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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Results on radiation hardness of silicon detectors up to neutron fluences of 10^{15} n/cm^2 *

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Our ongoing investigations of the radiation hardness for silicon detectors have been extended to neutron fluences up to 10^{15} n/cm^2. Emphasis was put on the damage induced change of the effective impurity concentration and its related room temperature annealing. The consequences for measurements of the bulk generation current are studied. While most results have been obtained for detectors irradiated without bias first damage experiments under operating conditions exhibit an additional effect attributed to the SiO_2–Si interface.

1. Introduction

For the next generation of collider experiments the radiation hardness of all detector components will be of utmost importance. In addition to an ionizing radiation dose in the Mrad range neutron fluences of some 10^{14} n/cm^2 accumulated during several years of operation have to be envisioned. Silicon detectors are in most respects among the best suited devices to meet the extreme requirements of the future experiments as far as fast response, high single mip resolution, flexible geometry for position sensitivity, compactness and insensitivity to magnetic fields are concerned. They are therefore widely employed in many proposals discussed for SSC or LHC experiments. Consequently radiation hardness in silicon, carried out by several groups, are under more systematic investigation than for any other type of detector. The neutron induced displacement effects play a dominant role, recent results are reported in eqs. [1–8]. Details of the different damage effects due to the various radiation components are discussed in ref. [1].

As already discussed in previous papers [1,9–11] the main degradation effects regarding the detector performance are:

– increase of the detector reverse current and a related worsening of the signal to noise ratio;

– enhanced carrier trapping probability leading to a charge collection deficiency in the signal response;

– change in the effective impurity concentration with consequences for the necessary bias voltage.

The current increase influences–via a worsening of the electronic noise–only the obtainable energy resolution for a single mip and the overall power dissipation in a large module. Most collaborations proposing silicon instrumentations judge this problem to be of minor importance since a moderate cooling will be necessary anyway. The other two effects will however directly influence the stability of the signal calibration and are therefore much more serious. As has been shown recently, the signal degradation does not exceed about 3% for a fluence of 10^{13} n/cm^2 [1]. This is probably acceptable keeping in mind that silicon detectors can easily be recalibrated on-line using proper radioactive sources [12]. The change of the effective impurity concentration with a possible conversion of the conduction type at moderate neutron fluences between 10^{12} and 10^{13} n/cm^2 and its implication on the operability of the detector is certainly the most discussed topic in recent radiation hardness studies [13]. So far all effects have been measured systematically only at room temperature and after irradiation without bias. Additional consequences may be expected under real operating conditions.

Although many thorough investigations have been reported by several groups the comparison of different damage results suffers from the fact that self annealing during and after irradiation is not always included. Hence the measured data depend not only on the neutron fluence but also on the irradiation flux respectively duration as well as on the time between irradiation and measurement [14]. Another source of uncer-

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tainty for a proper comparison of various results is the use of neutron sources with different energy spectra. The neutron spectrum in a collider experiment is believed to be centered around 1 MeV. Therefore it seems appropriate to normalize all different measurements by way of an energy dependent weight factor as outlined in ref. [19]. Only after these corrections with respect to self annealing and neutron energy have been performed we can expect that the different experimental results fall into a general picture which gives us a better understanding of the damage process and at the same time provides the tool to estimate the effects to be expected under real operating conditions.

With these remarks in mind, it is the main goal of this paper to present results for the change of the effective impurity concentration over a wide range of fluences up to 10^{15} n/cm^2 and for its self annealing during a subsequent period of several months. Consequences for the bulk current annealing will also be discussed.

