Phase-Related Techniques and Holographic Beam Shaping (inc. phase plates, DPC, vortices, electric and magnetic field imaging...)

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Towards model-based electron holographic tomography of magnetic vector fields in ferromagnetic nanostructures

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The development of an experimental technique that allows the three-dimensional magnetic state of a nanoscale object to be measured quantitatively is of great importance for fundamental and applied research in nanomagnetism. Off-axis electron holography is a powerful technique that can be used to record the phase shift of an electron wave that has passed through a specimen in the transmission electron microscope (TEM) [1]. The phase shift is, in turn sensitive to the in-plane component of the magnetic induction within and around the specimen projected in the electron beam direction. A combination of electron holography with backprojection-based tomographic reconstruction algorithms has been used to recover three-dimensional information about the magnetic flux density within and around materials [2, 3]. Such experiments typically require the acquisition of orthogonal tilt series of electron holograms and the separation of the magnetic from the mean inner potential contribution to the phase shift at each specimen tilt angle.

Figure 1 shows experimental and simulated magnetic induction maps of a GaAs/CoFeB core/shell nanowire. The magnetic induction maps shown in Figs. 1a and 1b were recorded at 300 kV using electron holography in an aberration-corrected FEI Titan TEM operated in Lorentz mode. They are taken from a tilt series of induction maps recorded over ±60º in 5º steps on a 2k x 2k charged coupled device camera. The acquisition time for each hologram was 16 s and the biprism voltage was 99.8 V, resulting in a holographic interference fringe spacing of 3.3 nm and a fringe contrast of 19.4 % in vacuum. Figures 1c and 1d show corresponding simulated magnetic induction maps derived, which are from finite element micromagnetic simulations and suggest that such nanowires can support a mixed magnetic state consisting of uniform magnetisation along their axis and vortices towards their ends [4].

We are currently developing a model-based approach to magnetic vector field tomography that can be applied to results such as those shown in Figs. 1a and 1b. The approach, which is described schematically in Fig. 2, involves using an iterative reconstruction algorithm to obtain the three-dimensional magnetization distribution in a specimen from a series of recorded phase images by the repeated application of a forward model to calculate phase images based on simulated magnetization distributions. We are also developing a tomographic holder that will allow a conventional 3-mm-diameter specimen to be rotated by 360º inside the electron microscope. The holder is equipped with an inclinometer, which allows the specimen tilt angle to be measured to a precision of 0.1°.

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1. M. Lehmann and H. Lichte, “Tutorial on Off-Axis Electron Holography”, Microsc. Microanal., 8, 447, 2002.
2. T. Tanigaki, Y. Takahashi, T. Shimakura, T. Akashi, R. Tsuneta, A. Sugawara and D. Shindo, “Three-dimensional observation of magnetic vortex cores in stacked ferromagnetic discs”, Nano Letters, 15, 1309, 2015.
3. A. Lubk, D. Wolf, P. Simon, C. Wang, S. Sturm and C. Felser, “Nanoscale three-dimensional reconstruction of electric and magnetic stray fields around nanowires”, Appl. Phys. Lett., 105, 173110, 2014.
4. P. Landeros, O.J. Suarez, A. Cuchillo and P. Vargas, “Equilibrium states and vortex domain wall nucleation in ferromagnetic nanotubes”, Phys. Rev. B, 79, 24404, 2009.

