Quantitative High-Resolution TEM/STEM and Diffraction

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A new direct electron imaging camera for transmission electron microscopy based on an ultrafast pnCCD

H. Ryll[1], K. Müller[2], S. Ihle[1], H. Soltau[1], I. Ordavo[3], A. Liebel[1], R. Hartmann[1], A. Rosenauer[2], L. Strüder[1]

[1]PNSensor GmbH, München, Germany
[2]University of Bremen, Bremen, Germany
[3]PNDetector GmbH, München, Germany

henning.ryll@pnsensor.de

Since their introduction to transmission electron microscopy (TEM), digital imagers have greatly improved the workflow and enhanced experimental techniques, for example quick successive image acquisition at cryo-tomography. Still, most digital imagers are based on the principle of indirect detection of electrons, with a phosphorous layer where the electrons are converted into photons. These photons are then guided via optical fibers onto a CCD or CMOS imager. Certain disadvantageous effects result from this design, mainly non-perfect conversion efficiency, scattering of photons, reflections at optical interfaces and absorption losses. However, the indirect approach was justified by the low radiation hardness of the imagers to direct exposition with electrons, which would deteriorate the detector performance. The disadvantages of indirect detection can be removed with devices that are radiation hard to electrons in the energy range of 20-300 keV and can therefore directly detect electrons. The pnCCD is inherently radiation hard because of the avoidance of active MOS structures [1]. The structured front side is additionally protected by the 450µm thick bulk volume of the detector in conjunction with backside illumination. While other groups have reported on mostly CMOS based direct imagers [2,3], we present a new TEM camera based on a pnCCD [3], along with first results and simulations. The type of pnCCD used in this camera has a pixel size of 48x48 µm² with 264x264 pixels. Up to 1000 full frames per second can be read out continuously due to the multiparallel readout scheme of the pnCCD. This ultrafast imaging enables the observation of dynamic processes and temporal changes of samples. Aided by adjustable amplification levels, the sensitivity is such that each primary electron can easily be distinguished from noise providing single electron detection capability, independent of the energy of the primary electron between 20 and 300 keV. This is advantageous for low and ultra-low dose imaging of radiation sensitive samples. The individual detection of single primary electrons in a low dose experiment with 100-1000 incident electrons per frame enables further analysis and processing of these electron events.

Final images can be obtained in two ways. In the first way, called intensity mode, multiple frames and their intensities are simply summed up, resulting in an image which is similar to a conventional intensity image. In the second way, called event imaging mode, individual electron events are analysed and processed. The full characteristic properties of each detected primary electron are determined from each frame. The point of entry for each event can be reconstructed with a subpixel precision much finer than the device pixel size. An advanced center of gravity method is used here. The image is then formed by binning and counting each event in a grid with subpixel dimensions.

Evaluation of the imaging capabilities of the pnCCD TEM camera was done at a FEI Titan80/300 at electron energies of 80, 120, 200 and 300 keV. The slanted knife edge method was applied to measure the modulation transfer function (Figure 2.). The contrast increased with lowering the electron energies. In intensity mode, the contrast was 10% at 0.58 and 0.34 Nyquist at 200 and 300 keV respectively. The lower electron energies of 80 and 120 keV showed better contrast with 24% and 11% at full Nyquist in intensity mode. Applying the event processing and a 5x5 subpixel grid, the contrast increased to 72% and 39% for 80 and 120 keV respectively, which in the case of 80 keV is close to the theoretical maximum of 84% at full Nyquist frequency.

Additionally to the camera performance values, a first application [5] will be presented, where single Bragg discs of diffraction patterns are imaged on a millisecond timescale (Figure 3.).

