Bulk damage effects in standard and oxygen enriched silicon detectors induced by ^{60}Co-gamma radiation[†]

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Abstract

The influence of oxygen in silicon on bulk damage effects induced by ^{60}Co-gamma irradiation has been studied in a dose range between 0.2 Mrad to 900 Mrad. The detector processing and oxygen enrichment were carried out in a common project by the Institute of Micro-sensors CiS using n-type high resistivity FZ silicon (3-6 kΩcm) with <111> and <100> orientation. Different oxygen concentrations were achieved by diffusion at 1150 °C for 24, 48 and 72 hours. This report on bulk damage effects is focused on the observed changes in the reverse current, the effective space charge density N_{eff} extracted from C/V measurements and investigations using the transient current technique (TCT). A substantial improvement of radiation hardness concerning the development of the macroscopic properties was found for detectors manufactured on oxygenated material compared to standard material. It will be demonstrated that the change of the effective space charge density as well as the increase of the reverse current can be attributed to the creation of two deep acceptor levels and a shallow donor level.

Keywords: silicon detectors; oxygen in silicon; radiation damage; ^{60}Co-gamma radiation; defects

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1. Introduction

It was demonstrated by the CERN RD48 (ROSE) collaboration that a considerable improvement in the change of the effective space charge concentration can be achieved in oxygen enriched silicon for charged hadron damage and gamma irradiation while after exposure to neutrons no or only little suppression was found [1-3]. The beneficial effect of oxygen had been discussed and modeled under the assumption that most probably the V_2O defect is responsible for a main part of the radiation induced negative space charge and that the formation of V_2O is suppressed in oxygen rich material [4, 5]. The model predictions support also the experimental observation that the oxygen effect is correlated with the radiation induced formation of point defects. This means that in neutron damage the oxygen effect is suppressed since the damage is dominated by the creation of defect clusters. On the other hand a maximal oxygen effect is expected when only point defects are created which is the case in ^{60}Co-gamma irradiation [2, 6-7]. Here we report on new results of bulk damage effects in standard and different oxygen enriched high resistivity float zone silicon with different orientation (<111> and <100>) for a wide dose range up to 900 Mrad. The experimental results for the radiation induced change of the effective doping concentration and the reverse current will be discussed in the frame work of recent microscopic studies [8,9].

2. Experimental procedure

The oxygen enrichment and the detector processing was carried out in a common project by the Institute for Microsensors CiS (Erfurt, Germany) using n-type high resistivity float zone (FZ) silicon from Wacker with <111> and <100> orientation. Different oxygen concentrations were achieved by diffusion at 1150 ^{0}C in N_2 atmosphere for 24, 48 and 72 hours. The oxygen depth profiles were measured by a special SIMS-technique and compared with IR absorption measurements [10]. In Table 1 the averaged concentrations of oxygen and carbon are listed for all samples under investigation. The p^+nn^+-detectors have an active area of 0.25 cm^2 surrounded by a guard ring with a gap of 10µm between the outer edge of the central diode and the inner rim of the guard ring. The thickness of the different samples varies between 291µm and 295µm.

The irradiation had been performed at the high intensity ^{60}Co-gamma source at the Brookhaven National Laboratory (BNL/USA) with a dose rate of about 600 krad per hour. The temperature during exposure was typically 27 °C. A set of 8 different samples was irradiated in consecutive steps of about 50 Mrad up to 500 Mrad and followed by larger steps up to 900 Mrad. Between each step standard I/V and C/V measurements were undertaken for the evaluation of the bulk generation current and the change of the depletion voltage V_{dep} needed to fully extend the space charge region to the depth d of the diode. This voltage is related with the effective space charge density $q_0 N_{eff}$ by:

$$N_{eff} = \frac{2\varepsilon\varepsilon_0}{q_0 d^2}\left(V_{dep} - V_{bi}\right) \qquad (1)$$

where $\varepsilon\varepsilon_0$ is the permittivity of silicon, q_0 the elementary charge and V_{bi} the build in voltage. Both I/V and C/V characteristics were measured at room temperature with the guard ring of the device properly connected to ground. All presented reverse current data are normalized to 20 °C.

