Simulation of Changes in CTI of CCD58 due to Space Ionizing Radiation

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ABSTRACT
Charge Coupled Devices (CCDs) are one of the best sensors for use in space explorations which is described as a closely spaced array of metal-oxide semiconductor (MOS) that allows collection, storage and transfer of charge. It is utilized for a large range of wave length including UV to visible light. The done experiments on these space sensors show that using them in environments with ionizing radiations can regard their functionality. Generally we can summarize the mechanism of these radiation damages in two category: Total Ionizing Dose effects (TID) and Displacement Damage effects(DD). DD effects result in Charge Transfer Efficiency (CTE) reduction, dark current noise increase and etc. In this article we have proceed the simulation of CTE degradation and related parameters for a model of CCD that is CCD58. These studies utilise the package ISE-TCad software. Then we have compared and have validated our simulation results with the experimental data from laboratory measurements. The experimental measurements have been carried out by researchers at the University of Liverpool.

KEYWORDS: CCD; Simulation; CTE; Radiation Damage; Space Sensor; CCD58.

1. INTRODUCTION

Charge-coupled devices (CCD) have found a use in the field of high-energy physics as a basis of effective vertex detection, able to separate secondary vertices from the primary interaction point. Charge Coupled Device (CCD) is one of the most important devices of kind of location sensible detectors which has a wide range of sensibility to wave length from UV to visible light. These CCDs are a kind of analog semiconductor sensors with an output which is convertible to digital and have different applications. For example thin frigorific CCDs are used in photon detector and energetic particles tracer in astronomy. Some kinds of them which are used in space applications are Black&White photography CCDs. These devices are used in accelerator stations and space missions as photography systems. Experiments have shown that CCDs are so sensitive to radiation damage you put them in ionizing and Non-ionizing radiation environments.The space radiation can cause damage to electronic components or functional failure on the electronics. A precisely methodology is needed to ensure that space radiation is not a threat on the functionality and performance of the electronics during their operational lives. . The mechanism of these radiation damage effects is classified in to two categories include of the Total Ionizing Dose (TID) and Displacement Damage (DD). These effects cause the loss of device efficiency in space missions and etc. So study and analysis of radiation damage effects in these devices is one of the most important issues.

Radiation to the CCD causes damage by the creation of traps within the silicon. Traps capture electrons from the conduction band, and hence reduce the effciency in charge transfer of signal packets. Trapping effects depend on the CCD design, the operating temperature, and the readout frequency, which is expected to be in the order of 50MHz.

This article summarizes radiation hardness simulations of a CCD which its characteristics are given. An examination is made on the effect of radiation damage on CTE, due to electron capture in traps from defects in epitaxial layer. Finally the results of this simulation will be compared with a simple physical model which is described in this article.

This article have considered the effect of radiation damage on the performance of a CCD,namely CCD58; a 2.1 Mpixel, 3-phase buried-channel CCD produced by E2V.[1] The effect of radiation damage is quantified by the charge transfer ineffciency,or CTI.A commercial software package developed by ISE is used to simulate the device and is compared to a toy model.

2. CCD

The light-sensitive area in a CCD consists of a two-dimensional array of metallic electrodes which is insulated from a semiconducting silicon wafer by a layer of silicon oxide.The application of a voltage to the electrodes creates an array of voltage “wells” within the silicon substrate. A photon falling onto the CCD may penetrate into the silicon and free an electron by the photoelectric effect, which then becomes trapped within a local voltage well. The number of electrons produced in each well is proportional to the number of incident photons in a given integration time, during which the CCD is exposed to light. In this way, an optical image is transformed into an electronic image in the substrate of the chip. The individual voltage wells are referred to as pixels (after “picture elements”) because of the imaging function of the CCD.

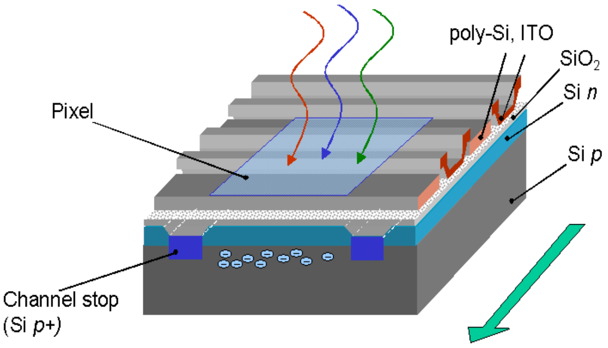

Fig. 1. Illustration of parallel charge transfer down a row of MOS capacitors. A 3 or 2 phase CCD is pictured, in which each pixel is composed of 3 or 2 electrodes for charge transfer. The signal charge travels in the buried channel and is restricted to a single row by implanted channel stops

The CTE is the most critical functional parameter of the CCD affected by radiation. CTE is defined as the fraction of charge that is successfully transferred from one pixel to the next during readout.

