Lorentz Microscopy Determination of Domain-Wall Width in Thick Ferromagnetic Films

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Width of the 180° domain wall in Ni–Fe alloy films as a function of film thickness up to 1800 Å was measured using the defocused mode of Lorentz microscopy. For the thinner films, the measured wall widths are in good agreement with earlier data obtained by Fuchs. For films thicker than 800 Å, the wall width increases with film thickness to about 9000 Å at 1800 Å film thickness. The validity of the classical determination of wall width is discussed.

INTRODUCTION

Calculations of theoretical domain-wall width in ferromagnetic thin films have been carried out by many workers based on simple models.[1–6] Recent experimental work[7] indicates that the wall structure in films greater than 1000 Å thick deviates markedly from the predictions based on these simple models. However, very little quantitative experimental data on wall widths have been reported, even though the domain-wall structures are the key to many basic problems in the study of ferromagnetic thin films. The Kerr and Faraday effect and the Bitter technique with the optical microscope give some qualitative information on wall structures, but only the electron microscope seems to have the resolution required to get quantitative information. However, it has been recognized recently that even this method has limitations imposed by quantum mechanical considerations.

This paper presents results of an extensive quantitative investigation of the width of 180° domain walls in 76% Ni–Fe alloy films between 200 and 1800 Å thick using the defocussed mode of Lorentz microscopy. For the thinner films the measured wall widths are in good agreement with earlier data obtained by Fuchs[8] using another method. Minimum wall width is about 2000 Å. For films thicker than 800 Å, the wall width increases with film thickness to about 9000 Å at 1800 Å film thickness. These structures are much wider than those calculated from one-dimensional wall models, which predict widths less than 400 Å.

EXPERIMENT

The 76% Ni–Fe alloy films used in the present study were vacuum-evaporated from a melt of 80% Ni and 20% Fe onto glass or cleaved NaCl substrates at room temperature in a moderate vacuum of about 10^{-7} Torr. Electron-diffraction analysis showed that the films were of fcc polycrystalline structure. Film thickness was determined magnetically, using a low-frequency hysteresis loop tracer. The specimens for Lorentz microscopy were mounted on microscope grids after being floated off the NaCl substrates in water.

Lorentz microscopy observations were made with an RCA EMU-3 microscope operated at 100 kV. Beam divergence was minimized by using a double condenser lens with the second lens overfocussed beyond the crossover as much as possible. Condenser apertures were 250 μ in diameter and a 20-μ objective aperature was used. Aperture angle of the electron beam was of the order of 10^{-4} rad or less. The specimens were raised above the focal plane of the objective lens mechanically by using a special specimen holder. For most measurements the out-of-focus distance was 0.55 mm. However, experimental difficulties made such measurements unreliable for thickness less than 600 Å, and for these cases the out-of-focus distance was increased to 1.1 mm. For films thicker than 1200 Å the illumination intensity on the observation screen was so weak that the exposure times of the photographic plates were longer than 10 min. Therefore, special precautions were taken to eliminate mechanical vibration of the microscope.

The photographic plates were analyzed using a scanning photodensitometer and the transmission data were converted to intensity with an experimental calibration curve for the emulsion. This calibration was linear over the exposure range utilized.

CALCULATION OF WALL WIDTH

Wall width was determined experimentally using the defocused mode of Lorentz microscopy, first reported by Fuller and Hale.[9] As discussed by Warrington,[10] the beam divergence of the incident beam must be considered for this technique. Using the classical theory for convergent wall images, the intensity profiles are dependent on the beam divergence, and the Fuller and Hale result is applicable only if the ratio of the beam divergence angle β to the Lorentz deflection angle φ is

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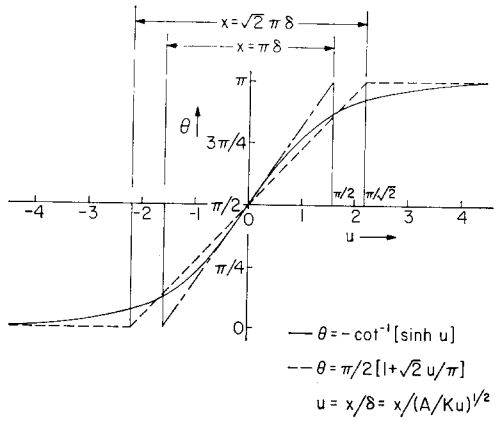

FIG. 1. Magnetization distribution in a one-dimensional 180° wall determined by exchange and uniaxial anisotropy energy without demagnetizing field (solid line) and for the linear rotation model (dotted line).

