Application of electron multiplying CCD technology in space instrumentation.

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ABSTRACT

Electron multiplying CCD (EMCCD) technology has found important initial applications in low light surveillance and photon starved scientific instrumentation. This paper discusses the attributes of the EMCCD which make it useful for certain space instruments, particularly those which are photon starved, and explores likely risks from the radiation expected in such instruments.

Keywords: EMCCD, space, read noise, radiation

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, so will not be described here. Robbins and Hadwen[2] 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). It must also 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[3,4] 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.

Such devices are now available in back illuminated format, for optimum QE which, combined with their ultra-low noise, high resolution, and robustness to over exposure make them ideally suited to applications traditionally served by image intensifiers. Clearly, such devices find uses in defense, but there are also a number of scientific applications, particularly where photon density/frame is low.

One such novel use, lucky imaging[5], has been demonstrated, in which ground based images have been produced with a resolution similar to that obtained from the Hubble Space Telescope. The high frame rate, low noise capability is also being used to advantage in adaptive optics[6,7]. The ability to perceive very low level bioluminescence is of growing importance in drug discovery and genetic engineering applications, and low light imaging enables X-ray dose reduction in radiography[8].

In this paper, we explore applications that are peculiar to space, and the ability of the EMCCD to operate in the space environment.

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2. PERFORMANCE REQUIREMENTS

Figure 1

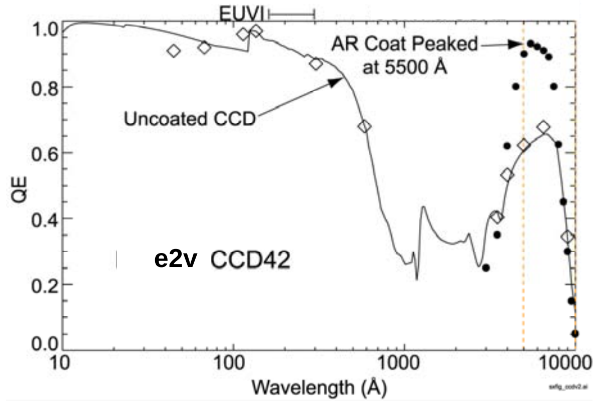
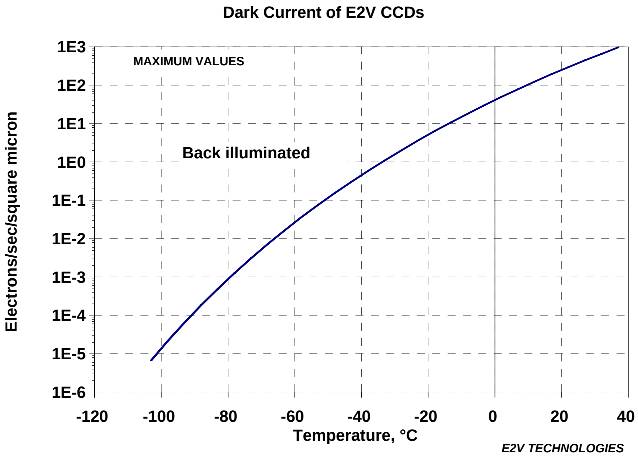


Figure 2



2.1 Quantum efficiency

To make best use of the low read noise, EMCCDs benefit from the high quantum efficiency (QE) available from back illumination (Fig 1). Choice of an appropriate process can promote useful QE anywhere in the wavelength range 1 Å to 1 µm.

2.2 Dark noise

In addition, they 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 2 shows that suitably low rates can be achieved. The alternative of using multi phase pinned (MPP) operation to neutralize surface dark current 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.

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[9].

2.3 Linearity

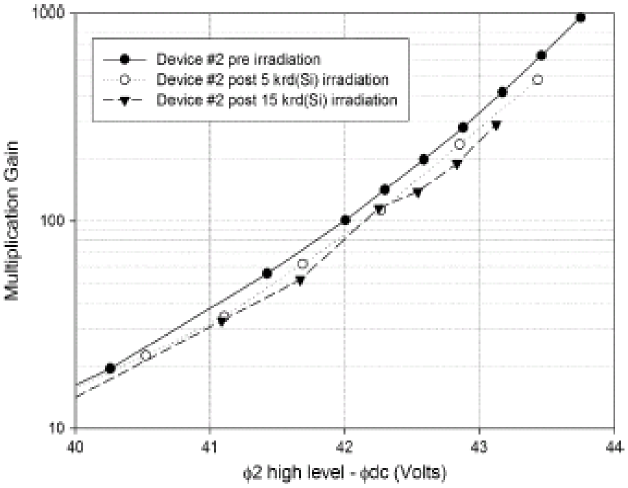
Provided the output circuit is not saturated, EMCCD gain registers have been shown to be linear to 3% up to ~75% of register capacity[10]. Such performance requires the high voltage gate to be operated with a flat-topped pulse, rather than a sinusoidal pulse, which is often used in surveillance applications, where control of power dissipation is more important than linearity

3. RADIATION EFFECTS

The effects of radiation damage on device performance is particularly important for space use, since performance can be degraded with few opportunities for reactive compensation. The nature of the damage from ionizing radiation is quite different from that caused by protons or, for deep space missions, neutrons from a nuclear thermal generator.

