BRU/PH/2XX
ROSE/TN/96-2

A NEW MODEL FOR GENERATION-RECOMBINATION IN SILICON DEPLETION REGIONS AFTER NEUTRON IRRADIATION

S. J. Watts, J. Matheson, I. H. Hopkins-Bond, A Holmes-Siedle, A. Mohammadzadeh, and R. Pace[1]

Centre For Radiation Damage Studies, Physics Dept., Brunel University, Uxbridge, Middx., UB8 3PH, UK.
[1] School of Applied Physics, University of South Australia, Australia.

Paper presented at IEEE Nuclear Science Radiation Effects Conference, 15-19 July 1996

A NEW MODEL FOR GENERATION-RECOMBINATION IN SILICON DEPLETION REGIONS AFTER NEUTRON IRRADIATION

S. J. Watts, J. Matheson, I. H. Hopkins-Bond, A Holmes-Siedle, A. Mohammadzadeh, and R. Pace[1]

Centre For Radiation Damage Studies, Physics Dept., Brunel University, Uxbridge, Middx., UB8 3PH, UK.
[1] School of Applied Physics, University of South Australia, Australia.

Abstract

Deep Level Transient Spectroscopy (DLTS) has been used to investigate defects in high resistivity silicon diodes after neutron irradiation. The leakage current in these diodes is found to be a factor of 50 to 600 greater than can be explained by standard Shockley-Read-Hall (SRH) theory for the observed defect concentrations. Three defects have been correlated with the leakage current. The results can be explained by an enhancement factor due to intercentre transfer of charge between defects in close proximity to each other. It is proposed that a possible mechanism for this process is rapid, direct transfer between a deep donor state and a deep acceptor state. An unidentified defect is observed at E_C -0.45±0.02eV which anneals at ~70°C. This defect is correlated to excess leakage current in both diodes and charge coupled devices (CCDs).

I. INTRODUCTION

In recent papers [1,2,3, and references therein], the damage created when high resistivity diodes and charge-coupled devices (CCDs) are irradiated with gamma-rays, neutrons and protons has been studied. Both types of device show a charge generation rate in the depleted silicon that is higher than that expected from consideration of the damage produced and Shockley-Read-Hall theory for generation-recombination [4].

In previous work [1], the introduction rates of defects created in high resistivity silicon diodes were measured after Co60 and neutron irradiation using deep level transient spectroscopy (DLTS). A defect kinetics model [5] was used to calculate the concentrations of defects present as a function of fluence based on these introduction rates. From these values, the expected leakage current from each defect species was calculated. The theory assumes that the total generation is the sum of the current from each defect. For Co60-irradiated diodes, the results were found to be in reasonable agreement with the predictions. However, for neutron-irradiated diodes the observed leakage current is a factor of ~100 greater than expected. The uncertainties in the model (approximately ±40%) are not sufficient to explain the large difference between the calculated and observed leakage currents after neutron irradiation.

The excess dark current in CCDs has been explained as a result of field enhancement however this cannot be the mechanism for excess leakage current in the diodes as the electric fields present are too small (~ 10^3 V/cm) [1]. The fact that excess leakage current is not seen in Co60-irradiated samples suggests that there may be a new mechanism for enhancement which is linked to the damage produced by high energy particle interactions.

In two recent papers by Chen et al. [6] and Frens et al. [7], enhanced recombination has been observed via a process where the electron is transferred *directly* between defects located near to one another without passing through the conduction band. This intercentre charge transfer had previously been thought to be inefficient in silicon however this new evidence shows that it can be very rapid and therefore dominate over the standard SRH process. In the light of this observation, the possibility that enhanced generation could occur via intercentre charge transfer in irradiated silicon has been examined.

This work describes a series of measurements undertaken to try to identify the dominant defects responsible for the leakage current using DLTS. A correlation is observed with defects (V_2 + others as yet unidentified) having energies in the Ec-0.40±0.05eV range. For these defects to be responsible for the observed current generation, the SRH generation rate must be enhanced by a factor ~50-600 assuming a typical cross-section ~10^{-15}cm^2. There is no evidence of significant amounts of any deeper levels.

For the intercentre charge transfer to occur, defects must be physically near to one another. The damage structure from neutron irradiation leads to clusters of intrinsic defects such as divacancies (V_2). These are therefore the most likely defects to have a dominant intercentre charge transfer path.

The interaction length of a 1MeV neutron is 4 cm and the introduction rate of the divacancy is ~5 cm^{-1}. Therefore ~20 divacancies are created per neutron. Assuming a 100Å diameter cluster region yields a density of divacancies of up to 10^{18} - 10^{19} cm^{-3}. This gives an average separation of 10^2Å but random distribution dictates that some defects will be closer than this value. Note that the statistical nature of damage processes allows for some defects to be close to one another even after gamma irradiation. Consequently, some possibility of this process occurring still exists in gamma-irradiated devices although at a much reduced level.

Although only magnetic resonance studies can directly show the intercentre charge transfer process occurring, the results found in this study are consistent with this mechanism. The process would affect depletion regions in many silicon devices, especially those with high resistivity material and so has widespread relevance.

II. THEORY

The principle behind enhanced generation through intercentre charge transfer is illustrated schematically in figure 1. The divacancy has three energy levels in the bandgap: a hole trap at E_V+0.2eV (denoted V_2^+), and two acceptor states at E_C -0.4eV and E_C -0.2eV. These have a negative and a double negative charge when filled and are denoted V_2^- and $V_2^=$.

