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Mobility and Loss Mechanisms for Domain Wall Motion in Thin Ferromagnetic Films*

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Domain-wall mobility for Ni–Fe alloy films has been measured as a function of film thickness from 300 to 1650 Å. Between 300 and 800 Å, the mobility decreases with increasing film thickness, ranging from 8×10^3 cm/sec·Oe at 300 Å to 3×10^3 cm/sec·Oe at 800 Å. Between 900 and 1000 Å, the mobility increases rapidly with increasing film thickness to about 7×10^3 cm/sec·Oe. Above 1000 Å, the mobility increases slowly with film thickness. These mobility data have been compared with predictions based on intrinsic and eddy-current loss mechanisms utilizing available static domain wall-shape information. Predictions based on a 180° Bloch or Néel wall model in which the magnetization rotates linearly through the wall are in disagreement with the present data over the entire range of film thickness. For the 300–800 Å thickness range, predictions based on Lorentz microscopy wall-shape measurements are in good agreement with the measured mobility values. The crosstie structure associated with Néel walls in this thickness range does not appear to affect the mobility. Bitter patterns indicate that the sharp increase in mobility between 900 and 1000 Å may be associated with a wall structure transition in this region. For thicker films, mobility predictions based on static Bloch wall-shape calculations are an order of magnitude lower than the observed mobilities. Lorentz microscopy wall-shape measurements for 1200-Å films yield wall widths of about 3000 Å significantly wider than calculated Bloch wall widths. Predictions based on these measured widths are in good agreement with the data. Although the calculation includes both intrinsic and eddy-current losses, intrinsic losses dominate for crosstie or Néel wall motion in the 300–800-Å thickness range and for Bloch wall motion in the 1000–1600 Å thickness range.

INTRODUCTION

THE limitation of domain-wall velocity in ferromagnetic films has been ascribed to both intrinsic damping[1,2] and eddy-current losses.[3] Intrinsic damping, which may be viewed as direct energy transfer from the moving wall to the crystal lattice, has been treated in a phenomenological manner by Landau and Lifshitz.[1] This treatment was extended by Galt[2] to obtain domain-wall mobilities for 180° walls in terms of an arbitrary magnetization direction within the wall. The dependence of the mobility on the shape of the moving wall, when limited only by intrinsic damping, was clearly demonstrated. Until recently, however, no wall-shape dependence has been taken into account in considering the effects of eddy-current losses on wall motion. In the classic calculation of eddy-current losses for wall motion by Williams *et al.* (WSK),[3] the 180° domain wall was represented by a transition region of zero width. In recent calculations, Patton *et al.*[4] have considered the effect of finite wall width on the eddy-current losses for Bloch wall motion. For static Bloch wall widths as calculated by Middelhoek[5] and others,[6–8] these calculations predict eddy-current losses nearly equal to those given by the WSK calculation.

Several experimental investigations have been reported, which undertake to characterize wall motion in terms of one loss mechanism or the other. Menyuk[9] observed the reversal time in Permalloy tape cores varying in tape thickness from 3×10^4 to 3×10^5 Å. He concluded that the eddy-current losses predicted by Williams *et al.* contributed only 10% to the total losses in his thinnest sample. Ford,[10] on the other hand, observed domain wall mobility in the 700–4000 Å thickness range which was inconsistent with the intrinsic loss mechanism but was consistent with the WSK eddy-current calculation. Recent mobility measurements by Copeland and Humphrey,[11] Patton and Humphrey,[12] and Middelhoek,[13] are at variance with Ford's data.

