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Domain Wall Velocities in Thin Magnetic Films

The relation between the domain wall velocity v in a magnetic film and the applied field H parallel to the easy axis is given by: $v = m_1(H - H_c)$, in which H_c is the wall motion coercive force and m_1 the wall mobility.

Measurements of v as a function of H in bulk magnetic material as well as in magnetic films have confirmed the linear relationship between v and H.

Ford[1] measured m_1 for films with thicknesses between 700 and 4000 Å and found m_1 to be determined mainly by eddy current damping. Copeland and Humphrey[2] measured m_1 on films and thicknesses between 128 and 495 Å and concluded that m_1 was determined by spin relaxation processes. In order to resolve the question of whether in the intermediate thickness region wall velocity is determined by eddy current or by spin relaxation damping effects, this communication reports measurements of m_1 on films with thicknesses ranging between 77 and 2800 Å, the same technique being used throughout.

Measurement method

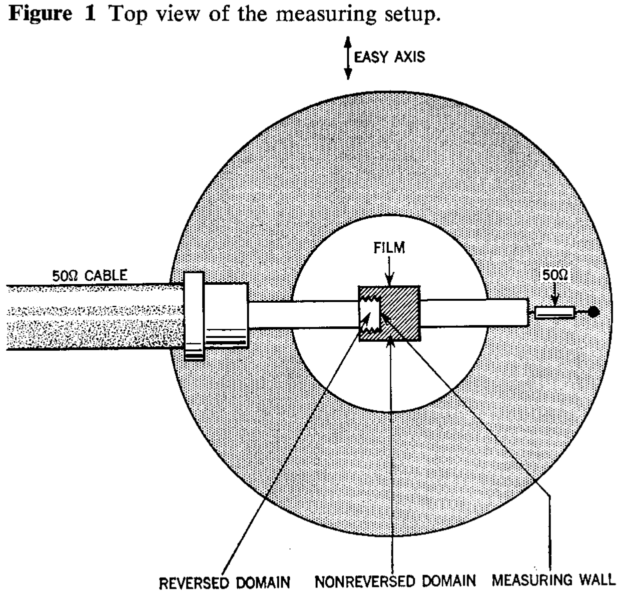
A Kerr magneto-optical apparatus was used, with which wall displacement could be directly observed through a measuring ocular. The Ni-Fe films were vacuum evaporated on heated glass substrates 1 mm thick and having an area of 5 × 5 cm, subsequently cut into pieces one cm square. The films were placed on a stripline 5 mm wide and 1 mm thick with the glass facing downwards and the easy axis parallel to the field direction (Fig. 1). The stripline was terminated with 50Ω and the return conductor was made in the form of a circle.

A mercury relay pulse generator supplied 50 c/sec field pulses 110 nsec wide with a rise time of 1 nsec and a decay time of 2 nsec. The width of the conductor was chosen to be 5 mm, so that film reversal only occurred by the motion of straight walls nucleated at the edges of the film perpendicular to the easy axis. The field at the edges of the film parallel to the easy axis was so small that the triangular domains always present at these edges could not grow. The pulse field due to the stripline was calibrated by superimposing the pulse field with a dc field. At different pulse amplitudes, the dc bias field for which wall motion started to occur was determined. A straight-line relationship between the pulse amplitude and the dc field was obtained, from which the field/current ratio of the stripline could be derived (Fig. 2).

The velocity of the walls was measured. The walls always remained about 5 mm straight across. Bending of the wall because of field inhomogeneities occurred only when glass substrates thinner or thicker than 1 mm were used. For thicker substrates the velocity and field in the center were larger than at the edges, whereas for thinner substrates the opposite was observed.

Before a wall velocity measurement was performed, the film was saturated in one easy direction. Subsequently, a pulse field of an amplitude larger than H_c was applied in the opposite direction. At the edge of the film, a straight wall was nucleated, which moved under the influence of many pulses to a certain predetermined location in the film. Now the pulse amplitude was changed to the required value and the time measured in which the wall moved

Figure 1 Top view of the measuring setup.



