The Noise Performance of Electron Multiplying Charge-Coupled Devices at X-ray energies

James H. Tutt, Andrew D. Holland, David J. Hall, Richard D. Harriss, Neil J. Murray

***Abstract*—Electron Multiplying Charge-Coupled Devices (EM-CCDs) are used in low-light-level (L3) applications for detecting optical, Ultra-Violet (UV) and Near Infra-Red (NIR) photons (10 nm to 1100 nm). The on-chip gain process is able to increase the detectability of any signal collected by the device through the multiplication of the signal before the output node, thus the effective read-out noise can be reduced to sub-electron levels, allowing the detection of single photons; however, this gain process introduces an additional noise component due to the stochastic nature of the multiplication. In optical applications this additional noise has been characterised. The broadening of the detected peak is described by the Excess Noise Factor. This factor tends to a value of $\sqrt{2}$ at high gain (>100x). In X-ray applications the situation is improved by the effect the Fano factor, f, has on the shot noise associated with X-ray photon detection (f $\approx$ 0.12 at X-ray energies). In this paper the effect of the detection of X-ray photons in silicon is assessed both analytically and through a Monte Carlo model of the gain amplification process. The Excess Noise on the signal is predicted (termed the Modified Fano Factor) for photon detection in an EM-CCD at X-ray energies. A hypothesis is made that the Modified Fano Factor should tend to 1.115 at high levels of gain (>10x). In order to validate the predictions made, measurements were taken using an ^{55}Fe source with Mn k-alpha X-ray energy of 5898 eV. These measurements allowed the hypothesis to be verified.**

***Index Terms*—CCD, EM-CCD, Excess Noise factor, Fano factor, X-ray, Modified Fano factor**

I. Introduction

Electron Multiplying Charge-Coupled Devices (EM-CCDs) share the same basic structure as conventional CCDs, with the addition of a multiplication gain register that uses impact ionisation to provide a gain to the detected signal in the charge domain. This gain can be of the order 10^3. When used in the detection of optical, UV and NIR photons, the charge collected in the pixel is read out and amplified before entering in the output circuit, thereby effectively reducing the amplifier noise and making photon counting possible; however, the amplification process also generates an additional noise component due to the probabilistic nature of the multiplication gain and so adds to the total noise of the system.

For a Poissonian noise source such as optically generated signal or dark signal, it is usual to define an Excess Noise Factor, F, such that:

$$F^2 = \frac{\sigma_{out}^2}{G^2\sigma_{in}^2} \tag{1}$$

where σ_{in}^2 is the variance on the input signal (i.e. before the gain register) and σ_{out}^2 is the variance on the output signal [1]. In applications where the incoming photon only has enough energy to produce one electron-hole (e-h) pair per interaction (optical, UV and NIR), F is found to approach $\sqrt{2}$ at high levels of gain, G, increasing from unity at a gain of 1. As the gain increases from 1 to 100, the photon peak becomes broader by a factor of $\sqrt{2}$. In optical applications the shot noise on the signal is given by $\sqrt{n}$ where n is the number of electrons in the device. When the multiplication register is used at high levels of gain (>10x), the associated noise generated by the multiplication is also given by $\sqrt{n}$. The total noise on the system generated by shot noise and the noise on the multiplication gain process is therefore given by $\sqrt{n+n}$ or $\sqrt{2n}$ as described in [2] and so shows why the Excess Noise Factor tends to $\sqrt{2}$. The value of σ is related to the Full-Width-Half-Maximum (FWHM) of the detected peak by:

$$FWHM = 2.355\sigma_{measured} \tag{2}$$

where $\sigma_{measured}$ is the total noise acting on the system, added in quadrature. The FWHM is a measure of the width of the peak at half the maximum value and is a way of measuring resolution.

When X-rays are detected in an EM-CCD, a cloud of electrons is generated in the silicon of the device for each incident photon through the initial photo-electric interaction and further impact ionisation. The number of electrons generated follows a Fano factor (f) adjusted Poisson distribution producing shot noise on the generated signal. The size of this component of noise is dependent on the number of electrons in the charge packet. Another component of noise is then added to the signal due to the charge multiplication process. The additional multiplication noise is analogous to the noise that creates the broadening described by the Excess Noise Factor in the optical photon scenario; however, the Fano factor adjustment causes F to vary from the single e-h pair generation per incident photon case in [2]. Applying the same analytical approach to that used for the definition of F with energies that produce single e-h pairs, it is possible to predict the behaviour of a system in which X-rays are being detected. In the optical case it was shown that the combined noise of the shot and multiplication noise is given by $\sqrt{n+n}$, whereas at X-ray energies, the same noise combination is described by $\sqrt{fn+n}$. This shows that the noise combination at high levels of gain is equal to $\sqrt{n}\sqrt{1+f}$. This $\sqrt{1+f}$ term is the result at high levels of gain. At gains of <10x, the increase in σ is smaller reducing to 0.115 (the Fano factor) at a gain of 1 and so this term is described as the Modified Fano factor (F_{mod}). It is related to the Excess noise factor by Equation 3 and is generalised by

The authors are with the Centre for Electronic Imaging, Planetary Space Sciences Research Institute, The Open University, Milton Keynes, UK.

equation 4.

$$F_{mod} = F^2 f \tag{3}$$

$$F_{mod} = \frac{\sigma_{out}^2}{G^2 \langle n_{in} \rangle} \tag{4}$$

where $\langle n_{in} \rangle$ is the mean number of electrons in the charge packet.

This paper applies this approach to analyse the effect of the noise associated with the multiplication process on the total noise of the device and shows how this empirical calculation for a particular material will yield a prediction of the variation in F_{mod} for X-rays at different levels of gain. The analytical results are then compared to the predictions made in a Monte Carlo model designed to mimic the operation of the multiplication register in an EM-CCD and to the data collected from an ^{55}Fe source in the lab.

