OFF-AXIS ELECTRON HOLOGRAPHY OF MAGNETIC MICROSTRUCTURE IN NANOMAGNET ARRAYS FABRICATED BY INTERFEROMETRIC LITHOGRAPHY

R E DUNIN-BORKOWSKI[a], S B NEWCOMB[b], M R MCCARTNEY[c], C A ROSS[d] and M FARHOUD[d]

[a] Dept of Materials Science and Metallurgy, Pembroke Street, Cambridge CB2 3QZ, UK

[b] Materials and Surface Science Institute, University of Limerick, Limerick, Ireland

[c] Center for Solid State Science, Arizona State University, Tempe, AZ 85287-1704, USA

[d] Dept of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Off-axis electron holography in the transmission electron microscope involves the measurement of the amplitude and phase shift of an electron wave that has passed through a material. A field emission gun is used to provide a coherent source of electrons and a biprism is used to overlap an electron wave that has passed through the sample with one that has passed only through vacuum. Information about electric and magnetic fields in the sample is recorded in the local position (the phase) of the holographic interference fringes that form in the overlap region. Unwanted compositional contributions to the contrast, such as those at the edges of submicron-sized magnetic elements, can be removed far more easily from a holographic phase image than from equivalent phase gradient images recorded using techniques such as differential phase contrast microscopy. As a result, both the magnetic fields within nanostructured elements and the magnetic interactions between them can be quantified at all points across an image on a nm-scale [1].

We have used off-axis electron holography to characterise the magnetic microstructure of periodic arrays of nanomagnets fabricated directly onto Si using interferometric lithography [2]. Samples were prepared for transmission electron microscopy using focused ion beam milling. Results were obtained from both evaporated 100 nm diameter 20 nm thick Co dots, which were arranged in square arrays of side 200 nm and examined in plan-view, and electroplated 50 nm diameter 200 nm high Ni pillars, which were arranged in square arrays of side 100 nm and examined in cross-section. Representative holograms of the two samples are shown in Fig. 1. Subtraction of the mean inner potential contribution to the measured phase was essential for successful characterisation of the magnetic microstructure in the two samples. Figure 2 shows examples of contours added to the resulting magnetic contributions to the phase. Such images provide semi-quantitative maps of the magnetic field within and around the dots and pillars, which are observed to interact strongly with each other in each sample. Equivalent images have been obtained that demonstrate coupling between closely-separated magnetic layers in individual deep-submicron spin valve elements.

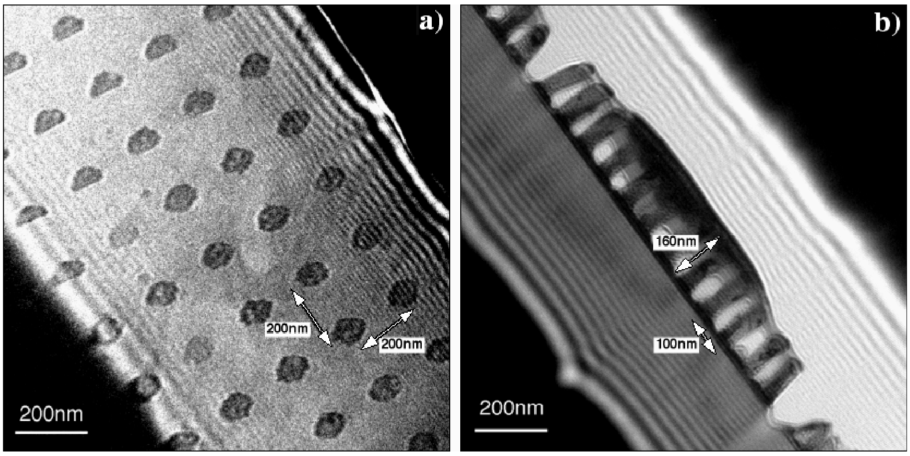

Fig. 1. Off-axis electron holograms of a) Co dots examined in plan-view and b) Ni pillars examined in cross-section, obtained at 200 kV using a Philips CM200 field emission gun transmission electron microscope. The microscope was operated in Lorentz mode with the conventional objective lens switched off. The holograms were recorded digitally using acquisition times of 4 s and biprism voltages of 160 and 140 V, respectively. Both samples were made using focused ion beam milling. Reference holograms were always recorded to take account of artefacts associated with the imaging and recording system.

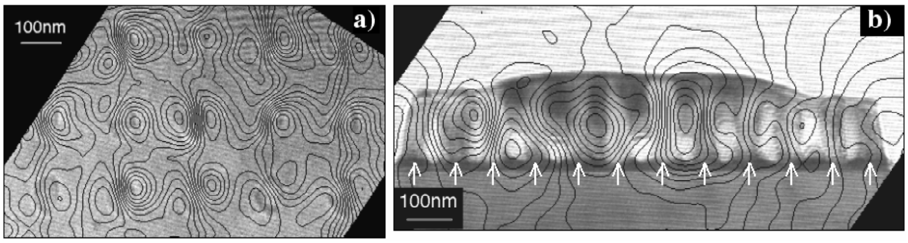

Fig. 2. Magnetic contributions to measured electron holographic phases for remanent states of a) Co dots (contour spacing 0.033 radians) and b) Ni pillars (arrowed, contour spacing 0.05 radians). The contour spacing is inversely proportional to the in-plane component of the magnetic induction integrated in the incident beam direction Note the strong interactions between the Ni pillars, which were initially thought to be perpendicularly magnetised, and the magnetic domains within them.

References:

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2. Farhoud, M., Hwang, M., Smith, H.I., Schattenburg, M.L., Bae, J.M., Youcef-Toumi, K., Ross, C.A. (1998): Fabrication of large area nanostructured magnets by interferometric lithography. *IEEE Trans. Magn.*, **34**, 1087-1089.