In standard Shockley-Read-Hall theory [4], current generation in silicon depletion regions is mediated by isolated defect levels in the forbidden bandgap. Generation occurs when a hole is emitted from the defect level into the valence band (i.e. electron captured from it) and an electron is emitted into the conduction band. Each transition occurs with a rate, e_n or e_p , and is governed by a time constant τ_{ne} or τ_{pe} , given by

$$\frac{1}{e_n} = \tau_{ne} = \frac{1}{\sigma_n \nu_{nth} N_C \exp\left(\frac{E_t - E_C}{kT}\right)} \qquad (1)$$

$$\frac{1}{e_p} = \tau_{pe} = \frac{1}{\sigma_p \nu_{pth} N_V \exp\left(\frac{E_V - E_t}{kT}\right)} \qquad (2)$$

σ_p and σ_n are the hole and electron capture cross sections, v_{th} is the carrier thermal velocity, N_t is the density of traps, E_t is the trap energy level, k is the Boltzmann constant and T is the temperature. This gives an electron generation rate given by

$$U = -\frac{\sigma_n \sigma_p \nu_{th} n_i N_t}{\sigma_n \exp\left(\frac{E_t - E_i}{kT}\right) + \sigma_p \exp\left(\frac{E_i - E_t}{kT}\right)} \qquad (3)$$

where n_i is the intrinsic carrier concentration and E_i is the intrinsic Fermi energy level. Assuming similar cross-sections, there is maximum current generation when E_t is close to the midgap. For defects above the midgap, $\tau_{pe} \rangle\rangle \tau_{ne}$ and so the rate limiting step is the emission of a hole to the valence band. If several defect levels exist, they are regarded as acting independently of each other and the total current generation is taken as the sum of the individual components.

In coupled defect generation, illustrated in Figure 1, an electron is first captured by the donor state in the bottom half of the bandgap (E_V+0.2eV in this example). This is an efficient process with τ_{pe1} being very short hence the fractional occupation of this level is ≈1. The electron can then transfer *directly* to a higher state in a nearby defect without going via the conduction band. The time constant for this step is denoted $\tau_{1\to2}$. The final transition to the conduction band then occurs as normal with a time constant τ_{ne2}.

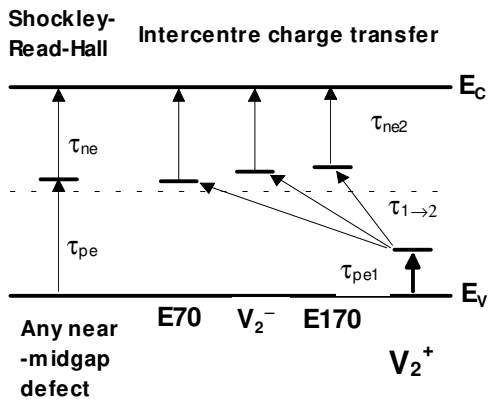

Figure 1. Schematic diagram of SRH and intercentre charge transfer generation processes. With intercentre charge transfer, the energy difference between the valence and conduction band is mediated by two steps instead of the single step in SRH generation.

The enhancement of the generation rate arises because the large transition from the valence band to the above midgap level is mediated by the donor level. This shortens the time taken for the upper state to become filled and hence increases its fractional occupancy. An estimate can be made of the degree of enhancement by the following method.

In SRH theory the number of electrons generated per unit time from a defect state can be expressed as the product of its fractional occupation, f_t , and the rate of electron emission to the conduction band, e_n ,

$$U = e_n f_t \quad \text{where} \quad e_n = \frac{1}{\tau_{ne}} \qquad (4)$$

where the fractional occupation in depletion is given by

$$f_t = \frac{e_p}{e_p + e_n} \qquad (5)$$

This can be written in terms of the time constants as

$$f_t = \frac{1/\tau_{pe}}{1/\tau_{pe} + 1/\tau_{ne}} = \frac{1}{1 + \tau_{pe}/\tau_{ne}} \qquad (6)$$

For the divacancy state, V_2^-, at energy of E_C -0.39eV, the values of the time constants at room temperature are

$\tau_{ne} = 7\times10^{-6}$ s and $\tau_{pe} = 5$ s

This gives a fractional occupation for this state from SRH theory of

$$f_t \approx \frac{\tau_{ne}}{\tau_{pe}} = \frac{7 \times 10^{-6}}{5} \approx 1.4 \times 10^{-6} \qquad (7)$$

In order to calculate the fractional occupancy when intercentre transfer occurs, the following assumption is made. The lower (donor) state is assumed to have an occupancy of ≈1. This is equivalent to saying that the emission time for holes from this level is short compared to the emission time

for electrons. This is true for defects with an energy in the lower half of the bandgap.

The time that limits the occupation of the upper (acceptor) state is now given by the intercentre transfer time, $\tau_{1\to2}$. Hence the enhanced occupation is given by

$$f_t^{\text{enhanced}} \approx \frac{\tau_{ne2}}{\tau_{1\to2}} \tag{8}$$

Therefore the enhancement of the generation rate will be given by

$$\frac{f_t^{\text{enhanced}}}{f_t} \approx \frac{\tau_{ne2}}{\tau_{1\to2}} \cdot \frac{\tau_{pe2}}{\tau_{ne2}} \approx \frac{\tau_{pe2}}{\tau_{1\to2}} \tag{9}$$