2. Experimental technique

The detectors used in the present investigations are mainly of the planar/surface barrier type fabricated in our own laboratory from 6 kΩ cm n-type Wacker silicon with a thickness of 400 μm [11]. Different detector geometries and sensitive areas between 0.05 and 2 cm^2 were used. The voltage necessary for total depletion was about 80 V and the reverse current only a few nA/cm^2 before irradiation. A considerable overbias voltage could always be applied. The irradiation was done at room temperature with monoenergetic 1.2, 5.0 and 14.1 MeV neutrons as well as with a mean energy of 6.2 MeV from a Be(d, n) source. For the latter case a maximum flux of 1.5×10^9 n/cm^2 s could be reached

Table 1
Weight factors η for normalization of the measured neutron fluence $\Phi(E_n)$ at different energies with respect to an energy of 1 MeV ($\Phi = \eta\Phi(E_n)$)

Neutron source	E_n [MeV]	η
T(p, n)	1.2	0.88
D(d, n)	5.0	1.69
T(d, n)	14.1	1.88
Be(d, n)	6.2 [a]	1.53

[a] Mean energy.

at small distances. Details of the irradiation experiments and neutron dosimetry will be published elsewhere [15]. In most cases the irradiation was done without applying any bias voltage to the detector. The exposures were kept as short as possible in order to facilitate self annealing corrections. All measured neutron fluences are normalized to an equivalent fluence for $E_n = 1$ MeV using the method described in ref. [9]. The individual weight factors are given in table 1. Throughout this paper all results are given as function of this equivalent 1 MeV fluence.

3. Effective impurity concentration

The effective impurity concentration can be derived from the depletion voltage extracted from C/V characteristics. After damage by a moderate fluence of several 10^{11} n/cm^2 these curves always look as expected for normal diodes and are practically frequency independent (fig. 1a), whereas after irradiation with high fluences above 10^{13} n/cm^2 we get a strongly frequency dependent shape which still lacks full understanding (fig. 1b). The steep decrease of the capaci-

