Characterization of a hybrid pixel counting detector using a silicon sensor and the IBEX readout ASIC for electron detection

S. Fernandez-Perez,* V. Boccone, C. Broennimann, C. Disch, L. Piazza, V. Radicci, M. Rissi, C. Schulze-Briese, P. Trueb and P. Zambon

DECTRIS Ltd., Taefenweg 1, 5405 Baden-Daettwil, Switzerland

E-mail: sonia.fernandez@dectris.com

ABSTRACT: In this paper we report on the performance of a Hybrid Pixel Detector — consisting on an IBEX ASIC bump-bonded to a 450 μm-thick Silicon sensor with a pixel size of 75 μm — used as a direct electron detector up to 300 keV. The count homogeneity was found to have a dispersion below 1%. Energy spectra were recorded for electron energies in the range 20–80 keV, showing a significant full-peak energy loss due to the entrance contact dead layer only for impinging electrons below 30 keV. MTF and DQE were measured at 100 keV and 200 keV in low-flux regime for several threshold energies. Zero-frequency DQE values are up to 0.85 and 0.9 for the two electron energies, respectively, while for increasing frequencies the DQE fall more rapidly for the 200 keV case as a consequence of the higher degradation in spatial resolution. Based on the analysis of the cluster distribution of single-events we were also able to estimate the DQE(0) at 300 keV, which is close to unity for low thresholds. The system response linearity was tested at 80 keV in both paralyzable and non-paralyzable counting mode, yielding a 10% count loss at 0.8 Mcts/s/pix and 1.7 Mcts/s/pix, respectively, and a 50% count loss at 7 Mcts/s/pix and 16 Mcts/s/pix, respectively. FLUKA-based Monte Carlo simulations were used to cross-validate the experimental results and to gain a better understanding of the underlying physical processes.

KEYWORDS: Hybrid detectors; Pixelated detectors and associated VLSI electronics; Solid state detectors; X-ray detectors

*Corresponding author.
1 Introduction

Electron microscopy is one of the major tools for investigating the structure of matter at angstrom resolution. High-quality electron sources and electron optics pushed the boundaries of the achievable performance, reaching a state in which a modern electron microscope offers remarkably high spatial and energy resolution associated with very high stability and ease of use. In the last decades, the development of electron detectors is playing a major role for the surge of electron microscope capabilities. The appearance of direct electron detection with Monolithic Active Pixel Sensors (MAPS), started in the early 2000s and popularized in the 2010s was a breakthrough compared to the photographic films and conventional CCDs [1, 2]. Direct detection devices enabled the detection of the incoming radiation without the need of a phosphor layer to first convert the electron flux into visible light and subsequently into electrical signals. The common core component of direct detection is a semiconductor sensor, in which electrons directly generate the electron-hole pairs responsible for the signal formation. This leadsto an improved signal-to-noise ratio, as well as a high spatial resolution. An increase of the detector efficiency, possibility to produce bigger arrays, faster readout, and less noise are the main advantages of MAPS over conventional CCD [2]. However, recently Hybrid Pixel Detector (HPD) concepts [3, 4], initially developed for X-ray applications at synchrotron sources, have started being used in Electron Microscopy [5–7]. For this reason,
many existing HPD like EIGER [8], MEDIPIX [9] or TIMEPIX [10] have been used for electron detection. Counting HPD have a very high dynamic range, can operate at frame rates of several thousand images per second, exhibit no noise associated to the readout operation nor to the sensor’s dark current, and are radiation hard [4]. Additionally, on HPD different sensor materials can be bump-bonded to the ASIC that reads out all sensor pixels in parallel. The capabilities of the latest generation IBEX photon counting ASIC developed at DECTRIS Ltd [11] promise high performance for electron microscopy applications. In this article we report on the performance of a counting HPD based on IBEX ASIC bump-bonded to silicon sensors up to electron energies of 300 keV. Detector uniformity, Modulation Transfer Function (MTF), Detective Quantum Efficiency (DQE), count rate, and detector stability are presented along with Monte Carlo simulations for a better interpretation of the corresponding outcomes.

