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Stable radiation-induced donor generation and its influence on the radiation tolerance of silicon diodes ☆

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Abstract

Four different kinds of silicon materials (standard float zone—FZ, oxygen enriched FZ—DOFZ, Czochralski—Cz and thin epitaxial layers grown on Cz substrates—Epi/Cz) have been investigated in this work. They have been irradiated with ^{60}Co-γ-radiation and 24 GeV/c protons. The differences in the changes observed in the effective doping concentration (N_{eff}) after proton irradiation of Cz and Epi silicon can be explained by the balance between the formation of two types of defects—a deep acceptor (the I center, referred to as I_p in this paper in order to avoid any confusion with interstitials) and a shallow donor (the bistable donor (BD) complex). While the formation of the $\mathbf{I_p}$ center depends on the concentration of interstitial oxygen, the BD is generated in materials with high concentration of oxygen dimers. Following the generation of the IO_{2i} defect—detected after low irradiation fluences only in Epi and Cz material—the average dimer concentration in 50 µm Epi/Cz was estimated to be of only 2.7 times lower than in Cz diodes. A value of $\sim 2.7\times 10^{-12}\,\mathrm{cm}^2$ for the electron capture cross-section of the Thermal Double Donors (TDDs), present in the Cz material, was also measured for the first time. The positive space charge introduced by ionization of the BD centers in Epi diodes was directly determined from TSC experiments for two irradiation fluences. The determined values show a linear fluence dependence for the formation of BD centers. By taking into account the BD and the I_p center generation as well as the donor removal, the change of the effective doping concentration N_{eff} at 20 °C in Epi/Cz and Cz diodes after an annealing time of 120 min at 60 °C can be explained up to a negative space charge introduction rate of $\sim 2.2\times 10^{-2}\,\mathrm{cm}^{-1}$ thought to be determined by negatively charged clusters. Long-time annealing experiments at 80 °C have shown that the generation of BDs represents a stable damage.

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1. Introduction

One of the most challenging applications for silicon detectors, in which a guaranteed performance is needed in an extremely hostile radiation field, is represented by the inner detectors in the forthcoming elementary particle experiments. The required detector properties have to be guaranteed even after irradiation with up to 10^{15} (for the Large Hadron Collider (LHC) at CERN) and 10^{16} hadrons/cm^2 (for the proposed LHC upgrade). The average brilliance expected for the free electron laser XFEL will even be 5 orders of magnitude larger than that of the synchrotron radiation source ESRF and the photon energy will extend to well above 100 keV demanding a likewise high radiation tolerance.

While for electronic devices the surface and interface effects are most important, for particle detectors, with the needed extended depletion thickness, bulk effects are more relevant since many electrically active defects are generated in large concentrations in the depleted zone (sensitive region) during the operational time. The defect formation reactions depend not only on the type and fluence levels of

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irradiation but on the engineering steps during device processing as well. First appreciable improvements in this respect were obtained for charged hadron- or γ-irradiation by enriching high-resistivity FZ silicon with oxygen as demonstrated by the CERN RD48 collaboration [1,2]. This oxygen enrichment of the FZ wafers was motivated by the hypothetical assumption that a high oxygen concentration would inhibit the formation of V_2O defects which are thought to be the main causes for the observed change in the effective doping. However, only recently a first breakthrough in understanding the macroscopic deterioration effects on the basis of a detailed defect analysis was 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 (DLTS) and Thermally Stimulated Current (TSC) measurements, a deep acceptor (I_p center) [3–5] and a bistable donor (BD) [6,7], both having a strong influence on the detector performance. The 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 bistable shallow donors similar to the earlier stage Thermal Double Donors TDD2 which proved to form not only in non-irradiated Cz silicon [12–19] but also during irradiation at high temperatures in the same type of oxygen-rich material [20]. The irradiation-induced BDs are able to even overcompensate the negative space charge introduced by deep acceptors such that no "type inversion" appears in DOFZ material even after very high doses [6,21]. The fact that both mechanisms (acceptor and donor formation) are correlated with the damage process opens a new perspective for controlling the detector performance as the balance between the two types of defects depends largely on how silicon is engineered prior to irradiation.

