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# **DLTS spectra of radiation-induced defects in silicon detectors** with heavily damaged Bragg peak region

#### D Mitina, V Eremin, E Verbitskaya and I Eremin

Division of Solid-State Electronics, Ioffe Institute, 26 Politekhnicheskaya, St Petersburg, 194021 Russian Federation

E-mail: daria.mitina@cern.ch

Abstract. The investigation is focused on the defects in silicon  $p^+$ -n-n<sup>+</sup> detectors irradiated with the 53.4 MeV <sup>40</sup>Ar ions, which generate a nonuniform defect distribution including a heavily damaged region inside the Bragg peak. The dependences of the bulk generation current and of the capacitance on bias voltage and the spectra of radiation-induced defects demonstrate new features: a step in the current rise, a region with a practically constant capacitance, and abnormal dependence of the peak amplitudes of vacancy-related defects on fluence. The changes of the DLTS spectra are assigned to the influence of silicon properties inside the Bragg peak region acting as a highly compensated insulating layer.

#### 1. Introduction

Silicon radiation detectors are widely used in high-energy physics as a component of the detection systems. Because of severe operating conditions in a harsh radiation environment, the degradation of the electrical characteristics of silicon detectors is inevitable. Thus, the task of the radiation degradation scenario development becomes the high of importance. The development includes the study of changes of both the macroscopic characteristics (the generation current, the detector signal and position sensitivity) and microscopic parameters of deep levels in the silicon bandgap. The latter are responsible for the deterioration of electrical characteristics and the degradation of the value and shape of the detector signal with the fluence increase. The structure of the defects, arising as a result of irradiation with light particles that lose less than 1 keV/ $\mu$ m in the detector volume and create a uniform distribution of the defects along the track, is thoroughly studied and the degradation of detector characteristics can be predicted [1].

Currently, there is lack of knowledge on the defects created by high-energy heavy ions penetrating through the detector volume, and even less information is available on the properties of the damaged region created in silicon by heavy ions stopped inside the detector bulk (the energy loss is tens of MeV/ $\mu$ m or even more). For short-range particles irradiation, simulations using TRIM program show that the primary defect distribution is nonuniform and contains a maximum at the particle stopping range known as *the Bragg peak* (BP). This feature should have an effect on the detector characteristics and can be revealed in the study of C-V and I-V characteristics as well in the results obtained with special techniques like DLTS and TCT.

The focus of the study is the demonstration of the results on the DLTS measurements for Si detectors irradiated with short-range <sup>40</sup>Ar ions. The importance of the results for practice consists in the development of the methodical background for future investigations in this field in respect of two aspects: prediction of the detector degradation in long-term experiments in nuclear and high-energy

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ion physics, and contribution to the physics of the detectors recovery via thermal annealing. The last issue becomes practically significant since the volume of the detectors requested for the upcoming experiments increases, and thus this point arises as a sensitive subject for the experiment planning and their budgeting.

# 2. Samples and Experimental

Two groups of the initially identical Si detectors were used in the study. The samples were processed on the n-type silicon wafers with 60  $\Omega$ cm resistivity (initial donor concentration of  $7.1 \times 10^{13}$  cm<sup>-3</sup>). The detector thickness and the area of active region were 300  $\mu$ m and 25 mm<sup>2</sup>, respectively. The samples were irradiated with the <sup>40</sup>Ar ions of 53.4 MeV energy at the Ioffe Institute Cyclotron (Saint Petersburg, Russia), and with 1.62 GeV ions at the U-400M cyclotron of Joint Institute for Nuclear Research (Dubna, Russia). The detailed information about samples under investigation (denoted below as LOW and HIGH-groups) is listed in table 1.

Table 1. Parameters of Si detectors					
Group	Irradiation Energy	Ion Range	Detector #	Fluence (cm <sup>-2</sup> )	
			F1	1×10 <sup>9</sup>	
LOW	53.4 MeV	15.2 μm	F2	$2 \times 10^{9}$	
	·	F3	$4 \times 10^{9}$		
			F4	$1 \times 10^{10}$	
HIGH	1.62 GeV	1.1 mm	F5	$5 \times 10^{10}$	
			F6	$5 \times 10^{11}$	

The values of ion range were extracted from the TRIM simulations. The DLTS measurements were performed at the spectrometer operated at frequency of 1 MHz using 100 averaging of the capacitance relaxation curves.

