APPLIED PHYSICS LETTERS VOLUME 82, NUMBER 13 31 MARCH 2003

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

I. Pintilie<sup>a)</sup>

National Institute of Materials Physics, P.O. Box MG-7, Bucharest-Magurele, Romania

E. Fretwurst, G. Lindström, and J. Stahl

Institute for Experimental Physics, Hamburg University, D-22761, Germany

(Received 6 November 2002; accepted 5 February 2003)

Radiation-induced defects in silicon diodes were investigated after exposure to high doses of Co<sup>60</sup>-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.

[DOI: 10.1063/1.1564869]

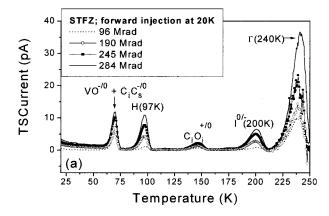
High resistivity silicon pixel and microstrip detectors will be used extensively for tracking applications in elementary particle physics experiments. The limiting factor to long-term operation of silicon detectors in harsh radiation environments is the change of the effective doping concentration ( $N_{\text{eff}}$ ). High resistivity n-type standard float-zone silicon (STFZ) diodes apparently invert to "p type" after a fluence of around  $10^{13} \, \mathrm{cm}^{-2}$  fast neutrons or high energy protons, or after ~200 Mrad dose of Co<sup>60</sup> gammas.<sup>1-4</sup> The CERN-RD48 (ROSE) collaboration had shown that a considerable improvement could be achieved for charged hadron and gamma irradiation by using diffusion oxygenated floatzone silicon (DOFZ).<sup>4</sup> The oxygen effect is maximal in the case of Co<sup>60</sup>-gamma irradiation where point defects are predominant. For DOFZ detectors no change in the initial  $N_{\rm eff}$ was reported up to 400 Mrad.<sup>3</sup> Present defect models attribute the non-linear change of  $N_{\rm eff}$  in STFZ at RT to the formation of a second-order defect, the V2O 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<sub>2</sub>O 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  $0.50\pm0.05\,\mathrm{eV}$  below the conduction band. 8,9 So far there are only a few investigations of electrically active defects related to the V<sub>2</sub>O 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<sub>2</sub>O 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  $\sigma_n = (1.7 \pm 0.2) \times 10^{-15} \text{ cm}^2$  and  $\sigma_p = (9 \pm 1) \times 10^{-14} \text{ cm}^2$ , respectively, which can contribute significantly to both the observed change in the  $N_{\rm eff}$  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  $N_{\rm eff}$  with increasing dose, is to perform thermally stimulated current (TSC) experiments.

In this work we have performed TSC studies of  $C_0^{60}$ -gamma induced centers in STFZ and DOFZ  $p^+nn^+$ diodes processed by CiS<sup>13</sup> on Wacker silicon with high resistivity  $(4 \text{ k}\Omega \text{ cm})$ . 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  $1.2 \times 10^{17}$  cm<sup>-3</sup> while in the STFZ ones it is less than 3  $\times 10^{16}$  cm<sup>-3</sup>. <sup>14</sup> The diodes were irradiated at RT by Co<sup>60</sup> gammas with doses from 96 to 300 Mrad. The initial  $N_{\text{eff}}$ was  $8\times10^{11}$  cm<sup>-3</sup> and  $1.1\times10^{12}$  cm<sup>-3</sup> for STFZ and DOFZ, respectively. The diodes have a  $p^+$  electrode of 25 mm<sup>2</sup> surrounded by a  $p^+$  guard ring. The  $n^+$  electrode area of 1 cm<sup>2</sup> is given by the geometrical dimension of the device. The diode thickness is 290  $\mu$ m. 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 ( $\sim 200 \mu A$ ) 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-

a) Author to whom correspondence should be addressed; electronic mail: ioana@alpha1.infim.ro



