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Deep defect levels in standard and oxygen enriched silicon detectors before and after ^{60}Co-γ-irradiation

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Abstract

Capacitance Deep Level Transient Spectroscopy (C-DLTS) measurements have been performed on standard and oxygen-doped silicon detectors manufactured from high-resistivity n-type float zone material with ⟨1 1 1⟩ and ⟨1 0 0⟩ orientation. Three different oxygen concentrations were achieved by the so-called diffusion oxygenated float zone (DOFZ) process initiated by the CERN-RD48 (ROSE) collaboration. Before the irradiation a material characterization has been performed. In contrast to radiation damage by neutrons or high-energy charged hadrons, were the bulk damage is dominated by a mixture of clusters and point defects, the bulk damage caused by ^{60}Co-γ-radiation is only due to the introduction of point defects. The dominant electrically active defects which have been detected after ^{60}Co-γ-irradiation by C-DLTS are the electron traps VO_i, C_iC_s, $V_2(=/-)$, $V_2(-/0)$ and the hole trap C_iO_i. The main difference between standard and oxygenated silicon at low dose values can be seen in the introduction rate of C_iC_s compared to C_iO_i. For highly oxygenated silicon the introduction of C_iC_s is fully suppressed, while the sum of the introduction rates $g(C_iC_s) + g(C_iO_i)$ is independent on the oxygen concentration.

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1. Introduction

The CERN RD48 (ROSE) [1,2] collaboration had shown that oxygen enrichment of the silicon bulk leads to a considerable decrease of damage effects, induced primarily by charged hadrons and γ-irradiation. But so far it had been shown, that the observed changes of the macroscopic properties like the change of the effective doping concentration as well as the leakage current cannot be fully explained by the dominant induced defects, which have been investigated by DLTS, TSC and other methods [3–6].

In this work we report on DLTS studies on ^{60}Co-γ-irradiated silicon detectors in order to avoid the complications caused by the generation of clusters and to search for possible defects, which might be responsible for the observed changes in the macroscopic properties.

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2. Experimental procedures

2.1. Deep Level Transient Spectroscopy (DLTS)

The measuring method, which has been mainly used in this work, is the Capacitance-Deep Level Transient Spectroscopy (C-DLTS), which was at first introduced by Lang [7]. The principle of this method is based on the temperature dependence of the emission process of trapped charge carriers in defect centers in the space charge region of a reverse biased diode. For an isolated defect level the emission process is an exponential function in time with a single emission time constant and is measured via the corresponding space charge capacitance transient. In our DLTS-system a Fast Fourier Transformation is applied to the measured transient for data reduction and evaluation of the emission time constant and trap concentration [8]. Performing a so-called temperature scan (repetition of the measurement as function of temperature) the determination of virtually all parameters associated with traps like activation energy, capture cross-section, and trap concentration is possible. However, the application of this method is limited by the requirement that the concentration of traps N_T has to be small compared to the shallow doping concentration N_S. This limit can be pushed to higher trap concentrations by using the Constant Capacitance-DLTS (CC-DLTS) technique [9]. Here the capacitance of the space charge region is kept constant by using a feedback scheme in the bias voltage-capacitance measurement system and the change of the bias voltage in the feedback loop is the DLTS-signal.

For DLTS peaks, which correspond to defect levels with similar activation energies and capture cross-sections a special deconvolution technique, developed by the company PhysTech [10] had been used.

In general the CDLTS spectra had been obtained with a time window of $T_W = 200\,\text{ms}$, a filling pulse duration of $t_{fill} = 100\,\text{ms}$ and a reverse bias of $U_R = 20\,\text{V}$.

2.2. Material

The p+nn+ diodes investigated in this work are manufactured from high-resistivity ($\rho = 3-4\,\text{k}\Omega\,\text{cm}$) n-type float zone (FZ) silicon grown in the $\langle 1\,1\,1\rangle$ and $\langle 1\,0\,0\rangle$ direction from Wacker. The processing and oxygen enrichment has been performed by the company CiS [11]. The oxygen doping was achieved by diffusion for 24, 48 and 72 h at 1150°C in nitrogen. This oxygenated material will be named DOFZ while the standard material will be labeled as STFZ. A detailed description of the material is given in Ref. [12].

