The measurement of magnetic fields in nanostructured materials and devices using electron holography

R.E. Dunin-Borkowski[1,2], T. Kasama[2,1], S.B. Newcomb[3], F. Castaño[4], C.A. Ross[4]

1 Dept of Materials Science and Metallurgy, University of Cambridge, Pembroke Street, Cambridge CB2 3QZ, UK
2 Frontier Research System, The Institute of Physical and Chemical Research, Hatoyama,Saitama 350-0395, Japan
3 Glebe Scientific Limited, Glebe Laboratories, Newport, Co. Tipperary, Ireland
4 Dept of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Off-axis electron holography allows magnetic fields in materials to be characterized in the transmission electron microscope (TEM) at a spatial resolution that can approach the nanometer scale [1]. The technique involves applying a positive voltage to an electron biprism in order to overlap a coherent electron wave that has passed through a specimen with a part of the same electron wave that has passed only through vacuum. Analysis of the resulting interference pattern allows the phase shift of the specimen wave to be recovered quantitatively and non-invasively. The phase shift is, in turn, sensitive to the magnetic induction in the specimen.

A scanning electron micrograph of a representative magnetic device sample that has been examined using electron holography is shown in Fig. 1. The specimen comprises adjacent, nominally identical $75 \times 280\text{-nm}^2$ rectangular pseudo-spin-valve elements, which were prepared from a polycrystalline $Ni_{79}Fe_{21}$ (4.1 nm)/ Cu (3 nm)/ Co (3.5 nm)/ Cu (4 nm) film that had been sputtered onto oxidized silicon. An approach based on focused ion-beam milling with gallium ions, which is described in Fig. 2, was used to minimize damage to the magnetic properties of the elements during preparation for TEM examination in plan-view geometry. Figure 3 shows six magnetic induction maps of three adjacent elements recorded at remanence using electron holography, after saturating the elements magnetically either parallel or antiparallel to their length using the field of the conventional microscope objective lens, followed by applying a reverse field [2]. These images were used to identify separate switching of the Co and NiFe layers in the individual elements and to measure their switching fields, as shown in the form of a remanent hysteresis loop in Fig. 4. The magnetic signal is lower than would be predicted from the nominal layer thicknesses. Comparisons with micromagnetic simulations suggest that approximately 20 nm of material at the edge of each element may not contribute to the magnetic signal, possibly as a result of oxidation or amorphization during sample fabrication. In addition, the in-plane component of the magnetic induction in the Co layer is reduced by at least 40% from its nominal value. Differences in the hysteresis behavior between the three elements are observed, and are thought to result from shape and microstructural variations. This variability must be minimized if such elements are to be used in ultrahigh areal density magnetic recording applications.

