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INVESTIGATIONS INTO DOMAIN WALL WIDTHS
OF THICK PERMALLOY FILMS BY HIGH-VOLTAGE LORENTZ MICROSCOPY

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I. Introduction. — In spite of considerable efforts to determine experimentally the widths of domain walls in thin ferromagnetic films, in particular by Lorentz electron microscopy, no clear picture has yet emerged. Although the method of Cohen and Harte [1], based on an inversion procedure from the electron intensity distribution, should in principle give accurate wall shapes, the results obtained at 80 kV show large scatter, presumably due to the strong influence of inelastic scattering on the wall image. The validity of the method of Reimer and Kappert [2], which is based on a linear variation of the half-width of a divergent wall image with the defocusing distance, has only been demonstrated for simple one-dimensional models. It is open to question whether this linear variation holds for the actual wall structure; nevertheless, the wall widths obtained in this way agree well with the theoretical predictions [3-5]. Suzuki et al. [6] deduced the wall widths from profile matching. Their results indicate significant discrepancies to the theoretical predictions, particularly for thick films. It is likely that the inelastic scattering strongly influenced the image profile at 100 kV for these thick films. In contrast to this method Guigay et al. [7] proposed a method by which the wall width is obtained from the contrast at the wall centre. The present work explores the feasibility of using high-voltage Lorentz electron microscopy in order to study, and if possible to eliminate, the effect of inelastic scattering on the determination of wall widths from both the profile matching and the contrast method. Only the divergent wall images taken at small defocusing distances (2 mm to 4 cm) were considered, since in this case classical optics can be applicable in interpreting the images [7, 8]. A Hitachi high-voltage microscope operated at 650 kV was used. The Permalloy samples investigated were evaporated in vacuum of about 10^{-7} torr at room temperature.

II. Domain wall width measurements. — Recently Suzuki et al. [9] discussed the effects of inelastic scattering on the wall image contrast, and reported energy loss parameters ok in the range 20 to 50 eV/1 000 Å. Based on these results, it is possible to deduce the wall width from (1) the contrast at the wall center, and (2) the profile match method. According to classical optics, the contrast C(ξ) at the image coordinate ξ is given by

\[
C(ξ) = \int_{-\infty}^{\infty} C_0(ξ(x + ω)) J(ω) \, dω
\]

where ξ = χ + ω, χ is the defocusing distance, ω is the magnetic scattering angle, x is the film coordinate normal to the wall direction, γ is the magnetization component parallel to the wall, C_0 is the contrast function with zero beam broadening, and J is a function describing the beam broadening due to the incident illumination angle α_0 and due to the angle α associated with inelastic scattering. Figure 1 shows the result of the contrast at ξ = x = 0 as a function of parameter S (= a_0/ω_m) for a one-dimensional wall model

\[
γ = \cos θ = \left( \frac{2}{π} \right) \tan^{-1} \left( \frac{x}{δ} \right)
\]

(θ = angle between the magnetization M(x) and the...
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domain magnetization direction; \( \delta \) defines the wall width. The function \( J \) was assumed to be a Gaussian \( e^{-(x/a)^2} \) with \( a = (\alpha_x^2 + \alpha_y^2)^{1/2} \). The angle \( \alpha_x \) is related to the energy loss through

\[
\alpha_x = \left( \frac{\sigma kd}{(m_0 e^2)} \right) \sqrt{1 - \beta^2/v^2},
\]

where \( d \) is the film thickness, \( \beta = v/c, v \) and \( c \) are the velocities of electrons and of light, respectively \((m_0 e^2 = 5.11 \times 10^6 \text{ eV})\).

\[\text{FIG. 2.} \quad \text{The measured contrast as a function of } z \text{ for the } 140^\circ \text{ wall in the } 1.500 \text{ Å thick Permalloy film. The theoretical curves with } \sigma k = 20 \text{ and } 50 \text{ eV/1000 Å are also shown. } R = 1.8 \text{ and } 3.2 \text{ at } z = 4.55 \text{ mm for } \sigma k = 20 \text{ and } 50 \text{ eV/1000 Å, respectively.}\]

The image profile is sensitive to the wall width. For a given \( S \), one can also find the wall width by adjusting \( \delta \) to match the experimental profile with that theoretically predicted [6]. An example of the profile match for the 140° domain wall in the 1.500 Å thick film is shown in figure 3.