2.3. Irradiation

Irradiations had been performed at the high intensity ^{60}Co-γ-source of the Brookhaven National Laboratory (BNL) in the US at room temperature. The samples were irradiated for this investigation in a dose range from 0.2 up to 10 Mrad.

3. Experimental results

3.1. Defects before irradiation

A search for process-induced defects had been performed before irradiation. Five different defect levels have been discovered in the material.

As an example Fig. 1 shows DLTS spectra for electron and hole injection. The properties of these defects are listed in Table 1, and their concentrations are listed in Table 2.

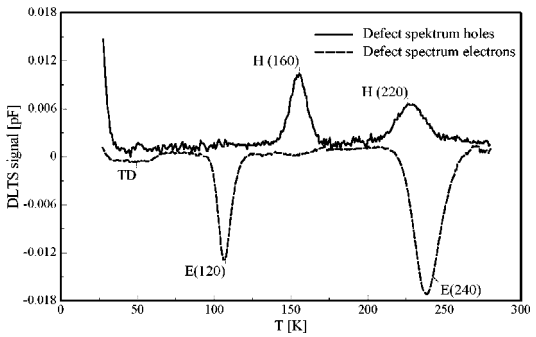

Fig. 1. CDLTS measurement of electron and hole traps in an oxygenated (24 h) $\langle 100\rangle$ sample before irradiation.

One of these defects is the so-called thermal double donor TD. The introduction of TDs depends strongly on the oxygen concentration [13]. As can be seen in Table 2 the amount of TDs is correlated with the oxygen content of the differently oxygenated devices, but the concentrations in the material with ⟨1 0 0⟩ orientation (CF-CH) are smaller compared to the material with ⟨1 1 1⟩ orientation. There is no measurable amount of thermal donors observed in STFZ-material (Wafers CA and CE).

The other four defects are so far unknown. The electron trap E(120) appears only in oxygenated ⟨1 0 0⟩ material. This defect has an activation energy and capture cross-section which are close to the values of the double charged state of the divacancy $V_2(=/-)$ as will be shown later.

The defect E(240) is a very deep level and from its properties this level is mainly responsible for the measured generation current.

H(160) is a hole trap. It was just visible in the ⟨1 0 0⟩ wafer with 24 h oxygenation by optical carrier injection.

Table 1
Electric properties of the material defects

Name	Sign	E_a (eV)	$\sigma_{n,p}$ (cm^2)
TD	e	−0.137	1.58×10^{-13}
E(120)	e	−0.236	1.00×10^{-14}
E(240)	e	−0.545	5.41×10^{-15}
H(160)	h	+0.370	2.88×10^{-13}
H(220)	h	+0.494	1.65×10^{-14}

H(220) is also a hole trap. It was already seen in former material investigations [5]. The concentration of this defect is independent of the oxygenation concentration and orientation of the wafer, but depends on the position of the diode on the wafer, i.e. the concentration increases with the distance from the center of the wafer to the edge. According to the material investigation the ⟨1 1 1⟩ material contains less defects than the ⟨1 0 0⟩ material.

3.2. Radiation induced defects

3.2.1. Dominant defects

The irradiation with a ^{60}Co-γ-source has the advantage that only point defects and no clusters are generated, while an irradiation with hadrons would also cause clusters. In Fig. 2a DLTS-spectrum is shown for a standard detector irradiated with a dose of 0.5 Mrad. The small peak at about 60 K is caused by the thermal double donor TD already observed before irradiation. The dominant peak at 85 K can be attributed to the creation of the VO_i (vacancy + oxygen interstitial) and the C_iC_s(A) (carbon interstitial + carbon substitutional, state A) defects, while the small peaks at 120 and 200 K are associated with the different charge states of the divacancy ($V_2(=/-)$ and $V_2(-/0)$). The superposition of the VO_i and the C_iC_s signal at 85 K cannot be resolved by high-resolution techniques, since their activation energies and capture cross-sections are nearly identical. But measurements of the amplitude of

