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Elevated Temperature Annealing of the Neutron Induced Leakage Current and Corresponding Defect Levels in Low and High Resistivity Silicon Detectors

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ABSTRACT

The leakage current (I_L) annealing at the elevated temperatures and the corresponding changes of the DLTS spectra of defects for fast neutron irradiated Silicon detectors, fabricated on high (4-6 k Ω -cm), moderate (0.5-1.0 k Ω -cm), and low (<100 Ω -cm) resistivity silicon material, have been investigated. For all the resistivities, three annealing stages have been observed: 1) the transformation of carbon related defects at 72 °C; 2) slight decrease of the peak $E_C - 0.4$ eV at 150 °C, and 3) significant decrease of the peak $E_C - 0.4$ eV at 350 °C. The leakage current has been found to decrease monotonously in the temperature range of 20-150 °C. A sharp decrease of I_L was observed at 350 °C due to the annealing of the V-V' center for heavily irradiated detectors, whereas I_L showed a slight saturation tendency for detectors irradiated to low neutron fluence. The V-V' center has been found to be dominant in the formation of the $E_C - 0.4$ eV peak and in the annealing of the leakage current. For low resistivity detectors, an anneal at 72 °C was needed to stimulate the decrease of the effective impurity concentration (N_{eff}) of the detectors irradiated by high neutron fluence $(1-2) \times 10^{14}$ n/cm². In addition, low resistivity detectors have been found to be tolerant in terms of N_{eff} stability to the 350 °C anneal, favorable to the recovery of I_L after irradiation with high neutron fluence.

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Summary

The applicability limit of high resistivity silicon detectors in the large collider with a significant neutron background arises mainly from the increase of the effective concentration of ionized space charges N_{eff} and the detector full depletion voltage.^[1-4] Such behavior results from the increase of radiation induced defect concentration which exceeds that of the main dopants. One of the possible ways to overcome these difficulties may consist in the use of Si detectors with a lower starting resistivity (ρ)^[4-5] and this possibility should be further investigated by analytical tools such as the deep level transient spectroscopy (DLTS).

The present study consisted of DLTS measurements of neutron induced defects with deep levels in the range of 77-300 K. The main defects were identified additionally by isochronal annealing of defects at elevated temperatures. The measurements were carried out for low ($\rho_0 < 100 \Omega\text{-cm}$), moderate ($\rho_0 = 0.5\text{-}1.0 \text{ k}\Omega\text{-cm}$), and high ($\rho_0 = 4\text{-}6 \text{ k}\Omega\text{-cm}$) resistivity Si $p^+n\text{-}n^+$ junction detectors. The low resistivity silicon detectors were irradiated to the fluence (Φ_n) of 10^{13} to $2.5 \times 10^{14} \text{ n/cm}^2$, the moderate resistivity ones to 10^{10} to 10^{12} n/cm^2 , and the high resistivity ones to 10^{12} to $6 \times 10^{13} \text{ n/cm}^2$. The annealing temperatures of 150°C and 350°C were chosen to correspond to the annealing of the dominant leakage current components - vacancy-phosphorus (V-P) and singly charged divacancy (V-V') centers, respectively. The duration's of the all elevated temperature anneals were one hour.

The following preliminary results have been obtained:

1. Similar DLTS spectra were observed in the entire range of neutron fluences for all detectors. Three peaks with the energy levels of $E_C - 0.17\text{eV}$, $E_C - 0.23 \text{ eV}$ and $E_C - 0.40 \text{ eV}$ in the upper half of the forbidden gap (the defects V-V' and V-P are not resolved in the $E_C - 0.40 \text{ eV}$ peak) could be visualized in case of high fluence irradiation of moderate and high resistivity Si after the annealing at 150°C and 350°C , respectively. Viable DLTS measurements could not be obtained for these highly compensated detectors unless elevated temperature annealings were performed. Just after irradiation the spectra corresponding to the deep levels in the lower half of the forbidden gap included overlapping peaks and a resolved one of a small amplitude. The overlapping with uncontrollable ratio of the constituents was revealed in highly compensated detectors (in high resistivity Si, even at Φ_n about 10^{10} n/cm^2) which could be removed by annealing at elevated temperatures.

2. Two other peaks in the lower half of the forbidden gap are attributed to carbon related defects - interstitial carbon C_i ($E_V + 0.33 \text{ eV}$) and complex including interstitials of carbon and oxygen $C_i\text{-}O_i$ ($E_V + 0.4 \text{ eV}$). The former was revealed in as-irradiated detectors regardless of the values of ρ_0 and Φ_n . Moreover, the transformation of carbon related defects occurred in consistence with the reduction of C_i and simultaneous increase of $C_i\text{-}O_i$ concentration. This transformation could proceed at room temperature within a few days or be stimulated by annealing at $\sim 75^\circ\text{C}$, as we have previously observed for alpha-particle irradiated detectors^[6]. Additionally, in moderate resistivity Si detectors, $C_i\text{-}$

O_i concentration continued to grow even after the exhaustion of C_i . The reasonable explanation is that in irradiated Si detectors, electrically inactive C_i in the as-processed detectors can be excited by irradiation, which is in turn captured by O_i atoms during migration in crystal lattice, affecting the fast changes in N_{eff} .

3. The annealing at 150 °C and 350 °C resulted respectively in the slight (10-15%) and significant amplitude decreasing of the peak $E_C - 0.4$ eV. Hence, the peak is dominated by V-V center rather than V-P complex.

4. The detector leakage current annealing has been found to correlate with the changes in DLTS spectra. The stage of low temperature annealing (72 °C) occurred simultaneously with fast transformation of carbon related defects in Si detectors just after radiation. The reverse current annealing at 150 °C was more pronounced compared with the amplitude decrease of the peak $E_C - 0.4$ eV. The annealing of the V-V center at 350 °C was accompanied by further decrease of the leakage current. The latter has showed a slight saturation tendency in the case of low Φ_n , whereas for highly irradiated detectors a sharp decrease of more than a order of magnitude has been found. These results suggest the difference in the contribution of singly charged divacancy center to the leakage current in low and highly irradiated detectors and the ambiguity in the origin of the detector leakage current.

5. Preliminary annealing at 72 °C did not affect either the reverse current or N_{eff} of the detectors irradiated long before measurements (RT anneal >30 days). Still, in practice it was needed to stimulate these parameters during the following annealing at 150 °C. The peculiarity of low resistivity detectors consisted in the fact that after irradiation with $\Phi_n = (0.8-2) \times 10^{14}$ n/cm², N_{eff} could be reduced to values comparable with those for as-irradiated high resistivity Si detectors induced by similar Φ_n (from a few times 10^{13} cm⁻³ down to a few times 10^{12} cm⁻³) only after the 72 °C preliminary annealing. The important applied aspect of this effect is that, in terms of the a workable N_{eff} , the low resistivity detectors are still more tolerant to the elevated temperature anneal at 350 °C, which is favorable to the leakage current recovery.

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