CCD Design Optimisation for Space Applications

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Abstract *The design of CCDs for scientific and particularly space applications has followed a significantly different course to the design for consumer applications. In general, for consumer applications of both CCD and CMOS sensors, the drive has been mainly towards smaller pixel size and lower operating voltages, giving reduced power consumption.*

For space imaging, most applications prefer a larger pixel size (no smaller than 8µm) and improvements have been focussed on enhancing radiation hardness, ensuring high reliability and on optimising the fundamental performance parameters such as quantum efficiency (QE), noise and spatial resolution or modulation transfer function (MTF).

This paper will show how both the design and fabrication of the CCD at e2v technologies have been optimised to meet the particular requirements of space-based imaging and what further advances are likely to be seen in the near future.

I. INTRODUCTION

CCDs for space applications have been provided by a limited number of small-scale fabrication facilities, where unique processes have been developed to meet the demands for this environment. Examples of the device optimisation are now discussed.

II. RADIATION HARDNESS

Radiation damage in semiconductor devices is a very broad topic that cannot be covered in detail here, however some of the basic principles of designing and processing devices for radiation environments are discussed. Radiation can affect a CCD in four main ways; it causes an increase in the background dark signal, the introduction of localised random telegraph signals (RTS), a change in the threshold voltage and a reduction in the charge transfer efficiency. In general ionising radiation causes the increase in dark signal and threshold shift, whereas high-energy particles cause lattice displacement damage which produces trapping centres leading to degradation of the charge transfer efficiency (CTE) and RTS effects. Different design and process approaches are required to mitigate for each of these effects, as now described.

Post radiation dark signal increase

The increase in dark signal is primarily a surface effect and is due to "reverse annealing". At a late stage in the device processing, a low-temperature hydrogen anneal is a performed for "passivation" purposes. This causes hydrogen atoms to be attached to the "dangling" silicon bonds at the Si-SiO_2 interface that are present through lattice mismatch and results in a considerable reduction in the surface component of the dark signal. However, ionising radiation releases free protons from the gate oxide and these can diffuse to the interface to combine with the surface hydrogen releasing H_2. The overall effect is to reverse the passivation, with a consequent increase in the dark signal. There are several ways in which the effect can be minimised:

- Devices with thinner gate oxide will release less hydrogen under radiation.
- LOCOS structures with very thick local oxide layers must be avoided in designs intended for environments with a high radiation level.

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- The use of pinning or surface inversion suppresses the surface component of dark signal (and any radiation-induced increase), but at the expense of decreasing the depletion depth and hence reducing the spatial resolution. Thus, if a pinned structure is not appropriate and a long integration time is required, the only solution is by temperature reduction. The dark signal is generated by mid-band traps and the value I_D at any temperature T (K) may be estimated from:

  $I_D = I_{DO} \times 122T^3 \exp(-6400/T)$.

  Where I_{DO} is the dark signal at +20°C.

- Other design details are also critical to minimise dark signal increase. For example, the peripheral regions of the device generally use thicker oxide to minimise parasitic capacitance and care must be taken to ensure that the resulting high levels of dark signal are prevented from reaching the active pixels by the use of dummy columns and drains. The precise location and size of the nitride apertures through which hydrogen accesses the Si-SiO_2 interface is also critical.

Random Telegraph Signal

It is commonly found that the trapping centres arising from bulk displacement damage can have a bi-stable energy level, with the result that the dark signal for any affected pixel switches randomly between two levels (or more levels if more than one trap is involved). These random telegraph signal (RTS) defects are seen in CCD and CMOS sensors and have been studied by several groups, for example [1]. The temporal fluctuations in dark signal are likely caused by two level or multi level defects created by non-ionising collisions. Detailed microscopic models for the process have yet to be developed but it has been suggested that the defects are due to vacancy related defect clusters. Since the RTS effects studied in [1] were very similar for CCD and CMOS, leads to the possibility of predicting their generation.

