State diagram of an orthogonal spin transfer spin valve device

Li Ye, Georg Wolf, Daniele Pinna, Gabriel D. Chaves-O’Flynn, and Andrew D. Kent

(Received 23 February 2015; accepted 29 April 2015; published online 15 May 2015)

We present the switching characteristics of a spin-transfer device that incorporates a perpendicularly magnetized spin-polarizing layer with an in-plane magnetized free and fixed magnetic layer, known as an orthogonal spin transfer spin valve device. This device shows clear switching between parallel (P) and antiparallel (AP) resistance states and the reverse transition (AP → P) for both current polarities. Further, hysteretic transitions are shown to occur into a state with a resistance intermediate between that of the P and AP states, again for both current polarities. These unusual spin-transfer switching characteristics can be explained within a simple macrospin model that incorporates thermal fluctuations and considers a spin-polarized current that is tilted with respect to the free layer’s plane, due to the presence of the spin-transfer torque from the polarizing layer.

© 2015 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4920991]

I. INTRODUCTION

Spin transfer torque (STT) devices continue to be intensively studied both for their potential to realize current controlled devices, such as magnetic random access memory (MRAM) and oscillators, and for fundamental interest in the nature of current induced magnetic excitations. An orthogonal spin torque (OST) device incorporates a perpendicularly magnetized spin-polarizing layer in an in-plane magnetized spin-valve or magnetic tunnel junction structure. The added perpendicular polarizer can either induce precessional magnetization switching of a free layer to significantly increase write speed and energy efficiency of STT-MRAM or excite steady state precession to function as a microwave oscillator. A distinct characteristic of OST devices is bipolar switching, i.e., current induced switching from parallel (P) to antiparallel (AP) resistance states and the reverse transition (AP → P) occur for both current polarities. The current-field switching state diagram of OST-MRAM devices, however, have not been measured or modeled.

In this article, we report the magnetic switching characteristics of elliptically shaped OST spin valve devices that have stable in-plane (left and right) magnetized states. In contrast to collinearly magnetized devices (i.e., devices without a perpendicularly magnetized spin-polarizing layer), either bipolar or unipolar switching can occur depending on the applied field. Further, we find hysteretic transitions into an intermediate resistance (IR) state with the IR state persisting to currents less than the threshold currents for P to AP and AP to P switching. A macrospin model, including spin transfer torques from the reference and polarizing layers as well as finite temperature effects, captures the hysteretic current-driven transitions observed in experiment. This demonstrates that asymmetric bipolar hysteretic current driven magnetic transitions are fundamental characteristics of orthogonal spin-transfer devices.

II. DEVICE STRUCTURE

The device layer stack is illustrated in the inset of Fig. 1. It consists of a perpendicularly magnetized Co/Pd and Co/Ni multilayer, with the Co/Ni multilayer closest to the free layer (FL), providing a spin-polarized current. The FL is a 3 nm thick CoFeB layer. The full layer stack is 6.2 [Co/Pd][Co/Ni]/10 Cu/3 CoFeB/10 Cu/12 CoFeB, with the layer thicknesses indicated in nanometers. The stack was patterned into nanopillar devices with various shapes and sizes using e-beam lithography and ion-milling. Here, we present results on 50 nm × 100 nm devices in the shape of an ellipse. The magnetic easy axis of free layer is in the film plane along the long axis of ellipse due to magnetic shape anisotropy. Shape anisotropy also sets the magnetization direction of the 12 nm thick CoFeB reference layer (RL).

