Direct Detectors for Electron Microscopy

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Abstract.
There is interest in improving the detectors used to capture images in transmission electron microscopy. Detectors with an improved modulation transfer function at high spatial frequencies allow for higher resolution in images at lower magnification, which leads to an increased effective field of view. Detectors with improved detective quantum efficiency are important for low dose applications. One way in which these performance enhancements can be achieved is through direct detection, where primary electrons are converted directly into suitable electrical signals by the detector rather than relying on an indirect electron to photon conversion before detection. In this paper we present the characterisation of detector performance for a number of different direct detection technologies, and compare these technologies to traditional indirect detectors. Overall our results show that direct detection enables a significant improvement in all aspects of detector performance.

1. Introduction
The majority of detectors in use for transmission electron microscopy utilise indirect electron detection. Indirect detection requires that primary electrons are converted to photons in the scintillator, which is coupled to the (CCD or CMOS) sensor through a lens or fibre optic coupling. Direct detection is an attractive alternative where signal in the CMOS or CCD sensor is generated directly by the primary electron beam. However CCD and CMOS sensors are prone to radiation damage which has a detrimental effect on detector performance and lifetime[1]. The use of enclosed-gate layout transistors (ELT) and thin gate oxide improves the radiation hardness of devices[2], which are now attractive as a technology for electron imaging.

There are a number of fundamental disadvantages to indirect detection. Scattering of the primary electrons in the scintillator leads to generation of photons in a volume larger than a single pixel. This implies that each electron generates signal in a cluster of pixels on the sensor. The effect of an electron being detected as signal in multiple pixels can be described quantitatively using the modulation transfer function (MTF). Direct detectors offer the possibility of significantly improving this MTF. Of particular interest are thin detectors where much of the inactive supporting substrate has been removed, leaving a thin active layer. Signal is generated in the active layer and then the electrons exit the active layer before significant lateral scattering has occurred. The removal of the supporting substrate prevents electrons scattering from the substrate back into the active layer, which considerably improves MTF[3].

The detective quantum efficiency (DQE) describes how the detector affects the signal to noise
ratio in the image, as defined by Equation 1.

\[ DQE(\omega) = \frac{(SNR_{out})^2}{(SNR_{in})^2} \]  

(1)

The DQE is a performance metric of particular interest in low dose work, as an improved DQE implies that a lower dose is required to separate signal from noise. A perfect detector would have a DQE of 1 over all spatial frequencies. However in practice there are no perfect detectors and the DQE is affected by both the MTF and noise added to the image by the detector. The noise in an image is described by the noise power spectrum (NPS) and it can be shown that the DQE is related to the MTF through Equation 2.

\[ DQE(\omega) = \frac{Dose \times MTF(\omega)^2}{NPS(\omega)} \]  

(2)

The MTF and DQE are a function of spatial frequency from 0 to 0.5 pixel\(^{-1}\). The upper limit is known as the Nyquist frequency or Nyquist limit. The Nyquist limit corresponds to a wavelength of 2 pixels and is the largest possible frequency obtainable by a pixelated image, spatial frequencies above the nyquist limit undergo aliasing.

2. Methodology

Two different direct electron detectors have been characterised together with one indirect detector as a basis for comparison. The commercial Gatan K2 Summit has a 5\(\mu\)m pixel size, with 3838 x 3710 pixels full frame and achievable sensor readout speeds of 400fps. We note that this detector also has a “Counting Super-resolution” mode which is not dealt with here, but can achieve up to an effective 7676 x 7420 pixels by splitting each physical pixel into 4 sub-pixels and assigning each electron a sub-pixel by analysis of the resulting cluster from an electron event\[^4\].

