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A study of the double-acceptor level of the silicon divacancy in a proton irradiated n-channel CCD.

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ABSTRACT

Radiation damage effects are problematic for space-based detectors. Highly energetic particles, predominantly from the sun can damage a detector and reduce its operational lifetime. For an image sensor such as a Charge-Coupled Device (CCD) impinging particles can potentially displace silicon atoms from the CCD lattice, creating defects which can trap signal charge and degrade an image through smearing. This paper presents a study of one energy level of the silicon divacancy defect using the technique of single trap-pumping on a proton irradiated n-channel CCD. The technique allows for the study of individual defects at a sub-pixel level, providing highly accurate data on defect parameters. Of particular importance when concerned with CCD performance is the emission time-constant of a defect level, which is the time-scale for which it can trap a signal charge. The trap-pumping technique is a direct probe of individual defect emission time-constants in a CCD, allowing for them to be studied with greater precision than possible with other defect analysis techniques such as deep-level transient spectroscopy on representative materials.

Keywords: CCD, radiation damage, divacancy, n-channel, image sensor.

1. INTRODUCTION

A long-term effect of radiation damage in a silicon detector is the ability of incoming particles to displace atoms from the lattice and create defects which can be stable at standard operating temperatures[1]. The most problematic defects are those which give rise to energy levels within the silicon bandgap. In an image senor such as a CCD these levels can act to capture and re-emit signal charge, reducing charge transfer performance and causing image degradation. For a mission such as the ESA Euclid mission, which aims to take high precision shape measurements of distant galaxies, this has the potential under certain operating conditions to significantly contribute to the total measurement error budget, since signal charge can be redistributed and cannot be traced back to its original location in the detector[2]. The detailed study of these defect levels is therefore vital for the mitigation of radiation damage effects and increased detector operational lifetimes.

The target of this study was the double-acceptor level of the silicon divacancy, which is expected to be a dominant source of image degradation at nominal temperatures and operating conditions for several detectors, such as Euclid. The single trap-pumping technique was used as a direct probe of the defect emission time-constant. With this technique defects can be studied individually and an overall time-constant distribution obtained from the population. This provides more accurate data within these devices than available using analysis techniques which observe the combined effects of multiple defects. An energy level and cross-section is also obtained for each individual defect by tracking the emission time-constant across the temperature range 170-184K, which covers a range at which the defect time-constant closely matches typical CCD line transfer times. Analysis of the defect parameter distributions is important both for possible mitigation of radiation damage effects and for improving understanding of the charge-capture process.

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2. RADIATION DAMAGE

2.1 Displacement damage

Space-based detectors are subjected to the harsh radiation environment outside of the Earth's atmosphere. Highly energetic charged particles can cause damage both through ionisation effects as the particle passes through the detector and also by potentially displacing atoms from the detector lattice. This paper is concerned with displacement damage effects and their potential for degrading detector performance.

An incoming particle with enough energy can displace a silicon atom from its lattice site and create a Frenkel pair consisting of the displaced atom as a self-interstitial defect and the vacant lattice site as a vacancy defect[3]. Both the self-interstitials and vacancies are highly mobile at room temperature, and will diffuse through the lattice where they can combine with each other or with impurity atoms to create stable point defects or defect clusters[4].

There are many possible species of point defects. Some are electrically active and can create allowed energy levels within the silicon bandgap. These so-called deep levels (since they usually lie "deep" within the bandgap, away from the band edges) can significantly enhance recombination (the annihilation of an electron-hole pair) in the silicon by providing transition states for electrons and holes. Silicon is an indirect semiconductor and therefore the predominant method of recombination is via these localized transition states. This is known as Shockley-Read-Hall (SRH) recombination[5,6]. Figure 1 shows an example of several deep-level defects in silicon and their respective energy levels[3].