In order to prove the reliability of the extracted values for the effective space charge density current pulse shape measurements have been performed using the transient current technique (TCT) [11,12]. For these measurements 6 sets of 8 samples each were exposed to fixed dose values.

3. Experimental results

Fig. 1 demonstrates the development of the depletion voltage V_{dep} or effective space charge concentration N_{eff} and the reverse current at total depletion I_{rev} with the accumulated dose, for standard float-zone (STFZ) and three differently oxygenated float-zone (DOFZ) devices manufactured from <111> and <100> material. The main differences in the behavior of standard and oxygen enriched devices are:

Table 1

Impurity concentrations of standard and oxygen enriched devices under investigation.

Device acronym.	CA	CB	CC	CD	CE	CF	CG	CH
Orientation	<111>	<111>	<111>	<111>	<100>	<100>	<100>	<100>
O-diffusion [h]	0	24	48	72	0	24	48	72
N_{eff} [10^{11} cm^{-3}]	7.97	10.5	10.1	10.2	7.75	8.06	7.90	7.79
[O] [10^{16} cm^{-3}]	≤3	6.2	10	12	≤3	2.0	3.2	3.1
[C] [10^{15} cm^{-3}]	<3	2.8	5.8	3.9	<3	3.3	3.9	3.9

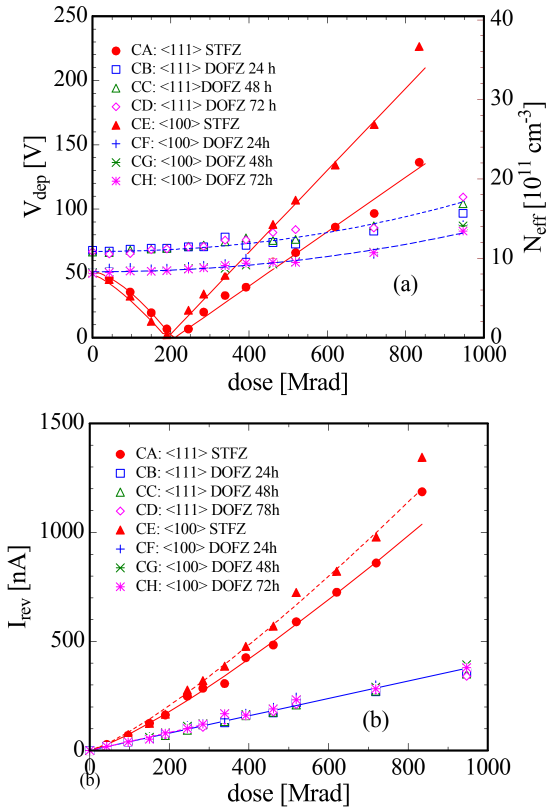

Fig 1: Dose dependence of the full depletion voltage (a) and the reverse current (b) for standard (<111>:full circle, <100> full triangle) and oxygenated (<111>:open symbols, <100>: crosses) devices.

- The detectors manufactured from standard material (CA,CE) show the well known effect of space charge sign inversion (SCSI). Initially the depletion voltage drops to a minimum value at a specific dose of about 200 Mrad before it increases again with increasing dose. This behavior is usually interpreted as a result of the creation of deep acceptor like defects and donor removal (e.g. formation of E-centers (VP_s)) which leads to a decrease of the initially positive space charge followed by a total compensation at a certain dose and thereafter to an inversion of the space charge sign. In contrast to this behavior, for all oxygenated devices (CB-CD, CF-CH) a small, monotonically and non-linear increase in the effective space charge density is observed. This implies that the effective space charge density becomes more positive possibly caused by an introduction of donor like defects.
- While the leakage current increase for standard material is found to be non-linear, all oxygenated detectors show a linear dose dependence. For an accumulated dose of 700 Mrad the estimated increase is about 3 times smaller compared to that of the standard devices. But no differences in the reverse current increase could be observed between the differently oxygenated sensors themselves.

