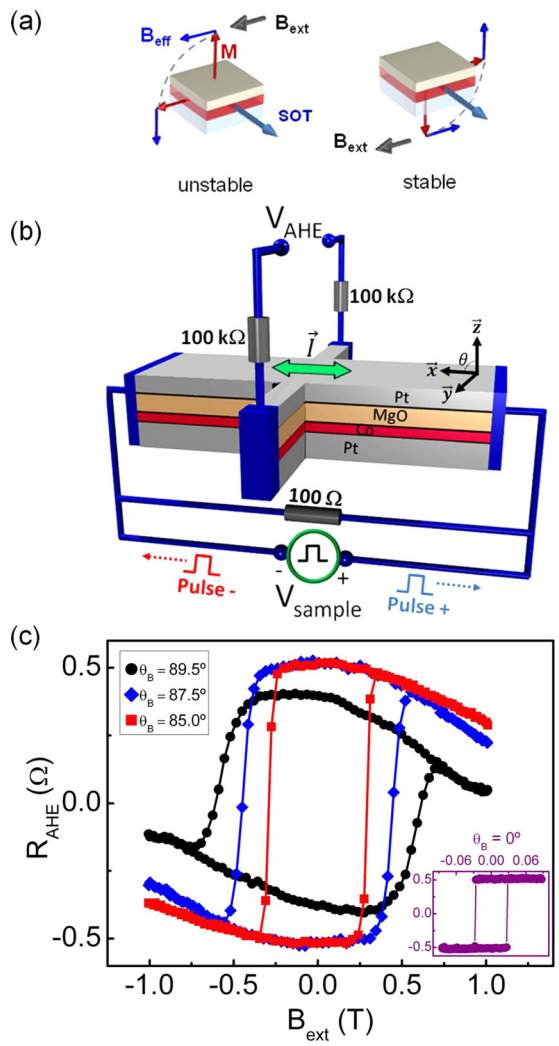

FIG. 1. (a) Schematic representation of the current-induced SOT, corresponding effective field (B_{eff}), and applied external field (B_{ext}). (b) Diagram of the sample and the electrical circuitry. (c) Hysteresis loops for different applied field angles. Inset: easy axis magnetization.

Our sample consists of a Pt(2 nm)/MgO(2 nm)/Co(0.6 nm)/Pt(3 nm) multilayer (from top to bottom) deposited on a thermally oxidized silicon wafer by dc magnetron sputtering. A Pt capping layer was deposited on MgO to avoid degradation of the oxide layer. The sample was patterned in the form of a Hall cross with lateral dimensions of 3 μm for the current injection and 0.5 μm for the Hall measurement branches by electron beam lithography and ion beam etching [Fig. 1(b)]. The resistance of the device is about 1.2 kΩ, which is 40% lower in comparison to the resistance of the devices without Pt capping, suggesting that the current flows homogeneously through all the conductive layers. Assuming homogeneous flow of the current and by taking into account the device geometry, the current density per mA is estimated to be 5.9×10^6 A/cm^2. As shown in the diagram, a 100 Ω resistance was connected in parallel to the sample to ensure the transmission of fast current pulses without significant reflection. The sample was mounted on a rotatable stage to control the applied field angle (θ_B) and placed in an electromagnet producing up to ± 1 T. The perpendicular component of the magnetization (M_z) was measured using the anomalous Hall effect (AHE) at room temperature using a dc current of 0.1 mA. The inset in Fig. 1(c) shows that the anomalous Hall resistance (R_{AHE}) varies by 1.0 Ω between fully saturated up ($+\hat{z}$) and down ($-\hat{z}$) states. The square hysteresis loop measured at $\theta_B = 0°$ is typical of a layer with perpendicular magnetic anisotropy. Figure 1(c) shows how M_z varies when B_{ext} is applied close to the in-plane direction ($\theta_B = 85°$ to 89.5°), which is the configuration employed to study current-induced switching. The magnetization still switches between up and down states, but the coercivity increases due to the reduction of the z-component of B_{ext} parallel to the easy axis of the layer. We note that M_z does not saturate at $\theta_B = 89.5°$, which is likely due to the presence of weakly pinned magnetic domains that do not reverse completely in this geometry. From the field dependence of M_z at different angles, using a macrospin model, we estimate the effective anisotropy field H_K to be about 0.8 T. This value is similar to that obtained for AlO_x/Co/Pt dots studied in Ref. 2. However, in the present case, the lateral dimensions of the layer are much larger and, consequently, the coercivity of the device relatively smaller.

