Radiation Damage in CCDs used as Particle Detectors

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February 1997

Introduction

CCDs sensitive to minimum-ionizing particles (hereafter referred to as min-I particles) have found a niche as very high precision tracking devices, used as vertex detectors for the detection of short-lived heavy flavor quarks or τ leptons, in high energy physics experiments [1-3]. As such, they must be located as close as possible to the interaction point (usually starting within 10 or 20 mm). In this environment the capability of these pixel-based devices to tolerate very high hit densities (typically $\sim 1/\mathrm{mm}^2$) is an important attribute. However, this environment may be quite demanding as regards radiation hardness, a situation also encountered by users of imaging CCDs in industry (nuclear, X-ray and electron microscopy, for example), for space-based optical and X-ray telescopes, etc. Radiation damage in these complex silicon devices is therefore relevant to numerous application areas and has been studied for many years [4-16]. Reference [11] provides a particularly valuable review. Despite being 17 years old, it remains the most comprehensive general paper on this subject.

Despite this extensive bibliography, there is no simple picture that summarizes radiation effects of concern to all CCD users, for two reasons. Firstly the uses made of these devices are highly variable. To a particle physicist (who is interested in the tracking precision given by the centroid of a min-I cluster) a 10% loss of signal (as long as it be slowly varying across the detector area) would not be serious. To an X-ray astronomer, using the cluster signal amplitude to determine the X-ray energy, such a degradation would be disastrous. Secondly, the radiation sensitivity depends strongly on the operating conditions, such as integration time, readout speed, etc. These conditions may be imposed by external factors peculiar to a specific application. For example, the limitations on operating temperature and power dissipation of space-based systems are likely to be more restrictive than in terrestrial applications.

In this paper an attempt is made to focus on the issues relevant to the particle tracking/vertex detector application, leaving aside issues of great important to other users.

Surface Damage

With regard to surface damage effects due to all forms of ionizing radiation (charged hadronic and electromagnetic) we can be brief. Process improvements over the years have reduced the build-up of interface charge, and CCDs (having on-chip gain less than unity, unlike microstrip detector readout ICs) are relatively insensitive to such effects. There is a level shift as the signal is transferred from beneath the Polysilicon gate structure (uniformly affected by interface charge build-up) onto the output node, whose potential is directly set by the external reset bias V_{RD}. As the radiation dose builds up, it may become necessary to raise V_{RD} to match the shift in buried channel potential. This has a knock-on effect to the drain voltage V_{DD} of the output transistors, in order to maintain the charge-sensing circuit at full gain. This procedure would eventually be limited by the breakdown voltage of the MOSFET to substrate. 'Standard' CCDs show voltage shifts due to trapped charge at the Si/SiO_2 interface of about 1 V/100 kRad, with half this for radiation tolerant devices having thin dielectric gate insulators, and around 0.1 V/100 kRad for experimental devices, soon to become generally available. Thus with modern radiation-hard dielectric, the practical limit can be >1 Mrad of ionizing radiation, which is entirely adequate for all CCD vertex detector applications in the past or contemplated to date. Incidentally, these voltage shifts are much smaller if the CCDs are powered off during irradiation (giving enhanced electron-hole recombination in the dielectric) but this option is not generally applicable in HEP applications, apart from beam-tuning periods. As well as causing flat-band voltage shifts, the interface states produced by ionizing radiation act as sources of electron-hole generation i.e. increased dark current. In HEP applications, there is no reason not to design the tracking detector for operation at cryogenic temperature, so reducing the dark current to completely negligible levels.

Bulk Damage

Regarding bulk damage, we need to consider the effects on dark current, charge collection efficiency and charge transfer efficiency. Even in heavily irradiated CCDs, the excess dark current can normally be dealt with by modest cooling. Given the thin epitaxial layer (~20 μm) from which the min-I signal is collected, the requirements made on minority carrier lifetime are not severe, and there is essentially no problem with charge collection into the potential wells. However, once the electron charge packet starts its long journey to the output node (possibly several centimeters, ~2000 pixels), the situation is far more dangerous. At every location where the charge packet is momentarily stored (and there are three such locations for every pixel of a 3-phase CCD) there is a finite probability that some of the signal charge may be trapped, leading to less-than-unity charge transfer efficiency CTE. Use is also made of the quantity CTI (=1-CTE), the charge transfer inefficiency. In order not to seriously degrade the signal-to-noise performance, the average CTI of a tracking detector in a large instrument should typically not exceed $\sim 10^{-4}$.