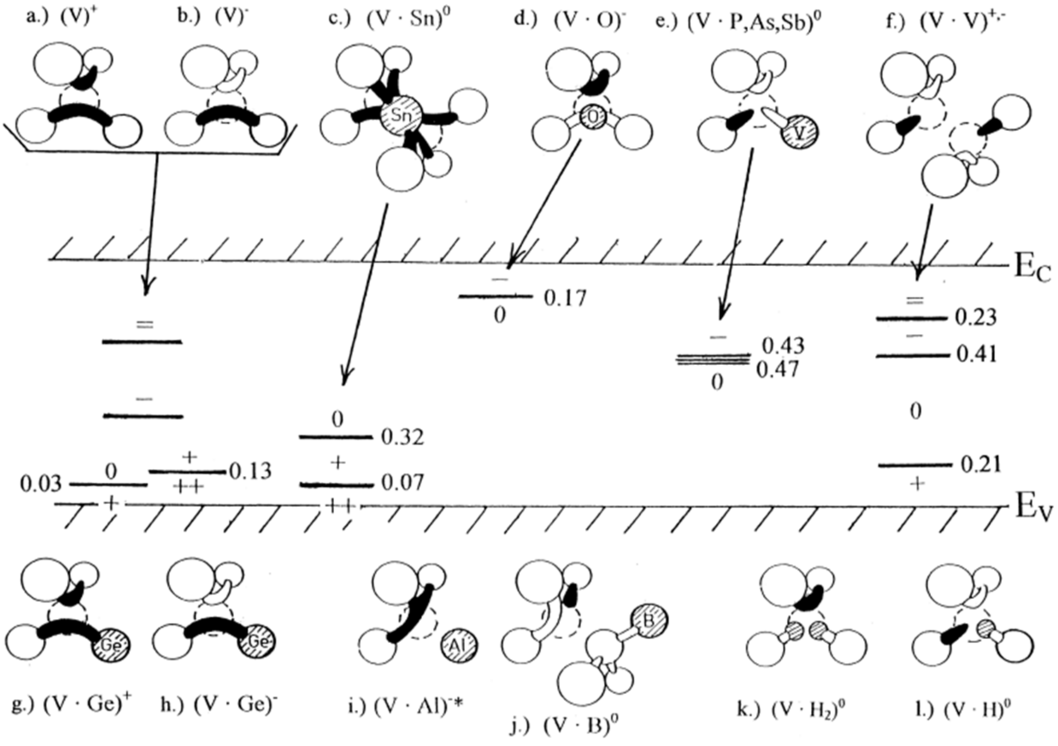

Figure 1 – A diagram depicting several defects which can produce mid-bandgap energy levels in silicon[3].

2.2 The silicon divacancy

The defect analysed in this paper is the silicon divacancy, created when two single vacancies combine (the divacancy is displayed as defect (f) in Figure 1). A silicon divacancy can exist in four possible charge states: V^{--}, V^{-}, V^{0} and V^{+} corresponding to a divacancy occupied by two electrons, a single electron, no electrons/holes and a single hole respectively[3]. The four charge states correspond to three divacancy energy levels, $V^{--/-}$, $V^{-/0}$ and $V^{0/+}$ within the bandgap. The first two are acceptor levels and can cause image degradation in an n-channel CCD by trapping electrons as majority charge carriers. The third level is a donor level and is a concern for p-channel devices. In this paper we study the double-acceptor level of the silicon divacancy ($V^{--/-}$). The value found in literature is E_c-0.23 eV for the energy of the double-acceptor level[3].

3. EXPERIMENTAL METHOD

The process of charge capture and emission by a deep level is modelled by Shockley-Read-Hall kinetics[5,6], which model the capture and release of electrons (or holes) through the use of two exponential time-constants, the capture time-constant and emission time-constant, shown in Equations 1 and 2 respectively. E_T is the energy of the defect level below the conduction band edge, σ is the capture cross-section, n is electron concentration, v_{th} is the thermal velocity for electrons and N_C is the effective density of states in the conduction band.

$$\tau_c = \frac{1}{n\sigma v_{th}} \tag{1}$$

$$\tau_e = \frac{1}{\sigma v_{th} N_c} \times \exp\left(\frac{E_T}{kT}\right) \tag{2}$$

It can be assumed at the signal levels used throughout this study that capture is effectively instant, i.e. $\tau_e \gg \tau_c$. As stated earlier the emission time-constant is the defect parameter concerned when considering the potential for image degradation. In this paper we probe the emission time-constant of double acceptor level of the silicon divacancy using the method of single trap pumping[7,8,9,10,11].