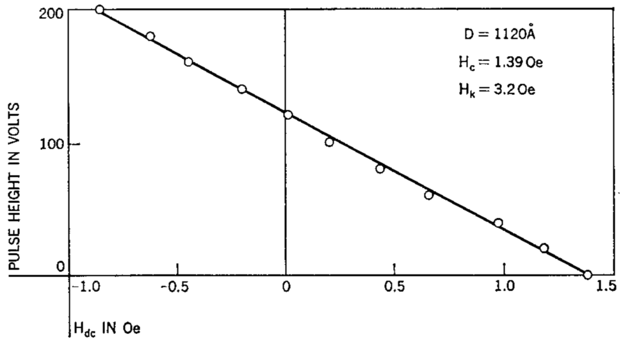


Figure 2 Calibration curve; *vertical:* the pulse height in volts; *horizontal:* the magnetic field in oersteds.

across a predetermined distance, usually 0.6 mm. From this time measurement, the effective wall velocity v was deduced:

$$v = \frac{s}{t_o \cdot t_p \cdot f},$$

in which

s = measuring distance
t_o = measuring time
t_p = pulse length
f = pulse frequency.

The reproducibility of the measurements can be very much improved when a given measuring distance in the film is always used.

The wall mobility m is obtained by plotting v as a function of H and by calculating the slope of this straight line.

Since a certain time is required to accelerate the wall to its final velocity during each pulse, erroneous results might be obtained when the pulses are too short. To check this, the wall mobility in one film was measured for different pulse lengths t_p. It appeared that the wall mobility is the same when the pulse length is varied between 20 and 800 nsec.

Results

Figure 3 shows the wall velocity of a 600 Å film as a function of the applied pulse field. For small fields, this relationship is a straight line that intersects the abscissa at H_c. The wall mobility m_1 can be determined from the slope of this line. When the field amplitude is larger than a certain field H_2 the curve starts to deviate from the straight line. The field H_2 at which the deviation becomes noticeable varies between 1.2 H_c and 1.7 H_c. It is also possible to approximate the curve beyond H_2 by a straight line. The mobility m_2 related to the slope of this second line varies between 0.05 m_1 and 0.6 m_1. A relationship between H_2 and m_2 with film parameters has not yet been found. Deviations of the straight-line relationship between v and H are also found in bulk material. However, m_2 is usually larger than m_1. This effect can be explained by the assumption that at high velocities walls tend to bend, thus increasing their surface. In the experiments described here, this did not occur; the walls remained straight for all field amplitudes, as could be observed by means of the Kerr effect.

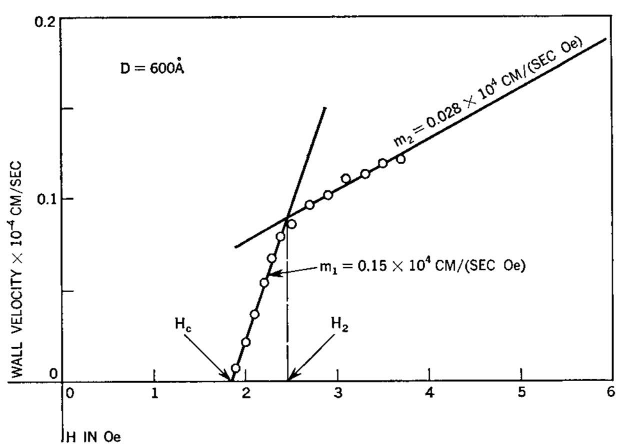
A spurious curve similar to that shown in Fig. 3 might result if the positive drive pulse were followed by a smaller negative one. Such a negative pulse might occur if the 50Ω termination is not correct. The pulse form was therefore continuously monitored on a sampling oscilloscope. Negative pulses did not occur.

When very large drive fields are used, wall nucleation starts to occur in the center of the film and further measurements are no longer possible.

Figure 4 shows a plot of the wall mobility as obtained from the slope of the first part of the curve as a function of the film thickness. About 50 samples were investigated. Thickness varied between 77 and 2800 Å, H_c between 0.5 and 3.9 Oe and H_k between 3.2 and 20.0 Oe. It appears that it is not possible to draw one curve through the measuring points, since films having the same thickness show different wall mobilities. Therefore the results are displayed as a band that contains all the measuring points. The most striking detail of the curve is the pronounced minimum at D = 600 Å.

