DLTS Measurement of Energetic Levels, generated in Silicon Detectors

SICAPO Collaboration

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Abstract

DLTS (Deep Level Transient Spectroscopy) measurements were performed on irradiated Si detectors to record data on the energetic levels traps generated by neutrons. For moderate fluences (ϕ) of neutrons ($\phi < 10^{12} \text{ n cm}^{-2}$) electron and hole trap levels have been detected. Four electron trap levels were found for both FZ (float zone) and MCZ (magnetic Czochralsky) types of Si detectors but only two hole trap levels in FZ and one in MCZ detectors. This indicates that the type of silicon has an influence on the traps generated by irradiation. From the values obtained for the relative concentration of E1 centers in MCZ and FZ detectors, it results that the E1 centers are oxygen and not vacancy limited. Since the concentration of the E2, E3, and E4 levels are larger in FZ than in MCZ detectors, it may be assumed that the "gettering effect" can control the formation of deeper traps. Filling pulses were applied for various voltages and at the flat band filling voltage, maximum ratio of N_t/N of the E1 center was achieved. This may indicate that the concentration of E1 centers, near the $p^+ - n$ interface, can be larger than in the rest of the junction.

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1. Introduction

Semiconductor detectors are used for measuring the energy deposition and reconstructing the tracks of particles generated in high energy collisions. Most of these detectors are diodes made of Si. The experiments, envisaged at the next generation of high energy hadron colliders, will have to face a high radiation environment. These conditions are expected to induce radiation damage to the Si detectors and their readout circuits. These damages to the detection system will appear mostly in regions close to the interaction region, particularly at small angle. For instance, neutron fluences, as high as $10^{14}n/cm^2$ [1], will be reached at the LHC in forward direction (large pseudorapidity)

In calorimeters, employing semiconductor detectors as readouts, source of radiation damage has several origins: A high flux of albedo neutrons and evaporation neutrons, which is due to nuclear spallation reactions in cascade showers, inside the calorimeter absorber materials. In addition, the high energy particles generated by the primary collisions, contribute to the damage. In the case of calorimeters with uranium plates as absorber, fast neutrons are produced by fission, which have a significant influence on the extent and type of damage. The evaluation of consequences, these damages may have on the accuracy and reliability of the data generated by the detectors, has triggered intensive investigations [2-5].

The essential mechanism of radiation damage, caused to Si detectors by neutron exposure, can be explained by considering the primary displacement of a Si atom from its position in the lattice. This displacement is the result of nuclear collisions by the transfer of kinetic energy from the particles to a Si atom. The knock-on primary Si atom has enough kinetic energy to be able to displace other Si atoms in the same lattice. A cascade of collision processes is then generated. As a consequence, several types of defects: divacancies, vacancy-donor, vacancy-impurity complexes and clusters, are created [2,4,6,7]. The formed vacancies act as energetic traps in the semiconductor and in the semiconductor space charge of the device. This results in a change of the Current - Voltage (I-V) characteristic due to an increase of the leakage current, which can be expressed as a function of fluence according to [5,8,9] :

$$(I - I_0)/Vol = \alpha\phi \tag{1}$$

where $I - I_0$ is the variation of the reversed biased detector current, before and after irradiation, Vol is the depleted volume of the detector, ϕ is the particle fluence, and α is a parameter, depending on the type of radiation. The increase of leakage current, as a consequence of created defects, is one of the main problems to be resolved. The DLTS method enables to obtain data on the energetic position (E_t), the trap concentration (N_t), and the cross section (σ_t). It also provides information on the distribution of defects created by irradiation. This paper presents data of DLTS measurements on Si detectors irradiated with neutrons. The understanding of these data may contribute to the reduction of damage in Si detectors.

