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Radiation-induced donor generation in epitaxial and Cz diodes

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Abstract

Thin epitaxial layers grown on Cz substrates (Epi) and high resistivity Cz diodes have been irradiated with fluences of $2 \times 10^{14}\,cm^{-2}$ 24 GeV protons. It is shown that the differences in the changes observed in the effective doping concentration (N_{eff}) after irradiation of Epi silicon can be explained by the balance between the formation of two type of defects—a deep acceptor (the I center) and a shallow donor (the BD complex). The BD concentration in Epi material is evaluated to be $\sim 1.3 \times 10^{12}\,cm^{-3}$.
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1. Introduction

The detection of elementary particles and electromagnetic radiation in applications employing extremely high radiation fields is of prominent importance for several fields of fundamental and applied research but so far poses an unprecedented challenge to instrumentation not met by present day's available techniques. Environments with particle fluences up to $10^{16}\,cm^{-2}$ high energy hadrons have to be expected for forthcoming high energy physics experiments at the foreseen upgrade of the Large Hadron Collider at the European research centre CERN. The key challenge for these experiments will be the radiation tolerance of sensors in the tracking area. Although there are several proposals for radiation tolerant semiconductors, silicon is still regarded to be the best choice because of its unsurpassed material quality, best developed technology and low cost for mass production. It has been already proven that the defect formation kinetics depends on engineering steps during device processing. Appreciable improvements in this respect are obtained for charged hadrons or γ-irradiation by enriching high resistivity FZ silicon with oxygen as

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demonstrated by the CERN RD48 collaboration [1,2]. However, the present understanding in the detailed relation between the "microscopic" reasons as based on defect analysis and their "macroscopic" consequences for performance deterioration of the devices is still limited. A first breakthrough in understanding the macroscopic deterioration effects on the basis of a detailed defect analysis was recently achieved for γ-irradiated standard (STFZ) and oxygenated float-zone (DOFZ) silicon detectors. Two new defect levels have been detected by Deep Level Transient Spectroscopy and Thermally Stimulated Current (TSC) measurements, a deep acceptor (I) [3–5] and a bistable donor (BD) [6,7], both having a strong influence on the detectors' performance. These results have demonstrated that the beneficial oxygen effect in FZ silicon after electromagnetic irradiation results not only in the suppression of deep acceptors (as predicted by the present defect models considering the formation of the V_2O defect [8–11]) but also in the creation of BDs similar to the earlier stage Thermal Double Donors (TDD2) [12–23] in oxygen-rich silicon. These donors can even overcompensate the negative space charge introduced by deep acceptors such that no "type inversion" appears in DOFZ material even after very high doses [6,24]. Experiments after irradiation of diodes processed on different silicon material (STFZ, DOFZ, Czochralski (Cz)) with high fluences of 23 GeV protons have shown that the "type inversion" effect as seen in STFZ and at larger fluences in DOFZ does not occur in Cz–Si. More recent irradiation experiments on epitaxial silicon grown on low resistivity Cz substrate (Epi/Cz) have shown that these devices are highly superior to any standard or oxygenated float zone silicon devices [7,25] and that contrary to those and similar to Cz material the Epi diodes do not get "type inverted". The effect has been explained on the basis of an enhanced generation of the BD, as detected by TSC measurements [6,26].

The purpose of the present work is to determine the concentration of the radiation induced BDs in Cz and Epi/Cz test diodes and on this basis to explain the changes in the effective doping concentration (N_{eff}) after 24 GeV proton irradiation.

2. Experimental details

Two different kinds of base materials (Cz and Epi on Cz substrate) have been investigated in this work. The materials are n-type silicon doped with phosphorous and were processed by CiS company [27]. The resistivity of the diodes is 1.2 kΩ cm and 50 Ω cm for Cz and Epi material, respectively. The diodes thickness is 285 μm for Cz silicon-based diodes. In the case of Epi structures, 50-μm-thick epitaxial silicon layers were grown on 0.01 Ωcm, 300-μm-thick Cz substrates by ITME, Warsaw. The diodes have a p^+ electrode of 25 mm^2 surrounded by a p^+ guard ring. The n^+ electrode area of 1 cm^2 is given by the geometrical dimension of the device. The diodes were irradiated with 24 GeV protons at PS-CERN.

The samples were investigated by the TSC method. In all TSC measurements the bias was applied to the n^+ electrode and the guard ring was connected to ground diminishing the surface generated current and allowing an accurate analysis of the TSC spectra [28]. The TSC experimental procedure consists in cooling the sample to low temperatures where traps filling is performed by forward biasing the diode and then heating up with a reverse bias applied on the sample. If the reverse bias is high enough to maintain full depletion of the diode during the TSC measurement then, the scanned volume of the sample is well known (determined by the guard ring surrounded area). Thus, the errors in determination of the charge released from the traps are within 1% for temperatures where the leakage current is negligible. For temperatures around 200 K (e.g. where the I center gives rise to a TSC peak), the errors in determination of the charge released from the traps may be as high as 5% due to the presence of the leakage current. The TSC set-up includes a closed cycle He cryostat, a Lake Shore 340 temperature controller and a Keithley 487 electrometer. The temperature it is measured with a silicon diode sensor (Lake Shore DT- 470 SD). A heating rate of 0.183(5) K s^{-1} was ensured

