doi:10.1017/S1431927617000976
Microsc. Microanal. 23 (Suppl 1), 2017

Advanced 4D STEM Imaging with the pnCCD (S)TEM Camera

Martin Huth[1,*], Martin Simson[1], Robert Ritz[1], Julia Schmidt[1], Heike Soltau[1], Hao Yang[2], Peter Nellist[2], Ryusuke Sagawa[3], Yukihito Kondo[3], Henning Ryll[4], Lothar Strüder[4,5]

1. PNDetector GmbH, Otto-Hahn-Ring 6, 81739 München, Germany
2. Department of Materials, University of Oxford, 13 Parks Road, Oxford OX13PH, UK
3. JEOL Ltd., 3-1-2 Musashino Akishima Tokyo 196-8558, Japan
4. PNSensor GmbH, Otto-Hahn-Ring 6, 81739 München, Germany
5. University of Siegen, Walter-Flex-Strasse 3, 57072 Siegen, Germany

Inspired by recent advancements in detector technology, there has been increasing interest in the technique of four dimensional scanning transmission electron microscopy imaging (4D STEM). Typically, a focused beam of electrons is applied to a sample in a two dimensional (2D) raster pattern. At each point, a 2D image is captured which intrinsically contains bright field (BF), dark field (DF), and high angle annular dark field (HAADF) signals. In total, a 4D dataset is recorded allowing a comprehensive analysis and enabling a number of techniques such as strain analysis, magnetic domain mapping, scanning electron diffraction, TEM tomography, and electron ptychography. All these 4D STEM imaging techniques are possible with the pnCCD (S)TEM camera, which meets the following key requirements: (i) Fast acquisition of data to minimize effects of beam and sample drift, and beam induced damage to the sample; (ii) a large number of detector pixels to precisely discriminate between diffraction spots or to determine the position of a bright field disk with high accuracy; and (iii) a sufficiently radiation hard detector compatible with high electron rates as used in scanning electron diffraction experiments.

Using a direct detecting, radiation hard pnCCD with 264x264 pixels, the pnCCD (S)TEM camera provides ultra-fast acquisition of 2D camera images [1]. Routinely, the readout speed is 1000 frames per second (fps) in full frame mode and can be further increased up to 8000 fps by binning and windowing. The pnCCD (S)TEM camera can be operated with electron energies ranging from 20 keV to 300 keV. By operating the camera in one of three predefined operation modes [2], optimum results are guaranteed for a wide range of experimental conditions: The Imaging mode covering common imaging applications, the Anti-Blooming mode designed for measurements at high electron rates, and the Single Electron mode optimized for very low electron rates. The acquired 4D datasets can be analyzed in a number of ways. E.g., phase informations can be extracted or virtual diffraction images can be obtained using flexible post-experiment schemes.

The pnCCD (S)TEM camera is a complete system including a data acquisition computer and software allowing a versatile live visualization and full raw data access. The camera head is available as fixed bottom mount or retractable design. The outstanding capabilities of the pnCCD (S)TEM camera were demonstrated in numerous experiments at various TEMs. For example, with the technique of electron ptychography, the reconstruction of the electron phases allows to image beam sensitive complex nanostructures containing light and heavy elements with atomic resolution (Fig. 1a-d) [3]. Lens aberrations can be corrected post-acquisition allowing to maximize the phase image contrast. Further, the pnCCD allows to precisely determine the deflection a magnetic sample imposes on a traversing electron beam by measuring shifts of the bright field disc. Therefore, direction and strength of internal magnetic fields can be determined in addition to location of magnetic domains and their boundaries typically measured with standard Lorentz TEM (Fig. 1e-g) [1].

