Multimode switching induced by a transverse field in planar magnetic nanowires

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We report how transverse fields affect the axial field needed to "inject" domain walls from a large Permalloy ($Ni_{80}Fe_{20}$) pad into planar nanowires of width 184 nm, 303 nm, 321 nm, and 537 nm fabricated by electron beam lithography. For the narrowest wire, different switching fields are observed under the same transverse field conditions, indicating that more than one mode or state for the domain walls may exist. In contrast, in the widest wires a transverse field causes each reversal event to occur in two stages. The different response may be attributed to the magnetostatic energy differences of domain walls in wires of different widths. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2162263]

Research into the behavior of magnetic structures with key dimensions deep into the submicron regime has developed rapidly in recent years as such structures present opportunities to study underlying physical processes[1,2] as well as being of interest for potential technological applications.[3,4] For elongated planar structures, reversal via the propagation of head-to-head or tail-to-tail domain walls has been understood through micromagnetic modeling and domain wall propagation experiments.[5–7] Domain wall propagation can be controlled using structures with a larger area pad of magnetic material connected to a narrower nanowire of interest.[8] Such structures have been widely used for "injecting" domain walls into nanostructures.[7–11]

More recently, the presence of metastable magnetization states has emerged as a significant issue even in simple magnetic nanostructures. Experiments have shown that switching can be complex, with reversal dependent on the metastable magnetization configurations in rectangular and elliptical Permalloy structures subject to short axis fields.[12] In other investigations, electrical measurements and magnetic force microscopy (MFM) have shown that a domain wall can be pinned in a variety of different states at a notch in an elongated structure.[9,10] It has also been observed that multiple temperature-dependent switching fields can occur in a wire and pad structure with an oblique field.[11] Controlling such multiple modes is important for potential applications since reliable switching and a narrow switching-field distribution can be critical requirements for device operation.

Here we report the effect of transverse field on the magnetization reversal behavior of planar Permalloy nanowires which have a large nucleation pad at one end. The pad can generate magnetic domain walls that are injected into the narrower nanowire structure during the switching process.

L-shaped Permalloy ($Ni_{80}Fe_{20}$) planar nanowires were fabricated on a thermally oxidized silicon substrate with a gold underlayer by electron beam lithography and metallization using thermal evaporation followed by resist lift-off. At one end of each nanowire, a larger rectangular nucleation pad of Permalloy was fabricated. The other end was pointed to suppress domain wall nucleation[13] and resultant domain wall motion from this end. The four L-shaped wires studied had widths of 184 nm, 303 nm, 321 nm, and 537 nm, as measured by scanning electron microscopy (SEM). Each nucleation pad was 1.5 μm wide $\times$ 15 μm long. The structures were all 8 nm thick. The L-shape geometry was developed to study domain wall behavior more generally and is not strictly needed in these experiments.

Axial magnetization reversal was detected using a magneto-optical Kerr effect (MOKE) magnetometer, capable of detecting "single-shot" switching events,[14] although most measurements involve averaging of many field cycles to improve the signal to noise ratio. The switching behavior of both the nanowires and the associated nucleation pads were measured separately in the presence of different combinations of orthogonal magnetic fields applied within the plane of the magnetic structures, at room temperature. Figure 1 shows schematically the geometry of the samples, the orientation of magnetic fields H_x and H_y, and the MOKE laser beam location used in the measurements. H_x and H_y were applied at 27 Hz with an amplitude of 116 Oe and H_y^0, respectively. MOKE measurements were sensitive to switching