By analogy with equation (1) the time constant for the intercentre transfer can be written as

$$\tau_{1\to2} = \frac{1}{\sigma_{1\to2} v_{th} N_{t2}^0 \exp\left(\frac{E_1 - E_2}{kT}\right)} \tag{10}$$

where N_{t2}^0 is the density of empty and therefore available acceptor states. So, the enhancement factor, **EF**, will be

$$\mathbf{EF} = \frac{\sigma_{1\to2} N_{t2}^0 \exp\left(\frac{E_1 - E_2}{kT}\right)}{\sigma_p N_V \exp\left(\frac{E_V - E_2}{kT}\right)} = \frac{\sigma_{1\to2} N_{t2}^0}{\sigma_p N_V} \cdot \exp\left(\frac{E_1 - E_V}{kT}\right) \tag{11}$$

For the $V_2^{0/+}$ state, the exponential term has a value of ~2000. $N_V = 2\times10^{19}$ cm^{-3} and a reasonable estimate for N_{t2}^0 is of the order 10^{18} cm^{-3}. Assuming similar cross sections, this gives an enhancement factor of ***114*** at room temperature. Enhancement of the current from the divacancy is measured to be 150 (see section IV-*B*). The value for the intercentre transition time constant is 5×10^{-2}s which gives an occupancy from equation (8) of 0.7×10^{-4}s. The values for the occupancies calculated by this method are in good agreement with those found by a numerical calculation in Gill et al. [8]. A theoretical treatment of this subject has also been constructed by Schenk et al. [9].

III. EXPERIMENT

Diodes

The diodes studied in this work were p^+nn^+ manufactured on float-zone silicon. The concentrations of the important impurities in the material have been estimated as follows;

[P] = ~ 10^{12} cm^{-3}
[O] = few × 10^{15}cm^{-3}
[C] = few × 10^{15}cm^{-3}

Consideration of the measured concentrations and annealing behaviour of the main defects gives an introduction rate for the vacancy-oxygen (V-O or silicon A-centre) that is nearly 1000 times the introduction rate for the phosphorus-vacancy (PV centre or E-centre) after gamma irradiation [1]. Hence, in these high resistivity diodes, the concentrations of the PV centre can be assumed to be negligible. This is an important point because an unidentified defect is seen in this work with an energy and annealing temperature close to that of the PV centre. Previous work on low resistivity diodes would not have distinguished this defect from the large amount of PV centre dominating the results.

The DLTS measurements were taken using a SemiLab DLS 82-E Deep Level Transient Spectrometer. This uses a lock-in technique with a 1 MHz capacitance bridge and has a sensitivity of 10^{-5} times the dopant concentration, N_D. Filling pulse times were made long enough to fill all available electron states (500μs). The diode was reverse biased at 10V and pulsed up to 0V. The energy level and cross-section of the traps can be determined by frequency scanning at six temperatures around the DLTS peak temperature.

Trap concentrations, N_t, are given by

$$N_t = 8N_D \frac{\Delta C}{C_0} \tag{12}$$

where N_D is the dopant concentration, C_0 is the capacitance of the sample at the reverse bias voltage and ΔC is the capacitance transient due to the traps releasing electrons.

CCDs

The CCD02 device used in section IV-*C* is manufactured by EEV (Chelmsford, UK) and has 385 (horizontal) x 288 (vertical) pixels, each of area 22μmx22μm. It has a standard n-buried channel format with a phosphorus dopant implant of density ~10^{16}/cm^3. The dark current is collected from defects in the implant region (~1μm) and in the depleted p-type epitaxial (~4μm). The image was integrated for ~5 s before readout and was analysed using PC based software.

IV. RESULTS AND DISCUSSION

A. Leakage current measurements

The diodes were irradiated using the Brunel Cf252 neutron source. The leakage current of the diodes, biased at 70V to ensure full depletion, was measured at fluences of 4.1×10^9, 1.1×10^{10}, 2.5×10^{10} and 4.7×10^{10} 1MeV equivalent neutrons cm^{-2}. The source activity was 5.6×10^7 neutrons cm^{-2}hr^{-1}. This means the total irradiation took 34 days and was carried out at room temperature. Consequently, some annealing will occur during the irradiation. Gamma irradiations were carried out using Brunel's Co60 source. Fluences up to 1.8×10^{17} cm^{-2} were used. Measurements of the leakage current were carried out at a temperature of 294±0.5K and corrected to 20°C.

The damage constant for the leakage current, α, is given by

$$\frac{\Delta I}{Vol} = \alpha\phi \tag{13}$$

where ΔI is the increase in the leakage current, Vol is the volume of the depletion region and ϕ is the fluence. The measurements yield the following values of α for neutrons and Co60 gammas at 20°C. The value for α from neutron irradiation is in good agreement with the values found by Fretwurst et al. [2].

	Damage constant, α A cm^{-1}	**NIEL** $keV.cm^2g^{-1}$
Co60 gammas	$2\text{-}3\times10^{-23}$	0.01
1 MeV neutrons	$4\text{-}9\times10^{-17}$	1

A factor of 10^6 difference is seen between the value of α for neutron and gamma irradiation. The NIEL of Co60 gammas has been assumed to be equivalent to that of a 0.6 MeV electron and is only a factor of 10^2 less than the neutron NIEL. Therefore the leakage current damage constant does not appear to scale with the NIEL for high resistivity diodes.

B. DLTS measurements

A diode was irradiated with neutrons to a dose of 10^{10} neutrons cm^{-2} and then subjected to a series of 10 minute anneals from 50-200°C. After each stage the leakage current was measured and a DLTS electron trap scan taken for the temperature range 100-300K. Initially, between 50-100°C, the anneal was performed at temperatures increasing in steps of 5°C and thereafter increasing in steps of 10°C. The DLTS scan is shown after each anneal step in figure 2.

