Bimodal switching field distributions in all-perpendicular spin-valve nanopillars

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Switching field measurements of the free layer element of 75 nm diameter spin-valve nanopillars reveal a bimodal distribution of switching fields at low temperatures (below 100 K). This result is inconsistent with a model of thermal activation over a single perpendicular anisotropy barrier. The correlation between antiparallel to parallel and parallel to antiparallel switching fields increases to nearly 50% at low temperatures. This reflects random fluctuation of the shift of the free layer hysteresis loop between two different magnitudes, which may originate from changes in the dipole field from the polarizing layer. The magnitude of the loop shift changes by 25% and is correlated to transitions of the spin-valve into an antiparallel configuration.

Magnetization reversal in nanopillar spin-valves with all-perpendicular magnetizations has a direct impact on magnetic information storage technologies, such as magnetic random access memories. Composed of ultrathin magnetic multilayers with tunable perpendicular anisotropy, spin-valves with lateral sizes down to tens of nanometers are being produced that are thermally stable at room temperature, with low critical switching currents. This geometry also gives rise to an out-of-plane dipole field from the polarizer, which can shift the center of the free layer minor hysteresis loop by a considerable fraction of the room temperature coercive field and has been shown to cause asymmetric reversal behavior for antiparallel to parallel (AP → P) and P → AP transitions.

We have recently investigated the thermally activated reversal of 75 nm spin-valve nanopillars to probe the barrier height to magnetization reversal. Here we report measurements of the distribution of switching fields by conducting over 1,000 free layer hysteresis loops under a linearly swept magnetic field as a function of temperature. The switching field distributions at low temperatures (below 100 K) reveal the onset of a bimodal switching field distribution (compare Figs. (b) & (c)). The bimodal switching distributions lead to the marked increase in switching field variance at low temperatures, as shown in Fig. (a). This behavior is inconsistent with a single energy barrier process described within the Néel-Brown model of magnetization reversal.

In this paper we show that random fluctuations of the center of the free layer hysteresis loop are the source of the second mode. The coefficient of correlation between AP → P and P → AP switching fields increases with decreasing temperature, suggesting that changes in the loop shift become more significant at lower temperatures. Finally, we present further details at a representative temperature (70 K) in which we show the rate at which the hysteresis loop shift telegraphs between two values and indicate that changes in the shift occur more frequently following the P → AP transition. We conjecture that this could be due to changes in the magnetization of the second ferromagnetic layer (polarizer) induced by the free layer switching.

The 75 nm diam nanopillars studied here are part of an all perpendicular spin-valve device consisting of a Co/Ni free layer and a Co/Ni and Co/Pt multilayered polarizer layer separated by a 4 nm Cu spacer. Details on materials and sample preparation have been reported previously.

FIG. 1. (a) Temperature dependence of the switching field variance. The blue points are the experimental data and the red curve indicates the best-fit curve from the Néel-Brown thermal activation (TA) model. (b) Switching field histogram used to obtain variance at T=293 K with best-fit curve from TA model. (c) Histogram at T=70 K showing bimodal switching distribution with best-fit curves from TA model.
FIG. 2. Sequential hysteresis loops of the free layer element of a 75 nm-diam nanopillar spin-valve at T=70 K. The first hysteresis loop (wide broken blue line) is more offset from zero applied field than the subsequent loop (narrow broken red line).

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 K - 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.

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 µA excitation current using standard lock-in techniques. Figure 2 shows two sequential resistance versus applied perpendicular field hysteresis loops at 70 K. The sharp changes in resistance indicates switching of the free layer into a parallel or antiparallel configuration with the reference layer. The approximately 85 mT shift of the center of the hysteresis loop denoted by the wider broken blue line drops to 65 mT in the immediately subsequent hysteresis loop denoted by the more narrow broken red line. These two distinct loop shifts are the source of the bimodal switching histogram in Fig. 1(c) and persist down to the lowest temperatures.

We present broader confirmation of this phenomenon by investigating the correlation between AP → P and P → AP switching fields with decreasing temperature. Figure 3 displays the correlation coefficient $\rho_{P,AP}$ for switching into the P and AP states as a function of temperature. The trend shows an increased correlation with decreasing temperature.

$\rho_{P,AP} = \frac{\sum_{i=1}^{n}(H^P_i - \bar{H}^P)(H^{AP}_i - \bar{H}^{AP})}{(n-1)\sigma_P \sigma_{AP}}$,  \hspace{1cm} (1)
The appearance of bimodal switching field distributions in nanopillar spin-valves reduces the reliability of device operation. For devices requiring efficient operation of spin-torque-induced switching, devices must be designed with narrow switching distributions. Changes in the loop shift adds noise to the system that can exceed the contribution of other random sources. Substantial changes in the magnitude of the loop shift may also reflect changes in the thermal stability of the free layer element in a way that could compromise device performance.

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1. A. D. Kent, Nature Materials 9, 699 (2010).
2. A. Brataas, A. D. Kent, and H. Ohno, Nature Materials 11, 372 (2012).
3. S. Mangin, D. Ravelosona, J. A. Katine, M. J. Carey, B. D. Terris, and E. E. Fullerton, Nature Materials 5, 210 (2006).
4. S. Mangin, Y. Henry, D. Ravelosona, J. A. Katine, and E. E. Fullerton, Applied Physics Letters 94, 012502 (2009).
5. S. Ikeda, K. Miura, H. Yamamoto, K. Mizumura, H. D. Gan, M. Endo, S. Kanai, J. Hayakawa, F. Matsukura, and H. Ohno, Nature Materials 9, 721 (2010).
6. D. P. Bernstein, B. Braeuer, R. Kukreja, J. Stoehr, T. Hauet, J. Cucchiara, S. Mangin, J. A. Katine, T. Tyliszczak, K. W. Chou, et al., Physical Review B 83, 180410 (2011).
7. D. B. Gopman, D. Bedau, S. Mangin, C. H. Lambert, E. E. Fullerton, J. A. Katine, and A. D. Kent, Applied Physics Letters 100, 062404 (2012).
8. D. B. Gopman, D. Bedau, G. Wolf, S. Mangin, C. H. Lambert, E. E. Fullerton, J. A. Katine, and A. D. Kent, Physical Review B 88, 100401(R) (2013).
9. L. Néel, Annales Geophysicae 5, 99 (1949).
10. W. F. Brown, Physical Review 130, 1677 (1963).
11. W. Wernsdorfer, E. Orozco, K. Hasselbach, A. Benoit, B. Barbara, N. Demoncy, A. Loiseau, H. Pascard, and D. Mailly, Physical Review Letters 78, 1791 (1997).
12. J. Z. Sun, L. Chen, Y. Suzuki, S. S. P. Parkin, and R. H. Koch, Journal of Magnetism and Magnetic Materials 247, L237 (2002).
13. T. Hauet, C. M. Guenther, B. Pfau, M. E. Schabes, J. U. Thiele, R. L. Rick, P. Fischer, S. Eisebitt, and O. Hellwig, Physical Review B 77, 184421 (2008).
14. M. Mohseni, R. K. Dumas, Y. Fang, J. W. Lau, S. R. Sani, J. Persson, and J. Akerman, Physical Review B 84, 174432 (2011).
15. X. M. Liu, P. Ho, J. S. Chen, and A. O. Adeyeye, Journal of Applied Physics 112, 073902 (2012).