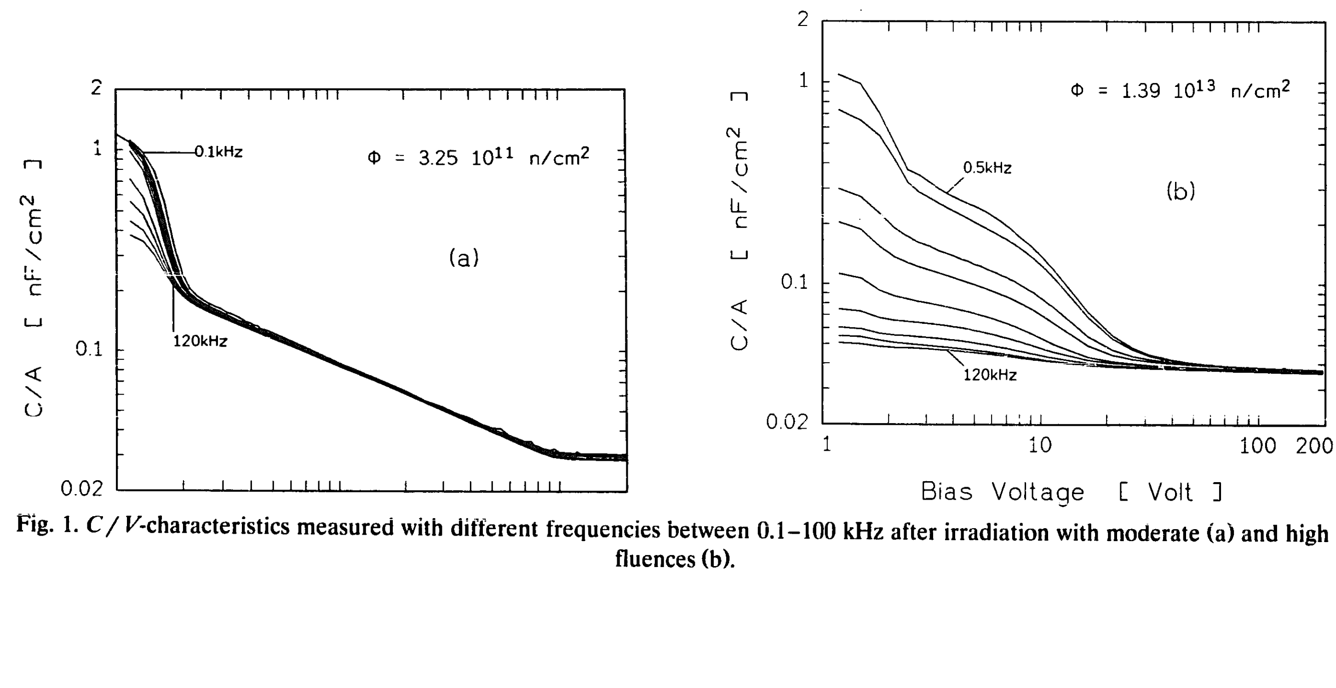

Fig. 1. C/V-characteristics measured with different frequencies between 0.1–100 kHz after irradiation with moderate (a) and high fluences (b).

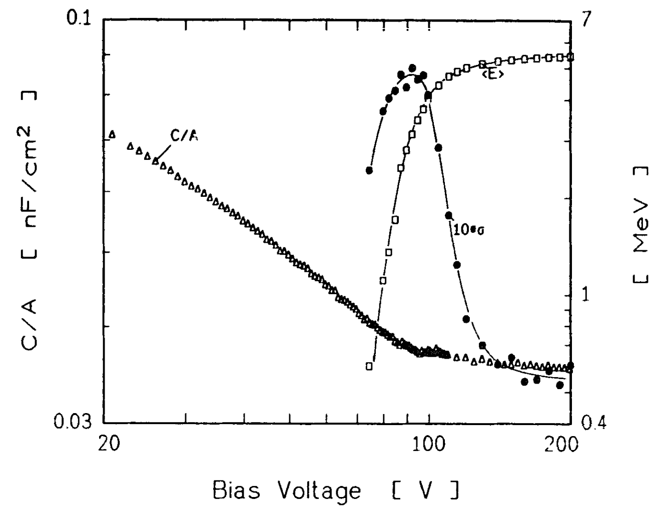

Fig. 2. Comparison between depletion voltage extracted from the C/V-characteristic and signal response to monoenergetic alpha particles (5.805 MeV) incident on the front side.

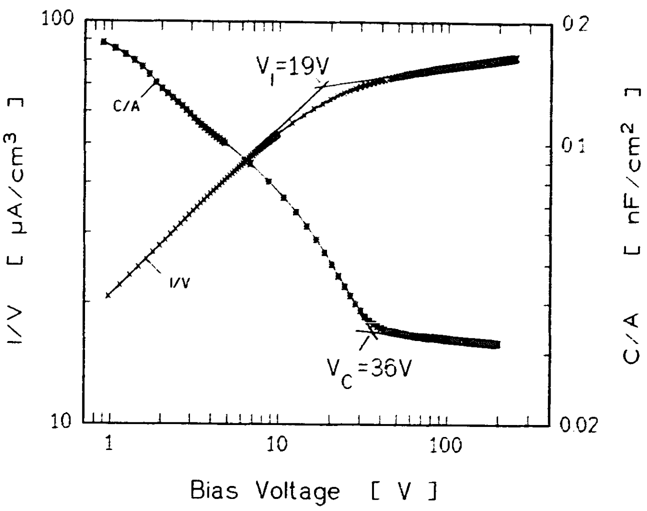

Fig. 3. C/V and I/V characteristics of a detector irradiated with 1.86×10^{13} n/cm^2. C/V measured at 10 kHz.

tance at about 2 V indicates that we still have a MOS like behaviour from the overlapping electrode which suggests the presence of a shallow n-type layer although the bulk is already converted from n- to p-type. This observation is in agreement with results recently discussed by Kraner and a first attempt for understanding was given by Walter [13]. It has been shown that the depletion voltage extracted from the C/V-curve always reflects the total depletion as measured with short ranged alpha particles [16]. This is clearly seen in fig. 2. As the detector is converted from n- to p-type the electric field starts from the rear side and reaches the front side at total depletion. Exactly at the same voltage we observe saturation of the alpha pulse height and a drastic improvement in the alpha peak width. This is again regarded to be a convincing proof that the depletion voltage extracted from the C/V-curves in the usual way gives the proper value and that we really observe type conversion. It is, however, interesting that the I/V-characteristic saturates at a lower voltage than expected (fig. 3). The discrepancy between the depletion voltage and the current saturation voltage was observed to increase considerably above 10^{13} n/cm^2, while both values are identical prior to type conversion.