The findings for the effective space charge density and in particular the speculation about the inversion had been proven by investigations of current pulse shapes recorded for injection of short (≈1 ns) 670 nm laser light pulses to the p^+- and the n^+-contact of the diodes. This way time-resolved electron and hole transport can be investigated separately. As an example Fig. 2a presents current pulse shapes of irradiated standard <111> devices for p^+-illumination and an applied bias voltage of 60 V that was set to be well above the full depletion voltages for this set of devices irradiated within the dose range of 43 to 284 Mrad. Since the 670 nm light is absorbed within a few microns near to the surface the presented pulse shapes are dominated by the transport of electrons in the electric field zone of the detector. In this case the negative slope of the pulse shape for doses up to 190 Mrad reflects an electric field distribution of a positive space charge and the flattening of the slope with increasing dose indicates a decrease of the space charge density as already demonstrated in the development of N_{eff} extracted from C/V measurements. For dose values larger than 200 Mrad the slope switches to positive values indicating the inversion to a negative space charge. For the same dose values and illumination of the p^+-electrode Fig. 2b shows current pulses recorded for an oxygenated <100> sensor for a constant bias voltage of 80 V.

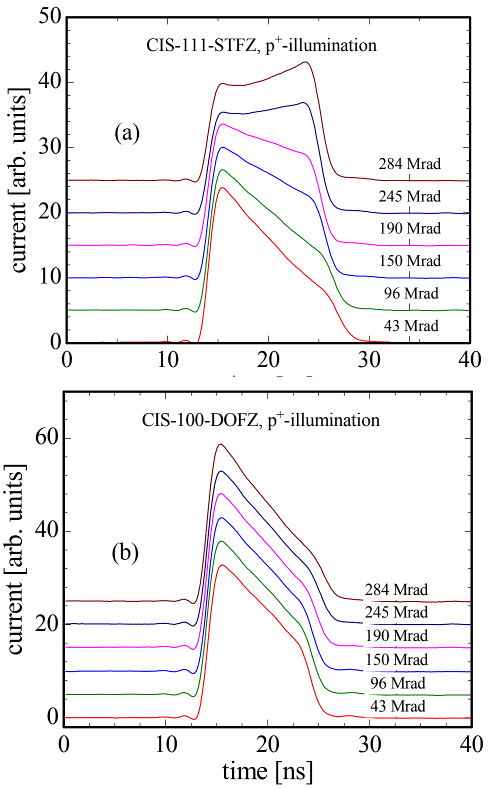

Fig. 2: Current pulse shapes after irradiation with different dose values (bottom: 43 Mrad, top: 284 Mrad) for standard <111> devices (a) and oxygen enriched <100> devices (b)

For all dose values the changes in slope of the pulses in the drift region are very small. The overall change of the slope in the range between 43 Mrad and 284 Mrad corresponds to a variation of the effective space charge concentration of $\Delta N_{eff} = 1.4\times10^{11}$ cm^{-3} only.

4. Discussion

According to C. B. MacEvoy et al [7] it is assumed that the V_2O defect, which was first identified in electron paramagnetic resonance (EPR) studies in heavily electron irradiated silicon [13, 14], plays the dominant role with respect to both the change of N_{eff} and the generation current increase induced by ^{60}Co gamma radiation. In his paper it is also demonstrated that the model predicts a non-linear increase of V_2O with dose. If this model is correct we should find a correlation between the reverse current increase and the change of the effective space charge concentration. In Fig. 3 the reverse current of a standard <111> detector (CA) is plotted as function of the corresponding change of the extracted effective space charge concentration defined by $\Delta N_{eff} = N_{eff,0} - N_{eff}(D)$. As indicated by the solid line we found an excellent correlation in the range below $\Delta N_{eff} = 1.3\times10^{12}$ cm^{-3} which corresponds with the dose range up to 300 Mrad. At higher doses the current increases more rapidly than the space charge concentration which cannot be explained by an introduction of only one deep acceptor like V_2O. Therefore, we suspect a possible compensation of the negative space charge due to the introduction of shallow donors that are positively charged in the depletion region.