The *n*-channel being relatively highly doped, the generation of bulk defects is considerably simpler than for the high resistivity material required for microstrip detectors, being closely similar to that encountered in electronic devices. The primary products of bulk damage are vacancy/interstitial pairs. Indeed, in the case of electromagnetic irradiation, these pairs (in the form of point defects) represent the complete picture. For hadronic interactions, the large energy transfer to the silicon atom results in damage clusters (local regions of the crystal having dimensions typically hundreds of Angstroms in longitudinal and transverse dimensions). These clusters constitute highly disordered regions within the crystal, and may be a source of mobile vacancies, di-vacancies etc. In the heavily doped CCD *n*-channel, the majority of active defects are formed from the capture of mobile vacancies by phosphorus dopant atoms (the Si-E center). These form positively charged donor-like defects when empty, with an energy level E_{tr} of 0.44 eV below E_c, the edge of the conduction band. In the case of electromagnetic irradiation, the Si-E center is probably the only significant defect generated. These defects have a high probability of capturing signal electrons which come within their electrical sphere of influence. Let us consider this case, a single type of bulk trap which is randomly distributed within the *n*-channel. This situation is described by a restricted case of the general Shockley-Hall-Read theory of carrier capture and emission from traps, in which only capture and emission of electrons from/to the conduction band plays a part. Hole capture and emission are irrelevant since we are concerned with donor-like traps in depleted material. This situation has been considered by various authors [4, 7, 12, 14].

Let us first take a qualitative look at the situation. As the charge packet is transported from gate to gate (within a pixel or between neighboring pixels) *vacant* traps that lie within the storage volume of the charge packet will tend to capture electrons. If the traps are already filled (either fortuitously, due to the passage of an earlier signal packet, or deliberately for this purpose by the injection of an earlier 'sacrificial' charge packet) they will permit the signal electrons to pass undisturbed. Also, if the signal packet is transported at a sufficiently high clock rate that the dwell time τ_g under any gate is small compared to the trapping time constant τ_c, the signal electrons will pass. Also, if the trap emission time constant τ_e is small compared with the clock pulse rise/fall time τ_r, the trapped electrons will be re-emitted in time to rejoin their parent charge packet. Only if electrons are *trapped and held long enough* to be re-deposited in the next or later potential well, does the process contribute to a loss of CTE. This is evidently a multi-parameter problem with some room for maneuver.

Let us now look at the process quantitatively.

Assuming all traps initially empty, the CTI is given by

$$\mathrm{CTI} = \sum_{j=1}^{N_F} F_j \times \frac{N_{tr}}{N_s}\left[1 - \exp\left(\frac{\tau_r}{\tau_e}\right)\right]$$

N_F is the number of phases per pixel (3 for a 3-phase structure).

F_j is the fill-factor for phase *j*, i.e. the probability that a trap in the charge packet storage volume will become filled during the dwell time.

$$F_j = 1 - \exp(-\tau_g / \tau_c)$$

For most cases of practical interest τ_c is of order of magnitude 10 ns and F_j may be taken to be unity. N_{tr} is the trap density and N_s, the signal charge density, is a function of the signal size, but is effectively constant (and approximately equal to the *n*-dopant concentration) for charge packets larger than approximately 1000 e^-[14]. For smaller charge packets, the effective signal density is reduced, and the CTI is correspondingly degraded. For very small charge packets of N_e electrons, one expects $N_s \propto 1/N_e$ since the signal electrons will occupy a constant volume determined by their thermal energy and the 3-dimensional potential well in which they are stored.

Now

$$\tau_e = \frac{\exp\left[(E_c - E_{tr})/kT\right]}{\sigma_n X_n v_n N_c}$$

The terms in the denominator are in turn the electron capture cross-section for that trap type, an entropy factor, the electron thermal velocity and the effective density of states in the conduction band. The numerator tells us that for shallow traps (or high temperature) τ_e is likely to be short, and conversely for deep traps and/or low temperatures, τ_e is likely to be long. In fact, for deep traps and appropriate clock times, by reducing the temperature, one can sweep the CTI through its full range from approximately zero (since the charge is re-emitted into the parent pixel during the drive pulse risetime) to $3N_{tr}/N_s$ (for a 3-phase CCD) and back to zero, as all traps are filled by some long preceding deliberate or accidental charge packets to have been clocked out of the device. Figure 1 nicely illustrates this point.

