Electron Multiplying CCDs

P.A.Jerram, P. J. Pool, D. J. Burt, R. T. Bell, M.S.Robbins
e2v technologies ltd, 106, Waterhouse Lane, Chelmsford, Essex, UK CM1 2QU

Electron multiplying CCD (EMCCD) technology has found important initial applications in low light surveillance and photon starved scientific instrumentation. This paper provides a description of the technology and discusses the attributes of the EMCCD which may make it useful for other detectors, particularly those which are photon starved

1. INTRODUCTION

The electron multiplying charge coupled device (EMCCD), such as the e2v L3CCD, uses impact ionization in silicon to provide gain in the charge domain [1]. This enables performance with an input equivalent noise of less than 1 rms electron at pixel rates up to and beyond those required for TV imaging applications. The structure and mode of operation of the EMCCD is well known [2,3] and so only an overview will be given here.

Since EMCCDs were first produced at e2v technologies in the late 1990s they have found use in many applications where either the signal level is very low or where high frame rate imaging is required. These include surveillance, astronomy (in Lucky Imaging [3] and as a wave-front sensor) for LIDAR and in other scientific imaging applications including very low level bioluminescence for drug discovery and genetic engineering applications. A number of these application will be descried briefly later in this paper.

2. PRINCIPLE OF EMCCD OPERATION

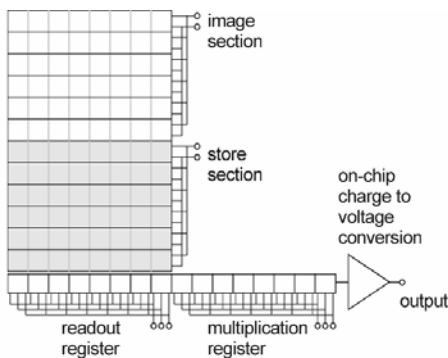The architecture of the EMCCD is shown in figure 1.

Figure1: EMCCD Schematic

The image, store and read-out register are of conventional design. An extended section of multiplication register is placed between the normal serial register and the charge to voltage conversion circuitry. Each section of the multiplication register comprises four gates, three of which are clocked. This is shown schematically in figure 2.
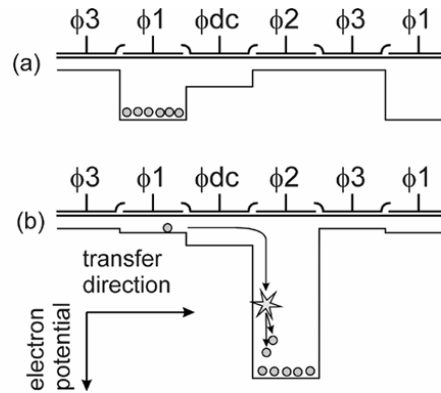

Figure 2: Charge transfer through a multiplication element

Two of the gates (Ø1 and Ø3) are clocked with normal amplitude drive pulses (~10V) and the same pulses can be applied to both sections of the readout register. The pulses applied to Ø2 of the multiplication register have a higher amplitude, typically 40-45V. A gate is placed prior to Ø2, which is held at a low dc voltage. The potential difference between the dc gate and the high level of Ø2 can be set sufficiently high so that signal electrons can undergo impact ionization processes as they are transferred from Ø1 to Ø2 during the normal clocking sequence. Thus the number of electrons in the charge packet increases as it passes through a multiplication element. Although the probability of impact ionization and thus the mean gain per stage, *g* is very low, the number of stages, N can be high. The total gain of the cascaded multiplication elements is given by $M = g^N$. For 600 elements a gain of 1.5% per stage will give a total gain in the charge domain of over 7,500.

3. PERFORMANCE REQUIREMENTS

3.1. Noise

Robbins and Hadwen [4] have shown that the multiplication process increases the input referred noise by a factor $\sqrt{2}$ above the ideal input shot noise level (sometimes interpreted as an effective halving of quantum efficiency).