Table 2
Concentration of material defects

Name	CA	CB	CC	CD	CE	CF	CG	CH
Orientation	⟨1 1 1⟩	⟨1 1 1⟩	⟨1 1 1⟩	⟨1 1 1⟩	⟨1 0 0⟩	⟨1 0 0⟩	⟨1 0 0⟩	⟨1 0 0⟩
O-diff (h)	0	24	48	72	0	24	48	72
O (cm^{-3})		6.2×10^{16}	1.0×10^{17}	1.2×10^{17}		2×10^{17}	3.2×10^{17}	3.1×10^{17}
C (cm^{-3})		2.8×10^{15}	5.8×10^{15}	3.9×10^{15}		3.3×10^{15}	3.9×10^{15}	3.9×10^{15}
TD (cm^{-3})	$<10^9$	6.0×10^9	1.6×10^{10}	2.4×10^{10}	$<10^9$	6.9×10^9	7.2×10^9	1.5×10^{10}
E (120) (cm^{-3})	—	—	—	—	—	1.7×10^{10}	5.0×10^9	2.0×10^9
E (240) (cm^{-3})	0.8×10^9	—	—	—	—	1.2×10^{10}	7.9×10^9	3.7×10^9
H (160) (cm^{-3})	—	—	—	—	—	9.7×10^9	—	—
H (220) (cm^{-3})	2.4×10^9	4.0×10^9	5.2×10^9	2.7×10^9	$<10^9$	6.3×10^9	5.7×10^9	1.0×10^{10}

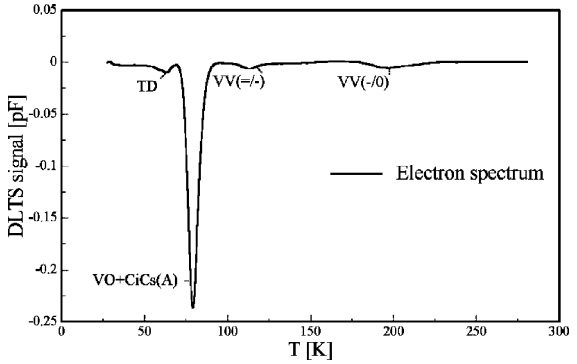

Fig. 2. CDLTS measurement of electron traps of a ⟨100⟩ STFZ detector irradiated with 0.5 Mrad.

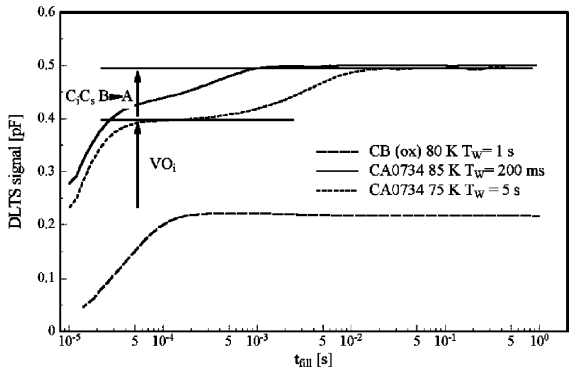

Fig. 3. Capture measurement of a standard and oxygenated detector irradiated with 0.5 Mrad.

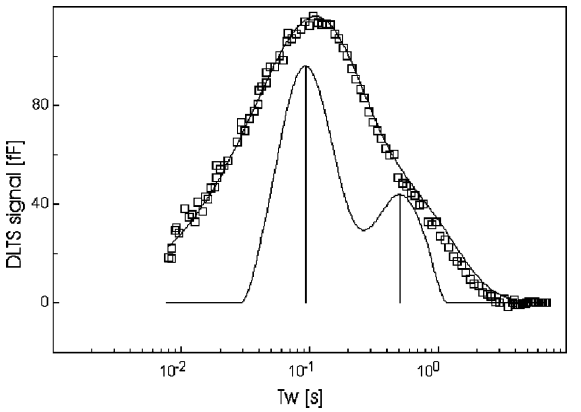

Fig. 4. Isothermal measurement at 112 K for a 24 h oxygenated ⟨100⟩ detector.