Fig. 4 shows various C/V-characteristics of one detector measured immediately after irradiation with fluences between 3×10^{12} and 1×10^{14} n/cm^2 with a frequency of 10 kHz. The depletion voltage is seen to drop from the original value of 75 to 12 V at 3×10^{12} n/cm^2 and then increases again up to finally 300 V for 1.2×10^{14} n/cm^2. Such a dependence on the neutron fluence is to be expected according to a reduction in the effective impurity concentration $N_{eff}=N_D-N_A$ as function of Φ from the original positive value (n-type material) to finally increasingly negative values after conversion to p-type silicon. With respect to the change in the individual C/V-characteristics it is interesting to see that at high fluences we get a universal shape if we normalize the bias to the voltage necessary for total depletion (fig. 5). This behaviour may serve as a first tool in trying to understand the shape of the C/V-curves. However, a model for a correct description has still to be devised.

The separation between the actual defect generation and its time dependent annealing was achieved using the following method. One detector was irradiated with 1.8×10^{12} n/cm^2 in a short-exposure of $T=16$ min and the change in the effective impurity concentration ΔN_{eff} was then carefully measured in small intervals between $t=2$ min and 2 months after

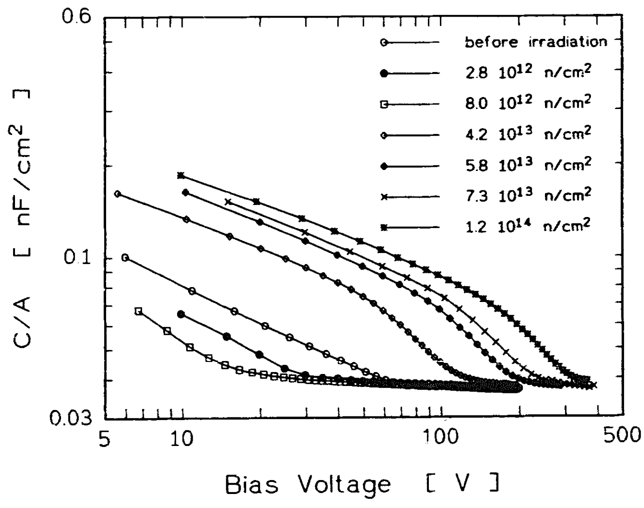

Fig. 4. C/V characteristics measured at 10 kHz immediately after irradiation by various neutron fluences up to 1.2×10^{14} n/cm^2.

