Close to midgap trapping level in ^{60}Co gamma irradiated silicon detectors

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The deep level transient spectroscopy method was applied on standard and oxygenated float-zone silicon detectors exposed to high doses of ^{60}Co–gamma irradiation. We have detected and characterized a close to midgap trapping level having an ionization energy of $E_C-(0.545\pm0.005)$ eV and electron/hole capture cross sections of $\sigma_n=(1.7\pm0.2)\times10^{-15}$ cm^2/$\sigma_p=(9\pm1)\times10^{-14}$ cm^2 respectively. This level has a strong impact on the detector performance being responsible for more than 90% of the change in the effective doping concentration. The defect is strongly oxygen related and a possible connection with the V_2O complex is discussed. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1490397]

High-resistivity silicon particle detectors will be used extensively in the tracking areas of future high-energy physics experiments. The CERN RD48 (ROSE) collaboration had shown that oxygen enrichment of the silicon bulk leads to a considerable decrease of damage effects, induced primarily by charged hadron and gamma irradiation.[1,2] Many radiation induced point defects are already well characterized by deep level transient spectroscopy (DLTS).[3–5] However, these defects can neither explain the macroscopic deterioration effects (change in the doping concentration and leakage current) nor the beneficial effect of oxygenation. Present defect models attribute the observed changes in device characteristics after high ^{60}Co–gamma irradiation doses of standard float-zone (STFZ) silicon detectors to the formation of the V_2O complex, suppressed in oxygen rich material because the oxygen acts as a sink for vacancies ($V+O\rightarrow VO$) reducing thus the probability of V_2O formation by the reaction of single vacancies with VO.[6–8] The V_2O defect in the neutral charge state was first identified via a detailed electron paramagnetic resonance (EPR) study in heavily electron irradiated silicon.[9] By photo-EPR measurements, an ionization energy of 0.5 ± 0.05 eV from the conduction band was evaluated for this defect.[10] However, such a deep level had so far not been detected by appropriate experimental techniques which could also reveal the capture cross section and introduction rate needed for any attempt of explaining the change of detector properties due to irradiation.

In the present article, we report on the DLTS detection of an oxygen related trapping level induced by ^{60}Co–gamma irradiation between 4 and 42.5 Mrad which is likely connected with the V_2O defect. Due to the high concentration of acceptor like states after intense irradiation, the DLTS method is not anymore applicable in a wide temperature range. However, it can still be used at high temperatures where most of these defects do not contribute anymore either to the space charge or to the capacitive transients. The p^+nn^+ silicon detectors investigated in this work are processed by CiS,[11] on STFZ and oxygenated float zone (DOFZ) silicon with high resistivity (4 kΩcm). The samples are labeled as STFZ1–3/DOFZ1–3 for 4 Mrad, 10 Mrad, and 42.5 Mrad doses, respectively.

The recorded DLTS spectra corresponding to majority carriers for both STFZ and DOFZ samples are shown in Fig. 1(a). Just for comparison, the spectrum for the lowest irradiation dose includes also the well known $V_2^{-/0}$ defect. With the exception of the $V_2^{-/0}$, the only deep dose dependent electron trap is labeled as I_E. The I_E defect appears in STFZ detectors starting after a dose of 4 Mrad, while in DOFZ it can be detected only at the highest dose of 42.5 Mrad. A first extraction of its trapping parameters evaluated from an Arrhenius plot leads to: enthalpy $\Delta H=0.54\pm1\%$ eV, electron capture cross section $\sigma_n=(1.3\pm0.7)\times10^{-15}$ cm^2. A better evaluation is achieved by direct analysis of transients at constant temperatures (263, 280, and 293 K). The electron capture cross section (σ_n) can be directly determined by measuring the amplitude of the emission transient as function of the filling pulse duration t_p at constant temperature.[12] Knowing $\sigma_n(T)$ the activation energy of the level $E_a(T)$ can be calculated as well as the concentration $N_T^{\mathrm{DLTS}}(T)$. The results obtained at 263 K and 293 K for the STFZ2 and STFZ3 detectors are given in Fig. 1(b). The high concentration of V_2 centers (e.g., 42% of the doping for 42.5 Mrad dose) influences both the capture and the emission process on the I_E defect. At the aforementioned temperatures, a delay time of $t_0=7$ ms between the end of the filling pulse and the beginning of the transient recording was shown to be long enough to avoid any contribution from the emission of V_2 centers. However, during the filling pulse the electron capture by V_2 centers will result in apparent smaller and temperature dependent σ_n and E_a values of I_E [see Fig. 1(b), comparing STFZ3 with STFZ2]. For the lower dose (STFZ2), the measurements show no temperature dependence of σ_n and E_a and, thus, an entropy factor close to 1 is expected for the I_E defect. In this case, the errors due to V_2 centers (in concentration of 10% of the doping) are of 1 meV and 2×10^{-16} cm^2 for E_a and σ_n, respectively. The differ-

