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Towards 3D electron ptychographic reconstruction

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Transmission electron microscope (TEM) is a powerful tool for material science due to its high spatial resolution. Coherent diffraction imaging (CDI)[1] is a "lensless" method that forms an image of an object by solving the phase problem from a single diffraction pattern with an iterative computer algorithm. This approach can, in principle, overcome the current image resolution limiting factors and ultimately achieve wavelength-limited resolution. However, conventional CDI requires an isolated sample and a priori knowledge about its shape or extent. Rodenburg suggested an extended ptychographical iterative engine (ePIE), which does not need this prior information and overcomes many of the other issues of CDI, such as non-unique solutions, limited field of view, etc. Recently, two-dimensional (2D) ptychographical reconstructions with atomic lateral resolution [2] have been achieved using ePIE [3] on a CeO_2 nanoparticle. However, when the sample becomes thicker, the multiplicative assumption of electron-sample interaction becomes invalid causing the ptychographical reconstruction to breakdown. To overcome this limitation, Maiden et al cooperated the well-known multiple slice calculation procedure into the ePIE algorithm (3PIE) [4] in which a sample is split into axial sections, to produce 3D optically sectioned images of the sample. This 3D multiple-section reconstruction of ptychography has been successfully demonstrated in both light [4] and X-ray [5] optics recently. However, this method still remains challenging for the electron case.

In this work, we demonstrate, for the first time a 3D multiple-section reconstruction of carbon nanotube (CNT) bundles using 3PIE [4] on a TEM. This experiment was carried out on a Tecnai F20 TEM. A probe-forming aperture with a semi-angle of 13.5mrad was used. Fig. 1 illustrates the optical geometry of the experiment and the reconstruction. Conventional TEM images (Figs. 2 a) and b)) at two different defoci were recorded to show that two bundles of nanotubes (vertical and horizontal) have a sample height difference of about 4.6μm along the optical axis. A ptychographic dataset with a total 36 diffraction pattern was acquired over the same sample area with a 60% overlap and a dwell time of 0.8 second at each position. Using the 3PIE [4] reconstruction algorithm we show preliminary results of the phase and amplitude of one reconstructed slice in Figs. 2 c) and d), respectively. The reconstruction results clearly show that only one of the CNT bundles appears in this slice at a fixed sample height in contrast to conventional TEM images, which show two CNTs. The shape of the reconstructed tube is consistent with that of the vertical one observed in the TEM images in Fig. 2 a). Furthermore, we will also show that the reconstructed phase slices along the sample height, give additional information about the sample. Here we demonstrate the potential applications of ptychography for imaging 3D nanostructured objects. Further improvement of the experimental conditions and reconstruction algorithms are underway would reduce the required separation of layers and improve the image quality.

References:

[1]R Gerchberg and WO Saxton, Optik **35** (1972), p. 237-246.
[2]AJ D'Alfonso, AJ Morgan, AW Yan, *et al.,* Physical Review B **89** (2014), p. 064101.
[3]AM Maiden and JM Rodenburg, Ultramicroscopy **109** (2009), p. 1256-1262.
[4]AM Maiden, MJ Humphry and JM Rodenburg, Journal of the Optical Society of America a-Optics Image Science and Vision **29** (2012), p. 1606-1614.
[5]A Suzuki, S Furutaku and K Shimomura, *et al.*, Physical Review Letters **112** (2014), p. 053903.
[6]M Dierolf, A Menzel and P Thibault, *et al.*, Nature **467** (2010), p. 436-482.
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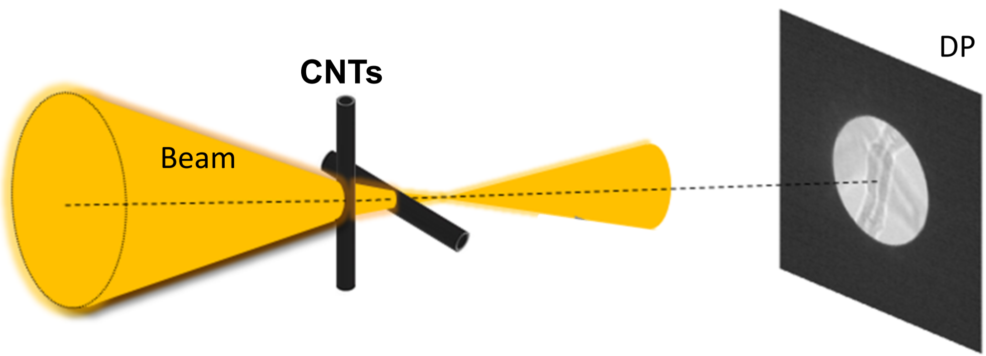

Figure 1. A schematic of the electron optical geometry of 3D ptychography. The electron beam propagates through two CNT bundles at different sample heights along the optical axis and far field diffraction patterns are recorded. Using the multislice method, the object is divided into slices along the beam direction.

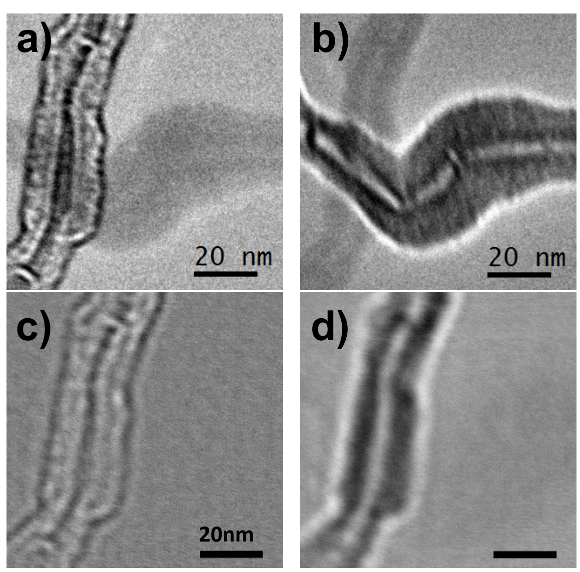

Figure 2. a) and b) Conventional TEM images taken at two defoci with a difference of 4.6μm; c) and d) reconstructed phase and amplitude of one of the slices of the CNTs at different sample heights.