# 3. Electrical characteristics of the samples

The results of TRIM simulation disclose the key difference between the interaction of ions with various energy with silicon crystal lattice [2]. In a silicon 300  $\mu$ m thick detector, high energy ions create a uniform distribution of the defects, whereas low energy ions produce strongly nonuniform defect distribution with the BP. Examination of the samples clarifies this difference, demonstrating standard I-V dependencies for uniformly damaged detectors (figure 1a) and specific features of these for low energy ion irradiation (figure 1b). For both sample groups, the current increases, however,



Figure 1. The current-voltage characteristics for the samples of (a) HIGH-, (b) LOW-group

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with the different rate. For the short-range ion sample series, the generation current shows a step rise in the bias range of 4-10 V with the following nearly flat region. The step can be attributed to the contribution of the BP forming a thin buried damaged layer at the distance of ~14-16  $\mu$ m with high concentration of radiation-induced defects acting as generation centers. Since the silicon resistivity is rather low, all samples are only partially depleted (estimated full depletion voltage is about 5000 V).

The C-V characteristics of the samples are shown in figure 2. According to the Hamburg model, initially positive effective concentration  $N_{eff} = N_D - N_A$  (where  $N_D$  and  $N_A$  are charged fractions of donors and acceptors) decreases with the irradiation fluence due to donor removal and acceptor introduction processes. [3]. In this study the dopant concentration in n-type Si is high, and so, even for the maximum irradiation fluence of  $5 \times 10^{11}$  cm<sup>-2</sup> (HIGH-group) the decrease of  $N_{eff}$  is insignificant. The C-V characteristics for the LOW-group show a region where the capacitance becomes independent of V, demonstrating a plateau or slight capacitance deviations within it. Obviously, such behavior is also a consequence of the BP presence. An analysis of specific features of the observed characteristics is going on and beyond the scope of this study.



Figure 2. The capacitance-voltage characteristics for the samples of a) HIGH-, and (b) LOW-group

# 4. DLTS spectra of radiation-induced defects

The DLTS technique is a high-sensitive method for the investigation of the defects microscopic parameters: the activation energy ( $E_t$ ), the carrier capture cross-section ( $\sigma_t$ ), and the concentration of the rechargeable levels ( $N_t$ ) [4]. The deep level (DL) spectra shown below are recorded using majority carrier injection by applying sequentially zero and reverse bias for activation of electrons emission (both periods are 5 ms). Variation of bias allowed obtaining the different thickness of the depleted region and tracing the contribution of different regions of the structure to the signal.

Figure 3 shows the spectra recorded at reverse bias U of 20 V; in this case the BP region should be inside the depleted region. For the HIGH-group samples (figure 3a), three peaks of radiation-induced defects corresponding to the known electron traps: DL1,  $E_t = 0.17$  eV, (V-O), DL2,  $E_t = 0.245$  eV, (VV<sup>-</sup>), and DL3,  $E_t = 0.434$  eV, (VV), are observed. The amplitudes of the peaks increase with the irradiation fluence, while the ratio between the amplitudes is almost the same. This agrees well with the results of [5] and provides a direct evidence of the uniform properties of the damaged region after irradiation of the samples with high-energy ions.



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**Figure 3.** The DL spectra for the samples: a) HIGH-, and b) LOW-group. Electron injection, U = 20 V. The fragment in (b) shows the scaled peaks for the (*V*-*O*) and (*VV*<sup>-</sup>) defects.

For the LOW-group samples, the spectra also reveal three peaks (figure 3b), demonstrating, however, specific behavior.

- 1. The amplitudes of traps DL1 and DL2 are very small in comparison with the DL3 amplitude.
- 2. Even for the low fluence, the ratio between the peaks DL1 and DL3 is opposite to that in figure 3a.
- 3. None of the peaks demonstrates the expected monotonous increase of the peak heights with fluence, which even go down for DL1 and DL2 (fragment in figure 3b).

In accordance with the TRIM simulation, the samples irradiated with short-range ions include two regions with different defect distribution. According to the figure 4 (the top part) in the first region L1 the silicon bulk is only partially compensated since the concentration of shallow donors  $N_{SD}$  is far above the concentration of radiation-induced donors and acceptors,  $N_{DD}$  and  $N_{DA}$ , respectively, i.e.

$$N_{SD} + N_{DD} > N_{DA},\tag{1}$$

and silicon bulk is conductive in the full range of DLTS run. Vice versa, at dominating  $N_{DA}$ , i.e.

$$N_{SD} + N_{DD} < N_{DA},\tag{2}$$

the silicon bulk with high defect concentration within the BP layer L2 (or its part) becomes overcompensated, and the conductivity reduces, being presumably comparable with the intrinsic one.

