Temperature dependence of the switching field in all-perpendicular spin-valve nanopillars


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(Received 10 July 2013; published 3 September 2013)

We present temperature dependent switching measurements of the Co/Ni multilayered free element of 75-nm-diameter spin-valve nanopillars. Angular dependent hysteresis measurements as well as switching field measurements taken at low temperature are in agreement with a model of thermal activation over a perpendicular anisotropy barrier. However, the statistics of switching (i.e. the mean switching field and the variance of the switching field distribution) from 20 up to 400 K are in disagreement with a Néel-Brown model that assumes a temperature independent barrier height and anisotropy field. We introduce a modified Néel-Brown model that fits the experimental data in which we attribute a $T^{3/2}$ dependence to the barrier height and the anisotropy field due to the temperature dependent magnetization and anisotropy energy.

DOI: 10.1103/PhysRevB.88.100401 PACS number(s): 85.75.—d, 75.30.Gw, 75.60.Jk

Thermally activated magnetization reversal in thin film ferromagnets with perpendicular anisotropy is of great fundamental interest and has a direct impact on magnetic information storage technologies, such as magnetic random access memories. Important predictions for thermally assisted reversal under applied magnetic fields and spin torques in nanometer scale magnetic elements follow from the Néel-reversal under applied magnetic fields and spin torques in spin orientation in a uniaxial potential energy landscape.3–7

Recent spin-torque and thermally assisted switching studies in perpendicularly magnetized nanopillar spin valves have applied this macrospin model at room temperature. Experimentally obtained energy barrier heights were shown to be much lower than the uniaxial barrier height determined by the entire macrospin volume.5–10 Nevertheless, the switching distributions appear well described by overcoming a single energy barrier, whose height is related to an excited magnetic subvolume in the free layer element.11 This description is in good agreement with spin-torque switching results on 100-nm lateral size nanopillar devices and the underlying behavior has been observed in micromagnetic simulations as well as dynamic imaging measurements.12

In order to test the validity of this uniaxial model, temperature-dependent measurements of the switching statistics can be used to probe the barrier height. We present dynamical measurements of the switching field in all-perpendicular Co/Ni spin-valve nanopillars as a function of temperature. There is significant fundamental interest in determining the origin of the perpendicular magnetic anisotropy in Co/Ni.13,14 Consequently, the temperature dependence of the perpendicular anisotropy in Co/Ni is not well understood and could significantly influence the performance of Co/Ni nanopillars at elevated temperatures. This system is also of significant interest for magnetic information storage due to the highly tunable perpendicular anisotropy, high spin polarization, and relatively low damping compared to other multilayered magnets showing perpendicular anisotropy.

In this Rapid Communication we demonstrate that while the Néel-Brown model is adequate for switching field measurements taken at constant temperature, the temperature dependence of the mean switching field and switching distribution width cannot be adequately treated by this simple model. Nevertheless, we demonstrate the validity of the macrospin model by introducing a $T^{3/2}$ dependence to the barrier height and coercivity to the Néel-Brown model. This temperature scaling reflects the underlying temperature dependence of the saturation magnetization and anisotropy energy of the Co/Ni nanopillar. While this was previously noted in experimental studies of extended films,15 a careful in situ study of the switching field statistics is indispensable to determine the behavior of Co/Ni nanopillars and also to demonstrate that the macrospin model remains valid even in this more complex multilayered structure.

The Co/Ni nanopillars studied here are part of an all-perpendicular spin-valve device. Details on materials and sample preparation have been reported previously.16 The magnetic multilayered structure consists of a Pt(3 nm) / [Co(0.25 nm) / Pt(0.52 nm)] × 5 / Co(0.2 nm) / [Ni(0.6 nm) / Co(0.1 nm)] × 2 / Co(0.1 nm) hard reference layer and a Co(0.1 nm) / Co(0.1 nm) / Ni(0.6 nm)] × 4 / Pt(3 nm) free layer separated by a 4 nm Cu spacer layer patterned into 75-nm-diameter nanopillars. Measurements were taken in a closed-cycle cryostat between the poles of an electromagnet oriented perpendicular to the device plane and at temperatures ranging from 20 to 400 K. The reference layer magnetization switches for an applied field close to 1 T. Since no fields greater than 0.5 T are applied during the measurements, the reference layer is expected to remain stable. For all the experiments shown here the reference layer magnetization points along the direction of positive magnetic fields.