The method of trap pumping involves operation of a CCD in such a way as to amplify the effects of any charge-capturing defects which are present in the lattice. This is done by moving charge backwards and forwards between adjacent pixels many times. If a defect is present in a pixel and can capture and re-emit charge efficiently, then characteristic signal “dipoles” will appear in the final image, corresponding to a dark pixel (with respect to the background signal level) neighbouring a bright pixel. Figure 2 shows an example of several signal dipoles in an image.

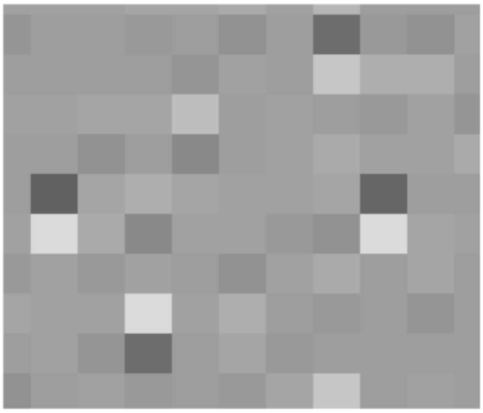

Figure 2 – Examples of signal dipoles in a trap-pumped image.

The parameter varied during the method is the "phase-time" t_{ph}, which is the time duration of each CCD clock phase electrode pulse. By analysing the strength of signal dipoles with respect to the device conditions and the phase time the emission time-constant of the responsible defect can be probed directly. A full explanation of the method of trap pumping is given in (Murray *et al*, 2012 and Hall *et al*, 2014) [9,10].

For this study an n-channel e2v CCD47-10 was used, which is a back-illuminated 1k ×1k pixel sensor with 13μm pixels. A single device was irradiated at the PSI facility in Switzerland with a 10 MeV equivalent proton fluence of 2.50×10^{9} pcm^{-2}. The actual beam energy during irradiation was 74 MeV. The irradiation was carried out at room temperature and the entire device was irradiated.

For the trap-pumping measurements a phase-time range of 1-500μs was covered over a temperature range of 170-184K, in increments of 2K. These values were chosen to easily cover the expected emission time-constant range for $V^{--/-}$ at these temperatures.

4. RESULTS AND DISCUSSION

4.1 Emission time-constants

The number of identifiable dipoles provides an estimate of the approximate defect density. For the analysed region of the irradiated device the defect density at a temperature of 170K is found to be $(3.8 \pm 0.1) \times 10^{-2}$ pix^{-1} where this value has been doubled to account for the fact that the trap-pumping method will only expose defects beneath barrier phase electrodes and not those beneath collecting phase electrodes. It is important to note that this value does not reflect the true defect density across the whole pixel, but instead the defects which can be assumed to interact with a signal charge cloud of a given size at these operating conditions.

The intensity of each observed signal dipole is tracked over the full phase-time range at each temperature to produce a curve as shown in Figure 3. Fitting the resulting curves allows for the identification of defects which behave according to SRH theory and gives the emission time-constant of those defects. Figure 4 shows the resulting distribution of emission time-constants at 174K. A split peak is observed in the main distribution, with two much smaller peaks at longer emission times. The split-peak distribution may correspond to two different defects, but with such similar time-constant values this might be considered unlikely. Other possibilities include that of two slightly different orientations of the defect within the silicon lattice, or minor differences based on the sub-pixel location of the defect. The two smaller peaks are of interest since they appear strongly Gaussian distributed, however there is not enough statistics to determine at this stage if they are divacancy related or a different defect species altogether. Divacancies can combine with oxygen and other impurities to form more complex defects, so it is possible that this is being observed[3].

