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STUDY OF BULK DAMAGE IN HIGH RESISTIVITY
SILICON DETECTORS IRRADIATED BY HIGH DOSE ^{60}Co γ -RADIATION*

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Study of Bulk Damage in High Resistivity Silicon Detectors Irradiated by High Dose of ^{60}Co γ -Radiation*

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Abstract

High dose (>200 Mrad) γ -radiation induced displacement damage (or bulk damage) in high resistivity (6-10 k Ω -cm) silicon detectors has been studied. It has been found that detector bulk leakage current increases with γ dose at a rate of 3.3×10^{-7} A/cm 2 /Mrad. This introduction rate of bulk leakage current makes the introduction of generation centres by 210 Mrad of γ -radiation comparable to that by 1×10^{12} n/cm 2 of neutron radiation. Significant carrier removal (or donor removal), about 100%, was found in detectors irradiated to 215 Mrad. Space charge sign inversion (SCSI) (or "type inversion") was observed in detectors irradiated to ≥ 215 Mrad using transient current technique (TCT). As many as seven deep levels have been observed by current deep level transient spectroscopy (I-DLTS). There was little or no annealing (or reverse annealing) for detectors irradiated to 215 Mrad. Some annealing for detectors irradiated to 500 Mrad have been observed.

SUMMARY

I. INTRODUCTION

Recently, the observed abnormal annealing behavior (or "reverse annealing", "anti-annealing", which is the effect of the increase of the net, acceptor-type effective concentration of space charges (N_{eff}) with annealing time) of neutron irradiated high resistivity silicon detectors has prompted renewed interest in microscopic defect measurements and identifications in such detectors [1-6]. The goal is to find the defect generation mechanism responsible for and/or, a model that describes, this abnormal annealing effect. This in turn will help one to find the way to develop radiation-hard detectors via impurity engineering. Experimental evidence to date has suggested a model involving the defect clusters for the generation of deep acceptor charges in the space charge region (SCR) [7-8], which attributes the abnormal annealing as the direct result of the breaking-up of defect clusters into ionized acceptor-like single defects.

If defect clusters are the main cause for the abnormal annealing effect observed in neutron irradiated high resistivity silicon detectors, then one expects to see little or no such abnormal annealing effect in γ irradiated high resistivity silicon detectors. This is because that γ radiation only produces random single defects (no defect clusters) in silicon. Study of γ -irradiated high resistivity silicon detectors and the subsequent annealing behavior can be therefore important in

resolving the defect cluster issue in neutron irradiated detectors.

II. EXPERIMENTAL

Planar Al/p $^+$ /n/n $^+$ /Al silicon detectors with original resistivity of 6-10 k Ω -cm (n-type) were fabricated at Brookhaven National Laboratory (BNL). Each detector is 0.1 cm 2 in area and 368 μ m in thickness. Detectors were irradiated with a calibrated 15kCi ^{60}Co source at BNL.

The experiments included traditional capacitance-reverse bias (C-V) and current-reverse bias (I-V) characteristics to monitor detector electrical degradation; measurements of radiation induced deep levels using I-DLTS and TSC with optical defect filling techniques [5], and applications of transient current/transient charge techniques (TCT/TChT) using laser pulse excitation of non-equilibrium free carriers to determine both the magnitude and sign of space charge concentration N_{eff} [9-10].

Elevated temperature annealing (ETA) was performed on irradiated detectors in N $_2$ ambient with fast heating time (about 10-15 seconds) to the annealing temperature T_0 and fast cooling time (about 5-10 seconds) to the RT. The temperature stability is within ± 1.0 $^{\circ}\text{C}$. Electrical measurements (C-V, I-V), TCT/TChT measurements (I-t, current-time/Q-V: charge-reverse bias), and defect measurements (I-DLTS, TSC) were carried out before ETA and after each ETA. Measurements of C-V, I-V, and TCT/TChT were done at RT.

III. RESULTS AND DISCUSSIONS

The I-V and C-V characteristics of a detector before and after γ irradiation are shown in Fig. 1. It is clear from the C-V curves that the detector was fully depleted at about 45 volts (full depletion voltage $V_d = 45$ volts). After a γ irradiation of 215 Mrad, V_d decreased to about 10 volts. A γ irradiation of 501 Mrad however, made V_d to increase to about 110 volts. This behavior is similar to that observed in neutron irradiated detectors before and after SCSI.

