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Radiation hardness of CCD vertex detectors for the ILC

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Results of detailed simulations of the charge transfer inefficiency of a prototype CCD chip are reported. The effect of radiation damage in a particle detector operating at the ILC is studied for two electron trap levels, 0.17 eV and 0.44 eV below the conduction band. Good agreement is found between simulations and an analytical model for the 0.17 eV level. Optimum operation is at about 250 K, approximately independent of readout frequency.

1. INTRODUCTION

Any experiment exploiting the International Linear Collider (ILC) will require a detector to detect and measure short-lived particles but remain tolerant to radiation damage for its anticipated lifetime. This might contain charge-coupled devices (CCDs) which suffer from both surface and bulk radiation damage. However, when considering charge transfer losses in buried channel devices only bulk traps are important. These defects create energy levels, hence electrons may be captured and later emitted back to the conduction band after a certain time. For a signal packet this may lead to a decrease in charge as it is transferred to the output and is quantified by its Charge Transfer Inefficiency (CTI), where a charge of amplitude Q_0 transported across m pixels will have a reduced charge given by

$$Q_m = Q_0(1 - \mathrm{CTI})^m.$$

Previous studies of radiation-induced CTI have been reported [1].

The UK LCFI collaboration[1] has been studying a device produced by e2V Technologies, with a manufacturer's designation 'CCD58'. It is a 2.1 Mpixel, three-phase buried-channel CCD with 12 μm square pixels. Simulations of a simplified model of this have been performed with the ISE-TCAD package (v7.5), particularly the DESSIS program. It contains nine gates (numbered 1 to 9) which form the pixels. Each pixel consists of 3 gates but only one pixel is important for this study—gates 5, 6 and 7. The overall length and depth of the simulated device are 44 μm and 20 μm respectively. The signal charge used in the simulation is chosen to be similar to the charge generated by a minimum ionising particle (MIP), corresponding to about 1620 electrons.

This CTI study, at nominal clock voltage, focuses only on the bulk traps with energies 0.17 eV and 0.44 eV below the bottom of the conduction band. These will be referred to simply as the 0.17 eV and 0.44 eV traps. An incident particle with sufficient energy is able to displace an atom from its lattice point leading eventually to a stable defect. These defects manifest themselves as energy levels. The trap concentrations and electron capture cross-sections used in the simulations are shown in table below.

E_t-E_c (eV)	Type	C (cm^{-3})	σ (cm^2)
0.17	Acceptor	1×10^{11}	1×10^{-14}
0.44	Acceptor	1×10^{11}	3×10^{-15}

Each electron trap in the semiconductor material can either be *empty* (holding no electron) or *full* (holding one electron). In order to simulate

[1]LCFI stands for Linear Collider Flavour Identification

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the normal operating conditions of CCD58, partial trap filling was employed in the simulation (which means that some traps are full and some are empty) because the device will transfer many charge packets during continuous operation.

2. ANALYTICAL MODELS

The following two simple analytical models are introduced to understand the underlying effects and to make comparisons with the DESSIS simulations (referred to as the "full simulations").

2.1. Simple CTI Model

Firstly, a simple analytical model is considered, based upon a single trapping level—a so-called Simple CTI model. This is significantly faster than a full simulation. It also provides a simple method to see the effect of changing parameters and demonstrates physics understanding. The charge transfer process is modelled by a differential equation in terms of the different time constants and temperature dependence of the electron capture and emission processes. In the electron capture process, electrons are captured from the signal packet and each captured electron fills a trap. This occurs at the capture rate $\tau_{\rm c}$. The electron emission process is described by the emission of captured electrons from filled traps back to the conduction band, and into a second signal packet at the emission rate $\tau_{\rm e}$.

The Shockley-Read-Hall theory [2] considers a defect at an energy $E_{\rm t}$ below the bottom of the conduction band, $E_{\rm c}$, and gives expressions for $\tau_{\rm e}$ and $\tau_{\rm c}$. At low temperatures, the emission time constant $\tau_{\rm e}$ can be very large and of the order of seconds. The charge shift time is of the order of nanoseconds. A larger $\tau_{\rm e}$ means that a trap remains filled for much longer than the charge shift time. Further trapping of signal electrons is not possible and, consequently, the CTI is small at low temperatures. A peak occurs between low and high temperatures because the CTI is also small at high temperatures. This manifests itself because, at high temperatures, the emission time constant decreases to become comparable to the charge shift time. Now, trapped electrons rejoin their signal packet.