II. Photon detection

Incident electromagnetic radiation on a CCD is detected via the photoelectric effect [3]. The radiation interacts with the silicon valence electrons creating an electron-hole pair (e-h) and the electron or hole (depending on the doping of the device) is then collected under the electrode structure of the CCD where it can subsequently be read out. UV to NIR photons (10 nm to 1100 nm) have sufficient energy to generate single e-h pairs through the photo-electric effect. As photons in this wavelength range are abundant, a large number of interactions can occur during an integration period. Integrating this signal allows the Signal-to-Noise Ratio (SNR) to be large enough to produce an image; however, as the light levels decrease, the amount of signal becomes smaller and so the SNR decreases. In the case of single photon counting, it becomes almost impossible to detect the incoming photons above the read-out noise of the device. Jerram et al. [4] showed how to make photon counting at optical wavelengths possible using on chip signal amplification in the form of EM-CCDs.

As X-rays are of a higher energy than optical photons, the created electrons continue to interact with the silicon structure after initial generation, producing more electrons through impact ionisation. The number of electrons generated in this cloud have a distribution between photon events that is expected to be Poissonian in nature [5] meaning that the determination of the energy of the incident photons is only possible by taking the average number of electrons produced by the interactions. However, when measured, the distribution is found to be narrower than would be expected in a Poissonian system. This difference has been described in terms of the Fano factor [6].

A. Fano factor

Fano showed that, when detecting photons with a semi-conductor, if the photon interaction produced a large number of e-h pairs the electron energy distribution across all photon interactions would have a narrower FWHM than is predicted by Poisson statistics. This reduction in the variance (which is related to FWHM by Equation 2) is due to the co-dependence between the generated electrons from each X-ray photon. Fano showed that the value of this factor for X-rays interacting in silicon is equal to 0.115 [7][8].

In order to correct for this narrowing of the distribution, a Fano factor, f, is applied to the ideal Poisson distribution so that the variance in the number of electrons produced by a photon interaction in a semiconductor, σ, with the charge cloud containing a mean number of electrons, $\langle n_e \rangle$, is given by:

$$\sigma^2 = f \langle n_e \rangle \tag{5}$$

The effect of this factor can be seen in Figure 1. A dark current generated signal of 100 electrons is shown by the broader line on Figure 1 and this peak's FWHM can be compared to the FWHM that would be expected for the same level of electron generation from an X-ray interaction. This clearly shows the effect of the Fano factor and is applied to the shot noise generated by the incident photons. The Fano factor causes a noticeable narrowing of the FWHM of the X-ray peak. This factor is important in the derivation of F_{mod} as it will cause a reduction in the variance of the number of electrons created by the incident radiation and so will have an effect on the output variance of the register. Therefore, this factor is taken into account in the mathematical derivation and Monte Carlo model that follow. The Fano factor has been shown to have some dependence on energy [9], but over the energy range examined in this paper the change is small and can be ignored.

III. Electron Multiplying CCD

EM-CCDs are identical to conventional CCDs apart from the addition of a multiplication register after the serial register of the device and before the readout node. This difference is shown in Figure 2.

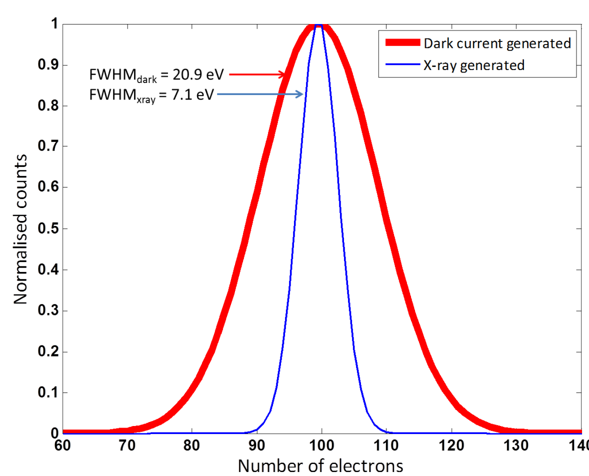


Fig. 1. Applying the Fano factor to a Gaussian distribution causes the distribution to narrow by a factor of $\sqrt{0.115}$ for X-rays in silicon as shown above. The broader line is for a dark current generated signal of 100 electrons compared to the narrower line for the same number of elecrons generated with an incident X-ray

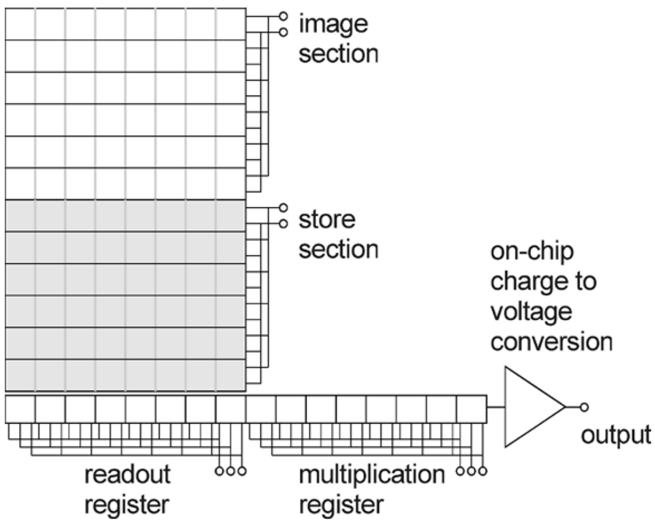


Fig. 2. EM-CCD layout showing the multiplication register between the read-out register and the output amplifier [2].