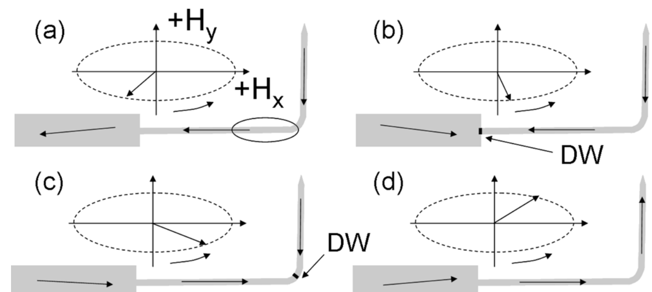

FIG. 1. A schematic of the nanowire structure showing the magnetic fields (H_x and H_y) and the magnetization states as a function of the counterclockwise rotating magnetic field from (a) to (d). The laser spot position for the MOKE measurements is indicated by the dotted ellipse in (a). DW denotes the domain wall position when a wall is present. Not to scale.

along the H_x axis. The phase of H_y (the transverse field) was shifted by $\pi/2$ with respect to H_x in order to generate a field vector (of varying amplitude) at the sample that rotated counterclockwise. A domain wall is formed at the junction between the pad and the wire when the pad magnetization is reversed [Fig. 1(b)]. As H_x increases, the wall propagates through to the corner and switches the horizontal arm of the nanowire [Fig. 1(c)]. As the field vector sweeps into the positive y-direction the wall is swept up through vertical section of the structure to complete the magnetization reversal [Fig. 1(d)]. In the subsequent part of the cycle, the process is repeated but this time the fields and the magnetization change have the opposite sign. In this way the reversal is always initiated from the nucleation pad and the domain wall is swept up the vertical section of the wire. Only for the counterclockwise rotating field do both switching events in the hysteresis loops represent reversal by domain walls propagating from the junction of the pad and wire. When $H_y^0=0$ or if a static field were applied along the y-axis, the reversal of an initially continuous magnetization will leave a domain wall at the corner of the structure. This wall can then propagate back towards the pad when the sign of H_x is reversed. Therefore, with $H_y^0=0$ Oe or a static y-axis field, only one side of the hysteresis loop represents reversal by domain walls propagating from the junction of the pad and wire. Switching using static fields was consistent with the results using the counterclockwise rotating field.

Figure 2 shows normalized axial MOKE hysteresis loops for 184 nm and 534 nm wide wires as a function of transverse fields with $H_y^0=0$ Oe, 34 Oe, 45 Oe, and 77 Oe, respectively. The loops are averaged over several hundred field cycles. For the 184 nm wire with $H_y^0=0$ Oe [Fig. 2(a)], the switching behavior is different under positive and negative fields, with a sharp switching event at negative fields and more slowly varying reversal at positive fields. This indicates that the laser spot is close to the corner and the switching is consistent with sharp switching from the pad at negative fields and back propagation of an existing wall from the corner at positive fields, as has been observed previously.[15]

Interestingly, when a moderate transverse field is applied [Fig. 2(b)], the switching transition occurs in multiple steps, with clear transitions around 42 Oe and 73 Oe. At higher transverse fields the switching becomes asymmetric with two steps at negative field and a single step at positive fields [Fig. 2(c)]. At still higher transverse fields [Fig. 2(d)], single-step magnetization reversal returns, but switching is sharper and at a lower field (35 Oe). By comparison, Figs. 2(e)–2(h) show similarly averaged axial hysteresis loops from a 537 nm wide wire. In the wider wire, two-step switching develops and becomes more pronounced at higher transverse fields [Figs. 2(g) and 2(h)], but not at lower fields [Figs. 2(e) and 2(f)]. Intermediate wire widths show aspects of both types of behavior, with reversal behavior more similar to the 537 nm wire for the wider wires.