Although RTS defects are now better understood, it is not yet known how to design devices to minimise their impact, the only mitigation currently available being a reduction in the operating temperature, which reduces both the defect level and the frequency at which it changes state.

Threshold Shift

Ionising radiation causes the generation of electron-hole pairs in the gate oxide. In the case of an oxide-only dielectric the electrons are mobile and can exit via the gate polysilicon or the underlying silicon. The holes are less mobile and appear not to be able to exit via the silicon. Thus, under positive gate bias the holes accumulate near the Si-SiO_2 interface and the charge build-up causes a shift in the threshold voltage. Under negative bias the holes reach the gate polysilicon and being far from the Si-SiO_2 interface now have little effect. In the case of oxide-nitride dielectric commonly used to fabricate multi-polysilicon CCDs, holes still accumulate near the Si-SiO_2 interface under negative bias, but become trapped at the oxide-nitride interface under positive bias and the charge build-up again causes a shift in the threshold voltage.

Any shift of threshold voltage requires adjustments to be made to the operating voltages if performance is to be unaffected.

The use of oxide-only dielectrics is attractive for devices with only negatively biased gates, e.g. those with only buried channel structures. The advantages are however somewhat outweighed by the problems of achieving the same thickness of oxide under different levels of polysilicon and oxide-nitride dielectrics are preferred. Minimising the threshold shift is then mainly achieved by reduction of the thickness of just the oxide part. For scientific CCDs this has typically been 50-100 nm, with the result that the increase of dark current and the threshold shift both become intolerably high once the ionising dose reaches about 10 kRads. The solution has been to develop a process with significantly thinner oxide, and devices can now be successfully operated after doses of up to 1MRad. (Note that CMOS sensors are little affected by threshold shifts because the gate oxides are very thin). Results from radiation testing of a recent radiation hard e2v CCD47-20 at a dose of up to 150 kRads at are shown in figure 1:

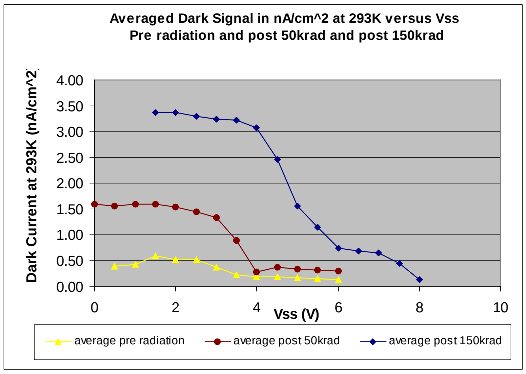

Figure 1: Radiation Test Data

CTE degradation

The lattice displacement damage caused by high-energy protons or neutrons introduces trapping sites, e.g. PV centre, which have an adverse affect on the CTE. The impact of these centres can be particularly severe in large area CCDs because the charge has to travel significant distances before the detection node and so can encounter many such traps. The level of charge trapping is nevertheless relatively small and the resulting CTE degradation is only significant for small signal and/or very high accuracy applications. In environments with a high background signal (for example earth observation) the traps tend to be permanently filled and the effect on CTE is small. If significant, there are a number of actions that can be taken in the device design, processing and operation to reduce the impact of displacement damage.

- The total charge lost from a charge packet is approximately constant and so the impact is much more severe at low signal levels. If the area of a device in which the charge is stored is reduced, then the number of traps that the charge packet will encounter as it travels through the device will be minimised. One method that has been used to implement this in devices having large pixels, is the use of supplementary channels or "notches" which confine small charge packets to the centre of the transfer channel, as shown in figure 2:

