doi:10.1017/S1431927611007057
Microsc. Microanal. 17 (Suppl 2), 2011

Electron Beams with Orbital Angular Momentum

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We demonstrated free electron beams carrying selectable amounts of quantized angular momentum using nanofabricated diffraction holograms in a TEM [1]. The beam is composed of electron wavefunctions imprinted with an azimuthal phase, such that the wavefronts are helical and carry quantized orbital angular momentum. This new state for the electron offers fundamental insights into quantum behavior and can be applied to new techniques in electron microscopy.

The initial demonstration of an electron vortex beam [2] used a spiral phase plate to directly imprint a helical phase onto an electron beam. The holographic approach used here and by another group [3] differs in that it is easy to manufacture, works at all beam energies, and produces electrons in single quantized orbital states with selectable amounts of angular momentum. Our diffraction holograms, gratings with a fork dislocation, consist of an array of 20 nm slits that are milled through a 30 nm suspended silicon nitride membrane using a focused ion beam. We made multiple holograms with slit spacing down to 50 nm and featuring various degrees of fork dislocations. We use the nanofabricated holograms to produce electron vortex beams with any desired amount of topological charge m. Beams with large orbital angular momentum per electron – up to 100 $\hbar$ – were produced using gratings with a high degree fork dislocation (Fig. 1).

The helical phase of the beams can be characterized using electron interferometry, in which an electron vortex beam interferes with a reference beam having flat wavefronts. In one experiment, an electron vortex beam diffracted at an angle from a grating interferes with a plane reference wave propagating at a slight relative angle, resulting in a characteristic forked interference pattern (Fig. 2a). In another experiment, the electron vortex and reference beams propagate in the same direction, producing a spiral interference pattern (Fig. 2b). The number of lobes in the spiral pattern corresponds to the topological charge of the electron vortex. A technique similar to this can potentially be used to implement spiral phase microscopy [3] in a TEM.

The unique helical phase, quantized angular momentum, and coherence properties of the electron vortex can be applied to new techniques in electron microscopy. For example, using vortex beams with electron energy loss spectra from a magnetic sample reveals the same contrast as magnetic circular dichroism measurements using a synchrotron [2]. This can potentially lead to high resolution, elementally sensitive magnetic imaging capabilities in a TEM. Electron vortices also open a path towards imaging transparent TEM specimens using spiral phase microscopy [3], analogous to a recent optical technique that provides additional information relative to other forms of phase plate microscopy.

References

[1] B. J. McMorran et al., *Science* 331 (2011) 192.
[2] M. Uchida, A. Tonomura, *Nature* 464 (2010) 737.

[3] J. Verbeeck et al., *Nature* 467 (2010) 301.
[4] S. Fürhapter et al., *Optics Letters* 30 (2005) 1953.