of the order of 10^{-2} or less. In the present situation $\beta \simeq \varphi \simeq 10^{-4}$ and $\beta/\varphi \simeq 1$. For divergent wall images, on the other hand, the intensity profiles are very insensitive to beam divergence and the Fuller and Hale result is applicable for β/φ as large as unity. For this reason, the wall-width determinations were made only on the basis of divergent wall images. It has also been pointed out by Wohlleben[11] that the classical determination has approximate validity only if the magnetic inhomogeneity being detected involves a flux change large compared to a fundamental flux quantity $h/2e$. This restriction is particularly severe for convergent wall images, and the classical approximation works better in the divergent case. The implications of this limitation will be discussed later. It should also be noted that for an aperture angle of 10^{-4} rad, the coherence condition of the beam is not satisfied and consequently no interference fringes could be observed in the wall images in the present study.

Figure 1 shows the theoretical magnetization distribution in a one-dimensional 180° wall determined by exchange and uniaxial anisotropy energy in the absence of demagnetizing fields. This distribution is

$$\theta = -\cot^{-1}(\sinh u) = -\cot^{-1}(\sinh x/\delta), \qquad (1)$$

where θ is the angle between the magnetization and the easy direction at a distance x from the wall center along the hard direction, and $u=x/\delta$, is the normalized distance from the center of the wall in the film plane. The value δ, is determined by the exchange and anisotropy constants $\delta=(A/K)^{1/2}$. The slope of the curve defined by Eq. (1) is $1/\delta$ at the center of the wall. The wall width may therefore be defined to be $\pi\delta$ for a 180° wall. An alternative definition is $\sqrt{2}\pi\delta$ in order to more nearly match the uniform rotation model. The latter definition will be used in this paper so that the approximate calculation of Middlehoek including the demagnetizing field will agree with the exact solution at the limits of zero and infinite film thickness. Using this magnetization variation, the classical intensity distribution of the divergent wall image can be written as[9]

$$I(U)/I_0 = (1+R\,\mathrm{sech}^2 u)^{-1}. \qquad (2)$$

In this equation, I_0 is the beam intensity far from a wall, the variable $U=X/\delta$ is the normalized distance from the center of the wall in the focal plane, and the normalized Lorentz deflection is $R=z\varphi/\delta$, where z is the out-of-focus distance.

In ferromagnetic films the existence of demagnetizing fields alters both wall width and shape. In experimental determinations of wall width, it has been customary to assume that the shape is unchanged and to choose a value of δ that most nearly reproduces the experimental data. This may introduce significant error in the case of Néel walls where there appears to be a fast rotation region at the center bordered by long tails where the magnetization turns over very slowly. Based on this assumption, there are two simple ways of determining δ from the intensity distribution on the Lorentz microscopy photograph. (1) The intensity ratio at the center of the wall ($u=U=0$) permits calculation of R from Eq. (2). The Lorentz deflection angle φ can be calculated from known and microscope data and the wall width is then obtained from $a=\sqrt{2}\pi\delta=\sqrt{2}z\varphi\pi/R$. (2) The wall width also can be obtained by adjusting δ in Eq. (1) to match the experimental intensity distribution with the theoretical intensity profile. As discussed in a later section, it appears that a more accurate measure of wall width results from the match of intensity distribution rather than from the peak intensity ratio. Consequently the data presented below were obtained from a profile match using only divergent wall images.

RESULTS

The width of 180° domain walls as a function of film thickness is shown in Fig. 2. Also shown are the theoretical curves based on the ellipsoidal model[2] for the demagnetization field for both Néel and Bloch walls with exchange and anisotropy taken to have the values $A=1\times10^{-6}$ erg/cm, $K_u=3.5\times10^3$ erg/cc. The value of

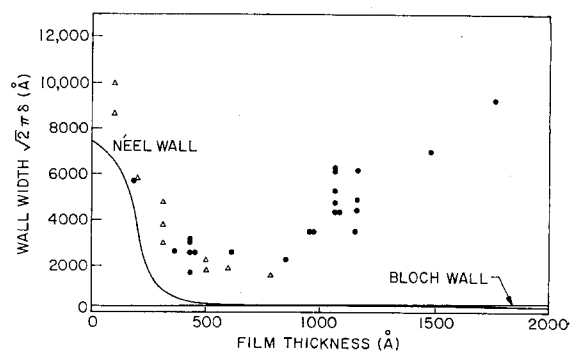

FIG. 2. Domain-wall width as a function of film thickness for 76% Ni–Fe alloy films. Δ: Data by Fuchs.[8] The theoretical curves (solid lines) are after Middlehoek.[2]

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A is an average of about ten experimental measurements made by ferromagnetic resonance. The value of K_u was obtained with a torquemeter used at high-field strength. The dependence of wall width on film thickness between 200 and 800 Å is not clear in the present study due to scatter in the data and increasing uncertainty for the thinnest films due to the quantum mechanical limitations. However, the data in this region are in reasonable agreement with that of Fuchs,[8] also obtained by Lorentz microscopy but using a different method.