From the fraction of filled traps, a differential equation can be derived where $r_{\rm f}(t) = n_{\rm t}(t)/N_{\rm t}$ is the time-dependent fraction of filled traps, $n_{\rm t}(t)$ is the density of traps filled by electrons, and $N_{\rm t}$ is the density of traps. Considering that the traps are partially filled and using the initial condition: $r_{\rm f}(0) = r_{\rm f}(t_{\rm sh})e^{-t_{\rm w}/\tau_{\rm e}}$ where $r_{\rm f}(0)$ is the fraction of filled traps after a mean waiting time, $t_{\rm w}$, the differential equation can be solved to provide an expression for the CTI:

$$CTI = \frac{3N_{\rm t}}{n_{\rm s}}\left(\frac{\tau_{\rm s}}{\tau_{\rm c}} - r_{\rm f}(0)\right)\left(1 - e^{-t_{\rm sh}/\tau_{\rm s}}\right)$$

where $\frac{1}{\tau_{\rm s}} = \frac{1}{\tau_{\rm c}} + \frac{1}{\tau_{\rm e}}$, and $t_{\rm sh}$ is the shift-time. For one gate, $t_{\rm sh} = 1/(3{\rm f})$, where f is the readout frequency. This definition is for CTI for a single trap level. The factor of three appears since there is a sum over the three gates that make up a pixel.

The Simple Model has been adapted by including initially filled traps and by the incorporation of a so-called P factor to CTI:

$$P = e^{-t_{\rm sh}/\tau_{\rm e}} + e^{-2t_{\rm sh}/\tau_{\rm e}} + e^{-3t_{\rm sh}/\tau_{\rm e}}$$

This models the situation where the trapped charge under gate 5 started to empty at time t minus three shift-times, that under gate 6 at t minus two shift-times and that under gate 7 at t minus one shift-time. An alternative factor, called P', has also been used to compare with simulated data. This is defined as:

$$P' = 1 + e^{-t_{\rm sh}/\tau_{\rm e}} + e^{-2t_{\rm sh}/\tau_{\rm e}}$$

and models the situation one shift-time earlier than for P.

2.2. Improved Model

The second analytical model is the Improved Model (IM), based on the work of T. Hardy et al. [3]. It is improved by adjusting initial assumptions to fit the study of CCD58 and also considers the effect of a single trapping level, but only includes the emission time in its differential equation where $n_{\rm t}$ is the density of filled traps. The traps are initially filled for this model and $\tau_{\rm c} \ll t_{\rm sh}$. Nevertheless, to be consistent with the full DESSIS simulations (that use partially filled traps) the Improved Model uses a time constant between the filling of the traps such that the traps remain partially filled when the new electron packet passes through the CCD. The solution of this differential equation leads to another estimator of the CTI:

$$CTI^I = \left(1 - e^{-t_{\rm sh}/\tau_{\rm c}}\right) \frac{3N_{\rm t}}{n_{\rm s}} \left(e^{-t_{\rm join}/\tau_{\rm e}} - e^{-t_{\rm emit}/\tau_{\rm e}}\right)$$

where $t_{\rm emit} = t_{\rm w}$ is the total emission time from the previous packet, and $t_{\rm join}$ is the time period during which the charges can join the parent charge packet.

3. SIMULATION RESULTS

The CTI dependence on temperature and readout frequency was explored using DESSIS simulations.

Figure 1 shows the CTI for simulations with partially filled 0.17 eV traps at different frequencies for temperatures between 123 K and 260 K, with a nominal clock voltage of 7 V.

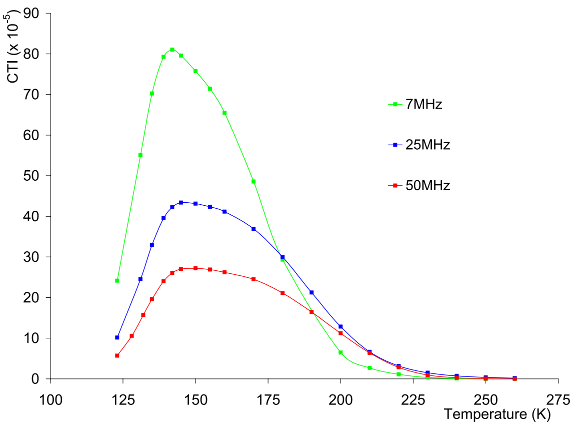

Figure 1. CTI for simulations with 0.17 eV partially filled traps clocked at 7, 25 and 50 MHz.

The CTI increases as frequency decreases. For higher readout frequency there is less time to trap the charge, thus the CTI is reduced. At high temperatures the emission time is so short that trapped charges rejoin the passing signal.