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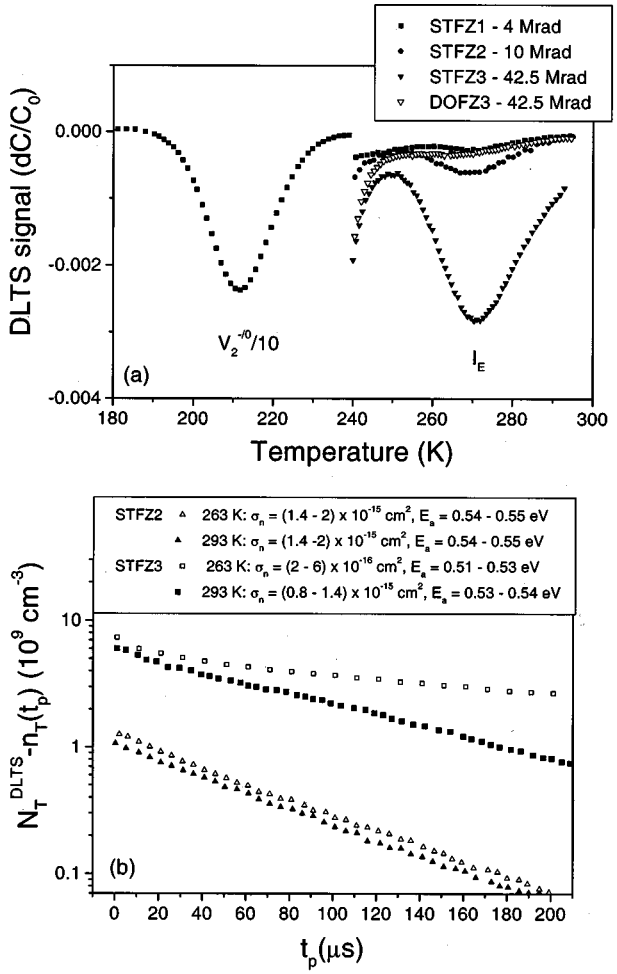

FIG. 1. (a) Majority carrier DLTS spectra recorded for: quiescent bias $U_R = -16$ V, pulse bias $U_p = -2$ V, pulse width $t_p = 1$ ms, and time window $T_w = 200$ ms. (b) Direct measurements of the electron capture cross section for the I_E level and the corresponding E_a resulting from the transients analysis at 263 K and 293 K. "$n_T(t_p)$" is the concentration of filled traps after pulse duration t_p; $U_R = -16$ V, $U_p = -2$ V; $t_0 = 7$ ms.

ence in the magnitude of N_T^{DLTS} measured at 263 K and 293 K is due to the change of the steady-state occupancy of the I_E level in the space-charge region (SCR). The concentration values shown in Fig. 1(b) are already corrected by taking into account the so-called "edge region."[12] The concentration evaluated from DLTS measurements-$N_T^{\mathrm{DLTS}}(T)$ is given by

$$N_T^{\mathrm{DLTS}}(T) = N_{TE} - n_E(T), \tag{1}$$

where N_{TE} is the total concentration of the I_E defect and $n_E(T)$ represents its steady-state occupancy in the SCR expressed by[13]

$$n_E(T) = N_{TE}^{*} \frac{c_n(T)^{*}n + e_p}{e_n(T) + e_p(T) + c_n(T)^{*}n + c_p(T)^{*}p},$$