Comparing mobilities of films having the same thickness, it appears that those films with the largest H_c/H_k ratios have the smallest mobilities. Figure 5 shows the dependence of m_1 on H_c/H_k for films about 475 Å thick.

Figure 3 Wall velocity in a 600 Å film as a function of the field pulse amplitude (H_c = 1.84 Oe, H_k = 6.1 Oe).



Discussion

Three new findings require an explanation: (a) The kink in the curve representing the relationship between the wall velocity and the applied field, (b) the pronounced minimum in the m_1 versus film thickness curve, and (c) the dependence of the wall mobility on the H_c/H_k ratio.

(a) The relation $v = m_1(H - H_c)$ is the so-called viscous flow approximation of the more complete equation of motion[3]

$$m_w \frac{d^2z}{dt^2} + \frac{2M_s}{m_1}\frac{dz}{dt} + 2M_sH_c = 2M_sH,$$

in which m_w is the effective wall mass per square centimeter. For small velocities the first term is negligible. As shown by Smith[4] and Stein[5] a similar viscous flow approximation applies also to coherent rotation of the magnetization in magnetic films when the angular velocity is low. For high angular velocities ($\varphi > 0.1\ \pi$ rad/nsec) the approximation is no longer valid; for large magnetic fields angular velocities using the extended equation of motion are calculated, which are smaller than those obtained with the viscous flow approximation. When a domain wall 1000 Å thick moves with a velocity of 10^3 cm/sec the angular velocity of the spins in the wall is also very large and equal to $0.1\ \pi$ rad/nsec. The kink in the velocity curve, therefore, can very well be due to the fact that for large wall velocities the viscous flow approximation is no longer valid.

(b) The film thickness at which the wall mobility is a minimum is also the thickness at which the cross-tie density of the cross-tie walls is a maximum. It is therefore obvious to try to correlate the mobility minimum with this cross-tie maximum. As shown by Stein[6] the wall mobility m_1 in case of spin relaxation effects is expressed by

$$m_1 = \frac{\gamma}{\alpha}\frac{b}{2\theta_w},$$

in which

γ = gyromagnetic ratio [10^7 (oe sec)$^{-1}$]
α = damping constant (≈ 0.02)
b = wall width
$2\theta_w$ = angle across which the magnetization turns.

A cross-tie wall consists of Néel wall segments of both polarities which are separated by Bloch lines[7]; the diameter of these Bloch lines is about 100 Å, as calculated by Feldtkeller and Thomas.[8] The value $b/2\theta_w$ in the Bloch lines is very small in comparison to the rest of the walls. It is therefore probable that the low wall mobility of cross-tie walls is due to the fact that Néel walls, which themselves could move much faster, have to drag along the slowly moving Bloch lines.

For comparison, the wall mobilities as measured by Ford,[1] Copeland and Humphrey[2] and Patton and Humphrey[9] are also plotted. Except for the wall mobilities measured by Ford in the thinnest films (700 and 1300 Å), agreement is very satisfactory.