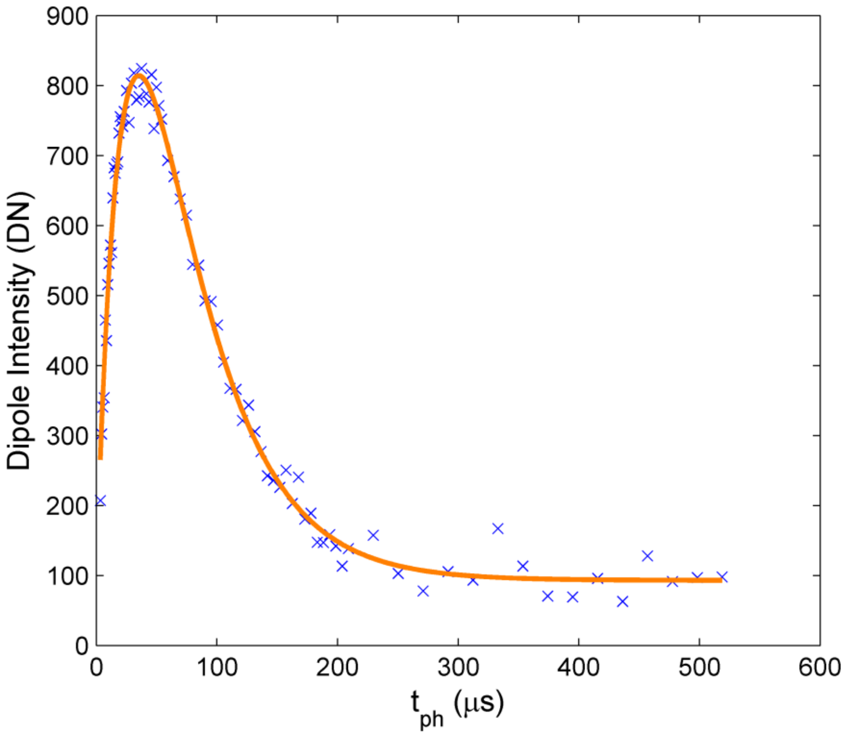

Figure 3 – Example dipole intensity curve. Fitting these curves and resolving the maximum point allows for the emission time constant of the responsible defect to be obtained.

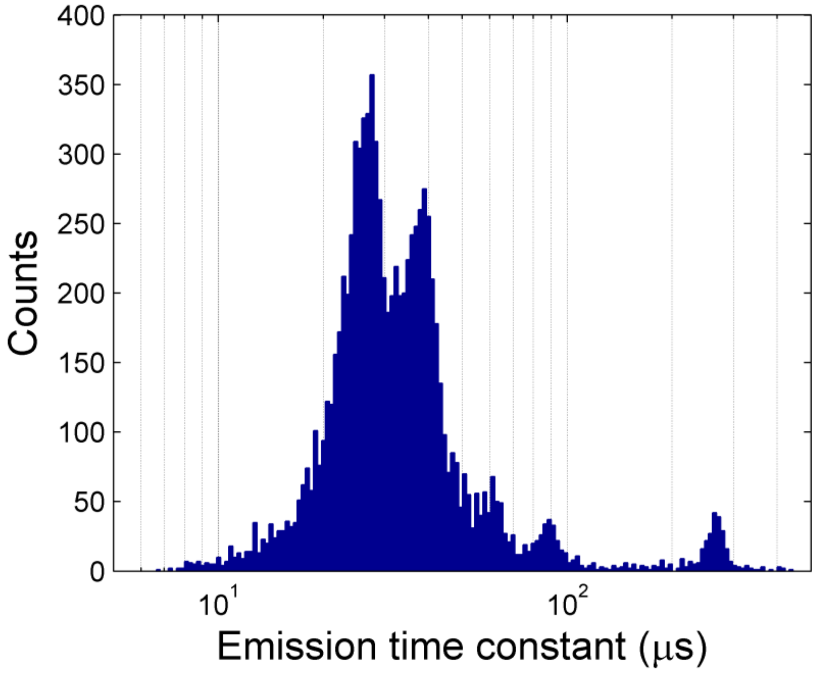

Figure 4 – Emission time-constant distribution for ~9000 defects at 174K.