There is a large peak at E_C -0.4eV which is seen to decrease in size and shift in temperature in two main stages. This corresponds to two electron traps annealing out at approximately 70°C and 170°C. The defects have therefore been termed E70 and E170. The signal due to these two defects can be extracted by taking the difference in the signal before and after the defect anneals. The final peak is the V_2^- state of the divacancy. The extracted signals are shown in figure 3. Estimates of the energies for the defects are E_{E170} = 0.37±0.02eV and E_{E70} = 0.45±0.02eV below the conduction band.

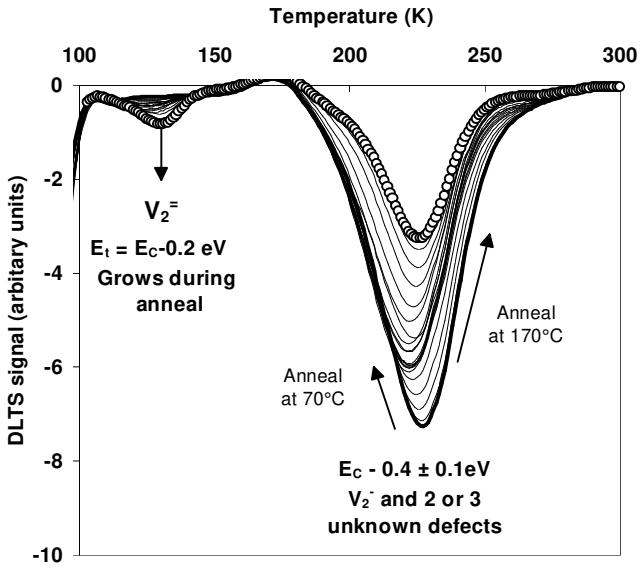

Figure 2. DLTS spectrum during isochronal annealing stages from room temperature to 210°C. A large peak at E_C -0.4eV is seen to anneal in two stages. The $V_2^{=/-}$ state at E_C -0.2eV is seen to grow during anneal. Anneal time of 10 mins/step.

The concentrations of the defects after 10^{10} neutrons cm^{-2} is therefore measured to be

$$[V_2] = 4.8\pm0.5\times10^{10}\,cm^{-3}$$
$$[E70] = 2.7\pm0.3\times10^{10}\,cm^{-3}$$
$$[E170] = 3.7\pm0.4\times10^{10}\,cm^{-3}$$

The $V_2^{=/-}$ state at E_C -0.2eV is seen to grow during the anneal. This will be discussed in section IV-D.

As has already been discussed, the low concentration of phosphorus in the sample means that the amounts of PV or C_iP will be negligible. The identities of E70 and E170 are not known but it is likely that they are intrinsic (i.e. not related to impurities) as they are not seen when these diodes are gamma-irradiated. Possible candidates are multivacancy defects such as the V_3, V_4, V_5 and V_6. There is some indication of small amounts of further defects both annealing in and out but these cannot be resolved with this data.

Figure 4 shows the leakage current and the amplitude of the 0.4eV DLTS peak as a function of anneal temperature. The behaviour of the two parameters on annealing is clearly correlated. Both the leakage current and the DLTS peak anneal out in two stages: a clear stage at ~70°C and a further stage at ~ 170°C. The correlation was investigated further by extracting the concentrations of E70 and E170.

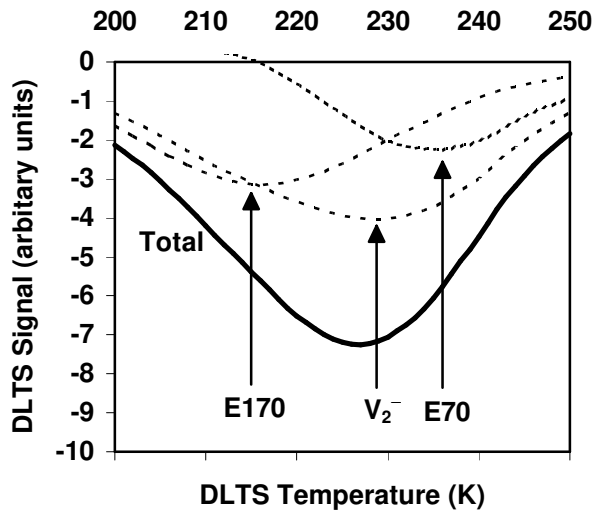

Figure 3. Three of the components of the DLTS peak at E_C -0.4eV can be resolved from the total peak by their annealing behaviour. The $V_2^{-/0}$ state is left at the end of the total anneal. The E70 peak is that part of the total which anneals out at ~70°C. The remainder is the peak denoted E170 which anneals out at ~170°C.

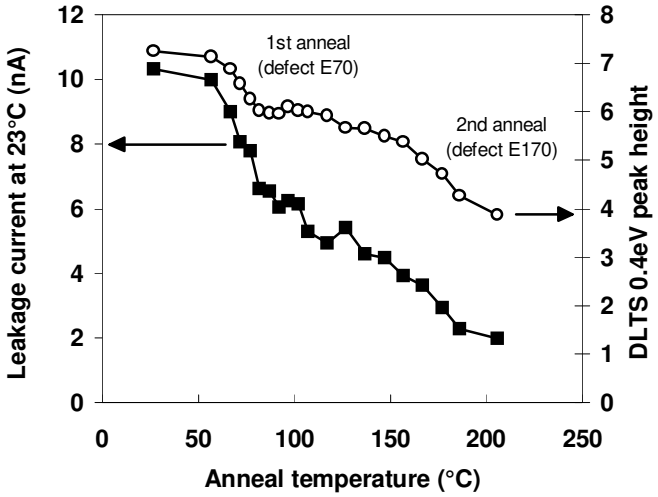

Figure 4. The leakage current at 70V reverse bias and 23°C is plotted as a function of the anneal temperature. Each anneal lasted 10 mins. The total peak height of the E_C -0.4eV DLTS peak is shown referred to the secondary axis.

