

Applications of a MAPS direct detector for high-resolution, low-kV electron microscopy

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Direct Electron
INNOVATION PROPELLING DISCOVERY

Low-kV Imaging

MAPS Direct Detection at Low-kV

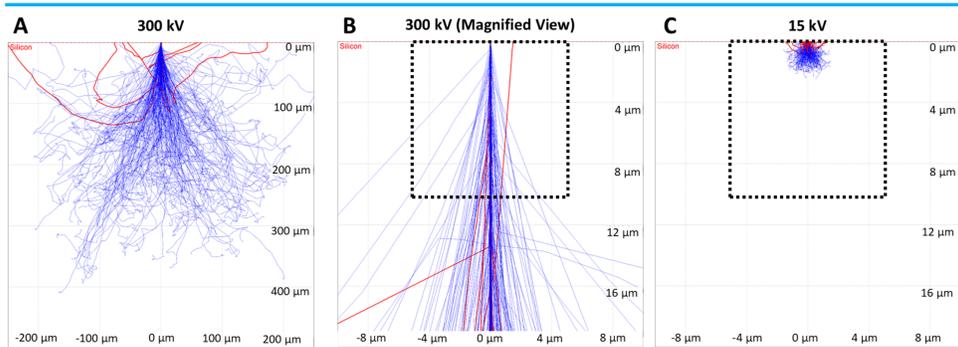


Figure 1: Monolithic Active Pixel Sensor (MAPS) direct detectors have been widely employed in Transmission Electron Microscopy for applications such as imaging beam sensitive biological specimens, making a major contribution to the "resolution revolution" in biological electron microscopy. (A) At typical TEM beam voltages (e.g. 300 kV), electrons incident on a silicon sensor scatter over a very large volume. (B) The scattering volume of a 300 kV electron is much larger than the typical volume of the sensitive layer of a MAPS pixel (represented by the dashed black box in the figure), so MAPS detectors can only sample a portion of the energy of incident electrons in TEM. As a result, various trade-offs must be made to optimize either detective quantum efficiency (DQE) or dynamic range and temporal resolution, while attempting to mitigate beam damage to the sensor. (C) However, at 15 kV, a typical beam voltage for applications such as low energy electron microscopy (LEEM) or electron backscatter diffraction (EBSD), an electron can be fully stopped by a MAPS pixel, potentially allowing MAPS detectors to be used for high DQE and high dynamic range imaging for these low-kV applications, with a much lower risk of beam damage to the sensor.

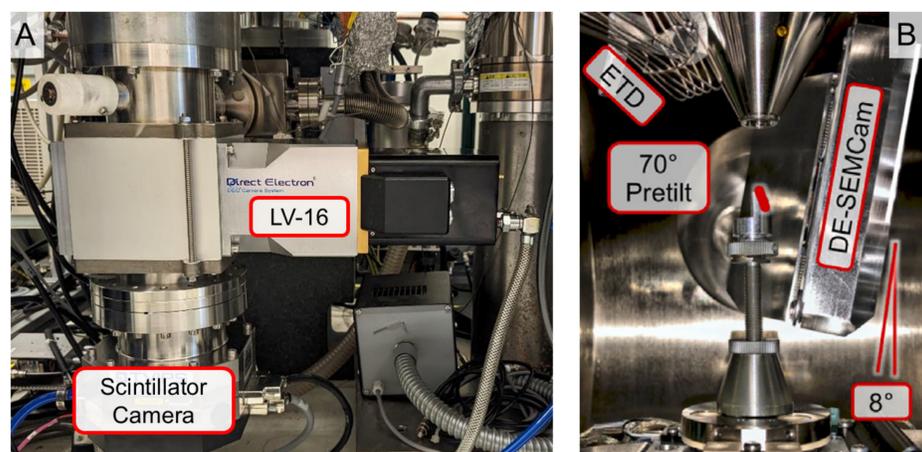


Figure 2: Direct Electron LP has developed a 4096 x 4096 pixel sensor with a 6.5 μm pixel pitch for low-kV applications (A) One application for this sensor is the LV-16 camera, which can be mounted onto a LEEM, or a low-kV TEM. Photo courtesy of Dr Ruud Tromp, IBM (B) A second application is for the DE SEMCam, which can be mounted onto an SEM. Photo from Wang et al. *Ultramicroscopy* 220 113160 (2021).