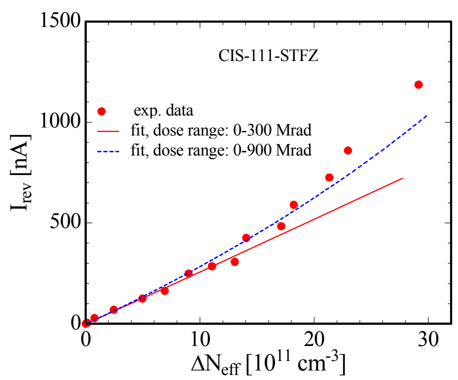

Fig. 3: Reverse current versus the change of the effective doping concentration for a standard <111> diode.

We will discuss now the experimental findings presented in chapter 3 according to recent results of detailed microscopic studies on the same material obtained by C-DLTS- and TSC-measurements [8,9]. Two close to midgap acceptor levels were discovered which are labeled as DA-I and DA-Γ. The DA-I level is most likely the V_2O defect while the DA-Γ level cannot be attributed so far to a known defect. As expected for the V_2O the DA-I defect is strongly reduced in oxygen rich diodes and the same behavior is also observed for the DA-Γ defect. Furthermore, in oxygen doped sensors an introduction of shallow donors (SD) had been detected in TSC-spectra. This defect is most probably the known bistable thermal double donor TDD_2 [15, 16]. For the calculation of N_{eff} and the reverse current I_{rev} as a function of dose the defect parameters and introduction rates given in [8,9] have been used.

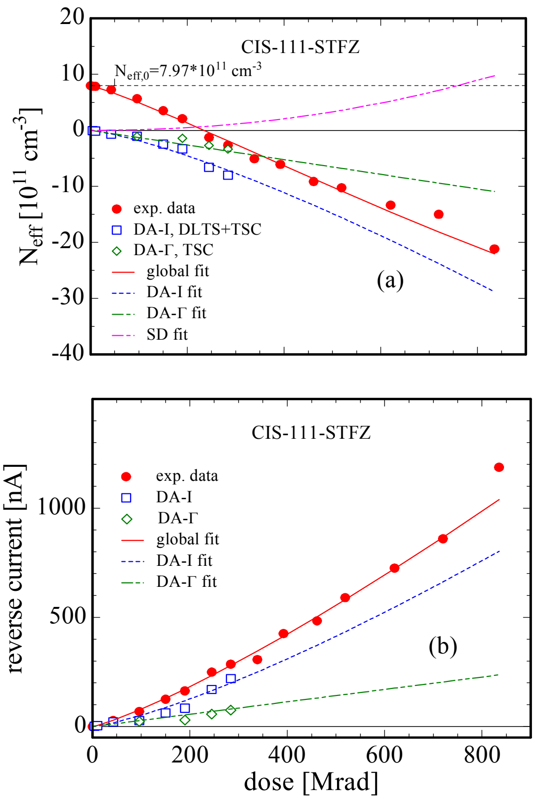

Fig. 4: Contributions of deep acceptors DA-I and DA-Γ and shallow donor SD to the effective space charge N_{eff} (a) and the reverse current (b) for standard material as function of dose.

Since most of the microscopic studies were performed on irradiated samples from <111> standard and oxygenated material, we present here only calculations for the corresponding detectors taken from the same wafer.

