IM1.002

The wave-particle duality of electrons demonstrated with sub-pixel resolution by recording off-axis electron holograms on a pnCCD direct detector

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A direct demonstration of wave-particle duality is performed by detecting single electrons during the build-up of an electron holographic interference pattern on a pnCCD direct digital electron detector, similar to the first direct electron interference experiment conducted by Donati, Missiroli and Pozzi [1].

The pnCCD is a special type of a charge-coupled device (CCD), whose high signal-to-noise ratio enables the detection of single electrons in the energy range between 5 and 300 keV in the transmission electrons microscope (TEM). The pnCCD that was used for this and previous experiments has a format of 264×264 pixels with a pixel size of 48×48 µm² [2]. The full frame readout rate is 1000 frames per second with a readout noise of only 4 el.. The signal to noise ratio is 300:1 for a 5 keV TEM electron. In binning or windowing modes, the readout rate increases linearly. For example, 66×264 pixels are read out at 4000 frames per second.

For the present experiment, an off-axis electron hologram was recorded without a specimen in the field of view using an electron biprism, which was inserted into the trajectory of the electrons in the TEM. The electron rate was reduced such that on average less than one electron hit the detector in each frame, ensuring that individual electrons did not interact with one another. It could be assumed that there was only one electron present in the TEM during the integration time of 1 ms per frame. Each electron hitting the pnCCD is clearly visible, arriving at seemingly random positions on the detector. However, as expected from quantum mechanics, the integration of many frames reveals a typical interference pattern (Figure 1).

The capability to distinguish single TEM electrons from noise over a wide energy range enables further processing of the raw data to determine the point of entry (PoE) on the detector of each TEM electron with a resolution that is much higher than the physical pixel size. One method that can be used to determine the PoE is to calculate the center of gravity (CoG) of the intensity distribution of each TEM electron (referred to as the CoG method) and to use the CoG as the PoE. As experimental data and simulations show, the resulting distribution of x and y coordinates is not equal, as it should be, especially for the case of homogenous illumination. This effect has been described for strip detectors [3] and can be corrected either using a statistical approach (referred to as the Eta method here) or using models based on simulations. The theoretical difference between the actual PoE and the calculated PoE can be calculated using simulations. For electron energies below 80 keV, the full width at half maximum (FWHM) of the distribution of differences between the actual and calculated PoE is less than one pixel (60 keV: Cog: 0.42 pix, Eta: 0.28pix) (Figure 2a).

A comparison between images obtained using the three different methods (integrating intensity images and the Cog and Eta methods) shows an improvement in fringe visibility from 0.49 to 0.50 and 0.58, respectively (Figure 2d).

In conclusion, single electrons can be detected in the energy range from 5 to 300 keV. The position precision is significantly better than the pixel size using the CoG and Eta methods, leading to improved image quality.

1. O. Donati, G. F. Missiroli, G. Pozzi, Am. J. Phys. 44 (1973), p.639-644.
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3. E. Belau, R. Klanner, G. Lutz, et al., Nucl. Instr. Meth. Phys. Res. (1983), p.252-260.

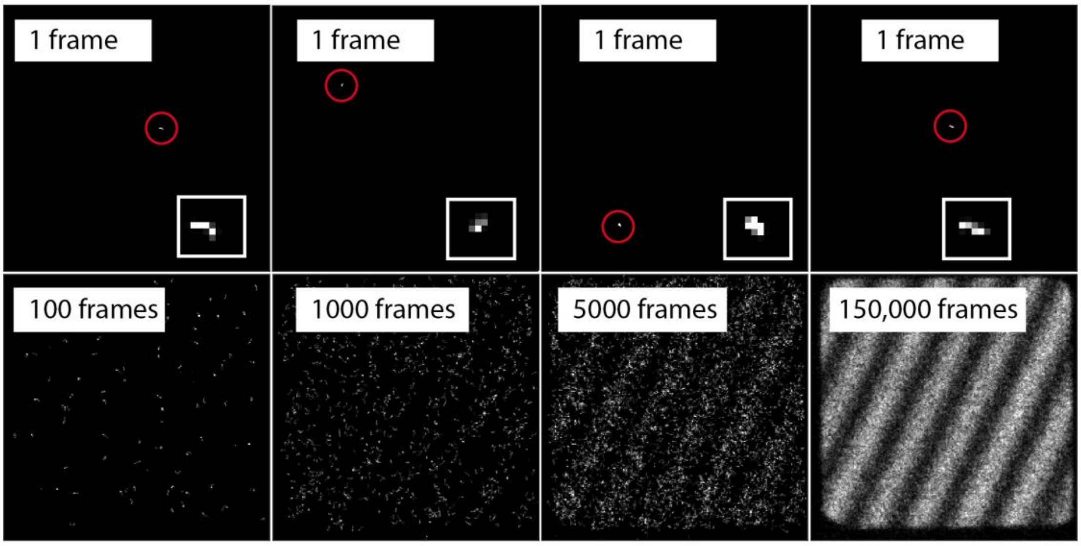

Figure 1. Single frames measuring single electrons in the TEM in the upper row. For better visibility, the electrons are highlighted with circles. The insets show magnified areas of the intensity distribution of each single electron. The integration of many such frames reveals an interference pattern in the images in the lower row.

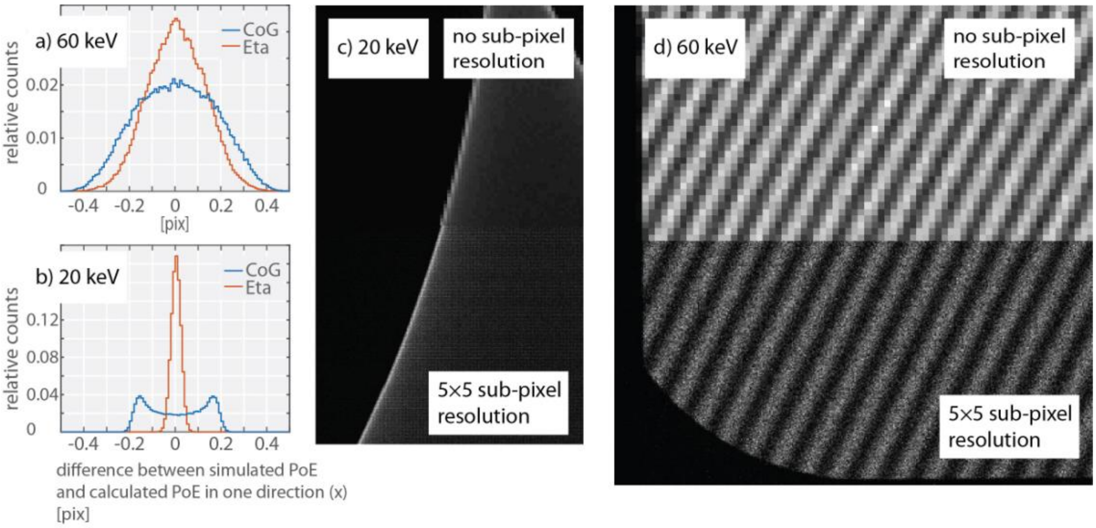

Figure 2. Distribution of the difference between the simulated point of entry (PoE) of TEM electrons and calculated PoE for the CoG and Eta methods for electron energies of 60 keV in a) and 20 keV in b). The pixel size is 48×48µm². A test image recorded using 20 keV electrons is shown in c). The upper half is obtained without and the lower half with 5×5 sub-pixel resolution. The image in d) displays interference fringes at an electron energy of 60 keV without and with 5×5 sub-pixel resolution, respectively.