The Radiation Damage Performance of EEV CCDs

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The radiation response of EEV CCDs have been subject to detailed investigation over many years by several independent groups (For example Centre for Radiation Damage Studies, Brunel University, UK and Leicester University, UK) for many performance critical applications within radiation environments including European Space Agency programmes and those for high energy particle physics experiments (at the Stanford linear collider and at CERN). The following is a brief summary of our current understanding of ionising radiation effects in EEV CCDs. A brief introduction to the additional effects of protons is also presented.

1 Flat Band Voltage Shift

As is common with all MOS devices, and therefore all CCDs, ionising radiation causes electron hole pairs to be generated within the gate dielectric structures. The electrons and holes can either recombine or leave the dielectric without causing any net effect, or the electrons alone can leave the structure whilst leaving some of the holes trapped within the dielectric. This results in a net positive charge and a shift in the flat band voltage of the MOS structures i.e. the device behaves as if the bias applied to the gate structures of the device has increased by the amount of the voltage shift.

The number of electron hole pairs that escape initial recombination is dependant on the temperature, the density of the generated electron-hole 'cloud' and the local electric field. The temperature dependance is not an issue at temperatures above about 120K or so. The density of the generated electron hole pairs is dependent on the rate of irradiation and the nature of the radiation. The electron - hole density obtained from an interacting low energy x-ray is higher, for example, than an interacting 1 MeV gamma ray and so, as the initial recombination is lower, the voltage shifts obtained per unit dose is higher for Co60 irradiated samples. The presence of an electric field tends to separate the electron-hole pairs before they can recombine and the direction of the electric field determines where the holes will be trapped within the dielectric. The voltage shifts are also dependent on the structure of the gate dielectrics and on the processing applied. The structure of CCDs is such that if the CCD is irradiated under bias the voltage shift will be greater than if it were irradiated with all pins grounded.

Latest measurements on EEV CCDs with our 'standard' dielectric irradiated with Co60 gammas gives a figure of approximately 14 mV per krad(Si) with the CCD unbiased during irradiation and a figure between 50 mV and 120 mV per krad(Si) with the devices biassed during irradiation. A figure of 100 mV per krad has recently been obtained from a detailed lot acceptance test of back illuminated devices from a major European Space Agency programme i.e. the effective gate voltages will shift by approximately 10 Volts after 100 krad (Si). No difference will be observed by operating the device at -25 °C. Devices from other manufactures do show similar or worse radiation induced voltage shifts. However, EEV has developed a radiation tolerant process that can reduce the voltage shifts by over a factor 20. This gives voltage shifts around 3.4 mV/krad(Si) for a device under bias.

2 Dark Signal Increase

2.1 Non -MPP devices

The increase in dark signal due to ionising radiation in all non-MPP devices is mainly due to an increase in the interface surface state density and thus an increase in the generation rate of electron - hole pairs within the device. The increase in dark signal for non-MPP devices measured as part of my thesis was in the order of 100 pA/cm^2/krad(Si) at 20 °C. However this figure does not take into account any 'reverse annealing' that takes place, possibly due to the transport of hydrogen to the silicon/silicon dioxide interface after irradiation. This causes an increase in the dark signal with time after the initial irradiation. The amount of 'reverse annealing' is dependent on the processing steps employed during fabrication and on the CCD design. The EEV devices show a particularly low level of reverse annealing. Recent devices characterised for the MERIS programme of the ESA Polar Orbit Earth-Observation Mission have been heated to 100 °C for 168 hours after 20 krad(Si) Co60 gammas to accelerate the reverse annealing process. These devices have shown a dark current increase at -25 °C over preirradiation levels of 350 pA/cm^2. Using the usual relationship for dark signal in EEV's non-MPP devices, i.e. $I \propto T^3 \exp(-6400/T)$ this increase in dark signal corresponds to approximately 1.5 nA/cm^2/krad(Si) at 20 °C. This figure can be regarded as a worst case figure for practical purposes since the time constant for the EEV annealing process is extremely long at room temperature and below. We have no detailed measurements on the activation energy of this annealing process. However measurements made on x-ray irradiated devices by Brunel University have shown that one days anneal at 100 °C is equivalent to between one and two years anneal at room temperature. Thomson CCDs have been particularly weak in this area. A detailed study of Thomson devices carried out for ESA by Sira Limited (UK) for the Silex programme (Estec Contract No: 7787/88/NL/DG) has shown a final increase in the average dark signal of approximately 7.5 nA/cm^2/krad(Si) at 22 °C for one device type and approximately 13 nA/cm^2/krad(Si) at 22 °C for another device type. These figures do not include some of the anomalously high increases also observed by Sira. The time constant for the Thomson reverse annealing process appears to be much shorter than EEV's, essentially completing the annealing process after only a few tens of days at room temperature.

Dither clocking can be used to reduce the radiation induced dark signal in non-MPP devices. The effectiveness of the dither clocking is dependent on the temperature and the dither period. Dither clocking was assessed for the MERIS program. Here the dither period was 0.77 ms and the temperature was -25 °C. The dithered dark signal was assessed after the devices had received a combination of Co^{60} gamma and 10 MeV proton irradiation and an annealing step. Dithering reduced the dark signal by approximately a factor 4. It can be expected that by optimising the biasses and dither period the dark signal may be reduced even further.

There has been some indication from recent work that the increase in interface state density (i.e surface dark signal) is dependent on the LET of the incident particle, for example 6 MeV protons will be relatively more damaging per rad than 60 MeV protons. More work is required to quantify and understand this phenomena.