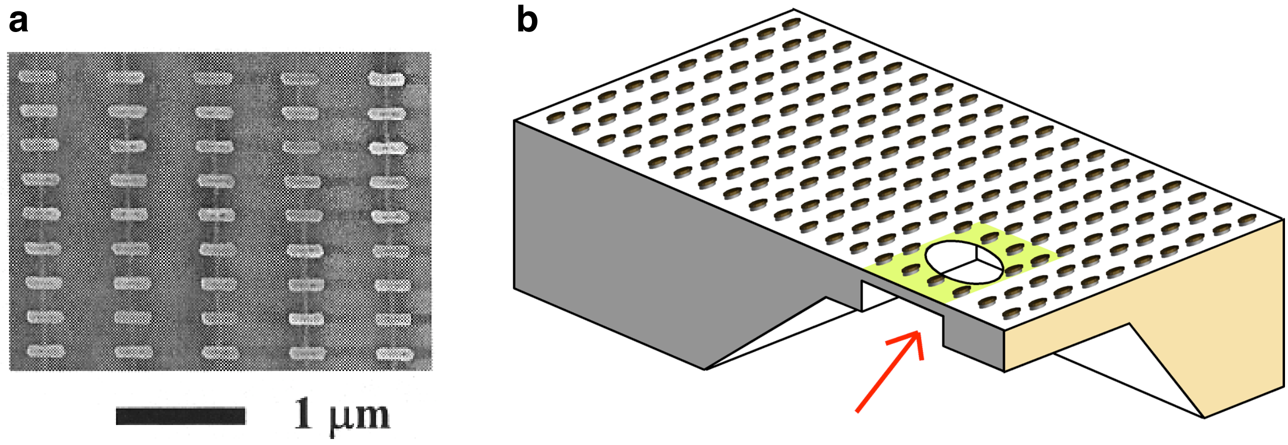

Figure 1 – (a) Scanning electron micrograph showing the rectangular array of pseudo-spin-valve elements. (b) Schematic diagram illustrating the final stage of the procedure used to prepare an electron-transparent plan-view sample of the pseudo-spin-valve elements for electron holography, by using focused ion-beam milling with gallium ions. A piece of the wafer is initially milled from the substrate side at one corner. A membrane is formed parallel to the wafer surface. A hole is then formed in this membrane by milling from below, at a glancing angle to the original wafer surface. In this way, the elements that are on the near side of the hole are protected from ion damage and implantation by the intervening substrate, and the hole can subsequently be used to provide a reference wave for electron holography.

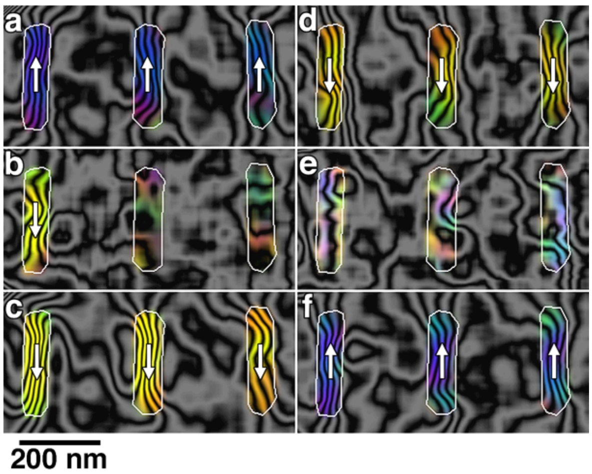

Figure 2 – Magnetic induction maps showing six remanent magnetic states recorded using electron holography from three pseudo-spin-valve elements. Eighteen images similar to these were recorded in total. The outlines of the elements are shown in white. The contour spacing is $2\pi/64=0.098$ rad, such that the magnetic flux enclosed between any two adjacent black contours is $h/64e=6.25\times10^{-17}$ Wb. The direction of the induction is shown using arrows and colors (red=right, yellow=down, green=left, and blue=up).

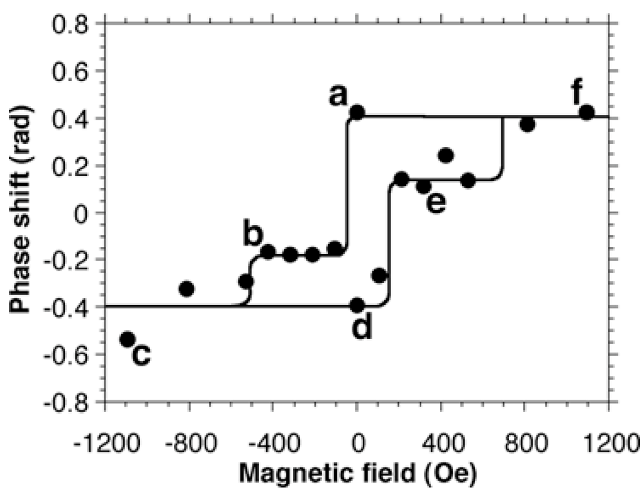

Figure 3 - Remanent hysteresis loop measured directly from the experimental electron holographic phase images, with the letters corresponding to the six individual figures shown in Fig. 2. The graph shows the magnetic contribution to the phase shift across each element, plotted as a function of the in-plane component of the field applied to the elements before recording the remanent states. Each point shows an average of the phase shifts measured from the three elements shown in Fig. 2.

Acknowledgments

We thank M.R. McCartney for assistance and P. Barpanda for calculations. RDB thanks the Royal Society for support.

[1] R.E. Dunin-Borkowski, M.R. McCartney and D.J. Smith, in Volume 3 of the "Encyclopaedia of Nanoscience and Nanotechnology", pp. 41-100, edited by H S Nalwa (American Scientific Publishers, 2004).

[2] T. Kasama, P. Barpanda, R.E. Dunin-Borkowski, S.B. Newcomb, M.R. McCartney, F.J. Castano and C.A. Ross, J. Appl. Phys. 98 (2005) 013903.