Electron detection characteristics of slow-scan CCD camera

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Abstract

The characteristics of two single-crystal YAG-based slow-scan CCD (SSC) cameras are measured and analyzed for various electron accelerating voltages. A stream-lined procedure for characterizing electron cameras is described, especially, the procedures for the measurement of modulation transfer function (MTF) and detector quantum efficiency (DQE). The limiting factors on the DQE of the SSC camera are studied, and possible improvements in the design are discussed. These analyses should be useful for the future improvement and optimization of SSC cameras for specific applications.

1. Introduction

The recent emergence of CCD camera systems or slow-scan CCD (SSC) cameras and the high-resolution imaging plate (IP) for direct electron image recording have fundamentally changed the way electron microscopists work, and film is no longer the only choice for electron image recording and storage. Each detector system has its strength and weaknesses, and in converting to digital recording both introduce new problems. For example, “blooming” between adjacent pixels has been a persistent problem with SSC camera systems, whereas the advantage of film as a data storage medium remains. Image plates provide the largest number of pixels in digital recording, but do not allow immediate viewing of the image. Cost is also a factor. Both the SSC camera and the IP are highly linear and have large dynamic range, and both record digitally. These qualities have made the quantitative analysis of electron diffraction patterns or images attainable. The amount of data available in a single image has also increased from a single byte for film to 4 bytes per pixel in both the SSC camera and IP. This is achieved by two remarkably different technologies in the SSC camera and IP. The slow-scan CCD camera detects photons from an electron scintillator using a charge-coupled device (for description of CCD, for example, see Ref. [1]). The imaging plates store incoming electron energy in a photostimulable phosphor. Details of the mechanism of these two detectors will be described later. The practical operation of the SSC camera and IP are also different. The SSC camera is a fixed accessory for TEM; images can be acquired, processed and viewed...
immediately by the microscope operator. The IP fits into a regular film cassette and is used like film except for the processing method. Instead of chemical processing of regular film, the IP is read out and digitally stored in an IP reader. Each plate may be reused indefinitely, and the plates are rather insensitive to light. A single plate reader may be shared among many microscopes, thus reducing costs.

In the past few years, the use of the SSC camera has already benefitted a number of existing techniques of transmission electron microscopy such as low-dose imaging, tomographic reconstruction, energy-filtered imaging, and quantitative electron diffraction. For a review of some applications using the SSC camera, see Ref. [2]. The use of IP for TEM is relatively new, although it has been widely accepted in the X-ray crystallography community since early 1980s. So far, most reports on the IP for electron recording have been confined to its evaluation, and have been highly promising [3].

Since the introduction of the SSC camera to TEM [4, 5], a number of papers have been published on the properties and design of the SSC camera [6–10, 2]. Most measurements on imaging plates are done with X-ray, while some results for electrons have also appeared in the literature [11]. The characteristic of film for electron recording has been studied extensively. A detailed review was given by Valentine [14].

In this paper, we report the performance of an SSC camera for high-energy electron recording in the following aspects: (1) camera response, (2) gain, (3) resolution, and (4) noise amplification (DQE). The camera response is defined by the ratio between the incoming and recorded signals. Two important response qualities are (1) the linearity between the averaged recorded and incoming signals and (2) the uniformity of the camera recording. The gain is the ratio of the averaged output and incoming signals over the detector linear response range. Camera resolution is defined by the point-spread function (PSF). Although the PSF can be removed by numerical deconvolution when the signal-to-noise ratio is large, however, PSF limits the camera's noise performance and reduces the effective number of pixels. The noise amplification is measured by the detector quantum efficiency (DQE). We will also describe the measurement methods. A similar measurement on IP is reported in Ref. [12].

2. Slow-scan CCD camera

The first use of a CCD camera for electron image recording may have been that of Chapman et al. [13]. This group experimented with direct exposure of the CCD to the beam (causing radiation damage) and with an optically coupled P22 transmission screen. Spence and Zuo [4, 5] designed and constructed the first CCD/YAG camera system for the direct recording of electron images in a TEM using a fiber-optics coupling and Photometrics CC210 16 bit liquid-nitrogen-cooled CCD camera. The fiber-optics plate also formed the vacuum seal, as shown in Fig. 1. This basic design is seen in other systems developed more recently [6–8].