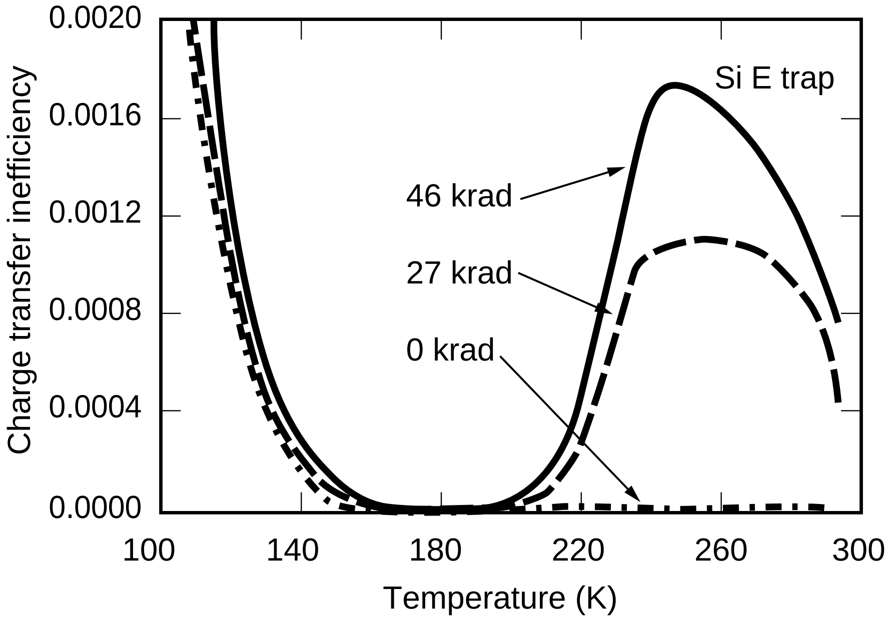

Fig. 1 From reference [14], effect of ionizing radiation damage on CTI, as function of operating temperature. (^{90}Sr β source)

This demonstrates the growth in CTI due to irradiation of a CCD with a radioactive β source. The density of Si-E centers increases, but the effect on CTI can be minimized by operating at or below

190 K, where the trap emission time becomes adequately long. The degradation in CTI below 160 K (even before irradiation) is not seen in later CCDs from the same manufacturer. It probably represents an artifact of the register design or processing of this particular device. In practice, one can normally reduce the operating temperature to ~85 K before the CTI rises to $\sim 10^{-4}$ at the onset of carrier freeze-out, the trapping of signal electrons by the phosphorus donor ions [12]. This sets an effective lower limit to the useful operating temperature of *n*-channel CCDs.

For hadronic irradiation of CCDs, because of the much greater non-ionizing energy loss or NIEL factor, the damage rates are greatly increased. In addition, several donor-like defect levels have been identified. The Si-E center (VP) still forms the predominant and deepest trap, though 15% of this deep trap is believed due to the di-vacancy (VV) [16]. Shallower traps at $E_c - 0.30$ and $E_c - 0.12$ eV are also observed [8, 16]. Protons are particularly damaging (due to the large p-Si Coulomb scattering cross-section) and Fig. 2 shows the CTI resulting from an irradiation with the very modest dose of 3.6×10^9 10 MeV proton/cm^2.

While these proton damage results are of great importance for their particular application area (space-based X-ray cameras) they probably give a pessimistic impression for the conditions relevant to particle detection systems, for two main reasons. Firstly, these results refer to very low signal densities, so the benefits of the long trap emission times at low temperature are not exploited to the extent possible in a particle physics experiment. Secondly, the only hadronic background likely to be significant at an e^+e^- collider are neutrons leaking through shielding. There is evidence that neutrons may be much less harmful than would be inferred from these proton data.

Taking the standard NIEL factor, the data of Fig. 2 correspond to an equivalent dose of 1 MeV neutrons of 3×10^{10} n/cm^2. Yet there are measurements on *n*-channel CCDs (buried channel) [5, 6], which demonstrate $\mathrm{CTI} < 10^{-4}$ for 10^{12} n/cm^2 at room temperature. Most significantly [6], at a temperature of 84 K and 30 ms between bursts of charge injection, the CTI of 10^{-4} is achieved for 10^{13} n/cm^2 (1 MeV equivalent). The clocking conditions between these experiments are quite different (protons in parallel register clocked very slowly, neutrons in linear register clocked at 500 kHz) but this should not be critical. The low temperature performance should be driven by the time between charge injections, and 30 ms would be quite realistic for an HEP experiment. There is the further difference that the neutron studies have all been made with large signal packets, but as already discussed, this should become an issue only if the packet size falls below ~1000 e^-, where the signal charge density falls significantly below the dopant level in the *n*-channel.