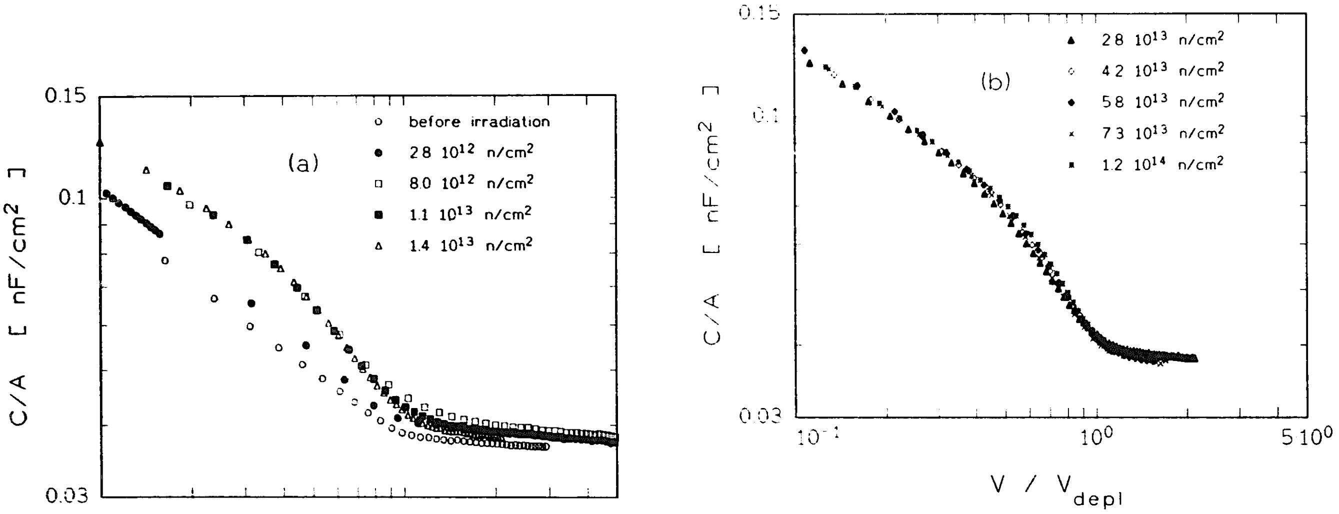

Fig. 5. Same data as in fig. 4 but plotted as function of the bias voltage normalized to total depletion.

irradiation. This curve was analysed in terms of exponentials as previously described in ref. [7,14]. Assuming that the annealing does not significantly depend on the neutron fluence we used this analytic function in order to correct all measurements for the self annealing during irradiation. After this correction $\Delta N_{eff}(0)$, the value extrapolated to $t = 0$ could be obtained and the ratio $\Delta N_{eff}(t)/\Delta N_{eff}(0)$ calculated as function of time after irradiation. As plotted in fig. 6 this ratio is indeed a universal function of time, independent of the individual irradiation parameters. It can be best described by eq. (1) with amplitudes and time constants given in table 2.

$$\Delta N_{eff}(t)/\Delta N_{eff}(0) = \sum_{i=1}^{6} A_i \exp(-t/\tau_i). \qquad (1)$$

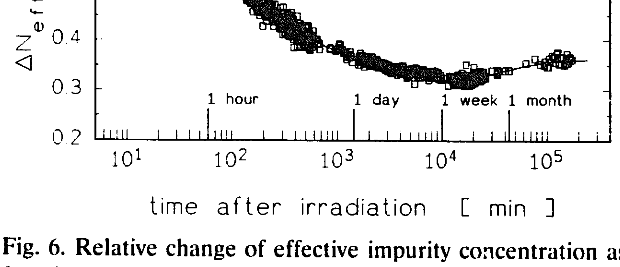

Fig. 6. Relative change of effective impurity concentration as function of time for room temperature annealing together with a fit according to eq. (1).

It should, however, be mentioned that the analysis was based on exposures not shorter than 5 min. A possible annealing with smaller time constants is therefore not included.

As mentioned above we could then also extract the net damage affected impurity concentration i.e. the absolute value of $N_{eff}(\Phi)$ as measured immediately after exposure and corrected for self annealing during irradiation. Results are plotted in fig. 7 for fluences up to 10^{15} n/cm^2 together with a fit according to

$$N_{eff}(\Phi) = N_{eff,0} \exp(-c\Phi) - b\Phi, \qquad (2)$$

with $b = (8.1 \pm 0.8) \times 10^{-2}$ cm^{-1}, $c = (6.7 \pm 0.5) \times 10^{-13}$ cm^2 and $N_{eff,0} = N_{eff}$ before irradiation. This dependence may be interpreted as originating from a removal of the phosphorus donors and boron acceptors ($dN_{P,B} \propto -N_{P,B}(\Phi)d\Phi$) leading to the first term of eq. (2) and a fluence proportional generation of acceptor like defects as given by the second term. It is however, not obvious that both donor and acceptor removals are governed by the same cross sections, as assumed and more accurate data may reveal a modified picture.

