The pnCCD (S)TEM Camera

The pnCCD (S)TEM camera contains a new, innovative detector concept dedicated for electron imaging and counting. The sensor is a pixelated, fast and direct electron detector for applications in both TEM and STEM. It is based on the concept of the pnCCD, and it has 264 x 264 pixels with a physical pixel size of 48µm x 48µm. Single primary electron detection from 20 keV to 300 keV is possible thanks to its outstanding signal-to-noise ratio and the direct electron detection capability. Its extreme radiation hardness, high sensitivity, ultra-fast readout and easy to apply operation modes enable new experimental possibilities in electron microscopy.

### Technical specifications of the pnCCD

<table>
<thead>
<tr>
<th>Parameter</th>
<th>pnCCD properties</th>
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<tbody>
<tr>
<td>Physical pixel size</td>
<td>48 µm x 48 µm</td>
</tr>
<tr>
<td>Active thickness</td>
<td>450 µm</td>
</tr>
<tr>
<td>Number of physical pixels</td>
<td>264 x 264 = 69,696 plus frame store area</td>
</tr>
<tr>
<td>Number of subpixels</td>
<td>1,320 x 1,320 = 1.75 x 10⁶ resolution points</td>
</tr>
<tr>
<td>Active area</td>
<td>12.7 mm x 12.7 mm (A = 161 mm²)</td>
</tr>
<tr>
<td>Binning modes (examples)</td>
<td>2-fold binning: 264 x 132 pixels (2,000 fps)</td>
</tr>
<tr>
<td></td>
<td>4-fold binning: 264 x 66 pixels (4,000 fps)</td>
</tr>
<tr>
<td>Windowing modes (examples)</td>
<td>132 x 264 pixels (2,000 fps)</td>
</tr>
<tr>
<td></td>
<td>24 x 264 pixels (10,000 fps)</td>
</tr>
<tr>
<td>Image integration time</td>
<td>down to 25 µs</td>
</tr>
<tr>
<td>Pixel readout rate</td>
<td>Up to 70 Megapixel/s</td>
</tr>
<tr>
<td>External trigger</td>
<td>yes (accepts up to 4 triggers)</td>
</tr>
<tr>
<td>Signal (per 80 keV primary electron)</td>
<td>22,000 signal electrons</td>
</tr>
<tr>
<td>Readout noise (RMS)</td>
<td>Typically 30 signal electrons</td>
</tr>
<tr>
<td>Subpixel spatial resolution</td>
<td>Δx &lt; 10 µm (rms) for 80 keV TEM electrons</td>
</tr>
<tr>
<td>Charge handling capacity</td>
<td>Up to 400,000 signal electrons per pixel</td>
</tr>
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</table>

- **Direct electron detection**
  Unique single electron sensitivity
  SNR 300:1 (80 keV)

- **Ultra-fast readout**
  Standard full frame rate 1,000 fps
  up to 8,000 fps using windowing and binning

- **Wide energy ranges**
  Standard from 20 keV to 300 keV
  Down to 5 keV possible

- **Radiation hard**
  > 1x10¹⁸ TEM electrons (80 keV) per cm²
  > 4x10¹⁷ TEM electrons (200 keV) per cm²
The pnCCD (S)TEM Camera
Applications in STEM

The unique properties of the pnCCD (S)TEM camera open up new fields of application which profit from the additional information of the recorded 4D dataset. Benefitting applications range from imaging on the micro- and millisecond timescale to strain analysis or electric field imaging.

With the pnCCD (S)TEM camera, 4D-STEM imaging, where a 2D pixelated diffraction pattern of every probe position is recorded, becomes feasible for the first time. Traditionally, only the summed intensity of the bright field (BF) or the dark field (ADF, HAADF) is recorded for each probe position, providing relevant, but limited information about the sample. Due to the high readout speed of the pnCCD (S)TEM camera, for example 4 000 frames per second using the 4x binning mode, a high resolution 4D-STEM image with 512 x 512 probe positions can be recorded in just over a minute.

Electron Ptychography

Electron ptychography is a 4D-STEM technique that was described theoretically in 1993 but so far was limited experimentally by the low readout speed of existing cameras. In this technique, the intensity distribution in the bright field disk is recorded in 2D for each STEM probe position. In an electron waveoptical approach, the phase and amplitude information is extracted from the recorded intensity images. The reconstructed phase image shows enhanced image contrast compared to the conventional annular dark field image.

Diffraction Pattern Analysis

Information like crystal structure and phases, lattice defects, or strain along interfaces can be determined by 2D diffraction pattern analysis. Recording the 2D diffraction pattern for each probe position with the pnCCD (S)TEM camera allows any pattern region or diffraction peak to be analysed from the raw data without loosing the conventional, well-established STEM view. The examples below show two possibilities to exploit this feature. For the first example, a selective area diffraction (SAD) analysis was done by selecting single diffraction discs to generate multiple synthetic STEM images.
The pnCCD (S)TEM Camera
Applications in TEM

TEM imaging with the pnCCD is especially useful when single electron sensitivity or fast readout speed is essential. By calculation of the subpixel position via advanced center of gravity methods, a spatial resolution of below 10 µm (at 80 keV electron energy) can be achieved. The readout speed of 1 000 fps up to 8 000 fps enables the examination of time dependent processes in the millisecond and sub-millisecond regime.

Single Electron Detection

Due to its extremely high signal-to-noise ratio of 300:1 at 80 keV, the pnCCD (S)TEM camera can detect single electrons. Each pattern in image (a) shows the signal of a single primary electron (80 keV). The single electron events can be processed to receive images with a spatial resolution better than the physical pixel size. This processing, which is called subpixel imaging, is based on advanced center of gravity methods. It works by taking into account the track and the distribution of the signal electrons in the detector that have been created by the primary electron. The example (b) below shows an electron hologram before (top) and after sub-pixel processing (bottom). Comparing the line profiles (red and blue curves in the graph underneath) demonstrates the improved resolution of the interference pattern.

Dynamic TEM Imaging

Based on the high readout speed of 1 000 - 8 000 fps (depending on windowing and binning mode), the pnCCD (S)TEM camera gives the possibility to investigate chemical or physical processes in the 0.1 - 1 ms regime. The example below shows an experiment where the induced resonant oscillation of a freestanding CdS nanowire was measured. The readout of the camera was externally triggered with a variable delay with respect to the zero crossing of the sine function driving the oscillation with 1.85 kHz. In the analysis of the measurement, the position of the nanowire revealed the resonant frequency of the nanowire to be approximately 4 times the excitation frequency. Elastic properties of the nanowire can be deduced from these measurements through further analysis.