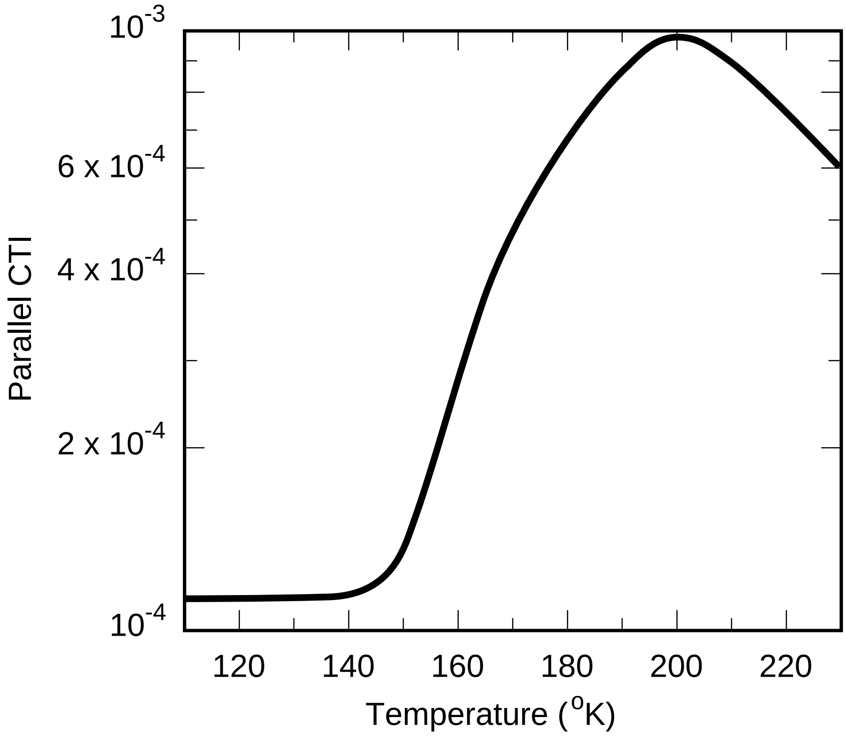

Fig. 2 From reference [16], effect of hadronic radiation damage on CTI, as function of operating temperature. (10 MeV protons)

Conclusions

Due to their long readout time, CCDs are not applicable as vertex detectors in continuous high flux environments such as LHC. They have a proven record in fixed target experiments (where the incident beam can be interrupted during the readout) and in the e^+e^- linear collider environment, where the interval between bunches (or between bunch trains) allows time for readout. In both these environments, radiation damage effects have so far been modest. In the fixed target environment, given the small number of CCDs required, they can simply be exchanged at intervals of 6 months or so. For the e^+e^- collider, with reasonable care over beam conditions, the detector lifetime can be many years.

For the future e^+e^- linear collider, the backgrounds may be substantially higher. The dumps for secondary e^+e^- pairs, for beamstrahlung and for the residual main beam, are all significant sources of neutrons. At this stage, it is not clear if any of these could cause problems for a CCD vertex detector. As we have seen, there is a possible discrepancy between the radiation damage data with neutrons and with protons, as regards charge transfer efficiency, so the actual performance limits for a CCD detector are far from clear.

What is long overdue is a comprehensive study of the radiation effects in one CCD design, comparing electromagnetic, neutron and charged hadron irradiation, with particular attention to the operating conditions (clocking, charge injection interval and temperature), covering the region of interest for particle detection. It should be noted that very high clocking rates for the readout register (~50 MHz) are envisaged for this environment. This will provide a significant suppression of CTI in this register due to the fact that τ_g will no longer be much larger than τ_c, so the above-mentioned fill factor can be far from unity. Equally important as these systematic studies of radiation effects is a serious evaluation of neutron background conditions likely to be encountered at the future e^+e^- linear collider (the next likely application area for a large scale CCD vertex detector). This work will reveal if there are any problems with the continued use of currently available CCDs in our field. Should there be difficulties with the anticipated neutron fluxes, there may be considerable room for improvements in the CCD design. The most obvious step (analogous to the use of hetero-structures in radiation hard GaAs electronics) would be to reduce the storage volume for the charge packets. This is possible in both dimensions orthogonal to the transfer direction, by the techniques of a narrow channel, and a highly doped shallow channel. It should be remembered that for min-I detection, a pixel well capacity of $10^4\ e^-$ would be entirely adequate; on current CCDs the signal charge floats around in a vastly excessive storage volume. Another option would be to consider *p*-channel devices, for which the Si-E center would be avoided. There is some evidence [10] that such CCDs do have enhanced radiation hardness, though this has not been studied with neutrons.

In short, there is currently a need for background simulations and for measurements with neutron irradiation of modern CCDs, to determine if the future linear collider presents significant radiation damage problems for a CCD-based vertex detector. Should there be such problems, the CCD designer has a variety of tools at his disposal with which to improve the radiation hardness of his designs. Many of these ideas will in any case be developed for non-HEP applications in radiation environments, but the conditions specific to a particle tracking detector do present opportunities that would not be universally available.

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