2 Materials

2.1 Detector system

Experimental results have been obtained with multiple HPDs. All of them consist of 450 μm thick silicon sensors bump-bonded to the IBEX photon counting ASIC [11]. The silicon sensor is pixelated into units of 75 μm × 75 μm and is operated in hole-collection mode with a bias voltage of 200 V. The IBEX ASIC is made in 110 nm CMOS technology in a radiation tolerant design, and it features 65'536 pixels of 75 μm × 75 μm size. The front-end electronics of each pixel is constituted by a charge sensitive preamplifier, whose gain can be adjusted to cope with the desired dynamic range, a fast shaper (tens of ns shaping time), and two independent comparators with selectable threshold energy. As the gain is tuned by varying the feedback resistance, high gains lead to larger shaping time and therefore to a better energy resolution. The charge sensitive preamplifier accepts signals of both polarities, making it compatible with hole and electron-collection mode. With a 75 μm pixel pitch, the IBEX ASIC provides two energy thresholds with two 16-bit counters each for continuous data acquisition. The instant retrigger technology with adjustable retrigger time [12] maintains a non-paralyzing counting mode up to values well above 10^7 cts/s/pix. Water cooling is used to stabilize the detector systems at room temperature.

2.2 Detector calibration

All detectors were calibrated before data taking. This involves the calibration of the (global) threshold energies as well as the pixel-wise threshold trimming with X-ray fluorescence lines according to the method described in [13]. A continuous gain adjustment as a function of energy threshold in the front-end electronics allows setting the threshold between 5 keV and 75 keV. In order to set the threshold above 75 keV, either an additional calibration with direct beam was performed or an extrapolation from the standard calibration was used.

The retrigger time was also calibrated for the different gains and for different electron energy and threshold energy combination. The retrigger time was set long enough to avoid double counting of isolated signal pulses at low electron fluxes.
2.3 Electron microscope

Measurements up to electron energies of 200 keV were performed with a FEI Tecnai F20 microscope at DECTRIS. Characterizations above 200 keV and up to 300 keV were carried out with a FEI Titan Themis microscope at the Electron Microscopy Center of the Eidgenössische Materialprüfungs- und Forschungsanstalt (EMPA) in Dübendorf, Switzerland. To access all required illumination conditions, measurements were performed with an empty sample holder inserted in the column. The column alignments have been manually optimized after every fine adjustment of the acceleration voltage to guarantee uniform illumination at the detector plane. Meanwhile, the highest and lowest electron fluxes were reached choosing appropriate extraction voltages, gun and condenser apertures, spot sizes, and image magnifications. Continuous variation of the electron flux on the detector for the count rate characterization was achieved with the microscope set in imaging mode and a Selected Area aperture inserted in the column. The excitation of the condenser lenses was controlled with the scripting interface offered by the SerialEM software.

2.4 Monte Carlo simulations

For a better understanding of the direct detection performance, Monte Carlo simulations were carried out. The interaction of the electrons with the silicon sensor was simulated with the FLUKA Monte Carlo package [14, 15]. The properties of the spatial distribution of the energy deposited by the electron tracks were investigated for incoming electrons of 100 keV, 200 keV and 300 keV. The tracks of $2 \times 10^9$ electrons, emitted by a point-like source and impinging at right angle onto the sensor, were simulated with a spatial resolution of $7 \times 5 \mu m$ ($x, y, z$ with $z$ being the direction of the electron beam) and their released energy recorded.

Figure 1 shows the simulated cumulative energy deposition in the case of 200 keV electrons normalized by the number of events projected on the $(x, y)$ plane (a) and as a function of sensor depth and radial distance from the impact point (b). The distributions have a high intensity around $(0, 0, 0)$, corresponding to the impact point of the electrons. In figure 1a the contour plot highlights the regions collecting 50%, 90%, 95%, and 99% of the charge. Their average radii are reported also in figure 1b. It is shown that about 50% of the total deposited energy is, on average, contained in within a radius of about 100 $\mu$m from the original electron impact point. This reflects the cumulative effect of electron energy deposition in the sensor, but misses the stochastic nature of the single tracks.