In light of this situation, it seems desirable to reexamine experimentally the domain-wall mobility for thin films over a significant range of film thickness and to compare these results with predictions based on intrinsic and eddy-current loss mechanisms, utilizing available static domain-wall-shape information. Vacuum evaporated Ni–Fe alloy films with thickness between 300 and 1650 Å were used. For all films examined, the measured wall mobility did not agree with predicted mobilities based on a simple 180° wall in which the magnetization rotates linearly through a wall with a width as calculated from static energy con-

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siderations,[5] even though both eddy-current[4] and intrinsic[1] losses were considered. However, for films less than 800 Å thick, mobilities calculated using Lorentz microscopy wall-shape measurements by Fuchs[14] agree with the experimental data. In this thickness range, intrinsic losses dominate. The crosstie wall segments which occur in this thickness range[15] do not appear to influence the mobility. For films thicker than 1000 Å, the mobilities are almost an order of magnitude greater than predicted by any existing Bloch wall-shape calculation.[5–8] Measured wall widths based on Lorentz microscopy observations are much greater than predicted by such calculations and are in agreement with the data. It is suggested that such wide walls result from the wall structure consisting of alternating Bloch wall segments separated by Bloch lines which has been discussed by several authors[16–19] and recently observed in thin films by Torok.[20]

EXPERIMENT

The Ni–Fe alloy films used in this study were vacuum evaporated from a melt of 80% Ni and 20% Fe, onto glass substrates at 300°C in a moderate vacuum of 10^{-6} Torr, in the presence of a uniform magnetic field in the plane of the substrate. Film composition was determined to be about 77% Ni using x-ray fluorescence techniques. Film thickness was determined magnetically, using a 20-cps hysteresis loop tracer, and optically, utilizing the Tolansky multiple-beam interference technique.[21] The apparatus used in the mobility determinations is shown in Fig. 1. Coils labeled A in Fig. 1 were provided to cancel the earth's magnetic field to ±0.005 Oe. The film specimen was mounted on a rotatable platform on which a 20-turn pickup coil was located. The geometry of this coil was similar to that for the single-turn loop described by Oguey.[22] Initial film alignment was accomplished by first saturating the film in the hard direction using Helmholtz pair B and then observing the induced voltage in the pickup coil as the magnetization relaxed to the easy direction upon removal of the hard-direction field. The film orientation was adjusted for zero induced voltage during this relaxation to the easy direction. A small Helmholtz pair (C) was arranged to provide an easy direction field homogeneous to one part in one thousand. Easy-axis field pulses with risetimes as short as 100 nsec and amplitudes as high as 5 Oe could be produced. Pulse lengths from 1 to 50 μsec were available, with risetimes always less than $\frac{1}{10}$ the pulse length.

Domain wall velocity measurements were carried out by pulsing the film specimen with a sequence of easy-axis field pulses of fixed amplitude. The domain wall positions were observed at the beginning and end of each sequence using the Kerr magneto-optic effect. In Fig. 2, a series of domain wall photographs is shown. Wall positions are shown after successive applications of a sequence of 10 easy-axis field pulses. The simple wall configurations and systematic wall displacements produced using this technique were typical of the observations used in all of the experimental mobility determinations presented in this paper. Field amplitudes were determined to ±0.010 Oe using a high-gain differential comparator. With a closed-circuit television system and a traveling microscope for measurement, domain-wall positions could be determined to ±0.05 mm, on films 1 cm in diameter. As shown in Fig. 3, wall velocities, determined from the wall displacement, pulse length, and number of pulses, were observed to vary linearly with the easy-axis field pulse amplitude. These velocity determinations were found to be independent of the number of pulses used, as well as the pulse length, in contrast with the erratic dependence reported by Ford[10] and Copeland and Humphrey[11] for this method. In the present experiment, pulse sequences with from one pulse (for 50-μsec pulse lengths) to 100 pulses (for 1-μsec pulse lengths) were employed and no dependence of velocity on these parameters was observed.

