AIP | Journal of Applied Physics

Systematic tuning of magnetization reversal in Permalloy nanowires using sloped ends

O. Petracic, D. E. Read, and R. P. Cowburn

Citation: J. Appl. Phys. **101**, 09F510 (2007); doi: 10.1063/1.2710958
View online: http://dx.doi.org/10.1063/1.2710958
View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v101/i9
Published by the American Institute of Physics.

Systematic tuning of magnetization reversal in Permalloy nanowires using sloped ends

O. Petracic,[a] D. E. Read, and R. P. Cowburn
Blackett Laboratory, Department of Physics, Imperial College London, London SW7 2AZ, United Kingdom

(Presented on 10 January 2007; received 31 October 2006; accepted 8 December 2006; published online 27 April 2007)

The magnetization reversal of Permalloy ($Ni_{81}Fe_{19}$) nanowires has been investigated by magneto-optic Kerr effect (MOKE) magnetometry, where one end of the wire exhibits a slope in the thickness. Straight nanowires with a thickness of 7.5 nm, widths of 150 nm, and length of 100 μm were prepared by electron-beam lithography. The sloped ends were achieved by using a penumbra shadow mask during NiFe deposition. The topography of the wires has been studied by atomic force microscopy. One finds that the slope profile can be tuned by the position under the mask, mask-to-sample distance, and angle of deposition. Corresponding MOKE hysteresis loops show a systematic reduction of the coercive field with increasing length of the sloped part. For example, wires where the slope has a length of 45 μm exhibit a coercive field of 11 Oe, whereas nanowires without sloped ends show 107 Oe. © *2007 American Institute of Physics*.
[DOI: 10.1063/1.2710958]

Ferromagnetic (FM) nanowires moved into the focus of intense experimental and theoretical studies due to their increased importance for both applications and fundamental investigations.[1] They not only promise to be building blocks in modern devices, e.g., in magnetic logic,[2] magnetic data storage, and spintronics,[3] but also gained huge interest in recent years in studies of current-induced domain wall (DW) motion.[4–10] One particular goal is the systematic control of DW nucleation and propagation and hence of the coercive or "switching" field H_c. Several groups investigated the influence, e.g., of material composition,[11] crystalline anisotropy,[12] width and thickness,[11] lateral shape of wire ends,[13,14] roughness,[15] or additional pinning sites.[16,17] In this article we present a method of tuning H_c by modifying the thickness profile of the nanowire. We show that it is possible to achieve a significant reduction of the coercive field by introducing a slope in thickness at one end of the wire.

Straight Permalloy nanowires with a thickness of 7.5 nm, width of 150 nm, and length of 100 μm were prepared by electron-beam lithography and subsequent lift-off on thermally oxidized Si(100) substrates. Each nanowire is at both ends laterally tapered.[2] Samples consist of an 8×14 array of identical wires, where each row is displaced horizontally relative to the other (see Fig. 1). During deposition of the NiFe film a penumbra shadow mask is used. This is a rectangular plate placed between the NiFe source and the substrate, which blocks the evaporated NiFe flux partially and hence creating a straight "shadow" boundary between a coated and an uncoated region on the substrate. The set of partially shadowed wires will thus exhibit a slope in the thickness with various lengths l_s of the sloped region.

Various arrangements of the shadow mask relative to the sample during deposition have been tested, i.e., the type of mask, mask-to-sample distance d, and tilt angle of the sample. The results reported in this article have been obtained on a sample without tilt and a straight scalpel blade as mask. The distance of the blade edge to the sample (resist) surface was $d=200$ μm. The thickness profile of wires has been recorded using atom force microscopy (AFM). Corresponding magnetization hysteresis curves on single nanowires were obtained by a high-resolution magneto-optic Kerr effect (MOKE) setup[18] at room temperature.

Figure 2 shows AFM profile scans over three different nanowires: No. 0 [plots (a) and (b)], 2 [(c) and (d)], and 4 [(e) and (f)]. Plots at the left hand side correspond to wire ends pointing away from the shadow mask and at the right hand side to those near or beneath the mask, respectively. Increasing wire numbers correspond to wires with a greater fraction covered by the mask. The left hand side end of each wire displays a sharp and squarelike profile [(a), (c), and (e)], whereas the profile at the opposite end [(b), (d), and (f)] strongly depends on how much it is covered by the mask. Wire 0 shows a steep edge at both ends and hence being without slope. However, wires 2 and higher exhibit a thickness profile. Two different slopes can be identified. First, a relatively steep one over a length of $l_1\approx5$ μm with a thickness change of $\Delta t\approx5$ nm. This slope seems to be similar for wires 2 and higher. Obviously this region is the immediate shadow boundary of the mask. An estimation of the expected length of the sloped region matches well with the measured

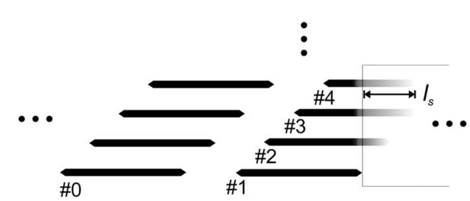

FIG. 1. Schematic subset of the 8×14 array of nanowires. A shadow mask (white rectangle) covers the array partially. A slope in the thickness with length l_s is symbolized by the gray shading.

