

Temperature Stimulated Reverse Annealing of Neutron Induced Damage
in High Resistivity Silicon Detectors

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Neutron irradiated high resistivity silicon detectors have been subjected to elevated temperature annealings (ETA). It has been found that both detector full depletion voltage and leakage current exhibit reverse annealing behavior for highly irradiated detectors: increase with ETA. Laser induced current shapes have indicated a net increase of acceptor type space charges associated with the full depletion voltage increase after ETA. Data of current deep level transient spectroscopy (I-DLTS) have shown that the dominant microscopic effect is the increase of a level at 0.39 eV. This level is tentatively identified as the $V-V^-$ level at $E_c-0.39$ eV and/or the C_i-O_i level at $E_v+0.36$ eV. Data of thermally stimulated current (TSC) have shown increases of levels at 0.26 eV and 0.40 eV with ETA, suggesting that the level responsible for the reverse annealing effects be the V-V center ($V-V^-$ at $E_c-0.25$ eV and $V-V^-$ at $E_c-0.39$ eV). Some local, non-uniform trappings of laser induced electrons and holes have been observed near the p^+ contact at low voltages after ETA at intermediate temperatures (110-150 °C).

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Solid State Devices and Radiation Damage Effects

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Summary

Application of high resistivity silicon detectors in experiments in the newly approved Large Hadron Collider (LHC) is restricted by degradation of silicon detector parameters after neutron irradiation. The increase of net effective concentration of space charges (N_{eff}) in the space charge region (SCR) of detectors during neutron radiation and the following storage period results in the corresponding increases of full depletion voltage. In turn, it affects negatively the charge collection efficiency through degradation of non-equilibrium carrier transport parameters.

The origin of these phenomena was investigated in this work in the course of the reverse annealing stimulated by elevated temperatures. The experiments included measurements of $C-V$ and $I-V$ characteristics, the study of the deep levels of radiation induced defects by current deep level transient spectroscopy (I-DLTS) and thermally stimulated current (TSC) methods with optical filling techniques, and applications of transient current/transient charge technique (TCT/TChT) with laser pulse excitation of non-equilibrium carriers. Detectors with starting silicon resistivity of 2 k Ω -cm were irradiated with neutron fluences Φ_n in the range of 1.1×10^{13} n/cm² to 3.5×10^{13} n/cm².

The experimental results are the following.

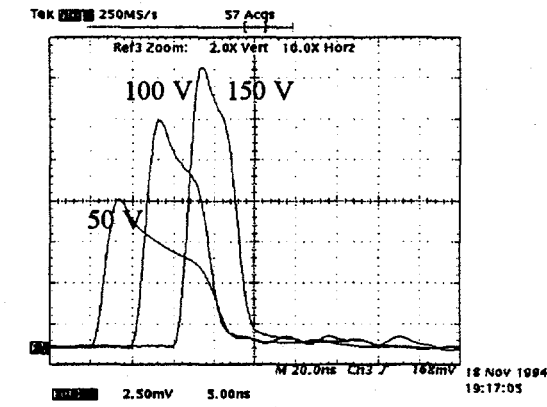
1. Transient current curves have showed changes of the electric field profiles in the depleted region (or SCR) of irradiated detectors after both isothermal and isochronal annealing in

the temperature range of 80-200 °C. These changes in field profiles corresponded to the accumulation of the negative space charges in the SCR. This accumulation of negative space charges occurred regardless of the initial space charge sign before heat treatment -- positive one of donor type charge for $\Phi_n < 2 \times 10^{13}$ n/cm² or negative one of acceptor type charge for larger Φ_n . In the former case, it resulted in the inversion of the space charge sign from positive donor type (Fig. 1) to negative acceptor type (Fig. 2) after successive steps of annealing at 110°C and higher. Corresponding changes of full depletion voltage were observed by both $C-V$ measurements and transient charge amplitude versus reverse voltage ($Q-V$) dependence and are summarized in Table I

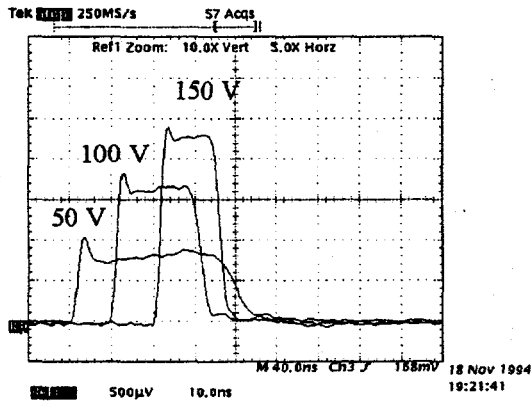
2. Reverse annealing consisted in the increase of N_{eff} and the detector reverse current. The latter occurred unambiguously after any annealing step (except that one at 80 °C) which is different to the annealing behavior of the detectors irradiated with low neutron fluence.

