Electron holography of nano-scale magnetic particles and cross-sectional tunnel junctions

M. R. McCartney and R. E. Dunin-Borkowski

Center for Solid State Science, Arizona State University, Tempe, AZ 85287

Off-axis electron holography[1] provides access to the phase of the electron wave which has passed through the sample and therefore has the potential to provide direct, quantitative information about the in-plane component of the magnetic induction. The Philips CM200-FEG microscope which was used for the holography described here is equipped with a powerful mini-lens below the specimen enabling 2nm spatial resolution and only a small residual field at the sample. This combination of high coherence and increased magnification can provide quantitative mapping of magnetic induction at the nanometer scale. One of the main challenges in determining magnetic induction from reconstructed phase images is the separation of phase shifts due to thickness and electrostatic effects from magnetostatic effects. For certain sample geometries which lend themselves to uni-directional remanent states, we have implemented an in-situ magnetization reversal procedure to remove electrostatic and thickness effects that would otherwise prevent quantification of the induction.[2]

Figure 1 shows a bright field image of an aquatic magnetotactic bacterium Magnetospirillum magnetotacticum. The dark particles are magnetite crystals which together form a dipole interacting with the earth's magnetic field to guide the bacteria to the proper depth for optimum chemical environment.[3] Each of the crystallites is of a size to be a single domain and attempts have been made to assess the crystallographic orientation and morphology of the crystallites in terms of the (111) easy magnetization axis of Fe_3O_4 and to measure dipole moments of the individual chains using MFM.[4,5] Figure 2a is the holographic phase image from the area outlined in Fig. 1, clearly showing individual 40nm x 30nm crystallites. The contrast is dominated by thickness-integrated mean potential phase shifts. The y-gradient of the phase image which is sensitive to the x-component of the induction is shown in Fig. 2b and is also dominated by thickness effects. In order to isolate the magnetic contrast, holograms were acquired after reversal of the magnetization of the chain in the microscope. Following careful alignment of the images, differences in the gradients reveal the magnetization components. The difference in the y-gradients, shown in Fig. 2c, between the magnetically reversed phase images clearly discloses the fringing fields between the crystallites. It should be noted that the absence of strong contrast at the edges of the crystallites indicates accurate alignment of the phase images. Combining the orthogonal components gives the in-plane induction map shown in Fig. 3. Analysis indicates that the induction field is dominated by magnetostatic effects.

Cross-sectional samples of multi-layered thin films can also be analyzed using this approach. Figure 4a shows part of a hologram of a magnetic tunnel junction (MTJ) consisting of 22nm Co / 4nm HfO_2 / 36nm CoFe on a Si substrate. The phase profile (Fig. 4b) illustrates the difficulties in analyzing the induction in a sample where the thickness and mean potential vary abruptly. Dividing the difference in the phase gradients of magnetically reversed layers by the average phase results in an image which is proportional to the magnetization (Fig. 4c). While a variety of artefacts may remain in this image, it is appropriately non-zero only in the magnetic layers and yields a value of the magnetization of Co (using a mean potential of 25V) of 1.5T.[6]

References

1. A Tonomura, *Rev. Mod. Phys.* 59 (1987) 639
2 R E Dunin-Borkowski, *et al*, *Ultramicroscopy*, in press
3. R. P. Blakemore, *Science* 190 (1975) 377 R P Blakemore and R B. Frankel, *Sci. Am* 245 (6) (1981) 58.
4 *Iron Biominerals* (Plenum Press, New York 1991) edited by R. B Frankel and R P Blakemore.
5 E D. Dahlberg, *et al.*, *J. Mag. Mag. Mat.* 140-144 (1995) 1459.
6 . We are grateful to the groups of Profs. R. Frankel and A E Berkowitz for provision of samples and ongoing collaborations