The process of electron detection in an SSC camera can be separated into three stages: (1) the conversion of electrons into photons in the scintillator, (2) transport of photons to the CCD array via fiber optic or lens coupling, and (3) conversion of photons to well electrons and readout of well electrons in CCD. This is shown in Fig. 1. A basic model of this process was given by Daberkow et al. [7]. The complications of channel mixing due to the spreading of electrons in the scintillator, and photon propagation were considered by Ishizuka [15]. In general, the relationship between an incoming electron image intensity \( f(x, y) \) with \( x \) and \( y \) as the continuous two-dimensional coordinates, and the recorded image \( I(i, j) \) with pixel index \( i \) and \( j \) can be written as

\[
I(i, j) = \int_{x_i - \Delta x/2}^{x_i + \Delta x/2} \int_{y_i - \Delta y/2}^{y_i + \Delta y/2} f(x, y) h(X - x, Y - y) \, dx \, dy \\
\times \left[ \int \int f(X, Y) h(X - x, Y - y) \, dX \, dY \right] + B(i, j).
\]
Here $h(x, y)$ is the point-spread function (PSF) of the detector, and the recorded image $I(i, j)$ is the integrated signal of the converted convoluted electron image over a single pixel plus the background signal of the CCD $B(i, j)$ in digital units. The coordinate $(x_i, y_i)$ marks the center position of pixel $(i, j)$, and $\Delta x$ and $\Delta y$ are the width and height of the pixel. The integration is carried out over the area of a pixel. The PSF and the pixel size determine the resolution of the recorded images. The conversion coefficients or overall gain of the camera $g$, in units of digital number per incoming electron, is a combination of a number of factors [7]:

$$g = n_e/S, \quad n_e = \frac{\Delta E}{E_{ph}} \frac{1}{\eta_h \eta_e}.$$  

(2)

Here $n_e$ is the average number of electron–hole pairs in the CCD generated per beam electron, and the $\Delta E$ is the average energy of an electron absorbed in the scintillator, $E_{ph}$ the energy of converted photon, $\eta_h$ the energy conversion efficiency, $\eta_e$ the efficiency of optical coupling system and $\eta_e$ the quantum efficiency of CCD. Here $S$ is the sensitivity of the CCD in units of e/ADU. For estimated values of these coefficients, see Ref. [7]. The quantum efficiency of the CCD depends on the specific type, and has improved with the development of technology. The overall gain varies due to the variations in the scintillator thickness, optical couplings, concentration of scintillation centers and efficiency of each CCD pixel. This can be approximately corrected by preparing a gain image with uniform illumination of intensity normalized to 1 and by dividing the acquired image (minus the background) by the gain image. This process is called gain normalization and is made possible by the fixed position of the SSC camera (see Section 4).

There are a number of choices for electron scintillator for electron microscopy [16, 17]. Those which have been tried with the CCD camera include: the single-crystal yttrium aluminum garnet doped with cerium (YAG) [4, 6–8], gadolinium oxysulphide (GOS) [6], CaF$_2$(Eu) [9] and P20 phosphor (Y3O$_5$ : Eu) [8–10]. The top of the scintillator is coated with a thin layer of aluminum to enhance the collection of photons and minimize charging. In choosing a scintillator for the SSC camera, the efficiency, homogeneity, decay time, emission energy and radiation damage or lifetime are deciding factors. Single-crystal YAG has more uniform light emission and high resistance to beam radiation, and thus is a favorite for electron detection in analytical microscopy [18]. The radiation resistance of single-crystal YAG is especially important since in the SSC camera, the scintillator is often bonded onto a fiber optical plate for enhanced optical coupling. The GOS [6] and P20 are about twice and four times [9], respectively, as efficient as YAG in light emission. The advantage of P20 reduces somewhat above 150 kV [9]. The efficiency of YAG also depends on the thickness, for example, efficiency increases 3 times from a 20 to 50 µm YAG [9]. CaF$_2$ has about the same efficiency as YAG, but is slightly less uniform [9]. The front-illuminated CCD has a quantum efficiency of about 30% at 500 nm, 50% at 700 nm and 35% at 900 nm wavelength. The light emission of P20 is sharply peaked at 625 nm, which fits well with the spectral response of CCD. The YAG emission is green and peaked at 550, 340 and 360 nm. The scintillator thickness should be chosen as an optimum between the detector quantum efficiency and resolution for the specific electron voltage [9].

