Imaging of Electric Fields with the pnCCD (S)TEM Camera

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The imaging of electric fields on the nanometer scale is of great interest for modern materials research. Techniques providing a fast, direct and precise measurement of local fields are thus useful for materials science applications. We present microscopic measurements of electric fields with the 4D-STEM technique using the pnCCD (S)TEM camera. In 4D-STEM, a 2D camera image is recorded for each probe position of a 2D scan area, yielding a 4D dataset. With this technique, small shifts of the bright field disc (BFD) due to a deflection of the electron beam through electric and magnetic fields in the sample region can be detected. Hence, the magnitude and direction of the local field at each probe position can be determined. Given the large number of necessary probe positions, this technique requires a fast camera system providing short enough readout times so that instabilities in the microscope and sample drift or radiation damage do not deteriorate the final STEM image. Furthermore, a pixelated detector is required to record and account for the intensity distribution variations caused by interaction of the electron beam with the sample.

The pnCCD (S)TEM camera allows fast acquisition of 2D camera images with a direct detecting, radiation hard pnCCD with 264x264 pixels [1]. Routinely, the readout speed is 1000 frames per second (fps) and can be further increased through binning and windowing. For example, with the pnCCD (S)TEM camera a 256x256 STEM image -- where a camera image is recorded at each probe position -- can be recorded in less than 70 s. The 264x264 pixel camera image allows precise determination of the BFD position, yielding information about electric and magnetic fields in the sample. For data analysis, image subsets can be selected freely to obtain virtual diffraction images or perform differential phase contrast (DPC) analysis. A major advantage over conventional segmented DPC detectors is that, with the pnCCD (S)TEM camera, movements of the BFD can be discriminated from intensity variations inside the BFD which is of particular importance for analysis of electromagnetic fields inside specimens. Further 4D-STEM applications benefitting from the pnCCD (S)TEM camera include imaging on the micro- and millisecond timescale [2], strain analysis [3], magnetic domain mapping [1], and electron ptychography [4].

A demonstration of electric field mapping in vacuum with the pnCCD (S)TEM camera is shown in Figure 1. A voltage of 50 V was applied to a tungsten needle mounted in an FEI Titan G2 80-200 ChemiSTEM microscope, operated at 80 keV. For each of the 256x256 probe positions, a 2D camera image was recorded (Fig. 1a). From these camera images an incoherent bright field STEM image (Fig. 1b, background) as well as the position in the x- and y-directions of the BFD at each probe position was calculated. A comparison of the position of the BFD with and without an applied voltage yields information about the magnitude and direction of the local gradient of the projected electrostatic potential (Fig. 1b, indicated by coloring and arrows). In addition to this direct mapping of the electric field around a needle with rather well-shaped BFDs, the large number of pixels of the pnCCD (S)TEM camera allows the precise determination of the BFD position, even in cases when the BFD is weak and deformed through the interaction of the electron beam with the sample (Fig. 1c).

In conclusion, 4D-STEM techniques like electromagnetic field mapping benefit significantly from the capabilities of the pnCCD (S)TEM camera. The readout speeds of 1000 fps and above allow the fast acquisition of 4D datasets with 2D camera images at each probe position. Through the large number of pixels, position and intensity variations of BFDs can be precisely determined.

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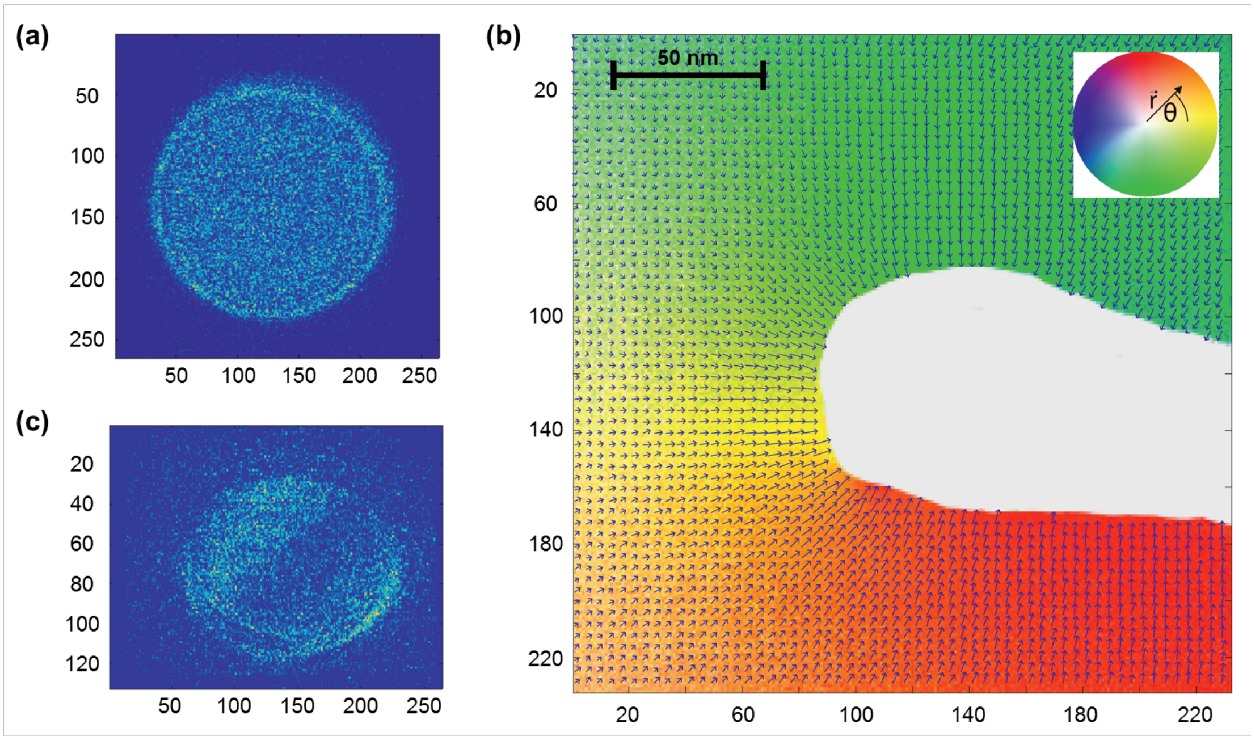

Figure 1: (a) Single camera image at one probe position (full frame readout, 1000 fps). The 264x264 pixels allows the precise determination of the position of the BFD. (b) STEM image of a tungsten needle. A voltage of 50 V was applied between the needle and a counter-electrode at a distance of ≈100 µm. The superimposed vector field was calculated from movements of the position of the BFD between a measurement with (50 V) and without (0 V) applied voltage. It indicates the direction and magnitude of the local gradient of the projected electrostatic potential. (c) Single camera image of a BFD recorded from a solar cell sample (two-fold binning, 2000 fps).