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Can energy filtered Fresnel imaging be used to determine the width of magnetic domain walls?

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ABSTRACT: Fresnel contrast in energy filtered images of magnetic domain walls in $Nd_2Fe_{14}B$ is examined as a function of specimen thickness and defocus. The experimental contrast is compared with simulations of model structures with domain wall widths varying from 2 to 20nm. The form of the contrast is explained as a combination of interference between the beams passing through adjacent domains and Fresnel contrast from the boundary itself. Images from foils of thickness greater than 100nm show a greater sensitivity to the domain wall width. The experimental contrast was consistent with domain walls 5nm wide.

1. INTRODUCTION

The width of domain walls is a critical parameter in determining the properties of magnetic materials, but it is surprisingly difficult to measure it reliably and accurately from TEM images, especially for domain walls only a few nm wide (Gong and Chapman, 1987). Here we reassess the possibility of using Fresnel imaging to measure domain wall widths in $Nd_2Fe_{14}B$ using a 300kV Philips FEG TEM. This microscope is equipped with a 'Lorentz lens' (C_s=8m, C_c=41mm) which allows field-free operation at high resolution (information limit of 2nm) and the FEG source ensures a high beam coherence. A Gatan imaging filter can be used to remove the inelastic scattering from the image and this enables the image intensity from domain walls for a large range of foil thicknesses to be compared quantitatively with simulation.

Here we examine a complete defocus series, rather than a single image, which is fitted with a model boundary, as has been successfully used in the past to determine the projected potential profile in non-magnetic materials (Lloyd and Dunin-Borkowski, 1999). An alternative model-independent approach would be to use the defocus series to reconstruct the exit wavefunction as suggested by Dooley and De Graef (1997).

2. RESULTS AND DISCUSSION

TEM specimens were prepared from a polycrystalline NdFeB disc by electropolishing and immediately transferred to the microscope to minimise any surface oxidation. A typical domain pattern is shown in Fig.1. Energy filtered defocus series with step sizes 0.12mm and 0.02mm were taken using the Lorentz lens with an objective aperture of 3mrad and a beam convergence semi-angle of ~0.005mrad. Foil thickness was estimated from the ratio of a filtered and unfiltered image using a calculated inelastic mean free path of 150nm (Egerton, 1996). For the larger defocus (Δf) steps the images were subsequently resampled to correct for magnification change and image rotation as a function of Δf.

Simulated images were generated from model wall structures of thickness 2 to 20nm as described in Gong and Chapman (1987). A tanh function was used to model the magnetisation profile (Fuller and Hale, 1960) and this produced the phase change in the exit wavefunction shown in Fig.2.

The experimental defocus series in Figs.3a and b were extracted from the region shown

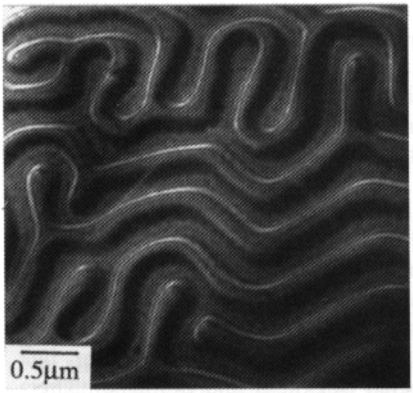


Fig.1. Domain pattern in $Nd_2Fe_{14}B$.

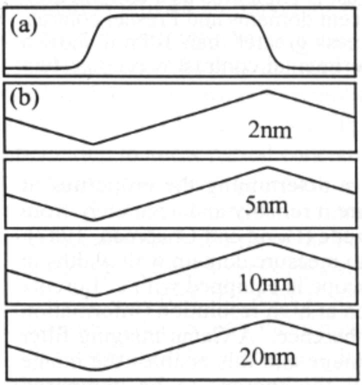


Fig.2. (a) Model magnetisation profile (a tanh function) for two 20nm domain walls of opposite sign separated by 205nm. (b) Phase change in the exit wavefunction for models with different domain wall widths.