4.1. Standard material

In Fig. 4a the effective space charge concentration defined by $N_{eff} = N_D - N_A$ is plotted versus the accumulated dose. Here N_D represents the concentration of all donors which are positively charged in the depleted zone, i.e. the initial concentration of phosphorus and radiation induced shallow donors, and N_A is the concentration of charged shallow and deep acceptors. It is obvious that both deep acceptors DA-I and DA-Γ are responsible for the inversion of the space charge sign. Their contributions to N_{eff} as evaluated from DLTS- and TSC-measurements are also included in Fig. 4a. As can be seen, the dose dependence of the DA-I contribution is non-linear while that of the DA-Γ defect is linear. Taking only both acceptors into account the experimental data should follow a non-linear development in the total dose range. This is obviously not observed, moreover in the high dose range the experimental data points favor a linear dependence. Such development can only be achieved if one includes a small contribution of radiation induced shallow donors (SD), and a non-linear increase is needed in order to reproduce the experimental data. It should be mentioned that from TSC- measurements on standard material one can only find an indication for the creation of shallow donors but quantitative estimations of their concentrations were not possible [9].

Fig. 4b shows once more the experimental data for the reverse current of the standard <111> detector where the contributions of both deep acceptors are included. Also in this case the different response of the DA-I and the DA-Γ defect on the dose is clearly seen and the agreement between the measured reverse current values and the evaluated values for both defects can be stated to be excellent.

Taking these results into account, the following parameterization for the dependence of N_{eff} as function of dose D was used:

$$N_{eff}(D) = N_{eff,0} + N_{SD}(D) - N_A(D) \qquad (2)$$

with $N_{eff,0} = N_{D,0} - N_{A,0}$ being the effective doping concentration before irradiation.

For the calculation of N_{SD} we assume that the shallow donors are thermal double donors and, therefore, their contribution to the space charge has to be counted twice since they are double positively charged when not occupied. Furthermore, the introduction is supposed to be non-linear. This leads to the relation:

$$N_{SD}(D) = g_{SD}\times D^{\gamma_{SD}}, \qquad (3)$$

and the contribution of both deep acceptors is supposed to be:

$$N_A(D) = g_{DA\text{-}I}\times D^{\gamma_{DA\text{-}I}} + g_{DA\text{-}\Gamma}\times D \qquad (4)$$

The g factors denote the effective introduction rates for the defects SD, DA-I and DA-Γ which are charged in the depleted volume (see also [9]) and the γ values describe the non-linearity of the defect introduction as function of dose. A possible donor removal has been neglected here since the phosphorus concentration is very small and from defect kinetic simulations a very small removal constant is expected [17].
The bulk generation current I_{rev} is caused by both deep acceptors only and is parameterized by:

$$I_{rev}/V = \alpha_{DA\text{-}I}\times D^{\gamma_{DA\text{-}I}} + \alpha_{DA\text{-}\Gamma}\times D \qquad (5)$$

Here V is the volume of the fully depleted detector and α describes the current related damage coefficients for both deep acceptor levels.
According to these parameterizations the data presented in Fig. 4a and b have been fitted. The dotted and broken lines represent the fits to the specific contributions of the defects to the effective space charge density N_{eff} and the generation current I_{rev} respectively. The full lines are the result of a fitting procedure which reproduces the experimental data for N_{eff} and I_{rev} at the same time. This procedure is denoted as "global fit".

4.2. Oxygen enriched material

The same fitting procedures were applied to the experimental data derived for the oxygenated device CD manufactured from <111> material. The results are shown in Fig. 5. In this case instead of N_{eff} the change of the effective doping concentration defined by $\Delta N_{eff} = N_{eff}(D) - N_{eff,0}$ is plotted as function of the dose. For this oxygenated material the contribution of shallow donors could be estimated from TSC-measurements making use of the bi-stability of this defect [9]. It can be clearly seen that the shallow donors overcompensate the introduction of the deep acceptors DA-I and DA-Γ. On the other hand the introduction of both deep acceptors is strongly suppressed compared to standard material.