The noise referred to the image area, σ_{eff} , is given by:

$$\sigma_{eff} = \sqrt{\left(F^2 \left(S + S_{dark} \right) + \frac{\sigma_{readout}^2}{M^2} \right)} \ .$$

Where $\sigma_{readout}$ is the readout noise, S is the signal, S_{dark} is the dark signal. M is the multiplication gain and F is the noise factor.

It can be seen that setting the multiplication gain to a sufficiently high value virtually eliminates the effect of readout noise. Although the readout noise increases as a function of frame rate as in a conventional CCD the multiplication gain is independent of readout rate and so the gain can be set sufficiently high to ensure that readout noise is still eliminated at very high frame rates.

If the signal level is sufficiently low the single electrons may be detected, however it must be borne in mind that the gain statistics of a multiplication register do not allow the unambiguous discrimination between integral numbers of input electrons (i.e. by means of measuring signal levels at the output), so photon counting is only possible when the event density is low enough to be confident that all events can be counted as single electrons [5, 6] and the gain is high enough to discriminate the full range of consequent output signals from read noise. If conditions allow operation in a photon counting regime, the excess noise referred to above is, of course, eliminated.

3.2. Dark noise

As can be seen from the formula above if the gain is sufficiently high the remaining noise sources are noise on the dark signal S_{dark} and noise on the signal, S. Thus it is clear that devices should be operated under conditions in which the dark charge/pixel does not contribute significantly to the noise. Dark charge can result from thermal generation and also from the clocking process, as clock induced charge (CIC).

In low signal scientific applications it is preferable, if possible, to control dark current generation rate by appropriate cooling of the device. Fig 3 shows that suitably low rates can be achieved. The alternative is to use multi phase pinned (MPP) operation to neutralize surface dark current, which allows operation at higher temperature. This is advantageous for some applications but results in significant hole multiplication during charge transfer and higher temperature-independent CIC. Since the charge magnitude increases exponentially with the clock amplitude, operation with the lowest-possible clock levels is necessary to minimize this contribution.
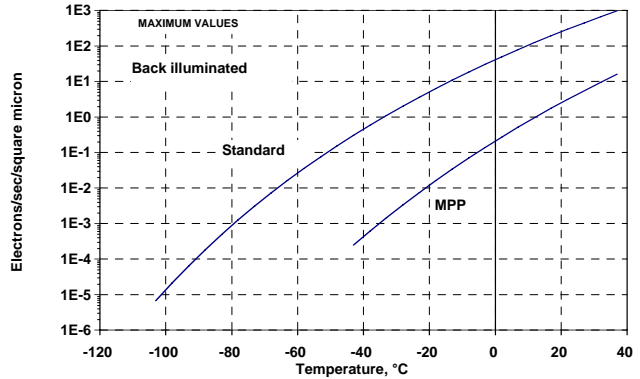

Figure 3: Dark signal in e2v CCDs

Note that, if using the device with MPP operation, as a gate is taken high (out of pinning) during transfer, holes are released from surface traps with a characteristic, temperature dependant, time constant. These holes are subject to multiplication as they release, so lowest CIC is observed with fast clocking which minimizes the clock high time [7].

3.3. Quantum efficiency

To make best use of the low read noise, EMCCDs benefit from the high quantum efficiency (QE) available from back-illumination. Choice of an appropriate process can provide useful QE anywhere in the wavelength range 1 Å to 1 μm. Figures 4 shows typical QE from backthinned CCDs with and without anti-reflection (AR) coating.
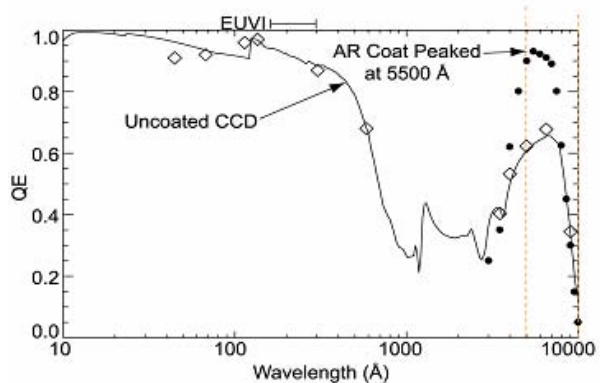

