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Spin torque switching in perpendicular films at finite temperature

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We show how the phase diagram for spin torque switching in the case of perpendicular anisotropy is altered at nonzero temperature. The hysteresis region in which the parallel and antiparallel states coexist shrinks, and a new region of telegraph noise appears. In a small sample, the region of coexistence of a precessional and parallel state can disappear entirely. We show that the phase diagram for both zero and nonzero temperatures can be understood and calculated by plotting an effective energy as a function of angle. A combinatorial analysis is useful for systematically describing the phase diagram. © 2008 American Institute of Physics. [DOI: 10.1063/1.2839339]

I. INTRODUCTION

In this paper, we consider a thin film magnetic element with perpendicular anisotropy. The phase diagram for this system has been studied theoretically\textsuperscript{1} at zero temperature on the assumption of a homogeneous single domain, and experimentally.\textsuperscript{2} Some discrepancies appear to be due to inhomogeneities, but some may be due to the fact that the zero-temperature theory does not take into account thermal fluctuations. The latter effects can be calculated semianalytically within the single domain model, whereas inhomogeneity effects probably can only be dealt with numerically. Thus, in this paper, we will generalize the single-domain phase diagram to nonzero temperature; to the best of our knowledge, this has not been done previously.

In uniaxial symmetry, the energy depends only on the angle \( \theta \) of the magnetization from the easy axis,

\[
E(\theta) = M_s \left( \frac{1}{2} H_K^{\text{eff}} \sin^2 \theta - H_c \cos \theta \right),
\]

where \( M_s \) is the saturation magnetization, \( H_K^{\text{eff}} = H_K - M_s \) is the easy anisotropy, and \( H_c \) is an external field along the easy axis (normal to the film). Any discussion of spin torque dynamics begins with the Landau–Lifshitz (LL) equation\textsuperscript{3} for the time derivative of the magnetization \( \mathbf{M} \), sometimes loosely referred to as “torque.” The LL equation has a precession term which contributes only to the azimuthal component \( M_\phi \) and does not change the energy; the changes in energy are controlled by the \( \theta \) component,

\[
\dot{M}_\phi = M_\phi \dot{\theta} + \gamma \sin \theta \left( \alpha M_s [H_K^{\text{eff}} \cos \theta + H_c] + J M_s \frac{\sin \theta}{1 + B \cos \theta} \right),
\]

where \( \gamma \) is the gyromagnetic ratio. The first term (proportional to the LL damping parameter \( \alpha \)) controls damping and pushes \( \mathbf{M} \) toward the easy axis, and the second (spin torque) term scales with a parameter \( J \) proportional to the current \( \dot{\theta} \).

II. EFFECTIVE ENERGY

Defining an effective energy in the presence of spin torque is nontrivial since only the precession term in the Landau–Lifshitz equation conserves energy; the damping and spin torque terms are nonconservative.

The most rigorous way to derive an effective energy is by finding a steady state solution of the Fokker–Planck equation,\textsuperscript{5} which has the form \( \text{exp}(-E_{\text{eff}}/k_B T) \), where

\[
E_{\text{eff}} = M_s \left[ \frac{1}{2} H_K^{\text{eff}} (1 - \cos^2 \theta) - H_c \cos \theta \right] - J \frac{\alpha B}{\gamma} \ln(1 + B \cos \theta).
\]

It is worth noting, however, that Eq. (3) can be obtained heuristically; in this special case of uniaxial symmetry, if we compute the “work” done against the torque [Eq. (2)], the result is proportional to the effective energy: \(-J M_d \dot{\theta} = \alpha \gamma E_{\text{eff}}\).

We will use a nondimensional form \( e_{\text{eff}} = E_{\text{eff}} / \mu_0 H_K^{\text{eff}} M_s \) of the effective energy,

\[
e_{\text{eff}} = \frac{1}{2} (1 - u^2) - hu - \frac{j}{B} \ln(1 + Bu),
\]

where \( u = \cos \theta \), \( h = H_c / H_K^{\text{eff}} \), and \( j = J / \alpha B H_K^{\text{eff}} \).

III. ZERO-TEMPERATURE PHASE DIAGRAM

The behavior of Eq. (4) for various values of field and current is shown in Fig. 1. The only free parameter is the Slonczewski parameter \( B \), which we have taken to be 0.5 in the figures. The horizontal and vertical axes are the dimensionless magnetic field and current, \( h \) and \( j \), and at each point of a \( 3 \times 3 \) grid there is an inset graph showing the effective energy as a function of \( u = \cos \theta \), at the field and current corresponding to the center of the inset. The center graph, at zero field and current, shows only the anisotropy energy \(-u^2/2\), a parabola. At this point, there are two stable states.
[minima of $e(u)$ at $u=\pm 1$—note that $e(u)$ need not be flat at minima that lie at the boundaries of the physical region $-1 < u = \cos \theta < 1$. Thus, in this region of the phase diagram, both the parallel (cos $\theta = 1$) and antiparallel (cos $\theta = -1$) states are stable, so we have labeled it AP & P.

