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Approaches to Phase Imaging in the Electron Microscope

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It is well-appreciated that the beam-specimen interactions that occur within the transmission electron microscope (TEM) cause phase changes across the wave-front of the incident electron beam. The ongoing challenge for the electron microscopist is to reliably extract the phase and then retrieve meaningful, preferably quantitative, information about the material under observation. Several approaches to phase imaging have been developed and pursued through the years, each with its own advantages (and shortcomings) for characterizing particular types of materials. Electron holography (EH) was originally proposed as a means to overcome the fundamental resolution limit imposed by spherical aberration (1), and that goal was eventually realized (2) following development of the field emission gun as a coherent TEM electron source (3). Since EH enables accurate measurements to be made of *relative* phase changes across the specimen, the technique has since proven to be highly beneficial for quantifying electrostatic (and magnetic) fields well into the nanoscale regime (4). The term differential phase contrast (DPC) refers collectively to TEM techniques that rely on sideways deflection of electrons due to the Lorentz force when passing through the sample. As initially implemented (5), DPC involved scanning a focused electron probe over the (magnetic) region of interest and collecting diffracted beam intensities on an array of segmented quadrant or even octant annular-ring detectors. The technique has since been extended to studying mesoscale electric fields due to polarization effects, such as domain wall boundaries in ferroelectric materials (6), while atomic-resolution DPC imaging of electromagnetic fields due to individual electric dipoles using aberration-corrected STEM has also been reported (7, 8). Variants of the latter approach, such as momentum-resolved 4D STEM (9) and center-of-mass (COM) detectors (10), have more recently been introduced, also assisting in the challenging task of differentiating between mesoscale polarization effects and atomic-scale fields. Applications of these various phase imaging techniques as well as prospects for further developments will be briefly discussed.

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