The CCD is an array of isolated metal–insulator–capacitors, which detect photons by collecting photon-excited electrons in potential wells created through bias. The collected electrons are read out serially by transferring charges through the shift of potential wells. The important parameters of the CCD are the readout noise and dark current. The dark current is thermally generated electrons,
which requires the CCD to be operated below room temperature. The multi-pinned phase (MPP) CCD somewhat reduces the problem of thermal electrons. For details on CCD performance, see Ref. [1]. The state-of-art technology is the 2048 x 2048 16-bit CCD.

The SSC camera is designed to reduce the width of the PSF and to optimize the gain. The PSF of the CCD camera is mainly determined by the width of the electron ionization volume and by photon propagation. The width of the ionization volume, defined by 70% energy deposited, in a 50 μm thick YAG scintillator ranges from 40 to 100 μm for 100–300 kV electrons [9]. Thus, it is difficult to match this to the 24 μm pixel size of scientific grade CCD's. The ionization volume was calculated using Monte-Carlo electron beam scattering methods (for example, see Ref. [19]).

Photon propagation in the YAG and fiber-optics couplings further decreases the resolution; this will be discussed in Section 6. The fiber-optics diameter is typically 6 μm. Kujawa and Krahl have tried the combination of a 2 : 1 reducing fiber-optics coupling and a P20 scintillator [8]. The efficiency ηL of fiber optics 1 : 1 couplings is about 0.06 [7], the 2 : 1 fiber-optics coupling reduces this by a factor of 10 [8]. A lens-coupled SSC camera system using P20 scintillator has also been built by Fan and Ellisman [10]. In their design, the CCD is placed at 90° to the electron optic axis with the aid of a mirror; this avoids X-rays that are problematic in high-voltage microscopes. Parts of the PSF can also be reduced by using appropriate optical filters in between the scintillator and the fiber-optical plate. In particular, a simple carbon absorption filter, or a Fabry–Perot-type interference filter with a coat of low-index materials such as MgF in between the high indexed YAG and fiber-optical plate can be very effective in reducing the “channeling” photons within the YAG. The channeling photons are the primary cause of “blooming” effects in the YAG-based SSC camera. This is also called “cross-talk”, referring to light generated by one electron being detected several pixel distances away. This is called the anti-reflection YAG. Details of the commercial version to be studied later are proprietary.

A number of variations can occur in an SSC camera system, making each camera unique even for the same design. The most important factors are the type of scintillator and its efficiency, the thickness and the coupling between scintillator and CCD array. This makes the characterization of each camera a necessity. For this reason also, it is desired to have a common set of procedures, which can be carried out routinely. This not only helps to optimize the design of the SSC camera, but also assists those interested in acquiring a particular camera with desired properties.

3. Experimental measurements

Experimental measurements were carried out in two microscopes. One is the Zeiss 912 Ω operated at 120 kV, and the other is the JEOL 4000EX operated at various voltages. The JEOL 4000EX was used to measure the voltage dependence of the SSC camera. Both microscopes are equipped with a Gatan model 679 SSC camera [6]. The basic design of detection system in this camera is similar to the one described by Spence and Zuo [4]; however, Peltier cooling is used. It uses a YAG scintillator and 1 : 1 fiber optics coupling. Both cameras have 1024 x 1024 pixels and are mounted on the bottom flange of the microscope. A two-stage Peltier cooler is used to cool the CCD chip to about − 30°C. Thompson Scientific CCD is used in this model with pixel size of 24 μm. A 12-bit A/D converter is used to digitize the CCD signal. The SSC camera on the Zeiss has a special anti-reflection coating. The effect of this will be compared with the second with regular couplings. For convenience, we will call the camera with anti-reflection coating and mounted on Zeiss microscope as camera I and the other one on JEOL 4000EX as camera II. Camera II has been previously measured by de Ruijter et al. [20].

The current meters on both microscopes were used to measure the electron dose. The current meter of the Zeiss 912 Ω electron microscope is calibrated, and was used to measure the electron dose. This meter is reliable when the entire viewing screen is uniformly illuminated [21]. The electron current meter using the small screen on the JEOL 4000EX was compared and calibrated with the current meter of the Zeiss 912 Ω with the help of
imaging plates [12]. In the medium- and high-dose regions, they agree within an error about 5%. In the low-dose region, the current meter of the JEOL 4000EX tends to give slightly higher readings, which was corrected with the help of imaging plates.