Defects which produced reliable dipole intensity curves at all temperatures were tracked with changing temperature. The resulting curve is shown in Figure 5 where each line corresponds to an individual defect. As seen from Figures 1 and 2 a large spread exists in the observed emission time-constants; however this spread does not come from measurement uncertainty. This can be seen from the parallel nature of the lines in Figure 5 and was tested by performing three repeat measurements of each defect at each temperature, allowing sufficient time for the temperature to re-settle between each measurement. The average variation in the measured emission time-constant values was ±3%, which is negligible in comparison to the overall range of the distribution.

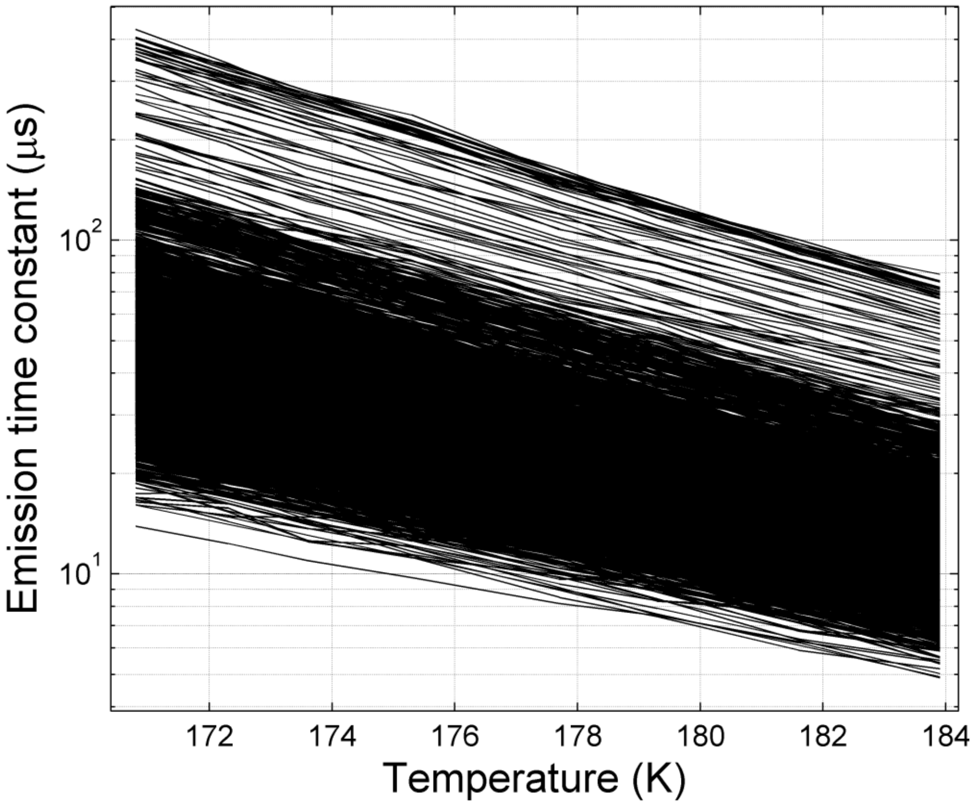

Figure 5 – Emission time-constant vs. temperature for ~4000 defects across the range 170-184K. Each line corresponds to a single defect.

The true source of the observed spread is not yet fully understood, and may arise from small variations in the structure of each defect and the surrounding atoms. Local temperature and electric field variations are also likely to contribute. It is possible that variations in electric field could cause spread in emission time-constants due to a Poole-Frenkel effect[12], where alignment with an external field can lower the energy required for a charge-carrier to be emitted from a defect level. With stronger fields it is also possible for tunneling effects to enhance emission[13].