\[\text{FIG. 3.} \quad \text{An example of the profile match for the } 140^\circ \text{ wall in the } 1.500 \text{ Å thick Permalloy film. } \bullet \text{ are the experimental values and } \cdot \text{ is the theoretical curve with } \delta = 574 \text{ Å.}\]

The summary of the wall widths \( a_1 \) and \( a_m \) obtained by both methods is given in Table I, with the values \( a_0 \) obtained by the linear extrapolation methods [2, 3, 4] and the theoretically predicted values [5]. Since \( a_{m,0} \) is related to \( a_0 \) as shown below, the values converted from \( a_0 \) are also given.

### Table I

<table>
<thead>
<tr>
<th>( d ) (Å)</th>
<th>( \theta )</th>
<th>( a_1 )</th>
<th>( a_m )</th>
<th>( a_0 )</th>
<th>( a_{m,0} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.500 Å</td>
<td>180°</td>
<td>1.560</td>
<td>1.570</td>
<td>2.200</td>
<td>895</td>
</tr>
<tr>
<td>1.500 Å</td>
<td>140°</td>
<td>2.010</td>
<td>2.820</td>
<td>3.400</td>
<td>1.373</td>
</tr>
<tr>
<td>1.500 Å</td>
<td>70°</td>
<td>3.000</td>
<td>3.080</td>
<td>4.140</td>
<td>3.760</td>
</tr>
<tr>
<td>2.000 Å</td>
<td>90°</td>
<td>4.140</td>
<td>3.760</td>
<td>4.210</td>
<td>1.712</td>
</tr>
<tr>
<td>3.000 Å</td>
<td>140°</td>
<td>1.560</td>
<td>1.570</td>
<td>2.200</td>
<td>895</td>
</tr>
</tbody>
</table>

The wall widths \( a_1 \) and \( a_{m,0} \) are obtained by \( \pi(d)(dx)^{-1} \) using the values \( \delta \) determined from the contrast at wall centre, and from the profile match method, respectively. The values in \( a_1 \) and \( a_{m,0} \) with and without \( (\) \) are for \( \sigma k = 20 \) and 50 eV/1000 Å, respectively. \( a_0 \) is the wall width determined by the linear extrapolation method and is defined by the half width of \( \gamma' \). The values \( a_1 \) are those converted from \( a_0 \) using \( a_1 = (\pi/2)^2 a_0 \) and should be compared with \( a_1 \) and \( a_{m,0} \). \( a \) is the theoretical wall width determined by \( \pi(d)(dx)x_{m,n} = 0 \).

### III. Discussion.

Though the influence of inelastic scattering becomes less important with accelerating voltage, one cannot neglect it even at 650 kV in deducing the wall width, as shown in Table I. Previous work carried out at low-voltages without taking into account the effects, therefore, should be reconsidered. The present data indicate the uncertainty in wall width, since the accurate value of \( \sigma k \) is not known, but even so there is a reasonable agreement between the theory and the measured values, using the reasonable value \( \sigma k \) in the range 20 and 50 eV/1000 Å.

In Table I, it should be kept in mind that \( a_0 \) corresponds to the wall width defined by the half width of \( \gamma' \) [8] (for the present model, \( a_0 = 2 \delta \)), whereas \( a_0 = a_{m,0} = (\pi/2)^2 \delta \). Since it is necessary to normalize the definition to compare these values, the values of \( a_0 \) are converted to those defined by \( \pi(d)(dx)x_{m,n} = 0 \). These values are given by \( a_1 = (\pi/2)^2 a_0 \). As shown in Table I, the measured wall widths \( a_1 \) are in reasonable agreement with \( a_1 \) and \( a_{m,0} \) except for the case of the 70° wall.

The discussion in the present work is based on the simple wall model. One may argue that the real wall structure may be significantly different from the present one. However, it should be stressed that the intensity profile is sensitive not to the wall shape but to the wall width. It is also confirmed that the image profile based on the wall model by Hubert [5] for a Néel wall is nearly the same as that based on the present model. Thus, we conclude that the values determined in the present work are representative for the wall widths in evaporated thin films.

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References