[a]Electronic mail: o.petracic@imperial.ac.uk

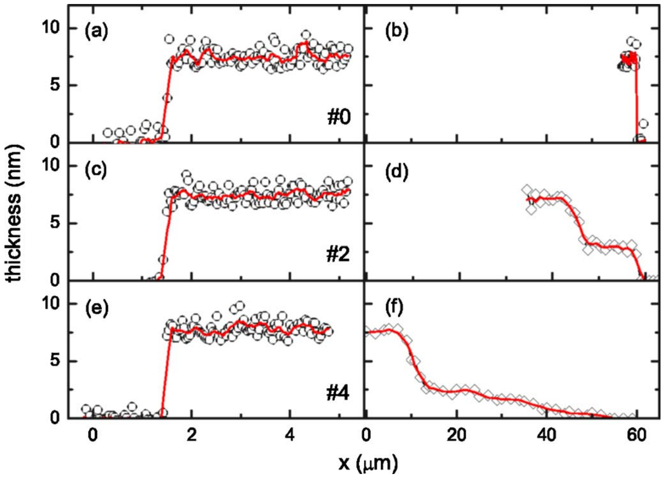

FIG. 2. AFM profile scans over three different nanowires: 0 [(a) and (b)], 2 [(c) and (d)], and 4 [(e) and (f)]. Plots at the left hand side correspond to wire ends pointing away from the shadow mask and at the right hand side to those near or beneath the mask, respectively. The circles correspond to 5 μm long AFM line scans and the diamonds to data collected from several cross-sectional line scans. The lines are guides to the eye.

value, i.e., $l_1(\text{expected}) \approx db/a \approx 4\ \mu$m, where $d=200\ \mu$m is the distance of the mask to the sample surface, $b=10$ mm the diameter of the Permalloy source crucible, and $a \approx 55$ cm the distance from the source to the mask.

The second slope is more shallow and extends even over a length of $l_2=40\ \mu$m, as seen from Fig. 2(f). For wire 2 this region terminates at the expected end of the wire [Fig. 2(d)]. We assume that this slope is due to elastic and inelastic collisions of the Ni and Fe atoms with the mask during deposition. A scattering at residual gas atoms can be excluded considering the relatively low base pressure of 2×10^{-7} Torr.

The appearance of two distinct slopes can be avoided, if the sample is tilted during deposition in such a way that the gap between the mask and the sample points away from the NiFe source. We tested this geometry for an angle of 30° and achieved only one and almost linear slope with an overall length of $l_s=25\ \mu$m.

For each nanowire individual hysteresis curves have been recorded. Figure 3 shows the longitudinal MOKE signal (L-MOKE) versus applied field along the wire axis for

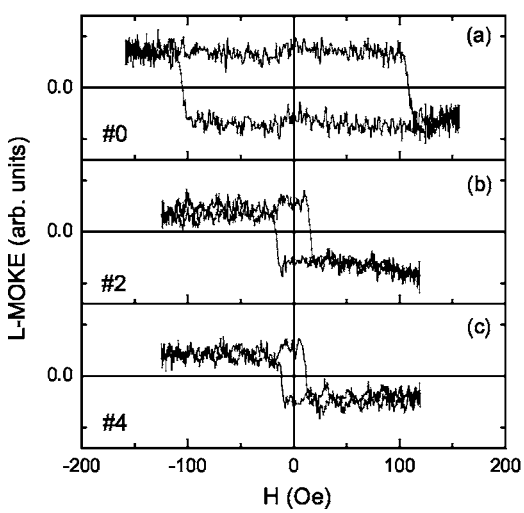

FIG. 3. MOKE hysteresis loops of wires 0 (a), 2 (b), and 4 (c).

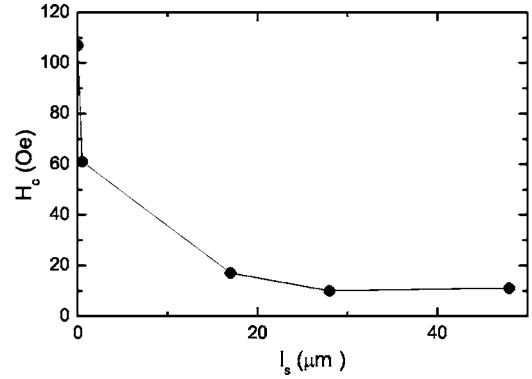

FIG. 4. Coercive field H_c of wires 0–4 vs overall length of the slope, $l_s = l_1 + l_2$. The line is a guide to the eye.

wires 0, 2, and 4. In all three cases [(a)–(c)] a squarelike hysteresis curve is found, indicating switching by DW motion. While wire 0 shows a coercive field of $H_c=107$ Oe, the values for 2 and 4 are reduced to 17 and 11 Oe, respectively.