3.1 Ionizing radiation

Figure 3



The principal effects observed from exposure of CCDs to ionizing radiation are an increase in fixed, positive, charge within the gate dielectric and an increase in the density of mid-band energy states at the interface between the silicon and that dielectric. The former appears as a fixed offset in gate bias (often referred to as a threshold shift) and the latter as an increase in the surface component of dark current. A practical evaluation of the effects of ionizing radiation on EMCCDs[11] has shown that, when irradiated, up to 15kRad, with the CCD biased to simulate normal operation, threshold shifts and increases in dark current generation rates are consistent with those previously demonstrated for e2v CCDs. The relationship between multiplication gain and the difference between the high level of the high voltage clock and the voltage of the DC phase may be expected to be effected only by the difference in threshold shift between the two gates. Measurement confirmed this expectation with a very small change in gain characteristic (Fig 3).

The conclusion is, therefore, that the gain mechanism in an EMCCD is not significantly affected by the levels of ionizing radiation likely to be encountered in the majority of space missions. However, as noted above, to benefit from the low effective read noise of an EMCCD, greater attention is needed to control thermal and spurious charge generation resulting from ionizing radiation.

3.2 Proton radiation

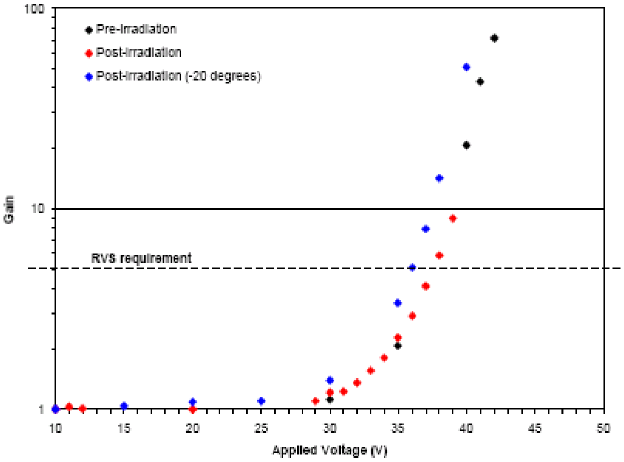
When a proton is incident on a silicon device, energy is lost along the track of the particle, mostly by ionization but also by displacement of atoms from the lattice, particularly as the particle comes to rest. Vacancies produced by the displacement can then diffuse from the point of generation and eventually combine with phosphorous atoms in the buried channel of a CCD to create phosphorous-vacancy complexes (the so-called e-center) and the e-center produces a near-mid-band energy state which is responsible for the majority of the loss of charge transfer efficiency resulting from such proton irradiation. Vacancies and interstitials can also generate other trapping states, discussion of which are beyond the scope of this paper. Similar effects are expected from neutron irradiation, which may be acquired in a deep space mission, from the use of a nuclear thermal generator.

The possibility has been considered of another proton irradiation effect, peculiar to an EMCCD multiplication register. A necessary condition for multiplication is a very high field, which is produced in the silicon by the voltage difference between the dc gate and the high voltage gate. Concern has been expressed that proton damage in this region could produce a damage site which would inject charge when subjected to such a field. Such injection may be at a low level, but if this occurs near the input end of the gain register, it would be subject to a gain factor in the region of 1,000 and become significant, even catastrophic.

There is no pre-existing knowledge of such an injection site, but the possibility exists that it could only be observed within a gain register, which has the combination of very high field and charge multiplication. Before recommending EMCCDs for space use, it was deemed necessary to collect the data needed to be able to assess the risk of such a defect occurring in a particular space mission. If the risk were shown to be unacceptable, mitigation strategies, such as the provision of redundant gain registers, could be considered.

The high field is localized in a very small volume of silicon, so the probability of a defect occurring in that volume is small. There is a limit to the level of proton irradiation to which a particular CCD can be subjected and still remain in a state to provide useful measurements. It has been necessary, therefore, to irradiate a large number of EMCCDs in order to give useful data on likely risk[12,13]. This work has been pursued at the e2v Centre for Electronic Imaging (CEI) in a

Figure 4



programme of work in which 94 e2v CCD97 devices have been irradiated to a 10MeV equivalent fluence of 2 x 10^{10} protons cm^{-2}. This is in addition to 20 such devices previously irradiated to the same level. None of these devices displayed the failure mode we were seeking and their gain characteristics remained unchanged (Fig. 4).