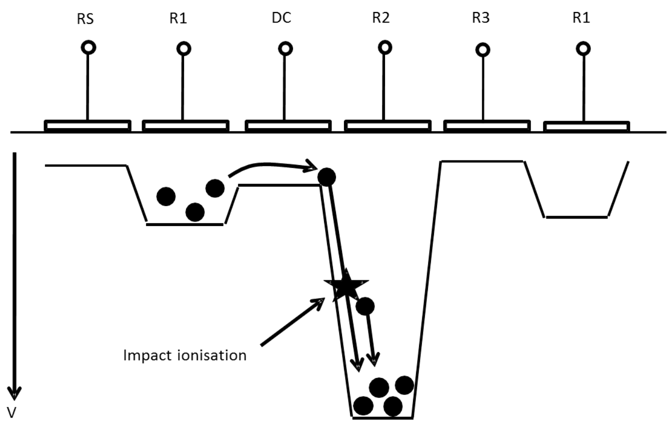


Fig. 3. Electron multiplication through impact ionisation in the potential well created below the high voltage electrode in the multiplication register.

A. Multiplication register

The multiplication register on an EM-CCD is of the same basic style as the serial read-out register. The multiplication is made possible by holding one of the electrodes in the register at a high potential so that the charge found in the register can be accelerated through the potential, allowing impact ionisation with valence electrons in the silicon to occur. This ionisation increases the number of electrons in the charge packet and so causes a multiplication of the signal. The higher the accelerating potential, the higher the probability that additional electrons will be produced through impact ionisation which results in a larger gain. The electrode clocking in the multiplication register is shown in Figure 3.

The DC electrode is held at a constant potential so that the high voltage potential (R2) can be increased without the charge packet being held under R1 falling into R2 before it has reached full potential. All other potentials on the electrodes in the multiplication register are clocked in the same way that would be expected in the image and serial read-out sections [10].

The total gain of a multiplication register, G, with a probability of a single gain element releasing an extra electron through impact ionisation, g, over N multiplication elements (typically > 500 on e2v devices [11]), is given by Equation 6.

$$G = (1+g)^N \tag{6}$$

with g being dependant on the voltage on electrode R2.

B. Excess noise factor and the Modified Fano factor

As described earlier, the stochastic nature of the multiplication process means that an extra component of noise will be generated on the Poissonian distributed output signal. At X-ray energies, there are large numbers of electrons in the charge packet, so the distribution can be approximated by a Gaussian. Thus, the multiplication noise is equal to $\sqrt{\langle n_{out} \rangle}$, where $\langle n_{out} \rangle$ is the mean number of output electrons from the multiplication register. Comparing the variance on the number of output electrons generated with the variance on the number of input electrons gives F^2 (Equation 1). When examined experimentally this factor can be predicted using Equations 2 and 8 [13], where $\sigma_{measured}$ is the total noise, $\sigma_{readout}$ is the readout noise, σ_{dark} is the dark current, f is the Fano factor, E is the average photon energy and ω is the energy required to generate an e-h pair in the semiconductor (∼3.68 eV in silicon at -120°C). The Excess Noise factor that operates on the dark current, F_{dark}, is always equal to what would be expected in the single e-h pair generation per incident photon case regardless of the energy of the incident photon as the dark current generation is independent of photon energy.

$$\sigma_{measured} = \sqrt{\left(\frac{\sigma_{readout}}{G}\right)^2 + F_{dark}^2 \sigma_{dark}^2 + fF^2 \left(\frac{E}{\omega}\right)} \tag{7}$$

Incorporating the Modified Fano factor, using Equation 3 results in the following equation:

$$\sigma_{measured} = \sqrt{\left(\frac{\sigma_{readout}}{G}\right)^2 + F_{dark}^2 \sigma_{dark}^2 + F_{mod} \left(\frac{E}{\omega}\right)} \tag{8}$$

Re-arranging Equations 2 and 8, makes it possible to arrive at a term for the additional component of noise added to the Fano-factor-adjusted shot noise by the gain multiplication register and gives an equation for the Modified Fano Factor when operating the system at high gain.

$$F_{mod} = \left(\frac{FWHM^2}{2.355^2} - \left(\frac{\sigma_{readout}}{G}\right)^2 - F_{dark}^2 \sigma_{dark}^2\right)\left(\frac{\omega}{E}\right) \tag{9}$$

At high gain F_{mod} tends to $(1+f)$, where $f = 0.115$ for silicon at X-ray energies and the equivalent value for f is 1 at single e-h pair generation energies. If the EM-CCD is cold (below -80°C) then the dark current can be considered to be negligible.

IV. Analytical approach

The Excess Noise factor is a specific form of the measurement of the ratio between the variance on the input and output signal from an EM-CCD. The general case for any device with a Fano factor, f, is derived from the original definition (Equation 1). F^2 is a measure of the additional noise introduced by the gain register. Following a similar method as described by Robbins et al., [2], and by assuming that the device is run cold enough for dark signal to be suppressed and considered negligible, it is possible to quantify F^2 including the Fano factor (Equation 10) and this can be used to define the Modified Fano Factor F_{mod}.

$$\frac{\sigma^2_{out}}{\langle n_{out}\rangle^2} = \frac{\sigma^2_{in}}{\langle n_{in}\rangle^2} + \frac{\sigma^2_G}{G^2} \tag{10}$$

where σ^2_G in the variance on the gain. The variance on the output signal from the multiplication register can be defined as:

$$G\langle n_{in}\rangle = \langle n_{out}\rangle \tag{11}$$

If we assume that the multiplication probability is constant and that successive trials are independent then we can describe the process using a Binomial distribution. If g is the probability of multiplication then the variance on the added electrons, σ^2_{added}, can be described by:

$$\sigma^2_{added} = \langle n_{in}\rangle g\,(1-g) \tag{12}$$

The variance on the gain is thus given by:

$$\sigma^2_G = \frac{\sigma^2_{added}}{\langle n_{in}\rangle^2} = \frac{g\,(1-g)}{\langle n_{in}\rangle} \tag{13}$$