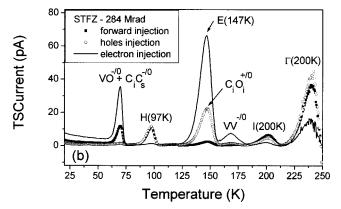


FIG. 1. TSC spectra recorded on STFZ diodes for a RB=500 V: (a) for different dose values after forward injection and (b) for 284 Mrad dose after forward, hole, and electron injection.

ters labeled H (97 K),  $I^{0/-}$  (200 K) and  $\Gamma$  (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  $\Gamma$ 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  $\Gamma$  (240 K) as determined from Arrhenius plots of the increasing part of the TSC peaks are  $0.23\pm0.01$ ,  $0.58\pm0.01$ , and  $0.68\pm0.03$  eV from the valence band, respectively. Using these values a proper fitting of the TSC peaks results in hole capture cross sections of  $(0.5-9)\times 10^{-14}$ ,  $(4-12)\times 10^{-14}$ , and  $(4-70)\times 10^{-15}$  cm<sup>2</sup> for H (97 K),  $I^{0/-}$  (200 K), and  $\Gamma$  (240 K), respectively. The trapping parameters of  $I^{0/-}$  (200 K) are in good agreement with the ones evaluated previously using the DLTS method.<sup>12</sup> The differences between STFZ and DOFZ diodes for an irradiation dose of 284 Mrad can be seen in

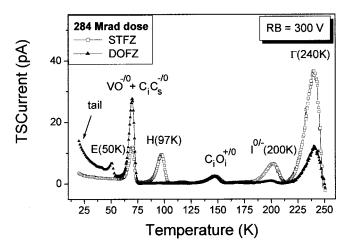


FIG. 2. TSC spectra for STFZ and DOFZ diodes irradiated with 284 Mrad dose recorded after forward injection at 20 K.

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  $\Gamma$  (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  $\Gamma$  (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<sup>-/0</sup>) 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  $N_{\rm eff}$ , in addition to the activation energies both capture cross sections ( $\sigma_n$  and  $\sigma_p$ ) 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-

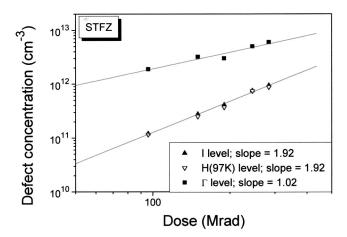


FIG. 3. Dose dependence of H (97 K), I (200 K), and  $\Gamma$  (240 K) level concentrations. The error margin is 5% except for  $\Gamma$  (240 K) level where it is 25%.

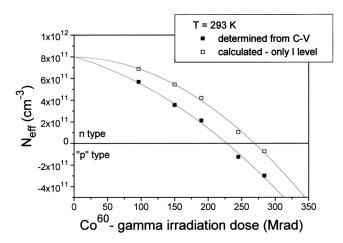


FIG. 4. Experimental dose dependence of  $N_{\rm eff}$  at 293 K in comparison with calculated values according to the I center.

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

$$n_{T}(T) = N_{T}^{*} \frac{e_{p}(T)}{e_{n}(T) + e_{p}(T)}$$
 with 
$$e_{n,p}(T) = c_{n,p}(T)^{*} N_{C,V}(T)^{*} \exp\left[\pm \frac{E_{a}(T) - E_{C,V}}{k_{b}T}\right],$$
 (1)

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  $N_{\rm eff}$  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  $N_{\rm eff}$  at RT one can speculate that the  $\Gamma$  level is responsible for the difference between experimental and calculated  $N_{\rm eff}$  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<sub>2</sub>O complex.<sup>10</sup> 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<sub>2</sub>O generation model.<sup>5-7</sup> Finally, the strongly generated I defect in oxygen lean material is the main cause for the type inversion effect observed in STFZ material.