Figure 2 shows the averaged cumulative energy deposition radius as a function of the primary electron beam energy for different fractional energy losses. While at 100 keV (200 keV), 95% of the energy is deposited within 50 $\mu$m (120 $\mu$m), at 300 keV the corresponding radius increases significantly to 250 $\mu$m. In a purely counting detector, with no subpixel resolution, the collection radius sets the “lowest useful pixel size” for a given energy. As a consequence, with the current pixel size we expect performance degradations above 150 keV. To determine the average amount of charge collected by one pixel, the deposited energy is projected onto the pixelated side of the sensor and convoluted with a two-dimensional Gaussian function (with a standard deviation of 8 $\mu$m [16]) to take into account the growth of the charge cloud during its drift to the readout pads.
Figure 1. Cumulative energy deposition for electrons of 200 keV normalized to the number of events projected on the \((x, y)\) plane (a) and as a function of penetration depth and radial distance to the impact point (b). Contour plots in (a) and vertical lines in (b) show radii containing 50\%, 90\%, 95\%, 99 \% of the deposited energy. The gray square frame in (a) represent the detector pixel matrix with 75 \(\mu m\) pitch.

Figure 2. Radii containing 50\%, 90\%, 95\%, 99\% of the deposited energy as a function of electron energy.

3 Experimental results

3.1 Detector uniformity

To quantify the detector uniformity, several frames are recorded and summed up to form one high statistics image. This measurement was performed at an electron energy of 300 keV and an energy threshold of 30 keV, since low threshold values allow for high DQE measurements as will be shown in section 3.5. The count distribution is evaluated on a representative square Region of Interest (ROI) of 100 \(\times\) 100 pixels. The ROI has a minimum distance of 10 pixels from any ASIC boundary to retain only variations due to calibration imperfection and sensor non-homogeneity. This allows to separate these effects from known deviations caused at ASIC and sensor borders.
Figure 3 shows the measured detector uniformity under uniform illumination displayed as a map (a) as well as in form of a count histogram (b). The map shows no significant patterns and the count distribution exhibits a small standard deviation of less than 1%. Even though this value is almost ten times bigger than the one imposed by the statistical Poisson limit, these variations are comparable to results from X-ray irradiation, which mainly arise from residual threshold variations after detector calibration. Since calibration imperfections, sensor inhomogeneity, and distortions at ASIC and sensor borders are all expected to be stable in time, an appropriate flat-field correction can compensate for these effects.

3.2 Energy spectra

Single pixels usually record only a fraction of the total electron energy. This is due to backscattering and electrons traversing several pixels, which results in partial energy deposition in a selected pixel. Furthermore, the diffusion of the originally deposited charge cloud tends to distribute the signal across multiple pixels, known as charge sharing. All these effects can be characterized by recording images while scanning the threshold energy. After deriving the number of counts with respect to the threshold energy, the spectrum of the detected energy in a pixel is obtained. For mono-energetic sources, the resulting spectrum is also known as detector response function.

Figure 4 shows the average energy spectra for energies in the range from 20–80 keV. A peak at the electron energies identifies events whose full energy is recorded in a single pixel. The tail to lower energies originates from events with partial energy loss due to charge sharing. At the electron energy of 20 keV the peak is shifted to lower energies by roughly 6 keV, in agreement with previous measurements [8]. This is due to the low penetration depth of electrons — 1–5 μm for Al and Si — in the energy range of 10-20 keV [8]. Thus, electrons entering the sensor by the Al layer and Si backplane loose their energy and are scattered.
Figure 4. Energy spectra for different electron energies in the range from 20–80 keV. A Gaussian is fitted to each data set.

3.3 Cluster size

The cluster size of a single-electron event — so called event multiplicity — depends on the electron track length in the silicon sensor and the thermal diffusion of the originally deposited charge cloud. The former increases with electron energy, the effect of the latter is mainly determined by the sensor thickness, pixel size, and the applied bias voltage. For counting detectors, the average multiplicity also depends on the applied threshold energy.

To quantify these dependencies, images at low fluxes were recorded. The exposure time was selected sufficiently short to have pixel occupancies of only a few per mil in order to avoid overlapping clusters. Figure 5 shows clusters of 300 keV electrons for an energy threshold of 30 keV (a) as well as measured and simulated normalized multiplicity distributions for different threshold energies (b). As expected, larger clusters are registered for lower energy thresholds. Monte Carlo simulations with a charge cloud size of 8 μm rms match the measurements very well. As shown in figure 5b, at low threshold energies, the cluster sizes are slightly overestimated. These results are in good agreement with [17].