When combined with Equations 10 and 12, this gives the variance on the amplified signal:

$$\sigma^2_{out} = (1+g)^2\,\sigma^2_{in} + \langle n_{in}\rangle g\,(1-g) \tag{14}$$

When looking at a Fano-limited system, standard Poissonian statistics do not apply and hence for X-ray processes $\sigma^2_{in} \neq \langle n_{in}\rangle$. Instead it was found that:

$$\sigma^2_{in} = f\langle n_{in}\rangle \tag{15}$$

where f is the Fano factor and σ^2_{in} is the Fano modified noise. As such we can develop our expression for σ_{out}:

$$\sigma^2_{out} = \langle n_{in}\rangle \left\{ f\left(1+2g+g^2\right) + g\,(1-g)\right\} \tag{16}$$

Equation 16 gives the noise on the output signal from the first gain element. This will therefore be the input noise for the second gain element with the mean input signal for that element being equal to $\langle n_{in}\rangle (1+g)$. Substituting these into the original expression for σ^2_{out} (Equation 14) gives the output noise for the second element and then this becomes the input noise for the third gain element, with the mean input signal being equal to $\langle n_{in}\rangle (1+g)^2$. This series can be generalised so that for the N^{th}gain element we have:

$$\sigma^2_{out} = \langle n_{in}\rangle (1+g)^{N-1} \times \left[f\,(1+g)^{N+1} + g\,(1-g)\sum_{k=0}^{N-1}(1+g)^k \right] \tag{17}$$

The final term in Equation 17 can be expressed as:

$$\sum_{k=0}^{n-1}(1+g)^k = \frac{1-(1+g)^N}{(-g)} \tag{18}$$

Using the fact that $G = (1+g)^N$ we can therefore simplify our expression for σ^2_{out}:

$$\sigma^2_{out} = \langle n_{in}\rangle \frac{G}{(1+g)} \left\{ fG\,(1+g) - (1-g)\,(1-G)\right\} \tag{19}$$

Applying Equation 19 to the original expression for F^2 (Equation 1) it is possible to obtain an expression for the Excess Noise Factor, noting that $\sigma^2_{in} = f\langle n_{in}\rangle$:

$$F^2 = \frac{1}{f}\frac{\left\{ fG\,(1+g) - (1-g)\,(1-G)\right\}}{G\,(1+g)} \tag{20}$$

In the optical region where $f = 1$, this simplifies to the original expression for the excess noise factor as described by Robbins et al. [2]:

$$F^2 = \frac{2G+g-1}{G\,(1+g)} \tag{21}$$

Finally, by using Equation 3, the Modified Fano Factor can be shown to be equal to:

$$F_{mod} = \frac{\left\{ fG\,(1+g) - (1-g)\,(1-G)\right\}}{G\,(1+g)} \tag{22}$$

As the gain of a system increases, G, becomes the dominant term in Equation 22, so the value tends to $\frac{f+(1-g)^N}{(-g)}$. As g is small, this tends to $(1+f)$ at large gain. If G is increased further, g gets bigger and so the approximation that F_{mod} tends to $(1+f)$ is incorrect, but for the basis of this work this simplification is adequate. This shows that, even though the Fano factor has the effect of reducing the variance on the initial generation of the input signal, the noise from the multiplication register follows a similar pattern to the optical case with F_{mod} increasing with increasing levels of gain up to a level of $(1+f)$. Therefore, in using an EM-CCD at X-ray energies, the resolution that can be achieved (FWHM) is shot noise limited. The gain amplification will make the signals generated in the device easier to see, but this will be accompanied by a broadening of the X-ray peak.

V. Monte Carlo simulation of the multiplication register for optical photons

A Monte Carlo model of an EM-CCD has been developed in order to demonstrate the mathematical predictions made by this paper. Each pixel of the modelled EM-CCD is considered to contain an isolated event of a given energy (300 eV = 82 electrons at -120°C). This energy was chosen as it is the lower energy of the Reflection Grating Spectrometer (RGS) on XMM-Newton and so the lowest energy soft X-ray that

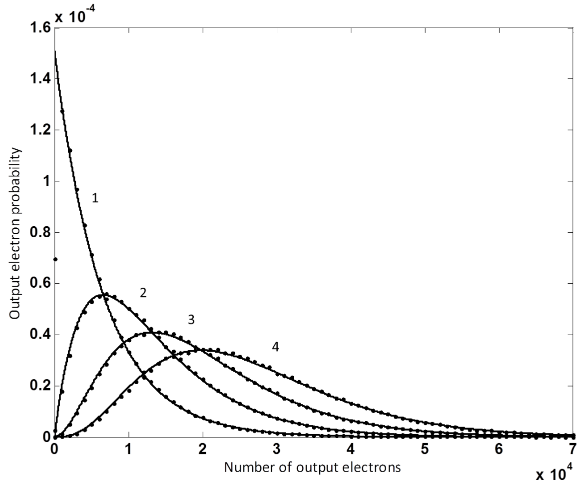


Fig. 4. Probability of generating a given number of output electrons based on a varying number of input electrons (1-4) for an optical scenario

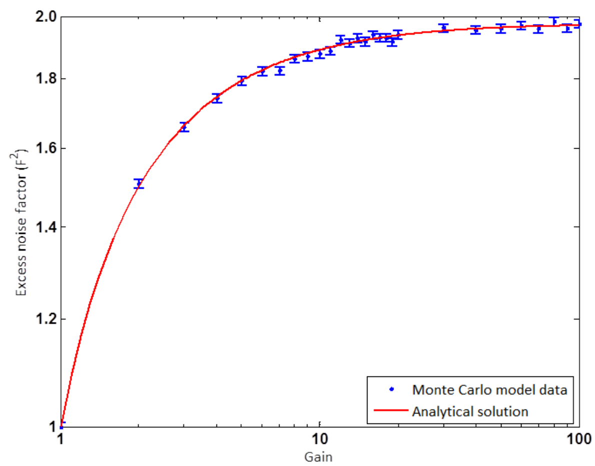


Fig. 5. Gain vs. Excess Noise Factor from theory [2] and through the use of the Monte Carlo model developed during this work for optical photon (equivalent Fano factor of 1).

