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Complete suppression of reverse annealing of neutron radiation damage during active gamma irradiation in MCZ Si detectors

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ABSTRACT

For the development of radiation-hard Si detectors for the SiD BeamCal (Si Detector Beam Calorimeter) program for International Linear Collider (ILC), *n*-type Magnetic Czochralski Si detectors have been irradiated first by fast neutrons to fluences of 1.5×10^{14} and 3×10^{14} n_{eq}/cm^2, and then by gamma up to 500 Mrad. The motivation of this mixed radiation project is to test the radiation hardness of MCZ detectors that may utilize the gamma/electron radiation to compensate the negative effects caused by neutron irradiation, all of which exists in the ILC radiation environment. By using the positive space charge created by gamma radiation in MCZ Si detectors, one can cancel the negative space charge created by neutrons, thus reducing the overall net space charge density and therefore the full depletion voltage of the detector. It has been found that gamma radiation has suppressed the room temperature reverse annealing in neutron-irradiated detectors during the 5.5 month of time needed to reach a radiation dose of 500 Mrad. The room temperature annealing (RTA) was verified in control samples (irradiated to the same neutron fluences, but going through this 5.5 month RTA without gamma radiation). This suppression is in agreement with our previous predictions, since negative space charge generated during the reverse annealing was suppressed by positive space charge induced by gamma radiation. The effect is that regardless of the received neutron fluence the reverse annealing is totally suppressed by the same dose of gamma rays (500 Mrad). It has been found that the full depletion voltage for the two detectors irradiated to two different neutron fluences stays the same before and after gamma radiation. Meanwhile, for the control samples also irradiated to two different neutron fluences, full depletion voltages have gone up during this period. The increase in full depletion voltage in the control samples corresponds to the generation of negative space charge, and this increase in concentration of negative space charge goes up with the neutron fluence. If we assume the reverse annealing is also taking place for the two gamma-irradiated samples with similarly different concentrations of negative space charge generated, the observed effect of no changes in space charge (no changes in V_{fd}) in these two gamma-irradiated samples would imply that concentrations of positive space charge created in these two control samples are different at the same gamma dose, and gamma irradiation effectively "switched off", the RT (room temperature) reverse annealing of neutron irradiation. It has also been found that as soon as the gamma irradiation stops, the RT reverse annealing of neutron irradiation-induced defects resumes with same rate as that of the control detectors. This behavior in mixed radiation samples (neutron plus gamma) would suggest some nonlinear effect (defects induced by mixed-radiations are not additive of those by individual radiation alone), or interaction of radiation induced acceptor-type and donor-type defects.

1. Introduction

For the development of radiation-hard Si detectors for the SiD BeamCal (Si Detector Beam Calorimeter) program for the future International Linear Collider (ILC), *n*-type Magnetic Czochralski (MCZ) Si detectors have been irradiated first by fast neutrons to

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fluences of 1.5×10^{14} and 3×10^{14} n_{eq}/cm^2, and then by gamma-rays up to 500 Mrad. The motivation of this mixed radiation project is to test the radiation hardness of MCZ detectors that may utilize the gamma/electron radiation to compensate the negative effects caused by neutron irradiation, all of which exists in the ILC radiation environment. This issue of mixed irradiation is also important for Si detectors developed for Large Hadron Collider in which the detectors operate in the mixed radiation environment with particle irradiation (protons, neutrons, pions) and gamma-rays. While negative space charge (SC) is generated by the listed particles, in detectors made of oxygen-rich Si and MCZ Si materials, gamma-rays introduce positive space charge [1–4]. Then, in principle, mixed irradiation by particles and gamma-rays can compensate or even cancel the negative space charge created by particles, thus reducing the effective space charge density N_{eff} and therefore the full depletion voltage V_{fd} of the detector. Our previous data [5] obtained apart from the SiD BeamCal program have shown that positive SC induced by gamma radiation does compensate the negative SC induced by low energy (10–20 MeV) protons to a certain degree depending on the dose and fluence of gamma and protons, respectively. This effect of SC compensation was also observed in *n*-type MCz and oxygenated FZ Si detectors irradiated first by charged hadrons and then by neutrons [6].

The one year neutron fluence for proposed calorimeter in the future ILC is estimated as $F_{neq} = 2.68 \times 10^{14}$ n_{eq}/cm^2 (at radius ≥ 100 cm), which will generate about 4×10^{12} cm^{-3} negative space charges in MCZ Si detectors [7]. The one year gamma radiation dose in the future ILC is estimated as 10^9 rad, which will generate about $3.0 \times 10^{12}/cm^3$ positive space charges in MCZ Si detectors if irradiated by gamma-rays alone. This positive SC will just about to compensate the negative space charge generated by neutron radiation if the neutron and gamma radiation-induced SC's are additive. If it is the case, the negative and positive SC will about cancel each other in the future ILC's mixed radiation environment for the proposed calorimeter if MCZ Si detectors are used.