$$\text{with } c_{n,p}(T) = \sigma_{n,p}(T)^{*}\nu_{th,n,p}(T), \tag{2}$$

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

where $N_{C,V}$ indicates the effective densities of states in the conduction/valence band, $E_{C,V}$ indicates the band edge energies, $E_T(T)$ indicates the energy of the trapping level, and n,p indicates the free-carrier concentrations in the SCR. The spatial distribution of free carriers in the presence of defects can be calculated only by numerical modeling.[14] However, the carrier concentrations in the silicon bulk are still very small and therefore the diffusion from the nondepleted volume can be neglected. Under steady-state conditions, this results in $\mu_n n = \mu_p p$.[5] In the following calculations, no temperature variation of σ_p and $(E_C\text{-}E_V)$ is considered. The N_T^{DLTS} determined at 263, 280, and 293 K together with the parameters σ_n and E_a obtained on STFZ2 detector and the condition $n/p = \mu_p/\mu_n$ allow the evaluation of N_{TE}, σ_p, n, and p from Eq. (2). We mention here that the temperature dependence of N_T^{DLTS} can only be described with $E_a = E_C - (0.545 \pm 0.002)$ eV and $\sigma_n = (1.7 \pm 0.2) \times 10^{-15}$ cm^2. The n, p, and N_{TE} parameters are dose dependent as given in Table I. The resulting value of the hole capture cross section which describe the $N_T^{\mathrm{DLTS}}(T)$ within the errors of 2% is $\sigma_p = (9 \pm 1) \times 10^{-14}$ cm^2. Although the distance of the I_E level to the valence band is higher than to the conduction band, the large ratio of $\sigma_p/\sigma_n \approx 50$ would shift the DLTS peak for hole emission to a lower temperature compared to that for electrons. The experimental DLTS spectra corresponding to a forward injection show that there is such a signal—the I_H peak in Fig. 2(a). If the I_H peak is due to the hole emission from the I_E level, a direct transient analysis should reveal an ionization energy given by the difference of the band gap and the activation energy for electron emission $(1.125 - E_a = 0.58 \pm 0.002$ eV). Moreover, the measured hole concentration should be equal to the predicted concentration of holes emitted from the I_E level after high injection pulses which is given by[12]

$$p_T^{\mathrm{DLTS}}(T) = (N_{TE} - n_E(T))^{*}\frac{c_p(T)}{c_n(T) + c_p(T)}. \tag{3}$$

TABLE I. Experimental (•) and calculated (°) results at 293 K for $E_a = E_C - 0.545 \pm 0.002$ eV $\sigma_n = (1.7 \pm 0.2) \times 10^{-15}$ cm^2 and $\sigma_p = (9 \pm 1) \times 10^{-14}$ cm^2.

Detector	Dose (Mrad) (±5%)	n° (cm^{-3}) (±50%)	$N_T^{\mathrm{DLTS}\bullet}$ (cm^{-3}) (±2%)	N_{TE}° (cm^{-3}) (±2%)	$\Delta N_{\mathrm{eff}}\bullet$ (cm^{-3}) (±5%)	n_E° (cm^{-3}) (±5%)	LC• (nA) (±5%)	J_E° (nA) (±5%)
STFZ1	4	10^5	5×10^8	7.3×10^9	8.0×10^9	6.8×10^9	2.6	1.75
DOFZ1	4	10^5	$< 10^8$				2.4	
STFZ2	10	2.5×10^5	1.15×10^9	1.65×10^{10}	1.6×10^{10}	1.55×10^{10}	4.5	3.9
DOFZ2	10	2.5×10^5	$< 10^8$				4.4	
STFZ3	42.5	10^6	6.4×10^9	8.9×10^{10}	8.6×10^{10}	8.3×10^{10}	25.9	21.3
DOFZ3	42.5	10^6	7.8×10^8	1.1×10^{10}	1.6×10^{10}	1.0×10^{10}	18.9	2.7

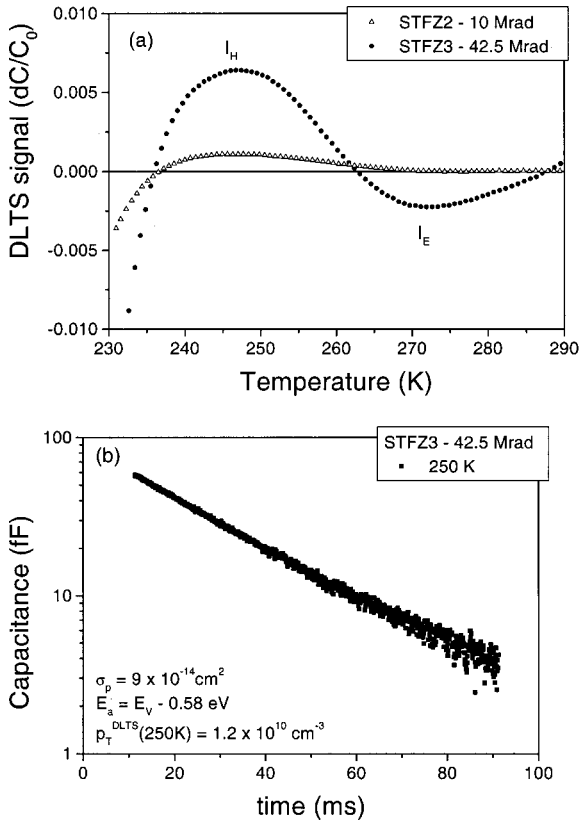

FIG. 2. (a) DLTS spectra recorded after high injection: $U_p=+3$ V; $U_R=-16$ V: $T_W=200$ ms. (b)I_H level: Transient recorded at 250 K after forward injection ($U_p=+3$ V) and analyzed considering $\sigma_p=9\times10^{-14}$ cm^2; $T_W=80$ ms; $t_0=11.3$ ms.