III. RESULTS

A. Switching characteristics

Figure 1 shows measurements of the differential resistance (dV/dI) as a function of applied field $H_{app}$ along the easy axis. The measurements are made at room temperature.
with a lock-in amplifier using an ac current of 200 μA at a frequency of 473 Hz. A field sweep from −200 to 200 mT (major hysteresis loop) shows steps in resistance of ΔR_{AP−P} = 0.1 Ω indicative of switching of the FL between P and AP magnetic states relative to the orientation of the magnetization of the RL. The coercive field of the RL is about 150 mT. A minor loop (D (major hysteresis loop) shows steps in resistance of For simplicity, the following results are presented in terms of 

\[ l_{0} = \text{responds (on average) to zero effective field applied to the FL.} \]

FL transitions is

\[ l_{0} = 23 \text{ mT.} \]

A minor loop (−50 mT−140 mT) shows the switching of only the FL. The coercive field for AP to P FL transitions is \( \mu_{0}H_{c}^{+} = 59 \text{ mT,} \)

and the coercive field for P to AP FL transitions is \( \mu_{0}H_{c}^{-} = 23 \text{ mT.} \)

The minor loop is centered at \( \mu_{0}H_{0} = \frac{\mu_{0}(H_{c}^{+} + H_{c}^{-})}{2} = 41 \text{ mT due to dipolar coupling between the FL and RL.} \)

Thus, an external field of \( H_{0} \) corresponds (on average) to zero effective field applied to the FL. For simplicity, the following results are presented in terms of a field that is zero when the applied field compensates the dipolar coupling field, i.e., \( H = H_{\text{app}} - H_{0}. \)

Current induced switching was characterized by measuring the differential resistance as a function of current for a series of easy axis applied fields. The magnetic state (P or AP) is first set by magnetic field. Then, the current \( I_{dc} \) was slowly ramped (≈ 0.1 mA/s) from 0 to ±5 mA and then ramped back to 0 mA, with \( dV/dl \) versus \( l \) recorded at each measuring field. Positive current corresponds to electron flow from polarizing to the reference layer, for which the spin-torque associated with the RL favors an AP state. Representative measurement results starting from the P state are shown in Fig. 2. Similar results were found in measurements starting from the AP state, which are discussed below.

In Fig. 2(a), as the magnitude of the current is increased (black curves), there is first a discrete increase in differential resistance of \( \Delta R_{AP−P} = 0.1 \Omega, \) associated with a P to AP transition. This occurs at \( I_{dc} = 1.5 \text{ mA} \) and \( I_{dc} = −1.2 \text{ mA,} \)

i.e., for both polarities of the current. On further increasing the current, there is a change in resistance that is a fraction of \( \Delta R_{AP−P}, \) a transition into an IR state at \( I_{dc} = 4 \text{ mA and} \)

\( I_{dc} = −1.7 \text{ mA.} \)

On decreasing the current (red curves), the resistance eventually returns to that of the device’s AP state (at \( I_{dc} = 0.5 \text{ mA} \) and \( I_{dc} = −1.3 \text{ mA.} \))

Near zero effective applied field (\( H \approx 0), \) P to AP switching is only seen at positive current polarity (Figs. 2(b) and 2(c)). Whereas, for negative current, only P to IR transitions occur as the current is increased. When the magnitude of the current is decreased, there is a transition from an IR state to an AP state for \( \mu_{0}H = −7, −1 \text{ mT (} H < 0) \) and to a P state for \( \mu_{0}H = 1 \text{ mT (} H > 0). \)

These discrete transitions are on top of a parabolic increase in differential resistance, which we associate with Joule heating of the device.

B. State diagram

This seemingly complex switching behavior can be summarized by plotting the threshold currents for switching between resistance states in a current-applied field state diagram (Fig. 3). Each symbol in Fig. 3(a) corresponds in a discrete change in the resistance. Figure 3(a) shows the current induced transitions observed with increasing current magnitude (\(|l|\)), indicated by the black curves in Fig. 2. While Fig. 3(b) shows the current induced transitions observed with decreasing current magnitude, which are the red curves in Fig. 2. The solid symbols represent differential resistance changes corresponding to transitions between P and AP states. They form a diamond-shaped central zone within which both P and AP states are possible depending on the device history. When the current is greater than 2.9 mA or is less than −1.4 mA, the step change in resistance is less than \( \Delta R_{AP−P}. \)

The boundaries are labeled by open symbols and correspond to P (AP) to IR transitions. These boundaries meet and join the P to AP transition boundaries. Further, they define two triangular zones that encompass IR states at high current magnitudes (both for positive and negative current polarities). As the current is swept back to zero, two parabolic shaped curves (green) show the IR to P (AP) transition thresholds (Fig. 3(b)). The final state (P or AP) is determined by the applied magnetic field. For \( H > 0 (H < 0), \) the ending state is P (AP), independent of the initial device state.