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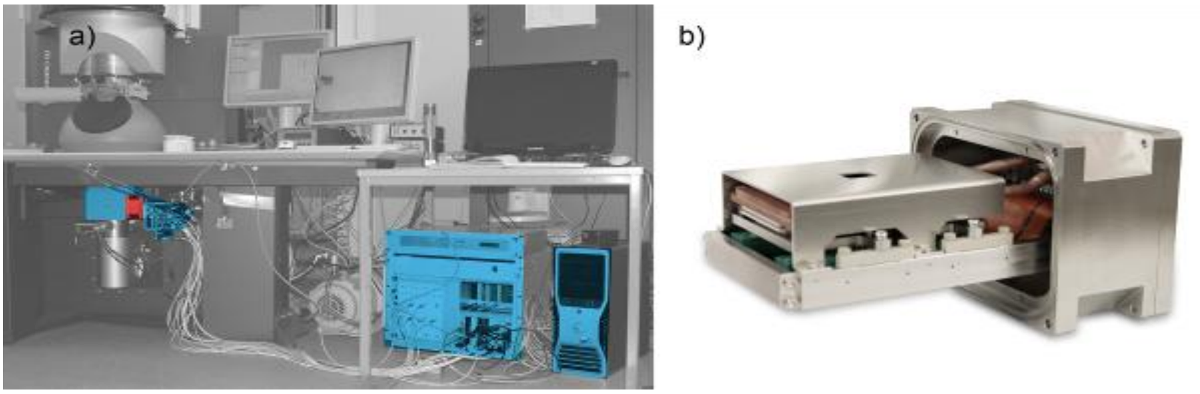

Figure 1. a) Setup of the pnCCD TEM camera at an FEI Titan80/300. The system is highlighted and consisted (from the right): PC, data acquisition and power supplies electronics and the camera mounted at an already installed Gatan Ultrascan camera housing. The compact camera head is highlighted in red and shown in **b)**.

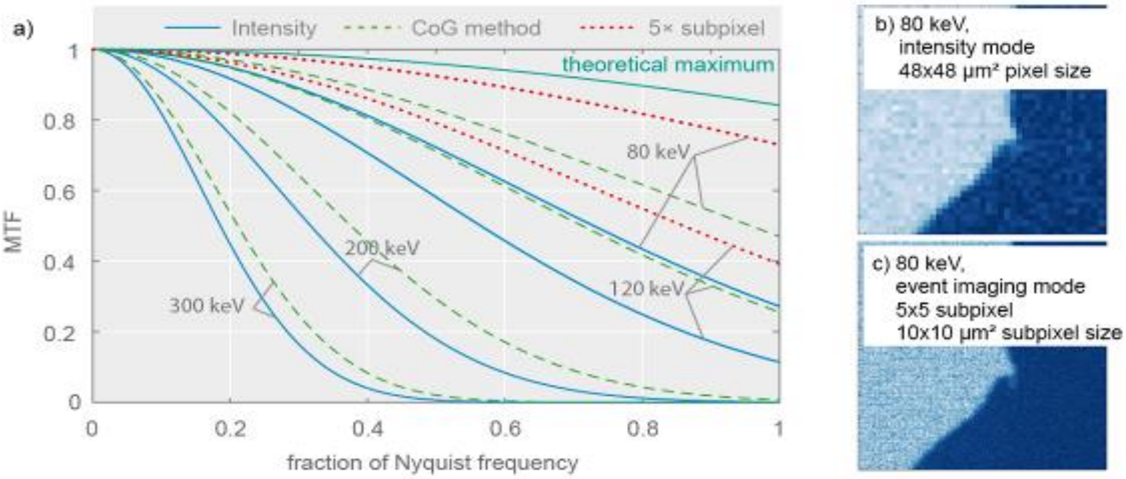

Figure 2. MTFs in **a)** measured with the pnCCD camera at a Titan 80/300 and analyzed with the slanted knife edge method for different imaging modes at primary electron energies of 80, 120, 200 and 300 keV. The solid blue lines correspond to images which were formed with integrated intensity images (Intensity). The dashed green lines correspond to images formed by processing primary electron events and applying the center of gravity method (CoG method) with no subpixel resolution. The dotted red lines for 80 and 120 keV correspond to the CoG method with a 5x5 subpixel resolution. The uppermost curve is the theoretical maximum given by sin(x)/x. An image at a primary electron energy of 80 keV is shown in **b)** formed in the intensity mode and in **c)** formed with event processing and 5x5 subpixels.

Figure 3. Single frame with 1 ms exposure time at a primary electron energy of 300 keV showing a Bragg disc of a diffraction pattern. The signal outside the disc is not noise but originates from primary electrons which are scattered at the sample, while the structure inside the disc is due to dynamical scattering.