Perpendicular Spin Torques in Magnetic Tunnel Junctions

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We quantitatively determine a perpendicular spin torque in magnetic tunnel junctions by measuring the room-temperature critical switching current at various magnetic fields and current pulse widths. We find that the magnitude of the torque is proportional to the product of the current density and the bias voltage, and the direction of the torque reverses as the polarity of the voltage changes. By taking into account the energy-dependent inelastic scattering of tunnel electrons, we formulate the bias dependence of the perpendicular spin torque which is in qualitative agreement with the experimental results.

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There has been considerable interest in the phenomenon of spin-polarized current-induced magnetic dynamics in magnetic tunnel junctions [1]. The essential physics has been well established [2]: when the spin-polarized current enters a magnetic layer, the component of the spin current which is transverse to the direction of the magnetization is absorbed within a short length scale, resulting in a spin torque on the magnetization. Since there are two independent vectors transverse to the magnetization, the spin torque can be written in general as [3],

$$\mathbf{T}_s = a_J \mathbf{M} \times (\mathbf{M} \times \mathbf{m}_p) + b_J \mathbf{M} \times \mathbf{m}_p, \tag{1}$$

where $\mathbf{M}$ and $\mathbf{m}_p$ are unit vectors representing the directions of magnetization vectors of the free and pinned layers, a_J is the in-plane spin-transfer torque, and b_J is the perpendicular spin torque. In metallic spin valves, it has been shown that b_J is very small [4–6]. In magnetic tunnel junctions, however, it remains a key unsettled issue about the dependence of b_J on current [7–9]. Sankey *et al.* [7] and Kubota *et al.* [8] have recently reported that b_J is proportional to the square of the voltage and it reaches 10% to 30% of a_J for a voltage bias about 0.3 V. Furthermore, the sign of b_J is independent of the polarity of the bias. Petit *et al.* [9], however, observed that b_J changes sign when the voltage bias reverses. In this Letter, we extend the determination of b_J to a large bias voltage $V_b > 0.7$ V.

We obtain b_J by carefully fitting the critical voltage (or current) to the spin torque model at room temperature [10–12]. We find that the magnitude of b_J is proportional to the product of the current density and the bias voltage. When the bias voltage is around 1.0 V, b_J plays a significant role during magnetization switching. Thus many previous analyses based solely on a_J omitted the important contribution from b_J. Another finding in this work is that the sign of b_J reverses when the polarity of the voltage is reversed; this sign reversal calls for a new interpretation of the origin of the perpendicular torque. The existing theories [13,14] based on the elastic tunneling correctly predict quadratic dependence of b_J on the voltage, but fail to account for the sign change when the current reverses its direction. Levy and Fert [15] included inelastic scattering in their analysis of the in-plane torque, but have not addressed the perpendicular torque. We propose a microscopic theory of the spin torque by taking into account the energy-dependent inelastic scattering of tunnel electrons and find that the experimental data can be explained well.

The magnetic tunnel junctions, Ta(5)/PtMn(15)/CoFe(2.0) / Ru(0.85) / CoFeB(2.3) / MgO(1.0) / free layer(2.2)/Ta(10) (the unit in parentheses is nm), were deposited in a magnetron physical vapor deposition cluster system and annealed at 250 °C–350 °C for 2.0 h in a magnetic field of 1 T. The free layer is CoFeB based materials. The films were subsequently patterned into ellipse-shaped pillars with the nominal size of 90×180 nm^2. The saturation magnetization of the free layer $M_s = 620$ emu/cc at room temperature. To determine the voltage dependence of the perpendicular torque, we selected 10 samples whose breakdown voltages exceed 1.7 V, and the data presented in this Letter are from one sample; the others have similar results.