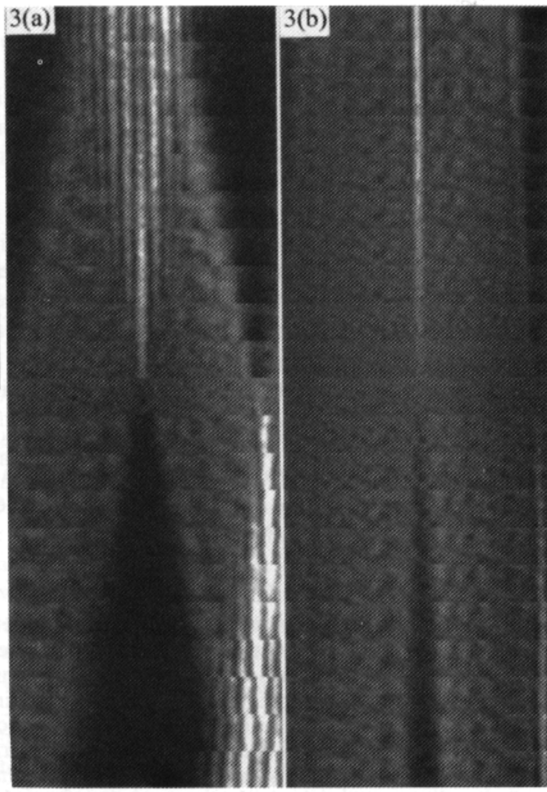
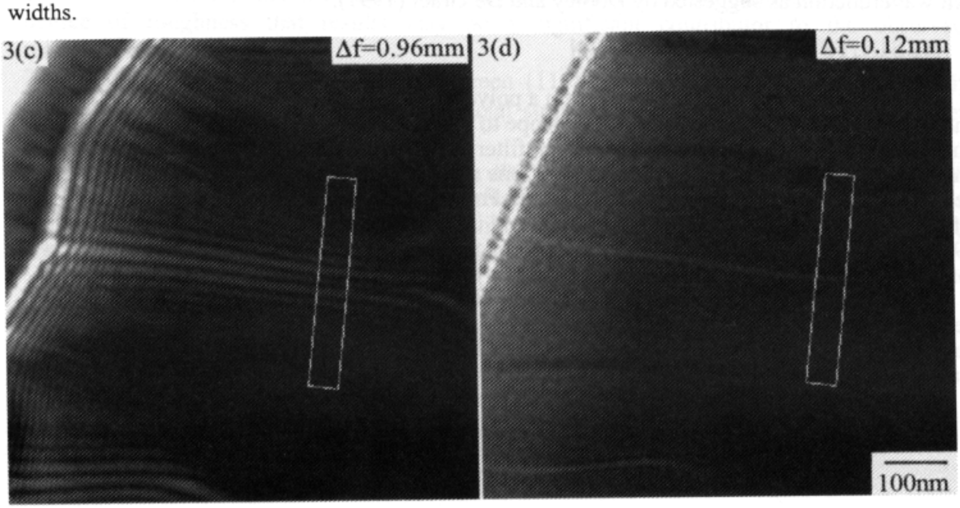


Fig.3a&b. Through focus series of images from the region containing a domain wall shown in (c) and (d). Defocus steps are 0.12mm in (a) and 0.02mm in (b). The Fresnel fringes at the edge of the specimen in (c) indicate the high coherence of the incident beam.



in Figs.3c and d at which the foil thickness was 220nm. The two defocus ranges show very distinct behaviour. For large Δf (Fig.3a) the fringe pattern seen in the 'convergent wall' is dominated by the interference between beams deflected in opposite directions either side of the domain wall; the fringe spacing is constant and the width of the overlap region increases with increasing Δf. The width of the overlap region also increases with thickness although this effect is obscured by interference from the adjacent 'divergent wall' as seen in Fig.3c in which the foil thicknesses increases from left to right in the image. Interestingly, the central fringe shows a maxima in its intensity at a Δf~0.48mm. For the smaller Δf (Fig.3b) the intensity and width of the central bright fringe increases with increasing Δf. The effect of fringing fields at the specimen edge can be clearly seen in Fig.3c. These have not been included in the simulations since to first order they should not change the contrast (Fuller and Hale, 1960). The effect of the fringing field associated with the domain wall itself will be less significant at the large foil thicknesses examined here.

At large Δf the fringe spacing decreases with increasing magnetisation-thickness product (B_0t) and is insensitive to the domain wall width. This can be used to determine a best fitting value for B_0t of 240Tnm and using the estimated foil thickness of 220nm, this gives B_0=1.1±0.3T. Intensity profiles from the images in Figs.3a and b are compared to profiles simulated for different wall widths and a B_0t of 240Tnm in Figs.4a and b. The visibility of the interference fringes at high Δf is very sensitive to beam convergence and this allowed the experimental beam convergence for this series to be measured as 0.004mrad.