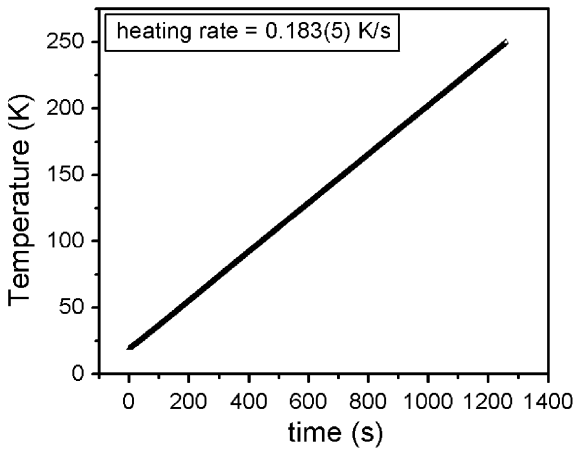

Fig. 1. The recorded time variation of temperature during the TSC scan.

for all TSC temperature scans between 20 and 250 K as it can be seen from Fig. 1.

3. Results and discussions

3.1. TSC measurements

As described in Ref. [6], the BDs are detectable via two TSC signals—BD(98 K) and BD tail, indicating that the BD center can exist in two configurations, labeled in the following as A and B, respectively. Similar to TDD2, structural transformations between the two possible BD's configurations (A and B) may be achieved by different illumination or bias conditions during the cooling procedure before the TSC measurement [6]. Exposing the material to daylight can easily change the BD's configuration from A to B. The reverse process may take place during long time storage in the dark at room temperature (RT), without any bias applied on the sample or heating the sample above 330 K, apply a reverse bias for few minutes and then cooling under zero bias. The latter method was not applied here because during the heating at these temperatures other defects (e.g. clusters, E centers) anneal out in a way which cannot be parameterized.

The existing experimental data regarding the BD center (donor activity, energy level position, bistability, enhanced generation in oxygen rich material) suggest an identification of BD with TDD2. Consequently, it is possible for BDs to exist in four charge states: BD_A^0, BD_B^0, BD_B^+ and $BD_B^{+\,+}$. For such a case, the TSC signal labeled BD_B will correspond to electron emission from BD_B^0 to BD_B^+ and further to $BD_B^{+\,+}$ charge states, while the TSC peak labeled BD_A will correspond to electron emission from BD_A^0 to $BD_B^{+\,+}$ states. For quantitative evaluations of the BDs concentration only the TSC corresponding TSC peak corresponding to electrons emission from the BD_A state can be fully recorded and integrated to evaluate the defect concentration. However, it should be mentioned here that, no matter the BDs configuration, these defects are all positively charged in the space charge region at RT.

As well as in the case of earlier TDDs (TDD1 and TDD2) the BDs cannot always be detected in their full concentration via only one of the configurations. The existence of the defect in one or the other configuration depends on the Fermi level position with respect to the defect energy levels [13,14]. An example in this respect is given in Fig. 2a, where the TSC spectra recorded on Cz diode after exposure to day light or after keeping it in the dark for 5 days are represented. The curve recorded after exposure to daylight shows no BDs in the configuration A (the full concentration of BDs exists in configuration B) while the curve after storing the sample in dark for 5 days shows a partial change to the A configuration. In contrast, the measurements performed on Epi material (see Fig. 2b) had shown that the BDs can be fully converted to the A configuration. This fact allows an accurate evaluation of the BD introduction rates in Epi material. The differences seen in the TSC spectra for Cz and Epi materials regarding the VO and VV peaks (see Fig. 2b) does not necessarily reflect the real concentration of these defects but rather the efficiency in filling them with electrons (first during the cooling process under zero bias and then by forward injection at 20 K). During the cooling under zero bias the existing free carriers will first be trapped by the deepest levels (like the I defect) and then by VV and VO centers. As higher the concentration of free electrons as better is the filling of electron traps.