Application of a MAPS for LEEM/PEEM Imaging

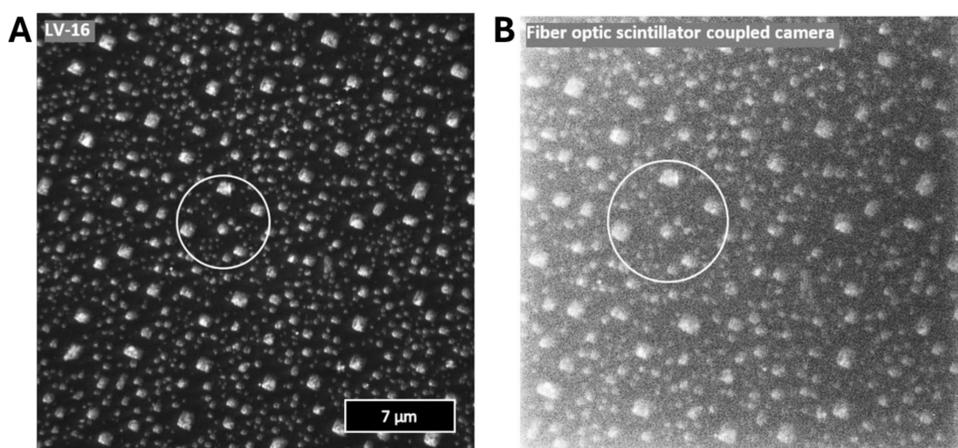


Figure 3: PEEM (photoemission electron microscopy) images at 15 kV of a silicon surface for (A) an LV-16 detector, and (B) a state-of-the-art scintillator coupled detector under identical imaging conditions. The integration time was 300 seconds for both cameras, and both were operated in a 2k x 2k pixel imaging mode. The circle marks the same area of the specimen in the two images. Data courtesy of Dr Ruud Tromp, IBM. These results suggest that the direct detector can acquire images with a significantly better signal to noise ratio than the scintillator-coupled detector.

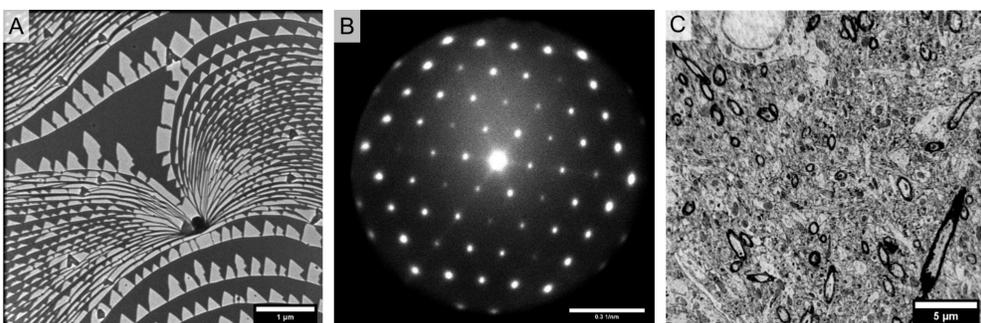


Figure 4: (A) LEEM image of Si(111) surface, with (7x7) (bright) and (1x1) (dark) reconstructions co-existing at about 860°C. (B) LEED image of a (7x7) surface reconstruction of Si(111) acquired at room temperature with 5.5 eV electron landing energy. The boundary of the circle is the edge of the Ewald sphere. (C) PEEM image of a mouse brain section. Data courtesy of Dr Ruud Tromp, IBM.

Electron Backscatter Diffraction

EBSD of Beam Sensitive Ceramics at 5 - 10 kV

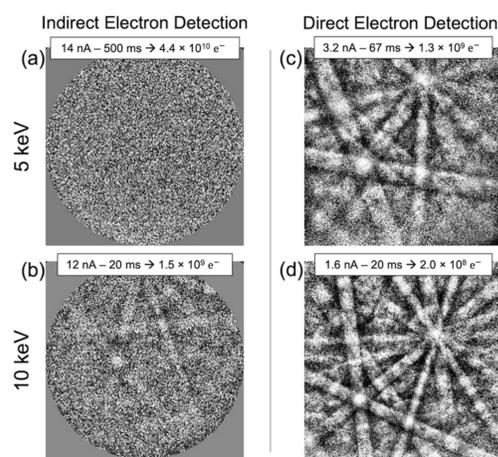
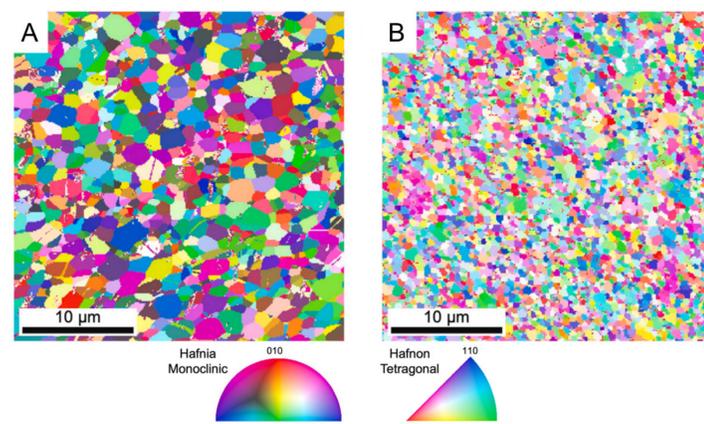


Figure 5: Electron backscatter diffraction patterns from hafnia acquired with (a) a scintillator-coupled detector at 5 kV, (b) a scintillator-coupled detector at 10 kV, (c) the DE SEMCam at 5 kV, and (d) the DE SEMCam at 10 kV.