The current switching measurements were carried out as follows. Prior to each resistance measurement we applied an external magnetic field $H_{\rm ext}$ parallel to the long axis of the pillar (easy axis of the free layer) and a bias voltage pulse with its amplitude V_b and width t_p. The resistance is then measured after the voltage pulse is turned off. We repeat the above procedure by gradually increasing the amplitude V_b of the voltage pulse until V_b reaches a critical value V_c, where the tunnel resistance shows a discontinuous jumps, indicating that the free layer switches from parallel to antiparallel (or vice verse) alignment with respect to the pinned layer. For each pulse width and the magnetic field, we determine the critical value V_c by repeating the measurements 50 times. We use the convention that the positive bias corresponds to the current flowing from the pinned layer to the free layer, favoring anti-parallel alignment of the two layers.

In Figs. 1(a) and 1(b) we show the typical hysteresis loop (R-H loop) and the I-V curve. Because of magnetostatic coupling between the free layer and the pinned layer, there is a small offset field in our measured samples. We have subtracted $H_{\rm off}$ from the applied magnetic field in Fig. 1(c). For a given thermal stability $\Delta = H_K M_s v_0 / 2k_B T$, where H_K is the anisotropic field including the magnetocrystalline anisotropy and the shape anisotropy, the switching field H_c at room temperature is [16]

$$H_c = H_K \left\{ 1 - \left[\frac{2k_B T}{H_K M_s v_0} \ln(t f_0) \right]^{1/2} \right\}, \tag{2}$$

where $t \approx 1$ s is the measuring time, v_0 is the volume of the free layer, and $f_0 \approx 10^9$/s is the attempt frequency of thermal agitation. From Fig. 1(a), we estimate $H_K = 245 \pm 10$ Oe and $\Delta = 55 \pm 5$, which is very similar to the predicted value $\Delta = 51$ calculated from the single-domain approximation. The switching voltage for a transition from antiparallel (AP) to parallel (P) states and vice versa is shown in Fig. 1(c). The switching voltage showed significant dependence on the width of the current pulse, indicating that thermal effect plays an important role in switching. To understand these data of Fig. 1(c), we use the simple thermally assisted model [10–12]

$$V_c(H_e) = V_{c0} \left[1 - \frac{k_B T}{E_b} \ln(t_p f_0) \right], \tag{3}$$

where

$$E_b = \frac{H_K M_s v_0}{2} \left(1 \mp \frac{H_e + b_J}{H_K} \right)^2 \tag{4}$$

is the energy barrier, V_{c0} is the critical voltage, the effective field $H_e = H_{\rm ext} - H_{\rm off}$. The direct fitting of Fig. 1(c) to the above model is difficult since the parameters such as H_K, M_s, and even V_{c0} are not independent constants due to expected voltage dependence of Joule heating. To remove the temperature variation for different switching voltages, we rewrite Eqs. (3) and (4),

$$H_e = \pm H_K - b_J \mp X_0 \sqrt{\ln(t_p f_0)}, \tag{5}$$

where $X_0 = \sqrt{2H_K k_B T / M_s v_0 (1 - V_c/V_{co})}$. For a fixed switching voltage, one would expect that the temperature of the device is a constant as long as the pulsed width exceeds a few nanoseconds [17]. Thus the fitting of H_e vs $\sqrt{\ln(t_p f_0)}$ would yield both X_0 and $\pm H_K - b_J$ for a given switching voltage. By varying the switching voltage, one obtains the voltage dependence of $\pm H_K - b_J$.

The effective field as a function of pulse width for given switching voltages is shown in Fig. 2. The straight lines for each switching voltages are well described by Eq. (5). The data in Fig. 2 were simply the reorganization of Fig. 1(c): for a fixed switching voltage, we obtain a set of data points of (H_e, t_p) and these equal-switching voltage lines are presented in Fig. 2. We note that the fluctuation of measured switching voltage becomes very large, as shown in Figs. 1 and 2 [light gray (red) solid circles], when the effective field is larger than 92 Oe. In these cases, the total field including the effective field and the perpendicular

