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100,000 Diffraction Patterns per Second with Live Processing for 4D-STEM

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Collecting a full two-dimensional (2D) diffraction pattern at each scan position can create more powerful and flexible datasets compared to traditional scanning transmission electron microscope (STEM) detectors, enabling imaging methods such a ptychography, center-of-mass analysis, or other 4D-STEM techniques [1].

There are challenges associated with 4D-STEM acquisition. First, speed—traditional STEM detectors are fast (typical per-pixel dwell times are ~10 µs or less), and the best images are typically acquired as stacks of fast scans, aligned and summed (a.k.a. dose fractionation). An ideal 4D-STEM detector would operate at the same speed and maintain high DQE for any dose. Second, information overload—raw 4D datasets are huge and quickly overwhelm regular computers.

We present a 4D-STEM system designed to address these challenges, consisting of a Nion UltraSTEM aberration corrected microscope equipped with DECTRIS ARINA hybrid pixel array direct electron detector for capturing diffraction patterns. The detector has 192x192 pixels of 100 um^2 each with 12-bit depth, where it can deliver electron-counted frames at 20 kHz. With 2x2 binning and on-chip compression, the speed is over 100 kHz. Using a threshold and electron counting, each pixel can take 10 pA without saturation. There is effectively no dark current or readout noise, so there is no noise penalty when acquiring many short exposures [2]. The electron-counted frames are streamed into the Nion Swift microscope control and data analysis application [3]. Nion Swift tools allow for live reduction, processing, and display of data as it is acquired at the full speed, 100,000+ diffraction patterns per second. The unreduced data is saved in a revolving buffer, so that it can be recovered and stored permanently if desired [4, 5].

Figure 1 shows this system applied to an InGaN insertion in a GaN nanowire. See [6] for more about the sample. Taking advantage of the detector speed, dose fractionation is employed to divide the total 4.4 minute acquisition time over 100 scans of 2.6s each (10 us/scan pixel, 512x512 scan $pixels^2$). This optimizes the images in the presence of dose-rate dependent beam damage and slow environmental instabilities. Live processing is used to reduce full 2D frames into a handful of channels useful for this experiment: X-shift, Y-shift, total intensity, and virtual HAADF. This reduces the data size for these few minutes of data from an inconvenient hundreds-of-GB to a lightweight few-MB, while maintaining options for post-processing such as non-rigid registration of the 4D-scans using the traditional HAADF signal. The shift maps are processed to give the electric field in the sample. Figure 1e shows strong electric fields at each atomic column, and also a weaker large-scale field at the InGaN/GaN interface, indicating charge build-up there. The charge density calculated from the electric field map is shown in

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figure 1f. The central column at the InGaN/GaN interface has the highest charge density (brightest red). This explains why the large-scale electric field points away from this column on either side in fig 1e.

The potential uses of this 4D-STEM system are not limited to the relatively simple center-of-mass analysis used here. The live processing is user-configurable in an open-source software environment (Nion Swift), and can be applied to crystallographic phase identification, ptychographic reconstructions, and more.

Further applications of 4D-STEM at 100,000 diffraction patterns per second will be shown at the meeting [7].

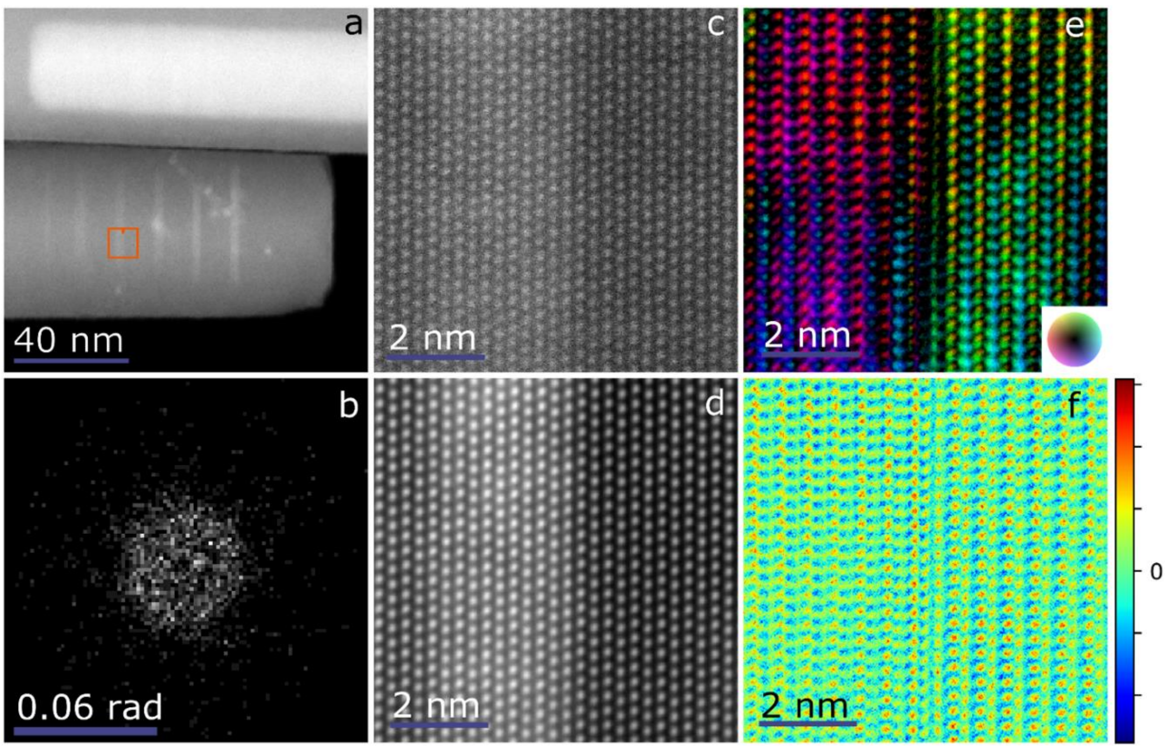

Figure 1. 4D-STEM imaging of a GaN nanowire with InGaN insertions using dose fractionation (100 scans): (a) overview of the nanowire, with the subscan region for c-f marked. (b) representative single diffraction pattern (10 us), (c) single-scan HAADF image, (d) 100 HAADF images aligned and summed, (e) center-of-mass analysis showing the local electric field (100 scan average, the inset shows how color corresponds to electric field direction, and saturation to field magnitude), (f) charge density map calculated from electric field. E_o=100kV, I_{probe}=60 pA, $\alpha/2$=25 mrad. c-f: 512 x 512 scan points and 10 us dwell time per scan point. 100 scans with 2.6 s per scan, 4.3 min total.

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