2. Materials and methods

2.1 Detectors

Two kinds of Si detectors were integrally processed by the producer ST (SGS-Thompson) who also supplied the following data: a) FZ-n-Si unsymmetrical one-sided junction, cut along the Si crystal direction $\langle 111 \rangle$, with an oxygen concentration of $10^{15}(1 \pm 4 \times 10^{-2})cm^{-3}$, a resistivity ranging between 4 to 6 $k\Omega cm$, and a wafer thickness of 400 μm , and b) MCZ-n-Si unsymmetrical one-sided junction, cut along the $\langle 100 \rangle$ direction, with an oxygen concentration of $10^{16}(1 \pm 4 \times 10^{-2})cm^{-3}$, a bulk resistivity similar to that of the FZ detector, and a wafer thickness of 525 μm . The $\pm 4\%$ error of the oxygen concentrations was determined by the FTIR (Fourier Transform InfraRed) spectroscopy. The energetic trap levels of these detectors, irradiated and non-irradiated, were measured, employing DLTS. The oxygen content was given in the producer's specification, for both FZ and MCZ.

The unsymmetrical junctions were of the $p^+ - n - n^+$ type, for both FZ and MCZ n-Si materials. The devices were made by employing the standard microelectronic technology and the doping was performed by ion implantation. This has enabled to produce reliable and very sensitive detectors, as compared to other technologies, where the processes of Si oxydation, passivation or metal deposition used, can introduce more defects or interface problems [3,10,11]. The front rectifying p^+ layer was made by boron implantation at a

concentration of 10^{19} cm^{-3} . The back n^+ layer, of the same depth and concentration, was formed to be suitable as a very good ohmic contact. The area of each detector was of $0.5 \times 0.5 \text{ cm}^2$. The data of doping and depth of boron implanted were given by the producer: ST (SGS-Thomson).

2.2 Irradiation facilities

The irradiation of MCZ and FZ samples was performed simultaneously, employing a ^{252}Cf neutron source, with a mean energy of about 1 MeV which ensured that the samples were exposed to the same neutron fluence. The fluences were ranging from 2×10^{10} to $2 \times 10^{11} \text{ n/cm}^2$. Several other irradiations, on the same type of detectors, were performed at the CERN-PSAIF facility, using fluences of $2 \times 10^{11} \text{ n/cm}^2$ and neutrons with a mean energy of about 1 MeV. The neutron yield was obtained by a proton beam, colliding on a fixed target. The values of fluences were determined by measuring the activation of indium foils. The irradiation fluences were kept low enough to avoid problems which appear at higher fluences (above $5 \times 10^{11} \text{ n/cm}^2$). This enables one to obtain and compare data on the energies and concentration of generated trap levels, for FZ and MCZ type detectors, in more accurate conditions.

2.3 DLTS System

The analysis of the Si detectors was carried out using a DL4600-DLTS system employing a Boonton C(V) meter of 1 MHz (manufactured by Bio Rad, UK). The DLTS method allows the measurement of energetic position, concentration profile, types of traps (minority or majority), thermal emission, and capture rate. Details on the DLTS method are presented in the paper of Lang [12]. This method is based on the measurement of a capacitance transient, associated with a slow emission of trapped carriers, as a function of temperature. The sign of the capacitance transient depends on the kind of traps. The capacitance transient, due to minority carrier traps, is positive, whereas the transient due to majority carrier traps is negative. The carriers capture rate is obtained by employing repetitive bias filling pulses, during the thermal scan. Various time intervals t_1 - t_2 (time windows) are used for sampling

the capacitance transient and thus, a DLTS spectrum is obtained. This spectrum contains several peaks, each corresponding to a given activation energy of a deep level of the defects, created in the semiconductor device. The activation energy of a defect, E_t , is given by the relation [12]:

$$\ln (e_n/T^2) = -(E_t/kT) + \text{const} \quad (2)$$

where T is the peak temperature, e_n the emission rate of electron traps and, k the Boltzmann constant. The concentration of traps, N_t , is related to the capacitance change. This change corresponds to the *complete filling* of the given type of traps with a *saturating* pulse. The relation for the concentration of traps is:

$$N_t = 2N(C1 - C2)/C \quad (3)$$

where $C1-C2$ is the capacitance change in the time window, C the capacitance at the given reverse bias, and N the carrier concentration of the semiconductor. From DLTS measurements, the capture cross section σ_n can be obtained if, for a given trap, the value of the peak height is known as a function of filling time. The value of the cross section, σ_n , as a function of time is given by:

