Effect of geometry on magnetic domain structure in Ni wires with perpendicular anisotropy: A magnetic force microscopy study

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We investigated the magnetic domain structure of thermally evaporated nickel wires with perpendicular anisotropy as a function of width and geometry. Magnetic force microscope images revealed the presence of stripe domains, which tended to orient themselves either perpendicular or parallel to the edges of the wires. This is in agreement with the result of the minimization of the total magnetic energy of a wire near an edge, which predicts the minima of energy in these two particular cases. The general orientation of the stripes in wider wires can be manipulated by using an in-plane external field, but the stripe orientation in the vicinity of the edge stays unaffected. A rough edge forces the stripe domains to orient themselves perpendicular to the edge, rather than parallel to it. In narrow wires, the stripe domains are parallel to the edge, and the width of the domain increases as the width of the sample is decreased in order to fit an integer number of domains in the wire.

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The magnetic domain structure in nanometer-scale magnetic elements strongly depends on the size and shape of the elements.[1] The magnetostatic energies associated with the edges of the sample become very important in small samples,[2–5] which allow their magnetic properties to be controlled by the geometry of the sample.[6–11] While most magnetic thin films have in-plane magnetic anisotropy due to the preponderance of the shape anisotropy, certain thin films have the less common perpendicular magnetic anisotropy (PMA),[12] such as thin films of Fe on Cu(100),[13] Co/Pt multilayers,[14] epitaxially grown magnetic thin films,[15] and thick single Ni crystals.[16] The control of the magnetic properties of materials with PMA is particularly relevant to perpendicular magnetic recording. There are only a handful of studies on the effects of geometry[17–20] in materials with PMA. A few recent studies focused on the dynamics close to the edges.[21,22] As is typically found for systems with PMA, these films are characterized by stripe domains, which reflect the periodic change of magnetization direction throughout the sample.[23] In this work, we study the effect of geometry on the orientation of magnetic stripe domains in thermally evaporated Ni wires. We find that the size and the orientation of the stripe domains depend on the lateral size of the wire, due to the fact that the edge effects start to dominate as the width of the wire is decreased.

Ni wires of various widths were prepared by using standard electron-beam lithography. The width of the wires ranged from 200 nm to 6 μm. Some Ni wires were deposited by electron-beam evaporation with a base pressure of 2×10^{-8} Torr and show similar results. The Ni wires were examined by using the magnetic force microscope (MFM) immediately after fabrication to determine the magnetic domain structure in their as-prepared state. MFM images were taken by using a Nanoscope III multimode atomic force microscope from Digital Instruments. A Veeco microetched silicon probe tip was magnetized along the tip axis by using a permanent magnet and used in the vibrating-lift mode. The tip was kept at a height between 30 and 50 nm above the surface of the sample. The MFM image of a set of wires of eight different widths is shown in Fig. 1. It is evident that the magnetic domains form stripes of dark and bright regions of opposite magnetizations. The stripe domains are typically observed in systems in which the magnetization is perpendicular to the plane of the substrate. Perpendicular anisotropy has been confirmed by the magnetometry measurements in thermally evaporated nickel films of similar thicknesses.

Figure 1 also seems to suggest that the orientation of the stripe domains depends on the width of the wire. In the widest wire [Fig. 1(a)], the stripes are randomly oriented and meander in the plane of the film. As the width of the wire is decreased, the stripe domains tend to orient themselves perpendicular to the long edge of the wire [Figs. 1(b)–1(d)]. As the width of the wire becomes comparable to the domain width, the stripes start to turn increasingly parallel to the edge of the wire [Figs. 1(e)–1(g)]. The thinnest wire [Fig. 1(h)] appears to contain only one domain.

The general orientation of the stripe domains can be understood by a closer examination of the stripes near the edges of the samples. Very close to the edge, the stripes are oriented either perpendicular or parallel to the edge, regardless of the stripe orientation in the bulk of the film. This behavior

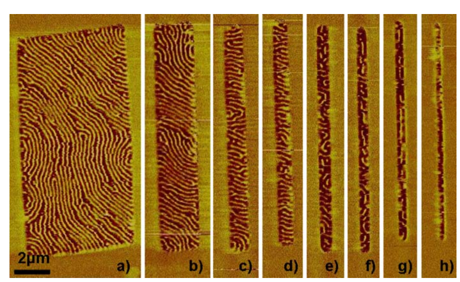

FIG. 1. (Color online) Magnetic force microscope images of thermally evaporated Ni wires showing stripe domains in their as-prepared state. The general orientation of the stripe domains changes as the width of the wire changes. (a) $w=6$ μm, (b) $w=2$ μm, (c) $w=1$ μm, (d) $w=800$ nm, (e) $w=600$ nm, (f) $w=400$ nm, (g) $w=300$ nm, and (h) $w=200$ nm.

is observed in all samples, independent of the width of the wire, as shown in Fig. 1.