B. Correlation of defects E70 and E170 to the annealing of the leakage current

The DLTS signal ($\Delta C/C_0$) from the E70 centre alone was extracted for each annealing step by subtracting the 117°C scan after the step. It is assumed that all the E70 has annealed out at this temperature. The concentration is given as a function of annealing temperature in figure 5. The defect is clearly annealing out at a temperature of ~70°C. This corresponds to a two week time constant at room temperature.

Similarly, the signal due to E170 was extracted for each annealing step by subtracting the DLTS scan after a final 4 hr anneal at 210°C. This was the highest temperature that could be reached and it is assumed that all the E170 is gone after this step. The concentration of E170 is shown as a function of annealing temperature in figure 6. The annealing behaviour is probably somewhat distorted by small quantities of other defects. However the defect appears to anneal out at ~170°C which corresponds to a time constant of ~ 4 years at room temperature.

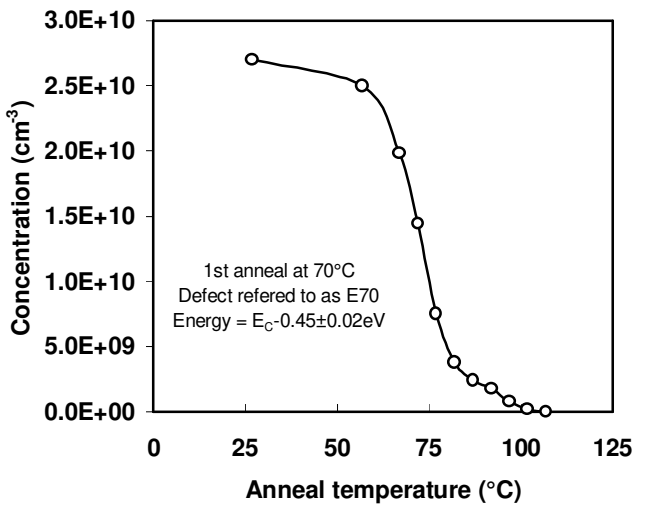

Figure 5. The concentration of the unidentified defect E70 is plotted as a function of the anneal temperature. A clear anneal behaviour is seen at ~70°C.

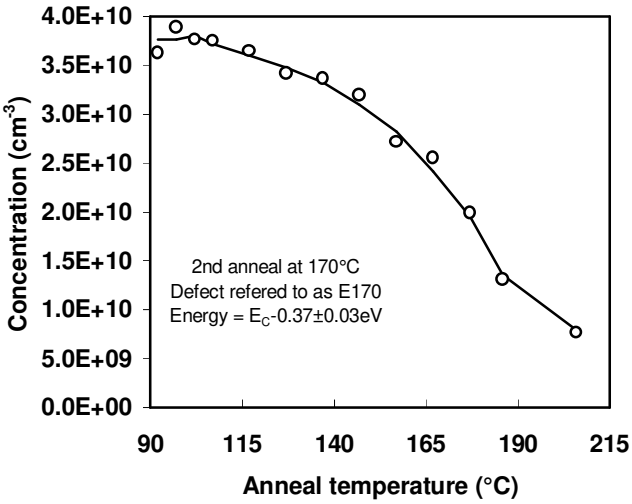

Figure 6. The concentration of the unidentified defect E170 is plotted as a function of the anneal temperature.

The leakage current at 70V reverse bias, 23°C is plotted as a function of the concentration of the defects E70 and E170 in figures 7 and 8 respectively. A linear correlation of leakage current to concentration is seen for both defects. There is some evidence of leakage current due to some other defect coming in at low concentrations of the E170 defect (temperature >190°C). This is seen in the DLTS data as a shift in the temperature of the peak maximum during these stages.

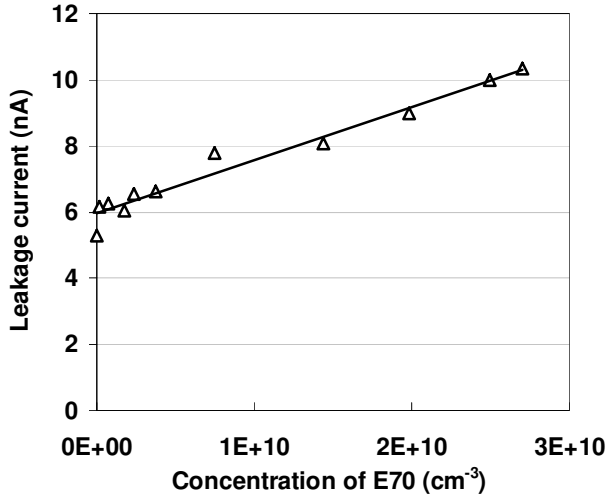

Figure 7. The leakage current at 23°C (70V reverse bias) is plotted as a function of the concentration of the unidentified defect E70. A good linear correlation is seen.

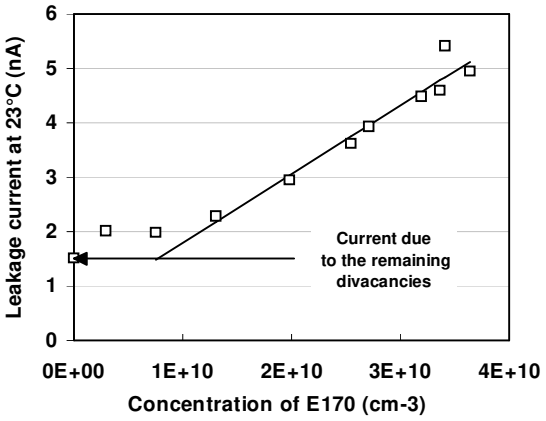

Figure 8. The leakage current at 23°C (70V reverse bias) is plotted as a function of the concentration of the unidentified defect E170.