Even at beam doses of about an order of magnitude lower than the scintillator coupled camera, the direct detector produces patterns of significantly higher quality. The ability to generate indexable patterns at lower beam doses at low kV facilitates EBSD analysis of more beam sensitive or charge sensitive specimens, historically unsuited for EBSD, including hafnia.

Figure 6: EBSD maps collected at 10 kV using the DE SEMCam from (A) hafnia, and (B) hafnon. A dictionary indexing algorithm was used to generate the maps from the data.



Images in this figure and Figure 5 are from Della Ventura et al. *Ultramicroscopy* 268 114079 (2025)

High-Resolution EBSD Strain Mapping

Figure 7:

High-resolution EBSD (HR EBSD) is a technique requiring a detector with a large number of pixels to record high resolution diffraction patterns from which strain information can be obtained.

With the high sensitivity of the DE SEMCam, it is possible to extract detailed, quantitative strain information from the patterns, as shown here for an indented silicon specimen. Data courtesy of Damien Dingley, BLG Vantage.

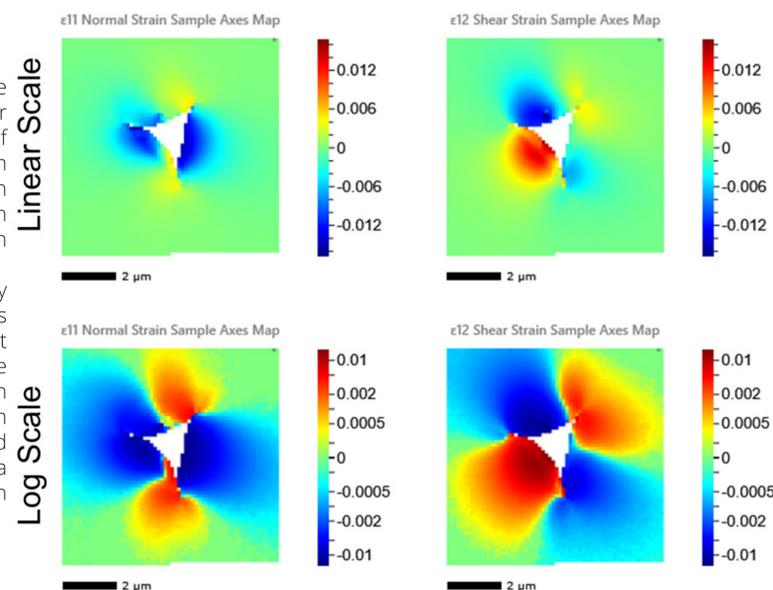


Figure 8: Preliminary investigation of the potential spatial resolution of HR-EBSD mapping with a DE SEMCam. A resolution of about 20 nm was obtained here using a 20 nm step size, which was the smallest tested. Future work aims to investigate step sizes of 10 nm and below. The sensitivity of the SEMCam below 10 kV is beneficial for spatial resolution due to reduced interaction volume. Data courtesy of Damien Dingley, BLG Vantage.

Summary and Future Work

A 4096 x 4096 pixel MAPS detector has been applied to low-kV electron microscopy applications, including LEEM/PEEM imaging, and HR-EBSD mapping. The detector has demonstrated superior performance in terms of its sensitivity to traditional indirect detectors, enabling high resolution imaging in LEEM/PEEM and mapping of more beam-sensitive specimens at 10 kV and below in EBSD.

MAPS direct detectors are more commonly used at 200 kV - 300 kV in TEM. At these energies, the physics of electron scattering within the sensor requires trade-offs to be made between DQE and dynamic range that are unnecessary for low-kV applications. However, certain techniques developed for processing data from the sensor for high-kV applications could be repurposed to be useful for low-kV applications. One such image processing technique is electron counting, which allows each individual electron striking the sensor to be counted under sparse illumination conditions. At low-kV, where the electrons are fully stopped within the sensor, the counting algorithm can be modified so that the energy of each incident electron can be measured. Future work will explore the application of this algorithm to HR-EBSD. We aim to investigate the degree to which energy filtering can improve the quality of diffraction patterns, and the orientation maps and strain maps that can be generated from the data.