In order to ascertain the nature of the multistep switching observed in the averaged loops, the MOKE magnetometer was set up to measure switching during a single field sweep. Figures 3(a) and 3(b) show two separate "single-shot" magnetization loops obtained from the 184 nm wide wire with $H_y^0=23$ Oe. The loops have a low signal-to-noise ratio as no averaging has taken place, but single switching events can still be seen in both loops. However, the switching events occur at markedly different fields of ±42 Oe [Fig. 3(a)] and ±78 Oe [Fig. 3(b)], suggesting two different modes for domain wall injection into the wire under nominally the same field conditions. Others loops for this sample showed that the injection mode could change during one field cycle;

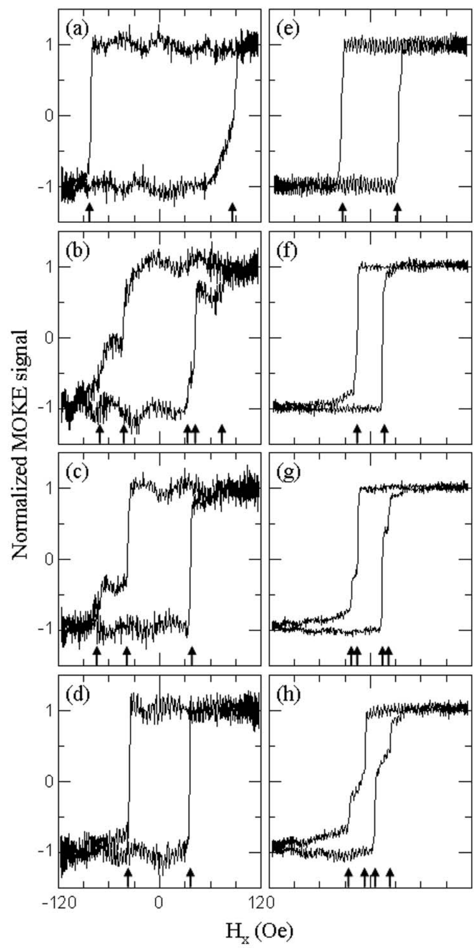

FIG. 2. Averaged magnetization hysteresis loops showing the switching fields of a 184 nm wide wire in transverse fields of amplitude 0 Oe, 34 Oe, 45 Oe, and 77 Oe (a–d) and a 537 nm wide wire in transverse fields of 0 amplitude Oe, 34 Oe, 56 Oe, and 77 Oe (e–h).

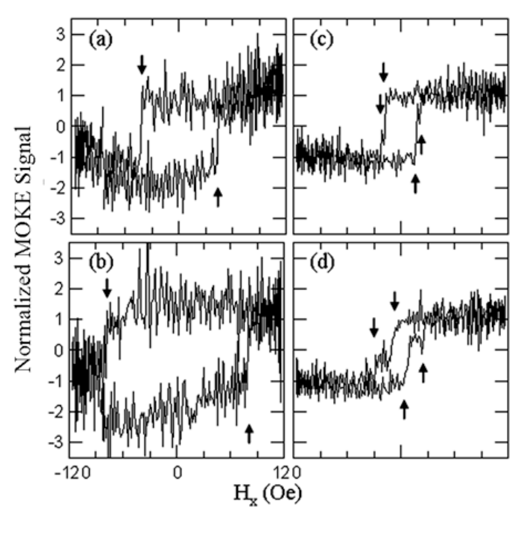

FIG. 3. "Single-shot" magnetization hysteresis loops showing: (a) and (b) two different switching fields in a 184 nm wide wire with the same amplitude transverse field (23 Oe) present in both and (c) and (d) two-stage switching in a 537 nm wide wire in transverse fields of amplitude 56 Oe and 86 Oe, respectively.

for example with one switch at a high positive field followed by another switch at a lower negative field. In all 15 of the single-shot loops recorded, reversal was always observed to involve a single sharp switch. In contrast to this, the widest wire shows two-stage switching in single field cycle measurements with $H_y^0=56$ Oe [Fig. 3(c)] and more clearly with $H_y^0=86$ Oe [Fig. 3(d)].

For the narrowest wire (184 nm wide), the switching measurements indicate that the addition of a magnetic field transverse to the axis of the wire and pad leads to more than one energetic state for the wall at the junction. These states or modes require different depinning fields to allow the wall to propagate through the junction and switch the wire.