Between 800 and 1800 Å film thickness the wall width increases nearly linearly from a minimum of about 2000 to 9000 Å. As shown in the figure, these values are in complete disagreement with calculations based on the simple models described above.

DISCUSSION

The most important question relating to the experimental measurements is the validity of the classical interpretation or calculation. The most fundamental limitation is that discussed by Wohlleben[11]: A magnetic inhomogeneity, that is, a change of magnetic field between two points, can be resolved classically if the flux of the inhomogeneity is much larger than a fluxon, $h/2e$. For the measurements shown in Fig. 2, the number of fluxons is a minimum of about five for the 160 Å film, increasing slowly to about ten for 850 Å and then increasing rapidly to about 100 for the 1800 Å film. This implies that as far as this criterion is concerned, the classical picture is quite adequate for films in excess of 1000 Å, but may be somewhat inaccurate for films less than 500 Å thick.

A second criterion[12] is that if $\Delta\varphi$ is not large compared to a fluxon, then the classical result is similar to the wave-mechanical result provided the out-of-focus distance z is small compared to the reciprocal of the gradient of the Lorentz deflection $(d\varphi/d\xi)^{-1}$. In the region where the number of fluxons is small, the experimental value of $(d\varphi/d\xi)^{-1}$ varied from about 1 cm for 160 Å thickness to about 2 mm for 600-Å thickness. This implies that if other things are equal the smallest z value possible (0.55–1.1 mm) should give more reliable results than larger values. In order to check this point, the out-of-focus distance was varied from 0.55 to 4.4 mm for two samples with thicknesses of about 1000 Å, and from 1.1 to 6.6 mm for one sample with thickness of 430 Å. Wall widths deduced from both profile match and peak intensity ratio are shown in Fig. 3. The values of δ obtained from the profile match showed remarkably little scatter, typically $\pm 20\%$. The values obtained from the peak intensity ratio were in reasonable agreement with the other method at the smallest z value, but were systematically high by a factor of about 1.7 for higher z values. In view of this result, only wall widths obtained by a profile match are considered in the discussion below.

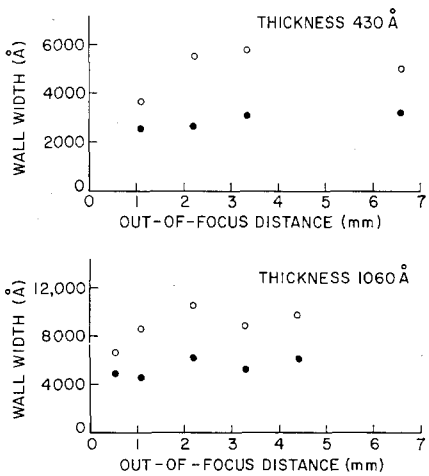

FIG. 3. The measured wall width of 76% Ni–Fe alloy films as a function of the out-of-focus distance for film thickness 430 and 1060 Å. ○: Measured by the intensity ratio at the center of wall. ●: Measured by matching the theoretical intensity profile with the experimental intensity distribution.

[12] D. Wohlleben (private communication).

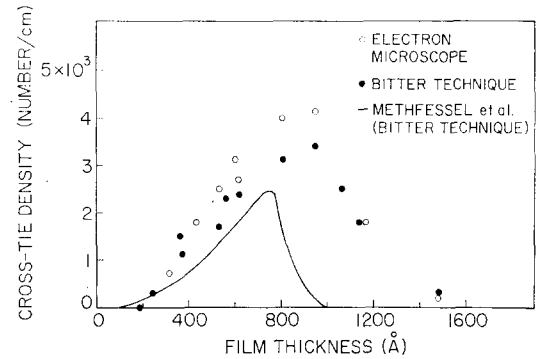

FIG. 4. Crosstie density as a function of film thickness for 76% Ni–Fe alloy films. The solid line is after Methfessel et *al.*[13]

The data of Fig. 2 were obtained from films evaporated onto and stripped from NaCl substrates. In order for such data to be taken as representative for films evaporated on glass as well, it is necessary to determine whether the substrate or stripping procedure modifies wall structure appreciably. A convenient wall-structure parameter which can be easily measured for films on glass using the Bitter technique and films on copper grids using Lorentz microscopy is the number of crosstie structures per unit length of wall. These data are shown in Fig. 4. The crosstie density is remarkably similar for both films on glass and films mounted on copper grids. The crosstie density increases with thickness to a maximum near 950 Å and decreases to zero again for thicker films. Earlier data by Methfessel *et al.*[13] using the Bitter technique are also shown. They are qualitatively similar but show a reduced maximum at about 750 Å instead of 950 Å.