Given the correlation of leakage current to the concentrations of these defects and the fact that they are the deepest states observed, it is likely that they are the source of the current. The expected generation rate from SRH has been calculated for the concentrations, energy levels and cross sections observed and is shown below. This is compared to the measured change in the leakage current after that defect anneals out. The enhancment necessary to give this current is listed. The leakage current before irradiation was typically ~500pA. The cross sections are taken to be ~10^{15} cm^2. These have been measured for the divacancy and for the E170 defect[10] and is assumed to be similar for the E70.

	Observed current (nA)	SRH calculated contribution (nA)	Hence enhancement factor, EF
E70	4	0.08	50
E170	3	0.005	600
$V_2^{-/0}$	1	0.013	80

Similar annealing of dark current in CCDs is seen over a few weeks at room temperature [11] and this was studied further.

C. Excess dark current in alpha-irradiated CCDs

In a previous study [12], a CCD02 was irradiated with 4.5 MeV alpha particles at normal incidence to the front surface. These will deposit most of their energy at the end of their range i.e. ~17μm into the silicon. Hence, most defects will be created in the epitaxial silicon below the buried channel and so the dominant dark current defect in this case will not be the PV centre as is the case with proton-irradiated CCDs [3].

After an irradiation of 10.3 hrs, a dark current histogram was taken at room temperature which showed significant numbers of pixels containing excess dark current. Pixels were designated 'hot spots' if they showed a dark current greater than a threshold value. The numbers of these hot spots were counted as the device was annealed. An isochronal anneal (15 mins) was performed at 10°C steps from room temperature up to 100°C. The number of hot spots is shown as a function of anneal temperature in figure 9.

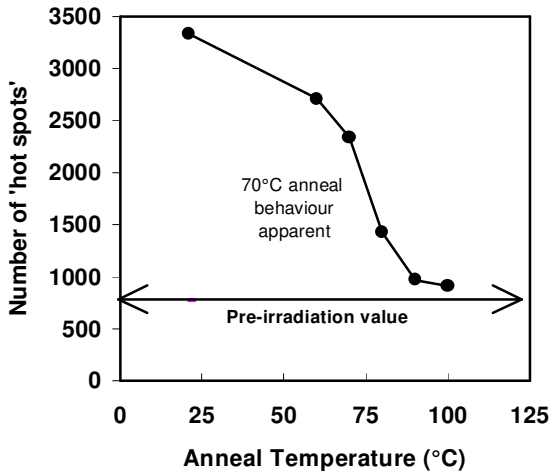

Figure 9. The number of pixels showing excess dark current ('hot spots') in an alpha-irradiated CCD is shown as a function of anneal temperature. A clear anneal behaviour is seen at ~ 70°C.

It can be seen that most of the hot spots anneal out at around 70°C. This is the same temperature at which defect E70 is seen to anneal in the diodes discussed in the previous section. Therefore it is likely that this is the same defect present in the CCDs. We have shown that the E70 defect is not phosphorus related due to the low levels of phosphorus in the high resistivity diodes in the previous section. Also, the defect causing the hot spots in the CCD after alpha-irradiation is probably created by an interaction outside of the buried channel and so again it is not likely to be phosphorus related.

D. Increase in the $V_2^=$ DLTS signal during anneal

The 130K peak in the DLTS scan is generally accepted to be the double negative state of the divacancy, $V_2^=$. The DLTS signal is shown after each annealing cycle in figure 10. It is clear that the amplitude is increasing during the course of the anneal.

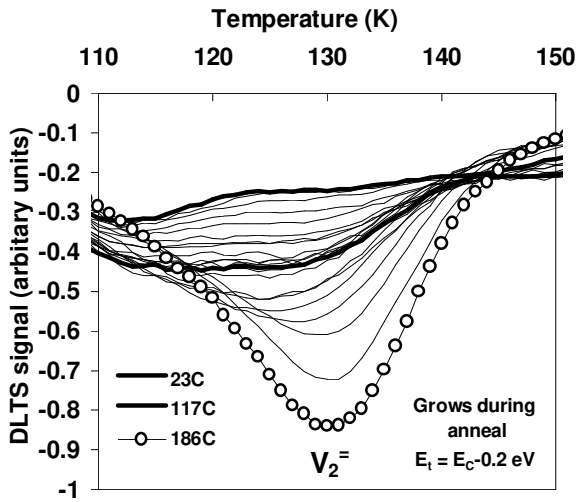

Figure 10. DLTS signal from the $V_2^=$ state at E_C -0.2eV grows during isochronal annealing stages from room temperature to 210°C.

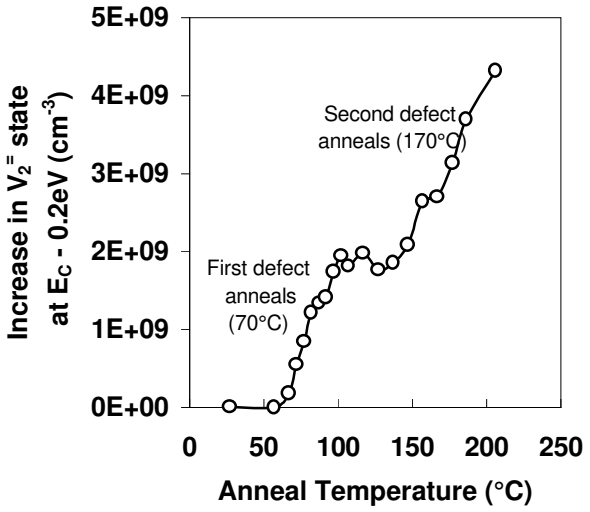

Figure 11. The concentration of the $V_2^=$ state is plotted as a function of the anneal temperature. This peak increases in two distinct stages that reflect the annealing of the E_C -0.4eV peak discussed earlier.