The magnetization of the free layer is probed indirectly with four-probe measurements of the differential resistance of the spin-valve device under a 50 $\mu$A excitation current using standard lock-in techniques. Figure 1 shows typical resistance versus applied perpendicular field hysteresis loops at room temperature and at 20 K. The sharp changes in resistance $\Delta R$...
layer element is therefore
\[ E(\theta) = K_1 \sin^2 \theta + K_2 \sin^4 \theta. \] (1)

This anisotropy function is used to derive parametric equations for the astroid boundary along the easy axis (Z) and the hard axis (X):
\[ \mu_0 H_Z(\theta) = \frac{2K_1}{M_S} \cos^3 \theta \left(1 + \frac{6K_2}{K_1} \sin^2 \theta \right), \] (2)
\[ \mu_0 H_X(\theta) = \frac{2K_1}{M_S} \sin^3 \theta \left(1 + \frac{2K_2}{K_1}(3 \sin^2 \theta - 2) \right). \] (3)

From the best-fit curve to our data, we extract the perpendicular anisotropy field \( \mu_0 H_K = \mu_0 H_Z(0) = 305 \) mT and extrapolate the in-plane asymptote \( \mu_0 H_Z(\pi/2) = 453 \) mT. These two values allow us to estimate the first- and second-order anisotropy energies \( K_1 = 9.2 \times 10^4 \) J/m\(^3\) and \( K_2 = 2.2 \times 10^6 \) J/m\(^3\), assuming that \( M_S = 600 \) kA/m. The presence of second-order anisotropies in Co/Ni multilayered films has been previously investigated using ferromagnetic resonance methods, and their presence in spin-valve devices has been predicted as the source of symmetry breaking in the current-field state diagram.\(^{17-19}\) This result is also a strong indication of the significance of the high uniaxial barrier to reversal, and the extracted zero-temperature \( \mu_0 H_K = 305 \) mT will be used subsequently in expressions for the energy barrier.

Thermally assisted escape of a nanomagnet’s magnetization from a metastable state can be described by an Arrhenius law: \( \Gamma = \Gamma_0 \exp(-\frac{\mu_0 H_K}{k_B T}) \), where \( k_B \) is Boltzmann’s constant, \( T \) is the temperature, \( \Gamma_0 \) is in the range of 1–10 GHz, and \( E(H) \) is a field-dependent energy barrier. From this escape rate, we can have the survival probability of a metastable state after time \( t \): \( P(t) = \exp(-\Gamma t) \). The above expression assumes a model system described by a single field-dependent energy barrier, for which we use the following expression:
\[ E(H) = E_B (1 - H/H_K)^\eta = E_B \varepsilon^\eta. \] (4)

The expression describes the energy barrier in terms of a barrier height \( E_B \), the anisotropy field \( H_K \), and \( \eta \), an exponent that rapidly decreases from 2 to 1.5 under a small misalignment between the external magnetic field and the easy axis of the ferromagnet; we will take 1.5 as the value for \( \eta \).\(^{20,21}\)