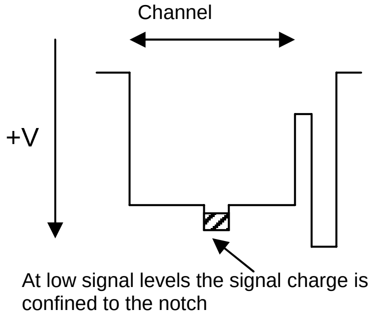

Figure 2: Potential cross section through a pixel with a notch

- The time constant for releasing charge from a trap increases as the temperature is lowered. This may be taken advantage of in two ways. Firstly, if the application has some small background signal then at lower temperatures most traps will be permanently filled and so the reduction in CTE is significantly reduced. If there is no background signal then, with an appropriate input structure, lines of charges may be injected at the top of the device and transferred down to fill all of the traps as they pass. Care must be taken to ensure that the time between injected charge packets is appropriate for the operating temperature used.

  Charge injection structures have been used in several devices, an example being the CCD43 supplied to Ball Aerospace for the WFC3 camera on the Hubble space telescope that will be used in May 2009 to replace the WFPC2 camera, using Loral CCDs

- An alternative method of device fabrication is to produce p-channel CCDs with holes as signal, rather than the more usual n-channel with electrons. The advantage of p-channel is that the density of the traps arising from lattice displacement damage is about a factor 3 to 4 lower. Such p-channel CCDs are relatively new, but do provide a significant advantage in environments where the proton radiation levels are exceptionally high.

While the effects of proton damage can be significant, appropriate choice of design and operating conditions can produce excellent results. For example XMM-Newton (an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA) has been producing low energy X-ray images and spectroscopy data for over 9 years and recently had a further life extension. This is one of the most challenging applications with respect to CTE degradation as the charge packets generated are very small and are required to be measured accurately to produce reliable spectroscopy data. As can be seen from the data below [2] the energy resolution of the EPIC-MOS CCDs on XMM has remained almost unchanged. Note that the step change in 2003 was due to a lowering of the operating temperature, which means that trapping sites are filled more effectively.

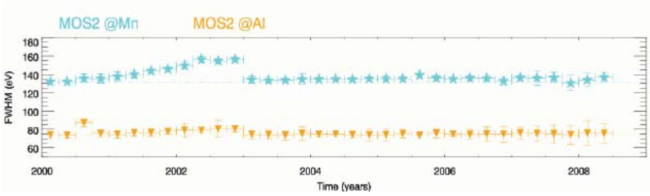

Figure 3: Energy resolution of EPIC cameras on XMM over nine years [2].

III. DETECTION EFFICIENCY

For the majority of the 100 plus space projects with which e2v has been involved, the most critical parameter is the detection efficiency. In general the cost of putting an instrument in space is large and so it is critical that every photon that enters the instrument can contribute to the output signal.

The most critical parameter is quantum efficiency (QE) and the majority of devices used in space are back-thinned in order to maximise this parameter. The exception is devices for ground scanning applications, which are discussed later in this paper. A typical QE curve from a device provided for GAIA is sown below optimised for visible response [3]

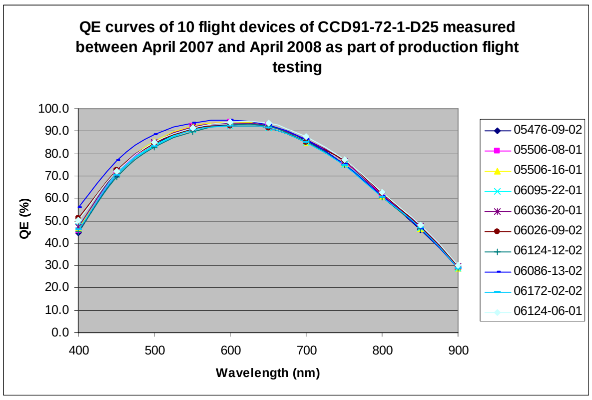

Figure 4: typical QE Curves for GAIA

Recent developments have focussed on increasing the QE in the NIR region of the spectrum. This is of particular interest for astronomers as the oldest galaxies have the largest red-shift. As silicon becomes rapidly more transparent at wavelengths approaching 1100nm, QE can only be increased by the use of a thicker active layer, but this must be fully-depleted to maintain the spatial resolution. This has been achieved up to about 50 µm thickness by e2v using high resistivity epitaxial silicon. More recently CCDs have been made on bulk silicon) with a separate back-surface bias (designated Hi-Rho) that can achieve over 300 µm of active thickness with good resolution [4,5].