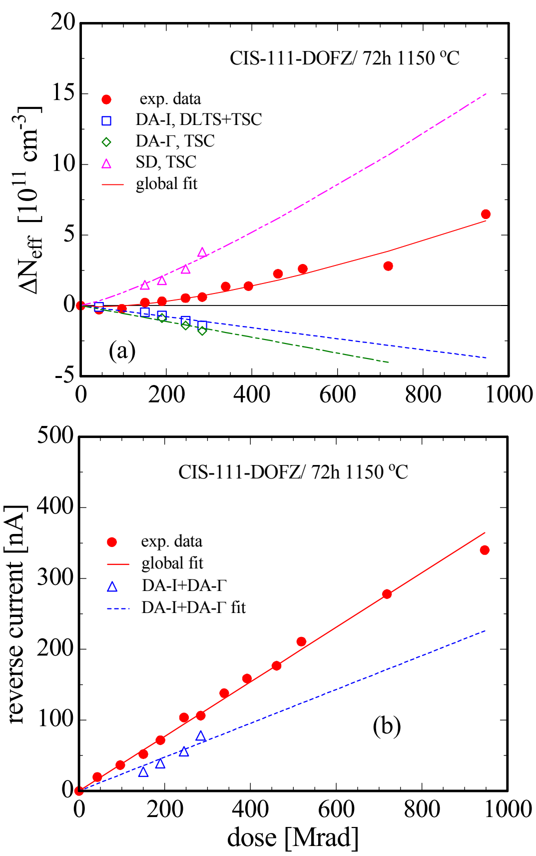

Fig. 5: Contributions of deep acceptors DA-I and DA-Γ and a shallow donor SD to the effective space charge N_{eff} (a) and the reverse current (b) for oxygenated material as function of dose.

As already mentioned before the generation current increases linearly with dose (see Fig. 5b) which is expected from the observed introduction of both deep acceptors in Fig. 5a and the increase is much smaller compared to that of standard material. But the contribution of both defects to the generation current cannot fully reproduce the measured values. As pointed out in [9] possible reasons might be an underestimation of the concentration for the DA-Γ defect and/or a contribution of other deep defect centers which possibly could not be detected by TSC-measurements.
A further point of interest is the question whether any dependence on the oxygen concentration could be seen in the macroscopic parameters. From Fig. 1b we

can see that the generation current is obviously not influenced by the different oxygen diffusion. This implies that already an oxygenation of 24 hours leads to the observed suppression in the creation of both deep acceptors. But an analysis of the dose dependence of ΔN_{eff} for all oxygenated detectors processed on <111> material show a very small variation of the increase with the oxygen content although the fluctuation of the data points is quite large. The result is that the introduction of shallow donors seems to be influenced by the oxygen concentration of the material but it is so far not possible to decide whether the introduction rate g_{SD} or the exponent γ_{SD} is the more sensitive parameter.
All parameters of the parameterization given by eq.(3-5) which had been evaluated from the described fitting procedures are summarized in Table 2.
Further studies of these and other differently processed detectors were perfomed for irradiations up to ultra-high dose values between 0.9 and 1.76 Grad. The results are described separately in [18].

Table 2

Extracted parameters according to eq.(3-5); g-values are given in units [10^8 cm^{-3} $Mrad^{-1}$] and α values in [10^{-8} cm^{-3} $Mrad^{-1}$].

Device	CA	CB	CC	CD
Oxygenation	Standard	24 h	48 h	72 h
g_{DA-I}	4.80	3.90	3.90	3.90
γ_{DA-I}	1.29	1.0	1.0	1.0
$g_{DA-\Gamma}$	1.31	0.559	0.559	0.559
g_{SD}	0.0065	5.45	5.59	3.25
γ_{SD}	2.12	1.12	1.14	1.23
α_{DA-I}	1.83	1.48	1.48	1.48
$\alpha_{DA-\Gamma}$	3.90	3.76	3.76	3.76

5. Conclusions

The presented study on bulk damage effects after ^{60}Co gamma irradiation up to 900 Mrad had substantiated the strong influence of oxygen in silicon for the development of more radiation tolerant detectors. For the first time the observed changes of the macroscopic detector properties concerning the effective doping concentration as well as the reverse current can be explained by radiation induced deep acceptors and the creation of shallow donors which had been discovered in microscopic studies.

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