The amplitude of this increase is plotted as a function of anneal temperature in figure 11. Two distinct stages to the increase are observed. These occur at the same temperatures and with the same general form as the anneal of both the E_C -0.4eV peak in the DLTS scan and the anneal of the leakage current.

It has been widely accepted that the divacancy is formed during neutron irradiation. Hence, the increase in the DLTS signal from the $V_2^=$ state is not regarded as evidence of the divacancy being formed. Rather it is suspected that the DLTS signal from this state is suppressed through some mechanism. The two states of the divacancy, V_2^- and $V_2^=$, should give equal amplitude signal in the DLTS scan. This is true in Co60 irradiated diodes. However, after neutron irradiation and annealing up to 200°C, the amplitude of the V_2^- state is 3-4 times greater than that of the $V_2^=$.

It has been proposed [13] that lattice strain in the cluster acts to reduce the signal from this state. However, intercentre charge transfer provides an alternative explanation.

The DLTS method looks at the change in capacitance caused by emission of electrons from a filled level to the conduction band. The level is filled by applying zero bias to the diode and emptying occurs when it is pulsed into depletion. The capacitance transient takes the form of an exponential decay characterised by the emission time constant of the state (see equation 1). The DLTS signal is effectively the difference between the capacitance sampled at two times. This is shown in figure 12.

The possibility of intercentre charge transfer affects the possible transitions for the electrons trapped in the $V_2^=$ state. As the state empties it can be refilled by charge transfer

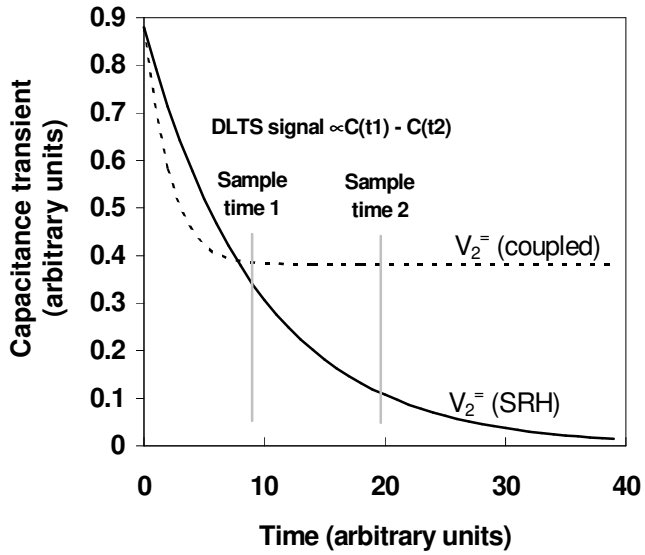

Figure 12. The capacitance transient from the V2= state for standard SRH theory and with intercentre charge transfer between the defects (coupled). The DLTS signal takes the difference between two samples. This will be effectively zero for the coupled level transient.

from the V_2^- state and also from the E70 and E170 defect levels. This changes the kinetics of the emptying of the state and so changes the DLTS signal. The equation describing the emptying of the $V_2^=$ state is now given by

$$\frac{1}{\sigma v_{th}}\frac{dN_{V_2^=}}{dt} = N_{V_2^-}N_{V_2^-}\exp\left(-\frac{E_{V_2^=}-E_{V_2^-}}{kT}\right) - N_{V_2^=}N_C\exp\left(-\frac{E_C-E_{V_2^=}}{kT}\right) \quad (14)$$

where $N_{V_2^=}$ and $N_{V_2^-}$ are the concentrations of the $V_2^=$ and V_2^- filled states and $E_{V_2^=}$ and $E_{V_2^-}$ are their energy levels referred from the valence band. For simplicity the cross-sections are assumed to be equal.

The first term describes filling of the $V_2^=$ state from the V_2^- state by intercentre charge transfer. The second term is the normal electron emission from the $V_2^=$ level to the conduction band.

Calculations show that the DLTS filling pulse results in 88% of the divacancies being in the $V_2^=$ state at 125K. The rest are in the V_2^- state. Note that, as the $V_2^=$ state loses an electron it turns into the V_2^- state.

A key fact about this system is that the change in energy between the $V_2^=$ and V_2^- states is similar to the difference between $V_2^=$ and the conduction band. This means that the time constant for the filling and emptying of the $V_2^=$ state by these two processes is similar.

$$E_{V_2^=} - E_{V_2^-} = E_C - E_{V_2^=} = \Delta E = 0.2eV \quad (15)$$

Thus, equation (14) can be written as

$$\frac{1}{\sigma v_{th}} \frac{dN_{V_2^=}}{dt} = \left(\left(N_{V_2^-} \right)^2 - N_{V_2^=} \cdot N_C \right) \exp\left(-\frac{\Delta E}{kT} \right) \quad (16)$$

with the initial conditions

$$N_{V_2^-} = 0.12\, N_{V_2} \quad \text{and} \quad N_{V_2^=} = 0.88\, N_{V_2}$$

where N_{V_2} is the total concentration of divacancies in any state. The solution of equation (16) for coupled divacancy states is illustrated in figure 12. It can be seen that the shape of the capacitance transient is distorted. The difference between the two DLTS sampling points is now very small hence little signal will be seen for the $V_2^=$ state.