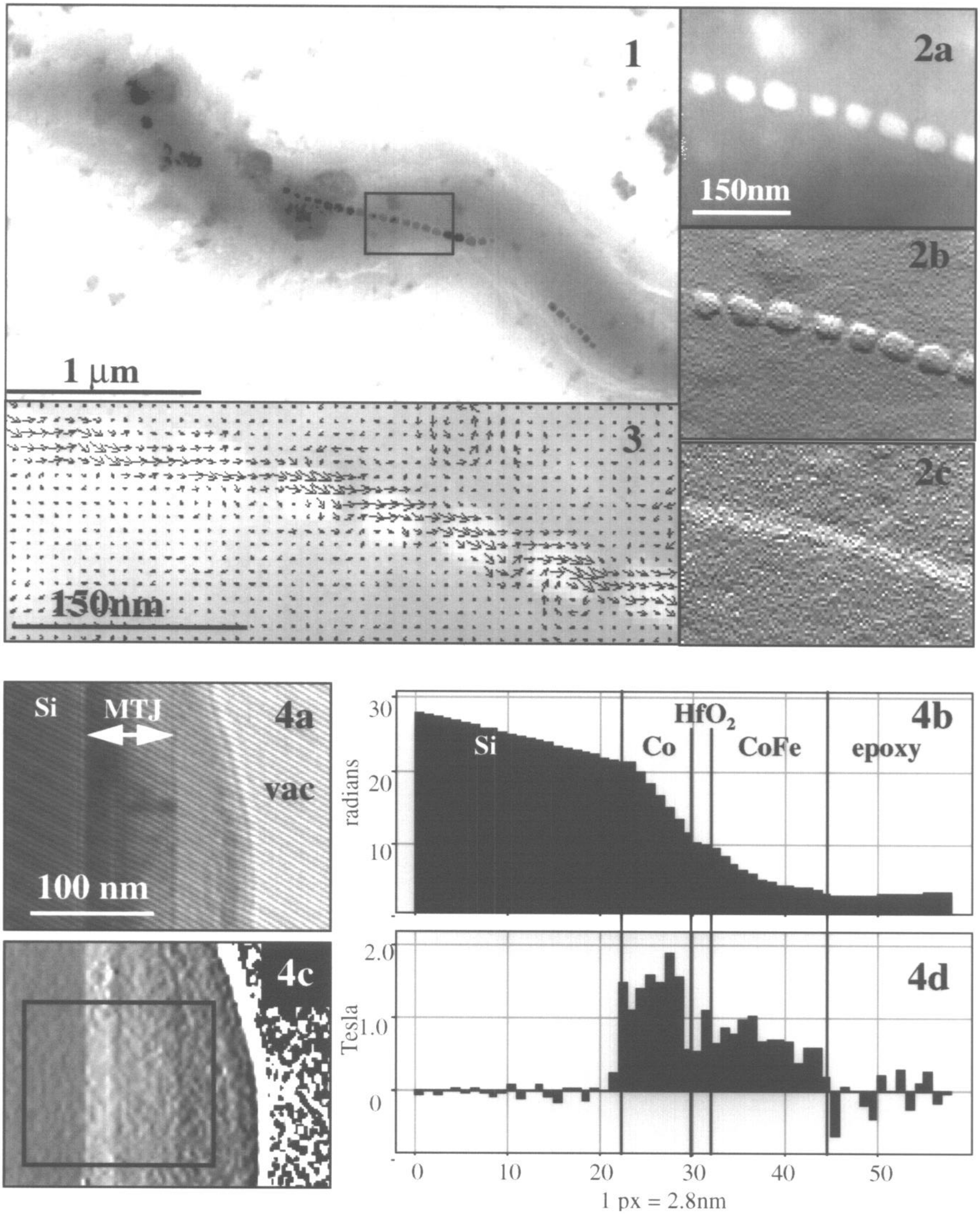

Fig. 1 M. magnetotacticum with chain of magnetite particles. Area for holography outlined. Fig. 2 a) phase image; b) y-gradient of phase image. c) difference in y-gradients following magnetization reversal. Grayscale -0.12rad/nm -> + 0.12rad/nm for b) and c). Fig. 3 Induction map derived from center of chain. Fig. 4 a) hologram of MTJ with 4nm HfO_2 tunnel barrier; b) phase profile; c) after processing, contrast proportional to magnetization; d) profile of c).