Electron Multiplying CCDs for Future 'Soft' X-ray Spectrometers

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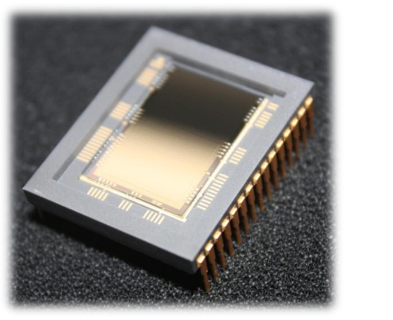
Introduction



Electron-Multiplying CCDs (EM-CCDs) use on-chip gain multiplication to amplify the signal integrated in the charge packet before it is read out from the CCD. The majority of the noise is added to the signal through the readout process and, as the amplification of the signal occurs before the readout, the Signal-to-Noise Ratio of the system increases, allowing the photons to be more easily detected. However, the gain multiplication does cause a degradation in the energy resolution of the device which could affect high resolution 'soft' X-ray spectrometer instruments. This posters discusses the advantages and disadvantage of using EM-CCDs for high resolution 'soft' X-ray spectroscopy with an energy range 0.3 keV – 2.5 keV.

Current and future soft X-ray spectrometers

Reflection Grating Spectrometer (RGS) on XMM-Newton[1]

- Energy range – 0.35 keV to 2.5 keV
- Launched in 1999
- Resolution $\frac{E}{\Delta E}$~ 400 @ 0.5 keV

Low Energy Transmission Grating (LETG) and High Energy Transmission Grating (HETG) on Chandra[2]

- LETG – Energy range – 0.08 keV to 2 keV
- HETG – Energy range – 0.4 keV to 8 keV
- Launched in 1999
- Resolution $\frac{E}{\Delta E}$~ 300 below 3 keV

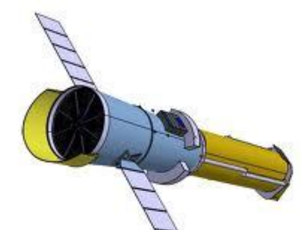
Resonant Inelastic X-ray Spectrometer (RIXS), Swiss Light Source (SLS) at the Paul Scherre Institut (PSI), Zurich[3]

- Spectroscopy instrument for biological imaging

WHIMex[4]

- NASA explorer mission
- Energy range – 0.2 keV to 2 keV
- Resolution $\frac{E}{\Delta E}$~ 4000

International X-ray Observatory (IXO) X-ray Grating Spectrometer (XGS)[5]



- NASA, ESA and JAXA collaboration
- Energy range – 0.3 keV to 1 keV
- Resolution $\frac{E}{\Delta E}$~ 3000

EM-CCD Advantages in spectroscopy

Noise vs. readout speed

Correlated-Double Sampling (CDS) is used to reduce the effect of reset noise on the CCD readout. Therefore, allowing a long CDS integration period minimises the readout noise while faster CCD readout causes the readout noise to be higher. EM-CCDs are able to suppress this readout noise through the increase of signal using EM-gain. This is shown in Figure 1 where an increase in speed is correlated to an increase in noise; however, by increasing the gain on the device, the equivalent baseline noise reduces and so the effect of increasing the readout speed is less pronounced. This allows the EM-CCD to be run warmer and look at higher flux sources.

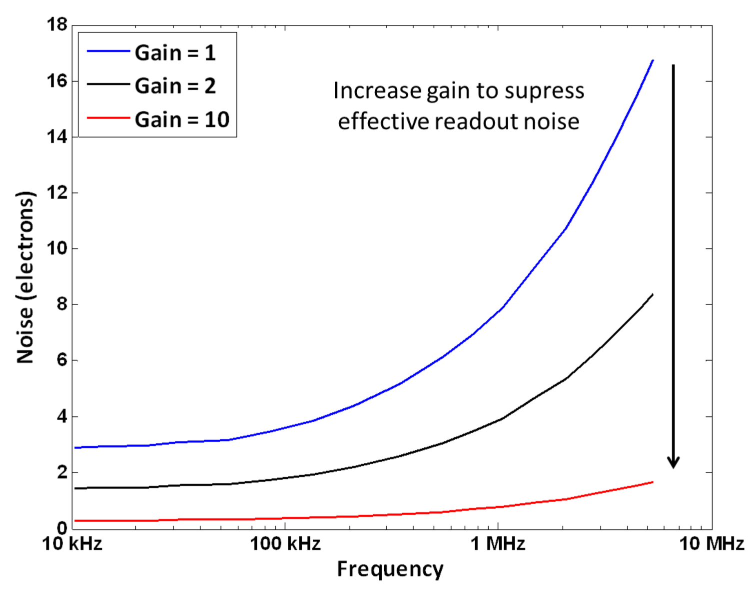


Figure 1[6]

