J. M. Daughton
G. E. Keefe
K. Y. Ahn
C.-C. Cho*

Domain Wall Energy Measurements using Narrow Permalloy Strips

Middelhoek[1] proposed in 1961 that the domain structure of narrow thin film strips could be used to measure energies of domain walls and Kuwahara et al. have likewise suggested this method.[2] When measurements were attempted by these authors it was found that experimental results of wall energy were about a factor of four lower than calculated values. Furthermore, and contrary to theoretical calculations, there was no variation of wall energy density with film thickness.[2] This note proposes improvements in the experimental procedure, and reports some results which resolve the inconsistencies in the literature.

The domain pattern of primary concern, as illustrated in Figure 1, gives no divergence of magnetization except in the walls, and hence magnetostatic energy is of no concern. The balance between the anisotropy energy stored in the 90° edge domains and the energy stored in the 180° walls will determine the domain width a. Because the 90° walls have a constant length regardless of the strip width l or spacing between 180° walls a, the energy stored in the 90° walls is not a factor. The value of a which minimizes the energy of this domain pattern is easily found to be

$$a = \left[\frac{2l\gamma_{(180)}}{K}\right]^{\frac{1}{2}}, \tag{1}$$

where K is the anisotropy constant and $\gamma_{(180)}$ is the surface energy density of a 180° wall in the film.[1]

The desired domain pattern should occur for a range of strip widths. Since this pattern is formed so as to minimize magnetostatic energy, too wide a strip cannot form the desired pattern. Also, if true 90° spikes are formed at the edges, there is a geometrical restriction that $l > a$. Within the proper range of strip widths, a plot of a as a function of $\sqrt{l}$ should be a straight line projecting back through the origin and having a slope

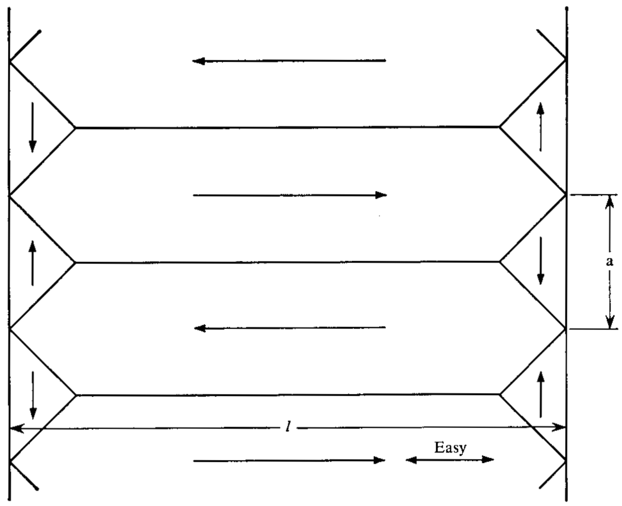

Figure 1 Domain pattern in a demagnetized state.

$$\left[\frac{2l\gamma_{(180)}}{K}\right]^{\frac{1}{2}},$$

thus revealing the wall energy.

Two improvements in experimental technique are suggested in this note. The *first* is that the film strips must be etched rather than formed by evaporation through a slit. This step is necessary to avoid large skew of the easy axis near the strip edges which arises from demagnetizing effects during deposition. The skew effectively reduces the anisotropy energy stored in the 90° edge domains. The *second*

* Department of Electrical Engineering, Louisiana State University, Baton Rouge, La.

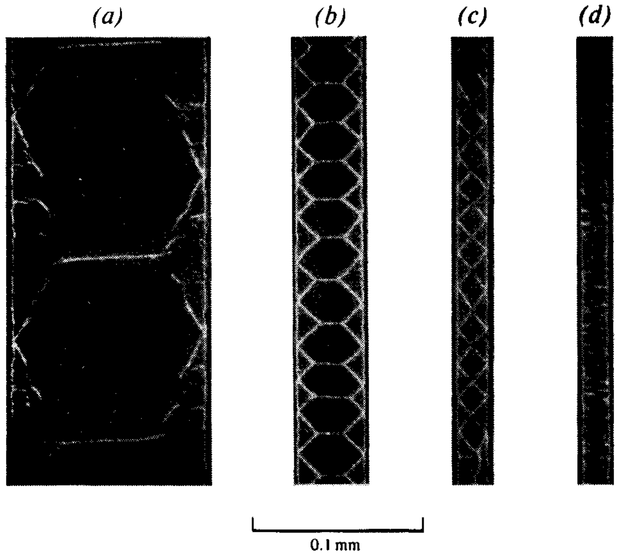

Figure 2 Bitter patterns in thin film strips: (*a*) a strip so wide it does not form the correct pattern; (*b*) a strip showing the correct pattern; (*c*) a strip so narrow that the 90° spike domains touch; and (*d*) a strip so narrow that the magnetization lies along the strip.

is that the demagnetization of the strip with a large a-c field along the hard axis leads to incorrect domain patterns because there exists magnetization rippling and a wall is really formed at angles with less than 180° difference between magnetizations in two adjacent domains. More consistent results are obtained by demagnetizing the strips with a slowly decreasing a-c field in the easy direction.