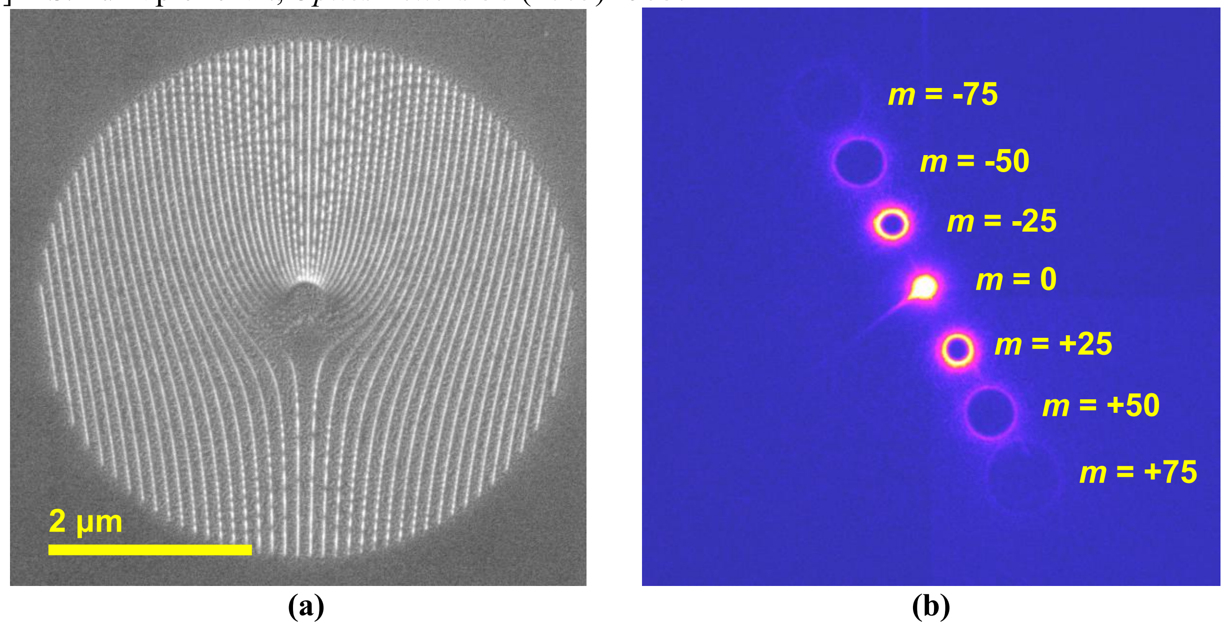

FIG. 1. (a) An SEM image of a nanofabricated diffraction hologram for producing electron vortices with large topological charge. The light areas are slits milled through a silicon nitride membrane. (b) TEM diffraction image of the electron vortex beams resulting from diffraction from the grating. A false color scale has been applied to make the higher orders more evident. The topological charge is indicated next to each beam.

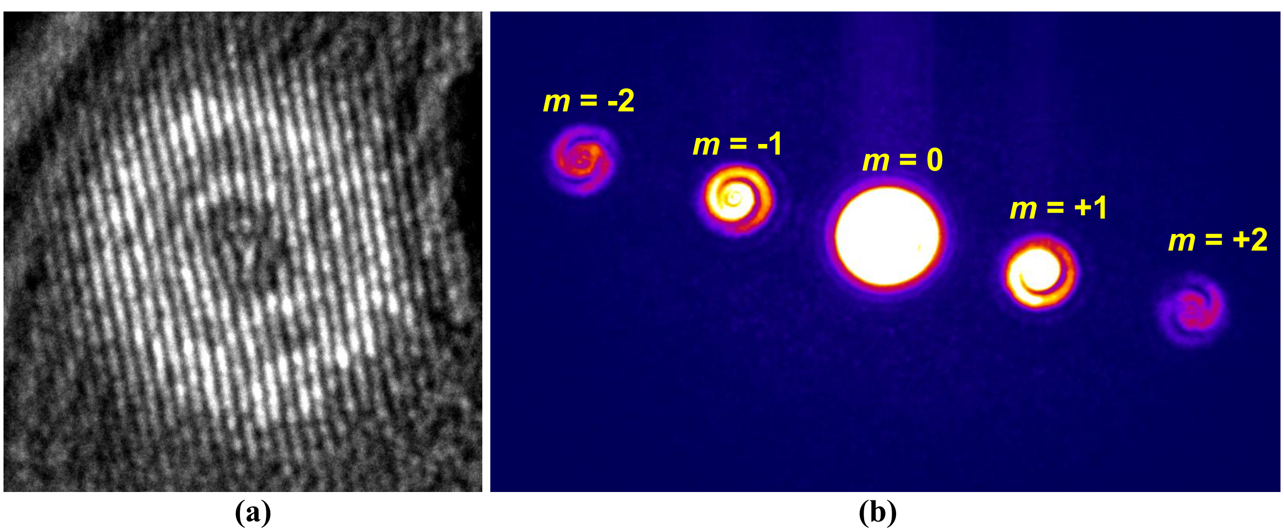

FIG. 2. The helical phase of electron vortex beams is revealed by interference between an electron vortex beam and a reference beam. (a) Electron vortex and reference beams converging at an angle relative to one another give rise to a characteristic forked interference pattern indicative of a topological phase singularity. (b) Multiple pairs of co-propagating electron vortex and reference beams provide spiral interferograms. The interferograms in (b) reveal that beams on opposite sides of the diffraction pattern have opposite helicity, and the topological charge in each beam (measured by the number of spiral arms in each diffraction spot) is proportional to the diffraction order number.