An initial test of the effect of electric field strength on defect emission time-constant was carried out by taking trap-pumping data at the same temperature but varying the clock phase electrode voltage from 8-14V in 1V increments. No change within uncertainties of the mean emission time-constant was observed, however this does not rule out the electric field as being responsible for spread of emission times. The true field experienced by a charge carrier is complex and includes self-induced fields from the signal charge-cloud itself. Further analysis of the effect of electric field on emission time-constants at different signal levels and temperatures would be required to draw more definite conclusions. Figure 6 shows for a random sample of defects the effect of changing phase electrode voltage on the calculated emission time-constant.

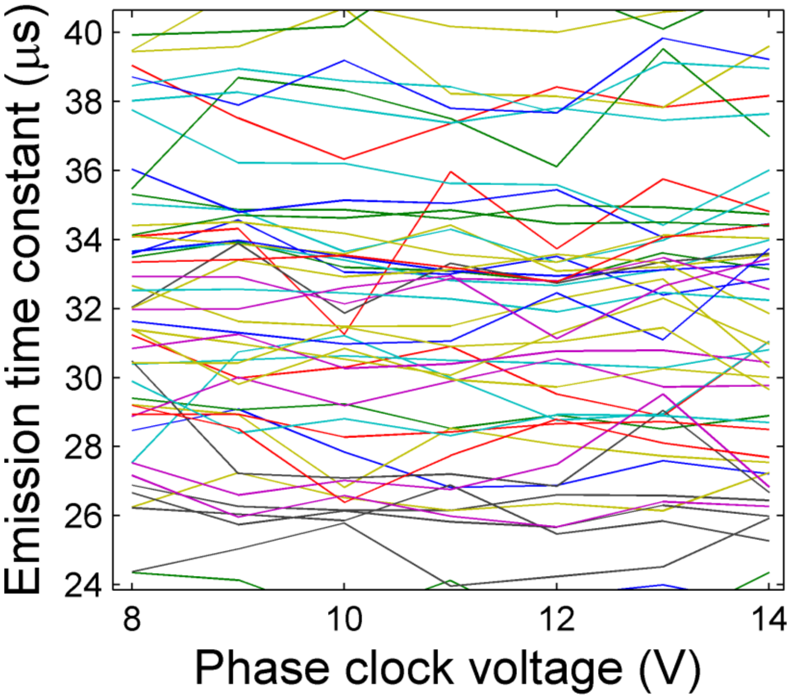

Figure 6 – Emission time-constants for a random sample of defects vs. changing clock phase electrode voltage. No discernible trends are observed.

4.2 Energy and cross-section

The curves shown in Figure 5 are fit based on Equation 1 to determine the energy level below the conduction band edge and cross-section of the responsible defect. The distribution of calculated energy levels is shown in Figure 7. The mean energy level below the conduction band edge band edge is found as 0.24 ± 0.015 (± 0.005) eV where the value of 0.015 eV represents a genuine spread which is seen in the calculated energy levels but does not arise from measurement uncertainty (measured at 0.005 eV). This value is in agreement with the literature value for $V^{--/-}$. Although we see a range of energies the distribution is Gaussian. This strongly suggests that we are looking almost exclusively at a single defect despite the split peak in the emission time-constant distributions.

A similar distribution is seen for the cross-section, with a mean value of 1×10^{-19} m^2. Uncertainties in the normal sense are not relevant here as we expect genuine spread in values due to field effects, small temperature variations and other effects contained within the cross-section. We see a range of 5×10^{-20} m^2 to 3×10^{-18} m^2 for approximately one sigma above and below the mean.

For each individual defect a value for energy, cross-section and emission time-constant has been calculated. The relationship between these three values can potentially provide insight into the source of the large spreads observed. No strong correlation is found between the emission time-constant and either energy or cross-section, which would appear to show that the spread comes from a variety of sources rather than a single dominant one.