Present charge coupled devices (CCDs) are available with picoampere dark currents1 and charge transfer efficiencies (CTE) in excess of 0.9999995 per pixel. Figure 1 shows the basic structure, typically an array of Si MOS capacitors built on a p-type epitaxial layer about 10-20 mm thick. Potential wells are created by applying a voltage to one of the gate electrodes. The n-type buried channel ensures that the potential minimum is situated ~1 mm into the silicon so that charge is kept away from the silicon-silicon dioxide interface. In the most simple CCD readouts, charge is moved from one pixel to another by switching the applied voltage from one electrode phase to the next, first vertically, one row at a time, (in parallel) to the serial register where each row is moved one pixel at a time, to a readout amplifier [2]. Three or four clock phases/pixel are commonly used for vertical transfers, and two (plus an implant to define the charge transfer direction) or three for serial transfers. The charge detection amplifier provides a voltage that can be further processed.

3. CHARGE RANSFER INEFFICIENCY (CTI)

An illustration of the reduction in signal charge during transfer is shown in figure 3. Here only one pixel is assumed to contain traps. The signal packet passes over this pixel and the traps capture electrons, which remain as the signal moves to the next pixel. This trapped charge is slowly released to the conduction band. A second signal charge passes over the pixel. Now, because there is already some trapped charge remaining, the signal packet loses fewer electrons. A measure of charge loses during transfer of a signal packet may be quantified by the charge transfer inefficiency (CTI). This is the fraction of charge lost per pixel as it is transported along the device. If a packet has initial charge Q_0 and is transfered over m pixels then the resulting packet size Q_m is given by:

$$Q_m = Q_0(1-\zeta_{CTI})^m \approx Q_0(1-m\zeta_{CTI})$$

where ζ_{CTI} is the charge transfer ineffciency. CCDs require near lossless operation for readout of charge due to the number of pixels involved in transferring charge.[3] The use of simulations are employed to help in the understanding of CTI measurements and the processes involved. CTI= 1-CTE

4. SIMULATION

We need an accurate simulation to enable study of processes affecting the performance of a real device and investigation into the effect of variation in parameters of the device. These studies utilise the package ISE-TCad [4] whose suite of programs include: GENESISe, a graphical front-end to the program; mdraw, design of the geometry and doping characteristics; mesh, generates from mdraw a spatially discretised mesh for use in the simulation; dessis, the device simulation program; and tecplot ise, for graphical analysis of the simulation output. It should be noted that the simulation uses a continuous charge distribution and not the simulation of individual holes and electrons. This section describes the model of CCD58 [1] used and the process of simulation. A proton energy of 12 MeV was chosen to yield a high Non Ionizing Energy Loss (NIEL), giving the greatest damage at the lowest radiation dose, while maintaining sufficient penetration depth to spread out the damage evenly over the device thickness. The dose can easily be scaled to other proton energies using the NIST PSTAR data [5].

Table 1. Doping profiles used in simulated CCD58

Region	Material	Profile	Peak depth (μm)	Peak conc. (cm^{-3})	σ(μm)
Bulk	Boron	Constant	…	$1*10^{15}$	…
Buried channel	Phosphorus	Gaussian	0	$4*10^{16}$	0.24
Input drain	Phosphorus	Gaussian	0	$1*10^{19}$	0.15
Output drain	Phosphorus	Gaussian	0	$1*10^{19}$	0.15
Substrate	Boron	Gaussian	20	$1*10^{18}$	0.16

5. DEVICE GEOMETRY

The device CCD58 is a 2.1Mpixel 3-phase CCD with 12µm square pixels. Since it is computationally unfeasible to simulate a complete CCD, simplifications are made.Three consecutive pixels are simulated to determine charge transfer. This reduces the cpu overhead required. The simulation also assumes a 1µm width, compared with 12µm in CCD58. This is equivalent to considering a device uniform in width and taking a 1µm slice. In making these assumptions edge effects are ignored, such as the p-channel stops used to contain charge within each channel.