At high fields, nucleation obscured the uniform motion of individual straight walls, making the determination of domain-wall velocities impossible for fields approaching the anisotropy field. The lowest field value for which uniform wall motion was observed was usually slightly greater than the film coercive force, as measured from the hysteresis loop. In some cases, however, over

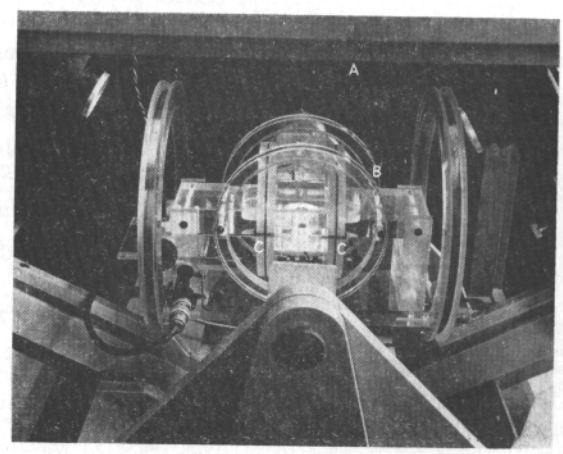

FIG. 1. Experimental apparatus for domain-wall mobility measurements. (A) coils for canceling the earth's magnetic field (B) hard-direction field coils, (C) easy-direction field coils.

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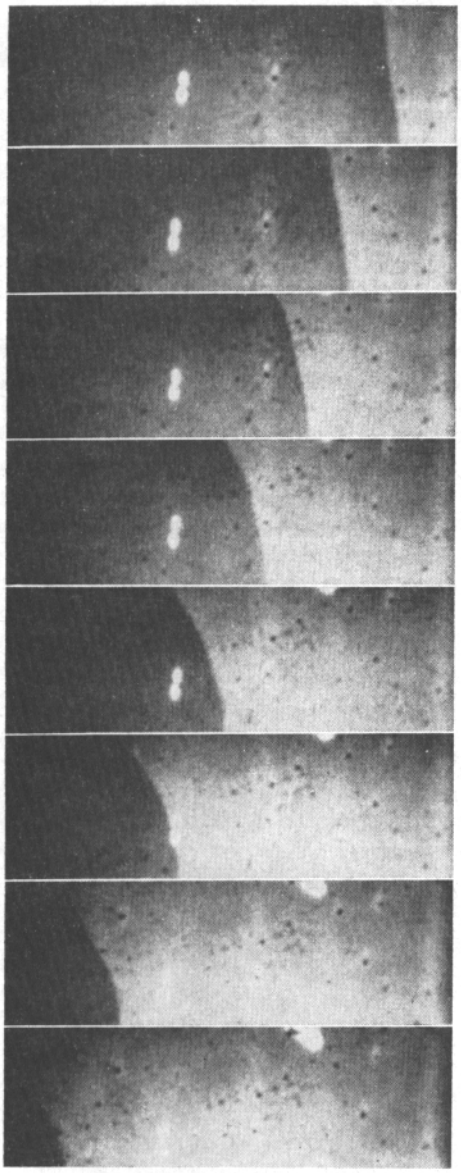

FIG. 2. Kerr effect observations of the simple wall configurations and the systematic wall displacements obtained after successive application of several field pulse sequences. Each pulse sequence was identical, consisting of ten pulses, 2.6 μsec long, with amplitudes of 2.5 Oe.

limited regions of a film, uniform wall motion was observed for field strengths less than this coercive force. The slope of the straight line giving the best fit to the velocity data was evaluated using the method of least squares. A typical plot is shown in Fig. 3. For each set of data, a chi-squared test for the probability of a linear fit was performed. All probabilities were greater than 0.9. These slopes correspond to the domain wall mobility.

THEORY

If intrinsic damping and eddy-current losses are considered independently, $G_\alpha=\partial v_\alpha/\partial H$ and $G_e=\partial v_e/\partial H$ may be taken to represent the intrinsic damping limited mobility and the eddy-current-limited mobility, respectively. Here v_α and v_e are the intrinsic-loss-limited velocity and the eddy-current-limited velocity, respectively, and H is the applied easy-axis field. In terms of G_α and G_e, the wall mobility, G, can be obtained from

$$1/G=1/G_\alpha+1/G_e. \tag{1}$$

In order to predict the domain-wall mobility in thin films, it is necessary to obtain expressions for both G_α and G_e in terms of the shape of the moving wall, the material parameters of the film, and the film thickness.