is currently being collected in a space application [12]. The lowest energy was chosen in order to test the detectability of the signal with the smallest charge cloud that would be generated and all X-ray events are assumed to occur in single pixels. Through the randomisation of the number of electrons in each pixel within a Gaussian distribution of mean $\langle n_{in} \rangle = 82$ electrons and variance $f\langle n \rangle$ it is possible to generate the shot noise on the input signal. Every electron in each pixel is then moved through N gain elements where each element has a probability, g, of generating another electron through impact ionisation (Equation 6). The final variance on the output signal can then be calculated and thus the Modified Fano Factor, F_{mod}, for a system with any Fano factor, f, can be determined.

In order to test the accuracy of the Monte Carlo simulation and in turn the analytical solution, the Monte Carlo simulation was used to predict the behaviour of an EM-CCD detecting optical photons ($f = 1$). Figure 4 shows the model used by Basden et al. [14] for an EM-CCD detecting 1, 2, 3 and 4 electrons. The points on the figure show the results of the Monte Carlo simulation made for this paper and the lines are generated from:

$$p(x) = \frac{x^{N-1} e^{\frac{-x}{g}}}{g^N (N-1)!} \tag{23}$$

This equation allows the probability, $p(x)$, of an getting a certain number of output electrons from the multiplication register to be found and so the effect of putting 1-4 electrons, x, through a 591 gain elements, N with a total gain, G, of 6629 can be modelled and compared with the results found in Basden et al. [14]. The probability of creating an electron though impact ionisation in the multiplication register, g, can be found from Equation 6.

It can be seen that the points from the Monte Carlo simulation fall on the lines generated from Basden et al, [14] increasing the confidence in the simulation.

The second benchmarking test used the model to predict the Excess Noise Factor behaviour in optical photon conditions. This was achieved by again setting the Fano factor to 1 (single e-h pair production per incident photon) and running through the same Gaussian distribution of electrons through the model at varying levels of gain. Theory predicts that the Excess Noise Factor, F^2, will vary with gain as has been shown by Equation 21 [2].

The results obtained from the Monte Carlo model can be compared to the plot formed by this equation with varying gain, helping to build confidence in the model. These results are shown in Figure 5.

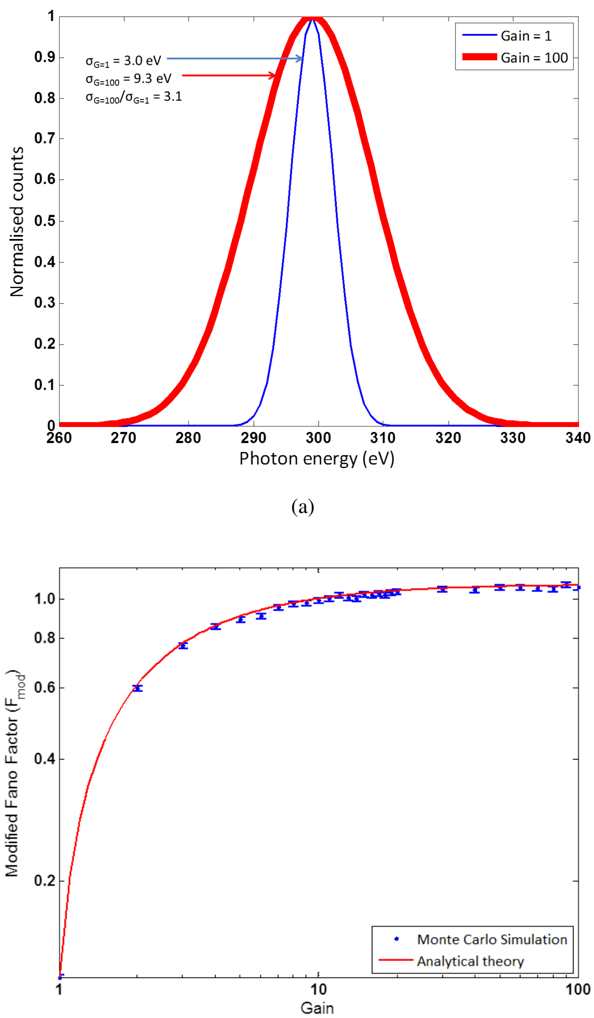
As both benchmarking methods for the Monte Carlo model show a good relationship with theory, confidence in the predictions made is high.

VI. Monte Carlo and analytical comparison at X-ray energies

With the Monte Carlo simulation proving accurate at optical energies, it was then possible to use the same model to make predictions about X-ray energy behaviour ($f = 0.115$). X-rays of energy 300 eV were put into the model and F_{mod} was found for a variety of levels of gain. Plots of gain against F_{mod} were made to compare the simulation to the analytical model, as shown in Figure 6(b). The plots show that for an increasing level of gain, there is an increase of the total noise in the system, due to the multiplication register, that tends towards $(1 + f)$ at high gain. This is the Fano/Poissonian limited result and the expected peaks for a situation with a gain of 1 and a gain of 100 are shown in Figure 6(a).