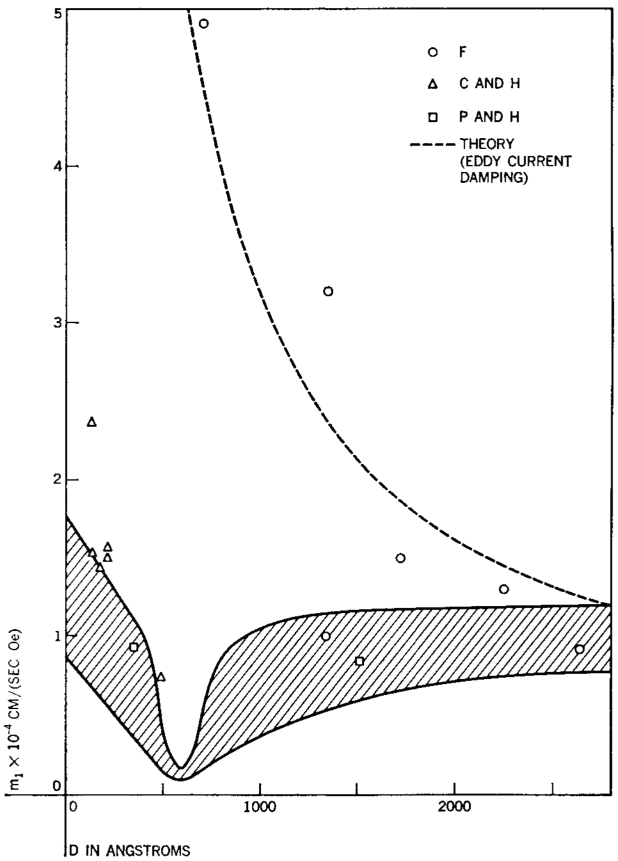


Figure 4 Band containing the wall mobility m_1 of about 50 films as a function of the film thickness D (shaded area). The wall mobilities as measured by Ford[1] (F), Copeland and Humphrey[2] (C&H) and by Patton and Humphrey[9] (P&H) are also indicated. The theoretical dependence of the wall mobility on the film thickness, based on eddy current damping, which gives the best fit with the mobilities as measured by Ford[1] in thick films (part of the measuring points not shown) is indicated by means of a dashed line.

The wall mobility in case of eddy current damping is expressed by

$$m = \frac{C}{M_s\sigma D},$$

in which

C = constant
σ = conductivity
D = film thickness.

The wall mobilities (especially in thicker films not shown in Fig. 4) as measured by Ford[1] fit this expression best, when $C = 1.6 \times 10^{20}$ (dashed curve). It seems therefore that, for films which are thinner than about 2000 Å, wall

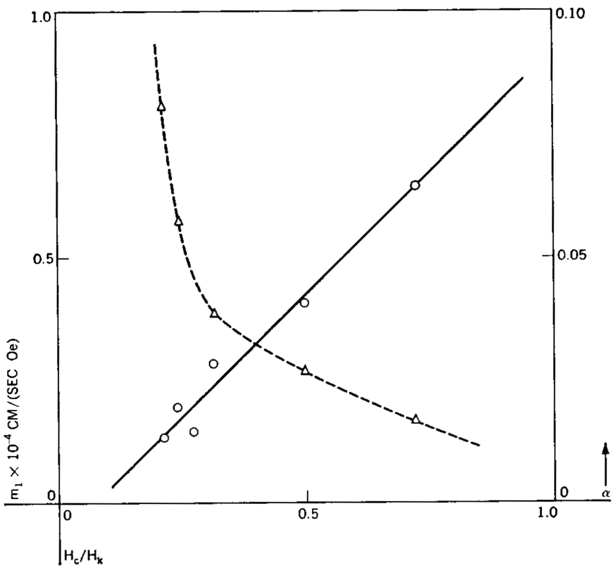


Figure 5 Wall mobility m_1 (dotted line) and damping constant α (solid line) as a function of the H_c/H_k ratio for 475 Å thick films.

mobility is mainly determined by spin relaxation effects.

(c) As shown by Stein[6] in the spin-wave damping theory the wall mobility m_1 is inversely proportional to the damping constant α and proportional to $b/2\theta_w$. Since $b/2\theta_w$ depends only on the film thickness, different wall mobilities in films with the same thickness can be explained only when it is assumed that the damping constant α varies from film to film. Using the b/θ_w value as measured by Fuchs,[10] α can be calculated from the measured wall mobilities. Figure 5 shows α as a function of the H_c/H_k ratio for films with a thickness of about 475 Å. One finds that α increases for increasing H_c/H_k ratio, which is in agreement with the results as published by Stein,[5] who obtained α from coherent rotation experiments. As the H_k's of the different films in these experiments reported here did not vary much, it is also possible that the dependence of α is really on H_c alone.

Conclusions

Wall mobility measurements employing short pulse drive fields show that in films with thicknesses up to 2000 Å the wall velocity is determined by spin relaxation effects rather than by eddy current damping. Further, it seems probable (a) that for high wall velocities the viscous flow approximation is no longer valid, (b) that Bloch lines are responsible for the low mobility of cross-tie walls and (c) that the energy dissipation that is related to α near moving domain walls is larger in films with higher H_c/H_k ratios.

Acknowledgments

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