Bringing STEM into phase: new opportunities with focused-probe STEM ptychography

Nellist, P.[1], Martinez, G.[1], O'Leary, C.[1] and Jones, L.[2]

[1] University of Oxford, United Kingdom, [2] Trinity College Dublin, Ireland

Phase contrast imaging in transmission electron microscopy (TEM) has long been regarded as being more appropriately performed in conventional TEM rather than scanning TEM (STEM). By the principle of reciprocity, it is possible to perform conventional phase contrast imaging in STEM; making use of aberrations to generate a phase plate and requiring an axial bright-field detector with a collection angle that is significantly smaller than the probe-forming convergence angle. This imaging geometry means that a significant fraction of the transmitted electrons go undetected and it is therefore inefficient in terms of electron dose. Here we present results that demonstrate dose-efficient quantitative phase imaging in STEM can be performed simultaneously with the more conventional incoherent STEM imaging and spectroscopy modes.

The development of direct-electron cameras with very high frame rates has led to them being used as fast-pixelated detectors in STEM, with frame acquisition synchronized so that one detector plane intensity frame is recorded per probe position pixel. The resulting 4D data-set is very rich with many potential applications. Here we focus on the use of ptychography, which efficiently uses the scattered electrons to reconstruct the phase of the specimen transmission function. It has been shown that the light-element sensitivity shown in the reconstructed phase image can be used in conjunction with the ADF image to enable structural characterization of materials [1]. Here we explore the phase precision in electron ptychography, and highlight how it can be used to detect the effects of bonding in materials. We go on to use electron ptychography to reveal information about the 3D structure of the specimen, and examine the effects of dynamical electron scattering on the phase reconstruction.

Data was recorded using a JEOL '4D Canvas' pixelated STEM detector which makes use of a pnCCD device [1] fitted to a JEOL ARM200-CF aberration corrected STEM. The detector has a grid of 264x264 pixels and operates at a speed of 1000 frames-per-second (fps). The detector can achieve a speed of up to 20,000 fps through binning/windowing. We typically operate the detector at 2,000 or 4,000 fps, which then dictates the dwell time for the STEM probe.

Figure 1 shows a reconstructed phase image from monolayer hexagonal boron nitride (hBN). It can be seen that the effects of charge transfer due to bonding is readily detected in the ptychographic reconstruction. Figure 2 shows a reconstructed image from a wedge sample of platinum oriented along <110>. Although the phase reconstruction method we use assumes that the sample can be modelled as a multiplicative transmission function, we show that even in thicker samples the reconstructed image shows phase localised to the atomic columns. As the sample thickness increases, the column intensity does start to become more complex, in particular showing a "donut"-like form. The origins of this form of contrast are discussed.

[1] H. Yang et al., Nature Communications 7 (2016) 12532.

[2] Ryll, H. et al., Journal of Instrumentation 11 (2016) P04006.

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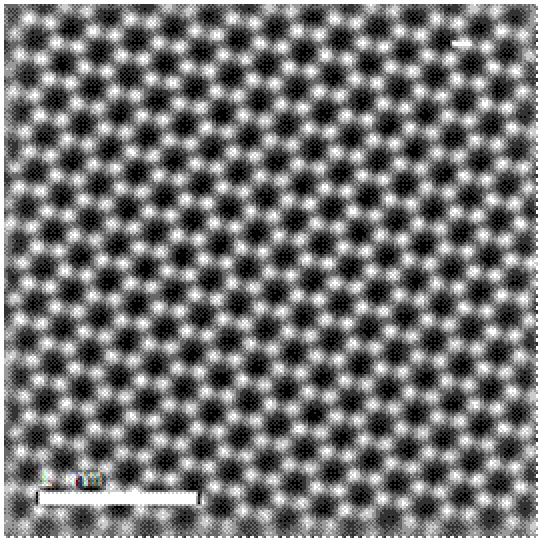

Figure 1. (left) The ptychographically reconstructed phase image of hBN. Unlike the simulation for neutral atoms, which shows a clear polarity between the N and B, the atoms show very similar phase in the experimental image.

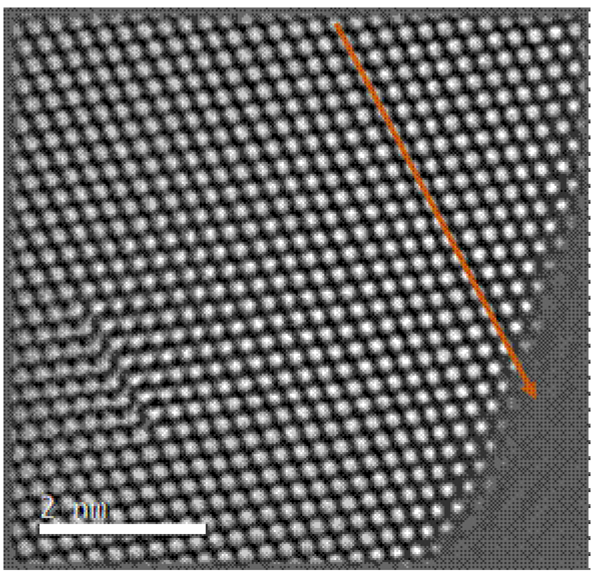

Figure 2. An experimental ptychographic phase image of a wedge sample of Pt recorded at 200 kV. Note the appearance of "donut"-like features in the thicker areas.