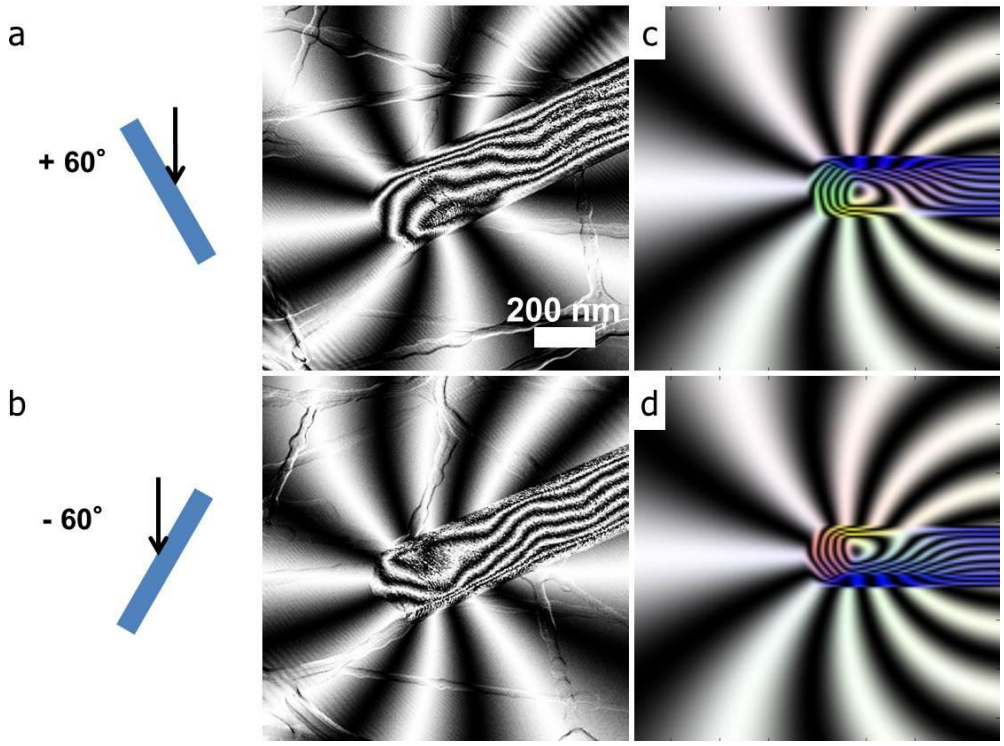

Figure 1. (a, b) Experimental magnetic induction maps recorded at specimen tilt angles of +60° and -60°. The phase contour spacing is π radians. (c, d) show corresponding simulated magnetic induction maps based on micromagnetic simulations.

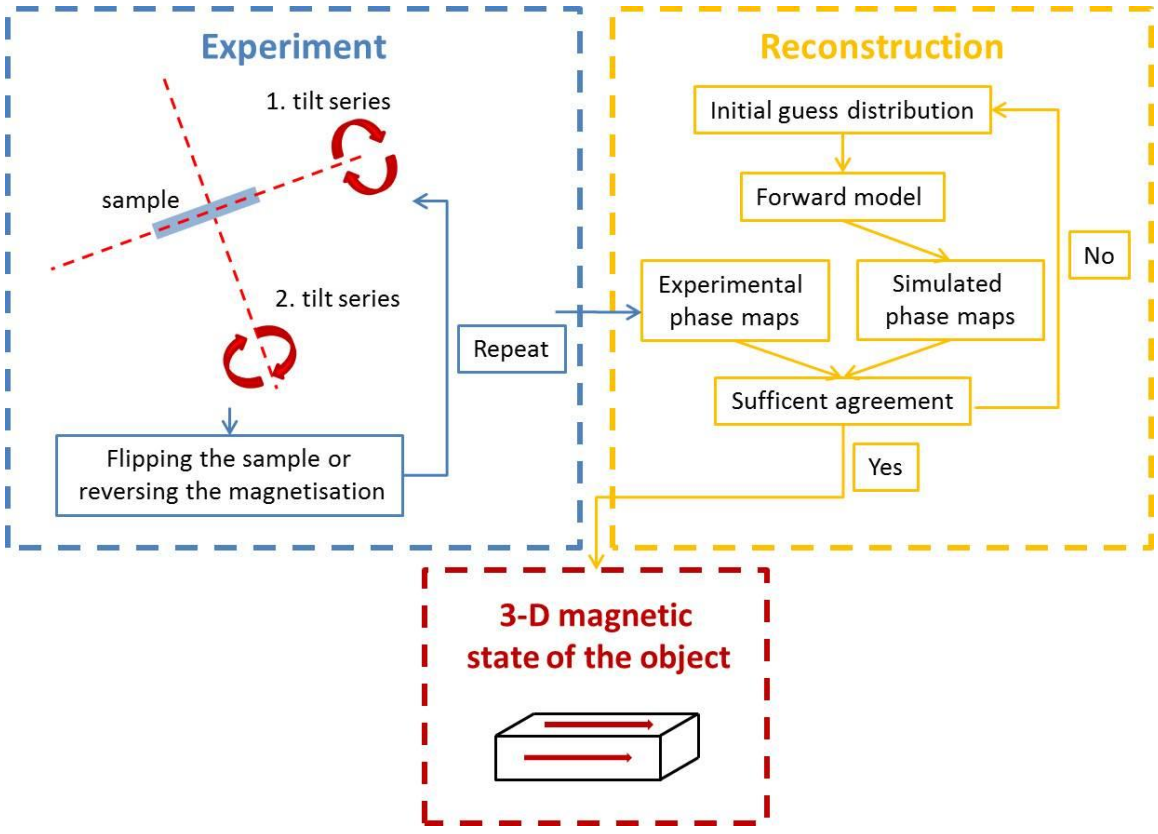

Figure 2. Schematic diagram showing the steps in hologram acquisition and model-based reconstruction used to retrieve the three-dimensional magnetic state of an object.