3. In addition, some local, non-uniform electron and hole trappings were observed near the p⁺ contact at low voltages after annealing at intermediate temperatures (110-150 °C) for detector irradiated with large Φ_n . This causes negative current shapes, as shown in Fig. 3, possibly due to the formation of a dipole layer that reverses the field. The capture of non-equilibrium carriers by these defects resulted in the screening of the electric field and dramatic decrease of charge

collection efficiency as a result of the degradation of transient current pulse.



a)

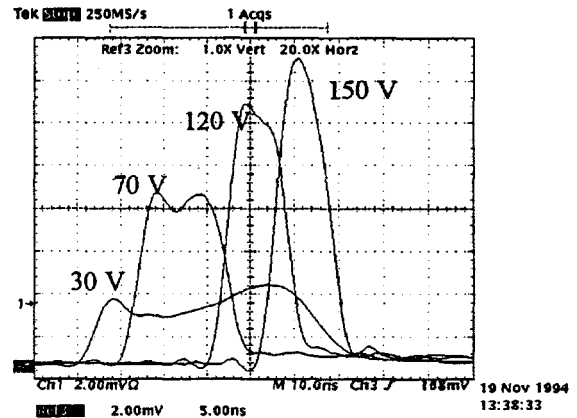


b)

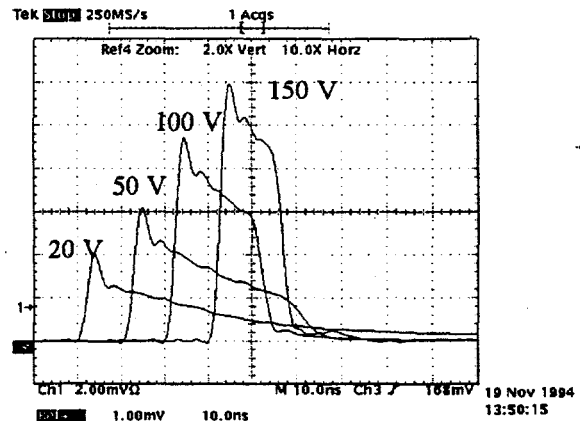
Fig. 1 Laser induced current shapes of a detector (#504-130) irradiated to $1.65 \times 10^{13} \text{ n/cm}^2$ before ETA: a) electron current shapes (laser on the p^+ contact), and b) hole current shapes (laser on the n^+ contact). The sign of N_{eff} is positive (junction on the p^+ side)

The results in this work have shown that temperature stimulated reverse annealing effect of N_{eff} in neutron irradiated high resistivity silicon detectors is similar to that observed at room temperature. Effects of space charge sign inversion and increase of the reverse current may be unambiguously explained by the formation of deep acceptors in the energy band gap. Our data of I-DLTS has shown that a level of 0.39 eV increases with elevated temperature annealing (ETA). This

level is probably the $V-V^-$ center at $E_C-0.39 \text{ eV}$. Our TSC data have also indicated the increase of the $V-V^-$ level at $E_C-0.26 \text{ eV}$ with ETA. The other possible candidate is the complex C_i-O_i at $E_V+0.36 \text{ eV}$, which is introduced by the annealing of interstitial carbon and acts as a hole trap. Concentration of this defect, as it was shown in our earlier experiments, also increases after room temperature or elevated temperature annealings.



a)



b)

Fig. 2 Laser induced current shapes of a detector (#504-130) irradiated to $1.65 \times 10^{13} \text{ n/cm}^2$ after ETA at 110°C for 1 hour: a) electron current shapes (laser on the p^+ contact), and b) hole current shapes (laser on the n^+ contact). The sign of N_{eff} is negative (junction on the n^+ side)

Table I. Reverse annealing effects of a detector (#504-130) irradiated to $1.65 \times 10^{13} \text{ n/cm}^2$ after ETA.