6. TOY CTI MODEL

Here a simple toy model is introduced and developed to compare with the ISE simulation results. An accurate model of the simulation, whilst significantly faster than a simulation, also provides a simple method to consider the effect of change parameters on the device, and demonstrates an understanding of physics involved. The model is constructed by considering two basic processes [6]:

1. electrons are captured from the signal packet, filling the traps;
2. electrons from filled traps are emitted back to the conduction band, depleting the trapped charge.

These processes occur at different rates that are described by time constants τ_c for process 1, and τ_e for process 2. The CTI can be calculated from the resultant net effect.

The CTI per pixel for a single trap level is given by:

$$\zeta_{CTI}=3\frac{N_t}{n_s}\frac{\tau_s}{\tau_c}\frac{(1-e^{-t_w/\tau_e})(1-e^{-t_{sh}/\tau_s})}{1-e^{-(t_{sh}/\tau_s+t_w/\tau_e)}}.$$

Where t_w is the waiting time between one signal packet arriving at a node and the next packet,t_{sh} is the shift time or occupation time of one node, and $1/\tau_s=(1/\tau_c+1/\tau_e)$, N_t is the trap concentration, n_s is the density of signal charge packet.[7]

7. COMPARISON BETWEEN TOY MODEL AND SIMULATION

The ISE simulation is compared to the toy model in figures2,3 and4 . There is reasonable agreement for each of the frequencies shown. As you see in the figure2,3 and 4 measured CTI by simulation and Toy model is plotted for energy levels of 0.17 eV below the conduction band ,7 MHz frequency and temperature range around 123 K to 260 K .

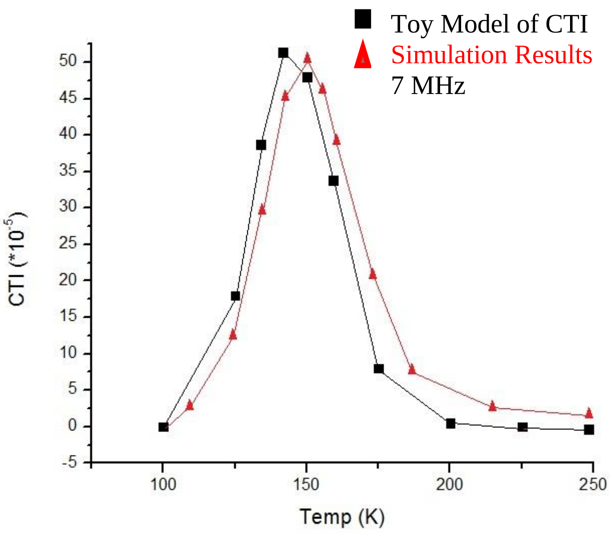

Fig. 2. A comparison between simulation results and simple toy model as a function of temperature for traps of Ec-0.17 eV and frequency of 7 MHz

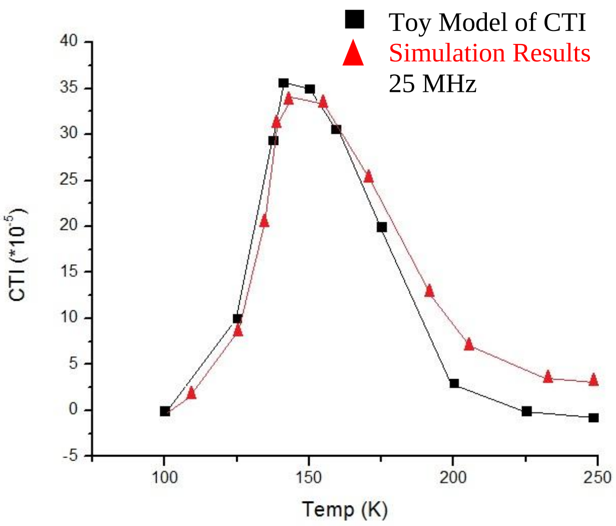

Fig. 3. A comparison between simulation results and simple toy model as a function of temperature for traps of Ec-0.17 eV and frequency of 25 MHz