Experiments after irradiation of diodes processed on different silicon materials (STFZ, DOFZ, Cz) with high fluences of 24 GeV/c protons have shown that the "type inversion" effect as seen in STFZ and at larger fluences in DOFZ does not occur in Cz-Si [22]. Comparing the oxygen concentration in these materials determined by SIMS measurements ($<5\times10^{15}\,\mathrm{cm}^{-3}$ in STFZ, $1.2\times10^{17}\,\mathrm{cm}^{-3}$ in DOFZ and $8\times10^{17}\,\mathrm{cm}^{-3}$ in Cz as given in Ref. [23]) the beneficial effect of oxygen seems to be a straightforward conclusion. However, recent irradiation experiments on Epi/Cz diodes (epitaxial silicon grown on low-resistivity Cz substrate) have shown that, despite an oxygen concentration ($\approx10^{17}\,\mathrm{cm}^{-3}$) comparable with DOFZ, these devices are highly superior to any standard or oxygenated float zone silicon devices and that contrary to those and similar to Cz material the Epi diodes do not get "type inverted" [7,21]. The effect has been explained on the basis of an enhanced generation of the BD, as detected by TSC measurements [6,24–26]. These latter investigations led us to consider that the beneficial effect of oxygen may not only be connected with the concentration of oxygen interstitials O_i, which influence the generation of deep acceptors (the I_p defect), but also with the concentration of oxygen dimers O_{2i}, which may determine the generation of shallow donors (BD) in the material. Even if the identification of the I_p defect (deep acceptor responsible for the type inversion after Co^{60}-γ irradiation) is still controversial, being presently attributed to the V_2O or V_3 defect [3–6,27], the I_p defect formation mechanism requires a low concentration of oxygen interstitials (O_i) in both cases. The O_i concentration can be determined via SIMS measurements. On the other hand, considering the experiments regarding the detection of the BD complex, the similarity to the earlier stage thermal double donor TDD2 and the fact that oxygen dimers are known to be precursors for the formation of TDDs (as present in non-irradiated oxygen-rich silicon like in Cz material) [19–20] correlate the irradiation-induced formation of the BD defect to the presence of a high concentration of oxygen dimers (O_{2i}). The oxygen dimer is electrically inactive (not detectable by DLTS or TSC techniques), but gives rise to local vibration modes and can hence be detected by IR-absorption measurements if its concentration is larger than $10^{15}\,\mathrm{cm}^{-3}$—the detection limit of the technique. The dimer was detected in as-grown silicon only in Cz material, where it exists in a concentration of about $10^{15}\,\mathrm{cm}^{-3}$ (i.e. about 2–3 orders of magnitude lower than the O_i concentration) [28,29]. Although its concentration in FZ-type silicon is below the detection limit, O_{2i} can nevertheless act as a sink for radiation-induced migrating interstitials I by forming the IO_{2i} defect which is electrically active and can be detected by more sensitive techniques like DLTS and TSC. It is worth noting that a competing reaction to the formation of IO_{2i} is the capture of vacancies by oxygen dimers which leads to the generation of the VO_2 defect, known to be neutral and therefore not detectable by DLTS or TSC methods. The IO_{2i} complex had first been detected by DLTS in low-dose γ-irradiated Cz silicon [28]. Its identification was achieved by comparing its annealing behavior after low γ-doses, resulting from DLTS measurements, with those deduced from IR-absorption spectra measured after very high γ-doses. Recently, using the TSC method, the IO_{2i} defect was detected also in other types of silicon (DOFZ and Epi/Cz) after exposure to high γ-doses or 24 GeV/c proton fluences (the $E(50\,\mathrm{K})$ TSC peak in Refs. [6,25]). Its identification is based on both the trapping parameters (activation energy and capture cross-section for electrons) and the thermal stability (annealing out at about 150 °C as reported in Ref. [28]). The purpose of the present work is to make a relative estimation of the dimer concentration in Cz and Epi silicon via the detection of the IO_{2i} defect and on this basis to explain the differences in the generation of radiation-induced donors (BD) in different types of silicon diodes (STFZ, DOFZ, Cz and Epi/Cz) after 24 GeV/c proton irradiation. Exploiting the compensation between irradiation-induced negative (I_p defect) and positive space charge (BD complex), these