Figure 2 shows the effect of 15 ns-long current pulses on M_z during a single sweep of the external field $B_{ext} \rightarrow -B_{ext}$ applied at an angle of $\theta_B = 89.5°$, nearly parallel to the current direction. For each value of B_{ext}, we applied positive and negative current pulses ($\pm I_p$) and measured the R_{AHE} after each pulse. The diamond dots (solid circles) represent M_z measured after the injection of a positive (negative) pulse. As shown in (a), the behavior of M_z is very different from the field dependence reported in Fig. 1(c). We observe that, within the field range delimited by the coercivity of the layer, M_z switches from up to down and vice versa after each current pulse down to $|B_{ext}| \approx 25$ mT. Upon crossing $B_{ext} = 0$, the effect of the pulses reverses, that is, $\pm I_p$ pulses stabilize $\pm M_z$ if $B_{ext} > 0$ and $\mp M$ if $B_{ext} < 0$. The action of the current is thus consistent with the symmetry discussed for AlO_x/Co/Pt in Ref. 2 and equivalent to an effective field rotating perpendicular to the magnetization in the xz plane, as schematized in Fig. 1(a).

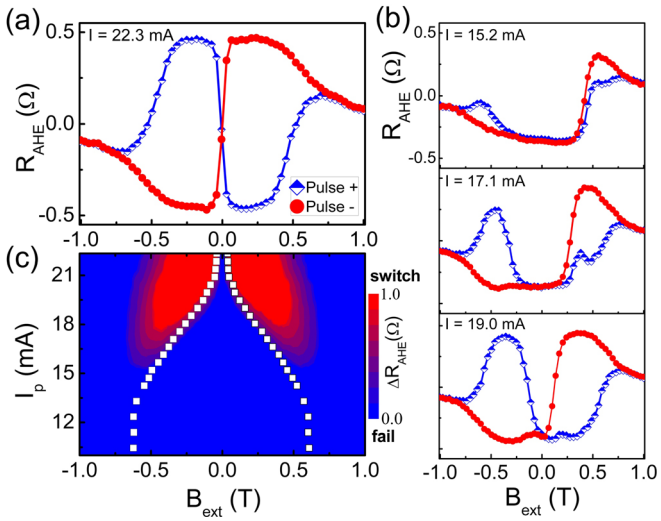

FIG. 2. (a) Magnetization switching induced by positive and negative current pulses of amplitude $I_p = 22.3$ mA. Note that B_{ext} is swept only once from +1 to −1 T. (b) Onset and evolution of switching at $I_p = 15.2$, 17.1, and 19.0 mA. (c) Switching plot showing the difference between the R_{AHE} measured after consecutive positive and negative current pulses as a function of I_p and B_{ext}. For $I_p > 13$ mA, the white dots represent the minimum B_{ext} at which bipolar switching is observed while for lower current values they correspond to the coercivity.

The gradual onset of switching due to current injection is shown in Fig. 2(b). We observe that at $I_p = 15.2$ mA positive pulses lower the R_{AHE} by about 20% close to the coercivity limit (± 0.5 T), which we interpret as the nucleation of reversed domains due to the current-induced SOTs. As the current amplitude increases, the nucleation of domains becomes more pronounced and, at $I_p = 19$ mA, we achieve full switching of M_z for $|B_{ext}| > 0.25$ T. The switching region at low field grows by further increasing the current until it takes the form presented in (a). We note also that current induced switching nearly saturates the R_{AHE}, as opposed to field induced switching in the same geometry. A systematic study of the switching behavior of the system as a function of $I_p = 10 \rightarrow 22$ mA and $B_{ext} = +1\,\text{T} \rightarrow -1$ T yields the switching diagram in Fig. 2(c). The white dots superposed to the diagram represent the minimum external field required to switch the layer. This coincides with the coercivity (0.6 T) at $|I_p| < 13$ mA and gradually decreases to about 25 mT at $|I_p| = 22.3$ mA, which corresponds to a current density of 1.3×10^8 A/cm^2. It is important to realize that a nonzero component of the external field parallel to the current is required to compensate the action of the current-induced SOT, which would otherwise always tend to destabilize the magnetization. At low pulse amplitude, the horizontal field plays a role also in destabilizing the magnetization, leading to the behavior reported in Figs. 2(b) and 2(c). The plot (c) further shows that the high field switching limits (outer boundaries of the red regions) decrease as $|I_p|$ increases above 20 mA, an effect which we associate to the decline of coercivity of the sample due to current-induced heating, which reduces the hysteretic range of M_z.

To determine the role played by thermal fluctuations in assisting the magnetization reversal process, we studied the relationship between I_p and the pulse width (τ_p). Figure 3(a) reports the minimum pulse amplitude required to fully switch M_z at constant $B_{ext} = 200$ mT vs. $1/\tau_p$. We observe

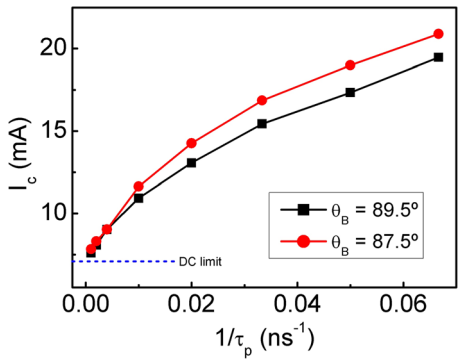

FIG. 3. Dependence of the critical switching current on inverse pulse width at $\theta_B = 87.5°$ (red full circles) and $\theta_B = 89.5°$ (black full squares). The dc limit is shown by the blue dashed line.