2.2 MPP devices

In EEV MPP devices running with the silicon inverted at the silicon/silicon dioxide interface almost all of the generation of electron hole pairs from this region is suppressed. Therefore the increase in dark signal from ionising radiation is extremely small. The only absolute measurement we have at present gives a figure of 1.5 pA/cm^2/krad(Si) at 30 °C. This measurement, however, was not made on our 'standard' production process. Measurements have been made by Brunel University on our standard devices and have certainly shown an increase in dark signal below their measurement limit of 1 pA/cm^2/krad(Si) at 20 °C. No reverse annealing has been observed.

3 Dark Signal Non-Uniformity (DSNU)

The major change in DSNU is caused by the voltage shifts causing a change in the depletion state at the Silicon/Silicon dioxide interface. This is discussed in Section 4 below. However, before this dramatic change occurs there will be only a small increase in the DSNU provided the irradiation is uniform. We have little quantitative measurements on the change of DSNU for MPP devices. However, it should not increase significantly. If MPP and cooling is employed the absolute value of DSNU and dark current will be insignificant, e.g. at -25 °C the dark signal will increase by roughly 1.6 electrons/pixel/second after 20 krad(Si) with the absolute value of DSNU being only a fraction of this.

4 Effect of the Voltage Shifts on Device Performance

Irradiation changes the operating point of the CCD as if the biases applied to the gates of the device have been offset by an amount equal to the flat band voltage shift. If no correction to the bias supplies can be made then a realistic maximum voltage shift that can be accommodated whilst still maintaining device performance is approximately 2 Volts.

The first major effect observed from the radiation induced shift in operating point of the CCD is a sharp increase in dark signal from MPP devices after an approximate 2 Volt shift (20 krad(Si)). At this point the silicon/silicon dioxide interface starts to come out of inversion and the dark signal rises to roughly the non-MPP level. An increase will also be observed in non-MPP devices at the same point but the dark current will increase by only around a factor 3. The transition from 'low' to 'high' dark signal will not be a sharp step but will occur over a shift of about 1 Volt (10 krad(Si)). During this transition phase the DSNU will be high due to different areas of the silicon/silicon dioxide interface coming out of inversion at slightly different points.

As the CCD is irradiated the channel potential under the output gate will increase and so the amount of signal charge that the output amplifier can handle will drop. Also, after a shift of approximately 3 Volts the reset FET will no longer be able to 'turn off' resulting in a severely smeared picture and failure of the device. The responsivity (Gain) of the amplifier will also have dropped by this time as the amplifier FETs are no longer biassed at the optimum point within their characteristics. .

If some form of bias tracking can be employed the voltage shift that can be accommodated will be much greater (between roughly 3 or 4 Volts). As the device is irradiated the low and high clock levels will have to be reduced, the output gate, dump gate and antiblooming gate bias reduced and the output drain voltage increased, all by the amount of the voltage shift. Alternatively the clock levels can be kept fixed with the drain and substrate biases increased. The output drain bias should be increased at twice the rate to preserve the gain. If the CCD has a dummy output FET and is not being used to cancel common mode noise, it is conceivable that it can be used to monitor the voltage shift and to feed back to some compensation circuitry. EEV, however, has not developed such a system.

5 Proton Irradiation

High energy protons can transfer enough energy to the silicon lattice to displace a silicon atom. In n-type silicon the most relevant stable defects are associated with the partnering of the resultant vacancy with other vacancies or with a phosphorus dopant atom (Si-E centre). These stable defects result in energy levels appearing within the silicon band gap. In CCDs these defect levels manifest themselves as dark signal generating centres and trapping centres which can trap signal charge as it passes within its vicinity. Therefore as a CCD is irradiated with protons it will experience the ionising damage described above and also show a reduction in charge transfer efficiency and an increase dark signal generated from the bulk silicon. The reduction of CTE is especially important for x-ray spectroscopic applications and has been characterised in detail by Leicester University. The effect of the change in CTE is dependent on the clocking scheme employed, the temperature, the background signal and the scene being viewed. EEV have developed a device structures that limits the effect of the proton interaction. However, these structures are not appropriate for all device types.

The proton induced dark signal non uniformity (DSNU) is caused by the stochastic nature of the proton interaction and is dependent on the pixel volume, incident proton spectrum and fluence.

Proton irradiation is mainly of concern to users of devices employed in space applications. EEV has developed several physical models to help in the prediction of the reduction of CTE and the increase in dark signal and DSNU from proton irradiation. Given the orbit and mission duration EEV can advise on the degradation to be expected. Assessment of the effects of shielding can also be given.

6 Conclusion

The change in performance for MPP devices operating within an ionising radiation environment is dominated by the flat band voltage shift. If the device can be left unbiased during the most severe irradiation episodes a non-hardened EEV device should survive up to 100 krad(Si) dependant on the fraction of time the device is biassed. If the CCD has to be constantly biassed, and without employing a biassing scheme that can track the flat band voltage shifts, the non-hardened CCD will survive a dose around 20 krad(Si). By employing a tracking scheme this may be increased to beyond 30 krad(Si). If EEV's full radiation hardened technology is employed these figures increase to approximately 600 krad(Si) and approximately 1 Mrad(Si) depending on whether bias tracking is used. If this extremely good radiation response is not needed an intermediate process could be used which would be less demanding of our manufacturing tolerances.

For non-MPP devices the increase in dark current must be considered. For an MPP device the increase in dark current after 100 krad(Si) will be approximately 70 pA/cm^2 at 20 °C. To match this performance a non MPP device will have to be cooled to approximately -30 °C. If reverse annealing effects are important the temperature will have to be reduced even further. Dither clocking can be used to reduce the radiation induced dark signal in non-MPP devices.