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Bistable damage in neutron-irradiated silicon diodes

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Abstract

Standard and oxygenated high resistivity silicon diodes were irradiated with neutrons to fluences up to 2×10^{14} cm^{-2} 1 MeV neutron NIEL equivalent. After beneficial annealing at room temperature diodes were kept at 20°C. *C–V* measurements were performed regularly to determine the full depletion voltage. Bistable damage was activated with bias application to the diodes. Its creation rate was measured during different stages of reverse annealing. For a comparison, a change of full depletion voltage was determined also from TCT measurements. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Silicon detectors at ATLAS and CMS experiments at the Large Hadron Collider will be exposed to fast particle fluences in excess of 10^{14} cm^{-2} NIEL[1] and ionizing doses above 100 kGy [1,2]. The latter poses a challenge for electronics and detector design and manufacturing. Bulk damage will result in well-established macroscopic manifestations [3]: increase of generation current, n→p type inversion with subsequent increase of depletion voltage and charge trapping. The combination of fast electronics and trapping demands sufficient over-depletion for these detectors to operate efficiently [4]. The knowledge of the full depletion voltage (FDV) changes with irradiation is therefore of prime importance for the proper design and operation of these detectors.

Many data have been accumulated during recent years and insight gained in understanding and even controlling radiation damage in silicon [5]. Considerable less has been however, done, to explore the influence of operating conditions under which the detectors at the LHC will be irradiated and operated. Fully biasing the detectors during and after irradiation was shown [6] to nearly double FDV at the minimum between annealing and reverse annealing. The annealing of this bias-induced damage was studied in Refs. [7,8] where a prediction of the additional bias needed to operate the detectors irradiated and annealed under LHC conditions was made. A part of the bias-induced damage was found to exhibit a bistable behaviour upon bias re-application.

In this paper, the study [7,8] has been extended with a detailed study of the bistable part of the

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[1] Non-ionizing energy loss equivalent of 1 MeV neutrons.

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damage. For that, in addition to the conventional C–V measurements of FDV, samples were studied with TCT (transient current technique) using a IR (1060 nm) fast pulsed laser emulating a minimum ionizing particle signal.

2. Experimental procedure

The purpose of the study was to determine the fluence dependence of the bistable damage. As it was shown earlier [7] the bistable damage appears after application of bias on the diodes irradiated with or without bias. Therefore, a set of standard and oxygenated high resistivity ($\rho \approx 15$ kΩ cm) diodes was irradiated at room temperature with neutrons from a nuclear reactor to fluences up to 2×10^{14} cm^{-2} NIEL. Neutron flux during irradiation was 2×10^{12} cm^{-2} s^{-1}. More details about neutron spectrum, dosimetry and irradiation facility can be found elsewhere [9].

After the irradiation, the diodes were kept at 20°C. Their FDV was measured regularly with the C–V method at 10 kHz frequency. After diodes had been annealed close to the minimum in FDV (250 h after irradiation) they were connected to a bias high enough (350 V) to fully deplete them. After application of bias C–V characteristics were measured only at voltages high enough to deplete more than $\frac{3}{4}$ of detector. In this way, a possible effect of annealing the bistable damage during the measurement at low voltages was reduced. Bias was switched off 230 h after its application. C–V characteristics were again measured regularly, now however, starting at the zero voltage.

1000 h after irradiation reverse annealing was accelerated by heating the diodes to 40°C for 74 h. Taking into account the activation energy of reverse annealing $E_a = 1.30$ eV it was accelerated by a factor of 27 compared to reverse annealing at room temperature. With this warm up reverse annealing was achieved corresponding to 10 years of operating conditions at ATLAS semiconductor tracker was achieved. During this heating period FDV of diodes was measured several times at 20°C.

After this, the bias was re-applied and measurements continued. As an example N_{eff}/Φ evolution after irradiation of a standard diode to 2×10^{14} cm^{-2} is shown in Fig. 1. A clear increase of its value after the application of bias at $t_1 = 250$ h and $t_2 = 3450$ h as well as annealing of the bistable damage after switching off the bias can be seen.

In order to quantify the activation of the bistable damage N_{eff}/Φ after the application of bias at $t = t_{on}$ was fitted with

$$\frac{|N_{eff}|}{\Phi_{eq}}(t) = g_0 + kt + g_{1b}(1 - e^{-(t-t_{on})/\tau_1}) + g_{2b}(1 - e^{-(t-t_{on})/\tau_2})$$

where g_0 represents the damage stable in time, k the slope of reverse annealing approximated with a linear function, g_{1b} and g_{2b} are amplitudes of two exponential functions having time constants τ_1 and τ_2, respectively.

