Exchange coupling, antiphase boundaries, and the origin of self-reversed thermoremanent magnetization

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Part I: Electron Holography

Self-reversed thermoremanent magnetization (SR-TRM) in the ilmenite-hematite system is thought to result from negative exchange coupling between antiphase domains (APDs) and antiphase domain boundaries (APBs), which form after rapid cooling through an Fe-Ti ordering transition. Here we present a study of exchange coupling at APBs using a combination of off-axis electron holography and Monte Carlo simulations.

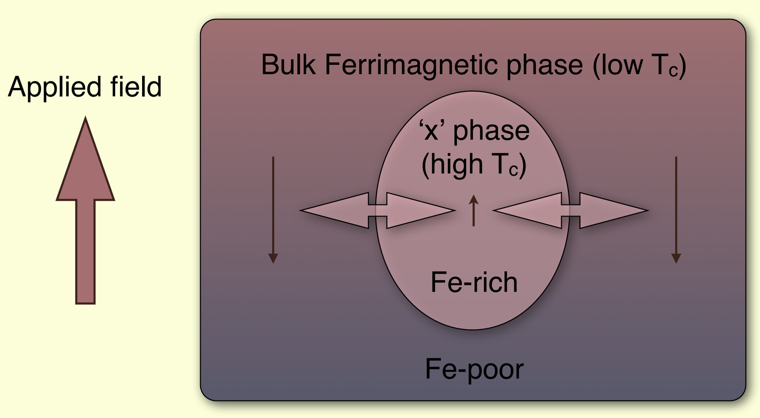


Fig. 1. Most theories of SR-TRM require two phases: an Fe-rich weakly magnetic 'x-phase' and an Fe-poor strongly magnetic bulk phase. Negative exchange coupling across the interface between the x-phase and the bulk phase leads to self reversal.

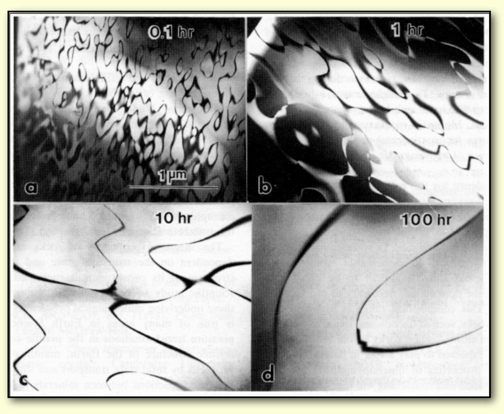


Fig. 2. Nord and Lawson (1992) and Hoffman (1992) proposed that APBs in ilmenite-hematite act as the x-phase. The model requires that the APBs are Fe-enriched relative to the APDs. The nature of the magnetic exchange coupling at APBs, and how it leads to self reversal, is still debated.

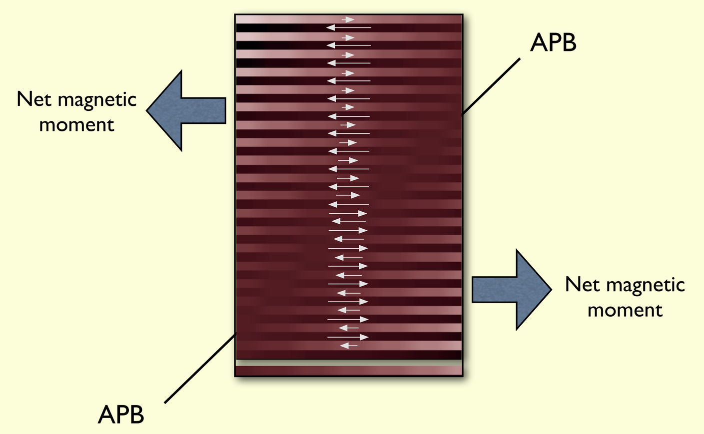


Fig. 3. A simple model of two APDs separated by an APB shows that the switch round of Fe-rich and Ti-rich layers at an APB should lead to a 180° reversal of the net ferrimagnetic moment.

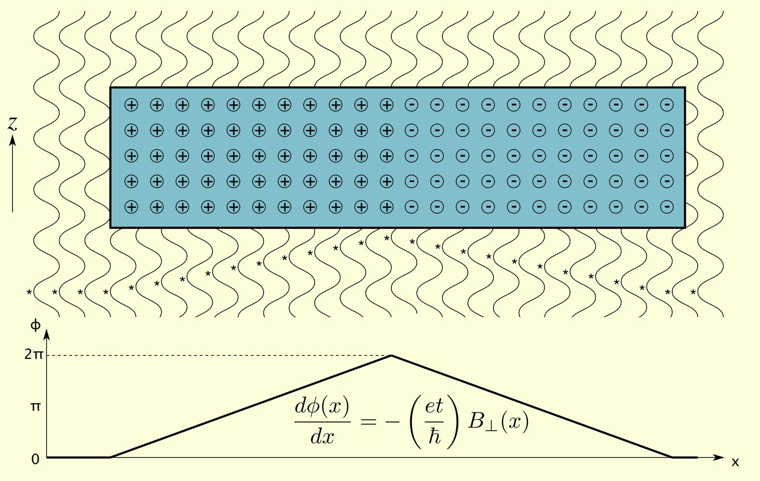


Fig. 4. When electrons pass through a magnetic sample, they undergo a phase shift determined by the in-plane component of magnetic induction

