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Electron multiplication CCDs for astronomical applications

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Abstract

Electron multiplication CCDs have been commercially available for the last few years but have yet to make a wider impact in the astronomical community. They have specifically been designed to use an avalanche gain process during the serial charge transfer process to give large signal gain. In all other respects they are identical to the very latest generation of CCDs. They have been used with great success in "lucky" imaging, for adaptive optics systems and also in high speed faint object spectroscopy science programs. Their sub-electron read noise makes them an obvious choice for any observation which is normally detector noise limited. I present a detailed summary of the typical performance and characteristics of these devices and compare and contrast them against standard low noise astronomical CCDs. I also present modeled and real data for these detectors with particular regard to some of their lesser known issues such as clock induced charge. Finally I present results from real world astronomical testing which shows the superior performance of these devices.

Keywords: CCD, electron multiplication, clock induced charge

1. Introduction

Conventional CCD detectors as used in the very best astronomical instruments are almost the perfect detector. However they still suffer from two main issues. They are slow to readout and they are detector readout noise limited, typically 3e- rms for the latest devices. These issues combine to make high speed astronomical spectroscopy and photometry of faint targets the most demanding of observations, whereby 'high speed' is meant on timescales down to hundredths of a second. It is possible to overcome the problem of slow frame speed by using small CCDs with multiple outputs, specialist architecture such as frame transfer and detector noise limited electronics and data acquisition systems. However reducing the readout noise in CCDs to negligible levels is more difficult since it is an inherent feature of the devices themselves. The development of electron multiplication devices (EMCCD) has come about specifically to address this read noise issue. These devices are in fact conventional CCDs, but with an additional extended serial register to which a gain structure has been added. This gain structure is similar to the standard serial shift register except that one of the three clocks is replaced with two electrodes. The first electrode is held at a fixed potential and the second is clocked as normal, except that a much higher clock voltage is applied, typically between 35V and 40V (c.f. 10V for standard CCD). The design of the fixed voltage electrode and the clocked electrode, and the relatively large voltage difference between them, results in an intense electric field that is sufficiently high for the transferring electrons to cause impact ionization through each single transfer in the multiplication register.

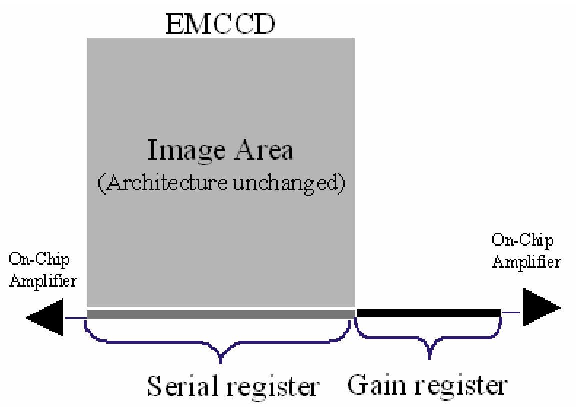

Figure 1 - typical EMCCD structure

A simple example of the architecture of a real EMCCD, shown in Figure 1, is used to highlight the extended gain register of the device. The probability of multiplication in this register is quite small for a single electron, of the order of 1% - 2% per transfer.. The probability of gain by impact ionization may be quite insignificant but when executed over a large number of transfers, a substantial gain is achieved. Typically an EMCCD will have approximately 600 stages to give huge possible gains to a single electron that has entered the first stage of the gain register. Avalanche multiplication has temperature dependence such that as the temperature increases then the lattice scattering increases which makes the impact ionization less probable because there is less likelihood of an electron colliding with the vibrating lattice. The avalanche gain is also adjustable by changing the upper clock voltage level. The fact that the gain is based on the probability of impact ionization producing more electrons means that there is variation in the gain process and therefore an extra source of noise called multiplication noise. A Monte Carlo analysis of the gain in an EMCCD has been performed[1] and the result of this is to show that in the shot noise regime of operation where the Poisson noise is expected to dominate then the use of the avalanche gain increases the expected noise by a factor of approximately √2 over a similar detector without the gain register. Another way of expressing this is to say that the additional multiplication noise due to the avalanche gain process is equivalent to a 50% drop in the detected quantum efficiency of the CCD.

