Towards Quantitative Mapping of Three-Dimensional and Weak Electrostatic Potentials and Magnetic Fields using Electron Holography

Rafal E. Dunin-Borkowski[1,a], Vadim Migunov[1,b], Jan Caron[1,c], András Kovács[1,d] and Giulio Pozzi[2,e]

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

[2]Department of Physics and Astronomy, University of Bologna, Viale B. Pichat 6/2, Bologna, Italy

[a]rdb@fz-juelich.de, [b]v.migunov@fz-juelich.de, [c]j.caron@fz-juelich.de, [d]a.kovacs@fz-juelich.de, [e]giulio.pozzi@unibo.it

Introduction

Off-axis electron holography is a powerful technique that can be used to record the phase shift of the electron wave that has passed through an electron-transparent specimen in the transmission electron microscope (TEM). The phase shift is sensitive to the electrostatic potential and magnetic induction in the specimen. Recent developments in the technique have included the use of specimen holders with multiple electrical contacts to study nanoscale working devices, the application of electron holographic tomography to record three-dimensional potentials with nm spatial resolution and the use of ultra-stable transmission electron microscopes and either phase-shifting electron holography or cumulative hologram acquisition to achieve sub-$2\pi/1000$-radian phase sensitivity.

Electrostatic potentials

We have applied off-axis electron holography to measure the electrostatic potential and electric field around an electrically-biased Fe atom probe tomography needle, as shown in Figs. 1 and 2. The experiment involved applying a voltage between the needle and a counter-electrode that was placed ~400 nm from it. The phase shift recorded using electron holography was analyzed both by fitting the recorded phase distribution to a simulation based on two lines of opposite charge density and by using a model-independent approach involving contour integration of the phase gradient to determine the charge enclosed within the integration contour [1]. In the present study, both approaches required evaluation of the *difference* between phase images acquired for two applied voltages, in order to subtract the mean inner potential and magnetic contributions to the phase. On the assumption of cylindrical symmetry, the three-dimensional potential and field around the needle were determined from the results, as shown in Fig. 1. Charge density profiles along the needle, measured using both approaches, are shown in Fig. 2 and are consistent with each other.

Magnetic fields

We are also 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 using electron holography. In order to develop the technique, we have generated simulated magnetic induction maps by projecting three-dimensional magnetization distributions onto two-dimensional Cartesian grids. We use known analytical solutions for the phase shifts of simple geometrical objects to pre-compute contributions to the phase from individual parts of the grids, in order to simulate phase images of arbitrary three-dimensional objects from any projection direction, with numerical discretization performed in real space to avoid artifacts generated by discretization in Fourier space without a significant increase in computation time. This forward simulation approach is used in an iterative model-based algorithm to solve the inverse problem of reconstructing the three-dimensional magnetization distribution in the specimen from a tomographic tilt series of phase images. Such a model-based approach avoids many of the artifacts that result from using classical tomographic techniques, as well as allowing additional constraints to be incorporated.

Towards improved sensitivity in electron holographic measurements

The need for greater sensitivity in electron holographic measurements is illustrated, for magnetic measurements, by the fact that a single Bohr magneton is associated with a step in phase of ~$2\pi/10^5$ radians, while even a 2 nm ferromagnetic particle produces a phase shift of only ~$2\pi/1000$ radians. Fortunately, it is possible to measure the magnetic moment of a nanocrystal quantitatively from a phase image by making use of the relationship between the volume integral of the induction and the true magnetic moment [2]. When considering experiments aimed at the retrieval of weak phase shifts, it is important to remember that the sample must remain clean, that electron-beam-induced charging due to secondary electron emission can contribute to the measured electrostatic potential contribution to the phase shift and that the quantitative interpretation of phase shifts measured from crystalline specimens can require comparisons with dynamical simulations, even for a specimen thickness of only a few atoms [3].

References

[1] M. Beleggia, T. Kasama, R.E. Dunin-Borkowski. S. Hofmann and G. Pozzi: Appl. Phys. Lett. Vol. 98 (2011), p. 243101

[2] M. Beleggia, T. Kasama and R.E. Dunin-Borkowski: Ultramicroscopy Vol. 110 (2010), p. 425

[3] We are grateful to M. Beleggia, A.H. Tavabi, P. Diehle, A. London, T.F. Kelly, D.J. Larson and M. Farle for valuable contributions to this work.

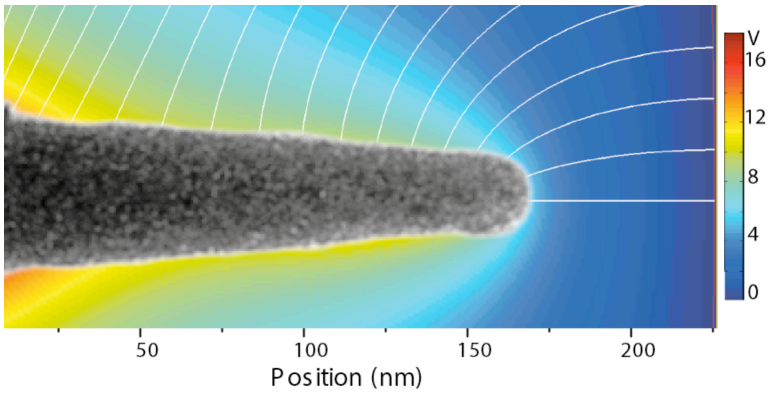

Figure 1 – Central slice of the 3D electrical potential (colors) and electric field (white lines) between an Fe atom probe tomography needle and a Au counter-electrode, determined from the charge density distribution in the needle measured from the *difference* between phase images recorded using off-axis electron holography at applied bias voltages between the needle and the counter-electrode of 0 and 5 V.

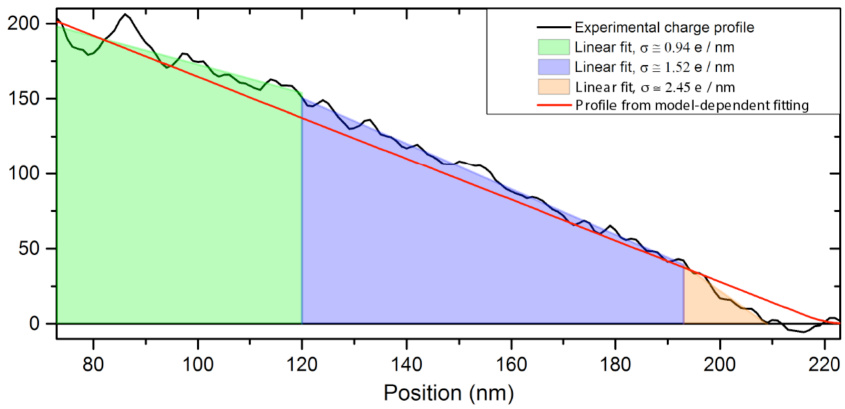

Figure 2 – Cumulative charge profiles along the needle shown in Fig. 1, measured by off-axis electron holography in units of electrons using model-independent (black) and model-dependent (red) methods.