Different modes for domain wall injection from a nucleation pad into a nanowire have been suggested previously.[11] There, the modes were identified with temperature-dependent domain structures within the nucleation pad, although it is interesting to note that the switching field used was applied at 30° to the pad-wire axis, so a transverse field component was present. Other studies[9,10] suggest that the depinning field and positioning of a domain wall in a constriction may be affected by the structure of the domain wall. On this basis, and considering that the pad can be saturated along the transverse (y-) axis with a field of about 50 Oe while the 184 nm wide wire is not saturated transverse to its long axis with fields up to 420 Oe, it is suggested that the application of a moderate transverse field leads to a situation where the domain wall formed at the pad-wire junction can have different forms or modes, each with different depinning fields, as observed. This variation may be largely due to the behavior of the pad, since the magnetization of the wire deviates much less from its long axis when a transverse field is applied. At higher transverse fields the magnetization in the pad is rotated more strongly and a single mode domain wall with a single switching field is obtained. Alternatively, the modal switching may be related to an interaction between the transverse field and the magnetization within the domain wall. A phase diagram of the switching field for each step in the averaged hysteresis loops of the 184 nm wire as a function of the instantaneous value of the transverse field (H_y) is shown in Fig. 4(a). The switching field of the wire initially decreases with increasing transverse field. Then around $H_y=10-20$ Oe, two modes of reversal occur. The switching fields of these modes fall with further increases of the transverse field until the switching abruptly becomes single mode again at approximately $H_y=45$ Oe (close to the hard axis saturation field of the pad).

The magnetization of the 537 nm wide wire is more sensitive to a transverse magnetic field than the narrowest wire, as its transverse saturation field is close to 150 Oe. In 38 single-shot observations of the switching transitions measured at high transverse fields, 28 involved a two-step reversal similar to that shown in Fig. 3(d). The phase diagram for this wire [Fig. 4(b)] shows switching fields at which each step in the averaged hysteresis loops occurs. We suggest that the change to two-step switching with a large transverse field may involve a field-induced transition to a vortex state[12] or perhaps a field-induced pinning event at the wire corner due to the sign of H_y opposing propagation around the corner at the instant of domain wall injection [Fig. 1(c)].

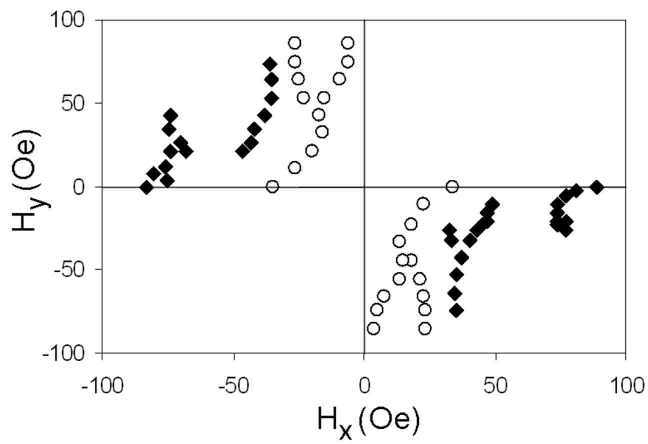

FIG. 4. Phase diagrams of the transverse, H_y, and longitudinal H_x, fields at the instant that switching steps occurs in the 184 nm wide wires (◆) and the 537 nm wide wires (○). Each step in a multistep switch is plotted separately.

The intermediate width wires display characteristics that are similar to both the widest and the narrowest wires, but with a smaller separation between the switching branches, supporting the interpretation that the shape anisotropy of a wire affects the depinning field from the pad-wire junction.

In conclusion, for the narrowest wire, different switching fields are observed under the same field conditions. These are attributed to different modes or states for the domain walls that are formed at the pad-wire junction. In the widest wires the transverse field leads to a change from simple switching to a vortexlike switching process. The different response may be attributed to the magnetostatic energy difference between the wide and narrow wires.

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