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Fourier Ptychography in the TEM: Developments and Opportunities

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Inspired by recent advances in Fourier ptychography using LED array illumination in optical microscopy, an effort was undertaken to develop a CTEM version capable of serving as a complement to ptychography and 4D-STEM [1, 2]. Rather than attempting to extend system capability beyond its resolution specification – as sought by traditional ptychography and tilted illumination super resolution [3] – the form of Fourier ptychography undertaken relies on stopping down the numerical aperture using the objective aperture while imaging at reduced magnifications, digitally recovering the full system resolution afterwards over a significantly larger field-of-view. Simultaneously, information normally associated with scanning diffraction methods – such as 4D-STEM – is acquired without relying on specialized detectors. A prototype method for image collection and reconstruction was developed on a Titan TEM, with proof-of-concept validation performed on a 35 nm thick silicon specimen in the <110> orientation. As shown in the figure below, an initial selected area electron diffraction pattern (SAED) is acquired, and a dark field scan pattern calculated to sample reciprocal space by beam tilting. A small objective aperture is inserted (10-um with a 3 mrad convergence angle at 200 kV), and the system switched to imaging mode. A dark-field scan pattern covering a collection semi angle of 24 mrad is executed, with a real space CCD image recorded over 350 scan points, producing an array of bright-field and dark-field images. Afterwards, an alternating projection reconstruction algorithm is used to generate 6x super-resolution images from 64x64 pixel patches, effectively improving imaging from a 0.6 nm pixel size during acquisition to a reconstructed resolution of 0.125 nm. Variations in diffraction contrast along the crystal seen in the low-resolution image are seen reflected in the reconstructed image as small shifts away from zone axis.

While currently in the early stages of development, a Python framework for both reconstruction and imaging will provide the foundation for extending the applications into low magnification and large angle diffraction regimes, Lorentz mode, energy filtered imaging, and when using an image corrector. Deployment on a wide variety of systems is relatively easy given careful management of dark field tilt alignments and acquisition synchronization. Reconstruction algorithms developed for light microscopy have proven to be directly applicable to TEM data [4], but improvements can be expected by accounting for dynamical effects and including improved aberration estimates. Differences between scintillator and direct electron detectors will be considered, along with comparisons of electron dose deficiencies as compared to 4D-STEM. Ultimately, Fourier ptychography may find a place in CTEM serving as a complement to 4D-STEM when performing specimen surveys or preparing to move analysis from low-end to high-end systems.

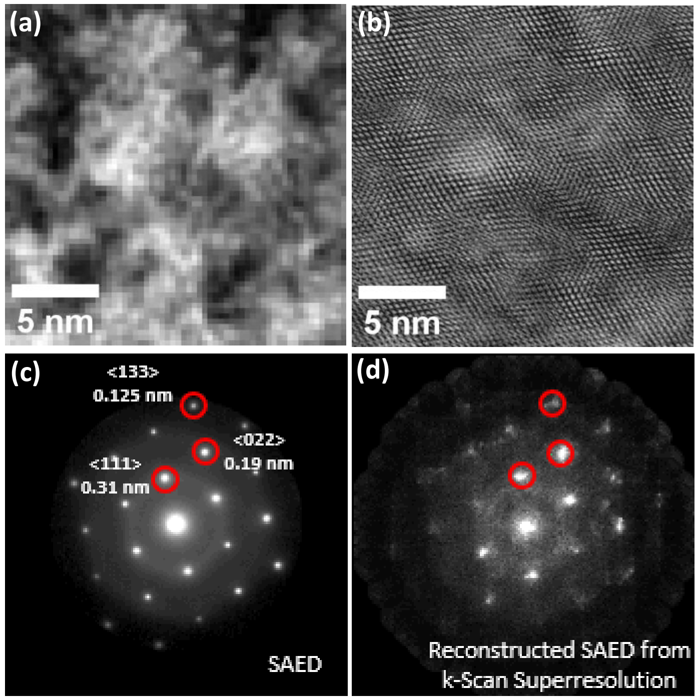

Figure 1. (a) 64x64 pixel patch from on-axis bright field TEM image of Si <110> on zone axis, but with an objective aperture of 3 mrad semiangle inserted. (b) 512x512 reconstruction using Fourier ptychographic algorithm (c) SAED pattern from specimen (d) reconstructed SAED pattern based

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