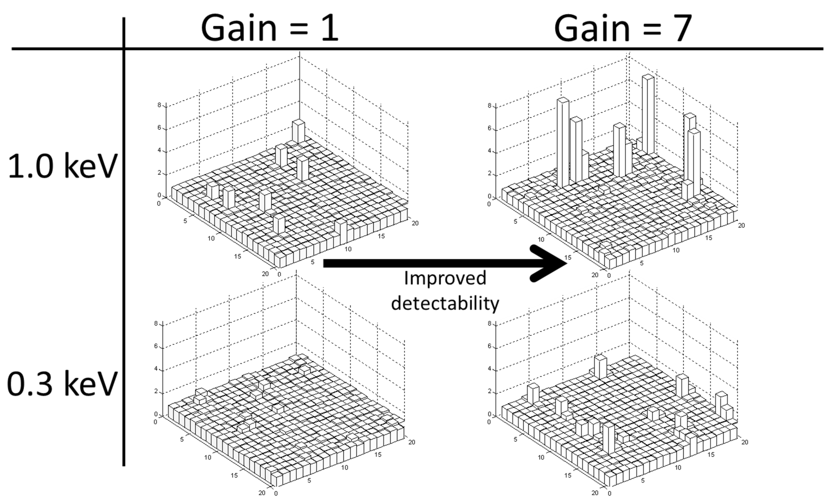


Figure 2

Improvements in X-ray detectability

Low energy X-rays produce relatively few e-h pairs through interaction with the silicon and the charge packet may be spread over several pixels. This causes some of the signal to be lost in the noise leading to incomplete charge collection. Through the use of EM-gain, the signal created by the interaction can be amplified above the noise floor, increasing the Signal-to-Noise Ratio for the readout, making the X-rays more detectable. This can be seen in Figure 2[7].

Increased noise immunity

Electro-Magnetic Interference (EMI) can cause fluctuations in the noise floor of a CCD and have an adverse effect on the noise. When using an EM-CCD, as the noise is suppressed through the increase in signal, the effect of EMI on the collected signal is minimal. Figure 3 shows a readout from the RGS on XMM-Newton with an EMI pattern on the devices. This EMI effects the X-ray detection at the lower end of the RGS' energy range. An EM-CCD would be able to amplify the signal at the lower energies, moving the X-ray events away from this EMI.

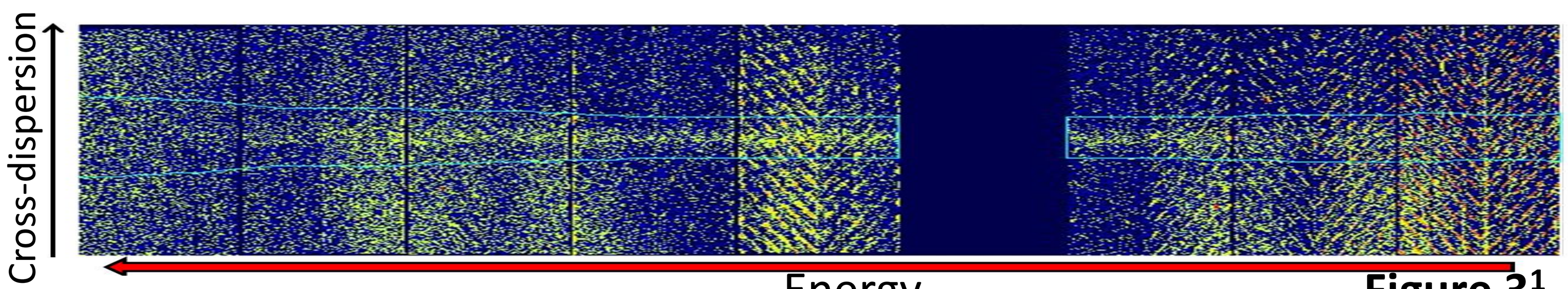


Figure 3[1]

EM-CCD Disadvantage in spectroscopy

Energy degradation – The Modified Fano Factor

The stochastic nature of EM-gain adds another component of noise to the signal collected by the CCD that is analogous to the shot noise on the detection of the incident photon. This Excess Noise was first identified in optical applications but, as the Fano Factor (f) acts on the initial X-ray's shot noise to produce a distribution that is better than expected from Poisson statistics[8], the X-ray case for this Excess Noise differs from the optical solution and is know as the Modified Fano Factor.