VII. Experimental verification of Modified Fano Factor vs. Gain with ^{55}Fe X-rays (5.9 keV)

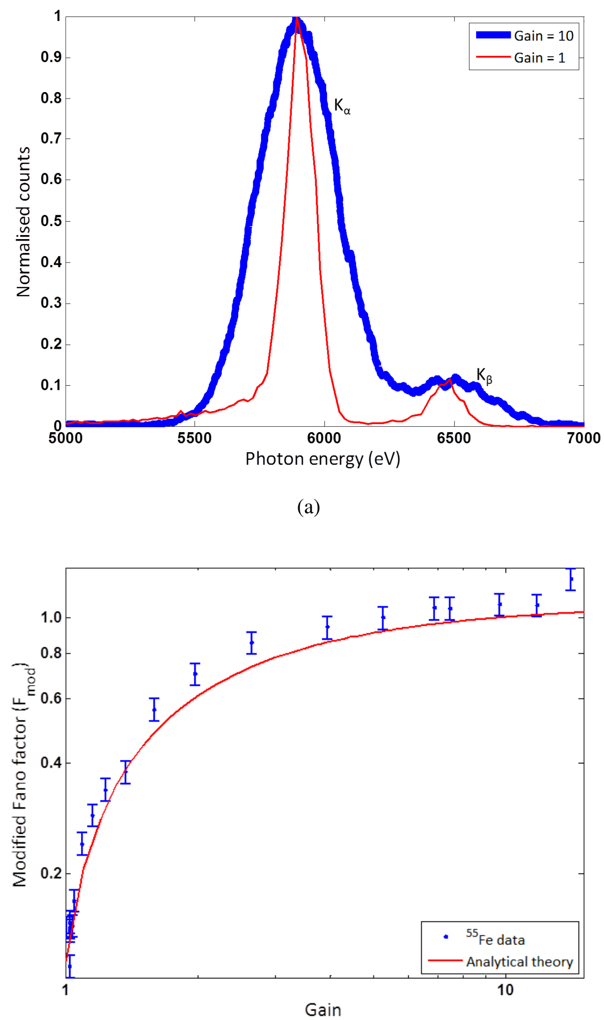
The aim of the experiment was to detect the manganese K-alpha X-ray emission at 5898 eV. As these X-rays are at high energy, the Mn K-alpha emission would be expected to penetrate deep into the device before interaction with the silicon (>20 nm [16]). This minimises the field-free region the X-rays travel through causing more X-ray events to occur



(a)

(b)

Fig. 6. Figure 6(a) shows the expected broadening of the peak due to a large increase in gain. Figure 6(b) shows how the Modified Fano Factor and so FWHM of the X-ray peak can be expected to broaden with increasing gain, tending to 1.115 at high gain when detecting X-rays.



(a)

(b)

Fig. 7. Figure 7(a) shows the effect of increasing the gain from 1 to 10 has on the FWHM of the X-ray peak when detecting $MnK\alpha$ X-ray. Figure 7(b) plots this broadening against increasing levels of gain. This closely matches the analytical prediction.

in single pixels leading to a more accurate prediction of the Modified Fano Factor without event reconstruction and across all levels of gain.

The CCD97 was placed in a chamber with a ^{55}Fe source, at a pressure of 10^{-4} mbar and cooled to -115°C in order to minimise the dark current generated. The X-rays incident on the CCD over 0.1 second integration times and 500 frames were recorded per gain setting allowing the FWHM of the Mn K-alpha and background noise peaks to be measured. This experiment was performed over a range of gain voltages (11 V to 34 V, gain of 1 and 15 respectively) in order to get a measurement of the effect of gain on the FWHM of the signal. It was not possible to increase the voltage above 34 V as the X-ray data started to saturate the ADC of the processing equipment and so the experiment was limited to modest levels of gain.

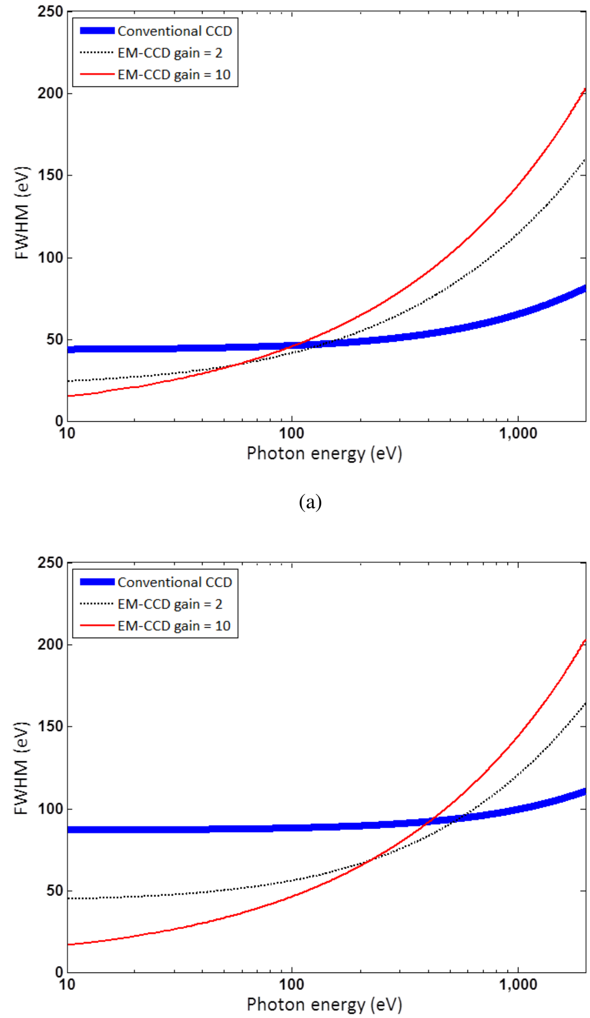
1) Results: It was possible to produce a plot of the Modified Fano Factor against the gain of the system to test the F_{mod} hypothesis. Figure 7(a) shows the ^{55}Fe X-ray peak for different levels of gain with the broadening of the peak clearly visible, giving an increase in sigma and a corresponding increase in the FWHM. The results can verify the Monte Carlo model and analytical prediction for the Modified Fano Factor at X-ray energies and can be seen in Figure 7(b). At a gain of 15, the experimental data moves away from the theoretical model as the ADC nears saturation.

