Second-order generation of point defects in gamma-irradiated float-zone silicon, an explanation for "type inversion"

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Radiation-induced defects in silicon diodes were investigated after exposure to high doses of Co^{60}-gamma irradiation using the thermally stimulated current method. We have found that, for high irradiation doses, a second-order defect can be detected. This defect is largely suppressed in oxygen-enriched material while it is the main cause for the space charge sign inversion effect observed in standard float-zone material. © *2003 American Institute of Physics.*
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High resistivity silicon pixel and microstrip detectors will be used extensively for tracking applications in elementary particle physics experiments. The limiting factor to long-term operation of silicon detectors in harsh radiation environments is the change of the effective doping concentration (N_{eff}). High resistivity *n*-type standard float-zone silicon (STFZ) diodes apparently invert to "*p* type" after a fluence of around 10^{13} cm^{-2} fast neutrons or high energy protons, or after ~200 Mrad dose of Co^{60} gammas.[1–4] The CERN-RD48 (ROSE) collaboration had shown that a considerable improvement could be achieved for charged hadron and gamma irradiation by using diffusion oxygenated float-zone silicon (DOFZ).[4] The oxygen effect is maximal in the case of Co^{60}-gamma irradiation where point defects are predominant. For DOFZ detectors no change in the initial N_{eff} was reported up to 400 Mrad.[3] Present defect models attribute the non-linear change of N_{eff} in STFZ at RT to the formation of a second-order defect, the V_2O complex, via the reaction $VO+V$, suppressed in oxygen rich material because the oxygen acts like a highly effective sink for vacancies ($V+O\rightarrow VO$).[5–7] The V_2O complex in the neutral charge state was identified in heavily electron irradiated silicon by electron paramagnetic resonance (EPR) and characterized by photo-EPR measurements at 0.50 ± 0.05 eV below the conduction band.[8,9] So far there are only a few investigations of electrically active defects related to the V_2O complex. They are based on the annealing of divacancy-related levels in low irradiated samples at temperatures above 200 °C. No change in the device performance correlated with the presumed V_2O complex were reported.[10,11] Recently, we have detected a deep acceptor level (*I* level) at 0.545 eV below the conduction band with electron and hole capture cross sections of $\sigma_n=(1.7\pm0.2)\times10^{-15}$ cm^2 and $\sigma_p=(9\pm1)\times10^{-14}$ cm^2, respectively, which can contribute significantly to both the observed change in the N_{eff} value and in the leakage current (LC).[12] The detection was possible only for quite high irradiation levels—4 and 42 Mrad dose for STFZ and DOFZ, respectively—where only the levels deeper than $VV^{-/0}$ could be investigated by deep level transient spectroscopy (DLTS). For even higher dose values the DLTS method is not applicable anymore. An alternative to study the dose dependence of the *I* defect concentration and thus, to follow its influence on N_{eff} with increasing dose, is to perform thermally stimulated current (TSC) experiments.

In this work we have performed TSC studies of Co^{60}-gamma induced centers in STFZ and DOFZ p^+nn^+ diodes processed by CiS[13] on Wacker silicon with high resistivity (4 kΩ cm). The oxygen enrichment for the DOFZ process was achieved by a 72 h postoxidation O diffusion at 1150 °C resulting in an average oxygen concentration of 1.2×10^{17} cm^{-3} while in the STFZ ones it is less than 3×10^{16} cm^{-3}.[14] The diodes were irradiated at RT by Co^{60} gammas with doses from 96 to 300 Mrad. The initial N_{eff} was 8×10^{11} cm^{-3} and 1.1×10^{12} cm^{-3} for STFZ and DOFZ, respectively. 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 diode thickness is 290 μm. In all 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.[15] The standard TSC experimental procedure consists in cooling down from RT to 20 K under 0 bias, followed by forward injection (~200 μA) for 30 s and then heating up with a reverse bias (RB) applied. In comparison 670 nm laser illumination from the n^+/p^+ side of the reverse biased diode was used for detection of hole/electron traps only (the diode was kept reverse biased also during cooling). The heating rate for the TSC experiments was always 0.183 K/s. The LC was separately measured and subtracted from each TSC curve.

The TSC spectra for STFZ diodes exposed to different irradiation doses are shown in Fig. 1(a). After forward injection at 20 K, a reverse bias of 300 V proved to be high enough to maintain full depletion of all investigated STFZ diodes over the total temperature range. On top of the well known VO, C_iC_s, and C_iO_i defects we get in addition cen-

