Imaging electron detectors for low-voltage TEM

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Abstract. There is an increasing effort for the development of transmission electron microscopes operating at accelerating voltages of less that 100 kV, down to 20 kV. This work aims to clarify if the technology of conventional indirect scintillator-CCD cameras is suitable to record images formed with electrons of such low energy and how its performance compare to that of novel direct silicon imaging detectors. The performance of these imaging detectors is discussed in terms of modulation transfer function and detective quantum efficiency. It is demonstrated that whilst the performance of conventional scintillator-CCDs improves as the electron energy is dropped, it then peaks at 70 keV and then drops again. Optimum imaging performance at even lower energies is expected for the novel directly exposed detectors, which are capable of near 100% detective quantum efficiency at very low electron energies.

1. Introduction
Degradation of radiation-sensitive materials under the electron beam of high-voltage transmission electron microscopes (TEM) imposes significant limitations to the characterization of new soft materials such as carbon-based structures. The principal approach to overcome this problem is to lower the voltage below the radiation damage threshold, thus preventing any degradation and allowing for high dose imaging.

However, as the voltage of the microscope is reduced, conventional imaging cameras are required to work outside their design parameters and may not have sufficient modulation transfer function (MTF) and detective quantum efficiency (DQE). Further, several detector technologies can be used for detection of electrons in this energy range, of which indirect scintillator-charge coupled device (SCCD), direct monolithic active pixel sensors (MAPS) and direct double-sided Si strip detectors (DSSD) will be considered here. Since experimentation in this voltage range is not yet available, simulations must be employed to calculate the expected performance of these detectors. The methodology used for simulations will be described first, followed by the resultant imaging metrics and selected model images that illustrate the expected performance of each detector.

2. Method
A simplified structural model was built for each detector, which was then used to simulate the trajectories of beam electrons and distribution of charge induced in each pixel for each microscope voltage. This was then used to calculate MTF, DQE and a low-dose model image. Simulations of induced charge use Joy's model, which consists of straight electron trajectories between discrete elastic Rutherford scattering events and continuous energy loss along these trajectories [1]. Accurate relativistic Rutherford and Bethe formulae were used, as well as the generation of fast secondary electrons [2].
The structural model used to simulate the performance of indirect SCCD consists of 40 µm thick scintillator with 70% volume content of ZnCdS phosphor grains in a SiO$_2$Z$_2$ glass support, coated with 1 µm of Al and mounted on a 2 mm thick glass support (Fig. 1a). The optical fiber bunch was considered to have an entrance aperture semi-angle of 60 degrees, an optical focus at 41 µm and an optical point spread function of 10 µm at normal incidence. To illustrate the importance of the mode of operation, the same structural model was used for the MAPS and DSSD detectors (Fig 1b). This consisted of back-illuminated fully-depleted 20 µm thin Si where the read-out layers were approximated as one front-side continuous 2 µm thick Al coating for MAPS and double-sided 0.2 µm thick continuous Al coatings for DSSD. The electronic noise was set to 25 well-electrons RMS for SCCD and MAPS, which is somewhat better than commercial SCCDs. Sensitivity of DSSD was set to 3,600 eV. A pixel size and pitch of 20 µm was considered for all models.

3. Results and Discussion

SCCD and MAPS operate as integrating detectors, where the signal recorded corresponds to the energy deposited in each pixel during the exposure time, whilst DSSD operate as a counting detector, where the signal recorded corresponds to the number of electrons detected in each pixel during a set time interval. Because of this difference in operation the two types of detectors will be discussed separately.

3.1. Integrating detectors

For the case of 100 keV electrons, both the 40µm thick scintillator and 20µm thick Si are relatively transparent, with some electrons penetrating through the sensor and depositing only a fraction of their total energy in the sensitive volume. Their corresponding signal distribution has two peaks corresponding to full and partial energy loss (Fig. 2a-b). For the case of 20 keV electrons, the sensors

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**Figure 1:** Diagrams of SCCD (a), MAPS and DSSD (b) models used for Monte Carlo simulations.