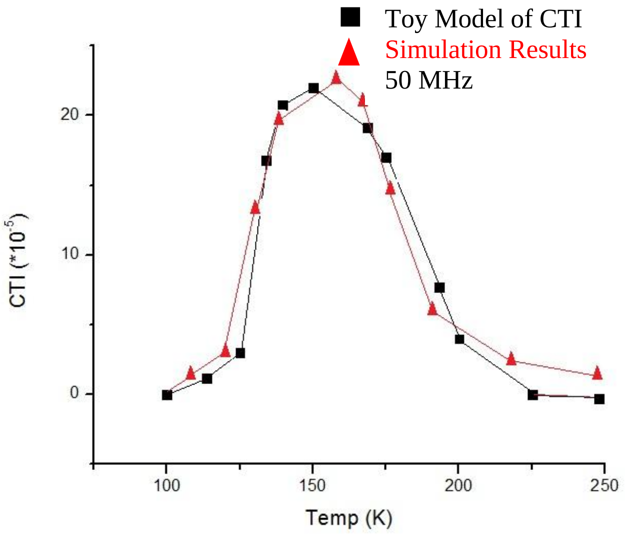

Fig. 4. A comparison between simulation results and simple toy model as a function of temperature for traps of Ec-0.17 eV and frequency of 50 MHz

The maximum difference between two curves is 3 * 10^{-5} at 200 K and minimum difference is approximately zero at 100 K. The maximum difference between the two curves for frequency of 25 MHz is 4 * 10^{-5} at 219 K and the minimum difference is at 130 K and zero. The maximum difference between the two curves for the frequency of 50 MHz occurs at 225 K and is 3 * 10^{-5} and minimum of that is at temperature of 140 K and 175 K which is approximately zero.

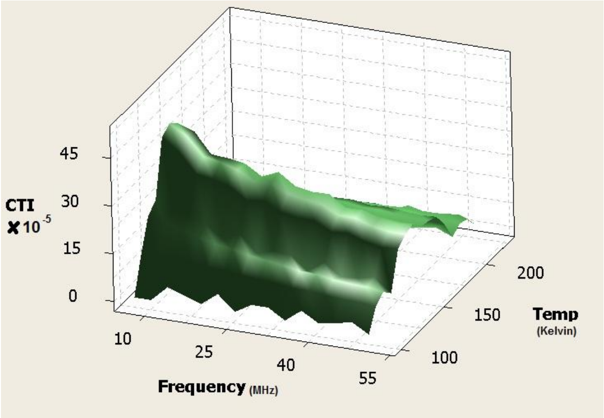

Fig. 5. CTI changes in terms of readout frequency and temperature obtained from simulations for EC-0.17eV trap levels

Figure5 shows CTI as a function of frequency and temperature. it can be safely stated that CTI will increase with the reduction of readout frequency. For higher frequencies, there is less time to capture charges so CTI decreases.[8] At high temperatures, the emission time of charges is so short that entrapped signals will come back to charge signal packet immediately.

Then we have compared and have validated our simulation results with the experimental data from laboratory measurements . The experimental measurements have been carried out by researchers at the University of Liverpool. [9] Although temperature range of experimentally measured CTI is limited and is performed at temperatures above 160 K, but at higher frequencies, the consistent of them with data obtained from the simulation is acceptable.

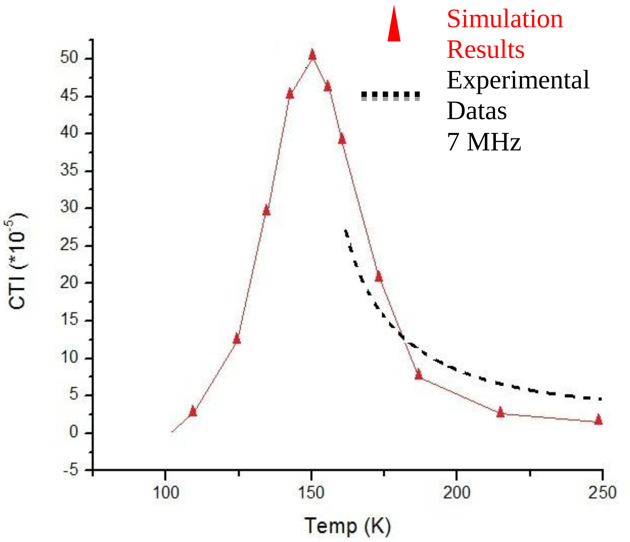

Fig. 6. Comparison of simulation data with data obtained from experimental measurements of CTI for frequency of 7MHz

