Magnetic induction mapping of nanostructured materials using off-axis electron holography

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Off-axis electron holography

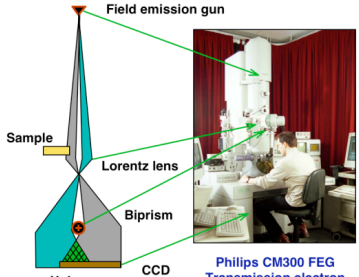
Off-axis electron holography is a powerful technique for mapping magnetic fields in materials in the transmission electron microscope.

The technique relies on the use of an electron biprism to overlap a high energy electron wave that has passed through the specimen with another part of the same electron wave that has passed only through vacuum.

The resulting interference fringe pattern contains quantitative information about the magnetic induction in the specimen at a spatial resolution that can approach the nanometer scale.

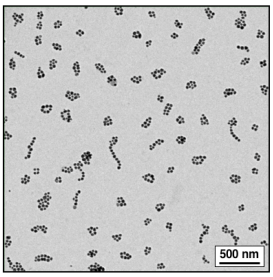
This poster shows examples of quantitative magnetic induction maps obtained from nanostructures that are smaller than 100 nm in size.

R E Dunin-Borkowski, M R McCartney & David J Smith. Electron holography of nanostructured materials. Chapter in the "Encyclopaedia of Nanoscience and Nanotechnology" (American Scientific Publishers, 2003). ISBN 1588830012.

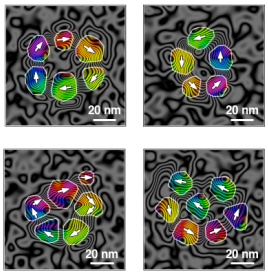


Philips CM300 FEG Transmission electron microscope

Co Nanoparticle Rings



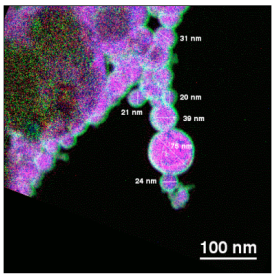
Bright-field TEM image of 20 nm Co particles that self-assemble into rings. An out-of-plane magnetic field can be used to switch the chirality of the rings.



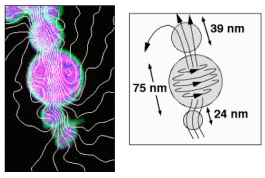
Magnetic flux closure states imaged using electron holography. The direction of the magnetic flux is shown using arrows and colors.

S L Tripp, R E Dunin-Borkowski & A Wei. Flux closure in self-assembled Co nanoparticle rings. Angew. Chemie (2003) in press.

FeNi Nanoparticle Chains



Chemical map of $Fe_{0.56}Ni_{0.44}$ nanoparticles of average diameter 50 nm, showing Fe (red), Ni (blue) and O (green).



3D magnetic vortex surrounding a 23 nm diameter flux tube in a 75 nm $Fe_{0.56}Ni_{0.44}$ particle imaged using electron holography.

The diameter of the vortex core (flux tube) depends sensitively on the orientation of the vortex with respect to the chain axis and on the Fe/Ni ratio in the particles.

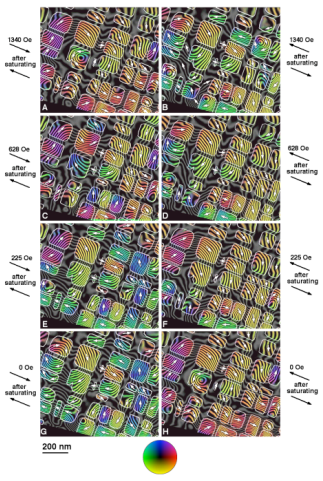
M J Hÿtch, R E Dunin-Borkowski, M R Scheinfein et al. Vortex flux channeling in magnetic nanoparticle chains. Phys. Rev. Lett. (2003) in press.

Magnetic Minerals

Magnetic remanent states in a natural finely exsolved intergrowth of magnetite (Fe_3O_4) blocks in an ulvöspinel (Fe_2TiO_4) matrix imaged using electron holography.

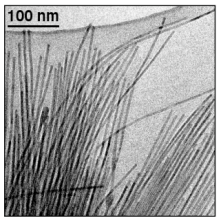
The direction of the magnetic flux is shown using arrows and colors. The outlines of the magnetite blocks are shown using white lines.

Magnetostatic interactions between adjacent magnetite blocks result in the stability of the magnetic microstructure over geological times, and can be used to understand the phenomenon of self-reversed thermoremanent magnetization.

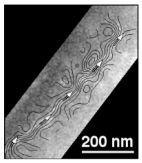


R J Harrison, R E Dunin-Borkowski & A Putnis. Direct imaging of nanoscale magnetic interactions in minerals. Proc. Nat. Acad. Sci. 99 (2002), 16556-16561.

4 nm Co Nanowires

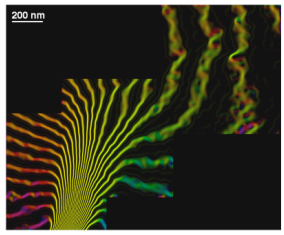


Bright-field TEM image of 4-nm-diameter single crystalline Co nanowires.



Magnetic flux contours measured from an isolated wire using electron holography are consistent with a wire that has the bulk properties of Co and is magnetized throughout its diameter.

Flux contours measured from the end of a bundle of 300 Co nanowires.

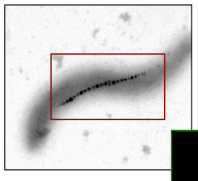


E Snoeck, R E Dunin-Borkowski et al. Quantitative magnetization measurements on nanometer ferromagnetic Co wires using electron holography. Appl. Phys. Lett. 82 (2003), 88-90.

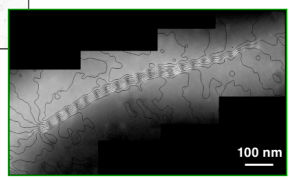
Magnetotactic Bacteria

Magnetotactic bacteria contain one or more chains of magnetite (Fe_3O_4) or greigite (Fe_3S_4) crystals, which are usually 40 - 100 nm in size.

The permanent magnetic moment of the crystals results in the alignment and motion of each bacterial cell parallel to geomagnetic field lines.



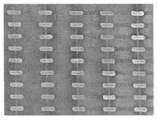
Bright field TEM image of a single cell of bacterial strain MS-1. The 1200 nm long chain contains 22 magnetite crystals.



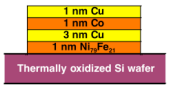
Magnetic flux contours along the chain of crystals imaged using electron holography.

R E Dunin-Borkowski, M R McCartney, R B Frankel, D A Bazylinski, M Posfai & P R Buseck. Magnetic microstructure of magnetotactic bacteria by electron holography. Science 282 (1998), 1868-1870.

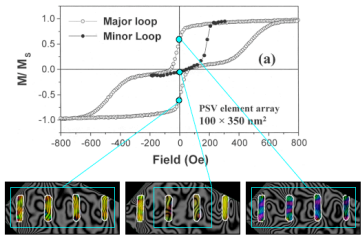
Pseudo Spin Valve Elements



250 x 80 nm pseudo spin valve elements fabricated on Si using interferometric lithography and examined in plan view



Cross-sectional layer structure of each element



Magnetic remanent states imaged using electron holography show parallel (ferromagnetic) and antiparallel (antiferromagnetic) coupling of Co and NiFe layers in individual elements directly.

Collaborative work with C A Ross & F Castaño (MIT), T Kasama and M R McCartney.