Eddy-Current-Limited Mobility

For Bloch wall motion, the eddy-current-limited mobility has been calculated previously[4] for a wall shape in which the magnetization rotates linearly through the wall. For this wall shape,

$$\theta=\pi(x/a+\tfrac{1}{2}) \tag{2}$$

within the wall. In Eq. (2), θ is the angle between the magnetization in the wall and the magnetization in the adjacent domain at $x\leqq-a/2$. This angle is assumed to depend only on the x coordinate which is directed along an axis perpendicular to the plane of the wall with $x=0$ at the wall center. The wall width is denoted by a. The eddy-current-limited mobility obtained in this calculation is:

$$G_e=\frac{dc^2}{32\pi^2\sigma M[I_{sq}(a,d)+I_{zsq}(a,d)]}. \tag{3}$$

In this expression

$$I_{sq}(a,d)=\frac{d^2}{\pi^3}\sum_{n\,\text{odd}}\frac{A(R_n)+B(R_n)e^{-\pi R_n}}{n^2(1+R_n{}^2)^3}, \tag{4}$$

and

$$I_{zsq}(a,d)=(da/8)[d/(a+d)]^2, \tag{5}$$

where

$$A(R_n)=2+\pi R_n+\pi R_n{}^3, \tag{6a}$$

$$B(R_n)=2, \tag{6b}$$

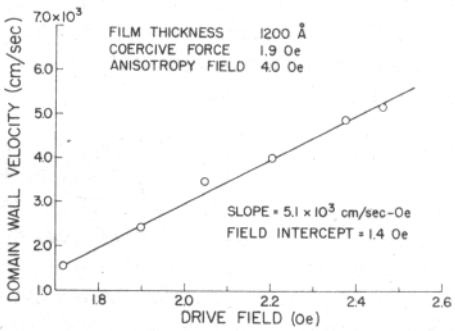

FIG. 3. Domain wall velocity as a function of applied easy-axis field. These data are typical for Ni–Fe alloy films in the 300–1650 Å thickness range.

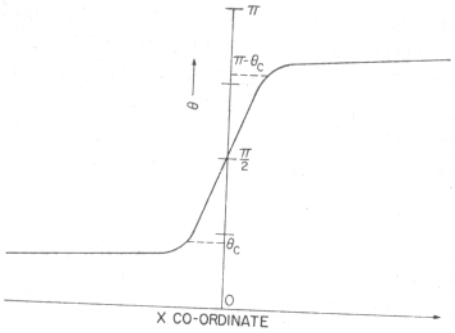

FIG. 4. Typical Néel wall shape observed in thin films, 300–800 Å thick [E. Fuchs, Z. Angew. Phys. **14**, 203 (1962)].

and $R_n=na/d$. In these equations, d is the film thickness, c is the speed of light, and M is the saturation magnetization (800 G for the Ni–Fe alloy films investigated experimentally). The conductivity of the medium σ is taken to be 0.57×10^{-17} sec^{-1}, corresponding to a resistivity of 16 $\mu\Omega\cdot$cm, typical for the films investigated experimentally. Gaussian units are employed throughout.

For Néel walls, similar results can be obtained, following the procedure outlined in Ref. 4. The current distribution is identical to that calculated for Bloch walls, except for the current component in the direction defined by the intersection of the film plane and the wall plane. This component is negligible for Néel walls. This difference requires that $I_{zsq}(a,d)\approx0$. The linear wall approximation expressed by Eq. (2) has been shown to be quite good for Bloch walls.[5] Néel walls, Eq. (2) is a poor approximation to the actual wall shape, but for more appropriate Néel wall shapes[14] a solution for the current in simple form is not possible.