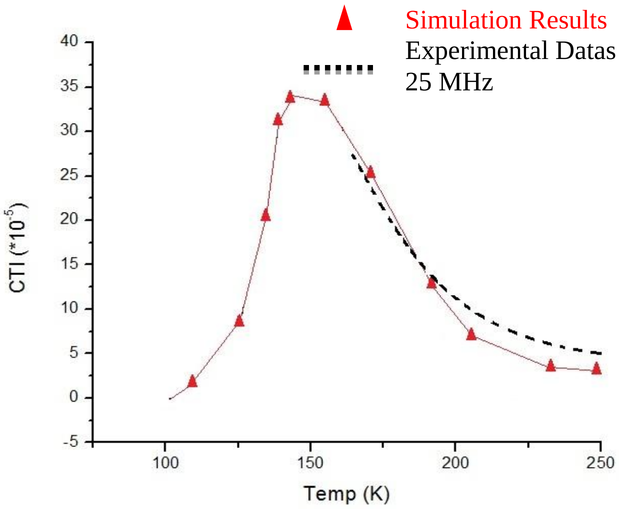

Fig. 7. Comparison of simulation data with data obtained from experimental measurements of CTI for frequency of 25MHz

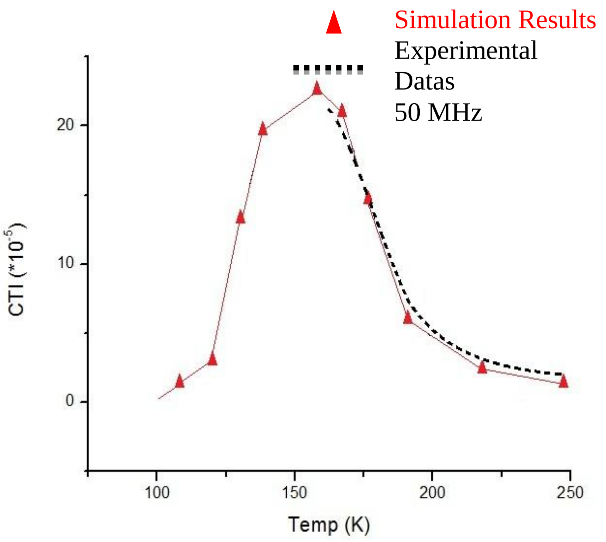

Fig. 8. Comparison of simulation data with data obtained from experimental measurements of CTI for frequency of 50MHz

We have repeated all of the previous simulations and modeling again for traps of Ec-0.44 eV. The simulation temperature range is from 250 K to 500 K . we have selected this temperature rang because repeated simulations performed before leads us to the conclusion that CTI parameter due to these traps (E_c-E_t=0.44 eV) for temperatures below 250 K is so small and negligible. The reason of this point is that electron emission time in temperatures below 250 is so long. Results from simulation and Toy model are shown in figures 9 to 11.

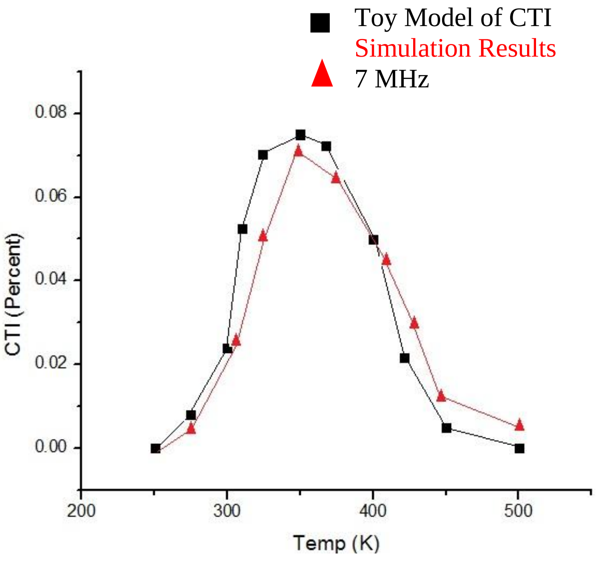

Fig. 9. A comparison between simulation results and simple toy model as a function of temperature for traps of Ec-0.44 eV and frequency of 7 MHz