VIII. Practical application

The effect of the Fano factor on the degradation of the FWHM of the X-ray peak when detecting the signal with an EM-CCD has been discussed, but what is the practical application of this information? Using the X-ray Modified Fano Factor as described in this paper it is possible to predict the best possible spectral resolution you would expect when using an EM-CCD at a specific energy and gain. This paper has assumed that all X-ray events are single pixel events for simplicity, but even though this is not normally the case, it is offers a useful guide for the use of EM-CCDs at X-ray energies. As an EM-CCD is design to suppress readout noise by amplifiying the output signal, it is expected that they would perform better than a conventional CCD (or an EM-CCD being operated with a gain of 1) in experiments where readout noise is the dominant source of noise. As shot noise is a function of energy, as the energy increases, this noise becomes dominant and so it is expected that an EM-CCD would begin to perform worse than a conventional CCD. The ability to predict the cross-over point between when an EM-CCD and a conventional CCD have the best spectral resolution performance allows a decision about the type of device to use in a particular experiment to be made. The determination of device performance depends on the temperature that the device is being operated at, the readout noise of the devices electronics and the energy of the detected photons and can be caluculated using Equations 2 and 8 in terms of FWHM. In this example, as in the rest of the paper, it is assumed that the device is running cold enough that the dark current generation is effectively suppressed and so can be ignored. It is also assumed that the readout noise of the EM-CCD and the conventional CCD are the same in each example so that the effect of the Modified Fano Factor is the only determining influence on the FWHM of the detected X-ray peak.

At low levels of readout noise (5 electrons r.m.s.), shot noise becomes dominant at low energy levels. Figure 8(b) shows that if you suppress readout noise using an EM-CCD then a conventional CCD will be better at resolving the X-ray photons at energies above 100 eV.

With a higher readout noise (10 electrons r.m.s.), the energy can get to a much higher level before the system becomes shot noise dominated (Figure 8(b)). High levels of gain (>10x) give you an improvement in spectral resolution up to 400 eV, compared with a conventional CCD, which is easily in the detectable energy range of a back-illuminated CCD. Running the EM-CCD with a low gain of 2 gives you a benefit in spectral resolution up to 500 eV due to the way that the Modified Fano Factor varies at low levels of gain. Over 500 eV however, the conventional CCD starts to give you an improvement in resolution..



(b)

Fig. 8. Comparison between the spectral resolution of an EM-CCD and a conventional CCD with readout noise of Figure 8(a) 5 eletctrons r.m.s. and Figure 8(b) 10 electrons r.m.s.

A. Discussion

The analysis above shows that EM-CCDs give you the most benefit with X-ray detection in noisy system. If the readout noise is the dominant source of noise then the ability of an EM-CCD to suppress this signal by amplifying the signal before it is readout will be beneficial to the experiment. As systems become less readout noise dominated, the ability of an EM-CCD to suppress this readout noise becomes less useful and so conventional CCD start to become the more attractive devices to use in terms of noise reduction. However, the EM-CCD will also enable photons of low energy to be detected in the device. As X-ray energies drop below 300 eV, it becomes harder to detected the whole of the generated charge cloud, especially if it is split over many pixels. An EM-CCD is able to amplify this signal and so increase the detection efficiency of the system.

In order to chose a device for an experiment at X-ray energies it is necessary to balance the effect of readout noise suppression with the increase in the energy dependant noise of the device, as well as considering how easily the X-rays will be to detect above the noise in the system. It can be seen from Figure 8(b) that will small amounts of gain, the increase in FWHM of the detected X-ray peak can be minimised, but the readout noise is still partially suppressed. There will also be an increase in the detectablility of the incident X-rays and so the application of gain the right situations can be beneficial.

As EM-CCDs can be operated at a gain of 1 or through a separate, no gain, output amplifier it would be possible to run an EM-CCD at a gain of 1 and so avoiding the affect of the Modified Fano Factor and only introducing a gain when the experiment would benefit from increased detectability and readout noise suppression.

IX. Conclusions

It has been shown analytically, through a Monte Carlo simulation and experimentally that the Fano factor has an effect on the Excess Noise Factor when detecting X-ray photons (termed the Modified Fano Factor). The Modified Fano Factor, F_{mod} of such a system will tend to $(1 + f)$. This result holds true for an optical system where the equivalent Fano factor is 1.

The effect of operating an EM-CCD at X-ray energies is that the FWHM of the X-ray peak widens despite the Fano adjusted shot noise on the input signal. This result has been verified experimentally. In order to look at the effect with lower energy soft X-rays, an EM-CCD with the potential for deep depletion will be required to minimise split events.

A future test campaign using an e2v CCD220 [17] will provide further verification of the predictions made in this paper through the improved resolution offered by a deep depletion device when detecting soft X-rays.

This paper has shown how the Excess Noise Factor for optical photon detection can be extended to a more general case for materials and energies that produce different Fano factors, specifically for X-ray detection in silicon. The Modified Fano Factor, F_{mod}, that provides a measure of output variance on the signal against the mean number of electrons initially generated in the silicon, has also been introduced. This has demonstrated that EM-CCDs can be used on X-ray spectroscopy systems and energies $<$1 keV and particularly when system noise or readout speed is a concern.