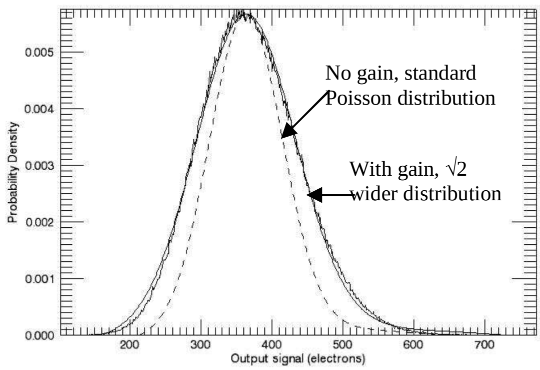

Figure 2 – Monte Carlo simulation showing effects of multiplication noise on signal distribution for EMCCD

This means that there is a real disadvantage in using a CCD with a gain register in the Poisson noise dominated regime since the noise is √2 worse than for a standard CCD. This result, as reported by others[2], shows that the avalanche process is not useful over the whole operating regime of a CCD detector. It only offers advantages when the CCD is in the read noise regime of operation, that is, where there is very a low signal level and the noise on the output stage of the CCD is then the dominant factor. However in the shot noise regime the avalanche gain can be switched off and the multiplication noise removed. The multiplication noise can also be minimized by operating the detector in a photon counting mode by using threshold detection.

2. Applications

EMCCDs can be used in any application which is photon starved. In astronomy they have found application in three areas: “Lucky imaging”, wave front sensing for adaptive optics and high speed spectrometry.

2.1. Lucky Imaging

The random motion of the atmospheric layers generates continuous disturbances of the diffraction patterns of the stars which causes variations in shape and position over very short timescales and limits the effective diffraction limit of all ground based telescopes. Lucky imaging uses very short exposures to sample this atmospheric instability. The very best images are then taken, that is, those minimally affected by the atmospheric turbulence and combined to produce images with resolutions approaching the theoretical limit of the telescope. This technique obviously requires very sensitive detectors, that is, those with very low readout noise and the fastest readout speeds and therefore is ideally suited to EMCCDs. Typically 1-10% of the images from a typical run of tens of thousands of images are used to produce the final result. The LuckyCam[3] produced at the University of Cambridge has been pivotal in promoting the use of EMCCDs in this application.

2.2. 2.2 Wave front sensing for adaptive optics

The present generation of 8 metre class telescopes and beyond depend on the ability of Adaptive Optics (AO) to provide excellent image quality and stability. This is achieved by sampling the incoming wave front error in real time and counteracting this by sending corrections to deformable mirrors.

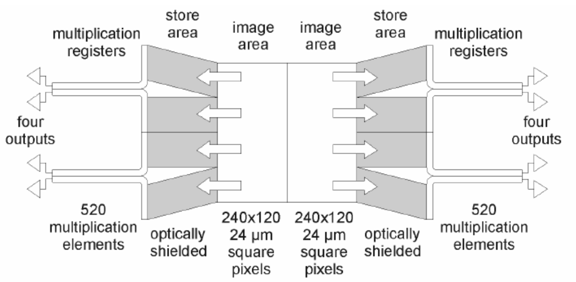

Figure 3 – CCD220 AO device from e2v

This requires a detector which has at least 240x240 pixels, a dark current rate of <<1e/pixel/second, readout noise of <<1e rms and can be run at frame rates in excess of 1 kHz. Such a device has recently been delivered by e2v Technologies to a European consortium funded by Opticon and ESO. The layout for this EMCCD is shown in Figure 3. It is a frame transfer device with 8 gain registers to give the required frame rate and also an avalanche gain of >>500. Testing of these devices has recently begun with a new camera system, OCam[4], which has been specifically developed to run at the high speeds, 220 Mbytes/s and be able to drive the highly capacitive electrode structure of the CCD at speeds greater than 10 M lines/s.

2.3. 2.3 High speed spectroscopy

EMCCDs have received much less attention for other astronomical applications. To address this problem, a consortium from the Universities of Sheffield, Warwick, the UK Astronomy Technology Centre and ESO, were awarded funding under OPTICON to investigate their use for high-speed spectroscopy. The resulting camera that has been developed is called ULTRASPEC. At the heart of ULTRASPEC is an EMCCD, the e2v Technologies' CCD201-20 device, which has an imaging area of 1024 × 1024 pixels.