Permalloy films of zero-magnetostrictive composition, 83% Ni — 17% Fe by weight, were evaporated from an alumina crucible at a deposition rate of ~5 Å/sec. The distance between the substrate and the source was ~15 inches. Films of graded thicknesses (250 Å to 1000 Å in four steps, and 500 Å to 2250 Å in eight steps) were deposited onto glass substrates (Corning Glass 7059) at 300°C. A steady magnetic field of 60 Oe was applied in the plane of the substrate during evaporation to induce a uniaxial anisotropy. The pressure during evaporation was in the low 10^{-6} Torr range. The static magnetic properties of the films were measured before etching on a Kerr magneto-optic hysteresigraph with a 60-Hz drive field.

The samples were etched, using photoresist techniques, to line widths varying between 80 and 0.5 mils. The etching mask was aligned so that the lines passed over different film thicknesses with the easy axis perpendicular to the lines. A positive resist (Shipley) was used instead of a negative resist (Kodak), in view of the fact that surface cleanliness is very important to good Bitter-pattern observations and a positive resist better fulfills that requirement. After etching, the film was aligned along the easy direction on a Kerr magneto-optic device using the cross-field technique (M_x vs H_y). All easy-direction stray fields were canceled at this time. The film was demagnetized by applying a 60-Hz easy axis field (~20 Oe) that was slowly reduced to zero. After visually observing the domain pattern (in the wider lines), the sample was removed from the Kerr magneto-optic apparatus to be coated with Bitter solution. In order to inhibit the drying of the Bitter solution, a thin cover glass (0.006 inch) was placed on the sample, and its edges were sealed with rubber cement. Being careful not to expose the sample to any magnetic fields, the sample was put into a microscope for examination at 150 × magnification.

Figure 2 shows photographs of typical domain patterns: **a** shows a film strip too wide for magneto-static energy to be a factor important enough to form the desired domain pattern, **b** shows a correct pattern from which the wall energy may be inferred, **c** and **d** show patterns which have no 180° walls in very narrow strips. Care was taken to select values of a from areas where the 90° walls made 45° angles with the strip edges. For each sample and film thickness a was plotted as a function of $\sqrt{l}$.

Considerable scatter in the data was observed in most cases, but a best-fitting straight line was drawn through data points. The values of γ_{180} were inferred from the value of the slopes of these lines and the static value of H_k. These values are plotted in Figure 3 as a function of film thickness.

Figure 3 Wall energy as a function of film thickness.

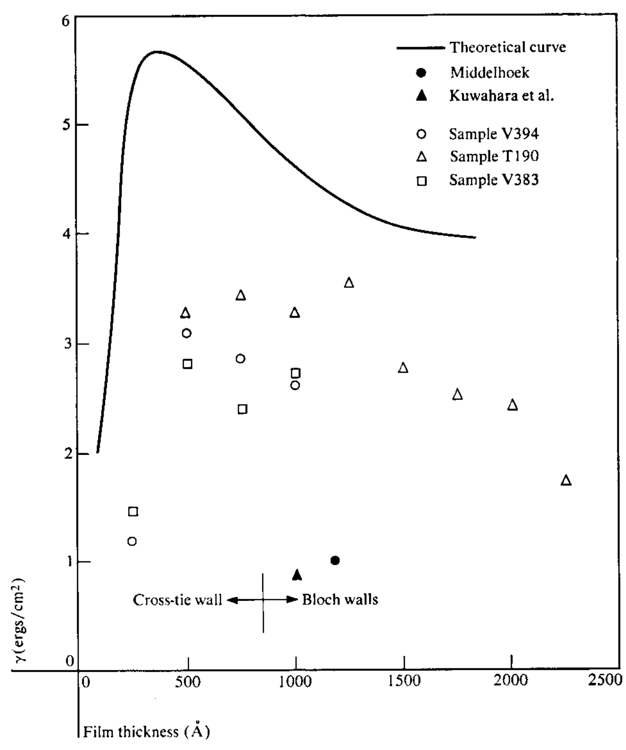

Figure 4 Superimposed domain patterns using hard-direction demagnetization and easy-direction demagnetization.

The general shapes of these curves as well as the magnitudes agree fairly well with calculations.[1] Figure 4 shows superimposed domain patterns which were produced by a demagnetization along the easy and the hard direction. The hard-direction demagnetization caused magnetization rippling and consequently the domains were smaller.

It appears that the wall energies can be measured using techniques described here. Although there is considerable variation in wall energy as a function of thickness, the values reported herein are much closer to calculated values than those previously reported.[1,2] That the values of wall energy remain lower than one would expect may be due to experimental error. However, even those calculated energies that have been obtained with most careful techniques[3–5] have to date included constraints in the magnetization through a domain wall, and this leads to an overestimate of wall energy.

Acknowledgments

It is a pleasure to thank J. M. Viggiano and A. Taranko for film fabrications.

References

1. S. Middelhoek, "Ferromagnetic Domains in Thin Ni-Fe Films." (Doctoral thesis, University of Amsterdam, 1961).
2. K. Kuwahara, T. Goto, A. Nishimura, and Y. Ozaki, "Domain Structure of Narrow Thin Films of Ni-Fe," *J. Appl. Phys.* **35,** No. 2, Part 2, 820–821 (1964).
3. H. Dietze and H. Thomas, "Bloch-und-Neèl-Waende in duennen ferromagnetischen Schichten," *Zeitschrift für Physik* **163,** *523–534 (1961).*
4. W. Brown and A. LaBonte, "Structure and Energy of One-Dimensional Domain Walls in Ferromagnetic Thin Films," *J. Appl. Phys.* **36,** No. 2, 1380–1386 (1965).
5. A. LaBonte, private communications.

Received January 5, 1967.