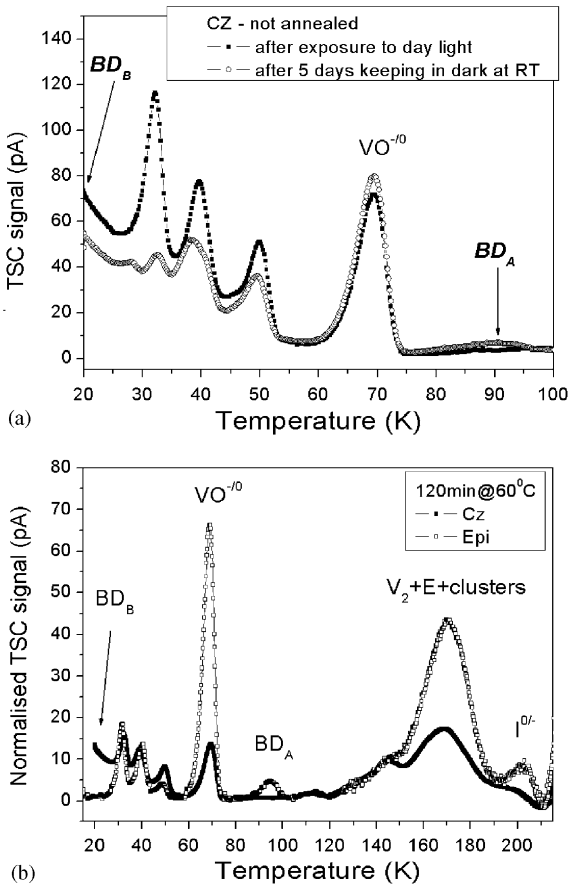

Fig. 2. TSC spectra after irradiation with 24 GeV protons with an equivalent fluence of $1.84 \times 10^{14}\,cm^{-2}$ recorded on: (a) Cz diode after exposure to day light or after keeping it in the dark for 5 days, (b) Cz and Epi material after an annealing treatment at 60 °C for 120 min. The diodes were kept for 2 days in dark at RT prior to TSC measurement.

The free electron concentration is 15 times higher in Epi than in Cz diode. Thus, much more electron traps can be filled during the cooling process in the case of Epi than in Cz diodes. By forward injection performed at low temperature, additional free electrons are generated but also free holes and the VO and VV defects cannot be fully filled with electrons at this temperature.

The I defect is partly negatively charged at RT and its contribution to the effective doping concentration Neff at this temperature can be determined by integrating the TSC peak corresponding to the 0/− charge state transition of the I centers. Thus, after an equivalent fluence of $1.84 \times 10^{14}\,cm^{-2}$, the concentration of negatively charged I centers at RT ($[I^{0/-}]$) is evaluated to be 6.8×10^{12} and $1.8 \times 10^{12}\,cm^{-3}$ for Epi and Cz materials, respectively.

The contribution of the BDs with positive space charge to N_{eff} can be estimated in our experiments only via the A defect state and only if most of the BDs are in this configuration. Such a situation was possible to be achieved only in Epi material. It is worth mentioning here that as well as in the case of TDD1 and TDD2 the change of the BD configuration, from B to A, may happen only at high temperatures (RT or above). Once the change of the configuration is successful this cannot be changed at temperature lower than 100 K no matter the filling procedure [14]. In our measurements the forward injection was performed at 20 K. In addition, the missing of the BD_B signal from the TSC spectrum corresponding to Epi material represents a good argument for an accurate evaluation of the BD concentration via the A state. The BD concentration in Epi material after $1.84 \times 10^{14}\,cm^{-2}$ equivalent fluence is evaluated to be $\sim 1.3 \times 10^{12}\,cm^{-3}$.

3.2. Contribution of BDs and I defects on the N_{eff}

The change in N_{eff} due to proton irradiation can be partly explained by the TSC evaluations presented above—the negative charge introduced by the I defect and the positive charge introduced by the BDs in the space charge region of the investigated Epi diode. The following equation can be written for N_{eff} at RT

$$N_{eff} = N^0_{eff} + [BD] - [E] - [I^{0/-}] - [Y]. \quad (1)$$

The [E] term represents the concentration of the E centers (V-P defects, removal of P donors) and [Y] the concentration of negative space charge introduced by clusters or other unkown defects at RT. Thus, due to the proton irradiation of $1.84 \times 10^{14}\,cm^{-2}$ equivalent fluence, the effective doping concentration at RT changes from 7.24×10^{13} to $5.70 \times 10^{13}\,cm^{-3}$. The positive space charge introduced by BDs in Epi material at

RT was evaluated to be $1.3 \times 10^{12}\,cm^{-3}$ for this equivalent fluence. By taking into account also the donor removal (the formation of E center in a concentration of $7.4 \times 10^{12}\,cm^{-3}$ [29]) our evaluations predict the change of the initial N_{eff} to a value of $5.95 \times 10^{13}\,cm^{-3}$. The missing part represents a concentration of negative charge of $\sim 2.5 \times 10^{12}\,cm^{-3}$ which may be due to clusters (expected to be in the same concentrations in both materials) or other deep defects not detected in our experiments. Unfortunately, in the case of Cz material the BD concentration could not be evaluated in a direct way as in the case of Epi material and thus an estimation of the changes in the N_{eff} was not possible.

4. Conclusions

The changes observed in N_{eff} after 24 GeV proton irradiation of Epi silicon can be explained by the balance between the formation of two type of defects—a deep acceptor (the I center) and a shallow donor (the BD complex). The BD concentration in Epi material after $1.84 \times 10^{14}\,cm^{-2}$ equivalent fluence is evaluated to be $\sim 1.3 \times 10^{12}\,cm^{-3}$. By taking into account the donor removal and the generation of the I center, the change of the N_{eff} at 20 °C in Epi diodes, for an equivalent fluence of $1.84 \times 10^{14}\,cm^{-2}$, can be explained up to a factor of $\sim -2.5 \times 10^{12}\,cm^{-3}$ which most likely is due to the negative charge introduced by clusters. In the case of Cz material, it was not possible to determine the full concentration of BDs from TSC experiments.

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