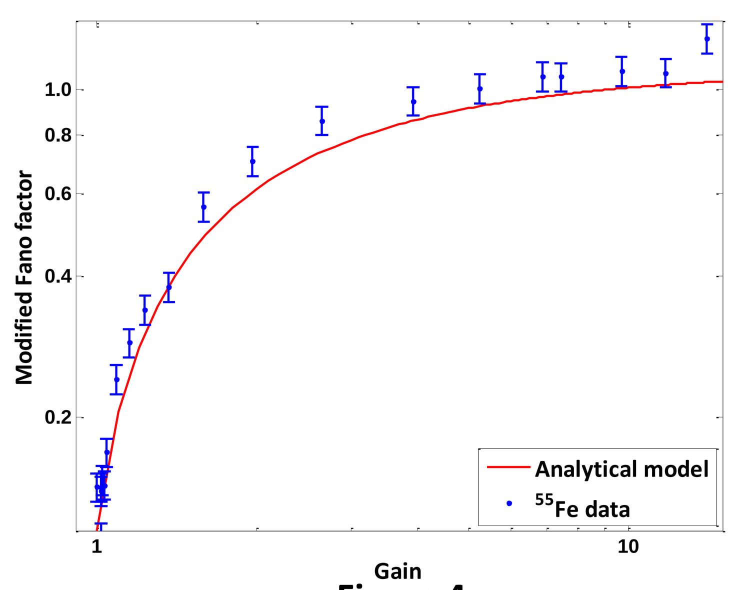


Figure 4

Figure 4 shows how this Modified Fano Factor, F_{mod}, varies with increasing gain. At a gain (G) of 1x on the EM-CCD, the multiplication process has no effect on the signal and so a Fano adjusted spectrum is produced. As the level of gain increases, so does the effect of the multiplication gain on noise, until it reaches its peak at gains of >10x at (1+f) = 1.115. The way that this Factor affects the FWHM of the X-ray peak is given by Equation 1.

$$FWHM = 2.355\sqrt{\left(\frac{\sigma_{readout}}{G}\right)^2 + \sigma_{dark}^2 + F_{mod}\left(\frac{E}{\omega}\right)} \quad (1)$$

where $\sigma_{readout}$ is the CCD readout noise, $\sigma_{dark}$is the dark current generated, E, is the photon energy and ω is the energy required to produce an e-h pair in the silicon.

This Modified Fano Factor describes the broadening of the X-ray peak that occurs due to the use of EM-gain on a signal. Figure 5 shows this effect on Mn k-alpha data. The signal that has had a gain of 10x applied to it is significantly broader than the gain of 1x signal and, as a result, the k-beta peak is beginning to be swamped by the broadening k-alpha peak[9].

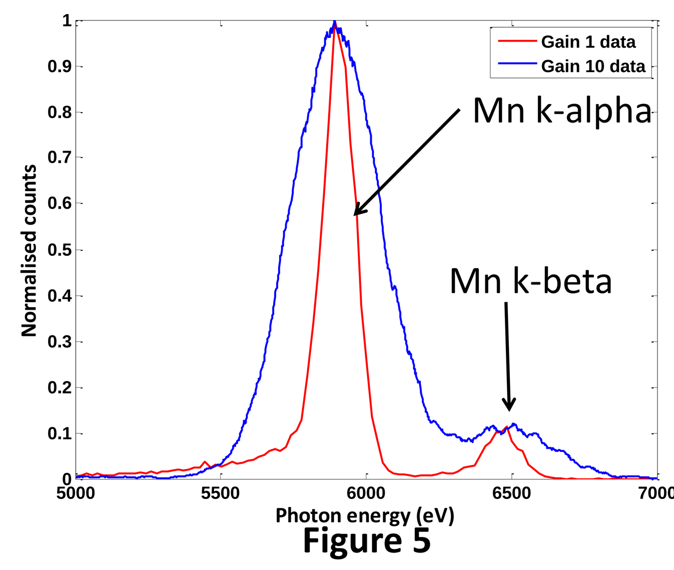


Figure 5

In spectrometers, the inherent energy resolution of the CCDs is necessary to separate out X-rays as different energy photons at different orders of dispersion overlap on the CCD array. If the energy resolution is severely degraded, this separation may no longer be possible reducing the instruments effectiveness.

Conclusion

EM-CCDs have advantages over the use of conventional CCDs as they are able to supress the readout noise of a system through EM-gain. This provides the system with an increased immunity to fluctuations in readout noise (EMI) as well as allowing the devices to be run faster, warmer and observing sources with high flux rates. They also allows small, low energy signals that have been split across several pixels to be amplified well above the noise floor, making them more easily detectable. However, as most spectrometers rely on the inherent energy resolution of the detectors to make order separation possible on the camera array, the degradation of this energy resolution could be damaging to the instrument. As this effect is predictable, it is possible to design the instrument to cater for this degradation making it possible for EM-CCDs to be very effective devices for the readout of high resolution 'soft' X-ray spectrometers.

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