Figure 4: Typical QE curves

3.4. Linearity

Provided the output circuit is not saturated, EMCCD gain registers have been shown to be linear to 3% up to ~75% of register capacity [8]. Such performance requires the high voltage gate to be operated with a flat-topped pulse, rather than a sinusoidal pulse, which is often used in surveillance applications, where control of power dissipation is more important than linearity

4. EXAMPLE APPLICATIONS

4.1. Surveillance

With its variable gain and resistance to overload the EMCCD is ideal for surveillance and most of the first designs have been intended for surveillance. When compared to conventional technology using an image intensifier coupled to a CCD the EMCCD gives significantly improved performance at high light levels as the extra gain is turned off and the device is operated as a standard CCD, whereas the image intensifier performance at high light levels is relatively poor.

At the lowest light levels the EMCCD still gives superior performance because the higher inherent quantum efficiency of silicon as compared to GaAs. EMCCDs provide usable images under overcast starlight conditions with less than one electron per pixel per frame where all alternative technologies fail to give useful images.

4.2. LIDAR [9,10]

Laser power available for LIDAR (LIght Detection And Ranging) applications is limited by available power and, more importantly, by eye safety considerations. In addition, the atmospheric backscatter coefficient is low and the diameter of the telescope limited, so the returning photon flux is very low and also needs to be sampled at high frequency to achieve depth resolution. These requirements combine to give an expected signal in the range 1 to 4,000 photons/μsec in the sampling window. For this application a single pixel CCD is being designed that will operate at up to 3MHz, which can be implemented with a scientific, low noise output circuit, so requires only moderate multiplication gain (~x80) to discriminate the signal to an adequate level. The high sampling rate from a small area of silicon results in very little dark current in each sample. In combination with the moderate gain, this allows the sensor to be operated at around 0 -10°C.

4.3. Adaptive optics [11,12]

CCDs have been used for adaptive optics for astronomy for many years. Adaptive optics requires a combination of very high frame rates and low noise. Hence sensors for this application have relatively small image areas and a large number of outputs. For example e2v's CCD50 has

16 separate outputs and an image format of only 128 x 128 pixels. This enables operation at frame rates of over 500Hz with a readout noise of approximately 6 electrons. EMCCD technology is being used to design an adaptive optics CCD for ESO (the European Southern Observatory) with an increased image area of 240 x 240 pixels that will operate at over 1kHz with 8 outputs with less than one electron of read noise. Figure 5 shows a schematic image of this CCD.
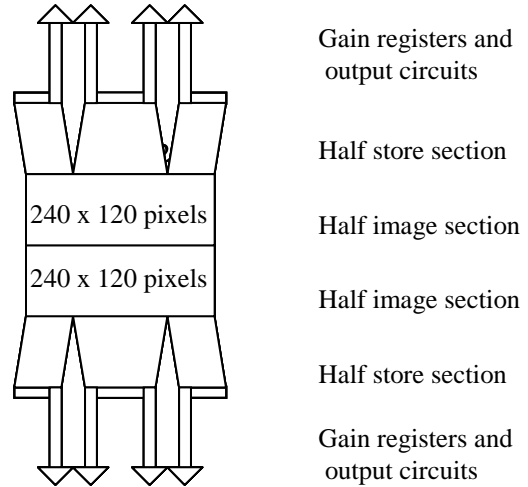