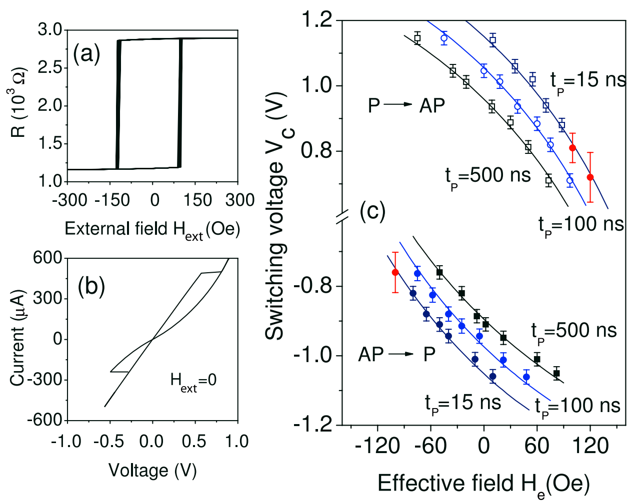

FIG. 1 (color online). (a) The R-H loop. The tunneling magnetoresistance is 146%, $H_{\rm off} \approx -10$ Oe. (b) I vs V loop for $H_{\rm ext} = 0$. (c) The switching voltage as a function of the magnetic field for several current pulse widths for AP to P and P to AP transitions. The solid lines are guides for the eye. The data error bars were determined by repeating 50 times for each acquisition; see text.

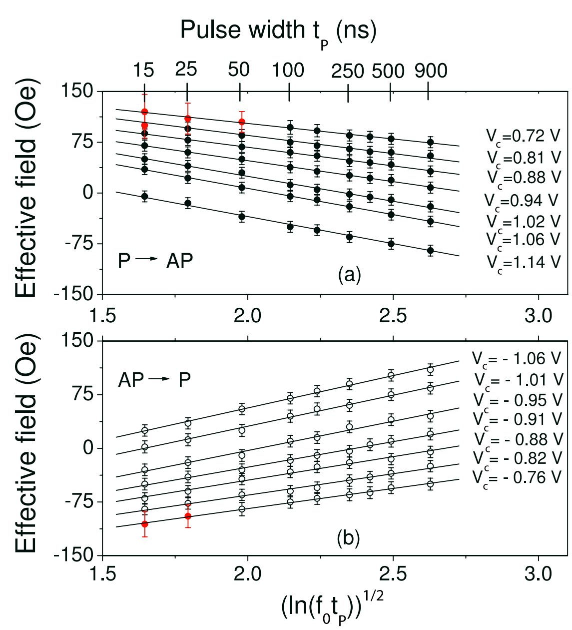

FIG. 2 (color online). The effective field H_e as a function of $\sqrt{ln(f_0 t_p)}$ for the fixed switching voltages: (a) from P to AP and (b) from AP to P transitions.

torque b_J is comparable to the coercive field, and the thermal model is expected to fail.

From Fig. 2 we extrapolate, from Eq. (5), $\pm H_K - b_J$ as a function of voltage, shown in Fig. 3(a). To determine the voltage dependence of b_J, we need to quantitatively estimate the voltage dependence of the anisotropy field H_K. Since the magnetocrystalline anisotropy is about 10 Oe derived from the magneto-optical Kerr effect measurement, the main contribution to the anisotropy field is from the shape anisotropy, and thus H_K is approximately proportional to the magnetization M_s. We then measured the temperature dependence of the magnetization M_s with a vibrating sample magnetometer (VSM) for a 2.2 nm free layer film similarly grown on the MgO layer. Our VSM measurement also determined that the blocking temperature of pinned layer PtMn/CoFe is about $T_B = 600$ K. The inset of Fig. 3(a) shows the magnetization as a function of temperature. When the temperature is increased from 300 to 600 K, the magnetization is decreased by 17%. To maximize the estimation of the Joule heating, we take the device to be $T_B = 600$ K at 1.14 V and use an empirical relation for the voltage dependence of the device temperature $T^* = \sqrt{T^2 + c_0 V_b^2}$, where $c_0 = 2.1 \times 10^5$ (K/V)^2 is taken a maximum value so that $T^* \approx T_B$ for $V_b = 1.14$ V. From Fig. 3(a), we conclude that the dependence of H_K on the voltage cannot explain the observed data. Note that in a different tunnel junction, Fuchs *et al.* [18] performed a dc current experiment and contributed the field dependence of the switching voltage to Joule heating. In our pulsed current experiment, it is only possible to explain the experimental data of Fig. 2 by attributing the presence of the perpendicular torque which we quantitatively show in Fig. 3(b) after subtracting the maximum contribution from H_K. From Fig. 3(b), we conclude that (i) b_J is proportional to the power IV [19] and (ii) b_J changes sign with respect to the current polarity.