Similarly, after switching off the bias at t_{off}:

$$\frac{|N_{eff}|}{\Phi_{eq}}(t) = g_0 + kt + g_{1b}e^{-(t-t_{off})/\tau_{1a}} + g_{2b}e^{-(t-t_{off})/\tau_{2a}}.$$

Examples of the fit are shown in Fig. 2.

The fit has shown that annealing and activation have a fast and a slow component, having a characteristic time of a few and about 100 h, respectively. While their amplitude is approximately equal at t_1, the amplitude of the fast component is reduced to about one-third

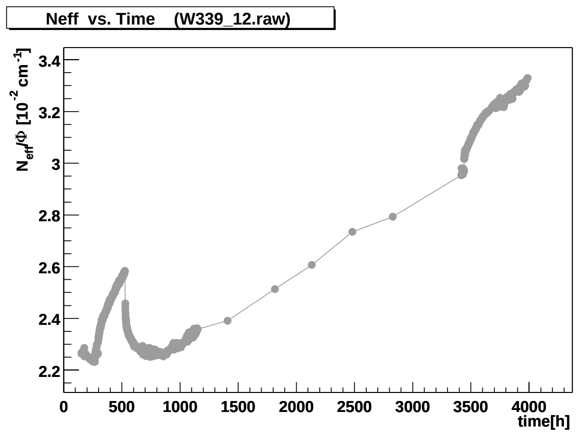

Fig. 1. Time evolution of N_{eff}/Φ after irradiation. Time is rescaled to 20°C with $E_a = 1.3$ eV. See the text for explanation of biasing conditions.

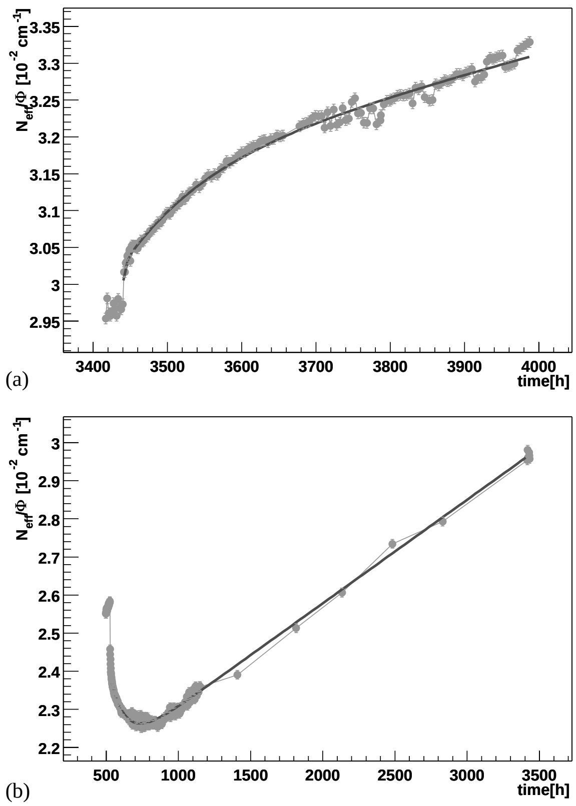

Fig. 2. A fit of the bistable damage: (a) activation, (b) annealing.

compared to the amplitude of the slow component after 3450 h of reverse annealing.

The total introduction rate of bistable defects was defined as

$$g_b = g_{1b} + g_{2b}.$$

The measured values of g_b 250 and 3450 h after irradiation are listed in Table 1. The average value at the minimum of FDV after irradiation of standard material (0.42) agrees within the experimental error (dominated with the error on the fluence) with the value for oxygenated material (0.38). That means that the additional oxygen in silicon has no influence on the creation of bistable defects.

The introduction rate of bistable defects is seen to be reduced during reverse annealing, 3450 h after irradiation it dropped to about a half of its initial value.