Figure 6 shows the measured average multiplicity as a function of electron energy and threshold energy. Zero-sized clusters from undetected electrons are not included. For threshold energies above half the electron energy, at most one pixel receives enough charge to exceed the threshold and the measured multiplicity is reduced to one. A small contribution from noise in the pixel front-end leads to an average multiplicity slightly above one. For lower threshold energies, clusters with more than one pixel lead to average event multiplicities up to 3 at electron energies of 300 keV.

3.4 Spatial resolution

The MTF is a direct measure of the spatial resolution of a detector. It gives an idea of how the amplitude of signals with different spatial frequencies is attenuated by the detector. The MTF was measured recording high statistics, flat-field corrected images under uniform illumination, partially shadowed by a highly absorbing metallic edge tilted by few degrees (1° to 3°) with respect to the pixels matrix orientation. The resulting oversampled 1-dimensional Line Spread Function (LSF) was derived to obtain the Edge Spread Function (ESF). At last, the Fourier transform of the ESF corresponds to the MTF. A smoothing filter was eventually applied in order to remove spurious statistical oscillations.
Figure 5. Measured clusters of 300 keV electrons for a threshold energy of 30 keV in a 40 \times 40 pixels ROI (a) as well as measured and simulated multiplicity distributions for 300 keV electrons for different threshold energies (b). The distributions have been normalized such that their integral is unity. Dashed lines in (b) denotes the simulated cluster size distribution given a threshold, the solid lines denote the corresponding measurements.

Figure 6. Measured average event multiplicity as a function of electron energy and threshold energy. Zero-sized clusters from undetected electrons are not included.

Figure 7 shows the MTF for two different incoming electron energy 100 keV (a) and 200 keV (b) for different threshold energies in the range from 5-100 keV. The MTF corresponding to the ideal pixel (perfect binary response, i.e. rectangle-like LSF and cardinal sine-like MTF) is also shown for comparison. The Nyquist frequency is the maximum spatial frequency that can be recorded in an image by the detector. The allowed Nyquist frequency for the current pixel size is \( (2 \times 75 \mu m)^{-1} = 6.6 \text{ mm}^{-1} \).

At the electron energy of 100 keV shown in figure 7a), the MTF shows in general high values and exhibits a notable dependence on the threshold energy. In particular, the MTF approaches the ideal value for increasing threshold energy. These properties are due to, firstly a relatively short electron track range in the sensor compared to the pixel size (52 \( \mu \text{m} \) average radius for a 99\% charge...
collection as shown in figure 2). Secondly, it is due to the non-negligible impact of the thermal diffusion experienced by the generated charge carriers on their path toward the collecting cathode (approximately 7–8 μm rms [16]). This causes the events to be split over multiple lower-energy events in neighboring pixels detected only with decreasing threshold energy.

At the electron energy of 200 keV depicted in figure 7b, the MTF drops faster for increasing spatial frequencies while it is almost independent on the threshold energy. In this case, the factor limiting the spatial resolution is the long electron track range compared to the pixel size (165 μm average radius for a 99% charge collection as shown in figure 2). The independence of the MTF on the threshold energy arises by the fact that the thermal diffusion component, which is roughly the same as for the 100 keV case, is now negligible. A better MTF at 200 keV or higher energies can be achieved with a bigger pixel size or by switching to high-Z sensor materials, where the electrons spread less sideways.

3.5 Detective quantum efficiency

The DQE describes the degradation of the SNR ratio during the detection process. The DQE is obtained combining the results of the MTF in section 3.4 with the measure of the Noise Power Spectrum (NPS). The latter is inferred from the Fourier transform of high statistics flat-field illuminations of the detector. The measurement was performed at low-flux conditions in order to assure a linear detector response, as required by definition of DQE. In this particular case, the count rate was in the range of 30 kcts/s/pix (10–15 ke/s/pix). The DQE was measured averaging several detector ROIs and over a series of flat-field corrected images in order to reduce the statistical uncertainty.

The knowledge of the absolute electron flux intensity was provided by the average event multiplicity, with the multiplicity at zero from undetected electrons taken from simulations.

The DQE is basically hampered by backscattered electrons, fluctuation in the event multiplicity, missed events with signals below threshold energy, and the limited spatial resolution described.
in section 3.4. Particularly, the fluctuation in the event multiplicity—including the backscattering component—affects the DQE as follow:

\[ DQE(0) = \frac{\langle m \rangle^2}{\langle m^2 \rangle} \]

where \( m \) is the event multiplicity. The mathematical formalism which leads to eq. (3.1) is derived in [9].