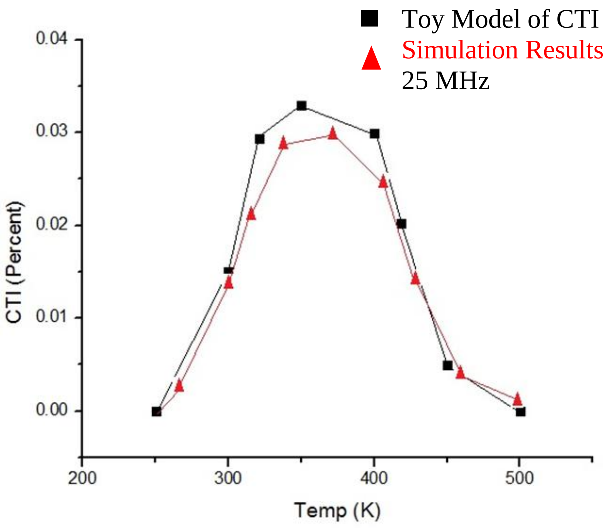

Fig. 10. A comparison between simulation results and simple toy model as a function of temperature for traps of Ec-0.44 eV and frequency of 25 MHz

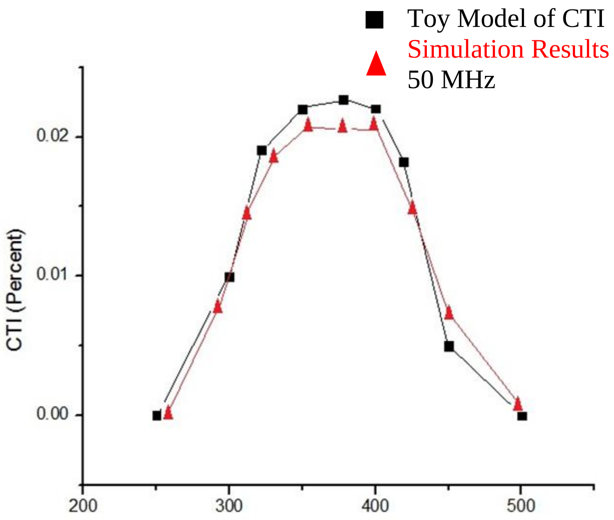

Fig. 11. A comparison between simulation results and simple toy model as a function of temperature for traps of Ec-0.44 eV and frequency of 7 MHz

As we see, the maximum of CTI for lower frequencies is higher and it's place depends to the temperature. For the frequency of 7 MHz, the maximum difference between two curves is 2 * 10^{-4} at 320 K and minimum difference is approximately zero at 400 K. The maximum difference between the two curves for frequency of 25 MHz is 5 * 10^{-5} at 350 K and the minimum difference occurs at 100 K and 443 K which is zero. The maximum difference between the two curves for the frequency of 50 MHz occurs at 381 K and is 3 * 10^{-5} and minimum of that occurs at temperature of 300 K and 430 K which is approximately zero.

As it is seen in figures 9 to 11, by increasing the temperature CTI grows rapidly at first and after getting maximum of itself, will decrease slowly. It's maximum for frequency of 7 MHz is so bigger from which occurs at 25 MHz and 50 MHz.

Figure12 shows the parameter of CTI as a function of readout frequency and device temperature. It is seen that the CTI will decrease by increasing the frequency so it will be one of our interested solutions to increase efficiency of device.

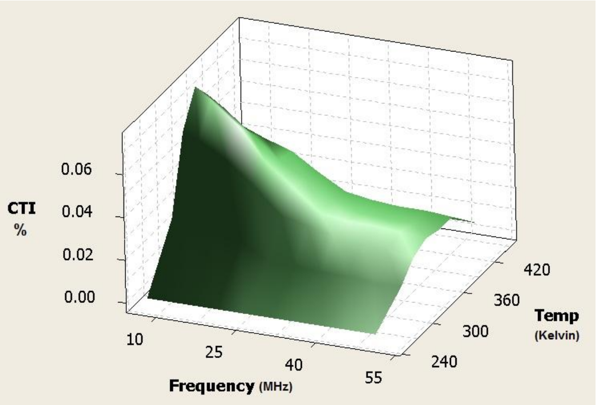

Fig. 12. CTI changes in terms of readout frequency and temperature obtained from simulations for EC-0.44eV trap levels

Finally the results from simulation due to trap energy of E_c-0.44 eV is compared with experimental data provided from laboratory measurements carried out by researchers at the University of Liverpool. These comparisons are plotted in figures 13 to15.