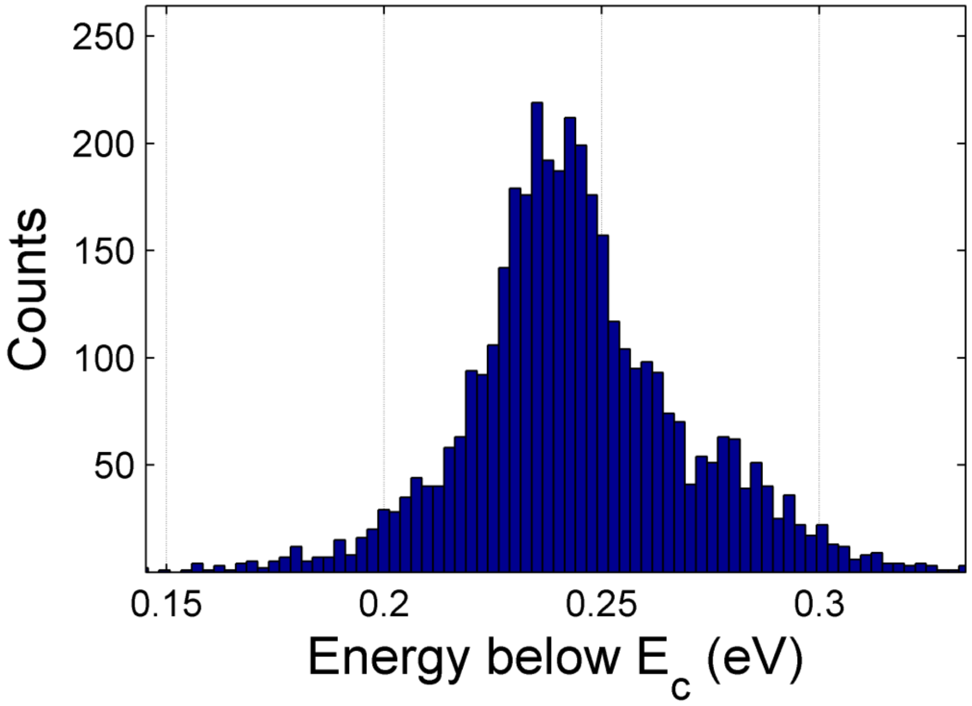

Figure 7 – The energy level distribution for all of the defects which were tracked across every temperature point.

5. CONCLUSIONS

The double acceptor level of the silicon divacancy has been studied in a proton irradiated CCD using the method of single trap-pumping. The defect emission time-constants were calculated with high accuracy over the temperature range 170-184K. A large genuine spread is seen in the resulting time-constant distribution, which also has a split main peak, possibly due to two orientations of the same defect.

The spread observed in the time-constant distribution appears to come from several sources. No strong correlation is seen between the emission time-constant of a defect and its calculated energy level and cross-section. One possible source could be local variations in electric field strength. Initial studies through the monitoring of the effect of increasing phase electrode voltage on the emission time-constant of a defect showed no change within the uncertainties. Further testing is required at more temperatures and signal levels to greater understand any field effects.

The energy and cross-section distributions strongly suggest that no other trap species was found in large numbers over this temperature and phase-time range. The calculated energy level of 0.24 ± 0.015 (± 0.005) eV is in agreement with the literature value of E_c-0.23 eV for $VV^{--/-}$.

The method of single trap-pumping is a valuable tool for accurately obtaining defect parameters. The ability to study defects individually allows for time-constant data to be obtained with much greater resolution than possible with other defect analysis methods. Accurate knowledge of defect parameters is beneficial when modelling radiation damage effects in order to correct for them[14]. This is particularly important for missions such as Plato and Euclid which aim to take high precision data. Further work is required to cover a greater temperature and phase-time range, and to investigate the source of the large spread found in the observed data.

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