The detector leakage current clearly increases with γ dose (Fig. 1a). A pinch-off effect near the full depletion bias was observed in irradiated detectors. This is due to the fact that SCSI caused the junction switching side from near the p $^+$ contact before irradiation to near the n $^+$ contact after irradiation. At the pinch-off, all the surface currents, including currents from the damaged edges on the n $^+$ side, are cut off by the guard ring (GR). The current measured beyond the pinch-off is the true bulk current. From Fig. 1a, one can

get a bulk leakage coefficient for ^{60}Co γ -radiation of the value of $3.34 \times 10^{-7} \text{ A/cm}^2/\text{Mrad}$. The introduction of generation centers by 210 Mrad ^{60}Co γ -radiation is about the same as that by $1 \times 10^{12} \text{ n/cm}^2$ fast neutrons (1 MeV).

a)

b)

Fig. 1 I-V a) and C-V curves b) for a detector before and after γ irradiation. Guard ring was grounded in all measurements (GRG).

The SCSI can be readily seen in laser light induced current shapes using TCT, as shown in Fig. 2. Fig. 2a displays the hole current shapes (laser light on the n^+ side) for a control detector (no irradiation). It is clear that holes drift from low electric field to high electric field, indicating that the junction is on the p^+ side.

After a radiation of 215 Mrad, the sign of the current shape top changes from positive (Fig. 2a, $N_{\text{eff}} = 4 \times 10^{11} / \text{cm}^3$) to negative (Fig. 2b, $N_{\text{eff}} = -1 \times 10^{11} / \text{cm}^3$), indicating a SCSI from positive to negative. The carrier removal (or donor removal) is about 100% at 215 Mrad. The junction is now located near the p^+ contact. Further irradiation will make the space charge more negative due to acceptor creation, as shown in Fig. 2c ($N_{\text{eff}} = -1.1 \times 10^{12} / \text{cm}^3$). The acceptor creation rate is about $b = 1 \times 10^{12} / \text{cm}^3 / 500 \text{ Mrad} = 2 \times 10^9 / \text{cm}^3 / \text{Mrad}$. This γ irradiation induced SCSI is very similar that caused by neutron irradiation.

a) Control sample (NO6-130).
R1: 40 V; R2: 50 V; R3: 70 V; R4: 100 V

b) 215 Mrad (11/3/95) (Sample NO6-109).
R1: 10 V; R2: 20 V; R3: 50 V; R4: 100 V

c) 501 Mrad (11/27/95) (Sample NO6-96).
R1: 100 V; R2: 110 V; R3: 120 V; R4: 130 V; R5: 150 V

Fig. 2 Hole current shapes for a) a control sample; b) a sample irradiated to 215 Mrad; and c) a sample irradiated to 501 Mrad.

However, the annealing behavior for γ irradiated high resistivity detectors are different from that for fast neutron irradiated high resistivity detectors. Fig. 3 shows the charge collection as a function of reverse bias (Q -V) for a detector before and after irradiation and after elevated temperature

annealing (ETA). In these measurements, laser light was on the low field side and the full charge was collected at full depletion ($Q/Q_0 = 1$ at $V = V_d$). After annealed at 110 °C for 15 minutes (equivalent of 1-year room temperature (24 °C) anneal), V_d is almost unchanged. Longer annealing at this temperature makes V_d to decrease. From the corresponding TCT measurements it has been observed that this decrease of V_d was correlated with a decrease of N_{eff} from negative to less negative, or a decrease of acceptor-like and/or an increase of donor-like space charges. This is expected from a normal annealing behavior and is opposite to the observed abnormal annealing (or reverse annealing) behavior in fast neutron irradiated high resistivity silicon detectors. Annealing at a higher temperature (150 °C) made N_{eff} back to positive (or donor-like), which made V_d to increase as shown in the figure. This difference is clearly consistent with the model in which defect clusters (that can be broken-up during annealing) are considered as the main source for the acceptor creation in the SCR during the anneal.

Fig. 3 Charge collection vs. reverse (Q - V) bias for a detector before irradiation, after irradiation, and after annealing at temperatures shown.

Very small amount of abnormal annealing in detectors irradiated to a dose of 501 Mrad have been observed. This data, along with the I-DLTS data in which as many as seven deep levels were found, will be presented in the full paper. Correlations between the I-DLTS data and detector electrical degradation data after irradiation and after annealing will also be made.

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