Towards Atomic Resolution and Ultrafast Electron Holography of Electrostatic Potentials in Working Devices

Rafal E. Dunin-Borkowski\textsuperscript{1}, Vadim Migunov\textsuperscript{1}, Andrew London\textsuperscript{2}, Michael Farle\textsuperscript{3}, Amir H. Tavabi\textsuperscript{1}, Giulio Pozzi\textsuperscript{4}

\textsuperscript{1}Ernst Ruska Centre for Microscopy and Spectroscopy with Electrons and Peter Gruenberg Institute, Forschungszentrum Juelich, D-52425 Juelich, Germany
\textsuperscript{2}Department of Materials, University of Oxford, Parks Road, Oxford OX1 3PH, United Kingdom
\textsuperscript{3}Fakultaet fuer Physik and Center of Nanointegration (CeNIDE), Universitaet Duisburg-Essen D-47048 Duisburg, Germany
\textsuperscript{4}Department of Physics and Astronomy, University of Bologna, Viale B. Pichat 6/2, 40127 Bologna, Italy

The ability to achieve high phase sensitivity with close-to-atomic spatial resolution in off-axis electron holographic measurements is offered by the latest generation of ultra-stable transmission electron microscopes, which are equipped with high brightness electron sources and aberration correctors. At the same time, advanced specimen holders with multiple electrical contacts allow the technique to be used to quantitatively measure electrostatic potentials in nanoscale working devices.

Figure 1 illustrates the result of applying off-axis electron holography to measure the electrostatic potential and electric field around an electrically biased Fe atom probe tomography needle. The experiment involved applying a voltage between the needle and a counter-electrode, which was placed ~400 nm from it. The recorded phase shift was analysed in two ways: (1) by fitting the experimental phase image to a simulation of the predicted phase shift based on two lines of constant but opposite charge density; (2) by using a model-independent approach that involves contour integration of the phase gradient to determine the charge enclosed within the integration contour [1]. Here, the latter approach required subtraction of the mean inner potential contribution to the recorded phase, which was achieved by calculating the difference between phase images recorded at applied bias voltages of 0 and 5 V. The charge density profiles along the needle measured using the two approaches were consistent with each other. However, only the model-independent approach was able to reveal the presence of charge accumulation at the apex of the needle. On the assumption of cylindrical symmetry, the three-dimensional electrostatic potential and electric field around the needle were inferred from the results, as shown in Fig. 1.

The coherence of the transmission electron microscope that was used to obtain the result shown in Fig. 1 also allowed other electron-optical phenomena to be observed. Interestingly, when two metallic tips similar to the needle shown in Fig. 1 were placed in front of each other at a separation of ~1 μm and a potential difference was applied between them, the positively charged wire acted like a terminating convergent electron biprism, producing an overlapping region of intensity containing two-beam fringes, while the negatively charged wire acted like a terminating divergent biprism. The combined effect of the fields from the two needles resulted in the formation of highly complex interference patterns in bright-field TEM images acquired out-of-focus, as shown in Figs. 2 and 3 for a nominal defocus of 9.5 mm and a potential difference between the needles of 130 V. The overlapping region has a triangular structure that is similar to the elliptic umbilic diffraction catastrophe.

We are presently developing new techniques, in combination with the use of...
chromatic aberration correction, to allow results similar to that shown in Fig. 1 to be measured at lower accelerating voltages for very small changes in potential with close to atomic spatial resolution. When recording weak phase shifts, it is important to remember that the sample must remain clean 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 careful comparisons with dynamical simulations may be required even for a thickness of only a few atoms. We are also developing new approaches to allow off-axis electron holography to be used to study ultrafast phenomena in situ in the electron microscope. These developments will be discussed.

References


FIG. 1. Central slice of the three-dimensional distribution of electrical potential (colours) 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 a phase image recorded using off-axis electron holography.

FIG. 2. Bright-field TEM image recorded at a defocus of 9.5 mm from two metallic needles similar to that in FIG. 1 for a potential difference of 130 V.

FIG. 3. Simulated image corresponding to the experimental conditions used to acquire FIG. 2, showing spots in the caustic with a hexagonal-like structure.