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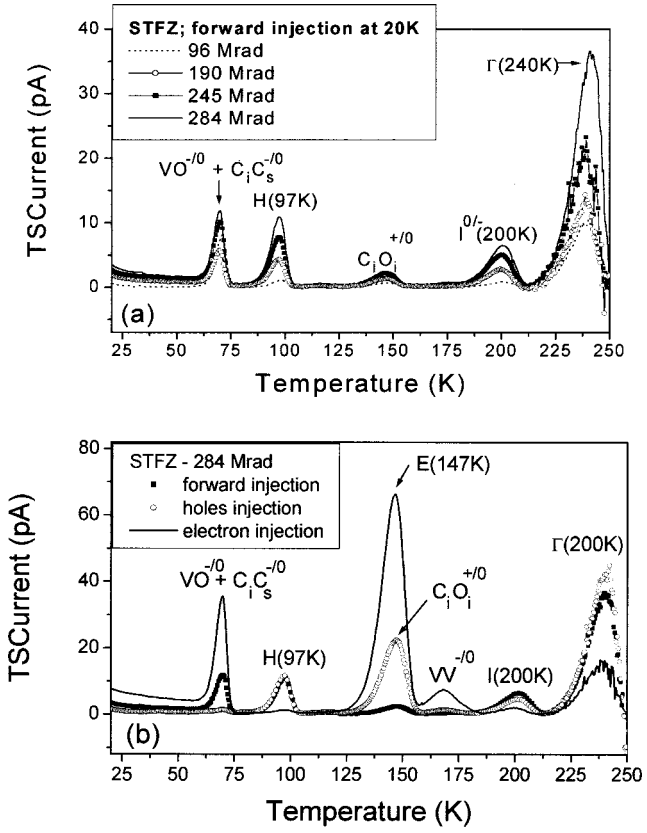

FIG. 1. TSC spectra recorded on STFZ diodes for a RB=500 V: (a) for different dose values after forward injection and (b) for 284 Mrad dose after forward, hole, and electron injection.

ters labeled H (97 K), $I^{0/-}$ (200 K) and Γ (240 K). By comparing the TSC spectrum obtained after forward injection with the one recorded after only hole/electron injection we conclude that all these three peaks, recorded after forward injection, correspond to emission of holes [see Fig. 1(b)]. The TSC peak at 200 K for electron injection [I (200 K) full line] corresponds to the $-/0$ transition from the I defect. This transition has a much smaller amplitude compared with the one for hole emission ($0/-$ transition) confirming the previous DLTS results that, following the electron emission, only a small fraction of total defect concentration can be detected.[12] It is worth noting that for both the I and the Γ level the TSC peaks corresponding to electron and hole emission occur at the same temperature, as expected from Shockley–Read–Hall statistics.[16,17] The E (147 K) electron trap was previously reported and will not be discussed in this letter.[15,18] For quantitative evaluations, the TSC spectra after forward injection were considered because all diodes are fully depleted over the total temperature range. The activation enthalpies for H (97 K), $I^{0/-}$ (200 K), and Γ (240 K) as determined from Arrhenius plots of the increasing part of the TSC peaks are 0.23 ± 0.01, 0.58 ± 0.01, and 0.68 ± 0.03 eV from the valence band, respectively. Using these values a proper fitting of the TSC peaks results in hole capture cross sections of $(0.5-9)\times10^{-14}$, $(4-12)\times10^{-14}$, and $(4-70)\times10^{-15}$ cm^2 for H (97 K), $I^{0/-}$ (200 K), and Γ (240 K), respectively. The trapping parameters of $I^{0/-}$ (200 K) are in good agreement with the ones evaluated previously using the DLTS method.[12] The differences between STFZ and DOFZ diodes for an irradiation dose of 284 Mrad can be seen in

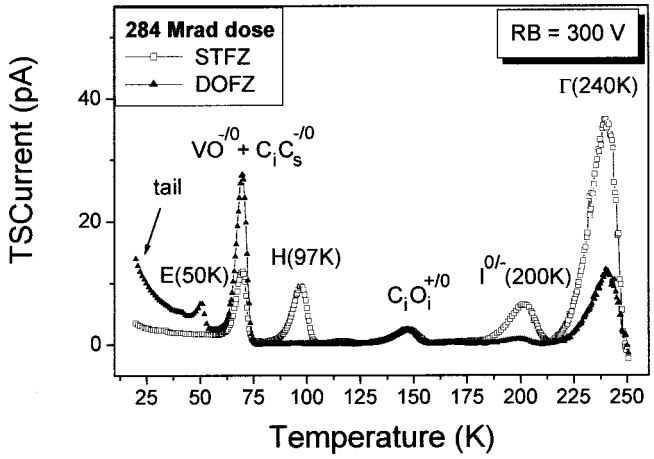

FIG. 2. TSC spectra for STFZ and DOFZ diodes irradiated with 284 Mrad dose recorded after forward injection at 20 K.

Fig. 2. The "tail" and the E (50 K) peak characteristic for DOFZ diodes are due to electron emission and further studies are needed for clarification. All H (97 K), $I^{0/-}$ (200 K), and Γ (240 K) peaks are largely suppressed in DOFZ silicon. Their dose dependence is shown in Fig. 3. The concentrations were evaluated by integrating the corresponding TSC peaks. The Γ (240 K) defect seems to have a linear dose dependence but due to the large LC in this temperature range the error margin is about 25%. Both the H (97 K) and $I^{0/-}$ (200 K) defects have nearly the same concentration and the same dose dependence. This behavior suggests that the H (97 K) level may actually be the donor state (+/0) of the same I defect. The almost quadratic dose dependence of the I center concentration is an evidence for being a second-order defect formed through a reaction between two primary irradiation induced point defects. Our experiments show that the A center ($VO^{-/0}$) is less generated in STFZ than in DOFZ material (see Fig. 2). Therefore, the A center could be one of the primary defects involved in the formation of the I center.