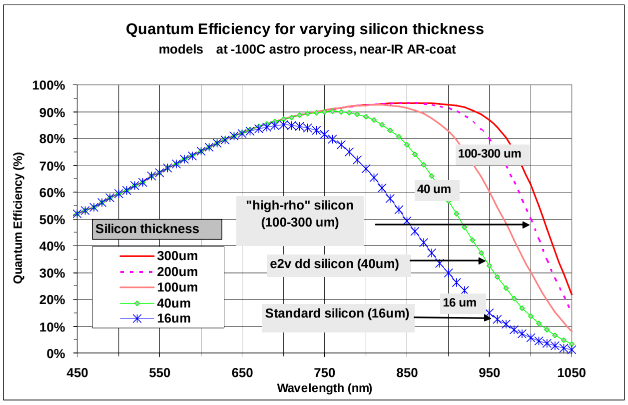

Figure 5: Hi-Rho QE curve

For maximum sensitivity, in addition to maximising signal, the noise must be minimised. In general the higher the output responsivity (in volts per electron), the lower the noise. At low frame rates CCDs can achieve exceptionally low output noise levels with 2e equivalent signal being routinely achieved.

Where very high pixel rates are required in combination with extremely low noise, the now well-proven electron multiplied (EM) CCD is starting to be considered for use in space applications. Initially there were concerns on the impact of radiation damage on the multiplication register. However, extensive proton radiation testing has now shown that this should not be a significant concern [6]. An EMCCD LIDAR (Light Detection and Ranging) device has been demonstrated [7] achieving a noise level of less than 0.5 electrons at an output frequency of 1.5MHz.

IV. Power Dissipation

In many space applications power can be in very short supply and hence there is a need to minimise consumption without compromising performance. In a CCD the power dissipation is mainly associated with the higher speed register clocks and the output amplifier loads. The clock dissipation can be reduced by manufacturing devices that may be operated with clock levels of 5-6 volts instead of the 10-12 volts more typically required for scientific CCDs. Achieving such lower voltages tends to go hand-in-hand with the thinner gate oxides required for increased radiation hardness. The power dissipated in the CCD drive electronics also significantly reduces. The on-chip fraction of the amplifier power dissipation is minimised if the final load is off-chip, but the total power is difficult to reduce if high operating rates are required. At lower operating frequencies the load current may be significantly reduced.

V. TDI Imaging

Ground scanning from space has significantly different requirements to science or staring imaging. For many commercial applications these are performed by linear array operating in a “pushbroom” mode. The results from Google Map are very well known and e2v has provided many linear arrays for these applications, such as Spot V [8].

