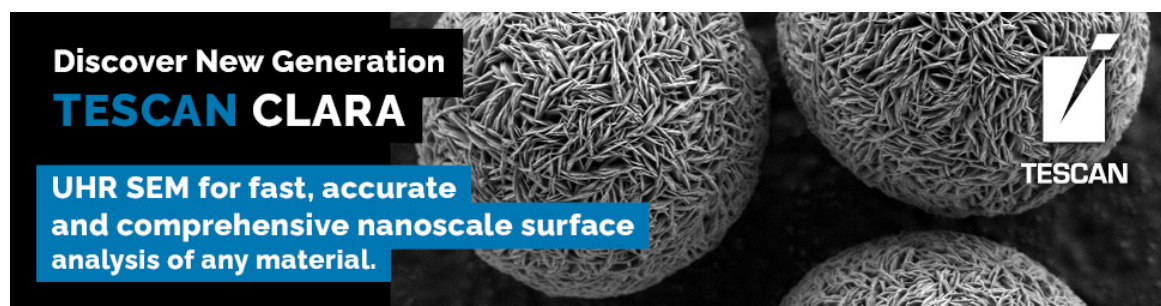


# Achieving Super Resolution Ptychography with a Quadrant Detector

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Meeting-report

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Xiyue S. Zhang<sup>1</sup>, Zhen Chen<sup>2</sup>, Yu-Tsun Shao<sup>1,3</sup>, Yi Jiang<sup>4</sup>, Ariana Ray<sup>1</sup>, and David A. Muller<sup>1,5,\*</sup>

<sup>1</sup>School of Applied and Engineering Physics, Cornell University, Ithaca, NY, United States

<sup>2</sup>School of Materials Science and Engineering, Tsinghua University, Beijing, China

<sup>3</sup>Mork Family Department of Chemical Engineering and Materials Science, University of Southern California, Los Angeles, CA, United States

<sup>4</sup>Advanced Photon Source, Argonne National Laboratory, Lemont, IL, United States

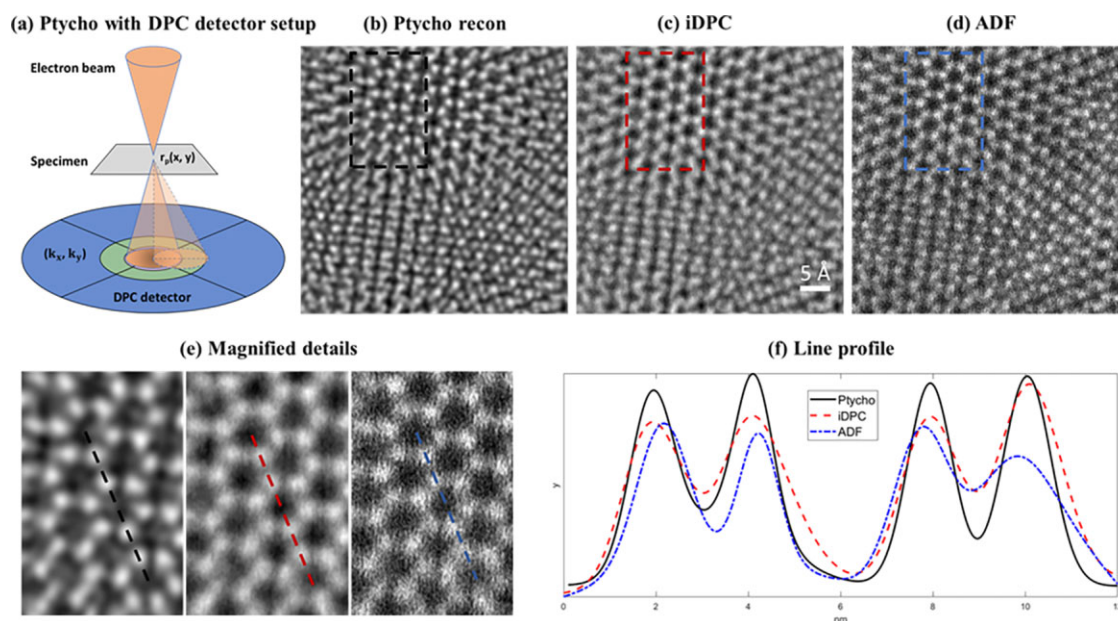
<sup>5</sup>Kavli Institute at Cornell for Nanoscale Science, Ithaca, NY, United States

\*Corresponding author: [dm24@cornell.edu](mailto:dm24@cornell.edu)