Table 1
Measured amplitudes of introduction rate of the bistable damage

Sample	Fluence 10^{13}n cm^{-2}	g_b (240 h)	g_b (3450 h)
Standard	5	0.41	0.23
	10	0.42	0.26
	20	0.42	0.17
Oxygenated	5	0.4	0.30
	10	0.35	0.15
	20	0.4	0.17

3. TCT measurement of bistable damage

We have checked if the increase of FDV due to activation of the bistable damage manifests itself also in a change of charge collection efficiency (CCE) for charged particles. Pulsed infra red light (1060 nm) with long absorption length in silicon was used to produce electron–hole pairs uniformly along the light beam. The number of electron–hole pairs was small enough (10^6) to avoid a plasma effect. The induced current due to movement of charge in the electric field was amplified with a fast amplifier and sampled with a fast (500 MHz, 1 G sample/s) oscilloscope. More details about the setup can be found in Ref. [10]. Signals were digitally integrated in a 60 ns wide internal. The diode used in these measurements was processed at ITE on a wafer with 5 kΩ cm resistivity. It was irradiated to 5×10^{13} cm^{-2} and reverse annealed for about 1 year at room temperature. A plot of the integrated signal as a function of bias voltage for a diode unbiased before the measurement, and after the diode was on the bias for 73 h is shown in Fig. 3. CCE reduction at low voltages can be seen after biasing the diode.

The effect of change of FDV due to the bistable damage can be seen also in Fig. 4, where the signals due to a red laser pulse ($\lambda = 670$ nm) with a short absorption length (3 μm) is plotted. The diode was biased to 130 V, close to its FDV. The laser illuminated the p side of the detector (electron injection). Since the detector bulk was inverted by irradiation from n- to p-type, a small

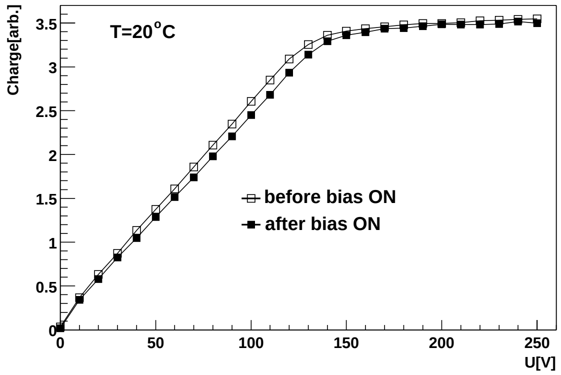

Fig. 3. Integral of the signal produced by IR laser pulse as a function of bias voltage: before bias on, after 70 h with bias.

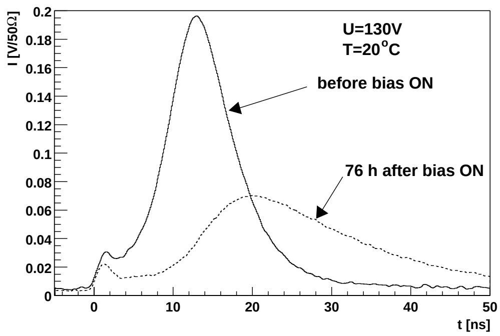

Fig. 4. Response on red light pulse on p side: immediately after detector was biased (full line) and 76 h after bias was switched on (dotted line).

change in the bias voltage changed the signal considerably.

If CCE at different voltages is measured, the measured CCE–V characteristic may be used to determine FDV in a similar way as C–V characteristic. Change of $|N_{\mathrm{eff}}|$ due to the bistable defect as determined from CCE measurements with TCT is shown in Fig. 5. Fit with two exponentials after biasing the detector gives $\tau_1 = 4.4$ h and $\tau_2 = 72$ h, with amplitudes 0.08 and 0.2, respectively, and is in good agreement with the data obtained by C–V measurements.

4. Conclusions

The introduction rate g_{b} of the bistable defect was measured. In the early stage of reverse

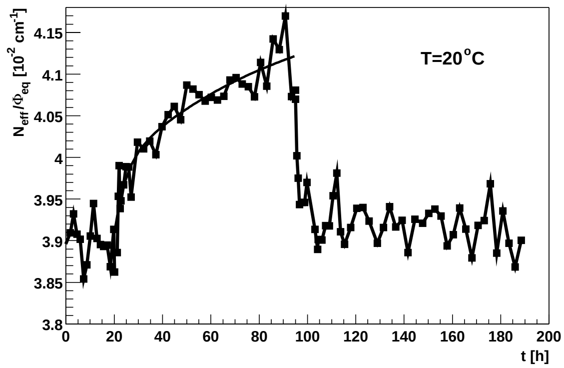

Fig. 5. The evolution of FDV as measured with TCT.

annealing (250 h at 20°C) its amplitude is about 0.4×10^{-2} cm^{-1} for both standard and oxygenated samples. Its annealing and activation show two components: a fast with a characteristic time of a few hours and slow with a characteristic time of about 100 h. After the reverse annealing equivalent to 3450 h at 20°C it is reduced to about half of its value.

The measurements with TCT confirmed the influence of bistable defect on charge collection efficiency.

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