The equivalent schematic adopted for the DLTS measurements includes the following elements connected in serial (figure 4, the bottom part).

- Region 1 acting as a capacitor C1, as an equivalent of the depleted region in the L1. The region contains radiation-induced DLs;
- Region 2 acting as a resistor R1, as an equivalent of the nondepleted region in L1. According to the relationship (1), the conductivity of the layer is high, which does not disturb the conditions for the DLTS measurements. At a certain U the region 2 covers a part of the L2 where the ratio (1) is also valid;
- Region 3 acting as a capacitor C2 originated from the part of L2 in which the concentration of DLs satisfies condition (2). As it follows from TRIM simulations, the concentration of the

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primary vacancies in the L2 can be up to 100 times higher than in the L1, and the silicon bulk in the layer can be overcompensated even at relatively low fluence. The width of the overcompensated region increases as the fluence rises. Overcompensation leads to dramatic reduction of the material conductivity, and, as the DLTS operates at frequency of 1 MHz, this layer acts as an insulator not only at low temperature but also at RT.



**Figure 4.** The equivalent schematic adopted for the DLTS measurements. *Top*: the primary defect distribution, where the L1 is the partially compensated layer and the L2 is the overcompensated layer with the BP. *Bottom*: the equivalent schematic (see details in the text).

Since in the DLTS measurements the signal is proportional to  $\Delta C$  (where  $\Delta C$  is the capacitance change in transients of the measured capacitance  $C_m$ ), the suggested three elements whose characteristics depend on the applied bias, temperature and fluence are influencing in extracting the DLs parameters from the experimental data. Using these definitions, specific features of DLTS spectra for LOW-group samples can be explained as following.

1. The origin of enhanced intensity of the peak around 240 K cannot be assigned to the response related to DLs in the BP region. It should be noted here, that the peak arises even at the bias low enough to achieve depletion of the L2, and its position and shape are very sensitive to the bias voltage and the fluence (figure 3b and 5). Such behavior is abnormal for the DLTS peaks associated with impurity/defects levels having stable parameters. Therefore, for LOW-group samples distortions of the peak including its splitting at ~240 K are presumably related to the response of the a local layer with enhanced concentration of radiation-induced defects on the sequence of the filling and depleting phases in DLTS measurements. In fact, in the non-compensated silicon surrounding BP layer the Fermi level is positioned close to the conductance band, while the Fermi level in the L2 layer is shifted towards the silicon midgap. This barrier of about 0.5 eV controls the carrier exchange between the potential valley inside the BP and the surrounding conductive media providing relaxation of the C2 and thus the DLTS signal.

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Figure 5. DL spectra for the LOW-group, electron injection, the bias voltages: a) 5 V, b) 10 V.

2. Suppression of the height of DLTS peaks DL1 and DL2 occurs due to the changes of  $C_m$ , which is a serial connection of C1 and C2 (resistor R1 is negligible):  $C_m = C_1 C_2 / (C_1 + C_2)$ . Appearance of  $C_2$  and its decrease with the fluence rise can lead to the reduction of  $\Delta C$ ,  $C_m$ , and DLTS peak heights. The abnormal reduction of the DL1 and DL2 peaks with the fluence increase is observed even for lower biases (figure 5), at which the depleted region does not cover the BP layer.

# 5. Summary

The study was focused on the characteristics of silicon  $p^+$ -n- $n^+$  detectors irradiated with the 53.4 MeV <sup>40</sup>Ar ions, which create nonuniform defect distribution with a heavily damaged Bragg peak region at the ion range end of 14-16 µm. This irradiation resulted in the unusual features in the I-V and C-V characteristics, evinced as a step rise in the bulk generation current and an extended region with the capacitance practically independent of the bias voltage. In contrast, irradiation with <sup>40</sup>Ar ions with the 1.62 GeV energy generate a uniform defect distribution displayed the gradual changes in the I-V and C-V curves.

For both groups of the samples, the DLTS spectra demonstrated three peaks of vacancy-related radiation-induced defects, V-O,  $VV^-$  and VV acting as electron traps. However, the spectra of the samples with the Bragg peak region showed suppression of the amplitudes of the peaks related to the V-O and  $VV^-$  defects and their inverse dependence on fluence, and, vice versa, a significant amplitude increase of the peak around 240 K that is close to signal arising from electron trap VV. Abnormal features of the DLTS spectra are presumably related to the influence of the Bragg peak as a highly compensated insulating layer.

The obtained results and a physical model of the processes responsible for distortion of the DLTS spectra for the samples with vastly nonuniform profile of radiation-induced defects requires further experimental study and data analysis, which are currently going on.

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