$$1 - n_t/N_t = K \exp(-\sigma_n \cdot v_{th} \cdot N \cdot t) \quad (4)$$

where n_t is the trapped carrier concentration corresponding to a given filling time t , N_t is the total trap concentration, K is a constant, v_{th} is the thermal velocity of the charge carrier, and n , the carrier concentration in the sample. As shown above, the DLTS measurements of the silicon detectors were made at fluences of about 3×10^{11} n/cm², since at $\phi \approx 5 \times 10^{11}$ n/cm², retrapping effects may make the capacitance transients not to be exponential any more. The basic relations shown above for the analysis of DLTS data are, in this case, not applicable.

Furthermore, systematic measurements of capacitance frequency dependence in the range of 100 Hz to 1 MHz, were carried out on samples irradiated at fluences up to the order of 10^{13} n/cm². No appreciable frequency dependence effects were found at fluences of less than 10^{12} n/cm². This is also in agreement with [13].

3. Results and discussion

The DLTS spectra obtained for FZ and MCZ detectors, after neutron irradiation with a fluence of $3 \times 10^{11} n/cm^2$, are shown in figs. 1 and 2, respectively. For FZ detectors, four levels (E1, E2, E3, E4) and two hole levels (H1, H2) have been detected. For the MCZ detectors, the same electron levels, but only one hole level, have been found. The measured centers, with the corresponding values of activation energies, are listed in Table 1. In Table 2, the relative concentrations of traps N_t/N are given for the levels E1 to E4. The errors Δ for measured values of C and, correspondingly, ΔC , Eq. (3), due to errors given by the apparatus were reduced to $\pm 1\%$, employing data processing and computerized smoothing, for all N_t/N . The levels, given in the various references for similar Si detectors, are listed in the same table for comparison. In the last column of Table 1, the cross section values are also given, for all measured centers. The hole center H2, obtained in the present paper, confirms the center which was found previously only in [13]. This is important, since the concentration of this level is very small and the uncertainty was appreciable in [13]. The DLTS measurements have shown that the first peak E1 has an activation energy attributed to an A center [3,13,14,15]. This is the V-O complex vacancy of 0.15 eV, found at 0.16-0.18 eV in another publication, (see Table 1) which was supposed to be due to the presence of oxygen in the Si detectors. The E2 peak is associated to a double negative charge state of divacancy [2], while the E3 center is considered as a contribution of a single negative charge of divacancy and an E center [2, 4]. The E4 center may be a different charged double vacancy defect [13]. In our measurements (figs. 1, 2 and Table 2), we found that the FZ detector, which contains less oxygen than the MCZ detector, has a smaller concentration of E1 (A traps) centers than the corresponding MCZ detector. This indicates that (unlike the suggestion in [14]) in our samples, a connection between the formation of A centers concentration and the oxygen content may appear. It can be thus assumed that no vacancy-limited formation appears in this case. The E2, E3 and E4 centers have a smaller N_{traps}/N_{donors} ratio for the MCZ, compared with the FZ detectors. A "getter" effect was expected in [14], when oxygen is present at the A centers, thus avoiding the formation of the deeper vacancy centers. More A centers were found in MCZ detectors than in FZ detectors (possibly due to the gettering

effect), which may explain the measured smaller concentration of the deeper levels in MCZ, in comparison with FZ. The dependence of N_t/N on the fluence was measured for the E3 level, from the DLTS data. A linear correlation (fig. 3) was obtained. Data on the trap concentration profile in the junction were analyzed for the E1 and E3 traps, by varying the filling pulse, which can give information on the profile concentration in the junction [14]. For a given value of the filling pulse, the barrier is reduced by a corresponding value and the "filling" takes place at another depth from the junction barrier. The dependence of the peak of the signal on the filling pulse voltage V_{fi} , for E1, is shown in fig. 4, where it can be seen that the maximum value of the peak is a function of the pulse voltage. For the pulse voltage of 0.7 V (which corresponds to the value to overcome the diffusion barrier), the relative maximum concentration N_t/N of the E1-A center is achieved. For $V_{fi} > 0.7V$, no increase in N_t/N was observed. For smaller pulse voltages, the value of relative concentration is smaller. Since the interface traps are obtained at the line-up voltage, the assumption can be made that the concentration of E1 centers is larger at the $p^+ - n$ interface than in the bulk. The dependence of N_t/N as a function of the pulse voltage is shown in fig. 5. These larger N_t/N concentrations were obtained only for the E1, but not for the E3 center.