that I_p scales strongly with $\tau_p < 100$ ns, whereas switching appears to be less dependent on τ_p above 200 ns, as expected when switching is thermally activated due to Joule heating.[18] Taking into account the amplitude and finite rise-time of the current pulses and using an analytic expression for the temperature of Joule heated nanowires in contact with a semi-infinite substrate,[19] the peak temperature reached by the sample can be estimated as 120 °C (165 °C) for $\tau_p = 15$ ns (1 μs). These values represent an upper temperature limit as they do not take into account heat and current dispersion in the Hall voltage probes. In Fig. 3(a), the difference in the curves for $\theta_B = 89.5°$ and 87.5° reflects the fact that the critical current amplitude is higher (lower) when the perpendicular component of B_{ext} opposing switching is higher (lower). We also performed the switching measurements using a dc current and observed that M_z reverses completely at current amplitude of 7 mA [blue dashed line in Fig. 3(a)].

In summary, we have demonstrated SOT-induced magnetization switching of a single layer of Co with MgO and Pt interfaces. Given the high tunneling magnetoresistance afforded by MgO barriers,[20] this is a necessary step to include SOT-activated layers in MTJ devices. We showed that extended layers with strong perpendicular magnetic anisotropy can be switched by in-plane current injection using dc to pulsed currents of density between 0.4 and 1.3×10^8 A/cm^2.

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[1] A. Chernyshov, M. Overby, X. Liu, J. K. Furdyna, Y. L. Geller, and L. P. Rokhinson, Nat. Phys. **5**, 656–659 (2009).
[2] I. M. Miron, K. Garello, G. Gaudin, P.-J. Zermatten, M. V. Costache, S. Auffret, S. Bandiera, B. Rodmacq, A. Schuhl, and P. Gambardella, Nature **476**, 189–193 (2011).
[3] A. Manchon and S. Zhang, Phys. Rev. B **78**, 212405 (2008).
[4] I. M. Miron, G. Gaudin, S. Auffret, B. Rodmacq, A. Schuhl, S. Pizzini, J. Vogel, and P. Gambardella, Nature Mater. **9**, 230–234 (2010).
[5] P. Gambardella and I. M. Miron, Philos. Trans. R. Soc. London, Ser. A **369**, 3175–3197 (2011).
[6] U. H. Pi, K. W. Kim, J. Y. Bae, S. C. Lee, Y. J. Cho, K. S. Kim, and S. Seo, Appl. Phys. Lett. **97**, 162507 (2010).
[7] T. Suzuki, S. Fukami, N. Ishiwata, M. Yamanouchi, S. Ikeda, N. Kasai, and H. Ohno, Appl. Phys. Lett. **98**, 142505 (2011).
[8] D. Fang, H. Kurebayashi, J. Wunderlich, K. Vyborny, L. P. Zarbo, R. P. Campion, A. Casiraghi, B. L. Gallagher, T. Jungwirth, and A. J. Ferguson, Nat. Nanotechnol. **6**, 413–417 (2011).
[9] I. Garate, and A. H. MacDonald, Phys. Rev. B **80**, 134403 (2009).
[10] D. A. Pesin and A. H. MacDonald, e-print arXiv:1201.0990v1.
[11] K.-W. Kim, S.-M. Seo, J. Ryu, K.-J. Lee, and H.-W. Lee, Phys. Rev. B **85**, 180404(R) (2012).
[12] L. Liu, O. J. Lee, T. J. Gudmundsen, D. C. Ralph, and R. A. Buhrman, e-print arXiv:1110.6846.
[13] S. Ikeda, J. Hayakawa, Y. M. Lee, F. Matsukura, Y. Ohno, T. Hanyu, and H. Ohno, IEEE Trans. Electron Devices **54**(5), 991–1002 (2007).
[14] J. A. Katine and E. E. Fullerton, J. Magn. Magn. Mater. **320**(7), 1217–1226 (2008).
[15] B. Dieny, R. C. Sousa, J. Herault, C. Papusoi, G. Prenat, U. Ebels, D. Houssameddine, B. Rodmacq, S. Auffret, L. D. Buda-Prejbeanu, M. C. Cyrille, B. Delaet, O. Redon, C. Ducruet, J-P. Nozieres, and I. L. Prejbeanu, Int. J. Nanotechnol. **7**, 591–614 (2010).
[16] Z. Diao, D. Apalkov, M. Pakala, Y. Ding, A. Panchula, and Y. Huai, Appl. Phys. Lett. **87**, 232502 (2005).
[17] B. Carvello, C. Ducruet, B. Rodmacq, S. Auffret, E. Gautier, G. Gaudin, and B. Dieny, Appl. Phys. Lett. **92**, 102508 (2008).
[18] K. Yagami, A. A. Tulapurkar, A. Fukushima, and Y. Suzuki, IEEE Trans. Magn. **41**(10), 2615 (2005).
[19] C.-Y. You, I. M. Sung, and B.-K. Joe, Appl. Phys. Lett. **89**, 222513 (2006).
[20] J.-G. Zhu and C. Park, Mater. Today **9**(11), 36–45 (2006).