Low-dose Electron Ptychography with a Fast Direct Electron Detector

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Developments in aberration correction and complementary electron optical components such as monochromators and high brightness guns [1] in Scanning Transmission Electron Microscopy (STEM), has enabled 0.5Å resolution at 300kV for radiation resistant materials. However, for many beam-sensitive specimens such as organic compounds, biological specimens, zeolites and ceramics, radiation damage is the limiting factor for the determination of the structure in the pristine condition. Beam-sensitive specimens have varying tolerances to electron dose due to different damage mechanisms. One possible dose-reduction strategy in the STEM mode is to decrease the electron beam current or the pixel dwell time. However, to preserve atomic resolution imaging, this still requires a large pixel array and manual adjustment of residual low order aberrations before acquisition, which further increases the total dose at the sample and could cause the sample beam-damaged.

Alternative approaches are electron coherent diffractive imaging (CDI) and ptychography, which have been widely used in light and X-ray optics. Conventional CDI can be used to solve the phase problem from a single diffraction pattern by computationally iterating between the diffraction and object planes, it however, requires *a priori* knowledge about the shape or extent of the object. The advantage of ptychography over traditional CDI is that it does not need prior information about the probe function and also overcomes other issues of CDI, including non-unique solutions and a limited field of view [2]. As this approach is diffraction limited, it can, in principle, overcome current image resolution limiting factors and ultimately and achieve wavelength-limited resolution. It also has the potential for super resolution [3], high phase sensitivity [5], three-dimensional [6] and low-dose [7] capabilities that have recently attracted great attentions in electron microscopy society. One of the major developments that has advanced this field is the availability of a new generation of direct detection cameras, which are particularly suited to ptychographic data acquisition using new modes of operation, such as electron counting and fast acquisition [8,9]. These new cameras also dramatically increase the detective quantum efficiency (DQE) and hence significantly improve the signal to noise ratio (SNR) of the recorded far field diffraction patterns (DP). Hence lower signals at higher scattering angles can be captured in each DP in a ptychographic dataset, which enables higher resolution in ptychographical reconstructions, even within the constraints of low electron dose work as required for beam sensitive samples.

In this paper, we will describe examples of defocused ptychography to achieve phase reconstructions of a nanocrystal at sub-Å resolution in 2D [4] and carbon nanotube bundles in 3D [7] using a traditional CCD camera. We will also l present recent low-dose experiments using a fast direct counting electron detector, where we are able to reconstruct the wavefunction of low dimensional materials under different low dose conditions. The experimental data were acquired on a JEM-ARM300F instrument [1] operated at 80kV with a Medipix3 direct electron detector [8]. Fig. 1a shows a schematic diagram of the optical configuration employed using a probe with a convergence semi-angle of 24 mrad and 17pA current and with the sample at a distance 80 nm above the focal point as shown in Fig. 1a. The sample used was monolayer <001>-oriented MoS_2 and was illuminated in a 20 × 20 raster scan of probe positions at an approximate step size of 0.48 nm with various sub-ms time intervals. A preliminary lose-dose reconstruction at a dose of $5x10^3 e/A^2$ is shown in Fig. 1b.

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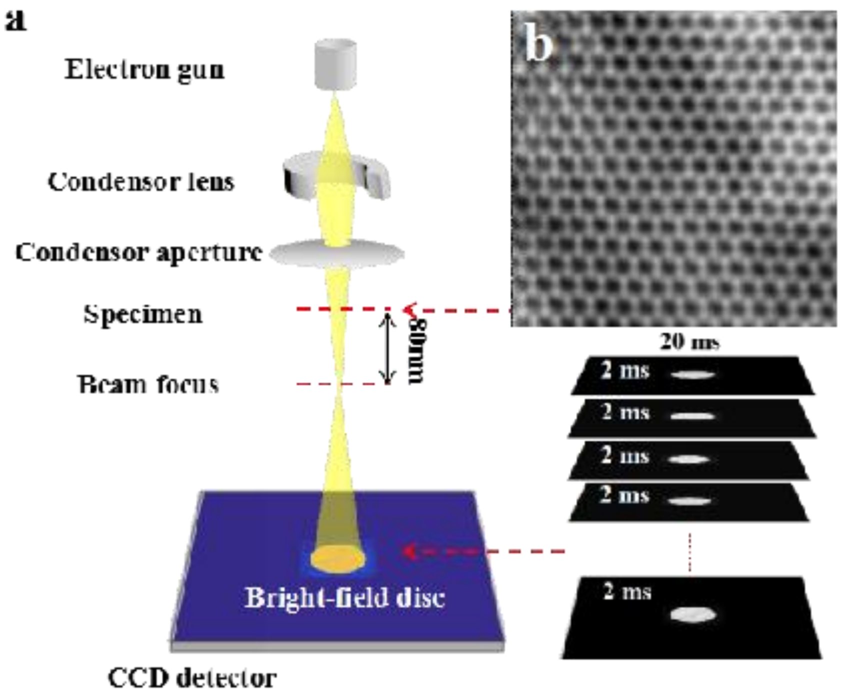

Figure 1. (a) Schematic of (a) the experimental configuration used for ptychographic reconstruction and (b) Ptychographical reconstruction of a MoS_2 monolayer oriented along a <001> direction.