Figure 8 shows the DQE for incoming electron energies of 100 keV (a) and 200 keV (b) for different threshold energies from 5–100 keV. The DQE corresponding to the ideal pixel detector (i.e. cardinal sine-like MTF and constant NPS, meaning white or spatially uncorrelated noise) is also shown for comparison. At both the incoming electron energies, the DQE exhibit a pronounced dependency on the threshold energy. In particular, the DQE increases at all spatial frequencies as the detector threshold is decreased, reaching a maximum at roughly 20 keV threshold. This is due to the lower fraction of undetected charge sharing events and backscattered events. Below such level, the DQE(0) does not increase significantly, indicating a convergence of the \( \frac{\langle m \rangle^2}{\langle m^2 \rangle} \) ratio. As shown in figure 8 DQE(0) is higher at 200 keV because the energy deposited by backscattered electrons is more likely to be above the threshold. While the behavior at all other spatial frequencies is worse at 200 keV, as expected from the corresponding MTF. The drop-off in MTF and DQE in frequency is more pronounced at 200 keV, due to the significant scattering length relative to the pixel size.

Figure 9 shows the behavior of the DQE(0) as a function of the threshold energy for electrons of 100 keV and 200 keV, including the expected values for electrons of 300 keV obtained using eq. 3.1 on the event multiplicity distributions shown in figure 5b (with the multiplicity at zero estimated with simulations). As expected, the DQE(0) increases for increasing electron energy, for equal threshold energy. However, at higher spatial frequencies, the trend is the opposite as a consequence of having a charge collection radius more than three times bigger than the current pixel size, as described in section 2.4.

For the 100 keV electron case, at lower thresholds and in a certain frequency range, the DQE is actually higher than the one of the ideal pixel. This is due to the intrinsic low pass-like filtering effect, isotropic in the two dimensions of the pixel array, of an increased event multiplicity and the consequent increase of the SNR ratio at intermediate frequencies. While the range in which it happens is a consequence of the fact that the DQE(0) is fixed by eq. (3.1) and the low pass-like filter. This fits to previous measurement of the DQE at 100 keV [19].

3.6 Count rate capabilities

At high electron fluxes, counting detectors fail to register all absorbed quanta due to the finite processing time for each event. They usually exhibit a paralyzing counting behavior with a vanishing count rate in the limit of very high flux. The retrigger technology as implemented in the IBEX ASIC is able to partially recover lost events and provides a non-paralyzing counting behavior at very high electron fluxes.

To characterize the detector at high count rates, image series with increasing intensities were recorded with enabled and disabled retrigger mode. The electron beam was restricted to a region of about 150 pixels. Background radiation outside this area was used to estimate the intensity of incoming electrons, since it maintains its linear behavior at increasing beam fluxes. In figure 10, the observed count rate at 80 keV electron energy and 30 keV threshold energy is plotted as a function of the incoming count rate, which is normalized such that the observed count rate is equal to the incoming count rate at low fluxes. Due to electron backscattering and an event multiplicity larger
Figure 8. Measured DQE as a function of threshold energy and electron energies of 100 keV (a) and 200 keV (b). The DQE corresponding to the ideal pixel is shown for comparison.

Figure 9. Zero-frequency DQE as a function of the threshold energy measured for the electron energies of 100 keV and 200 keV, obtained applying eq. 3.1 to the event multiplicity distributions reported in figure 5b for the electron energy of 300 keV.

than one, this incoming count rate is not equal to the electron flux in a single detector pixel. For this measurement, a middle low gain setting and retrigger time 73 ns were used. The maximum count rates are about 5 Mcts/s/pix (about 4 Me/s/pix) in paralyzing mode and more than 12 Mcts/s/pix (about 10 Me/s/pix) in retrigger mode. The maximum count rate is given by the cut-off, defined as value in which the count rate derivative intersect with $y = 0$ ($y = 0.3$) for retrigger on (off), respectively. This definition is widely used in the X-ray community. In both cases, the ASIC is able to process up to 50 Mcts/s/pix incoming count rate.