A similar argument holds for intercentre charge transfer between the $V_2^=$ state and the E70 and E170 defects. This mechanism means that the signal from the $V_2^=$ state is suppressed by the presence of the deeper levels. Hence as these defects anneal out the DLTS signal will grow. This explains why the growth of this state reflects the reduction in the E70 and E170 defects.

After annealing of the E70 and E170 defects, the $V_2^=$ state is still suppressed by a factor 3-4 through coupling to the V_2^- state. This implies that 75% of divacancies remain coupled.

The divacancies are not close enough together after Co60 irradiation and hence no coupling can occur. This explains the lack of suppression of the $V_2^=$ state in gamma irradiated devices.

V. CONCLUSION

Excess leakage current in high resistivity diodes has been correlated to three main defects with energies of around E_C - 0.4eV. The concentrations of these defects have been measured with DLTS during a programme of annealing from 20 to 210°C. There are two unidentified defects, E70 and E170, and the divacancy. The E70 and E170 defects are not seen in gamma-irradiated devices and are therefore assumed to be the product of cluster type damage. For example, the multivacancy state V_4 is known to anneal around 150°C and so is a possible candidate for E170.

In CCDs irradiated with alpha particles, pixels showing excess dark current anneal at 70°C. This suggests that this current is due to the same E70 defect seen in the diodes.

SRH theory has been used to calculate the expected currents from each defect species. In each case the expected current was too low by a factor of 50-600.

A theory of generation enhancement through intercentre charge transfer has been developed to explain this observation. An enhancement factor for divacancies in a cluster has been calculated by this method to be 114. This theory has also been used to explain the suppression of the $V_2^=$ state in the DLTS data.

Intercentre charge transfer may also be responsible for the large amplitudes of random telegraph signals [3]. For example, enhancement from a donor state coupled to a metastable acceptor would cause such behaviour.

To conclude, enhanced generation through intercentre charge transfer explains our observations of excess generation in diodes and CCDs. It should be possible to directly measure these transfer mechanisms with ESR and optical methods in the future.

VI. ACKNOWLEDGEMENTS

The authors would like to acknowledge K. Gill (CERN), G. Hall and B. MacEvoy (Imperial College, London) for many useful discussions. The project was funded by the UK Particle Physics and Astronomy Research Council. The diodes were processed for the RD20 Collaboration. We are grateful to CERN for providing support to the RD20 and RD48 (ROSE) collaborations within which this work was performed.

VII. REFERENCES

[1] J. Matheson, M. S. Robbins and S. J. Watts, "The effect of radiation induced defects on the performance of high resistivity silicon diodes", RD20 Technical Report CERN RD20/TN/95-36, January (1995)

[2] E. Fretwurst, H. Herdan, J. L. Lindström, U. Pein, M. Rollwagon, H. Schatz, P. Thomses and R. Wunstorf, "Silicon detector developments for calorimetry; technology and radiation damage", *Nucl. Instr. and Meth. in Physics Research*, A288, pp. 1-12, (1990)

[3] G. R. Hopkinson, C. J Dale and P. W. Marshall, "Proton effects in CCDs", *IEEE Trans. Nucl. Sci.*43 (2), pp. 614-627 (1996)

[4] W. Shockley and W. T. Read, "Statistics of the recombination of holes and electrons", *Phys. Rev.,*87 (5), pp. 835, (1952)

[5] B. C. MacEvoy, "Defect evolution in silicon detector material", Conference on Radiation Effects on Semiconductor Materials, Detectors and Devices, Firenze, Italy, March 6-8, (1996)

[6] W. M. Chen, B. Monemar, E. Janzén and J. L. Lindström, "Direct observation of intercenter charge transfer in dominant nonradiative recombination channels in silicon", *Phys. Rev. Lett.*, vol. 67, no. 14, pp 1914- 1917, (1991)

[7] A. M. Frens, M. T. Bennebroek, A. Zakrzewski, J. Schmidt, W. M. Chen, E. Janzén, J. L. Lindström, and B. Monemar, "Observation of rapid direct transfer between deep defects in silicon", *Phys. Rev. Lett.*, vol. 72, no. 18, pp 2939- 2942, (1994)

[8] K. Gill, G. Hall and B. MacEvoy, "Divacancy clustering and the origin of leakage current in bulk damaged silicon detectors" CERN CMS/TN/96-17 (1996)

[9] A. Schenk and U. Krumbein, "Coupled defect-level recombination: Theory and application to anomalous diode characteristics", *J. Appl. Phys.*, vol. 78 (5), pp 3185-3192, (1995).

[10] M. Moll, H. Feick, E. Fretwurst, G. Lindström and C. Schütze, "Comparison of defects produced by fast neutrons and Co60 gamma rays in high resistivity silicon detectors using Deep

Level Transient Spectroscopy", presented at the Conference on Radiation Effects on Semiconductor Materials, Detectors and Devices, Firenze, Italy, March 6-8, (1996)
[11] G. R. Hopkinson, "Radiation-induced dark current increases in CCDs", RADECS 93, IEEE Proceedings, pp. 401-408 (1994)
[12] R. Pace, S. Watts, A. Holmes-Siedle, A. Mohammadzadeh, M. Solanky, D. Paix, and M. Haskard, "Evaluation of charge coupled Devices as alpha particle detectors", Conference on Engineering in Physics and Medicine, New Zealand, November (1995)
[13] G. Svensson et al., NIM B 80/81 pp. 583 (1993)