Intrinsic Damping-Limited Mobility

The basis of the calculation of the wall mobility, limited only by intrinsic damping, is the Landau–Lifshitz equation[1]:

$$d\mathbf{M}/dt=\gamma(\mathbf{M}\times\mathbf{H})-(\alpha\gamma/M)[\mathbf{M}\times(\mathbf{M}\times\mathbf{H})], \quad (7)$$

where γ is the gyromagnetic ratio ($\gamma=1.76\times10^7$ Oe$^{-1}\cdot$sec^{-1}), α is the intrinsic damping parameter, and $\mathbf{H}$ is the applied field. Galt has shown[2] that, for the uniform motion of a 180° wall in a uniaxial material, the wall mobility can be written as follows:

$$G_\alpha=\frac{2\gamma}{\alpha}\left[\int_0^\pi\left(\frac{d\theta}{dx}\right)d\theta\right]^{-1}. \quad (8)$$

This expression assumes that the 180° wall does not change its shape, $\theta(x)$, during motion at a constant velocity v. For calculations using Eq. (8), α will be taken to be 0.014, consistent with ferromagnetic resonance data.[23]

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Equation (8) clearly shows the importance of wall shape in calculating wall mobilities. The simplest model which may be used is the linear wall discussed in the previous section, in which the magnetization rotates linearly through the wall. This model has been treated in detail for both static Bloch and Néel walls by Middelhoek.[5] Using this linear model, Eq. (8) may be written as $G_\alpha=2\gamma a/\pi^2\alpha$. For Bloch walls, several more accurate wall-shape solutions have been published.[6–8] These solutions give essentially the same mobilities as calculated from the linear wall model.

For film thickness less than 800 Å, more accurate static Néel wall shapes have been deduced from Lorentz microscopy photographs by Fuchs.[14] Néel wall width as a function of film thickness from 100 to 780 Å has been reported. These widths correspond to values for $\pi(d\theta/dx)^{-1}$ evaluated at the wall center ($x=0$). However, as shown in Fig. 4, the static wall shapes observed by Fuchs are not linear, but exhibit regions where $d\theta/dx$ is nearly zero. These regions start abruptly at θ values which may be defined by a critical angle θ_c. For $0<\theta<\theta_c$ and $(\pi-\theta_c)<\theta<\pi$, $d\theta/dx$ can be taken to be zero, and the mobility can be written as follows:

$$G_\alpha=[2\gamma/\alpha(\pi-2\theta_c)][(d\theta/dx)_{x=0}]^{-1}. \quad (9)$$

A good estimate of the thickness dependence of θ_c can be obtained from the 3-parameter wall-shape calculation developed by Feldtkeller and Fuchs.[7,24]

DISCUSSION OF RESULTS

In Fig. 5, experimentally determined mobilities are displayed as a function of film thickness. Earlier data

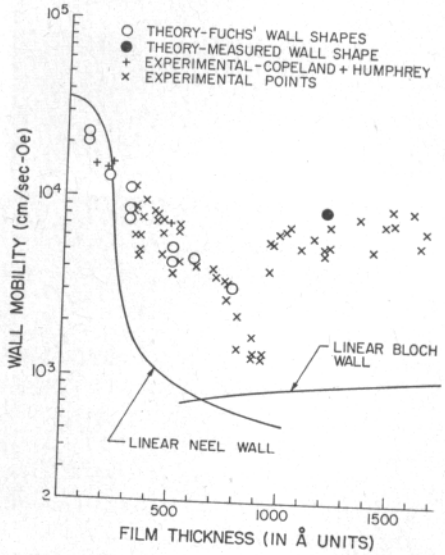

FIG. 5. Domain-wall mobility as a function of film thickness for Ni–Fe alloy films. Calculations were performed assuming an exchange constant of 1.0×10^{-6} erg/cm, an anisotropy constant of 1000 erg/cm^3, and a saturation magnetization of 800 G. The electrical conductivity was taken to be 0.57×10^{17} sec^{-1}.

