Experimental Measurement of Three-Dimensional Magnetization Distributions in Nanoscale Materials and Devices using Electron Holography

Rafal E. Dunin-Borkowski

Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons and Peter Grünberg Institute, Forschungszentrum Jülich, D-52425 Jülich, Germany

Off-axis electron holography is a powerful technique for recording the phase shift of a high-energy electron wave that has passed through an electron-transparent specimen in the transmission electron microscope. The phase shift is, in turn, sensitive to the electrostatic potential and magnetic induction in the specimen, projected in the electron beam direction. Recent developments in the technique have included the use of advanced specimen holders with multiple electrical contacts to study nanoscale working devices and the use of ultra-stable transmission electron microscopes to achieve sub-$2\pi/1000$-radian phase sensitivity.

We are currently working on a model-based approach that can be used to reconstruct the three-dimensional magnetization distribution in a specimen from a series of phase images recorded as a function of specimen tilt angle using off-axis electron holography. In order to perform the reconstruction, we generate simulated magnetic induction maps by projecting best guesses for the three-dimensional magnetization distribution in the specimen onto two-dimensional Cartesian grids. Our simulations make use of known analytical solutions for the phase shifts of simple geometrical objects, with numerical discretization performed in real space to avoid artifacts generated by discretization in Fourier space, without a significant increase in computation time. Our forward simulation approach is used within an iterative model-based algorithm to solve the inverse problem of reconstructing the three-dimensional magnetization distribution in the specimen from tilt series of two-dimensional phase images recorded about two independent tilt axes. In this way, we avoid many of the artifacts that result from the use of classical backprojection-based tomographic techniques, as well as allowing additional constraints and known physical laws to be taken into account. Results will be presented from studies of magnetite and FeNi nanocrystals, skyrmions and lithographically patterned magnetic elements.

In such applications of off-axis electron holography, which require the recording of weak phase shifts, it is important to remember that both the sample and the support film must remain clean, stable and undamaged for the time required to acquire images with a sufficient signal to noise ratio, that electron-beam-induced charging can affect the measured phase shift and that for crystalline specimens the effects of dynamical diffraction may be important even for a specimen thickness of only a few atoms [1].

References:
[1] J. Caron, J. Ungermann, M. Riese, A. Kovács, Z.-A. Li, A. H. Tavabi, V. Migunov, P. Diehle, G. Pozzi, T. Almeida, A. Muxworthy, W. Williams, Y. Champion and N. Kiselev are gratefully acknowledged for their valuable contributions to this work.