The general features of the state diagram of an OST-SV device are the following: (1) for magnetic fields near the FL coercive fields (\( H_{c}^{+} \) and \( H_{c}^{-} \)), current induced switching is bipolar. For fields close to but less than \( H_{c}^{+}, \) AP to P transitions occur for both positive and negative currents and for fields near but greater than \( H_{c}^{-}, \) P to AP transitions occur for both current polarities. (2) Near the center of the FL’s hysteresis loop, the switching occurs for only one current polarity, positive current for the P to AP transition and negative current for the AP to P current. (3) At large currents, transitions into an IR state are observed, and this state persists even as the current is reduced well below the threshold current for P to AP transitions. These features were seen in all ten 50 nm × 100 nm ellipse shaped devices that we studied.
C. Macrospin model of device characteristics

To understand the device switching characteristics, we consider the spin-transfer torques acting on the FL along with its magnetic anisotropy in a macrospin model. The dynamics of \( \mathbf{m} \), a unit vector in the magnetization direction of the free layer \( (\mathbf{m} = \mathbf{M}/M_s) \), is given by the Landau-Lifshitz-Gilbert-Slonczewski (LLGS) equation

\[
\frac{d\mathbf{m}}{dt} = \Gamma_{LLG} + \Gamma_{th} + \Gamma_S,
\]

where \( \Gamma_{LLG,th,S} \) represents the LLG, thermal torque, and spin-torque. The LLG torque is given by \( \Gamma_{LLG} = \mathbf{m} \times \mathbf{h}_{eff} = \gamma \mathbf{m} \times (\mathbf{m} \times \mathbf{h}_{eff}) \) with effective field \( \mathbf{h}_{eff} = \frac{1}{\mu_0 M_s} \nabla_m U(\mathbf{m}) \), volume of the magnetic element \( V \) and damping constant \( \gamma \). Time in Eq. (1) has been normalized by the precession frequency, \( \gamma \mu_0 M_s \) (i.e., \( \tau = \gamma \mu_0 M_s \gamma \)), where \( \gamma \) is the gyromagnetic ratio. The thermal torque \( \Gamma_{th} \) is induced by a Gaussian distributed random field \( \mathbf{h}_{th} \). The FL has a biaxial magnetic anisotropy energy

\[
U(\mathbf{m}) = U_0(Dm_z^2 - m_x^2)
\]

with an easy axis along \( \hat{x} \) and hard axis along \( \hat{z} \), where \( D \) is the ratio of the hard to easy axis anisotropy \( D = 2M_sH_K \) and \( U_0 = \frac{1}{2} \mu_0 M_s H_K V \) is the energy barrier to magnetization reversal.

Spin-torque contributions due to both the polarizer (magnetized out-of-the film plane, along \( \hat{z} \)) and RL (magnetized in the film plane, along \( \hat{x} \)) can be described in terms of effective spin-polarization direction that is tilted with respect to the plane

\[
\Gamma_S = \tilde{I} \mathbf{m} \times (\mathbf{m} \times \mathbf{n}_S),
\]

\[
\mathbf{n}_S = \frac{\eta_R}{1 - \lambda_R m_z} \hat{x} + \frac{\eta_P}{1 - \lambda_P m_z} \hat{z}.
\]

Here, \( \eta_R,P \) and \( \lambda_R,P \) are the spin polarizations and spin-torque asymmetry parameters for the RL and OP, respectively. \( \tilde{I} = (\hbar/2e)I/(\mu_0 M_s^2 V) \) is a normalized applied current.