Simulations were also carried out with partially filled 0.44 eV traps at temperatures ranging from 250 K to 500 K. This is because previous studies on 0.44 eV traps have shown that these traps

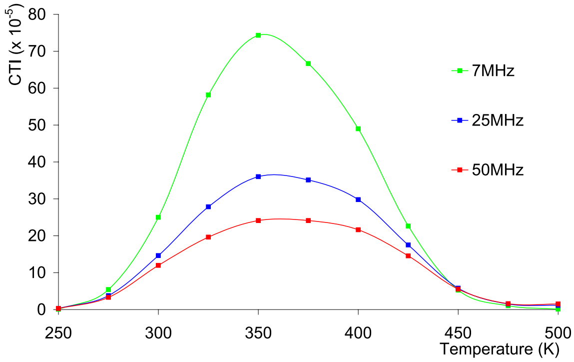

Figure 2. CTI for simulations with 0.44 eV partially filled traps clocked at 7, 25 and 50 MHz.

cause only a negligible CTI at temperatures lower than 250 K due to the long emission time and thus traps remain fully filled at lower temperatures (Fig. 2).

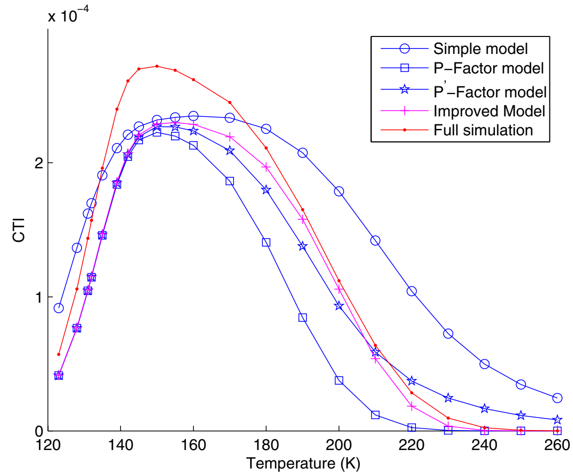

Figure 3. CTI values against temperature for different models with 50 MHz readout. See text.

The peak CTI is higher for lower frequencies with little temperature dependence of the peak position. The optimal operating temperature is about 250 K. Figure 3 shows that the basic Simple Model does not agree well with the full simulation. Applying the P factor appears to overcompensate for the deficiencies and the P' factor gives a reasonable but not perfect agreement.

Figure 4 compares the full DESSIS simulation for 0.17 eV and 0.44 eV traps and clocking frequency of 50 MHz to the Improved Model. It emphasises the good agreement between the model and full simulations at temperatures lower than 250 K with 0.17 eV traps, but shows a disagreement at higher temperatures for the 0.44 eV traps.

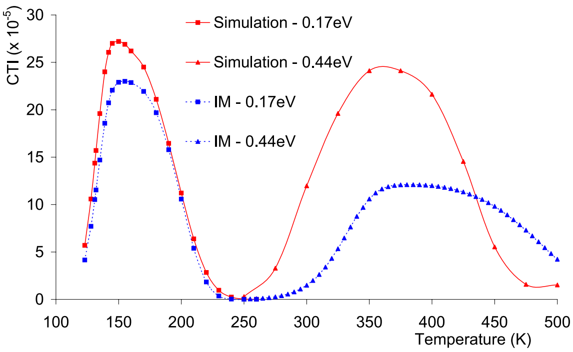

Figure 4. CTI values for simulations for 0.17 eV versus 0.44 eV partially filled traps at clocking frequency 50 MHz. Comparison of Improved Model (IM) with full DESSIS simulation.

If the 0.44 eV trap electron capture cross-section in the Improved Model is increased to $10^{-14}\,\mathrm{cm}^2$, a somewhat better agreement is found. However it is clear that there are limitations with the Improved Model. They could relate to a breakdown of the assumptions at high temperatures, to ignoring the precise form of the clock voltage waveform, or to ignoring the pixel edge effects. Further studies are required.

4. CONCLUSIONS

The Charge Transfer Inefficiency (CTI) of a CCD device has been studied with a full simulation and compared with analytical models.

Partially filled traps from the 0.17 eV and 0.44 eV trap levels have been implemented in the full simulation and variations of the CTI with respect to temperature and frequency have been analysed. The results confirm the dependence of CTI with the readout frequency. At low temperatures (< 250 K) the 0.17 eV traps dominate the CTI, whereas the 0.44 eV traps dominate at higher temperatures.

Good agreement between simulations and a so-called Improved Model has been found for 0.17 eV traps but not for 0.44 eV traps. This shows the limitations of the Improved Model with respect to the full simulation. The optimum operating temperature for CCD58 in a high radiation environment is found to be about 250 K.

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