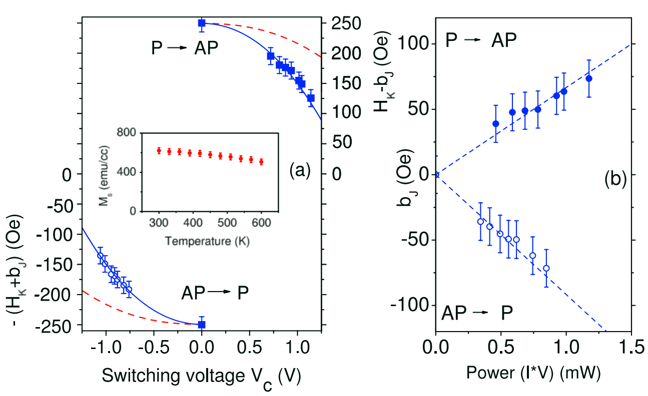

FIG. 3 (color online). (a) $\pm H_K - b_J$ as a function of switching voltage for the two transitions between P and AP states. The inset shows the magnetization versus the temperature derived from VSM measurement. The dotted lines are for a $b_J = 0$ and $c_0 = 2.1 \times 10^5$ (K/V)^2, and the solid lines for $b_J \propto V_b^2$. (b) b_J as a function of the product of current and voltage.

Aside from the Joule heating, we also want to mention other effects caused by the high current density. The recent experiment [20] shows that the current can increase or decrease the exchange bias. It would be interesting to see whether the blocking temperature depends on the direction and magnitude of the current. Another interesting effect might be the current-driven spin excitation which makes the magnetic temperature higher than the Joule heating temperature [21]. All above complications have not been quantified and they could alter the estimation of the temperature of the free layer.

While our conclusion seems different from Sankey *et al.* [7] and Kubota *et al.* [8], we determine the voltage dependence of the perpendicular torque for $V_b > 0.7$ V while they confined to $V_b < 0.45$ V. It is unclear why the voltage dependence of the perpendicular torque changes sign in the voltage range between 0.45 and 0.7 V. It would be interesting to explore the entire voltage range to evaluate the relative merit of these different experiments.

We now discuss the possible mechanisms responsible for our observation. First, we can immediately rule out the current-induced Oersted field as the origin of the perpendicular torque because b_J would be proportional to the current. Furthermore, the Oersted field is circular and its maximum magnitude ($\sim$22 Oe) is much smaller than the value of b_J ($\sim$75 Oe) for the maximum switching voltage. Another appealing model is based on the elastic tunnel [13,14] which predicts the quadratic voltage dependence but fails to account for the sign change of b_J when the direction of the current reverses. We propose below that the bias dependence of inelastic scattering of tunnel electrons is responsible for the perpendicular spin torque.

The interaction between the spin $\mathbf{s}$ of the conduction electron and the magnetization can be conveniently modeled by an $s-d$ Hamiltonian, $H_{\rm int} = -J_{\rm ex}\mathbf{s}\cdot\mathbf{M}$ where the magnetization $\mathbf{M}$ is treated classically. The equation of motion of the nonequilibrium conduction electron $\delta\mathbf{m} = \langle\mathbf{s}\rangle$ in the layer $\mathbf{M}$ is

$$\frac{\partial\delta\mathbf{m}}{\partial t} + \frac{\partial\mathbf{j}_s}{\partial x} = -\frac{J_{\rm ex}}{\hbar}\delta\mathbf{m}\times\mathbf{M} - \left(\frac{\partial\delta\mathbf{m}}{\partial t}\right)_{\rm scatt}, \quad (6)$$

where the last term represents the spin-flip scattering of conduction electrons. If we replace the scattering term by the relaxation time approximation $\delta\mathbf{m}/\tau_{\rm sf}$ and only consider the transverse component of $\delta\mathbf{m}$, Eq. (6) becomes