The behavior of the stripe domains near an edge of a thin film was recently studied theoretically.[24] The minimization of the total magnetic energy of a thin magnetic film with perpendicular anisotropy yielded a stripe domain phase for a certain range of parameters, such as magnetic anisotropy and the applied field. In the vicinity of an edge, Clarke *et al.* found that the energy of the system strongly depended on the angle between the orientation of the stripe domain and the edge of the system. Specifically, the magnetic energy of the system has a local minimum when the stripe domains are perpendicular to the edge, and it approaches its maximum value when the stripes are almost parallel to the edge. However, when the stripes are exactly parallel to the edge, there is a sharp dip in the energy. The authors suggest that this might be the global energy minimum of the system, although the system is more likely to settle into the perpendicular configuration when starting from random stripe orientations. In other words, near the edge of the sample, stripe domains prefer to be either perpendicular or exactly parallel to the edge of the wire, with all other orientations being less favorable.

The strong effect of the edge on the orientation of the stripe domains brings up the question of edge roughness. One might expect that a very rough edge would force the domains to choose the perpendicular orientation, as it may not be energetically favorable for a domain to bend in order to follow a rough edge. Therefore, parallel edge domains might be expected more often in samples with very smooth edges. This is, indeed, what we observe when we vary the edge roughness by changing the thickness of the e-beam resist used in the sample fabrication process (a thicker resist resulted in smoother edges). Figure 2 shows two sets of Ni wires: one with the edge roughness on the order of the width of the stripe domains [Fig. 2(a)] and the other with the edge roughness much smaller than the width of the stripe domains [Fig. 2(b)]. The scanning electron microscope (SEM) images of the edges are shown in the insets. It is evident that the stripe domains in Fig. 2(a) are predominantly perpendicular to the edge of the strip. In contrast, there are many more domains that are parallel to the smoother edge in Fig. 2(b). In this case, the stripe domains can follow the edge without significantly deforming their shape, which would incur a cost in energy. When the edge roughness is of the order of the stripe domain width, the perpendicular configuration is much more energetically favorable.

It must also be noted that the stripe domains parallel to the edges are also observed more often when the width of the wire becomes comparable to a few stripe domain widths. Additionally, the stripe domains in this regime appear to be wider (this can be seen in Figs. 1 and 2). In order to investigate the width of the domains as a function of the wire width, we measured the domain width by taking the peak-to-peak distance of the MFM signal of the wires. The results are shown in Fig. 3. We find that the domain width does not depend on the width of the wire when the stripes run perpendicular to the edge. In narrow wires, as we have seen above, the domains tend to run parallel to the edge. When the width of the wire becomes comparable to a few typical domain widths, the domain period starts to depend on the width of

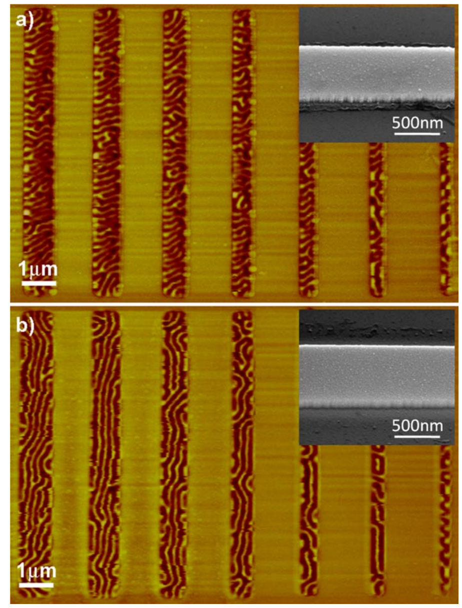

FIG. 2. (Color online) MFM and SEM images of two sets of Ni wires. (a) Stripe domains tend to align predominantly perpendicular to the edge of the wire when the edge is rough. (b) A much larger proportion of the stripe domains align parallel to the edge of the wire when the edge is smooth. Insets show SEM images of a representative wire (800 nm) from each set, with a visible difference in edge roughness. The edge roughness was varied by controlling the e-beam resist thickness. The scale bars in the SEM images apply only to the lateral distances due to the tilted stage angle of the SEM.

the wire: it increases with decreasing wire width. This occurs because the domains adjust their size in order to fit an integer number of domains in the width of the wire, which is obviously energetically more favorable than having only a fraction of a domain. In the wires in which the domains are perpendicular to the edge, this is not an issue, and the domain period is unaffected.

