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Application of Single-Electron-Detection Cameras to Phase Contrast Imaging

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The advent of commercially-available direct detection cameras (DDCs) for transmission electron microscopy (TEM) offers the opportunity to reduce noise in images and diffraction patterns to levels that approach the Poisson noise of the electron beam. For sufficiently low dose rates, their design can enable significant improvements in detective quantum efficiency (DQE) and modulation transfer function (MTF) when compared to conventional charge-coupled device (CCD) cameras. Existing literature on DDCs is focused predominantly on structural biological applications, where they provide clear advantages under low dose conditions, e.g., typically $< 10\ e^{-}Å^{-2}$. For example, DDCs have been utilised for resolving high-resolution structural information in biological materials in cryo-electron microscopy. Whereas the characteristics of DDCs at dose rates and spatial resolutions that are applicable to biological materials are already well established, in many other areas of TEM the dose rate can exceed $1000\ e^{-}Å^{-2}$, while the spatial resolution can vary from nanometers to better than 1 Å. In these contexts, the benefit of DDCs is less clear.

Here, we examine this question in the context of high-resolution phase contrast imaging and off-axis electron holography and demonstrate that the improved MTF and DQE of a DDC result in clear benefits over conventional CCD cameras. For electron holography, we find a significant improvement in the holographic interference fringe visibility and a reduction in statistical error in the phase of the reconstructed electron wavefunction. For high-resolution phase contrast TEM imaging of a $BiFeO_3$ thin film, we show that images recorded using a DDC reveal individual atomic columns with a good signal-to-noise ratio (SNR) at low dose rates. Further improvement in SNR could be obtained by correlation and averaging over a series of images. As a result of the low camera noise, the correlation of individual images is robust even at low dose rates. Similar findings apply to the multiple acquisition of electron holograms, where averaging leads to an improvement in SNR that is close to the ideal root-N behavior (N being the number of images).

Our results show that DDCs are highly beneficial for the acquisition of high-resolution TEM images and electron holograms at low dose rates, thereby minimising potential specimen damage while maintaining an adequate SNR for analysis