To test the single barrier model, we have conducted switching field measurements as a function of temperature. Switching field measurements constitute applying a linear magnetic field sweep and recording the field at which the magnet reverses, which for our spin-valve pillars is defined by a step change in device resistance as seen in Fig. 1.\(^{8,22}\) Thermal activation predicts a characteristic distribution of switching fields sensitive to the sweeping rate and the temperature. For modeling our switching field measurements, we follow the change of variable introduced by Kurkijärvi to transform the survival time expression into a survival probability versus field under a linearly ramped magnetic field \( (\upsilon = dH/dt = \text{const}) \). Taking the derivative of the probability with respect to time, we have \( dP/dt = -\Gamma \exp(-\Gamma t) = -\Gamma P \).\(^{23}\) Rearranging terms, we have \( dP/dt = -\Gamma dt \), from which we apply the change of variable \( dt = dH/\upsilon \) and obtain \( \frac{dP}{P} = -\frac{1}{\upsilon} \Gamma dH \). Finally, we integrate this expression to get this final expression of the
survival probability as a function of field:

\[ P_{NS}(H) = \exp \left\{ -\frac{\Gamma_0}{V} \int_0^H \exp \left[ -\frac{E(H')}{k_BT} \right] dH' \right\}. \quad (5) \]

Correspondingly, the switching probability as a function of field is given in terms of the derivative of the survival probability \( p(H) = \frac{dP_{NS}}{dH} \).

For each temperature we conducted 100 switching field measurements under a field sweeping rate of 50 mT/s, from which we determined \( \mu_0 H_0 \), the mean switching field, and \( \sigma \), the variance of the switching field distribution. Figure 3 displays the temperature dependence of the mean switching field and switching variance from 20 to 400 K. According to our thermal activation model, the mean switching field and switching variance should follow the following expressions valid in the high barrier limit (\( \xi = E_B/k_BT \gg 1 \)):\(^{24,25}\)

\[ \overline{H} \cong H_K \left( 1 - \left[ \xi \ln \left( \frac{\Gamma_0 H_0}{\eta \nu \xi e^{-\eta/\nu}} \right)^{1/\eta} \right] \right), \quad (6) \]

\[ \sigma \cong H_K \frac{1}{\eta} \left( \frac{1}{\xi} \right)^{1/\eta} \left[ \ln \left( \frac{\Gamma_0 H_0}{\eta \nu \xi e^{-\eta/\nu}} \right)^{(1-\eta)/\eta} \right]. \quad (7) \]

Assuming an attempt frequency of \( \Gamma_0 = 1 \text{ GHz} \) and an exponent \( \eta = 1.5 \), for a sweeping rate of \( \nu = 50 \text{ mT/s} \) and an experimentally determined anisotropy field \( (\mu_0 H_K = 305 \text{ mT}) \) from Fig. 2, we obtain a best fit to the mean switching field for a barrier height of \( E_B/k_B = 20700 \text{ K} \). It is clear qualitatively from Fig. 3(a) that the mean switching field data is poorly fit by the green hashed line, and that Fig. 3(b) definitely does not agree with this best-fit parameter.

Recent results on the saturation magnetization and anisotropy energy of similar Co-Ni multilayered films demonstrated a strong temperature dependence and low Curie temperature (435 K).\(^{15}\) It has been demonstrated that the Bloch law temperature dependence for the saturation magnetization provides a good description for magnetic thin films composed of Co-Ni multilayers even at temperatures in excess of 90% of the Curie temperature.\(^{26,27}\) Furthermore, \textit{ab initio} calculations suggest that the temperature dependence of uniaxial perpendicular anisotropy energy in single crystals and in sputtered films scales with the magnetization squared \((M^3)\).\(^{28,29}\) Equation (4) for the energy barrier therefore may have an implicit dependence on the magnetization and anisotropy:

\[ E_B(T) = K(T)V - \frac{1}{2} \mu_0 M_S^2(T)V, \quad (8) \]

\[ H_K(T) = \frac{2K(T)}{M_S(T)} - \mu_0 M_S(T), \quad (9) \]

\[ K(T) = K(0) \left( \frac{M_S(T)}{M_S(0)} \right)^2, \quad (10) \]

where \( V \) is the activation volume, \( M_S \) is the saturation magnetization, and \( K \) is the uniaxial anisotropy energy. We attribute a \( T^{3/2} \) temperature dependence of the magnetization to the Bloch law. This temperature dependence of the magnetization implicitly couples into the expressions for the barrier height and anisotropy field. Our expressions up to \( O(T^{3/2}) \) in temperature are sufficient to fit the entire dataset:

\[ E_B(T) \sim E_B(0)(1 - 2B_0 T^{3/2}). \quad (11) \]

\[ H_K(T) = H_K(0)(1 - B_0 T^{3/2}). \quad (12) \]