4. Conclusions

DLTS measurements have shown that, at moderate neutron irradiation of the Si detectors, four electron trap levels appeared in both FZ and MCZ detectors and two hole trap centers in FZ, but only one in the MCZ detectors. This indicates that differences, between the centers formed in FZ and MCZ detectors, are possible. The relative concentration of the E1 centers is larger in MCZ compared with the FZ detectors. This shows that the initial content of oxygen can determine the concentration of A centers. Thus, in our case, the concentration of A centers is, possibly, oxygen and not vacancy limited. The concentrations of E2, E3 and E4 centers are larger in FZ than in MCZ detectors. This result may confirm the hypothesis of the "gettering" effect of deeper trap formation since, the concentration of A centers in MCZ is larger than in FZ detectors. Filling pulses measurements, at various voltages, show that the maximum ratio, N_t/N , for the E1 center is obtained at flat band filling voltage.

This may indicate that more E1 centers are concentrated near the $p^+ - n$ interface, rather than in the rest of the junction. **Acknowledgements** One of us (C.L.) wants to thank the Killam Foundation and Canada Council for their support.

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Table captions

Table 1: Energy levels for traps (of electrons and holes) and cross sections values detected by DLTS measurements.

Table 2: Values of N_t/N for E1,E2,E3 and E4 electron levels for FZ and MCZ detectors. The error of these values ($\pm 1\%$) was achieved by employing data processing and computerized smoothing.

Figure captions

Fig. 1: The ratio N_t/N versus temperature for FZ detectors

Fig. 2: The ratio N_t/N versus temperature for MCZ detectors

Fig. 3: N_t/N for level E3 versus fluence ϕ . The fit of the data to a straight line is shown in the upper part of the figure.

Fig. 4: N_t/N versus temperature for several filling pulse voltages (V_{fi}) for E1 center. The maxima are depending on the pulse voltage.

Fig. 5: N_t/N versus filling pulse voltage (V_{fi}) for E1 center.

Table 2.

Type of level	N_t/N	
	FZ	MCZ
E_1	0.075	0.085
E_2	0.05	0.015
E_3	0.54	0.50
E_4	0.018	0.0007

Table 1.

Energy of levels (eV)						
Level	This paper	[1]	[3]	[15]	[13,14]	Defects
E_1	$E_C - 0.16 \pm 0.01$	$E_C - 0.15$	$E_C - 0.18$	$E_C - 0.16$	$E_C - 0.17$	A center
E_2	$E_C - 0.25 \pm 0.02$	$E_C - 0.21$	$E_C - 0.25$	$E_C - 0.24$	$E_C - 0.21$	V V -
E_3	$E_C - 0.40 \pm 0.02$	$E_C - 0.39$	$E_C - 0.46$	$E_C - 0.41$	$E_C - 0.41$	V V - and V P
E_4	$E_C - 0.54 \pm 0.02$			$E_C - 0.47$	$E_C - 0.55$	V V
H_1	$E_V - 0.30 \pm 0.01$				$E_V - 0.30$	
H_2	$E_V - 0.50 \pm 0.02$				$E_V - 0.54$	
Capture Section (cm^{-2})						
Σ	This paper	[15]				
	$(1.4 \pm 0.2) \times 10^{-16}$	10^{-15}				
Σ_2	10^{-16}					
E_3	$(0.7 \pm 0.4) \times 10^{-15}$	4×10^{-16}				
E_4	$(2.0 \pm 0.2) \times 10^{-16}$

fig. 1

FZ

fig 2

1000

Fig. 3

fig. 4

fig. 5