Higher count rates can be achieved by increasing the threshold energy, which essentially reduces the number of counts per incoming electron, as shows figure 6. In this particular case, 10% and 50% count loss are observed at the incoming rate of 0.8 Mcts/s/pix and 7 Mcts/s/pix for retrigger OFF, at 1.7 Mcts/s/pix and 16 Mcts/s/pix for retrigger ON.
3.7 Optimal operating parameters

We found out that, as long as the collection radius is similar to the pixel size, the MTF increases at all spatial frequencies as the detector threshold is increased. Similarly, higher count rates can be achieved by increasing further the threshold energy. On the other hand, lower threshold values allow for high DQE at all spatial frequencies. The optimal operating threshold is a trade off among MTF, DQE and rate capability, depending on the application needs. If an application aims for the highest DQE, the detector should be operated at the lowest possible threshold. If instead, highest rate capability is required the threshold should be set high. Another such an adjustable and competing parameter is the preamplifier gain, since for the given circuit topology it affects the signal timing. A high gain setting enables higher DQE due to the better SNR, while a low gain setting allows higher rate capabilities since the dead time is smaller.

3.8 High flux stability

Threshold and electronics fluctuations can result in a drift of the detector count rate. To evaluate the stability of the detector system, a few hundred pixels were illuminated with an intense 300 keV electron beam and exposure frame of 1 ms while monitoring the count rate. The beam intensity was increased in three steps up to a final count rate of 10 Mcts/s/pix and each intensity is kept constant for some minutes. At the highest flux, the stability test was extended to about 50 minutes. In order to compensate for intensity variations of the electron source, the observed count rate was normalized by the amount of background radiation measured in a low-flux region of the acquired images outside the main beam.

Figure 11 shows the corrected median count rate at 300 keV as a function of time (a) as well as the relative intensity variations within the four time intervals normalized by the background region outside the beam (b). As expected, a higher statistical error is observed at low rates. This is due to the low amount of counts in the selected background region at low beam energy. To highlight long-term variations, the normalized count rates have been smoothed with a Savitzky-Golay filter with a window size corresponding to one minute. This average intensity remains stable within one percent except for some outliers due to the limited count statistics at low beam intensity. This is in very good agreement with the Poisson noise expected to be 1% from the number of counts in the frame.
Figure 11. Count rate stability at 300 keV electron energy for four beam intensities. Observed count rate versus time (a) and relative intensities within the four time intervals normalized by the background region outside the beam (b).

4 Conclusion

Calibrated IBEX detectors with 75 μm pitch pixel silicon sensors have been characterized with electrons up to energies of 300 keV. The experimental results are compared to Monte Carlo simulations and exhibit a very good level of agreement. The detector uniformity is measured to be better than a percent. The energy spectra show good detector performance above 20 keV. As expected, the average event multiplicity increases for higher electron energies and lower threshold energies. The observed behavior matches well with simulated events. For an electron energy of 100 keV, the MTF improves with higher threshold energies and is close to the characteristics of an ideal binary pixel. At 200 keV, the MTF degrades due to the significant scattering length relative to the pixel size of 75 μm. As a consequence, also the DQE at 200 keV rapidly drops for increasing spatial frequency. Analysis of the event multiplicity distributions allowed to estimate the DQE(0) for 300 keV electrons, giving values close to unity for lower thresholds. However, a more severe degradation of the DQE is expected at higher spatial frequencies, with the used pixel size. High frequency signal can be better resolved with 100 keV electrons. Lower values of the energy threshold always yield a better DQE than higher values. Measurements at high electron fluxes and operating at relative high threshold show that the IBEX ASIC is capable to process more than 50 Mcts/s/pix. In paralyzable counting mode the detector achieves a 10% count loss at 0.8 Mcts/s/pix and a 50% count loss at 7 Mcts/s/pix and, while in non-paralyzable counting mode the same limits are achieved at 1.7 Mcts/s/pix and 16 Mcts/s/pix, respectively. The optimal operating threshold is a trade off among MTF, DQE and rate capability, depending on the application needs. Stability measurements show that these fluxes can be sustained over one hour without any significant deviations. Altogether, the tested detector works best for electron energies between 20 keV and 150 keV. For lower energies, interactions in insensitive sensor layers limit the detection efficiency. For energies above 150 keV, the current pixel size of 75 μm is too small compared to the electron track length. As a consequence, spatial resolution and SNR ratio degrade with increasing electron energy.
Acknowledgments

The authors would like to thank Rolf Erni from the Electron Microscopy Center at the Eidgenössische Materialprüfungs- und Forschungsanstalt (EMPA) for facilitating the characterization at electron energies above 200 keV with the FEI Titan Themis microscope. His assistance during the measurement campaign is very much appreciated.