References:

[1]Ryll, H., Simson, M., *et al* A pnCCD-based, fast direct single electron imaging camera for TEM and STEM, Journal of Instrumentation **11** (2016)
[2] J. Schmidt, R. Hartmann *et al* Journal of Instrumentation **11** (2016)
[3]Yang, H., Rutte, R.N. *et al* Simultaneous atomic-resolution electron ptychography and Z-contrast imaging of light and heavy elements in complex nanostructures, Nature Communications **7** (2016)

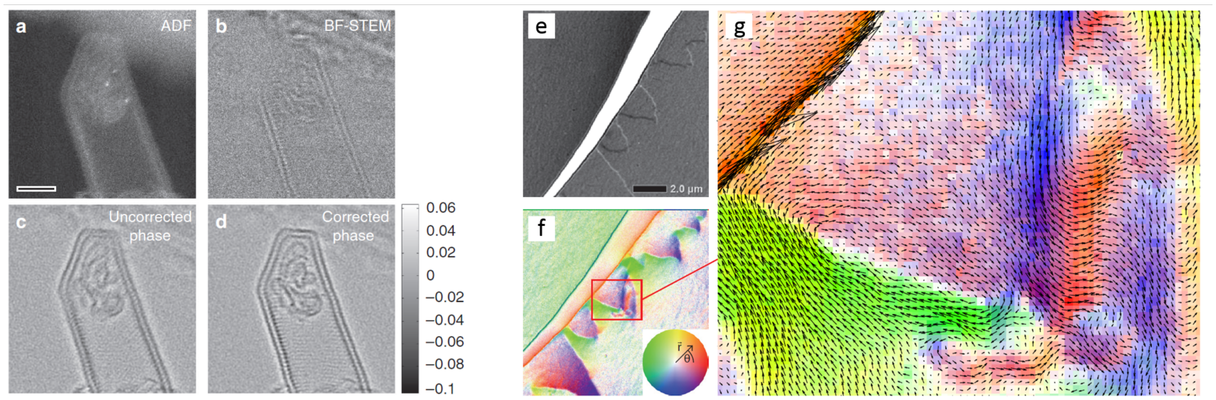

Figure 1: Double wall carbon nanotube. Comparison of (a) ADF image, (b) simultaneous BF image, and the phase image (c) before and (d) after correcting residual aberrations, respectively. The BF and the phase images were calculated from a 4D-STEM dataset acquired with the pnCCD (S)TEM camera installed on a JEOL JEM-ARM200F. Figure from [3]. (e) Visualization of magnetic domain boundaries inside a magnetic Ni sample using standard Lorentz TEM. (f) Same sample area imaged with the pnCCD installed at a JEOL JEM-2800 microscope using the 4D-STEM imaging method visualizing a proportional amplitude and direction of the magnetic field inside the sample. (g) Enlarged view of the marked region in (f) with the magnetic field vectors as overlay revealing a greater detail of information compared to the standard Lorentz TEM imaging mode. Figure from [1].

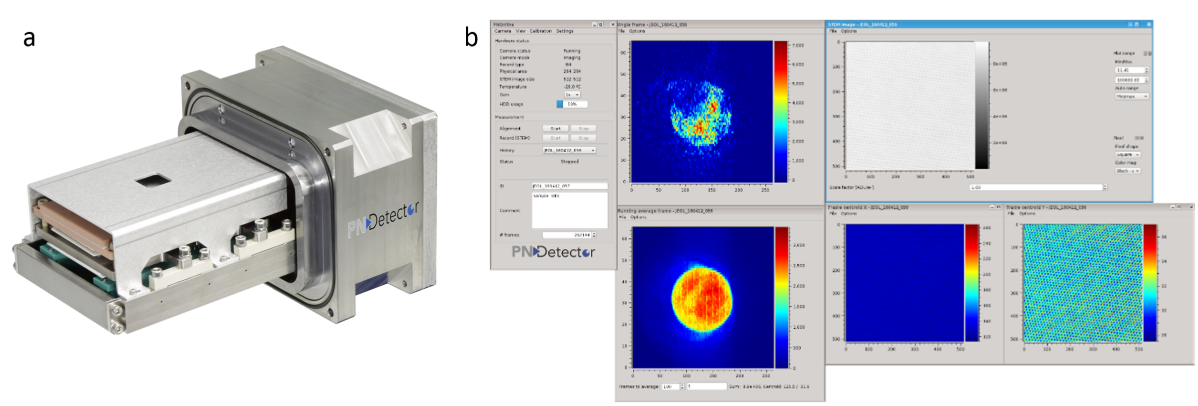

Figure 2: (a) pnCCD (S)TEM camera. (b) PNOnline data acquisition and camera control software.

https://doi.org/10.1017/S1431927617000976 Published online by Cambridge University Press