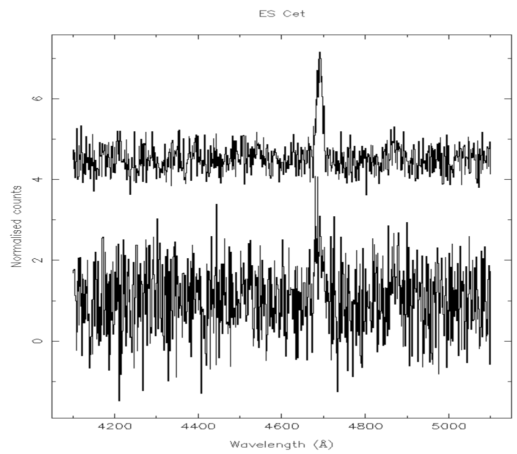

Figure 4 - ULTRASPEC spectra of the star ES Cet. Top: A 10-second spectrum using the avalanche output of ULTRASPEC. Bottom: A 10-second spectrum taken using the normal output of ULTRASPEC.

The CCD201 is also a frame transfer device, thereby offering high frame rates with negligible dead time, as well as essentially zero readout noise through the electron multiplication process as described.

ULTRASPEC has been mounted on the EFOSC2 instrument at the ESO 3.6 metre telescope in La Silla. Figure 4 shows ULTRASPEC spectra of the star ES Cet. The top plot is a 10 second spectrum using the avalanche output of ULTRASPEC. The bottom plot is a 10 second spectrum taken using the normal output of ULTRASPEC. The latter is identical to what would be obtained using a conventional CCD. The gain in signal-to-noise is approximately a factor of 3, turning the ESO 3.6m into the equivalent of a 6.3m telescope.

3. EMCCD Performance

Much has been reported elsewhere on modeled performance of these detector types[1,5]. For high speed astronomical spectrometry in the photon counting regime, clock induced charge (CIC) can be a major issue since it can reduce the signal to noise performance of an EMCCD compared to an ideal shot noise limited detector.

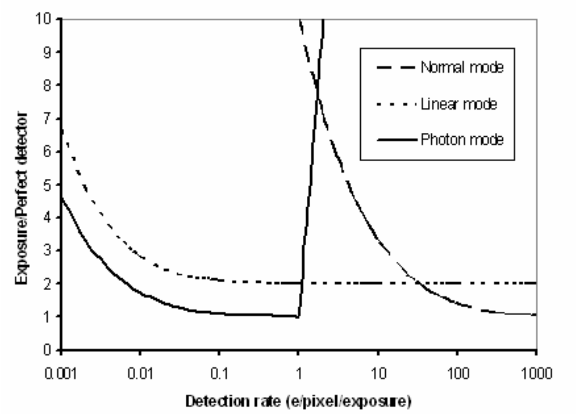

Figure 5 – Efficiency of EMCCD versus an ideal detector for different read out modes

The clock induced charge takes the form of electrons randomly distributed throughout the CCD which are typically generated by the CCD clocks during the readout process. Similar to dark generated events they are indistinguishable from true signal events and so constitute a faint background with associated noise. A simple way to emphasise the importance of reducing the CIC rate is to plot the exposure time required for an EMCCD to give the same performance as an ideal detector limited only by the photon shot noise on the received signal. This plot is shown in Figure 5 for a case where the avalanche gain is set to 1000, the readout noise is 10 e- rms and the CIC rate is 0.02 electron/pixel/frame. There are three regions in this plot. The “normal” region is for a standard CCD, the main sources of noise are the photon shot noise for high signal levels and the read out noise for lower signal levels. The next region is the “linear” mode of operation, where the avalanche gain is used to minimise the read out noise, but the CIC is also included together with the effective loss in quantum efficiency due to the probability distribution of the avalanche gain process. The final mode is the “photon” mode where a “thresholding” algorithm is used to implement photon counting. Obviously this mode can only be used for signal rates of much less than 1 electron/pixel/exposure as significant coincidence losses will kick in well below this mean count rate.

The CCD201 device is the largest EMCCD device available. However it is still too small to sample the available spectrum from most astronomical spectrographs. The author is looking to fund a larger 4kx2k pixel device. There is also a need to reduce the clock induced charge further to get the absolute best from these devices. However, real world results have shown these detector types to be well suited to the low noise and low signal astronomical regimes.

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