To avoid complications from non-uniformity in the illumination, the gain function and most measurements (except the low-dose cases) were done at the same illumination conditions. The exposure time was used to control the electron dosage. The CCD image was acquired with the dark current subtracted and gain normalized. The gain function on the Zeiss 912 microscope was prepared with count levels of about 2048, and averaged about 20 times. This gives the relative error in the gain image of about 0.113%, which is 3 times less than the best noise and signal ratio achievable on this camera. The effect of residual noise in the gain image on the performance of the SSC camera is discussed in Section 7. All the measurements in the following section were done by acquiring electron images with the best achievable uniform illumination, under the operating conditions of the electron microscope. The mean and variance were calculated by statistical averaging.

4. Gain

The gain \( g \) of the camera is defined by the ratio of the average number of CCD output counts \( \bar{I} \) to the electron dose per pixel \( N_e \),

\[
g = \frac{\bar{I}}{N_e}. \tag{3}
\]

The gain of the SSC camera with the anti-reflection coating was measured at 120 kV over a range of electron doses. Fig. 2 shows the CCD output counts versus the electron dose for a count level from a few counts to about 4000 counts. In the high-dose region the gain decreases slightly, which is expected from the saturation of detectors [22]. The averaged gain in the medium-dose region is about 0.25 for this camera. The gain of the second camera without the special anti-reflection coating is measured to be 0.61. This suggests a loss of about 60% of photons due to the anti-reflection coating.

The ideal gain of the SSC camera should use the full capacity of the CCD with the designed dynamic range. For the Gatan model 679 SSC camera with 12-bit (0-4096) dynamic range, the CCD has a well-electron capacity of 500000 per pixel. The quantum efficiency \( \eta_e \) of the CCD is about 60 e/ADU, which is larger than the readout noise of about 25 e/pixel, at the readout speed of 500 kHz [6]. This indicates that the ideal gain for the camera is about 2.0, or one output count for every 0.5 beam electrons. For camera II, the energy conversion coefficient is about 4% with a gain of 0.61 according to Eq. (2), or for every incident 120 kV electron about 2000 photons are generated. This is in rough agreement with Refs. [7,8]. About 6% of photons are transmitted to the CCD, and about 30% of them are converted to well electrons. The gain can be adjusted in the camera controller electronics by varying the signal amplification, which changes the ratio of the number of well electrons per output count. However, it is difficult to increase the efficiency further because of the limit of readout noise (see Section 7).

The dependence of gain on the accelerating voltage was investigated using a combination of both cameras. The gain at 120, 225 and 400 kV was measured using camera II on the JEOL 4000EX, and gain at 60, 80, 100 and 120 kV was measured with camera I on the Zeiss 912 and normalized to camera I. The results are shown in Fig. 3. The
The decrease of gain above 120 kV can be explained based on the Bethe loss formula [20].

5. Linearity, uniformity and camera response

The overall response of the SSC camera is a combination of the response of scintillator and the CCD. The linearity of the CCD can be measured by exposing it directly to photons. Epperson et al. [23] put an upper limit of deviation from a perfect linear response as 0.03% by using computer-controlled light-emitting diode. The linearity of the scintillator was experimentally confirmed by Liu [9].
Fig. 2 shows the averaged number of counts as a function of electron dosage for the slow-scan CCD camera. The deviation from a straight line at high counts is due to the saturation of detector [22], while the scatter in the medium counts region indicates the gain variation of the SSC camera during separate measurements, and the error in the measured electron dosage. In normal use, linearity within a single picture is most important.

The as-acquired image from the SSC camera is highly non-uniform. Fig. 4 shows an as-acquired image from camera I. The origin of the ring pattern may be due to the doping variations in the YAG; the origin of the dark marks is unknown. Both of these contrasts are not seen in camera II. Accumulation of dust and contamination can also change the gain. The gain variations can be removed by performing the gain normalization operation:

\[ I(i, j) = \frac{I_{\text{raw}}(i, j) - I_{\text{dark}}(i, j)}{I_{\text{gain}}(i, j) - I_{\text{dark}}(i, j)} I^{\text{gain}} - I^{\text{dark}}, \]

with the “gain image” acquired with uniform illumination. The gain normalization works well, if the variation is small. Ideally, the gain image \( I_{\text{gain}}(i, j) - I_{\text{dark}}(i, j) \) is prepared by averaging multiple images of uniform illumination below saturation to minimize the noise present. The uniformity of the SSC camera depends on the illumination used for gain normalization. In general, it is difficult to obtain entirely uniform illumination in the electron microscope by using a defocused image of the electron source. Non-uniform illumination often results in a ramp in gain-normalized images. This must be minimized, if possible, by using a smaller probe size and larger condenser defocus. It is also possible to check the uniformity of the illumination using an imaging plate; for details see Ref. [12].