2. Experimental

The $p^+/n/n^+$ Si detectors were processed by the BNL's Silicon Detector Development and Processing Lab using 100 mm diameter *n*-type MCZ Si wafers. The thickness of the wafers is 390 μm, and the resistivity is about 1 kΩ cm. The area of the detector is $0.5\ cm \times 0.5\ cm = 0.25\ cm^2$, with a 2-mm diameter window in the Al on the front side, and an Al mesh on the backside to allow laser penetration into the silicon bulk.

Detectors were first irradiated at room temperature (RT) by fast neutrons (0.8–1 MeV, Hardness Factor is 1.3 with respect to 1 MeV neutron) at the Annular Core Research Reactor in Sandia National Lab to fluences up to 3×10^{14} n_{eq}/cm^2. After neutron irradiation and 22 day of RTA, half of the samples (Set #1) were irradiated at RT by gamma at BNL's ^{60}Co Radiation facility (1.25 MeV) to a total dose of 500 Mrad. The other half of the samples (control samples, Set #2) were set aside at RT for storage. The details of irradiation for samples studied in this work are listed in Table 1. During the 5.5 month period needed for gamma irradiation at RT for samples from the Set #1, the RT reverse annealing behavior to neutron irradiated Si detectors [8] is assumed to take place for both sets of the samples. After this 5.5 month period, both sets of samples were stored at RT without radiation of any kind for 31 months, when additional long-term RT annealing of about 31 months were taking place for all samples.

Table 1
Samples used in the study.

Sample #	1480-13	1480-5	1480-14	1480-16
1st irradiation neutrons (n_{eq}/cm^2)	1.5×10^{14}	1.5×10^{14}	3×10^{14}	3×10^{14}
2nd irradiation gamma (Mrad)	0	500	0	500

The detectors were characterized in BNL at RT by *I–V* and *C–V* measurements and Transient Current Technique (TCT) [9] using a red laser that has an 5 μm absorption depth in Si at RT. The measurements were carried out before and after each radiation, and at various RT annealing stages. The detector full depletion voltages V_{fd} were determined by the *C–V* measurement. Current pulse response shapes obtained by TCT were also used to obtain the value of the detector full depletion voltage as an additional or alternative method, and for the determination of the space charge sign and the estimation of the electric field profile $E(x)$.

3. Experimental results

3.1. I–V characteristics

Before irradiation the full depletion voltage V_{fd} and the corresponding effective space charge concentration N_{eff} of all detectors were 350 V and 2.9×10^{12} cm^{-3}, respectively. *I–V* characteristics (all measured at RT) of irradiated detectors #1480-13 and #1480-5 measured after RTA of 22 day, 5.5 months and 36.5 months are presented in Fig. 1a and b. Saturation of the current occurred at the bias voltage close to V_{fd} and was observed only for the detectors irradiated to low fluence (1.5×10^{14} n_{eq}/cm^2). As shown in Fig. 1a, for detector #1480-13 (no gamma irradiation), the *I–V* dependences showed a reduction of the reverse current during RTA at full depletion resulted from the annealing out of mid-gap defect levels responsible for the detector leakage current. The *I–V* dependence of the detector #1480-5 stays practically the same after gamma radiation as seen from the comparison of the curves at 22 day and 5.5 months of RTA (Fig. 1b) due to the increase of leakage current by gamma radiation that is about the same of the decrease of neutron-induced leakage current during the RTA. The pronounced change in *I–V* characteristic of this detector occurs after 36.5 month RTA in which a bump of increased current is observed. This bump is typical for $p^+/n/n^+$ detectors (with guard ring grounded) at V close to V_{fd} after space charge sign inversion (SCSI) when the guard ring takes some current away from the total current when full depletion is achieved [4]. *I–V* curves of detectors irradiated to F_{neq} of 3×10^{14} n_{eq}/cm^2 were almost linear and their slope went down during RTA. All *C–V* characteristics were typical for irradiated detectors. Note that within the measurement range of 500 V, full depletion in *C–V* dependences was observed only for detectors irradiated to 1.5×10^{14} n_{eq}/cm^2.

3.2. Current pulse response

The current pulse shapes of detector #1480-13 irradiated by neutrons to 1.5×10^{14} n_{eq}/cm^2 (at the 22-day RTA mark) are shown in Fig. 2a and b. Current shapes from electrons are obtained by the measurements of the current induced by the drifting electrons generated by a red laser illuminating the detector's p^+ contact (Fig. 2a). The double peak (DP) shape in the electron pulse is observed at low bias voltages (low V), indicating positive SC in the space charge region (SCR) near the p^+ contact and negative SC near the n^+ contact [10]. These pulses convert to a single peak (SP) pulse at high V with an ascending slope (electrons drifting from low electric field at the p^+ contact to high electric field at the n^+ contact), indicating the extension of SCR with negative charge from the n^+ contact towards the p^+