Figure 5: Adaptive optics EMCCD

4.4. Ground scanning

EMCCDs have been considered for ground scanning applications. However, the usual ground image has a high background signal with a small, superimposed, modulation. Reference to Fig 6 shows that, for such signals, the EMCCD excess noise, referred to in the introduction, would degrade the performance below that of a conventional output.
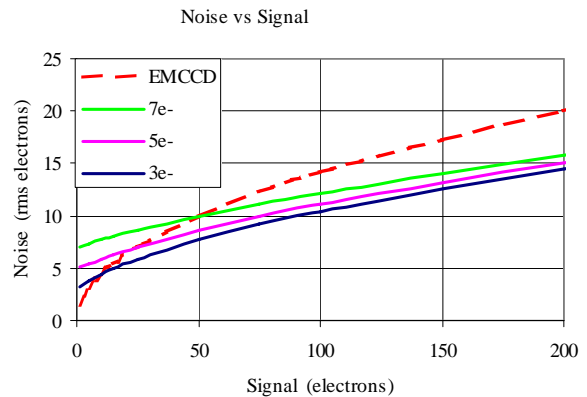

Figure 6: Noise as a function of signal

The main reason that EMCCD is unsuitable for ground scanning is that such instruments are normally operated over a sun-illuminated scene. If there were requirements to ground scan the dark side of the planet, an EMCCD solution would clearly be beneficial.

5. OTHER POTENTIAL DETECTOR APPLICATIONS

5.1. Particle and Synchrotron radiation detection

5.1.1. Indirect detection

Indirect detection typically consists of detecting the light output from scintillating fibres. Detectors used are either photodiodes or photomultiplier tubes (PMTs), when the signal level is low. For these low signal applications the EMCCD would give very significant advantages in detection efficiency and system complexity and cost as compared to PMTs.

For applications where a relatively low frame rate can be used a number of fibres could be bundled together onto an EMCCD operating at a standard frame rate of 50Hz. For higher detection rates an adaptive optics device could be used at up to 1kHz or for very high frame rates a LIDAR EMCCD would allow detection at up to 3MHz. Several LIDAR devices could be fabricated monolithically to provide a well-defined pitch for coupling of the ends of the optical fibres.

5.1.2. Direct detection

CCDs have been used for direct particle detection for example the VXD2 and VXD3 vertex detectors at SLAC. However in general for direct detection the signal level is relatively high and so the electron multiplying output is not expected to give significant advantages over a conventional CCD.

One of the main requirements for direct detection is radiation hardness. It has been shown [13,14,15] that the addition of the multiplication register in the EMCCD has no effect of the radiation hardness of the device. Hence if there are applications where an EMCCD would give advantages it could be used in the same environments as a conventional CCD.

5.2. Astronomy and Space instrumentation

Apart from the lack of atmospheric distortion, astronomical imaging from space is performed against a very low background, compared with that presented by sky glow, which can appear as around 21st magnitude/arcsec at a good terrestrial site. Though useful for spectroscopy, lucky imaging and adaptive optics, the presence of sky glow limits the application of EMCCD in ground-based imaging astronomy. The very low background in space raises the possibility of imaging very

faint objects. In addition, such objects may be imaged in the presence of much brighter objects by operating the imager at high frame rate and integrating a wide dynamic range image in a frame store. In this case, photon flux from the faintest objects may be low enough to assume that all events are single photons, giving best possible signal/noise ratio.

Applications have been proposed in which the projected photon flux from discrete objects would be ~10^{-4} photons/pixel/sec. Such requirements raise interesting questions. Operation at low temperature and with low clock swing should ensure that signal electrons are not lost in dark signal and CIC, and cosmic ray events can be discriminated by the magnitude of deposited charge. However, there's going to be a growing problem of how to understand the signal since, in the steady state, the average signal will equal the input signal, but we have no way of knowing which electrons have been cycled through traps and therefore lost their spatial/temporal identity. In space, after the collection of proton damage, the device will accumulate an increasing number of single electron traps, which will further complicate the analysis. Further analysis of the dynamics of single electron trapping is essential, leading to recommendations for an optimum operating regime. Only then do we have a chance of predicting the lower limits of object intensity that can be imaged with such devices.

6. ACKNOWLEDGMENTS

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