The time response of single-crystal YAG has been measured by Schauer and Autrata [24], which has a fast decay of 110 ns and an after-glow of about 2% after 5 \( \mu \)s, making it useful for video-rate STEM applications. The after-glow exponentially decreases with a lifetime of about 2.2 \( \mu \)s. For most SSC camera operations, the time scale is in seconds and the after-glow of YAG is negligible. The time response of CCD is limited by the readout speed. The efficiency of charge transfer during CCD readout is about 0.99998 [1]. Some of the charges can be trapped due to a prolonged or intense illumination. This results in a residual image, which can last days and can be removed by warming up the SSC camera. Weak residual images can also be covered up by exposing CCD to a bright uniform illumination.

6. Resolution

The resolution of the SSC camera is described by its point-spread function. This roughly corresponds to a recorded image of point object much smaller than the size of a pixel. The best achievable resolution in the SSC camera is a pixel. For the SSC, the spreading occurs mainly in the scintillator and fiber-optics coupling. In both cases, the spreading is symmetrical in all directions. For a rotationally symmetric resolution function, it is more commonly measured by the modulation transfer function (MTF) \( M(\omega) \), which is

\[ M(\omega) = \left| \int \int h(x, y) \exp(-2\pi i \omega x) \, dx \, dy \right| = |H(\omega, 0)| \]

with

\[ H(u, v) = \int \int h(x, y) \exp(-2\pi i (ux + vy)) \, dx \, dy \]

as the Fourier transform of the PSF. The ideal MTF is a \( \sin(x)/x \) function with \( x = \pi u \Delta/2 \) with \( \Delta \) as the pixel size. The MTF is a better measurement of the camera’s resolution, since it can be directly used in the removal of the PSF through deconvolution. Experimentally, the MTF can be measured by a number of methods including the sine wave method, holographic fringe method, edge method and noise method (for details, see Ref. [22]). Both sine wave and holographic method require the setup of special waves covering a large range of frequencies, and it is not easily carried out in EM. Direct differentiation of edge profiles is too noisy for practical use. Zuo [25] proposed a fitting procedure with multiple Gaussian functions to extract the point-spread function from the edge profile, which proves to be particularly powerful for the tails.
of the PSF [25, 26]. Imperfections, electron scattering and X-rays generated around the edge tend to overestimate the spreading between adjacent pixels. The noise method extracts the MTF from the correlation between noise in different pixels. It is a very convenient and fast method, especially effective in estimating the MTF in the high-frequency region. Here both the edge and noise methods are used.

In the noise method, the Wiener spectrum of a uniformly illuminated electron image is calculated using

$$W(u, v) = \left( \frac{1}{N^2} \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} [I(i, j) - \bar{I}] \right) \times \exp\left[2\pi i(u + jv)/N\right]$$

$$\times \left| \frac{1}{N^2} \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} [I(i, j) - \bar{I}] \right| ^2,$$

which is the average (as marked by < >) of many squared Fourier spectra of electron noise images. The Wiener spectrum is the Fourier transform of the autocorrelation of the deviations in each pixel, as stated by the Wiener–Khintchin theorem. It can be shown that the measured Wiener spectrum is

$$W(u, v) \approx W_0(u, v)|H(u, v)|^2$$

when the detector's added noise is small compared to the signal noise. Here $W_0(u, v)$ is the ideal Wiener spectrum of the signal. Each CCD pixel can be considered as an individual detector. Without the PSF in the detection process, the variance in each detector would be independent of each other, and this gives a constant $W_0(u, v) = \sigma^2$.

The noise method is generally applicable when the signal noise is dominant, and can be applied to any type of PSF. However, for a PSF with circular symmetry, additional averaging around a circle can also be done within a single image to obtain the MTF. This significantly reduces the number of individual images required for good statistical averaging. This is especially true for the medium and high frequencies. In acquiring images for noise method analysis, the presence of external features, such as the low-frequency ramp in the electron illumination or X-ray spots at high voltages should be carefully eliminated. The ramp can be avoided by using the same illumination used for the gain preparation.

