The measurement of local magnetic and electric fields using off-axis electron holography

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Off-axis electron holography in the transmission electron microscope (TEM) is a powerful technique, which allows the amplitude and the phase shift of the aberrated electron wave that has passed through a sample to be determined directly. The phase shift of the electron wave deduced from a medium-resolution electron hologram can be used to provide quantitative information about electrostatic and magnetic fields within the sample to a resolution that can approach the nanometre scale under optimal conditions.

The present work centres on the application of off-axis electron holography to lithographically patterned magnetic elements that have lateral dimensions of 70-500 nm, thicknesses of 3-30 nm and a wide range of shapes and layer sequences. A detailed understanding of the magnetization reversal behaviour of such elements, which have properties that differ markedly from those of both larger elements and continuous films, is essential for their utilisation in high density magnetic recording media and read heads for hard-disk drives. The behaviour of 30 nm-thick Co elements is compared with that of 10 nm-thick Ni and Co elements, as well as with Co/Au/Ni trilayers. The hysteresis loops of individual elements are determined directly from measured holographic phase images. The reproducibility of an element's domain structure in successive cycles is found to be affected by the out-of-plane component of the applied magnetic field and by the exact details of its initial magnetic state. Close proximity to adjacent elements leads to strong intercell coupling, and remanent states (such as that shown in Fig. 1) include domain structures that are never observed during hysteresis cycling. Narrow rectangular bars are found to reverse without the formation of end domains, while closely-separated magnetic layers within individual elements are observed to couple to each other antiferromagnetically during field reversal.

The examination of dopant contrast in transistors prepared for TEM examination using focused ion beam milling (FIB) is also addressed. Off-axis electron holography is used to form two-dimensional maps of the electrostatic potential, in which *n*- and *p*-type regions are distinguished as bright and dark contrast in phase images, respectively. Artefacts associated with sample thickness variations, charging and electrically 'dead' layers on the sample surface are described. For example, FIB milling results in thickness corrugations in doped regions, causing rapid variations in both the amplitude and the phase of the reconstructed image wave . Possible solutions to this problem include image processing the phase image to extract the depletion region potential of interest and performing the final FIB milling from the substrate side.

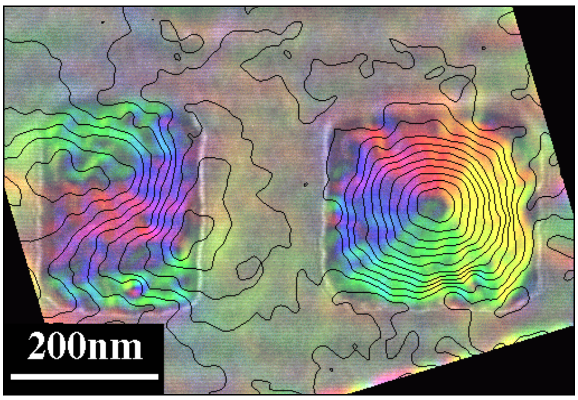

Figure 1. Magnetic contribution to phase of hologram showing remanent state of two 30 nm-thick Co rectangles (with sample in small residual out-of-plane field of 130 Oe). Phase contours lie parallel to lines of constant magnetic induction integrated in incident beam direction. Contour spacing is 0.21 π radians. Image was obtained directly after applying large out-of-plane field of ~30,000 Oe to sample and then reducing this field to 130 Oe.