Microsc. Microanal. 24 (Suppl 1), 2018

# Focused-Probe STEM Ptychography: Reconstruction Methods, Transfer Functions and Signal-to-Noise

P D Nellist[1], G T Martinez[1], C O'Leary[1], H. Yang[2], A. Stevens[3,4], N.D. Browning[5]

[1]. Department of Materials, University of Oxford, Parks Rd, Oxford UK.
[2]. Lawrence Berkeley National Laboratory, Berkeley, California.
[3]. OptimalSensing, Southlake, Texas.
[4]. Duke University, ECE, Durham, North Carolina.
[5]. University of Liverpool, Materials Engineering, Liverpool, UK

The scanning transmission electron microscope (STEM) has historically not been widely used for low-dose imaging of radiation-sensitive materials. The conventionally used imaging modes of annular dark-field (ADF) or annular bright-field (ABF) use only a fraction of the electron transmitted by the sample. The development of high-speed pixelated detectors for the scanning transmission electron microscope is allowing the recording of the 4D STEM data set to be increasingly routine. The data set comprises the two real-space dimensions of the probe scan and the two reciprocal-space dimensions of the diffraction pattern recorded at the STEM detector plane, thereby making use of all the transmitted electron. A powerful and increasingly used application of the 4D data set is the reconstruction of the specimen complex transmission function, including the phase, using electron ptychography. It has been shown experimentally that the phase image is robust to low-dose conditions [1,2] suggesting that ptychography may be a powerful method for low-dose conditions.

Here we show how the ptychographic reconstruction method has an intrinsic denoising effect. The interference features in the STEM detector plane that lead to the image signal occur at specific locations controlled only by the size of the beam-limiting objective aperture (Figure 1) whereas the noise is distributed over the whole detector plane. By carefully selecting only those regions containing signal, much of the noise is rejected, explaining the robustness to low-dose conditions. An advantage of focused-probe ptychography is that no image registration process is required, which can be problematic at low-doses for methods that do require image registration.

The phase contrast transfer function (PCTF) is often used to compare different phase contrast images and reconstruction algorithms. We show how the PCTF of a ptychographical reconstruction can be arbitrarily selected, and therefore does not offer a useful metric to compare approaches. Figure 2 shows the line profile through a ptychographic phase image of a single atom of Au using the PCTF intrinsic to the single side-band reconstruction [3]. The figure also shows results when a uniform PCTF is selected, and shows how the dip in phase surrounding the atomic peak can be avoided. This approach can be regarded as a deconvolution step, with the associated danger of noise amplification. We discuss how the crucial quantity to compare reconstructions is the signal to noise as a function of spatial frequency.

Compressive sensing (CS)-inpainting has been demonstrated as a method to reduce the dose in STEM imaging [4]. In addition to provide a route to lower-doses, CS also has the potential to reduce the data-volume in ptychography, easing the challenges of data streaming and storage and leading to higher speeds. Figure 3 shows ptychographic reconstructions from data when only 20%, 5% and 1% of the detector pixels are retained. The detector plane intensity is restored using inpainting (punctured median filter on the Fourier magnitude image) and a normal ptychographic reconstruction follows. Even with only 1% of the detector pixels being used, the image maintains strong visbility [5].

References:

[1] H. Yang *et al,* Nature Communications **7** (2016), p. 12532.
[2] Y. Jiang *et al,* arXiv:1801.04630
[3] H. Yang, T. J. Pennycook and P. D. Nellist, Ultramicroscopy **151** (2015), p. 232.
[4] A. Stevens *et al,* Appl. Phys. Lett. **112** (2018), p. 043104.

[5] The authors acknowledge the contribution to the experimental data used below from JEOL Ltd (Y. Kondo and R. Sagawa) and PNDetector (M. Huth, M. Simson and H. Soltau). Financial support from JEOL UK Ltd and the EPSRC (grant number EP/M010708/1) is gratefully acknowledged.

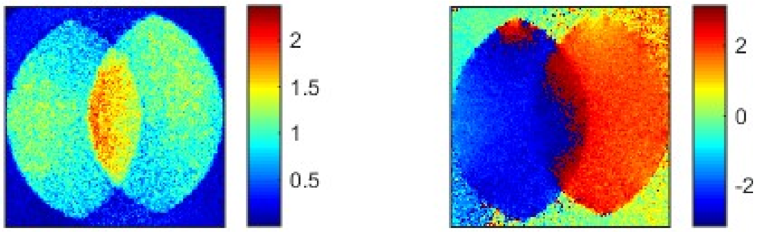

**Figure 1.** For a specific spatial frequency in the reconstructed phase image, the information can be derived from interference observed in the detector plane leading to a map of the amplitude (left) and phase (right) associated with the spatial frequency. For all images the phase unit is radians.

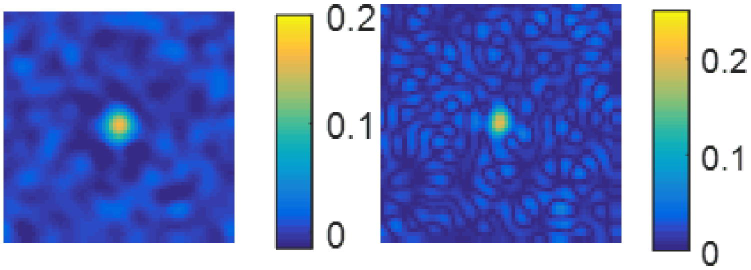

**Figure 2.** Ptychographic reconstructions of the phase image of a single atom of Au with data simulated assuming a total fluence of 20,000 $e^-$ $Å^{-2}$. (left) The instrinsic transfer function of the single side-band method has been used. (right) The algorithm has been modified to reconstruct with a flat transfer function.

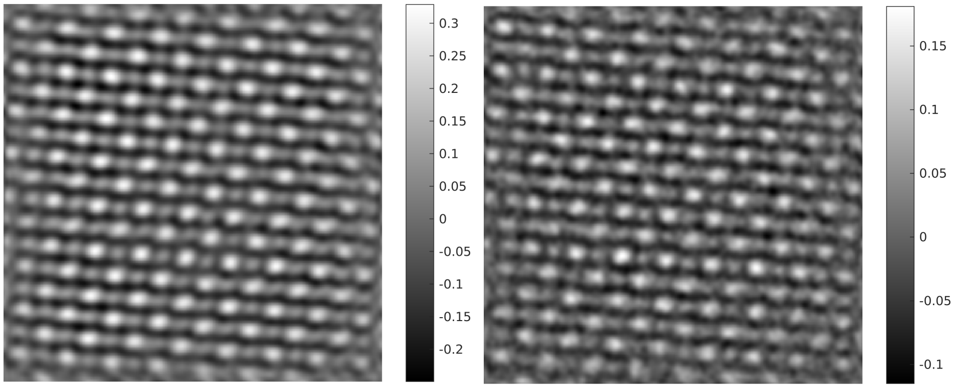

**Figure 3.** Experimental ptychographic phase image of $SrTiO_3$ making use of 5% (left) and 1% (right) of the recorded detector plane pixels followed by CS-inpainting.