This detector has been characterised in both integrating and counting mode\[^5\] at 300kV with 2x2 binning giving a Nyquist frequency of 50 lp/mm. The DUOS detector is a non-commercial integrating direct detector with a 20\(\mu\)m pixel size, manufactured on 20\(\mu\)m thick EPI SOI wafers, mechanically thinned to 50\(\mu\)m with a 1024 x 1024 pixel full frame readout at 30fps. This was characterised at 200kV with no pixel binning giving a Nyquist frequency of 25 lp/mm. A Gatan UltraScan 4000 is an indirect detector with 4080 x 4080 15\(\mu\)m pixels and 0.2 fps full frame readout which was characterised at 200kV with 2x2 binning, giving a Nyquist frequency of 17 lp/mm. For all of the above detectors the MTF was measured using the edge method, where a suitably sharp edge is projected onto the detector, for the data reported here using a beam stop\[^6\]. The NPS was calculated from an analysis of 32 uniformly illuminated images. The pixel values were converted to electron units by taking a series of images with the entire beam focused on the detector, the pixel values summed over the detector were compared to the total number of electrons in the image to yield a conversion factor (Equation 3).

\[ C = \frac{Current \times ExposureTime}{PixelSum \times e} \]  

(3)

The electron beam current was measured with a Faraday cup for the DUOS and UltraScan detectors, and for the Gatan K2 camera the current measurement from the microscope fluorescent screen was used. The DQE was acquired from the experimental measurements of MTF and NPS and the relationship given in Equation 2.

3. Results and Discussion

3.1. MTF results

Comparative MTFs are shown in figure 1. It is immediately obvious that the performance of the CCD detector is significantly worse than the direct detectors. Comparison of the Gatan K2...
operating in counting mode with the same detector operating in integrating mode shows that the MTF at the Nyquist limit in counting mode is 4x higher than that in integrating mode. This is expected based on previous models of these two modes. However the integrating mode outperforms the counting mode at low spatial frequency. This indicates that in counting mode a larger proportion of the signal is recorded in pixels far away from the initial electron impact position on the sensor. We believe this can be attributed to signals that arise from electrons which undergo a large lateral scattering producing a secondary cluster far from the primary cluster. In integrating mode the signal from this secondary cluster would be smaller, as in counting mode any cluster that exceeds an energy threshold value is counted with equal weight. Figure 2 shows the DUOS detector performance is similar to that of the Gatan K2 detector operating in counting mode. This can be attributed to the larger pixel size of the DUOS detector which enables a larger proportion of signal to be deposited in the pixel corresponding to the electron impact.

The above data indicates that increasing the pixel size from 10\(\mu\)m to 20\(\mu\)m has a similar effect as switching to counting mode. There are advantages of both methods. Integrating mode is often desirable as the usable primary beam current is much higher, since there is no requirement that the detector needs to be able to distinguish individual events. Larger pixel sizes improve detector resolution but lead to slower sensor readout due to the physical distances that any signal needs to travel prior to readout. Conversely, smaller pixels in counting mode can achieve higher frame rates. Counting mode also makes sub pixel resolution possible by allocating each event to a pixel subarray.

3.2. DQE Results

The DQE data shown in Figure 3 show a similar pattern to the MTF, integrating mode performs better at low spatial frequencies, but drops off sharply at higher spatial frequency. The cross over point for the two modes is at a higher spatial frequency due to counting mode increasing high frequency noise[7]. The DQE results presented here for the Gatan K2 Camera are different to those published by Gatan Inc[8]. DQE results in figure 4 show a marked improvement for the DUOS sensor compared to the UltraScan camera. Considering the DUOS and Gatan K2 integrating modes we can see an improvement in DQE arising from the improvement in MTF. Comparing with the the data published by Gatan Inc for the counting mode of the detector at
200kV, at low spatial frequencies the counting detector performs better, as the counting mode records every event with equal weight low frequency noise is reduced. At the Nyquist frequency the DUOS detector has a DQE 50% higher due to lower high frequency noise.

4. Conclusions
Comparison of direct electron detection with indirect detection shows significantly improved performance in both MTF and DQE performance for the former. Within direct detection there are also variations in readout modes. Counting mode where each electron is given a binary assignment to a pixel significantly improves the MTF at high spatial frequency for detectors with small physical pixels. However increasing the physical pixel size, in an integrating mode yields a similar MTF as the interaction volume of the electron approaches the pixel size.

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Figure 3. DQE for the Gatan K2 detector in counting and integrating mode and the indirect UltraScan 4000 camera up to the Nyquist limit.

Figure 4. DQE for the prototype DUOS and the indirect UltraScan 4000 cameras up to the Nyquist limit.