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Further confirmation was obtained by measuring the uniaxial anisotropy of films deposited on glass and films deposited simultaneously on NaCl and subsequently stripped from the NaCl. There was some variation depending in part on the mechanical damage to the films from the stripping procedure. However, for samples removed with minimum deformation, the two values of anisotropy were in satisfactory agreement.

The present data show that for films thicker than 300 Å, the wall width is much larger than that predicted by the simple one-dimensional models. This finding is important since it indicates that these models are completely inadequate. The discrepancy cannot be explained in terms of a reduced anisotropy, since the films stripped from the substrates were found to exhibit about the same uniaxial anisotropy as that for films on glass substrates. It may be that the crosstie and Bloch lines or Néel lines associated with wall structures in thick films may be very efficient in reducing the wall magnetostatic energy, thus widening the walls, although this would not explain the large discrepancy at 1800 Å thickness where the crosstie density appears to be very low. In any case, the experimental data indicate that existing calculations may be in considerable error in overestimating the magnetostatic energy of the wall for thick films.

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Modulation Broadening of the Shape of Unsaturated Gaussian Magnetic Resonance Absorption Lines

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An expression is derived for the Fourier coefficients a_n^G of a modulation-broadened, unsaturated Gaussian absorption lineshape.

INTRODUCTION

Wahlquist[1] was the first worker to derive a closed, analytic expression for the Fourier coefficients a_n^L describing a modulation broadened, unsaturated Lorentzian lineshape. This expression was obtained from the integral defining the Fourier coefficients by the use of contour integration. Smith[2] noted that the integrand of the corresponding integral for a modulation broadened, unsaturated Gaussian line shape contained an essential singularity.[3] The presence of this singularity invalidates the use of contour integration. Berger and Günthart[4] employed an alternative mathematical procedure to derive a closed, analytic expression for each Fourier coefficient of a modulation broadened, unsaturated Lorentzian lineshape. It has been shown by Buckmaster and Dering[5] that the Fourier coefficients a_n^L derived by Wahlquist[1] and Berger and Günthart[4] are similar for $n=0$, 1, and 2, except that $a_n^{(W)}$ defined by Wahlquist and $a_n^{(BG)}$ defined by Berger and Günthart are related by $a_0^{(W)}=a_n^{(BG)}$ and $a_n^{(W)}=2a_n^{(BG)}$, $n\neq 0$. The object of this paper is to demonstrate that the mathematical procedure of Berger and Günthart[4] can be employed successfully to derive a general expression for a_n^G. This expression has been given without proof by Buckmaster.[6]

THEORY

The normalized form of a Gaussian lineshape is

$$g(H)=(1/H_\Delta)(\ln 2/\pi)^{1/2}\exp[-(\ln 2)(H-H_0)^2/H_\Delta^2], \quad (1)$$

where

$$\int_0^\infty g(H)\,dH=1.$$

H_Δ is the half-width at half-maximum amplitude (Wahlquist's $\frac{1}{2}H_{1/2}$), H_0 is the magnetic field corresponding to the resonance center, and H is the magnetic field. When the magnetic field is time dependent, then Eq. (1) becomes

$$g(t)=(1/H_\Delta)(\ln 2/\pi)^{1/2} \times \exp(\{-(\ln 2)[H_a(t)-H_0+H_\omega\cos\omega t]^2/H_\Delta^2\}), \quad (2)$$

where $H(t)=H_a(t)+H_\omega\cos\omega t$, $H_a(t)$ is assumed to be constant over a time interval $(2\pi/\omega)$, H_ω is the peak amplitude of the magnetic field modulation, and ω is the angular frequency of the magnetic field modulation.

Following Berger and Günthart, define

$$\alpha'\equiv H_\delta T_2=H_\delta/H_\Delta; \qquad \alpha\equiv H_\omega T_2=H_\omega/H_\Delta, \quad (3)$$

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