Fast pixelated detectors in STEM for quantitative phase imaging

Peter D. Nellist¹, Hao Yang¹*, Gerardo T. Martinez¹, Lewys Jones¹, Martin Huth², Martin Simson², Heike Soltau², Yukihito Kondo³, Ryusuke Sagawa³ and Timothy J. Pennycook⁴

¹ University of Oxford, Department of Materials, Parks Rd, Oxford, UK
² PNDetector GmbH, Sckellstraße 3, 81667 München, Germany
³ JEOL Ltd.,3-1-2 Musashino Akishima Tokyo 196-8558 Japan
⁴ Faculty of Physics, University of Vienna, Vienna, Austria

* Now at Molecular Foundry, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA

In the scanning transmission electron microscope (STEM), the commonly-used imaging modes, for example annular dark-field (ADF) or annular bright-field (ABF) make use of monolithic detectors that sum the intensity over a region of the detector plane and the image is formed by displaying that total intensity as a function of probe position as the probe is scanned. Such detectors are able to respond at the timescales required for typical STEM scanning speeds where dwell times per image pixel position are typically less than 100 μs. Monolithic detectors, however, integrate over much of the wealth of information that is present as fine detail in the intensity at the STEM detector plane. Recent development in detector technology have resulted in cameras with frame-speeds that can exceed 1 kHz, and can therefore be used to record the detail in the detector plane for each probe position during a STEM scan without inordinate increase in dwell time. Here we explore how the recorded four-dimensional (4D) data-set can be used to extend the capabilities of STEM to unlock new applications.

The experiments were performed using the pnCCD (S)TEM camera, a direct electron pixelated detector from PNDetector, mounted on the JEOL ARM200-CF aberration corrected microscope. 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. ADF images can be recorded simultaneously, as shown by the schematic in Fig. 1.

Our initial work on the applications of the 4D data set has focused on the generation of phase images. It was shown nearly 20 years ago that ptychography could be used to generate phase images that exceeded the conventional diffraction limit of the microscope used [1]. Here we make use of ptychography to form a quantitative image of the phase shift of the electron wave due to the sample, and to use those alongside the simultaneous formed ADF image to characterize the sample. We show how the phase transfer function of ptychography is higher than either using ABF or differential phase contrast modes, the latter making use of segmented quadrant detectors [2], with enhanced noise suppression.

The ptychography approach has now been applied to a range of materials types, with some example results shown in Fig. 2. We show results of an Au nanoparticle with five-fold twinning (Figure 2a-d), and gallium nitride GaN viewed along the a lattice vector (Figure 2e-h). Using the 4D dataset which records the diffraction patterns that contains the entire BF and part of DF regions, synthetic BF, ABF and differential phase contrast (DPC) can be obtained along with the ptychographic phase reconstruction. The reconstructed phase of the Au nanoparticle (Figure 2c,d) shows...
clear contrast on every atomic column. In comparison, ABF, as a nonlinear imaging mode, shows contrast that decreases towards the edge of the Au particle (Figure 2b). In the case of GaN, the N columns are hardly visible in the ABF image (Figure 2f), but are clearly resolved in the reconstructed phase (Figure 2g,h).[3]

References

[3] The authors acknowledge funding from the EPSRC (grant numbers EP/K032518/1 and EP/K040375/1) and the EU Seventh Framework Programme: ESTEEM2..

FIG 1. A schematic diagram of the STEM showing electron scattering being detected by an ADF detector and a fast pixelated camera simultaneously.

FIG 2. Simultaneous atomic resolution ADF, synthetic ABF image, and the reconstructed amplitude and phase of (a-d) an Au nanoparticle and (e-h) GaN bulk lattice viewed along the [2\overline{1}10] orientation. The probe forming aperture for both datasets is about 14.4 mrad, and the synthetic ABF has a collection angle of 7.2-14.4 mrad. Both the Au nanoparticle and GaN datasets contain 128x128 probe positions, and were recorded with a camera speed of 1000 and 4000 fps, respectively.