A qualitative understanding of central zone of the state-diagram can be seen from the form of the spin-transfer torque in Eq. (3). The torque associated with the reference layer is initially collinear with the damping torque. It thus leads to switching via the antidamping mechanism, typical of spin-transfer devices with collinear magnetizations. However, the spin-transfer torque from the polarizer (\( \propto \mathbf{m} \times (\mathbf{m} \times \hat{z}) \)) is equivalent to an effective field in the direction \( \mathbf{m} \times \hat{z} \), which is initially in the direction of the FL’s medium axis \( \hat{y} \). Such a field reduces the FL’s easy axis coercive field (for both current polarities), as is the case in the Stoner-Wohlfarth model with a medium axis magnetic field. In the Stoner-Wohlfarth model, the result is an astroid shaped switching boundary, which resembles the diamond shaped bistable central zone of our state diagram.

More quantitatively, the spin-torque asymmetry parameters \( \lambda_R,P \) lead to torques that depend on the magnetization state of the FL. For example, different current magnitudes are typically necessary for AP to P and P to AP switching. For simplicity in our model, we consider \( \lambda_R = 0 \), as \( m_z \) is typically small during the switching process. Therefore, \( \lambda_R \) accounts for the main asymmetries we observe in spin-torque switching. We study the switching by simulating an ensemble of 5000 macrospins under the influence of spin-torque, thermal noise, and an applied field. Simulation results are plotted in Fig. 4 with parameters determined as follows. \( D \) is governed by magnetic shape anisotropy and is calculated based on the FL’s shape to be 17. The spin-torque asymmetry is taken to reproduce the measured ratio of positive \( I^+ \) to negative \( I^- \) switching currents at effective zero field \( I^+/I^- = 2 \), giving \( \lambda_R = 0.5 \). \( U_0 = \frac{1}{2} \mu_0 M_s H_K V \) is estimated to be \( 3.5 \times 10^{-10} \) J (i.e., \( \mu_0 H_K B = 80 \) with \( T = 300 \) K), taking \( \mu_0 M_s = 1.5 \tau \) and \( \mu_0 H_K = 35 \tau \). With damping coefficient \( \alpha = 0.04 \), we ran simulations with a series of spin torque ratios \( \eta_P/\eta_R = 0, 0.24, 0.51 \), and 0.68. The simulated state diagram using \( \eta_P/\eta_R = 0.68 \) most closely resembles the experimentally determined state diagram. It is shown in Fig. 4(a) as a colormap, where red (green) represent in-plane AP (P) state and blue corresponds to out-of-plane...
polarization (OPP) states. Results for the other spin-torque ratios studies are shown in the supplementary material.\textsuperscript{16} In certain regions, simulation shows mixed state configuration: P+OPP (dark green) and AP+OPP (purple). Fig. 4(b) shows state composition profile as the current is ramped up from 0 mA to 5 mA for $\mu_0H = 0$. Simulations are run starting from either P (Fig. 4(b) upper panel) or AP (Fig. 4(b) lower panel) states.

The simulation captures the main switching features observed in the experiment both for current ramping up and down. First, we observe a diamond shaped central P/AP bistable central zone, which shows bipolar switching near the layer’s coercive field and an asymmetry in current thresholds for switching that is associated with spin-torque parameter $\lambda_R$. Second, there are transitions into an out-of-plane precessional state, which we associate with the IR state. Dashed curves show simulation results of OPP $\rightarrow$ P/AP state as current is ramped down to 0. We find that the threshold current for P/AP $\rightarrow$ OPP transitions is higher when the current is increasing than the IR to P/AP transitions when the current is decreasing, as observed in experiment. The hysteretic transitions to the IR state can be understood in a recent analytic theory, which examined the influence of the tilted angle $\omega$ (defined as $\tan(\omega) = \eta_p / \eta_s$) on the magnetization dynamics.\textsuperscript{14,17} The theory considered a zero field case in the absence of spin-torque asymmetries (i.e., $\lambda_{R,P} = 0$, $\omega_{\text{eff}} = \omega$). A key result was that for spin-polarization tilts ($\omega$) larger than a critical value, there are hysteretic transitions into a stable OPP state. The condition is $\omega > \omega_c = \tan^{-1}(1/\sqrt{D})$. In this case, a critical threshold current $I_{\text{opp}} = (2/\pi)\sqrt{1+D/\sin \omega}$ exists, above which OPP states are stable. However, a larger current $I_p = \sqrt{D}I_{\text{opp}}$ must be applied to establish an OPP state starting from a P or AP state. This analytic theory thus predicts hysteretic transitions between IR and P/AP states that are observed in this experiment.