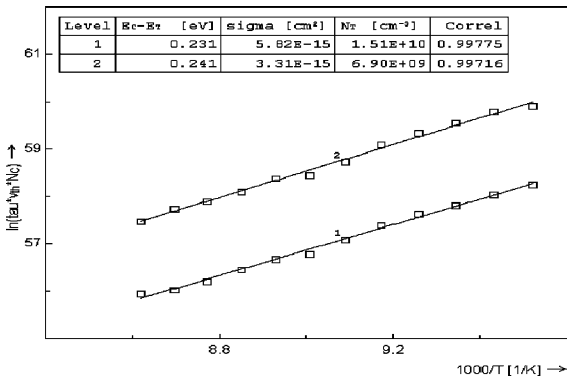

Fig. 5. Arrhenius plot of the separation levels shown in Fig. 4.

the DLTS signal as function of the filling pulse duration t_{fill} at constant temperature allow to separate the signals arising from the C_iC_s(A) and VO_i by making use of the bistability of the C_iC_s defect [4] as demonstrated in Fig. 3 (upper curves). The first increase corresponds to the filling of the VO_i while the second one reflects the configurational change from state C_iC_s(B) to state C_iC_s(A). For this change an activation energy has to be overcome and therefore the t_{fill} value at which this step occurs depends on the temperature (see curves at $T = 85$ and 75 K). The lower curve in Fig. 3 was measured for an oxygenated sample where such step could not be detected. This indicates that in oxygenated material the C_iC_s defect is strongly suppressed. For the extraction of the level parameters and the concentration of the double charged divacancy $V_2(=/-)$ in the ⟨100⟩ material this defect had to be separated from the material defect that appears at the same temperature in the spectra as mentioned before. This was possible by using the high-resolution DLTS method. As an example Fig. 4 shows the measurement of the DLTS signal as function of the transient time window (open squares) and the separation of both levels by a special refolding technique (solid line) [10]. Measurements at different temperatures result in the corresponding Arrhenius plot demonstrated in Fig. 5. Here level 1 corresponds to the material defect E(120) while level 2 is attributed to the $V_2(=/-)$ level. Fig. 6 shows spectra for the hole trap C_iO_i for samples irradiated with different doses up to 10 Mrad. As

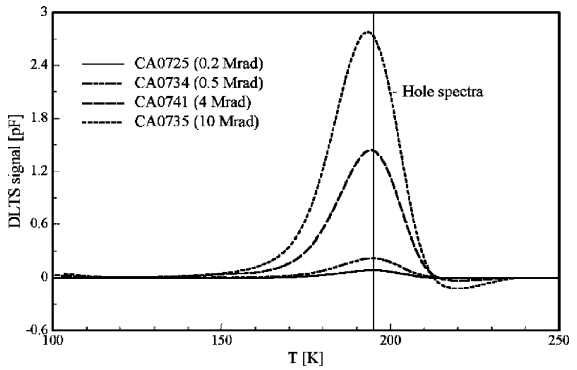

Fig. 6. CDLTS spectrum after hole injection for STFZ samples irradiated with different doses.

Table 3
Properties of radiation induced defects

Defect	E_a (eV)	$\sigma_{n,p}$ (cm^2)	E_a [4] (eV)	$\sigma_{n,p}$[4] (cm^2)
VO_i	−0.172	1.6×10^{-14}	−0.175	1.5×10^{-14}
V_2 (=/−)	−0.251	3.0×10^{-14}	−0.224	7.1×10^{-16}
V_2 (−/0)	−0.426	3.1×10^{-15}	−0.423	2.1×10^{-15}
C_iO_i	+0.351	7.3×10^{-16}	+0.357	1.7×10^{-15}

Table 4
Introduction rates for the impurity-related defects

Name	CA standard ⟨111⟩	CD 72 h ⟨111⟩	CE standard ⟨100⟩	CH 72 h ⟨100⟩
g(VO)	70.5	58	67.3	80.6
$g_1(C_iC_s)$	17.1	0	16.3	0
$g_2(C_iO_i)$	47.8	63.4	33.4	58.5
$\Sigma(g_1+g_2)$	64.9	63.4	49.7	58.5

Values given in $10^4\,\mathrm{rad}^{-1}\,\mathrm{cm}^{-3}$.