In the case of the STFZ3 detector and for a temperature of 250 K, this would result in an expected value of $p_T^{\mathrm{DLTS}}(250\ \mathrm{K})=1.214\times10^{10}\ \mathrm{cm}^{-3}$. The experimental transient for hole emission recorded at 250 K for this detector [see Fig. 2(b)] was directly analyzed assuming $\sigma_p=9\times10^{-14}$ cm^2, as taken from the aforementioned text. A delay time of $t_0=11.3$ ms was used to avoid the contribution of emission from V_2 centers to the recorded transient. The resulting activation energy and concentration are $E_V+0.58$ eV and $p_T^{\mathrm{DLTS}}=1.2\times10^{10}\ \mathrm{cm}^{-3}$, respectively, values which are in excellent agreement with the calculated ones.

Being close to midgap the I_E level has a strong impact to the detector performance. The contribution of the I_E defect to the leakage current is given by

$$J_E(T)=V*q_0*e_n(T)*n_E(T), \tag{4}$$

where q_0 indicates the electron charge and V indicates the volume of the detector ($25\ \mathrm{mm}^2\times290\ \mu\mathrm{m}$).

The change in the doping concentration due to the I_E is given by $n_E(T)$. The total changes in the doping (ΔN_{eff}) and in the leakage current (LC) induced by ^{60}Co–gamma irradiation are determined experimentally at 293 K from capacitance–voltage and current–voltage measurements. These results together with the calculated contributions of the I_E defect (J_E and n_E) at 293 K are given in Table I. As can be seen, this defect can explain more than 90% of ΔN_{eff} and in case of the standard STFZ detectors it contributes to more than half of the LC.

In conclusion, we have shown that the detected close to midgap trap is strongly generated in STFZ detectors but largely suppressed in oxygenated ones. This defect has a large impact on the detector performance. It is responsible for more than 90% of the change in the effective doping concentration. Taking into account that its ionization energy is within the limits of the V_2O defect in a neutral charge state as determined from photo-EPR,[10] we conclude that the I_E level detected in this work is most probably connected to the V_2O complex.

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[1] G. Lindström, for the ROSE collaboration, Nucl. Instrum. Methods Phys. Res. A **465**, 60 (2001).
[2] G. Lindström for the ROSE collaboration, Nucl. Instrum. Methods Phys. Res. A **466**, 308 (2001).
[3] A. Hallen, N. Keskitalo, F. Masszi, and V. Nagl, J. Appl. Phys. **79**, 3906 (1996).
[4] M. Moll, H. Feick, E. Fretwurst, G. Lindstroem, and C. Schutze, Nucl. Instrum. Methods Phys. Res. A **388**, 335 (1997).
[5] M. Moll, Ph.D. thesis, DESY thesis 1999-040, ISSN 1435-8085, 1999.
[6] G. Davies, E. C. Lighttowlers, R. C. Newman, and A. S. Oates, Semicond. Sci. Technol. **2**, 524 (1987).
[7] K. Gill, G. Hall, and B. MacEvoy, J. Appl. Phys. **82**, 126 (1997).
[8] B. MacEvoy and G. Hall, Proceeding of the First ENDEASD Workshop Santorini, Greece, 21–22 April 1999, edited by C. Claeys (1999), pp. 57.
[9] Y. H. Lee and J. Corbett, Phys. Rev. B **13**, 2653 (1976).
[10] Y. H. Lee, T. D. Bilash, and J. Corbett, Radiat. Eff. **29**, 7 (1976).
[11] CiS Institut für Mikrosensorik gGmbH, Erfurt, Germany.
[12] D. V. Lang, in *Thermally Stimulated Relaxation in Solids*, edited by P. Bräunlich (Springer, Berlin, 1979) Chap. 3, pp. 93–128.
[13] P. Bräunlich, *Thermally Stimulated Relaxation in Solids*, edited by P. Bräunlich, (Springer, Berlin, 1979) Chap. 1, pp. 1–16.
[14] G. Lutz, Nucl. Instrum. Methods Phys. Res. A **377**, 234 (1996).