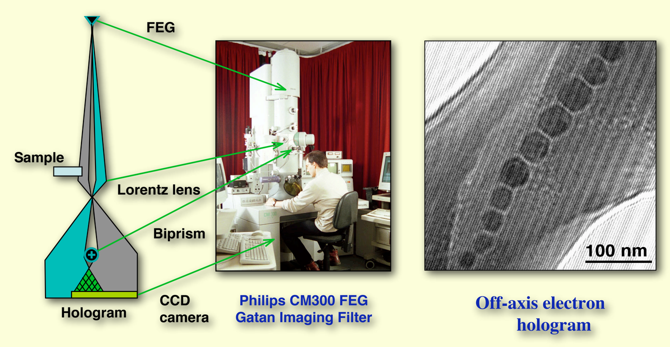


Fig. 5. Normally when a TEM image is recorded, we see the spatial distribution of intensity: all information about the phase of the electrons is lost. Electron holography is an interference technique that allows the phase information to be recovered.

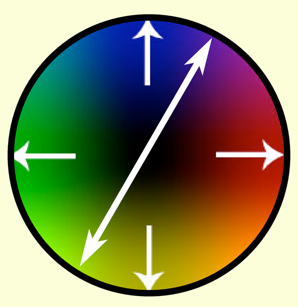


Fig. 6. The direction and magnitude of the in-plane component of magnetic induction can be calculated from the gradient of the holographic phase shift. This is then represented by the hue and intensity of a colour. Blue-purple and yellow-green colours correspond to magnetisation in opposite directions, as shown by the double arrow. Black corresponds to zero in-plane component of magnetisation.

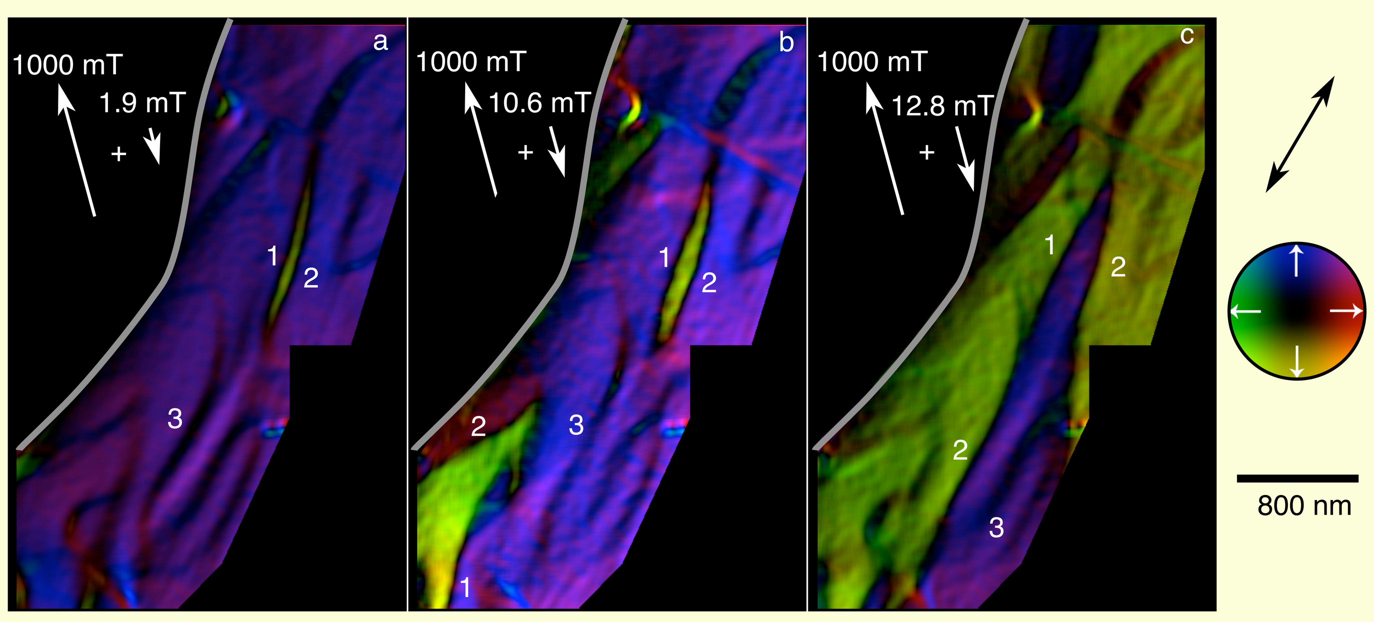
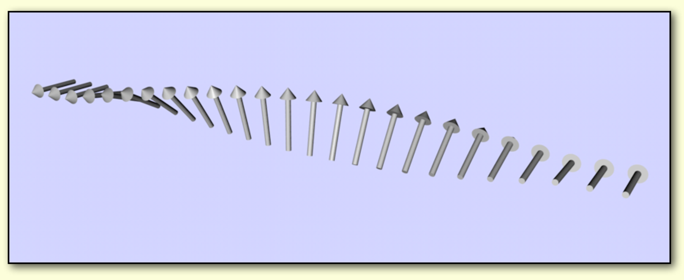