Special thanks are due to Z. Li and E. Verbitskaja for the help in gamma irradiations at Brookhaven National Laboratory. This work is part of the CiS-SRD project under Contract No. 642/06/00 supported by the German Ministry of Economy BMW; under contract R&D No. 289/00 and has been performed in the frame of the CERN-RD50 collaboration. Financial support of the German Ministry for Education and Research BMBF and of the Romanian Ministry for Education and Research under Contract No. WTZ-ROM 00/01 and of the German Research Foundation DFG under Contract No. FR1547/1-1 is gratefully acknowledged.

- <sup>1</sup>R. Wunsdorf, M. Benkert, E. Fretwurst, G. Lindström, T. Schulz, N. Croitoru, R. Darvas, M. Mudrik, R. Böttger, and H. Schölermann, Nucl. Phys. B **23A**, 324 (1991).
- <sup>2</sup>M. Edwards, G. Hall, and S. Sotthibandhu, Nucl. Instrum. Methods Phys. Res. A 310, 283 (1991).
- <sup>3</sup>Z. Li, B. Dezillie, M. Bruzzi, W. Chen, V. Eremin, E. Verbitskaya, and P. Weilhammer, Nucl. Instrum. Methods Phys. Res. A 461, 126 (2001).
- <sup>4</sup>G. Lindström for the ROSE collaboration, Nucl. Instrum. Methods Phys. Res. A 466, 308 (2001).
- <sup>5</sup>G. Davies, E. C. Lighttowlers, R. C. Newman, and A. S. Oates, Semicond. Sci. Technol. 2, 524 (1987).
- <sup>6</sup>K. Gill, G. Hall, and B. MacEvoy, J. Appl. Phys. **82**, 126 (1997).
- <sup>7</sup>B. MacEvoy and G. Hall, Mater. Sci. Semicond. Process. 3, 243 (2000).
- <sup>8</sup>Y. H. Lee and J. Corbett, Phys. Rev. B **13**, 2653 (1976).
- <sup>9</sup>Y. H. Lee, T. D. Bilash, and J. Corbett, Radiat. Eff. **29**, 7 (1976).
- <sup>10</sup> M. A. Trauwaert, J. Vanhellemont, H. E. Maes, A. M. Van Bavel, G. Langouche, and P. Clauws, Appl. Phys. Lett. 66, 3056 (1995).
- <sup>11</sup> E. V. Monakhov, B. S. Avset, A. Hallen, and B. G. Svensson, Phys. Rev. B 65, 233207 (2002).
- <sup>12</sup> I. Pintilie, E. Fretwurst, G. Lindstroem, and J. Stahl, Appl. Phys. Lett. 81, 165 (2002).
- <sup>13</sup>CiS Institut für Mikrosensorik gGmbH, Erfurt, Germany.
- <sup>14</sup> A. Barcz, M. Zielinski, E. Nossarzewska, and G. Lindström, Appl. Surf. Sci. 203–204, 396 (2003).
- <sup>15</sup>I. Pintilie, L. Pintilie, M. Moll, E. Fretwurst, and G. Lindström, Appl. Phys. Lett. 78, 550 (2001).
- <sup>16</sup> W. Shockley and W. T. Read, Phys. Rev. 87, 835 (1952).
- <sup>17</sup>R. N. Hall, Phys. Rev. **87**, 387 (1952).
- <sup>18</sup>I. Pintilie, C. Tivarus, L. Pintilie, M. Moll, E. Fretwurst, and G. Lindstroem, in *Proceedings of the Second ENDEASD Workshop*, edited by C. Clays, Kista, Stockholm, Sweden, 27–29 June 2000, pp. 79–88.

Applied Physics Letters is copyrighted by the American Institute of Physics (AIP). Redistribution of journal material is subject to the AIP online journal license and/or AIP copyright. For more information, see http://ojps.aip.org/aplo/aplcr.jsp Copyright of Applied Physics Letters is the property of American Institute of Physics and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.