References

[1] G. McMullan, S. Chen, R. Henderson and A. Faruqi, Detecting quantum efficiency of electron area detectors in electron microscopy, Ultramicroscopy 109 (2009) 1126.
[2] G. McMullan, A. R Faruqi and R. Henderson, Direct electron detectors, in The Resolution Revolution: Recent Advances In cryoEM, Methods in enzymology, Vol. 579, Elsevier (2016), pp. 1-17.
[3] L. Rossi, P. Fischer, T. Rohe and N. Wermes, Pixel Detectors From Fundamentals to Applications, Springer (2006).
[4] C. Brönnimann and P. Trüb, Hybrid Pixel Photon Counting X-ray Detectors for Synchrotron Radiation, in Synchrotron Light Sources and Free-Electron Lasers, E.J. Jaeschke et al. eds., Springer Reference (2015).
[5] G. McMullan, A. Faruqi, D. Clare and R. Henderson, Comparison of optimal performance at 300 keV of three direct electron detectors for use in low dose electron microscopy, Ultramicroscopy 147 (2014) 156.
[6] A. Faruqi and G. McMullan, Direct imaging detectors for electron microscopy, Nucl. Instrum. Meth. A 878 (2018) 180.
[7] G.W. Paterson, R.J. Lamb, R. Ballabriga, D. Maneuski, V. O’Shea and D. McGrouther, Sub-100 nanosecond temporally resolved imaging with the medipix3 direct electron detector, Ultramicroscopy 210 (2020) 112917.
[8] G. Tinti, H. Marchetto, C.A.F. Vaz, A. Kleibert, M. Andrä, R. Barten et al., The EIGER detector for low-energy electron microscopy and photoemission electron microscopy, J. Synchrotron Rad. 24 (2017) 963.
[9] G. McMullan, D. Cattermole, S. Chen, R. Henderson, X. Llopart, C. Summerfield et al., Electron imaging with Medipix2 hybrid pixel detector, Ultramicroscopy 107 (2007) 401.
[10] S. Vespacci et al., Exploring transmission Kikuchi diffraction using a Timepix detector, 2017 JINST 12 C02075.
[11] M. Bochenek, S. Bottinelli, C. Broennimann, P. Livi, T. Loeliger, V. Radicci et al., IBEX: Versatile readout ASIC with spectral imaging capability and high count rate capability, IEEE Trans. Nucl. Sci. 65 (2018) 1285.
[12] T. Loeliger, C. Brönnimann, T. Donath, M. Schneebeli, R. Schnyder and P. Trüb, The new PILATUS3 ASIC with instant retigger capability, IEEE Nucl. Sci. Symp. Conf. Rec. N6-2 (2012).
[13] P. Zambon, P. Trüb, M. Rissi and C. Brönnimann, A wide energy range calibration algorithm for X-ray photon counting pixel detectors using high-Z sensor material, Nucl. Instrum. Meth. A 925 (2019) 164.
[14] T. Böhlen, F. Cerutti, M. Chin, A. Fassò, A. Ferrari, P. Ortega et al., The FLUKA code: Developments and challenges for high energy and medical applications, Nucl. Data Sheets 120 (2014) 211.
[15] A. Ferrari, P.R. Sala, A. Fasso and J. Ranft, *FLUKA: A multi-particle transport code*, Program version 2005 [INFN-TC-05-11].

[16] P. Zambon, V. Radicci, M. Rissi and C. Brönnimann, *A fitting model of the pixel response to monochromatic X-rays in photon counting detectors*, *Nucl. Instrum. Meth. A* 905 (2018) 188.

[17] G. Tinti, E. Fröjdh, E. van Genderen, T. Gruene, B. Schmitt, D.A.M. de Winter et al., *Electron crystallography with the EIGER detector*, *IUCrJ* 5 (2018) 190.

[18] A.R. Faruqi and G. McMullan, *Electronic detectors for electron microscopy*, *Quart. Rev. Biophys.* 44 (2011) 357.

[19] K. Naydenova, G. McMullan, M.J. Peet, Y. Lee, P.C. Edwards, S. Chen et al., *CryoEM at 100 keV: a demonstration and prospects*, *IUCrJ* 6 (2019) 1086.