Table 5
Introduction rates for the divacancies

Oxygenation	g (V_2(=/−)) $10^4\,\mathrm{rad}^{-1}\,\mathrm{cm}^{-3}$	g (V_2(−/0)) $10^4\,\mathrm{rad}^{-1}\,\mathrm{cm}^{-3}$
Standard	1.8	1.8
24 h	1.7	1.5
48 h	1.5	1.4
72 h	1.5	1.4

Values given in $10^4\,\mathrm{rad}^{-1}\,\mathrm{cm}^{-3}$.

can be seen in the spectra the peak shifts slightly for higher doses to lower temperatures which is mainly caused by the fact that the concentration of this defect exceeds already at 4 Mrad, the shallow doping concentration and thus the DLTS requirement is not fulfilled anymore. The activation energies and the capture cross-sections of all radiation induced trap levels are summarized in Table 3 and compared with values given in Ref. [4].

The extracted introduction rates for the impurity related defects VO_i, C_iC_s and C_iO_i are presented in Table 4 for standard and oxygenated devices (72 h) manufactured from ⟨111⟩ and ⟨100⟩ material. For the creation of VO_i no dependence on the oxygen concentration is seen while the generation of C_iC_s is fully suppressed in oxygenated material. This suppression is due to the fact that in oxygen rich material the probability of the reaction $C_i+O_i->C_iO_i$ is much larger compared to the reaction $C_i+C_s->C_iC_s$. But it is expected that the sum of the introduction rates $g(C_iC_s)+g(C_iO_i)$ stays constant for all materials. This holds with the exception observed for the standard ⟨100⟩ material (device CE) which shows a slightly lower introduction rate.

On the other hand the introduction of divacancies V_2 is about two orders of magnitude smaller compared to the introduction of the impurity related defects as can be seen from Table 5. A very small dependence on the oxygen concentration cannot be excluded. Furthermore, it is clear that the introduction rate for both charge states should be the same. This holds for all extracted values within the error limit of 10%.

It is instructive to compare the introduction rates of all C_i related defects with the vacancy related ones. Assuming that the introduction of C_i related defects reflects the primary generation of silicon interstitials I via the Watkins replacement mechanism $I+C_s->Si+C_i$ and the subsequent formation of C_iC_s and C_iO_i,

$$\frac{g(C_iC_s)+g(C_iO_i)}{g(VO_i)+2*g(V_2)}=1$$

i.e. the sum of the introduction rates $g(C_iC_s) + g(C_iO_i)$ should be equal to the total introduction of Interstitials $g(I)$. On the other hand each primary interaction will create the same number of vacancies and hence the total number of vacancy related defects should balance the interstitial related ones. As a consequence the following equation for the introduction rates should be fulfilled.

This relation holds for $\langle 1\,1\,1 \rangle$ material with a ratio of 0.91 ± 0.12 but for $\langle 1\,0\,0 \rangle$ material the extracted ratio of 0.71 ± 0.02 is too small. An explanation of such a small value can so far not be given.

All these defects described above are well known and characterized, but they still cannot explain the macroscopic properties like the increase in the leakage current and the change in the effective doping. In recent studies of our group on these devices at larger doses a close to midgap level at $E_C - 0.545\,\text{eV}$ was observed which can mainly explain the radiation induced changes of the macroscopic detector properties [14].

4. Conclusions

After irradiation with ^{60}Co-γ-radiation we observed for the different materials the dominant introduction of carbon and oxygen related defects and a much smaller generation of divacancies. The main influence of oxygen in the defect formation is seen in the formation of C_iC_s and C_iO_i where already oxygen enriched material by a diffusion of 24 h shows a full suppression of the C_iC_s defect. In this report no difference is seen in material with different orientation. For the creation of divacancies the introduction rate is about two orders of magnitude smaller compared to the creation of impurity-related defects and a very small dependence on the oxygen concentration was observed. A difference between $\langle 1\,1\,1 \rangle$ and $\langle 1\,0\,0 \rangle$ material had only been established in the ratio of introduction rates for interstitial related defects. All of these defects seen by DLTS in the investigated dose range are not responsible for the change of the macroscopic device properties. Only a recently detected deep level close to midgap can explain the macroscopic parameters.

Acknowledgements

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