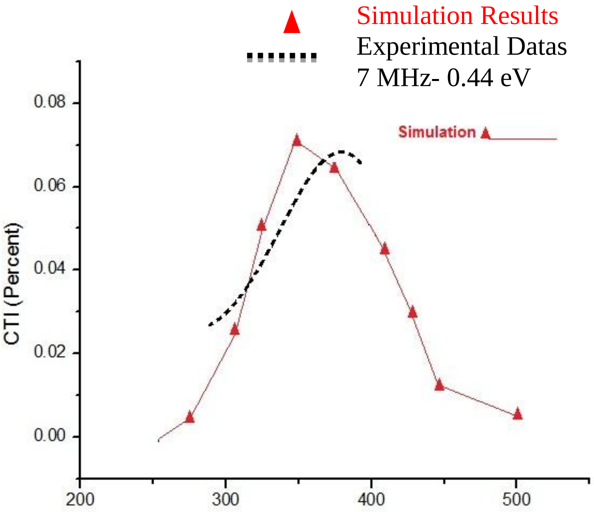

Fig. 13. Comparison of simulation data with data obtained from experimental measurements of CTI for frequency of 7MHz

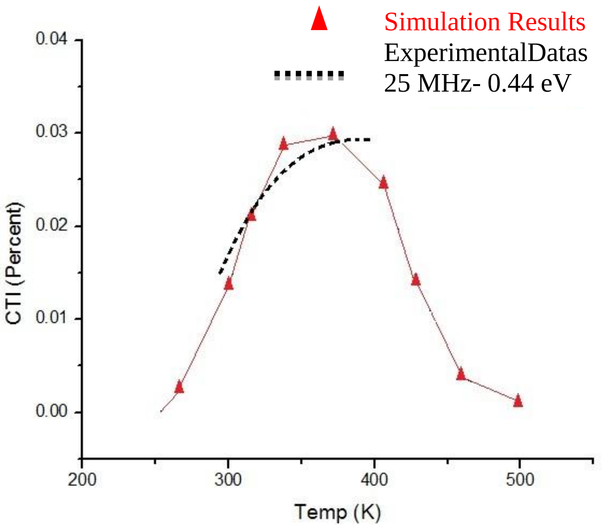

Fig. 14. Comparison of simulation data with data obtained from experimental measurements of CTI for frequency of 25MHz

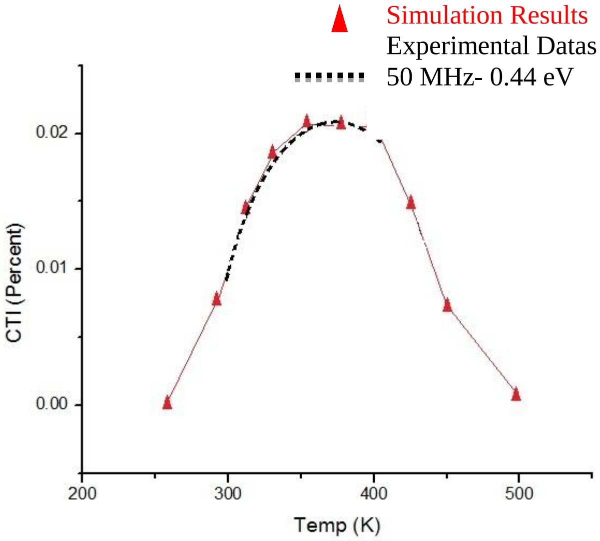

Fig. 14. Comparison of simulation data with data obtained from experimental measurements of CTI for frequency of 50MHz

For the frequency of 7 MHz, the maximum difference between two curves is 2 * 10^{-4} at 348 K and minimum difference is approximately zero at 320 K. The maximum difference between the two curves for frequency of 25 MHz is 1 * 10^{-4} at 340 K and the minimum difference occurs at 320K which is zero. The maximum difference between the two curves for the frequency of 50 MHz occurs at 419 K and is 1*10^{-5} and minimum of that occurs at temperature of 300 K which is approximately zero.

8. CONCLUSION

There are many techniques used to measure the CTE of a CCD, each with their own advantages and applicability to a particular situation. The simple toy model which considers only rates emission and capture was shown to be in reasonable agreement with the ISE simulation. It is important to note that the CTE is extremely application dependent [10]. At high readout frequencies which is more and widely useful like 50 MHz, we can see the best consistent between our simulation method and experimental data.

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