[24] E. Feldtkeller and E. Fuchs, Z. Angew. Phys. **18**, 1 (1964).

by Copeland and Humphrey[11] for very thin films are also shown. The measured mobilities can be conviently discussed in two groups. The first group is for films thinner than about 950 Å, where the mobility decreases rapidly with increasing film thickness. The second group is for thicker films, where the mobility slowly increases with increasing film thickness.

For both groups, the majority of films had a wall velocity-field dependence as shown in Fig. 3 and discussed in the experimental section. However, a number of films in the first group exhibited two mobilities. A typical velocity vs field plot for these films is shown in Fig. 6. In addition to the characteristic low-field curve, which extrapolates to $v=0$ near the coercive force, another linear curve with a significantly reduced slope was observed for high drive fields. This high-field effect was not observed for any of the thicker films in the second group. Some dynamic wall-shape effect may be involved in producing this reduced slope at high fields. Or, this reduced slope may simply be due to the rapid growth of end domains rather than the simple lateral motion of straight domain walls at high fields. For films exhibiting this effect, the wall mobility was determined from the low-field curve.

As shown in Fig. 5, there is considerable scatter in the observed mobilities for both groups in spite of the fact that the reproducibility was well within 5%. For many films, imperfections noticeably impeded wall motion to such an extent that meaningful velocity measurements could not be performed. It is reasonable to assume, therefore, that even for films which exhibited apparent uniform wall motion, and for which mobility determinations were made, film imperfections still contributed to the losses limiting wall motion. On the basis of this argument, the upper bound of the experimental points can be taken to represent wall motion unimpeded by film imperfections, limited only by eddy-current and intrinsic losses.

Mobility predictions, based on the two static wall-shape models discussed previously, are also plotted in Fig. 5. In the thickness range 100–900 Å, a linear Néel wall model does not adequately explain the experimental data. However, the static wall-shape

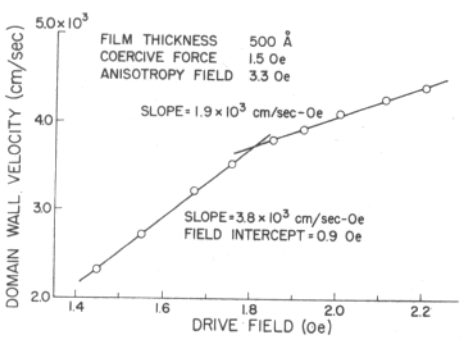

FIG. 6. Domain-wall velocity as a function of applied easy-axis field observed for several Ni–Fe alloy films in the 300–1000 Å thickness range.

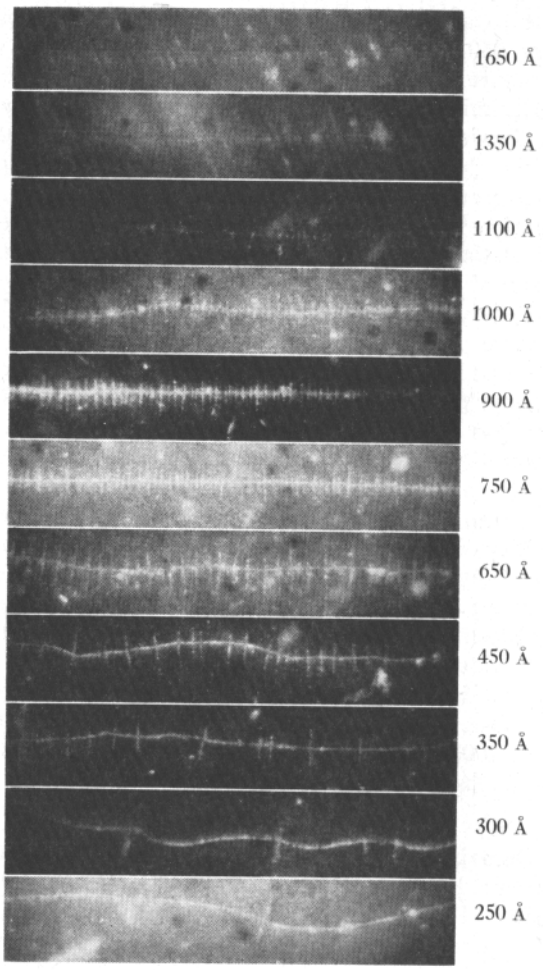

FIG. 7. Photographs of Bitter patterns showing domain walls for film thickness between 250 and 1650 Å. Each photograph corresponds to a wall section approximately 300 μ long.