If we move to the right from the center of Fig. 1, we add the Zeeman term $-hu$, which simply shifts the parabola to the left so its maximum is outside the physical region, and there is only one (parallel) minimum at $u = 1$, and we have crossed a phase boundary (red circles) to the P region where only the parallel state is stable. At this boundary, the maximum is just leaving the physical region at $u = -1$, i.e., $de(u = -1)/du = 0$. On the left, at $h = -3.0$, the parabola shifts in the opposite direction (right)—the maximum passes out of the physical region at the black (square symbols) phase boundary, where $de(u=1)/du = 0$, and only the AP state is stable.

Moving up from the center of Fig. 1 (increasing the scaled current to $j = 2.5$), the effective-energy inset graph includes the logarithmic spin-torque term $-\ln(1 + Bu)$. This has a divergence at $u = -1$/$B = -2$, outside the physical region, but starts to rise at the left as seen in the top center inset. This mimics the effect of a positive field $h$ at the left enough to create a minimum away from the $u = \pm 1$ boundaries, physically corresponding to a precessional state—thus this region of the phase diagram is labeled PS. The effective energy in the remaining small sliver of the phase diagram, between the curved line (blue triangles) and the straight phase boundaries, is shown as a tenth inset—both the precessional and parallel states are stable, so this region is labeled PS & P.

Making the current negative (bottom center inset) causes a decrease in energy at the left side of the inset, mimicking a negative field. The only minimum is now the AP (left) minimum, and the system is below the black (squares) phase boundary in the AP region. At the lower left, adding a real negative field further stabilizes the AP state. Moving to the lower right (positive field) restores the $u = 1$ (parallel) minimum and returns us above the black phase boundary to the AP & P region.

IV. SYSTEMATIC COMBINATORIAL CONSTRUCTION OF PHASE DIAGRAM

It is not obvious from the above approach to the phase diagram how many regions there can be. We now enumerate the regions more systematically. The physical behavior depends on the number and position of extrema of the effective energy $e(u)$. The condition $de/du = 0$ gives a quadratic equation for $u$, with two solutions $u^2 < u^+$ if $j < (B/4)(h - (1/B))^2$, i.e., below the parabola shown by blue triangles in Fig. 1. Above this parabola, there are no flat maxima or minima (as opposed to the boundary extrema at $u = \pm 1$), and the boundary minimum always occurs at $u = 1$: this region is a parallel (P) state. The lowest straight line [black squares, $j = -1/(1 + B)$] in Fig. 1 is where $de(u=1)/du = 0$, i.e., one of the extrema occurs at the right boundary, and the other straight line [circles (red) $j = -(h-1)/(1-B)$] has $de(u=-1)/du = 0$. Below the parabola, we classify the positions of the extrema relative to the boundaries $u = \pm 1$ of the physical region by a four-character string such as $|x|$, where the vertical lines represent $u = -1$ and $u = +1$, respectively, and the the $x$’s represent the minimum and the maximum (in that order). There are exactly $\binom{2}{1} = 4/2! = 6$ ways to pick two of the four positions for $x$, i.e., to order these four characters; if we add the string $||$ to represent the P region without extrema, these are exactly the seven light gray (yellow) circles in Fig. 2, a distorted cartoon of the phase diagram. The boundary between each adjoining pair of regions (light circles) is labeled by a darker gray circle (blue) with a string in which two of the symbols are superposed.
(e.g., $\times\times$, where $\times$ indicates a $|$ and $\times$ superposed, near the bottom center of Fig. 2, means that there is an extremum at the left boundary $u=-1$; there the $|$ and $\times$ pass each other, converting $[\times\times]_1$ into $[\times\times]_2$). Each boundary similarly involves the crossing of two symbols, except that $|$ and $\times$ cannot cross, and $\times$ and $\times$ “cross” only when they merge—beyond this boundary (the distorted parabola), there is no minimum or maximum. At the intersections of boundaries (darkest gray circles, green), there are two coincident symbols: at the rightmost intersection, $\times$ crosses $\times\times$ at that point the minimum and maximum annihilate at $u=-1$.

V. PHASE DIAGRAM AT NONZERO TEMPERATURE

At nonzero temperature, the system will not remain in a well with a very low barrier. If we assume an Arrhenius–Néel model for the switching rate with a prefactor $\nu$, an experimental time scale $\tau$, and an experimental temperature $T$, the critical value (call it $e$) of the dimensionless barrier $\Delta e$, below which a well is not stable, is given by $\tau \nu \exp(-\mu_0 H_K^2 M_s V_e/k_B T)=1$; here, we use the value 0.03 for $\epsilon$. Only three of the regions have barriers that can trap the magnetization: $[\times\times]$, $[\times\times]$, and $[\times\times]$. The energy $e(u)$ is sketched in Fig. 2 in each of these regions, showing the barriers at the left (L), middle (M), and right (R). The zero-$T$ phase boundaries (solid lines) are where $L=0$, $M=0$, and $R=0$. The dashed lines where $L=\epsilon$, etc., are the $T>0$ phase boundaries. For example, in the center of Fig. 2 between the $M=0$ and $M=\epsilon$ labels, the parallel and precessional states are both stable at zero temperature, but at $T$ the precessional state will jump the M barrier and only the parallel state is stable—thus, this point is effectively in the P region, and the boundary moves down to the dashed curve.

The actual $T>0$ phase diagram is shown in Fig. 3. It is topologically equivalent to the cartoon, but because the boundary shifts are very small in places, the topology is easier to see in the cartoon. The main result is that the P & PS coexistence region shrinks, and a region of telegraph noise appears near its boundary.

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