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Deep Levels Profile in Neutron Irradiated Silicon Detectors

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Abstract

Measurements of radiation induced defects for high resistivity silicon detectors irradiated by high fluence fast neutrons have been performed using a Thermally Stimulated Current spectrometer. The TSC signals have been measured approximately 2 months and one year after irradiation to observe the changes in the radiation induced lattice disorder for storage at room temperature. Energy levels inside the band gap and trap concentrations have been measured at different depletion depths to analyse the defect profile inside the silicon bulk. Up to 17 traps have been observed, which energy levels seem to be independent on the depth inside the bulk. The concentration of the deeper levels have found to increase by measuring deeply inside the junction.

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1. Introduction

In recent years, silicon detectors radiation hardness has been very fruitfully studied by means of the Thermally Stimulated Current spectroscopy [1,2,3,4,5]. This method has been used to determine the presence in the detector bulk of the radiation induced defects which are responsible of the degradation of the device after exposure. The TSC technique may be moreover very useful in particular to investigate the microscopic damage which causes the changes in the effective doping of the detector bulk for high fluences of irradiation. Experimental investigations have pointed out in fact that n-type silicon detectors turns to p-type after strong irradiations [6], while a thin n-type layer has been supposed to exist around the detector bulk to preserve the correct operation of the detector [7]. To explain the absence of the type inversion near the surface of the silicon a model has been proposed by Lutz [7] in which radiation induced defects are supposed to disappear when they reach the silicon surface. By opportunely changing the reverse voltage during the TSC measurement [8] the profile of the microscopic damage inside the detector may be analysed to test the uniformity of the radiation induced lattice disorder in the silicon bulk.

This paper summarizes the TSC results obtained measuring an highly irradiated silicon detector at different depletion depths. The results have been discussed in view to understand the radiation induced lattice profile inside the detector.

II. Experimental Set-Up

Silicon p n junction detectors used for this experimental study were made on n-type <1 1 1> wafers with resistivities of 2-6 K Ω cm at the Brookhaven National Laboratory and irradiated with fast neutrons with an average energy of 1 MeV and a fluence of 5.67×10^{13} n/cm² at the University of Lowell.

Thermally Stimulated Current measurements have been carried out at the Dipartimento di Energetica di Firenze (DEF), Italy, by means of a TSC spectrometer [9]. The facility mainly consists of a liquid helium dewar in which a descend carrying the sample holder is inserted. The thermal scans are obtained by pulling up and down the sample holder on the helium vapours. The temperature during the TSC measurements is monitored with a Lake Shore temperature controller, connected to a silicon sensor. The sample current is measured with a Keithley 617 electrometer. The data acquisition apparatus is completely computer controlled.

III. Experimental Results

To study the radiation induced disorder the TSC general procedure [8] has been applied to the detectors. The TSC spectra obtained approximately 2 months and 14 months after irradiation are shown in figure 1. The samples were kept at room temperature during the delay time between the two measurements so that the changes in the silicon detector lattice disorder caused by self annealing may be derived by directly comparing the two TSC spectra of figure 1. From the plots, it is evident that the major changes are observed for peaks appearing at high temperatures. This corresponds to a general increase of the trap concentration of the deeper energy levels inside the forbidden gap with the selfannealing time.

Five TSC analysis have been carried out 14 months after irradiation applying to the samples different reverse voltages with the following absolute

values:

$$V_1 = 5V; \quad V_2 = 20V; \quad V_3 = 35V; \quad V_4 = 50V; \quad V_5 = 70V.$$

The junction depletion depths related to these bias have been determined by measuring the capacitance versus reverse voltage characteristic of the samples. The C-V analysis revealed the type inversion of the bulk. The strong room temperature reverse annealing [10] during the storage time after irradiation, brought the occurrence of the full depletion at very high bias (far above the 100V) so the following values have been obtained for the five voltages applied:

$$W_1 = 22\mu m; \quad W_2 = 37\mu m; \quad W_3 = 50\mu m; \quad W_4 = 63\mu m; \quad W_5 = 81\mu m.$$

A sixth reverse voltage of 100V was used too, but the TSC signal was almost totally hidden by the exponential increase with temperature of the leakage current, so that only the results for the first five bias will be reported in the following.

Figure 2 presents the TSC signals related to the five reverse voltages in the temperature range between 10K and 210K. Each TSC spectrum has been obtained by subtracting to the current measured during the heating scan the background measured during the cooling one. Data have been obtained by applying forward filling voltages to fill the traps before the measurements. Figure 3 shows the normalized spectra I_{TSC}/W , in which each TSC signal I_{TSC} is divided by the respective detector depletion depth W . Both figure 2 and figure 3 show that the TSC peaks observed in the range from 10K to 100K are quite similar at different depletion depths, while an increase in the TSC signal is clearly visible for high temperatures for high W values. This indicates that the concentration of the radiation induced traps related to deeper energy levels increases when measurements are carried out deeply inside the detector pn junction.

The deconvolution method [11] has been applied to the TSC signals to measure both the energy level and the concentration of the radiation induced defects. Results are summarized in table I and II. Up to seventeen energy levels have been measured in the range from 0.030eV to 0.500eV. Table I shows their values at different depletion depths: no significant changes in the energy levels are observed by changing the reverse voltage, indicating a good uniformity in the radiation induced disorder inside the bulk of the detector. The deepest level, located near the middle of the forbidden gap, with an average energy value of 0.490eV, is hidden by the leakage current when the sample is biased with V_1 . Table II shows the concentrations of the observed defects, in the left column the average value of the related energy levels is reported. The concentrations of the shallower defects changes slightly with the depletion depth, with values generally below 10^{12}cm^{-3} . Levels in the range from 0.4eV to 0.5eV suffer a significant increase in concentration by increasing the depletion depth from W_1 to W_5 . The fact that the deeper levels increase the concentration when measurements are carried out deeply inside the detector bulk may be in accordance with the Lutz model [7] suggesting a drastic decrease of the defect concentration in the nearby of the detector surface.