\( B_0 = 2.5 \times 10^{-5} \text{ K}^{-3/2} \) was determined as a best-fit parameter for both the mean switching field and switching variance in Fig. 3 and is comparable to the prior result on the temperature dependence of the saturation magnetization in a Co-Ni film.\(^{15}\) The solid red lines in Figs. 3(a) and 3(b) demonstrate the best-fit mean switching field and switching variance trend lines as a function of temperature. We note that the increased variance at low temperatures (e.g., below 50 K) shown in Fig. 3(a) deviates from the modified Néel-Brown model, but does not reflect a limitation of our model’s scope. Instead, this is a device-related effect in which changes in the field from the second ferromagnetic layer leads to bimodal switching distributions at low temperatures and is the subject of an ongoing investigation. In the inset of Fig. 3(a), we also demonstrate the fit of our model switching probability density curve to our switching field distribution at 200 K. Given our anisotropy field value of 305 mT, we extrapolate a zero-temperature barrier height of \( E_B(0)/k_B = 35000 \text{ K} \). From these values, we can determine a thermally activated subvolume of \( d \cong 48 \text{ nm} \), or approximately 41% of the estimated free layer volume, assuming a zero-temperature saturation magnetization of \( M_S \approx 600 \text{ kA/m} \).

We present additional confirmation of this model on a second nanopillar device in which we acquired statistics from
In summary, we have demonstrated the sensitivity of the temperature-dependent switching field measurements to the temperature-dependent material properties in Co/Ni multilayers. The data is consistent with a single energy barrier process described within the Néel-Brown model of magnetization reversal. Upon introducing a temperature dependence to the energy barrier, we demonstrate that the temperature evolution (50–400 K) of the mean switching field, switching field variance, and the survival function of Co/Ni multilayered nanopillars can be described by thermal activation over a single perpendicular anisotropy barrier. The agreement of our experimental data with this simple extension of the Néel-Brown model of magnetization reversal is also evidence of the temperature dependence of perpendicular anisotropy and magnetization in Co/Ni multilayered films.

The origin of the temperature dependence of the perpendicular anisotropy in Co/Ni may be expected to have a more complicated scaling, as magnetoelastic bulk and interfacial strains as well as band structure changes could all significantly impact the perpendicular anisotropy. This study points to the importance of a careful investigation of the relative influence and scaling of these parameters. Nevertheless, our model demonstrates that the Néel-Brown model with an energy barrier that is scaled appropriately with temperature can be generally applicable to spin-valve nanopillar devices in a way that predicts spin-valve performance across a broad range of temperatures.

This research was supported at NYU by NSF Grants No. DMR-1006575 and No. NSF-DMR-1309202, as well as the Partner University Fund (PUF) of the Embassy of France. Research at UL was supported by ANR-10-BLANC-1005 “Friends,” the European Project (OP2M FP7-IOF-2011-298060), and the Region Lorraine. Work at UCSD was supported by NSF Grant No. DMR-1008654.

*\[ \Delta = \frac{E_b(T)}{k_B T} \left[ 1 - \frac{H}{H_K(T)} \right]^{3/2}. \] (13)

Assuming the same temperature dependencies for \( E_B, H_K \) as in Eq. (12), we obtain \( E_B(0)/k_B = 41,000 \) K and 306 mT for the zero-temperature barrier height and anisotropy field, respectively. From these values, we determine a thermally activated subvolume of \( d \approx 52 \) nm, or approximately 48% of the estimated free layer volume, again assuming a zero-temperature saturation magnetization of \( M_S \approx 600 \) kA/m.

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