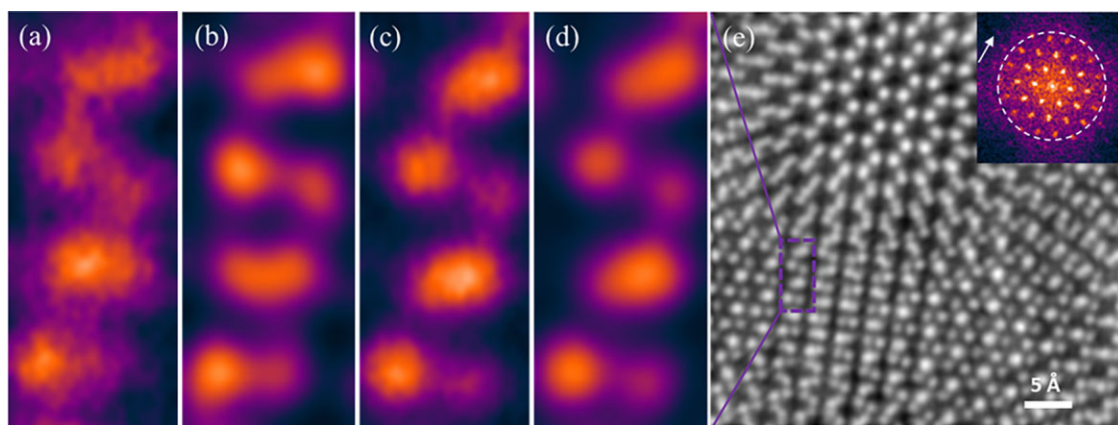
Resolution limits in conventional scanning transmission electron microscopy (STEM) are determined by size of the probe forming aperture. Enabled by high-speed, high-dynamic-range pixelated detectors, it has been possible to overcome this limit with electron ptychography [1]. While electron detectors with thousands or millions of pixels provide rich angular information, they are thousands of times slower than differential phase contrast (DPC) detectors with 4–16 pixels [2], making it more difficult to outrun scan instabilities and damage during acquisition. Ptychography is a phase space measurement method constructed from real and reciprocal space information. The ptychographic sampling ratio, defined as the reciprocal of real space sampling times reciprocal space sampling, is the key factor to quantify redundancy in this sampling and suggests we can still achieve super resolution imaging with under-sampled diffraction patterns by oversampling in real space [3, 4]. Our previous simulations using the ePIE phase retrieval algorithm with reciprocal space upsampling showed ptychography with a 4-segment quadrant detector is sufficient to achieve super resolution imaging if the ptychographic sampling ratio criterion is met [5].

Here we performed ptychographic measurements on a WSe<sub>2</sub>/MoTe<sub>2</sub> bilayer moiré pattern using the Thermo Fisher Scientific Panther DPC detector (Figure 1(a)) with experimental parameters optimized by our earlier simulation results [5]. Acquiring 12 segments simultaneously allows multimodal imaging including integrated-DPC (iDPC) and annular dark field (ADF) imaging as well as ptychographic reconstruction with different cutoff angles. iDPC imaging is widely used for imaging beam sensitive samples due to its dose efficiency and here we use it as a resolution benchmark [6]. Figure 1(b)–(d) shows ptychographic reconstructions with 12 segments binned to 4 quadrants, iDPC on the same 4-quadrant data, and ADF from the summed outer rings. A magnified area (Figure 1e)) shows ptychography has the best resolution and SNR, quantified by line profiles (Figure 1(f)). With only a 2×2 detector-pixel setup, ptychography with reciprocal space upsampling enables super resolution resolving the moiré structure with 67% fringe contrast, which surpasses the value of 45% by iDPC imaging and 52% by ADF imaging.

To study the effects of beam dose and cutoff angle on ptychographic reconstructions, we bin 12-segment and 8-segment data to study the reconstruction vs. cutoff angle and use 1  $\mu$ s dwell time along with 49 continuous frames to study the reconstruction vs. beam dose. Ptychography with higher cutoff angle shows a slightly better reconstruction than the lower cutoff angle reconstruction, and both conditions have higher resolution and contrast than iDPC. Figure 2(a)&(b) show iDPC and ptychography at a low beam dose of  $2 \times 10^4$  e<sup>−</sup>/Å<sup>2</sup> and we can see ptychography is already resolving more fine details in this condition. Figure 2(c)&(d) show iDPC and ptychography at a high beam dose of  $10^6$  e<sup>−</sup>/Å<sup>2</sup> and again ptychography has better resolution. The highest order peak in the fast Fourier transform (FFT) from ptychography (Figure 2(e)) shows 0.63 Å resolution and is beyond the diffraction limit of 0.98 Å at 60 kV. We successfully achieved super-resolution ptychographic reconstruction with rapid acquisition conditions (37.5 pA and only 1  $\mu$ s dwell time) at 60kV using a quadrant detector [7].



**Fig. 1.** 4D-STEM with 12-segment DPC detector. (a) Experimental setup. (b) Ptychography reconstruction with binned  $2 \times 2$  pixels. (c) iDPC with the same binned  $2 \times 2$  pixels. (d) virtual ADF from summed outer rings of DPC detector. (e) Magnified details of ptychography, iDPC and ADF at the position of dashed boxes in (b)-(d). (f) Line profiles at the position of dashed lines in (e).



**Fig. 2.** Comparison of experimental iDPC and ptychographic reconstructions at different dose conditions. (a)&(b) iDPC & ptychography at beam dose  $2 \times 10^4 \text{ e}^-/\text{\AA}^2$ . (c)&(d) iDPC & ptychography at beam dose  $10^6 \text{ e}^-/\text{\AA}^2$ . (e) Full reconstruction at condition of (d) with dashed box showing where (a)-(d) are cropped. White dashed circle in the FFT inset marks diffraction limit and white arrow points to the highest order peak from ptychographic reconstruction. Resolution of ptychography is  $0.63 \text{ \AA}$ , which is beyond diffraction limit of  $0.98 \text{ \AA}$ .

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