ETA temp. (°C)	RT	80 (1hr)	110 (1hr)	150 (1hr)	200 (1hr)
I_d (μA)	4.0	3.0	3.5	9.0	50
V_d (volts), C-V	16	15	25	60	70
V_d (volts), Q-V	20	15	36	50	100
Sign of N_{eff}	+	+	~ 0	-	-
Effective "type" in SCR	n	n	i	p	p

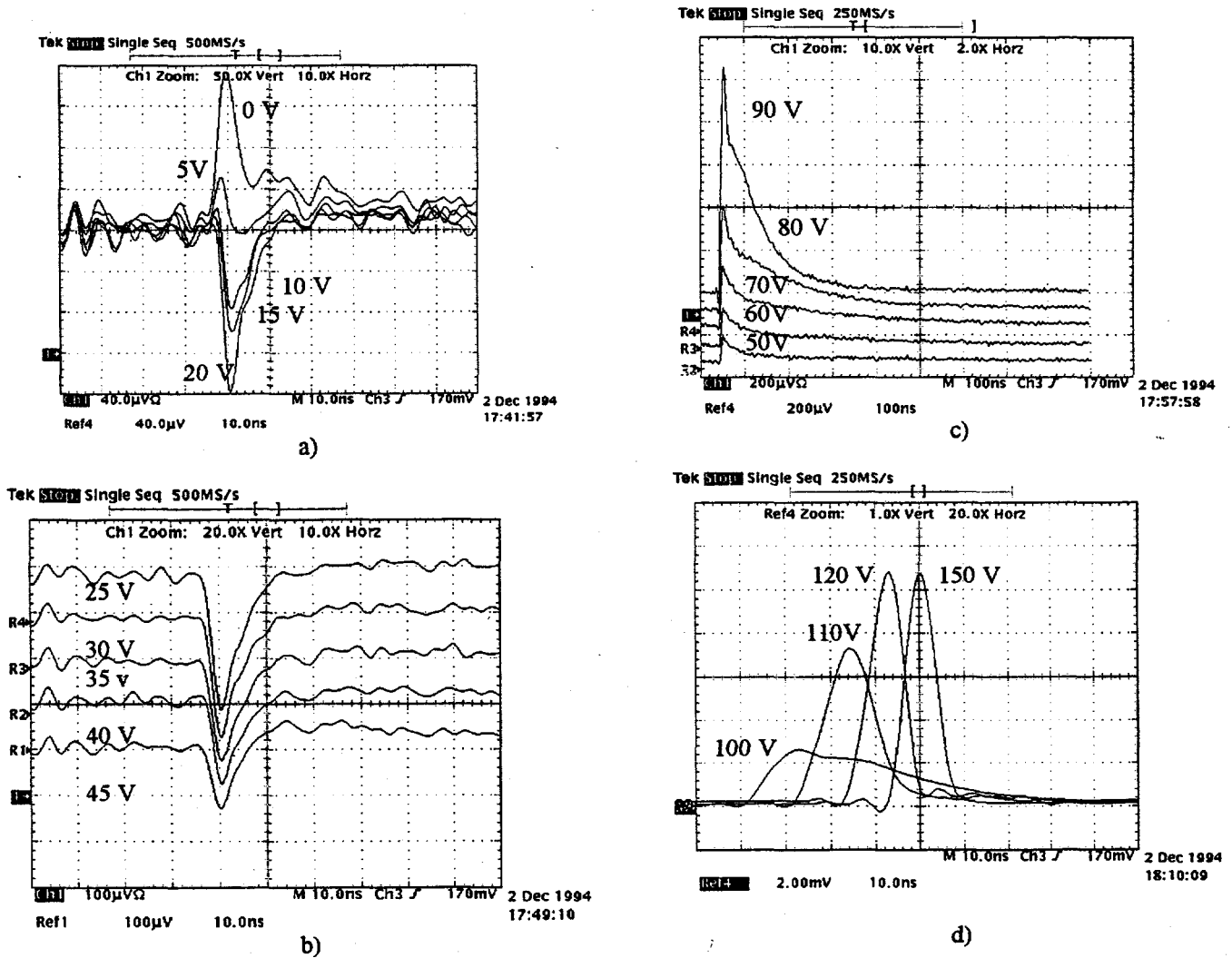


Fig. 3 Laser induced electron current shapes (laser on the p^+ contact) of a detector (#504-99) irradiated to $3.18 \times 10^{13} \text{ n/cm}^2$ after ETA at 150 °C for 10 minutes: a) at low biases, negative shapes starting to form, b) at medium biases, negative shapes reaching maximum, c) and d) high biases, positive shapes restored.