Fig. 5 shows the MTF as measured for cameras I and II at 120 kV. The MTF of the SSC camera can be modeled by a simple function

$$M(\omega) = \frac{a}{1 + \alpha \omega^2} + \frac{b}{1 + \beta \omega^2} + c.$$  \hspace{1cm} (9)

Here $\omega$ is the frequency in units of 1/pixel. In Eq. (9), the first two functions model the head and tail part of PSF, and $c$ is a constant representing a delta-function contribution in the PSF. Parameters in Eq. (9) are obtained by fitting the measured Wiener spectrum of Figs. 5 and 6. The results are listed in Table 1. The improvement of MTF for camera I is due to the anti-reflection coating of

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Fig. 5. Experimentally measured MTF of slow-scan CCD camera at 120 kV. The dashed and solid curves show the difference with and without antireflection coating in YAG. For details, see text.

Fig. 6. Experimentally measured MTF of slow-scan CCD camera at 120, 225 and 400 kV for camera II.
Table 1
Parameters for measured MTF curves in Fig. 5 and Fig. 6. For definition of these parameters, see Eq. (9) (the mixing factor defined in Section 7 is also listed)

<table>
<thead>
<tr>
<th>HV(kV)</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera I with ARF*</td>
<td>120</td>
<td>0.2125</td>
<td>3357.2</td>
</tr>
<tr>
<td>Camera II</td>
<td>120</td>
<td>0.3293</td>
<td>3328.8</td>
</tr>
<tr>
<td></td>
<td>225</td>
<td>0.2801</td>
<td>2378.5</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>0.46683</td>
<td>1724.3</td>
</tr>
</tbody>
</table>

*ARF: Antireflection YAG.

**Fig. 7.** Integrated point-spread function of Gatan model 679 SSC with (a) and without (b) antireflection YAG. The Y-axis gives $2\pi\text{PSF}(r)$, and the x-axis is the radius in pixels. The first pixel is the origin of PSF.

This is probably due to the fact that for each primary electron several thousand photons are generated, which is sufficient to represent the continuous PSF. The MTF of the SSC camera does depend on the electron high voltage, contrary to previous findings of Ref. [20]. Fig. 6 shows the MTF of camera II measured at high voltages of 120, 225 and 400 kV. In this case, the tail of PSF increases significantly at 400 kV.

In general, it is not possible to obtain the PSF from the measured MTF because of the lack of phase information. It is possible when there is a suitable physical model for the PSF. This is the case for the SSC camera. Expressions used in Eq. (9) are based on a realistic model of light scattering [22], and good agreement between the experimentally measured MTF and Eq. (9) suggests that this model works well for the YAG. For the PSF, Eq. (9) gives two zero-order Bessel functions of the third kind plus a delta function [22]. Fig. 7a and b plot the integrated point-spread function $2\pi\text{PSF}(r)$ for cameras I and II as a function of the radius. The long-tail structure of PSF is clearly visible in this plot. The contribution to the tail reduces to about 35% with the anti-reflection YAG.

7. Noise and detector quantum efficiency of CCD camera

The noise performance of the detector is commonly characterized by the detector quantum efficiency (DQE), which is the squared ratio of output signal-to-noise-ratio (SNR) to input SNR. The ideal value of DQE is 1, in which case every single
Table 2
As-measured characteristic parameters of slow-scan CCD cameras (Gatan, model 679) (for details, see Section 7)

<table>
<thead>
<tr>
<th></th>
<th>Camera I with ARF</th>
<th>Camera II</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>120 kV</td>
<td>120 kV</td>
</tr>
<tr>
<td></td>
<td>120 kV</td>
<td>225 kV</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>0.14</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>(F)</td>
<td>0.075(^a)</td>
<td>0.075(^a)</td>
</tr>
<tr>
<td>(G\ (\text{well-e-/beam-e}^-))</td>
<td>10</td>
<td>28</td>
</tr>
<tr>
<td>(S\ (\text{well-e-/count}))</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>(\text{var}(B)b) (counts)</td>
<td>1.12</td>
<td>1.1</td>
</tr>
<tr>
<td>(\sqrt{\alpha^c%\ counts})</td>
<td>0.12</td>
<td>0.2</td>
</tr>
<tr>
<td>Mixing factor (1/m)</td>
<td>4.97</td>
<td>8.27</td>
</tr>
</tbody>
</table>