Analysis indicates that silicon displacements occur at ~0.01 displacements/proton/µm of track length, 98% of which re-combine, leaving an estimated 2E-4 damage sites/proton/µm. The volume of silicon in which the field is above a critical level is not clear, but we have assumed a depth of 0.5µm over a nominal area of $20µm^2$/gain element. We conclude, therefore, that the applied proton flux of $2E10/cm^2$ produced damage sites in high field regions at the rate of ~0.4/gain element. With ~500 gain elements/ CCD and ~100 CCDs, we may expect ~20,000 damage sites to have been created in the vicinity of high field regions, and ~2000 within the first 10% of the gain register, where their presence would be more obvious. This estimate is, of course, subject to great error, but even an error of a factor of 100 would leave an expectation of many observed defects, if they exist.

All devices exhibited the expected increase in dark current and bright pixel population as a result of radiation damage. The increase in dark current as a result of radiation damage reduced the level of gain that could be reached before the onset of register saturation, so the measurements were repeated at –20°C to allow comparison over the full range. The –20°C characteristic shows the same shape, but shifted to a lower voltage due to the increased electron mobility at reduced temperature, as is expected from measurements in un-irradiated devices.

This work is raising confidence that EMCCDs can be used in space with a low risk of catastrophic failure. It is considered significant that 94 devices, irradiated with a 10 MeV equivalent fluence of 2×10^{10} protons cm^{-2}, is equivalent to testing ~5 complete Radial Velocity Spectrometer (RVS) focal planes to the expected end of life Gaia[14] mission fluence (see below).

4. POTENTIAL SPACE APPLICATIONS

4.1 LIDAR[15,16]

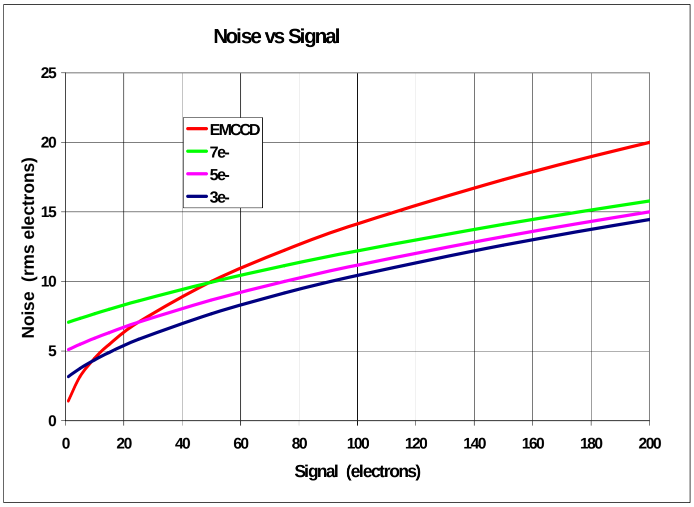
Laser power available for LIDAR applications is limited by available power on the spacecraft and, more importantly, by eye safety considerations for a laser pointing towards Earth. In addition, the atmospheric backscatter coefficient is low and the diameter of the telescope limited, so the returning 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. This is expected to be sampled at 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.

4.2 Gaia-RVS[17,18]

The Radial Velocity Spectrometer (RVS) instrument on Gaia seeks to measure radial velocity of stars down to at least 17th magnitude. To measure Doppler shift in the calcium lines, the star image is dispersed and the dispersion truncating in the spectral range 850 -875 nm. By virtue of the fixed exposure time (set by the *Gaia* scan rate) and modest Spectro telescope aperture, the RVS is a photon-starved instrument. At its limiting magnitude, where much of the RVS science will be performed, each CCD in the focal plane records on average less than one photon per pixel. Only after all focal plane transits are added, and after a cross-correlation is performed to extract the radial velocity, is the required performance attained. It is imperative therefore that signal levels are maximized throughout the system, and that internal noise levels are minimised, so an EMCCD solution is being considered. To maintain the best possible charge transfer efficiency after radiation, the focal plane will be operated at -100°C, which also effectively suppresses thermal charge generation. In this case, pixel rate is low (~130kHz), so conventional read noise will be <5 electrons rms, so the required multiplication gain needed is <10.

To achieve high QE in the region of 850nm, CCDs are often made in high resistivity, deep depletion silicon. The use of lightly doped silicon reduces the field in the silicon, reducing the probability of multiplication gain, so process modifications are being introduced to compensate.

Figure 5



4.3 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 5 shows that, for such signals, the EMCCD excess noise, referred to in the introduction, would degrade the performance below that of a conventional output.

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.

4.4 Other applications

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.

5. SUMMARY AND CONCLUSIONS

The capabilities of the EMCCD have been discussed with reference to space application. Reference to a small number of space applications currently being considered indicate that there is a class of instrument in which the EMCCD could produce scientific data not achievable by any other known technology. Concern has been expressed over possible radiation-induced degradation specific to the EMCCD, but experimental evidence has been presented which has been unable to demonstrate radiation effects not seen in standard CCDs. Further work is needed to improve our understanding of the dynamics of single electron trapping in the context of very sparse signal applications.

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