Determination of aberration coefficients in a TEM using electron ptychographic imaging

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Quantum electron microscopy (QEM) has been proposed as a method for high-resolution imaging of radiation-sensitive samples[1,2]. QEM uses electron interference in a resonator to image a sample. An important step in building the QEM resonator is characterizing the spherical and chromatic aberration coefficients (C_s and C_c, respectively) of each optical element.

We have used ptychographic electron imaging[3] as a method of extracting C_s and C_c in our resonator elements. In ptychography, the image of a sample is reconstructed from a series of diffraction patterns, recorded at overlapping beam positions. The extended Ptychography Iterative Engine (ePIE) is a commonly used ptychography reconstruction algorithm that also reconstructs the imaging probe simultaneously[4]. C_s and C_c can be extracted from the reconstructed probe image.

We simulated the technique using a TEM image of gold nanoparticles as the object. As the probe for this simulation, we used a 200 kV electron beam with a defocus of 100 nm, C_s of 1 mm and radius of 2 nm. We numerically generated 25 (5×5) diffraction patterns with a step size of 1.6 nm, by taking Fourier transforms of the product of the probe and the object at each probe position. The diffraction intensities were used in the reconstruction algorithm, with a transparent object and collimated probe with the correct radius as initial guesses. Figures 1 (a) and (b) show the 'true' object and the beam used for generating diffraction patterns, respectively. Figures 1 (c) and (d) show the reconstructed object and probe, respectively. We extracted C_s by minimizing the difference in intensity between the reconstructed probe and test probes with varying C_s. Figure 1 (e) shows the extracted vs. nominal C_s for 5 different values; the mean absolute error was ~ 5%.

We also implemented this technique in a JEOL 2010F TEM at 200 kV, using gold nanoparticles on a carbon support film. According to specifications, the C_s for this TEM is 0.5 mm. Figures 2 (a), (b) and (c) show diffraction intensities collected from different positions on this specimen. The extracted C_s was ~ 1 mm. We suspect that this value may have been affected by drift in the TEM optical axis and deflector coil currents during diffraction pattern acquisition. We are refining our reconstruction algorithm to make it more robust against these issues.

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[2] P. Kruit *et al*., Ultramicroscopy **164**, 31–45 (2016)
[3] J. M. Rodenburg and H. M. L. Faulkner, Appl. Phys. Lett. **85**, 20 (2004)
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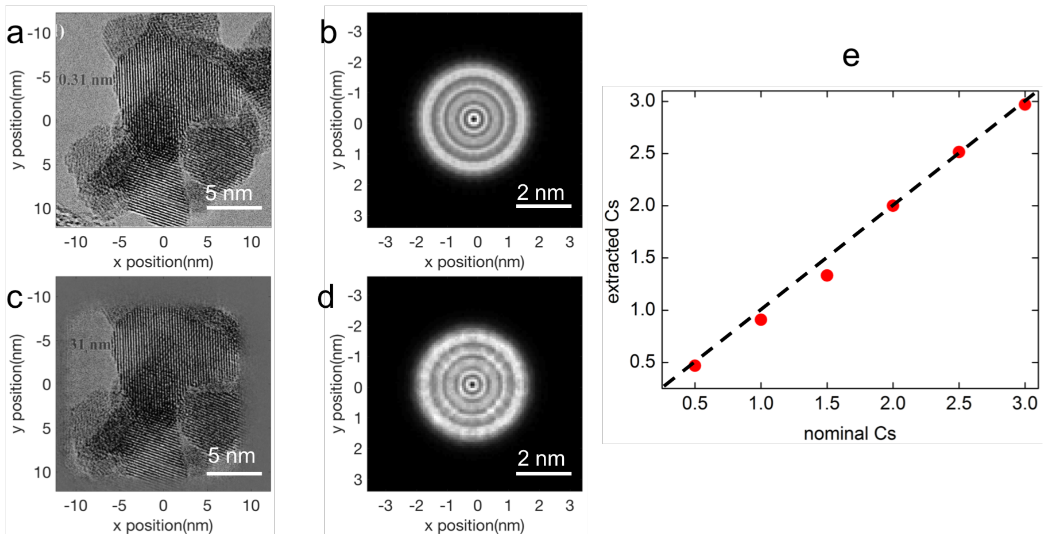

Figure 1: Ptychographic reconstruction. (a) Original TEM image of gold nanoparticles (b) Intensity of electron probe used for numerically generating diffraction patterns. Probe radius = 10 nm, defocus = 100 nm and C_s = 1mm (c) Reconstructed object after 200 iterations (d) Intensity of reconstructed probe (e) Extracted C_s from ePIE simulations vs the correct C_s used in the electron probe for generating diffraction patterns.

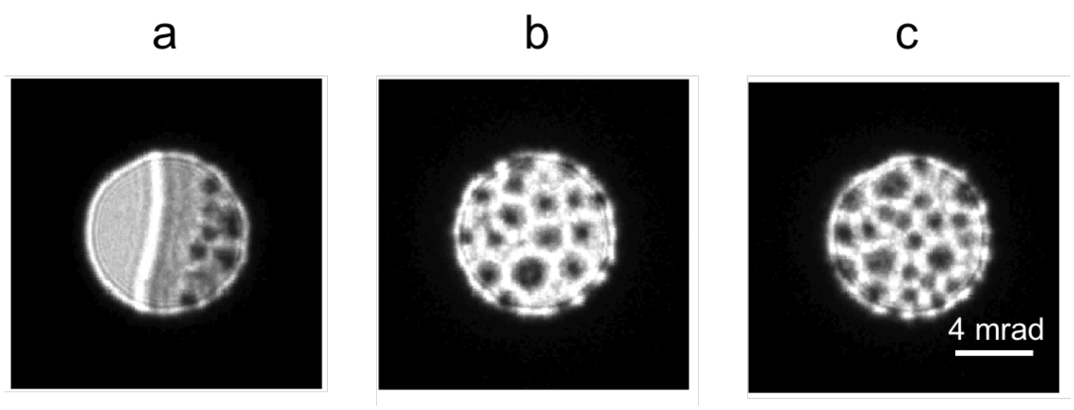

Figure 2: Experimental implementation of ptychographic imaging. (a), (b) and (c) are examples of diffraction patterns collected from the gold nanoparticle sample. These patterns were generated on a JEOL 2010F TEM operating at 200 kV. The electron beam on the sample had a radius of 20 nm and defocus of 2 μm. The diffraction patterns were acquired at a camera length of 40 cm.