\(^a\) As taken from Ref. [7].
\(^b\) Averaged for exposure time between 0.2 and 1 s.
\(^c\) The linear noise largely depends on the average number of counts in gain image and the number of images averaged. The gain image for cameras I and II at 120 kV were prepared with counts about 2048 and averaged over 20 images.

beam electron is detected with no additional noise added. With uniform illumination, we consider the SSC camera as an array of discrete detectors, and each of them is illuminated with an average number of \(N_e\) electrons. The variance in a pixel is [15]

\[
\text{var}[n_e] = \sum_{l,m} h_{l,m}^2 \text{var}[N_e(l, m)] = \sum_{l,m} h_{l,m}^2 N_e = mN_e. \tag{10}
\]

Here \(h_{l,m}\) is the discrete point-spread function, or the contribution to pixel \((i,j)\) from illumination at pixel \((l,m)\), with \(\sum h_{l,m} = 1\). The factor \(n = 1/m = 1/\sum h_{l,m}^2\) is called the mixing factor [15]. It can be shown that

\[
m = \sum_{l,m} h_{l,m}^2 = \frac{1}{N_e^2} \sum_{u=0}^{N-1} \sum_{v=0}^{N-1} |H(u, v)|^2. \tag{11}
\]

which can be readily calculated from measured MTFs. The results obtained are shown in Table 2. Using Eq. (10), we have

\[
\text{DQE} = \frac{\text{SNR}_{\text{out}}^2}{\text{SNR}_{\text{in}}^2} = \frac{\bar{I}^2/\text{var}(I)}{N_e} = mg\bar{I}/\text{var}(I). \tag{12}
\]

It should be noted that the input signal noise ratio refers to the one arriving at each CCD pixel, not the one of the electron beam. Both the mean and variance are measured from the recorded gain-normalized image with uniform illuminations. Details of the measurement are given in Section 3. Fig. 8 shows the measured DQE as a function of electron dose for camera I.

In the SSC camera, additional noise is introduced in the electron–photon well-electron conversion and in the CCD readout processes. However, the latter is independent of illumination. Applying the error propagation rules to the electron detection process of Eq. (1) and (2), we have

\[
\text{var}[I] = g^2mN_e + N_e^2\text{var}[g] + \text{var}[B]. \tag{13}
\]

The variance in the gain results from the noise in the electron–photon and photon well-electron conversion processes, and errors in prepared gain.
The noise in electron-photon conversion process is expected to be proportional to the number of electrons and is averaged by the PSF, for which we can write \( mFN_e \). This noise is also called Fano noise [2]. The noise in the photon well-electron conversion equals the number of well electrons. Error in the prepared gain image leads to a linear noise. Following the method of Refs. [2, 7, 15], we write
\[
\overline{N_e^2 \text{var}[g]} = g^2 \left( mFN_e + \frac{N_e}{G} + \Delta N_e^2 \right).
\]  
(14)

Here \( G \) is the number of well electrons associated with one incident electron and \( \Delta \) is the squared percentage error in gain image. The background noise comes from the readout noise, dark current and cutoffs due to variation in the gain [2]. The dark current due to thermal excitation of well electron is proportional to the exposure time \( t \). Combining the above equations together, we obtain a theoretical expression for the DQE of the SSC camera:
\[
\text{DQE} = \frac{mgT}{\text{var}(I)} - \text{var}(B) - \frac{F + l/mG}{mg^2N_e}.
\]  
(15)

Eq. (16) combines the expressions given previously by Ishizuka [15] and de Ruijter [2]. A procedure for measuring \( G \), readout noise \( r \) and dark current \( d \) has been described by Ishizuka based on an analysis of noise in the dark images [15]. This method can be used for those CCDs without the thermal noise suppression technology. The newer CCD camera, such as camera I, has a much less uniform distribution of thermal noise among different pixels, for example, camera I has an average dark current rate 0.04 counts/s and deviation of 24 counts with some pixels at full count levels after 300 s exposure. In this case, we can estimate these parameters from DQE measurements.

Fig. 8 shows the fit to the experimentally measured DQE of camera I using Eq. (16), with parameters of \( F + 1/mG = 0.566 \), \( \sqrt{\Delta} = 0.5\% \) and \( \text{var}(B) = 1.12 \) counts. The measurements at the low-dose range are done with exposure times of 1 s or less. The Fano noise of the YAG has been studied by Monte-Carlo simulations [7]. At 120 kV, Fano noise \( F \) approaches the backscattering limit of about 0.075. Using this, we estimate \( G \approx 9.8 \) well electrons per beam electron or 40 well electrons per count for camera I. Estimates of camera I characteristics from these numbers are listed in Table 2. The 0.12\% linear noise agrees well with the estimated 0.113\% error in the prepared gain image (see Section 3). This suggests that the noise in the gain image is the major source of linear noise in the SSC camera.