A plot of H_c as function of the overall slope length, $l_s = l_1 + l_2$, is shown in Fig. 4. The H_c value decreases with increasing l_s and then levels off at $H_c=10$ Oe for $l_s > 25\ \mu$m. This behavior is to be expected since previous studies[11] revealed $H_c = c + 3M_s t/w$, where t is the thickness, w the width of the nanowire, M_s the saturation magnetization in cgs units, and c a constant near zero. Consequently, a reduced thickness at one end of the wire will result in a reduced DW nucleation field and hence a reduced H_c. Using the above expression a value of $t=7.5$ nm yields $H_c = 120$ Oe, which corresponds well to the measured value of 107 Oe for the wire without slope. On the contrary, if a slope is present nucleation will occur at the thinnest part first. In the case of wire 2 one finds from Fig. 2(d) $t_{\text{end}} \approx 2.5$ nm, which yields the too large value $H_c=40$ Oe. For wire 4 the terminal thickness is even zero. Further investigations beyond this simplified picture are necessary, where a deeper understanding of the nucleation process in the sloped region using micromagnetic simulations has to be gained.

In conclusion, we have investigated the magnetization reversal in patterned magnetic nanowires, where one end exhibits a slope in the thickness. By using a penumbra shadow mask during Permalloy deposition one creates two sloped regions. One finds a systematic reduction of the coercive field with increasing length of the slope. This shows that modifying the thickness profile is a very effective means of tuning the switching properties of nanowires and probably generally of nanostructures.

[1] J. I. Martin, J. Nogues, K. Liu, J. L. Vicent, and I. K. Schuller, J. Magn. Magn. Mater. **256**, 449 (2003).
[2] D. A. Allwood, G. Xiong, C. C. Faulkner, D. Atkinson, D. Petit, and R. P. Cowburn, Science **309**, 1688 (2005).
[3] S. A. Wolf, D. D. Awschalom, R. A. Buhrman, J. M. Daughton, S. von Molnar, M. L. Roukes, A. Y. Chtchelkanova, and D. M. Treger, Science **294**, 1488 (2001).
[4] N. Vernier, D. A. Allwood, D. Atkinson, M. D. Cooke, and R. P. Cowburn, Europhys. Lett. **65**, 526 (2004).
[5] M. Yamanouchi, D. Chiba, F. Matsukura, and H. Ohno, Nature (London) **428**, 539 (2004).
[6] A. Yamaguchi, T. Ono, S. Nasu, K. Miyake, K. Mibu, and T. Shinjo, Phys. Rev. Lett. **92**, 077205 (2004).
[7] M. Kläui *et al.*, Phys. Rev. Lett. **94**, 106601 (2005).

[8]D. Ravelosona, D. Lacour, J. A. Katine, B. D. Terris, and C. Chappert, Phys. Rev. Lett. **95**, 117203 (2005).
[9]G. S. D. Beach, C. Knutson, C. Nistor, M. Tsoi, and J. L. Erskine, Phys. Rev. Lett. **97**, 057203 (2006).
[10]L. Thomas, M. Hayashi, X. Jiang, R. Moriya, C. Rettner, and S. S. P. Parkin, Nature (London) **443**, 197 (2006).
[11]W. C. Uhlig and J. Shi, Appl. Phys. Lett. **84**, 759 (2004).
[12]J. P. Jamet, J. Ferré, P. Meyer, J. Gierak, C. Vieu, F. Rousseaux, C. Chappert, and V. Mathet, IEEE Trans. Magn. **37**, 2120 (2001).
[13]K. Shigeto, T. Shinjo, and T. Ono, Appl. Phys. Lett. **75**, 2815 (1999).
[14]T. Schrefl, J. Fidler, K. J. Kirk, and J. N. Chapman, J. Magn. Magn. Mater. **175**, 193 (1997).
[15]M. T. Bryan, D. Atkinson, and R. P. Cowburn, Appl. Phys. Lett. **85**, 3510 (2004).
[16]L. Thomas, C. Rettner, M. Hayashi, M. G. Samant, S. S. P. Parkin, A. Doran, and A. Scholl, Appl. Phys. Lett. **87**, 262501 (2005).
[17]D. Petit, A.-V. Jausovec, D. E. Read, and R. P. Cowburn, Phys. Rev. Lett. (submitted).
[18]D. A. Allwood, G. Xiong, M. D. Cooke, and R. P. Cowburn, J. Phys. D **36**, 2175 (2003).