By concluding, we may try, using literature indications, to relate the observed energy levels to radiation induced lattice defects. The shallowest two levels in table I and II may be caused by the presence in the silicon bulk of the Boron (B) and Phosphorous (P) dopants. In particular, P should be related to the average value of 0.035eV, the second level in table I, which is very low, indicating an almost complete removal of the n-type dopant inside the irradiated bulk. Level at 0.164eV, having concentration lower than 10^{12}cm^{-3} inside the detector, may be related to Vacancy - Oxygen complex [12]. Levels at 0.248eV and 0.400eV are probably due to the divacancy in double and single minus charge states respectively: V_2^{--} and V_2^- [13]. A strong increase in the V_2^- concentration is observed at the deepest depletion depth of 81 μm . Energy level at 0.428eV should be related to phosphorous-vacancy complex (E centre) [14] the very high concentration observed for this defect nevertheless suggests that some other important contribution to this energy level by another trap should be taken into account. The initial resistivity of 2K Ωcm in fact, limits the presence of the P atoms to values around 10^{12}cm^{-3} . The level at 0.490eV, observed in

very high concentrations deeply inside the bulk, could be related to Boron-Vacancy complex [15]: authors have nevertheless pointed out that this defect should annihilate at room temperature [10].

The problem to definitively relate the energy levels observed to the lattice defects is still a matter of interpretation and will be discussed in forthcoming works.

III. Conclusions

TSC measurements have been carried out on high resistivity silicon detectors irradiated by fast neutrons. The energy levels and the trap concentrations of the radiation induced defects have been measured at different reverse voltages. Seventeen defects have been observed, which energy levels seem to be independent on the depletion depths, indicating that the radiation induced lattice disorder is uniform inside the detector volume and that it is not confined in the region immediately below the detector surface, extending itself deeply inside the bulk. Some increase in the concentration of the deeper levels with selfannealing seems to occur. A strong increase in the concentration of the deeper energy levels have been observed by increasing the depletion depth inside the detector. These observations may be in accordance with recent models on silicon radiation damage in which the concentration of the radiation induced defects is supposed to decrease drastically near the detector surface.

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Figure Captions

Figure 1.

TSC signals observed in a sample irradiated with a fast neutron fluence of $5.67 \times 10^{13} \text{ n/cm}^2$ respectively (-) 2 months and (--) 14 months after irradiation.

Figure2.

TSC signals observed in the range from 10K to 210K in a sample irradiated with a fast neutron fluence of $5.67 \times 10^{13} \text{ n/cm}^2$. Plots are related to the following depletion depths W:

(--) 22 μm ; (-) 37 μm ; (o)50 μm ; (x) 63 μm ; (+) 81 μm .

Figure3.

Normalized TSC signals observed in a sample irradiated with a fast neutron fluence of $5.67 \times 10^{13} \text{ n/cm}^2$. The thermally stimulated current spectra have been divided by the following depletion depth W:

(--) 22 μm ; (-) 37 μm ; (o)50 μm ; (x) 63 μm ; (+) 81 μm .

Table Captions

Table 1.

Energy levels measured by TSC analysis at different depletion depths in a sample irradiated with a fast neutron fluence of $5.67 \times 10^{13} \text{ n/cm}^2$.

Table 2.

Trap concentrations measured at different depletion depths in a sample irradiated with a fast neutron fluence of $5.67 \times 10^{13} \text{ n/cm}^2$.

Depletion Depth [μm]				
22	37	50	63	81
Energy Levels [eV]				
0.031	0.031	0.030	0.030	0.029
0.035	0.035	0.034	0.034	0.034
0.058	0.053	0.054	0.054	0.054
0.072	0.069	0.070	0.070	0.070
0.102	0.098	0.099	0.099	0.099
0.168	0.164	0.160	0.165	0.165
0.188	0.182	0.185	0.182	0.182
0.200	0.200	0.203	0.203	0.203
0.210	0.215	0.215	0.215	0.215
0.250	0.250	0.247	0.247	0.247
0.308	0.308	0.308	0.308	0.308
0.337	0.334	0.334	0.334	0.334
0.362	0.358	0.364	0.360	0.364
0.395	0.395	0.407	0.395	0.402
0.423	0.425	0.430	0.430	0.432
0.450	0.440	0.457	0.465	0.453
0.485	0.480	0.490	*	0.500

table I

E_t [eV]	Depletion Depth [μm]				
	22	37	50	63	81
	Trap Concentration [10^{12} cm^{-3}]				
0.030	1.8	1.7	1.2	1.1	0.9
0.035	0.3	0.3	0.2	0.2	0.2
0.055	0.1	0.1	0.1	0.1	0.1
0.070	0.5	0.5	0.7	0.5	0.9
0.100	0.2	0.2	0.4	0.3	0.5
0.164	0.2	0.3	0.4	0.2	0.3
0.184	0.1	0.3	0.6	0.4	0.4
0.202	0.3	0.5	0.4	0.4	0.6
0.214	0.1	0.45	0.4	0.4	0.7
0.248	1.0	1.5	1.5	1.5	2.0
0.308	2.0	2.0	1.0	1.0	1.5
0.335	2.2	3.5	4.0	3.0	3.0
0.362	3.0	5.5	8.5	5.0	13.0
0.400	3.4	8.5	14.0	7.5	31.0
0.428	3.0	6.0	7.0	5.0	38.0
0.455	7.0	14.0	32.0	28.0	44.0
0.490	2.0	43.0	63.0	*	200.0

table II