$$-\frac{J_{\rm ex}}{\hbar}\delta\mathbf{m}\times\mathbf{M} = \frac{1}{1+\xi^2}\left(\frac{\partial\mathbf{j}_s}{\partial x} - \xi\mathbf{M}\times\frac{\partial\mathbf{j}_s}{\partial x}\right), \quad (7)$$

where $\xi = \hbar/J_{\rm ex}\tau_{\rm sf}$, and we have assumed the steady-state current, $\partial\delta\mathbf{m}/\partial t = 0$. The total spin torque on $\mathbf{M}$ is thus

$$\mathbf{T} \equiv \int dx \frac{J_{\rm ex}}{\hbar}\delta\mathbf{m}\times\mathbf{M} = \frac{1}{1+\xi^2}[\mathbf{j}_s(0) - \xi\mathbf{M}\times\mathbf{j}_s(0)], \quad (8)$$

where $\mathbf{j}_s(0)$ is the transverse spin current at the interface between the insulator barrier and $\mathbf{M}$, and we have used the fact that the transverse spin current is zero at the other side of $\mathbf{M}$ layer.

To determine $\mathbf{j}_s(0)$, we consider a generalized Julliere model [22] for noncollinear magnetic layers: the spinor tunnel current $\hat{j}$ is proportional to the product of two spin-polarization factors of the pinned and free electrodes, i.e.,

$$\hat{j} = 2j_0\hat{N}_p\hat{N} = 2j_0U\begin{pmatrix} \frac{1+P_p}{2} & \\ & \frac{1-P_p}{2} \end{pmatrix}U^\dagger\begin{pmatrix} \frac{1+P}{2} & \\ & \frac{1-P}{2} \end{pmatrix}, \tag{9}$$

where j_0 is the spin-independent tunneling current, $\hat{N}_p$ and $\hat{N}$ are the spin-polarization matrices of the pinned and free layers which are diagonal with respect to the quantization axis along their own local magnetization, P_p and P are the polarization factors, and U is the unitary rotation matrix so that Eq. (9) represents the tunneling spin current spinor in the representation of the quantization axis along the magnetization of the *free* layer. The transverse (with respect to the free layer) tunnel spin current is thus

$$\mathbf{j}_s(0) \equiv \frac{\hbar}{eM_s t_F}\mathrm{Tr}_\sigma(\boldsymbol{\sigma}\hat{j}) = \frac{\hbar j_0 P_p}{eM_s t_F}\mathbf{M}\times(\mathbf{M}\times\mathbf{M}_p), \tag{10}$$

where we introduce the prefactor $\hbar/eM_s t_F$ (t_F is the thickness of the free layer) to convert $\mathbf{j}_s(0)$ to the unit of the magnetic field. By placing the above tunnel spin current in Eq. (8), we identify the spin torque coefficients Eq. (1):

$$a_J = \frac{\hbar j_0 P_p}{eM_s t_F(1+\xi^2)}; \qquad b_J = \xi a_J. \tag{11}$$

The above identification shows that the transfer of the transverse spin current $\mathbf{j}_0(0)$ to the free layer could generate both the in-plane and the perpendicular torques. The sign of both torques follows the direction of the current. At a low bias voltage, the spin-flip relaxation length $l_{\mathrm{sf}} = v_F\tau_{\mathrm{sf}}$ is of the order of 10–30 nm while the spin decoherence length $l_{\mathrm{ex}} = \hbar v_F/J_{\mathrm{ex}}$ is about 1 nm; thus, $\xi = l_{\mathrm{ex}}/l_{\mathrm{sf}}$ is less than a few percentage and one can discard the b_J term in Eq. (1). At a high voltage bias, however, the spin-flip scattering length l_{sf} can be as small as l_{ex} as we explicitly show below.