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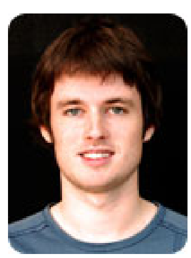
References

[1] J. Hynecek., ”Impactron - A New Solid State Image Intensifier” IEEE Trans. Electrons Devices, Vol. 48, No. 10, 2001.
[2] M. Robbins et al., ”The Noise Performance of Electron Multiplying Charge-Coupled Devices” IEEE Trans. Electrons Devices, Vol. 50, No. 5, 2003.
[3] A. Einstein., ”ber einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt” Abbalen der Physik, Vol. 17, p.p 132-148, 1905.
[4] P. Jerram et al., ”The LLLCCD: Low light imagining without the need for an intensifier,” Proc. SPIE 4306, p.p 178-186, 2001.
[5] J. Hiraga et al., ”How Big Are Charge Clouds Inside the Charge-Coupled Device Produced by X-ray Photons,” ISAS Research note, ISAS RN 656, 1998.
[6] U. Fano et al., ”Ionization Yield of Radiations. II. The Fluctuations of the Number of Ions” Phys. Rev., Vol. 72, Issue 1, p.p 26-29, 1947.
[7] G.W. Fraser et al., ”The X-ray energy response of silicon Part A. Theory” Nucl. Instrum. Methods Phys. Res. A, 350, p.p 368-378, 1994.
[8] A. Owens et al., ”The X-ray energy response of silicon Part B. Measurements” Nucl. Instrum. Methods Phys. Res. A, 382, p.p 503-501, 1996.
[9] F. Perotti et al., ”Observed energy dependence of Fano factor in silicon at hard X-ray energies” Nucl. Instrum. Methods Phys. Res. A, Vol. 423, p.p 356-363, 1999.
[10] J.R. Janesick, ”Scientific Charge-Coupled Devices,” SPIE Press, Bellingham, Washington, USA, p.p 22-25, 2001.
[11] e2v CCD97 datasheet, A1A-CCD97BI-2P-IMO, Issue 3, 2004.
[12] J.W. den Herder et al., ” The Reflection Grating Spectrometer on board XMM,” Astronomy and Astrophysics manuscript, 2000.
[13] J.R. Janesick, ”Photon transfer,” SPIE Press, Bellingham, Washington, USA, p.p 34, 2007.
[14] A.G. Basden et al., ”Photon Counting Strategies with low-light-level CCDs,” Mon. Not. R. Astron. Soc., Vol. 345, p.p 985-991, 2003.
[15] J.H. Tutt et al., ”A study of electron-multiplying CCDs for use on the International X-ray Observatory off-plane x-ray grating spectrometer,” Proc. SPIE., Vol. 7742, pp. 774205-774205-12 , 2010.
[16] B.L. Menke et all., ”X-ray interactions: photoabsorption, scattering, transmission, and reflection at E=50-30000, Z=1-92,” Atomic Data and Nuclear Data Tables, Vol. 54 (no. 2), pp. 181-342, 1993.
[17] e2v CCD220 provisional datasheet, CCD220BI Provisional, Issue B, 2007.

Biographies

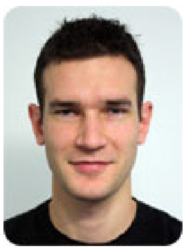
James Tutt James is a third year post-graduate student studying under Andrew Holland and Neil Murray. James started his professional career at e2v Scientific Instruments where he worked on the characterization of Si(Li) detectors for high resolution X-ray spectroscopy. He is working toward a PhD on detector developments for the International X-ray Observatory, and specifically the detector array to read out the X-ray grating instrument. This work involves the development and characterization of soft X-ray imaging spectrometers, based on both CCD and EM-CCD technology covering the 0.2$-$2 keV energy range.

Andrew Holland Andrew is an expert in detector physics and has worked on the development of a number of successful space instruments. Working on a range of detector developments over the past two decades, he has a wealth of knowledge and experience advising on instrument related issues, in particular radiation damage effects and the prediction of orbital performance.



David Hall David J. Hall was born in the UK in 1984. In 2006 he received an MPhys degree in Physics from Oxford University, UK. He received his Ph.D. degree in the impact of detection physics in X-ray CCD imagers and spectrometers from the Open University in 2010. From 2009 to 2010 he continued as a Research Associate within the *e2v centre for electronic imaging*, part of the Planetary and Space Sciences Research Institute at the Open University in Milton Keynes, UK. His research has included the modelling of charge transfer in CCDs following radiation damage and a study of the impact of radiation damage on spectra for the Radial Velocity Spectrometer forming part the ESA Gaia mission. Since his appointment as an e2v Research Fellow in 2010 he has continued his research within the *e2v centre for electronic imaging* into the modelling of CCDs and novel imaging techniques, with particular interest in the development of innovative techniques and applications for the Electron-Multiplying CCD in synchrotron-based research and medical imaging. Dr. Hall is a member of the Institute of Physics.

Richard Harriss Richard is a second year post-graduate student working under Andrew Holland and Neil Murray. His thesis is based around looking at advanced CMOS imagers for scientific applications. Richard is interested in radiation damage, in particular the radiation environment of the Jovian system for EJSM (Europa Jupiter System Mission). This work involves looking at both conventional CCDs as well as novel CMOS imagers that could meet the requirements of the HRC (High Resolution Camera) that is to be flown on the JGO and JEO satellites. Following his undergraduate studies at Oxford University Richard completed a brief stint in the Army before joining the PSSRI.



Neil Murray Neil received his PhD degree for work on improvements to MOS CCD technology for future astronomy missions from Brunel University in 2008, where he characterised the X-ray performance of e2vs high-rho sensors that had been developed for near-IR astronomy . In 2008-2010, he followed similar research themes as a Research Associate within the e2v centre for electronic imaging at the Open University (Milton Keynes, UK) developing a soft X-ray camera for an Off-Plane X-ray Grating Spectrometer in collaboration with the UCL-MSSL, University of Iowa, University of Colorado and NASA-Goddard. Currently, the main aspects of his work as an e2v funded PDRA still in the centre for electronic imaging, is to design and build a variety of experiments and techniques to perform detailed characterisation of CCDs in support of the space missions that the group is involved with. Neil also contributes with his technical expertise to the groups wider research interests, as well as those of e2v technologies and provides practical training to groups post-graduate students.