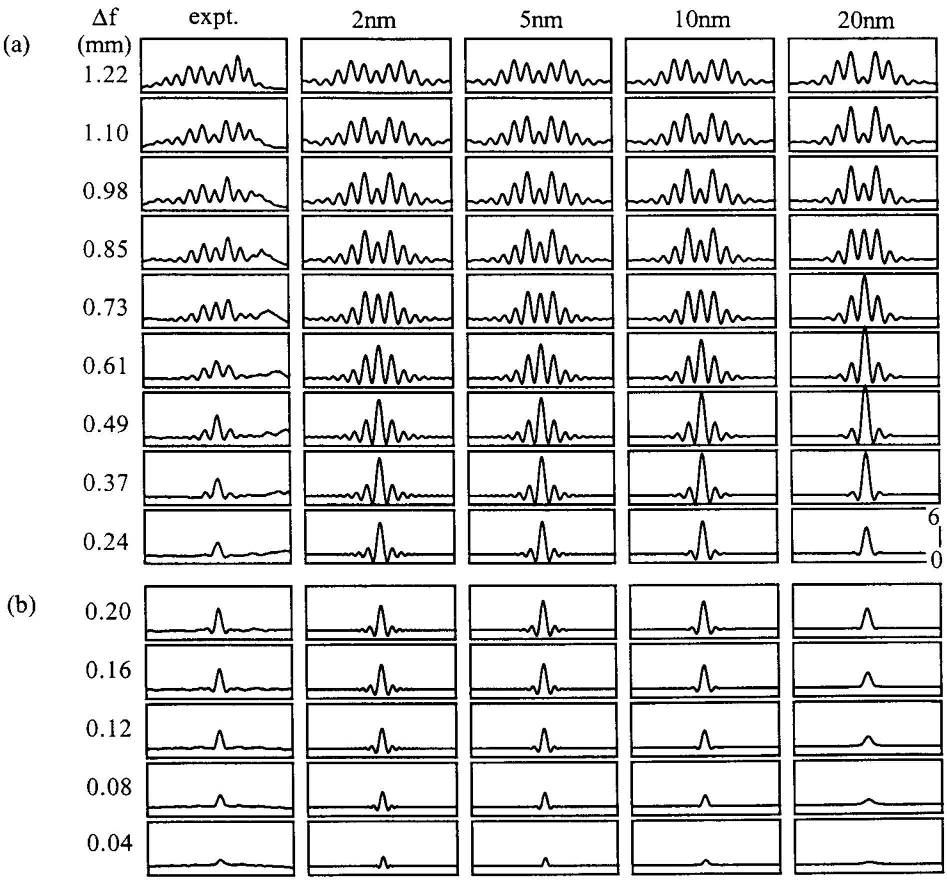


Fig.4a&b. Experimental fringe intensity profiles compared with simulations with domain wall widths 2 to 20nm.

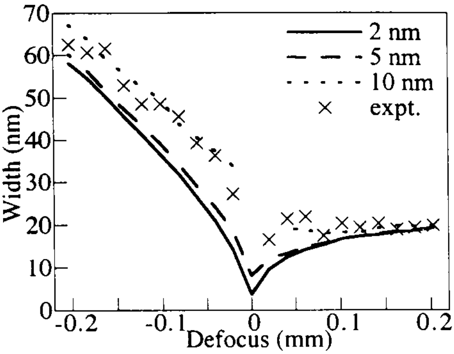


Fig.5. Width of central fringe as a function of defocus.

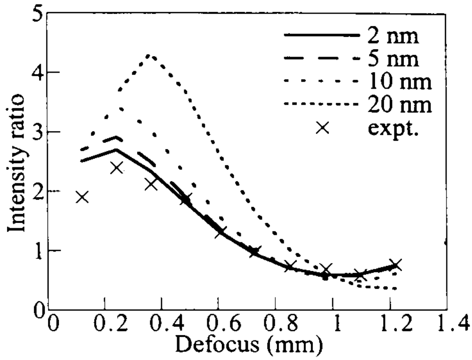


Fig.6. Intensity ratio of central and first subsidiary fringe as a function of defocus.

Traditionally the width of domain walls has been measured by extrapolating the central fringe width to zero Δf as plotted in Fig.5. The divergent wall width is more sensitive to changes in the wall width than the central fringe of the convergent wall image, but experimentally it is very difficult to measure its width accurately, especially if there is interference from adjacent domain walls. From Fig.5 it would appear that the wall thickness is around 10nm, but there is a large systematic error inherent in such an approach due to the difficulty in defining the edge of the divergent wall. However, the *intensity* pattern of the convergent wall profiles is also affected by the domain wall width. For small Δf the narrower domain walls can be distinguished by the larger number of subsidiary fringes, although experimentally noise would preclude these providing a reliable way to determine wall thickness. However at large Δf the intensity of the high contrast fringes also varies as a function of wall width as has been noted previously by Warrington (1964). Simulations showed that this modulation of the interference fringe intensity by the Fresnel diffraction from the domain wall was only significant for $B_0t>160$Tnm. Fig.6 plots the ratio of the intensity of the central and the first subsidiary fringe as a function of defocus. For greater wall widths the period of this intensity oscillation 'envelope' is reduced because Fresnel effects from the boundary are more significant. The experimental profiles fit best with the 5nm wall model at Δf sufficiently large for the contrast of the subsidiary fringes to be greater than the noise.

3. CONCLUSIONS

The width of narrow magnetic domain walls is most reliably measured by examining the intensity distribution of the interference fringes of convergent walls at relatively large foil thicknesses for which energy filtering is essential. Using this approach the domain wall width in $Nd_2Fe_{14}B$ was determined to be ~5nm.

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