Fig. 9 shows the experimentally measured and fitted DQE of camera II for beam energies of 120, 225 and 400 kV. The same fitting procedures for Fig. 8 were used. The camera characteristics obtained from fittings are listed in Table 2. Both the background noise and the gain of the CCD or number of well electrons per counts are similar to camera I, which however has a much smaller dark current generation rate. The reduced DQE at higher voltage is due to a decrease in the gain \( g \) and an increase in mixing factor \( n = 1/m \), and an increase in the Fano noise. The increase in the Fano noise at 225 and 400 kV is somewhat smaller than those predicted by Ref. [7].

The DQE described above is an average over the frequencies in the detector [22]. For some applications such as high-resolution imaging, which has limited number of frequencies, a frequency-dependent DQE may be more appropriate. The
frequency-dependent DQE is defined as \[22, 2\]

\[
\text{DQE}(u, v) = \left[ 1 + F + \frac{1}{H^2(u, v)} \right] \times \left( \frac{1}{G} + \Delta N_e + \frac{\text{var}(B)}{g^2N_e} \right)^{-1}.
\]

(16)

Its use in electron microscopy has been advocated by Ref. [2]. Generation of this function is straightforward once the MTF and averaged DQE have been measured. Fig. 10 plots the DQE\((u, v)\) for camera II at 400 kV using numbers listed in Tables 1 and 2.

8. Discussions and conclusions

The measurements in this paper show that the quantum detector efficiency of the slow-scan CCD camera in the medium- and high-dose region is limited by the fundamental noise in the scintillation process, the resolution of the camera and the efficiency in terms of the number of CCD well electrons created per beam electron. For the Gatan model 679 slow-scan CCD camera studied here with the regular YAG and fiber-optics coupling, the DQE approaches a constant value of about 0.7 at 120 kV in the absence of linear noises. The DQE drops off at the low-dose region to a DQE level below 0.1 at the single-count level. This drop-off is due to the background noise of the CCD, which is exacerbated by a large mixing factor resulting from the limited camera resolution. Improvement to the camera resolution using the anti-reflection YAG improves the mixing factor by 1.7, but reduces the gain by a factor of 2.4. Overall, the DQE decreased.

The modulation transfer function or MTF of the CCD camera is limited by the ionization volume of the beam electron and by photon propagation in the scintillator. The measured MTF of the YAG scintillator-based SSC camera has a sharp drop at the low-frequency region, which amounts to a long tail of several tens' of pixels wide. This is largely due to the reflected photons in the YAG. The anti-reflection YAG improves the MTF at the expense of reduced gain and DQE. A simple function was found to represent the MTF of the CCD camera. The measured MTF at the Nyquist frequency of
0.5 l/pixel drops to about 0.3. Straightforward deconvolution of PSF leads to excess amplification of the detector’s added noise, which may be tolerated in the medium-to-high-signal region where the dominant noise comes from the signal. When the output signal is desired as close to the input signal as possible, the optimum deconvolution filter is given in the form of a Wiener filter (for example, see Ref. [27]). In this case, removal of the PSF depends on the power spectrum of the signal and the added noise and their ratio.

The performance of both cameras measured here suggests that they are optimized for use at about 100 kV. Performance at high voltage can be optimized by changing the design of the scintillator. For example, the gain of the camera may be increased by increasing the scintillator thickness, which also leads to a worse PSF. The optimum choice of thickness should maximize the DQE. In this case, systematic measurements of the dependence of gain and mixing factor are desired for optimization of the DQE.

A set of procedures for measuring the performance of the electron camera has also been described. This involves a three-step measurement process: (1) measurement of gain, (2) measurement of MTF and (3) measurement of DQE as a function of dose. All three measurements can be done by acquiring uniformly illuminated images and no modifications to the instruments are needed. Important camera characteristics can be obtained through fitting of the measure DQE curve. The most difficult part of measurement is the calibration of the electron dose. This can be done with the imaging plate, which provides a unique standard measure and can be used in any electron microscope, since the plates fit the standard film cassettes.

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