measurements of Fuchs[14] yield mobilities which are in good agreement with the experimental data. For this thickness range (100–900 Å), intrinsic losses constitute almost 100% of the losses influencing the calculated mobility. Eddy-current losses are negligible. Since these calculated mobilities do not include the effects of the crosstie structure associated with Néel walls for film thickness between 300 and 800 Å, the agreement between theory and experiment shown in Fig. 5 indicates that the crossties have little effect on the wall motion.

For film thickness in the vicinity of 950 Å, the mobility increases by a factor of five, with increasing film thickness. Photographs of Bitter patterns shown in Fig. 7 clearly show that some type of wall transition occurs in the vicinity of 1000 Å. For film thickness less than 1000 Å ,the wall is of the Néel type, characterized by the usual crosstie structure. For film thickness greater than 1000 Å, the colloid accumulation is significantly reduced, the Bitter patterns are very faint, and the crosstie structure does not appear. It is reason-

able to suppose that the sharp increase in mobility near 950-Å film thickness is associated with a wall structure transition in this region.

For thicker films, the mobility appears to slowly increase with film thickness. The observed mobility values in the thickness range 1000–1650 Å are much higher than predictions based on static Bloch wall-shape calculations[5–8] and Eq. (1). Mobilities predicted by such calculations are almost an order of magnitude lower than observed experimentally. A previous suggestion involved dynamic shape effects for moving Bloch walls.[12] A more plausible explanation for this discrepancy can be found in the Bloch-line structure discussed by several authors[16–19] and recently observed in thin films by Torok *et al.*[20] Lorentz microscopy observations in this laboratory on 1200-Å films similar to the samples used in the mobility determinations reveal a static wall structure similar to that observed by Torok.[20] The intensity distributions of these wall images have been analyzed by Feldtkeller.[7] This analysis yields wall widths of about 3000 Å, which are much wider than expected for Bloch walls in thin films.[5] Using this measured static wall width for the 1200-Å-thick film, the mobility calculated from Eq. (1) is in reasonable agreement with the observed values (see Fig. 5). The wall mobility in films 1000 to 1600 Å thick is limited primarily by intrinsic losses.

SUMMARY

Domain wall mobility for Ni–Fe alloy films has been measured as a function of film thickness from 300 to 1650 Å. Between 300 and 800 Å, the mobility decreases with increasing film thickness. It increases rapidly with increasing film thickness by a factor of five between 900 and 1000 Å. Above 1000 Å, the mobility slowly increases with film thickness out to 1650 Å, the limit of the present measurements. For several films in the 300–1000 Å thickness range, reduced mobilities were observed for high drive fields. No similar effect was observed for thicker films. At present there is no explanation for this effect at increased drive fields. For the 300–800 Å thickness range, the low-field mobility data are in good agreement with predictions based on Lorentz microscopy static wall-shape measurements by Fuchs. The crosstie structure associated with these walls does not appear to affect the mobility. For films thicker than 1000 Å, the mobility is not in agreement with predictions based on static Bloch wall-shape calculations. It is suggested that the sharp increase in mobility at about 950 Å is associated with the wall transition from the crosstie structure to the Bloch-line structure. Static wall-shape measurements performed on 1200-Å-thick films utilizing Lorentz microscopy yield mobility predictions which support this possibility. Intrinsic losses appear to be the dominant loss mechanism for wall motion in films thicker than 1000 Å, due to the extremely large wall width for the Bloch-line structure. For crosstie or Néel walls in thinner films, intrinsic losses are also dominant.

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