IV. SUMMARY

In summary, we have systematically studied the current-induced switching in OST-SV devices. We have constructed a field-current state-diagram, illustrating the range of conditions in which three different resistance states occur: P, AP, and IR states. Deterministic bipolar switching between P and AP states is observed in a range of fields near the FL coercive field, resulting in a distinct diamond shaped AP/P bistable region in the state-diagram. The main features of the state diagram are quantitatively reproduced with a macrospin model that considers the effective spin-torque acting on the free layer as a superposition of the torques from the OP and RL. This simple model thus provides guidance in understanding and optimizing the switching characteristics of OST-devices. These results also show the unique spin-transfer switching characteristics of devices with non-collinear magnetizations.

ACKNOWLEDGMENTS

This research was supported by NSF-DMR-1309202 and in part by IARPA and SPAWAR Contract No. N66001-12-C-019 and IARPA Contract No. W911NF14-C-0089.

1A. D. Kent and D. C. Worledge, Nat. Nanotechnol. 10, 187 (2015).
2A. Brataas, A. D. Kent, and H. Ohno, Nat. Mater. 11, 372 (2012).
3A. D. Kent, B. Ozyilmaz, and E. del Barco, Appl. Phys. Lett. 84, 3897 (2004).
4H. Liu, D. Bedau, D. Backes, J. A. Katine, J. Langer, and A. D. Kent, Appl. Phys. Lett. 97, 242510 (2010).
5D. E. Nikonov, G. I. Bourianoff, G. Rowlands, and I. N. Krivorotov, J. Appl. Phys. 107, 113910 (2010).
6O. J. Lee, D. C. Ralph, and R. A. Buhrman, Appl. Phys. Lett. 99, 102507 (2011).
7G. E. Rowlands, T. Rahman, J. A. Katine, J. Langer, A. Lyle, H. Zhao, J. G. Alzate, A. A. Kovalev, Y. Tserkovnyak, Z. M. Zeng, H. W. Jiang, K. Galatsis, Y. M. Huai, P. K. Amiri, K. L. Wang, I. N. Krivorotov, and J-P. Wang, Appl. Phys. Lett. 98, 102509 (2011).
8H. Liu, D. Bedau, D. Backes, J. A. Katine, and A. D. Kent, Appl. Phys. Lett. 101, 032403 (2012).
9J. Park, D. C. Ralph, and R. A. Buhrman, Appl. Phys. Lett. 103, 252406 (2013).
10L. Ye, D. B. Gopman, L. Rehm, D. Backes, G. Wolf, T. Ohki, A. F. Kirichenko, J. V. Vernik, O. A. Mukhanov, and A. D. Kent, J. Appl. Phys. 115, 17C725 (2014).
11D. Houssameddine, U. Ebels, B. Delaet, B. Rodmacq, I. Firastrau, F. Ponthenier, M. Brunet, C. Thirion, J.-P. Michel, L. Prejbeanu-Buda et al., Nat. Mater. 6, 447 (2007).
12U. Ebels, D. Houssameddine, I. Firastrau, D. Gusakova, C. Thirion, B. Dieny, and L. D. Buda-Prejbeanu, Phys. Rev. B 78, 024436 (2008).
13I. Firastrau, D. Gusakova, D. Houssameddine, U. Ebels, M.-C. Cyrille, B. Delaet, B. Dieny, O. Redon, J.-C. Toussaint, and L. D. Buda-Prejbeanu, Phys. Rev. B 78, 024437 (2008).
14D. Pinna, A. D. Kent, and D. L. Stein, Phys. Rev. B 88, 104405 (2013).
15J. C. Slonczewski, J. Magn. Magn. Mater. 159, L1 (1996).
16See supplementary material at http://dx.doi.org/10.1063/1.4920991 for simulated state diagram with various torque ratios.