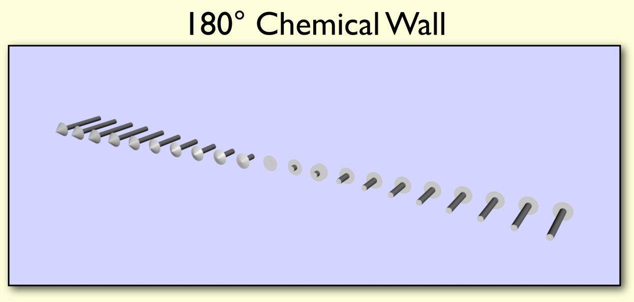
Fig. 7. The sample edge is indicated by the grey line. Prior to each measurement, the sample was exposed to a saturating field with an in-plane component of +1000 mT, followed by a smaller field with an in-plane component of (a) -1.9 mT, (b) -10.6 mT, (c) -12.8 mT. The dark bands indicate regions with weak in-plane magnetisation (magnetic domain walls). Dark bands that separate regions of blue and green colour correspond to 180° magnetic and chemical walls (e.g., at regions labelled '1' and '2', respectively). Dark bands that are surrounded by regions of the same colour correspond to 0° magnetic walls (e.g., at regions labelled '3').

180° Bloch Wall



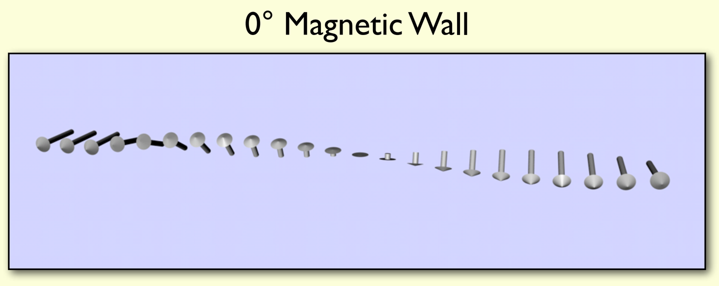
Magnetic moments gradually rotate out of the plane. Wall is free to move throughout the interior of an antiphase domain.

180° Chemical Wall



Magnetic moments stay in plane. The net magnetisation decreases to zero at the APB (antiferromagnetic) and then increases in the opposite direction due to the switch round of Fe and Ti layers

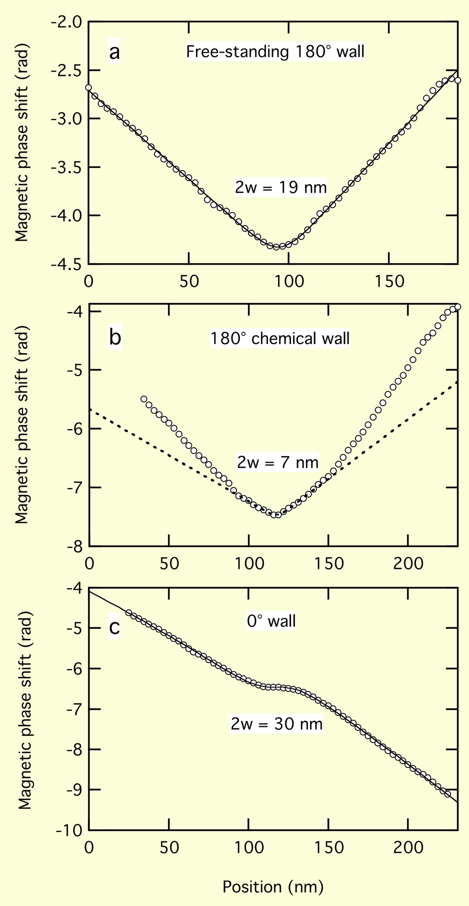
0° Magnetic Wall



When a Bloch gets trapped at an APB, the magnetisation on either side of the wall points in the same direction. These walls form when the applied field is high enough to overcome the negative exchange coupling.

Fig. 8

Wall profiles determined by holography



Slope of phase shift gives in-plane magnetisation

$$\frac{d\phi(x)}{dx} = -\left(\frac{et}{\hbar}\right) B_\perp(x)$$

Bloch wall magnetisation described by:

$$B_\perp(x) = B_0 \tanh\left(\frac{x}{w}\right)$$

Chemical wall can be approximated with the same function.
0° wall is superposition of two, giving:

$$B_\perp(x) = B_0 \tanh^2\left(\frac{x}{w}\right)$$

Fig. 9. Line profiles taken across the three different domain wall types allow the magnetisation profile across the wall to be determined quantitatively. Free standing 180° walls are well described by classical equation for a Bloch wall with width 19 nm. Chemical walls show a more complex profile with a sharper reversal of magnetisation (upper limit of 7 nm). 0° walls are well described by a tanh² profile, and are significantly wider than free-standing walls (average of 50 nm).