The as-prepared configuration of magnetic stripe domains appears to be stable over time. In order to investigate its response to magnetic fields, we have demagnetized the

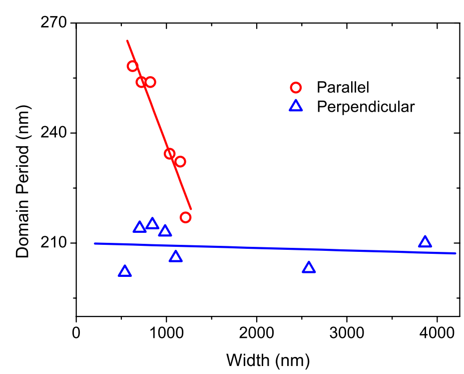

FIG. 3. (Color online) The dependence of the stripe domain period on the width of the wire. In narrow wires, the domain period decreases linearly with the width of the wire when the stripe domains run parallel to the edges (open circles). When the stripes are perpendicular to the edges, the domain period is not sensitive to changes in the width of the wire (open triangles).

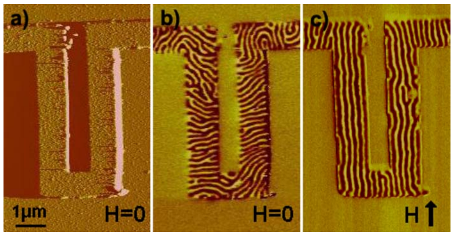

FIG. 4. (Color online) AFM and MFM images of a 100 nm thick and 1 μm wide Ni wire with four elbows. (a) Topographical image of the sample, (b) MFM image of the sample in the as-prepared state with no field applied, and (c) MFM image of the sample after the demagnetizing process with the field of 1 T applied parallel to the plane of the substrate, in the direction shown by the black arrow.

samples by applying a magnetic field with the maximum magnitude of 1 T parallel to the plane of the substrate. During the demagnetization process, the magnetic field is swept alternately between positive and negative values, while gradually reducing the field amplitude in each cycle. MFM images of a 100 nm thick U-shaped wire in its as-prepared state and after the demagnetization process are shown in Fig. 4. The topographical image of the sample is shown in Fig. 4(a). This geometry is particularly interesting because it combines five different sections that meet at right angles with respect to each other. In the as-prepared state, the stripe domains prefer to be perpendicular to the edges of the wire, as shown in Fig. 4(b). At each elbow of this structure, where the stripe domains meet at right angles, a competition between the two different orientations creates ripplelike domains. After the sample has been demagnetized with an in-plane field, the stripe domains clearly followed the direction of the applied field, regardless of their as-prepared configurations, as can be seen in Fig. 4(c). Additionally, when the sample was demagnetized by applying a magnetic field at 45° with respect to the edge of the wire, the stripes followed the field direction in the bulk of the wire, as shown in Fig. 5. However, near the very edge of the wire, the stripes remained perpendicular to the edge.

We found that the roughness of the edge and the geometry of the sample strongly affect the orientation of the stripe domains in thermally evaporated Ni wires. Our results are in excellent agreement with calculations of the total magnetic energy near an edge of a film with perpendicular magnetic anisotropy, which found that the stripe domains tend to be either perpendicular or parallel to the edge of the wire. This is true even in films and wide wires, in which the general orientation of the stripe domains in the bulk can be set in arbitrary directions by demagnetizing the sample using an external magnetic field applied parallel to the plane of the sample. As the lateral size of the wire is decreased, the proportion of the material that is in the vicinity of an edge increases, and the ordering effect of the edges is more pronounced. In a particular range of wire widths, which is roughly 5–10 stripe domain widths, the majority of the stripes strongly prefer to be oriented either perpendicular or exactly parallel to the edges. As the edges are close together in such narrow samples, this ordering extends throughout the wire. The ability to precisely order the stripe domains is well suited for unambiguous measurements of the domain wall resistance[25,26] and possibly for unconventional magnetic memory applications,[27] in which the information can be encoded in terms of the orientation of the stripe domains.

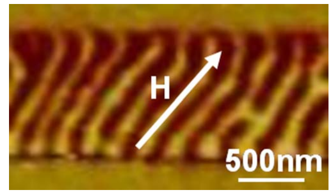

FIG. 5. (Color online) MFM image of a 100 nm thick and 1 μm wide Ni strip demagnetized at an angle of 45°. The stripe domains in the bulk of the sample follow the direction of the applied field, but they bend in the vicinity of the edge in order to be perpendicular to the edge.

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