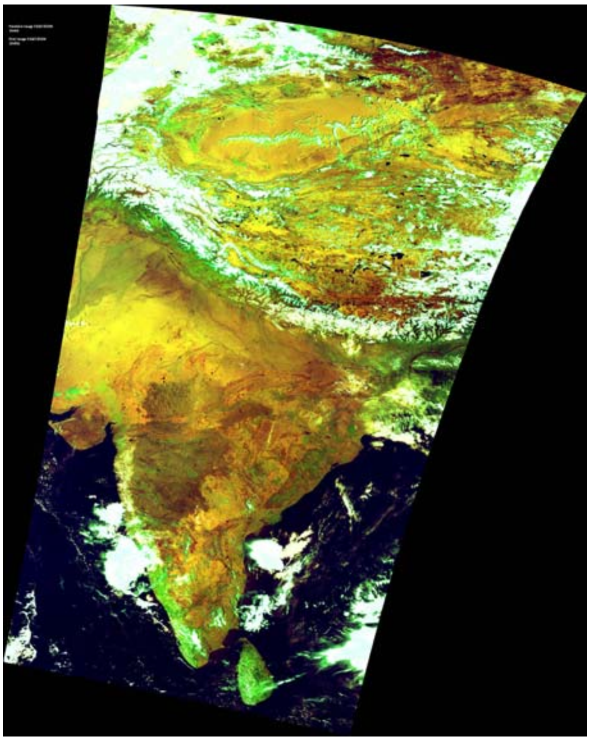

Figure 6: Spot Vegetation Image of India

However the sensitivity of simple linear arrays is limited and the signal is not sufficient as the resolution and scanning rate are increased. In order to overcome this problem, high performance ground scanning applications now make use of the TDI (Time Delay and Integration) mode of operation that is inherently available with CCDs.

The design challenges for TDI imagers for Earth observation are significantly different to other space based applications. In general signal levels are not a major limitation and the effective integration time is low so the impact of radiation damage is not severe. The challenge for this application is to obtain the maximum resolution and signal to noise ratio under a wide range of illumination levels.

With TDI operation, the device is clocked continuously and the sensitivity is determined by the number of lines that are used to integrate the signal. The target is to always operate as close to the maximum signal level as possible as the scene illumination level changes. To achieve this TDI imagers are equipped with anti-blooming and bring out separate electrodes that can be held at a fixed potential to block the charge transport within the image area, thereby controlling the number of lines used for integration. Any charge generated above the blocked electrode is lost into the antiblooming drain. Thus it is possible to rapidly adjust the effective sensitivity of a TDI device while in orbit.

Recent images from the HiRise instrument built by Ball Aerospace for NASA on the Mars Reconnaissance Orbiter show the performance that can be obtained from TDI imagers [9]. This instrument has a ground resolution of 30cm.

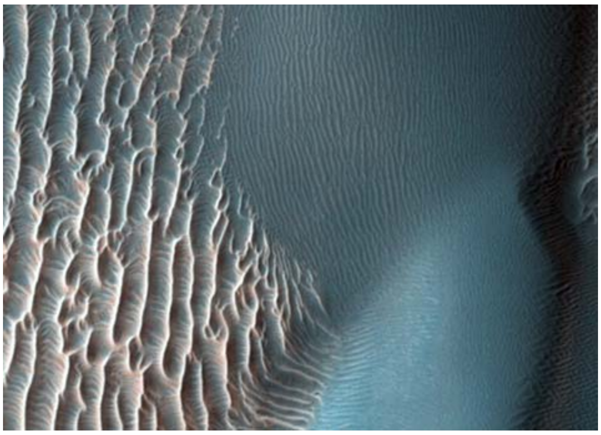

Figure 7: Sand dunes and Ripples in the Proctor Crater

TDI operation is most frequently used to improve the sensitivity of devices used for ground scanning applications, but the GAIA mission will also operate in TDI mode to map the position of 1 billion stars to unprecedented accuracy [10].

VI. Future Developments

A number of areas where CCD performance is being developed have already been discussed, including:

- Increased hardness to ionising radiation
- P-channel CCDs
- EMCCDs for Space applications
- Hi-Rho CCDs for Space applications

In addition e2v are working on a new generation of devices that can be both fully depleted to achieve maximum MTF but operated fully pinned to remove surface dark signal. This would provide a significant performance advantage for Earth observation and will become critical as the pixel size is decreased for these applications to below 8 µm.

VII. Conclusion

Despite being extremely mature, the rate of development of CCD technology has never been greater, especially for Space and Scientific imaging. This has partly been driven by the challenge from the CMOS image sensor and the ongoing debate about which technology is better.

The reality is that for some Space applications CMOS sensors offer potential performance advantages and so are likely to be adopted in the near future, whereas CCDs will continue to be the technology of choice for applications such as TDI imaging and where very high red QE is required. At e2v we will continue to develop both technologies in parallel.

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