Imaging magnetisation using Lorentz microscopy

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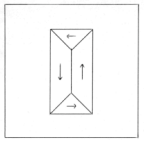
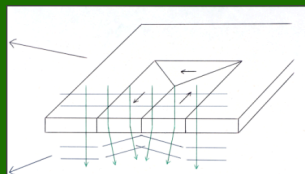
Magnetic domains in thin films are not normally visible in transmission electron microscope images because magnetic fields only deflect the electrons, thus changing their phase, without affecting their intensity. Domains can be made visible by changing the microscope focus to look either above or below the specimen, and this technique is called Lorentz microscopy. In Lorentz images the magnetic domains are outlined by black or white lines but it is difficult to tell the direction of magnetisation. Here a method is illustrated for determining the magnetisation from a Lorentz image.

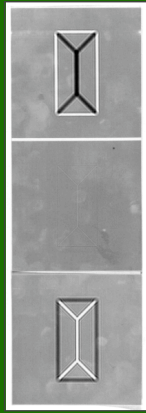
Simulated images of a test domain structure



Test magnetic domain structure. Arrows show direction of magnetisation (**B**)



Interaction of the electron wave with a test magnetic structure (above) in an electron microscope. The magnetisation causes a phase change in the electron wave (shown on the left). Simulated Lorentz images of this structure are shown on the right.



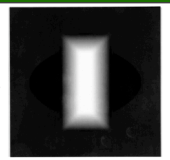
Underfocus, focused 20 μm above specimen

At focus

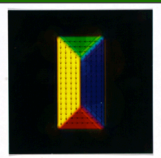
Overfocus, focused 20 μm below specimen

Simulated Lorentz images of a test magnetic structure. Note that the magnetisation is virtually invisible when imaged in focus (middle image).

Phase change induced in electron wave on passing through test structure

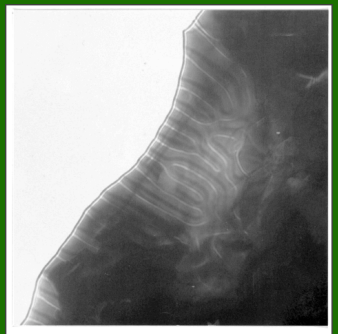


Electron phase change recovered from the underfocus image above



Magnetisation determined from the phase image (left). The colours represent the direction of magnetisation, as shown by the arrows and the intensity represents the strength of the magnetic field

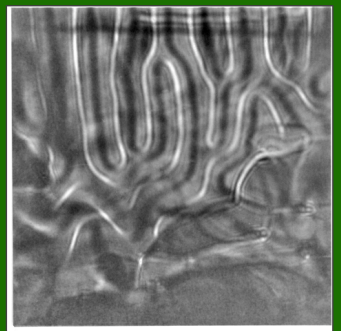
Magnetic domains in NdFeB



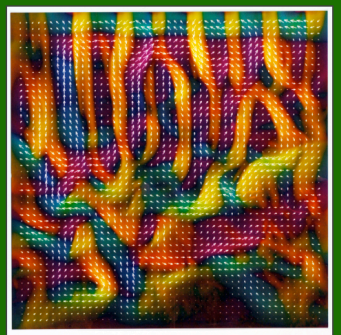
Original Lorentz image of $Nd_2Fe_{14}B$ showing domain boundaries at the edge of a thin foil

Thanks to M R McCartney at ASU for this image

Electron phase change recovered from the above image

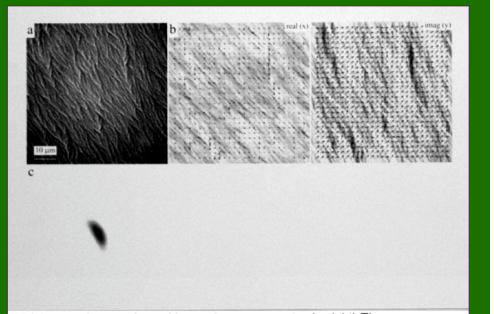


Region at the centre of the Lorentz image on the left corrected for intensity variations due to specimen thickness



Strength and direction of magnetisation in NdFeB. Such images can be compared with electron phases determined by holography, which is a more accurate but also more difficult technique for measuring electron phases and hence magnetisation

Magnetic domains in Co

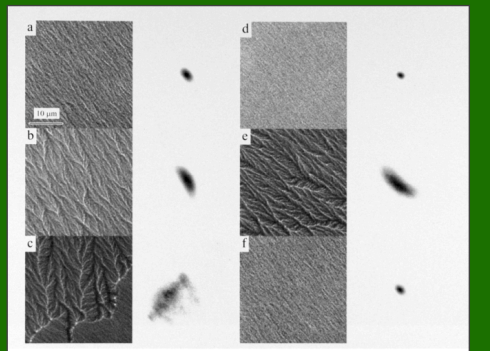


a) Lorentz image of a 15 nm thick Co film within a tunnel junction (IBM Almaden) with an applied field of -2.6×10^{-3} T.

b) x and y components of magnetisation recovered from a) with arrows on left image showing strength and direction.

b, right) The arrows on the right image show the magnetisation after correction for the average magnetisation. The average magnetisation is found by ensuring that the arc in the histogram in c is centred at the origin.

c) Histogram of x and y components of magnetisation from b with the x component horizontally, the y component vertically and the origin in the middle. Dark means higher frequency and it can be seen that the histogram forms an arc of a circle.



Lorentz images and histograms of the magnetisation direction (as above) as the Co film is taken through a hysteresis cycle. The field applied for each image is: a) 0, b) -2.6×10^{-3}, c) -2.8×10^{-3}, d) -6.7×10^{-3}, e) $+2.9\times10^{-3}$, and f) $+3.2\times10^{-3}$ T. Note that the magnetisation in c) is not recovered properly as there is a reversal of magnetisation across the image on a scale larger than the area of the image, thus making the corresponding histogram difficult to interpret.