**Figure 2:** Distribution of signal generated in the SCCD (a), MAPS and DSSD (b).
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Figure 3: Modulation transfer function as a function of energy for SCCD (a) and MAPS (b).

(a)  
(b)  

Figure 4: Detective quantum efficiency as a function of energy for SCCD (a) and MAPS (b).

(a)  
(b)  

are opaque for both phosphor and Si sensors; however the 1 µm thick Al coverage of the SCCD absorbs an important fraction of the electron energy. Overall, significantly more energy is deposited in the MAPS sensing volume as compared with SCCD, suggesting that a much higher signal/noise ratio is expected for direct detectors operating in this energy range.

As is the case for high-voltage TEM, the SCCD suffers not only from significant lateral displacement and back-scattering of beam electrons in the scintillator, but also from internal reflection and poor collection of photons from the scintillator. Whilst the modulation transfer function of SCCD does improve for 100 kV compared with higher voltages (Fig. 3a), the MTF of MAPS is close to ideal behaviour throughout the entire energy range (Fig. 3b). This is attributed to the MAPS 20µm thin sensor that limits lateral spreading and the lack of support that prevents backscattering.

Detective quantum efficiency of SCCD at 100 kV is somewhat better than that of high-voltage operation, showing a DQE of ~80% for frequencies below 5 lines/mm, which then drops to less than 5% at Nyquist (Fig. 4a). As the voltage is dropped to 60 kV, a much improved DQE is observed due to a smaller frequency of electrons with partial energy loss and therefore lower scattering noise. However, as the voltage is dropped further, the DQE decreases because of the absorption of electrons in the Al coating (Fig. 2a). For the case of high-voltage, the much improved MTF of the MAPS detector results in an increased DQE for frequencies above 15 lines/mm with a Nyquist value of ~20%. As the voltage is dropped to 20 kV, much improved DQE is obtained due to near-ideal MTF and full electron absorption. MAPS DQE is limited by the fraction of electrons that are backscattered as they enter the detector and thus do not deposit sufficient energy to be detected (Fig. 2b).

Whilst MTF and DQE characterize the performance of these detectors under high-dose conditions, simulated images are better suited to illustrate operation under low-dose conditions. Low-dose images have been simulated using a 256 x 256 pixels model consisting of a dark clock in a white background (Fig. 5). A total electron budget of 1,000,000 electrons was used, giving an average dose of 15.3
electron / pixel. The poorer MTF of the SCCD can be observed as blurring of small features and the lower DQE can be observed as stronger noise in the bright background.

3.2. Counting detector

Given the similar structure with the MAPS detector, the DSSD has the same signal distribution (Fig 2b). However, for each electron arriving at the sensor, the energy deposited in each pixel is compared with a threshold set by the sensitivity of the readout electronics and a counter incremented with one if signal is higher than threshold. To remove lateral scattering, a further condition was added before the counter is incremented, that no neighboring pixel holds signal above threshold. This results in ideal MTF limited only by spatial sampling, i.e. pixel size.

Following these two conditions for detection, there are only two cases where a beam electron is not detected (a) if the electron deposits signal below threshold and (b) if the electron deposits energy above threshold in several neighboring pixels. For this voltage range the second condition predominates, resulting in a low efficiency of 42% for the case of 100 kV and high efficiency of 88% for the case of 20 kV.

4. Conclusions

Performance of SCCD, MAPS and DSSD detectors has been calculated in the 20-100 kV voltage range using Monte Carlo simulations of the electron-sensor interaction. At the low end of this voltage range, ideal MTF and a DQE of ~90% have been obtained for the MAPS and DSSD detectors. At the high end of this voltage range it is only the DSSD that retains ideal MTF due to its counting mode, however with a much reduced detective efficiency of 42%. SCCD and MAPS show similarly poor DQE at 100 kV, suggesting that further structural optimisation such as reduced thickness or increased pixel size must be used to obtain higher counting efficiency.

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