To estimate the influence of electrically active centers on N_{eff}, in addition to the activation energies both capture cross sections (σ_n and σ_p) have to be known. From all the three mentioned levels only the single-acceptor state of the I defect is fully characterized and its influence on the diode perfor-

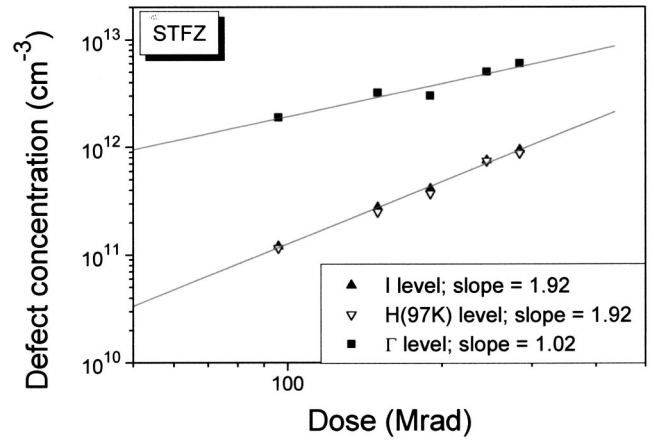

FIG. 3. Dose dependence of H (97 K), I (200 K), and Γ (240 K) level concentrations. The error margin is 5% except for Γ (240 K) level where it is 25%.

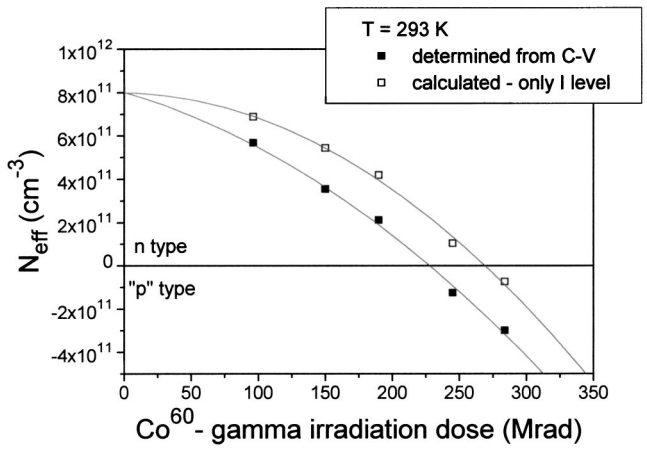

FIG. 4. Experimental dose dependence of N_{eff} at 293 K in comparison with calculated values according to the *I* center.

mance can be calculated. The change of N_{eff} at RT due to the single-acceptor state of the *I* defect is given by its steady state occupancy in the space charge region

$$n_T(T) = N_T^* \frac{e_p(T)}{e_n(T) + e_p(T)} \quad \text{with} \quad (1)$$

$$e_{n,p}(T) = c_{n,p}(T) * N_{C,V}(T) * \exp\left[\pm \frac{E_a(T) - E_{C,V}}{k_b T}\right],$$

where $c_{n,p}(T) = \sigma_{n,p}(T) * \nu_{\text{th},n,p}(T)$ are the respective capture coefficients, $N_{C,V}$ are the effective densities of states in the conduction, respectively, valence band, $E_{C,V}$ are the band edge energies, $e_{n,p}$ are the respective emission rates of electrons and holes, and $E_a(T)$ is the energy level of the defect.

The results for the STFZ silicon diodes are given in Fig. 4. As can be seen the *I* defect describes the nonlinear dose dependence of N_{eff} as extracted from $C-V$ curves at RT. The type inversion in STFZ material takes place at about 225 Mrad. If only the *I* level would be responsible for this effect, this value would be 270 Mrad. Since none of the already studied point defects ($VV^{-/0}$, $C_iC_s^{-/0}$, $VO_i^{-/0}$, $C_iO_i^{+/0}$) contributes to the change of N_{eff} at RT one can speculate that the Γ level is responsible for the difference between experimental and calculated N_{eff} values, but further work is needed for clarification.

In conclusion, we have shown that the close to midgap *I* level corresponds to a second-order defect. It is very probable that this defect is of amphoteric nature with both the already reported acceptor state and in addition a donor state identified in this work with the *H* (97 K) level. It is worth noting that a donor level with similar parameters like *H* (97 K) was previously detected in *p*-type Si and was associated with the V_2O complex.[10] It has also been shown that while the *I* defect is largely suppressed in oxygen rich material, the VO complex has a larger concentration compared with standard material. This is regarded to be a strong evidence for the formation of the *I* defect via VO as suggested by the V_2O generation model.[5–7] Finally, the strongly generated *I* defect in oxygen lean material is the main cause for the type inversion effect observed in STFZ material.

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