The inelastic magnetic scattering of hot tunnel electrons is primarily due to spin wave (magnon) emissions and Stoner excitations [23]. We can estimate the inelastic mean free path by considering the same *sd* Hamiltonian except that the hot tunnel electrons are allowed to interact with the low energy excitations of the magnetization (magnons). A straightforward Fermi golden rule leads to the following approximate inelastic mean free path,

$$l_{\mathrm{sf}} = \frac{8\pi J_F\hbar^2}{maJ_{\mathrm{ex}}^2}\left(\frac{\epsilon_F}{|eV_b|}\right), \tag{12}$$

where J_F is the ferromagnetic exchange energy, a is the lattice constant, and ϵ_F is the Fermi energy. The inverse relation between l_{sf} and V_b is from the fact that the hot electron is able to emit more magnons for a larger V_b and thus reduces the mean free path. From Eqs. (11) and (12), we conclude that b_J is proportional to $j_0|V_b|$ but changes sign when j_0 reverses. A rough order of magnitude estimation can be readily done for a typical magnetic tunnel junction. If we take the following parameters, $V_b = 1$ V, $a = 3.5\times10^{-10}$ m, $J_{\mathrm{ex}} = 0.6$ eV, $J_F = 0.2$ eV, and $\epsilon_F = 5$ eV, the above equation would produce the mean free path about 0.5 to 2 nm for a bias voltage of 1 V; this is consistent with the estimation by using a more detailed calculation [23].

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[1] Y. Huai *et al.*, Appl. Phys. Lett. **84**, 3118 (2004); G. D. Fuchs *et al.*, *ibid.* **85**, 1205 (2004); Z. Diao *et al.*, *ibid.* **87**, 232502 (2005).
[2] J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).
[3] S. Zhang, P. M. Levy, and A. Fert, Phys. Rev. Lett. **88**, 236601 (2002).
[4] K. Xia *et al.*, Phys. Rev. B **65**, 220401 (2002).
[5] M. A. Zimmler *et al.*, Phys. Rev. B **70**, 184438 (2004).
[6] S. Urazhdin, N. O. Birge, W. P. Pratt, Jr., and J. Bass, Phys. Rev. Lett. **91**, 146803 (2003).
[7] J. C. Sankey *et al.*, Nature Phys. **4**, 67 (2008).
[8] H. Kubota *et al.*, Nature Phys. **4**, 37 (2008).
[9] S. Petit *et al.*, Phys. Rev. Lett. **98**, 077203 (2007).
[10] Z. Li and S. Zhang, Phys. Rev. B **69**, 134416 (2004).
[11] R. H. Koch, J. A. Katine, and J. Z. Sun, Phys. Rev. Lett. **92**, 088302 (2004).
[12] D. M. Apalkov and P. B. Visscher, Phys. Rev. B **72**, 180405(R) (2005).
[13] I. Theodonis *et al.*, Phys. Rev. Lett. **97**, 237205 (2006).
[14] J. C. Slonczewski and J. Z. Sun, J. Magn. Magn. Mater. **310**, 169 (2007).
[15] P. M. Levy and A. Fert, Phys. Rev. Lett. **97**, 097205 (2006).
[16] M. P. Sharrock, IEEE Trans. Magn. **26**, 193 (1990).
[17] It is assumed that the free layer and the pinned layer have the same temperature (thermal equilibrium) when $t_p \geq 15$ ns. This assumption has been validated by I. L. Prejbeanu *et al.*, J. Phys. Condens. Matter **19**, 165218 (2007).
[18] G. D. Fuchs *et al.*, Appl. Phys. Lett. **86**, 152509 (2005).
[19] Note that the resistance at $V_b = 1.1$ V is about 5% smaller than that at the low bias for the P configuration while it is 65% for the AP configuration. Thus the $b_J \propto IV_b$ is not equivalent to $b_J \propto V_b^2$ for the AP configuration.
[20] Z. Wei *et al.*, Phys. Rev. Lett. **98**, 116603 (2007).
[21] A. S. Nunez and R. A. Duine, Phys. Rev. B **77**, 054401 (2008).
[22] M. Julliere, Phys. Lett. **54A**, 225 (1975).
[23] J. Hong and D. L. Mills, Phys. Rev. B **62**, 5589 (2000); **59**, 13 840 (1999).