Table 2

Time constants τ_i and relative amplitudes A_i for ΔN_{eff} (eq. (1)) obtained from fitting the data given in fig. 6

Time constant τ_i [min]	Relative amplitude A_i
$(9.40 \pm 0.80) \times 10^0$	0.214 ± 0.030
$(6.87 \pm 0.14) \times 10^1$	0.262 ± 0.007
$(3.43 \pm 0.12) \times 10^2$	0.118 ± 0.008
$(4.00 \pm 0.04) \times 10^3$	0.097 ± 0.002
$(3.77 \pm 0.02) \times 10^4$	-0.065 ± 0.001
∞	0.375 ± 0.004

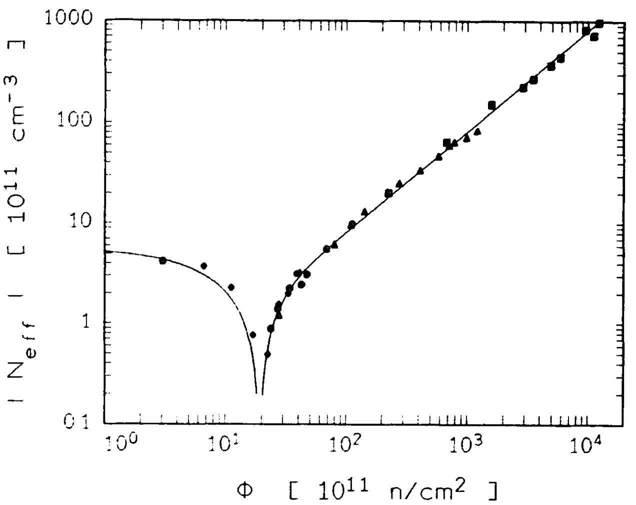

Fig. 7. Absolute value of the effective impurity concentration versus fluence up to 10^{15} n/cm^2. The solid curve represents a fit according to eq. (2).

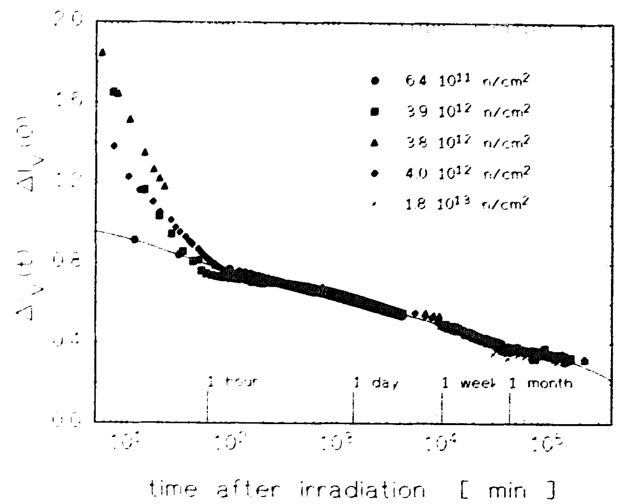

Fig. 9. Comparison of room temperature current annealing for detectors irradiated with different fluences. The solid curve represents a fit according to eq. (3).

4. Effective bulk current

The discussion of section 3 is of course also relevant for the measurement of the bulk current annealing. These functions can only be measured if the time dependence of the depletion voltage is taken into account. An example is given in fig. 8. Results for different fluences are summarized in fig. 9 from which it can be seen that the fluence normalized bulk current follows an approximately universal behaviour for annealing times larger than 1 h. As discussed above all values have been corrected for self annealing during irradiation in order to obtain a time scale not depending on the irradiation parameters.

Taking all existing data for fluences lower than 10^{12} n/cm^2 into account we obtain a fit also shown in fig. 9 according to eq. (3) with amplitudes and time constants given in table 3.

$$\Delta I(t)/\Delta I(0) = \sum_{i=1}^{5} A_i \exp(-t/\tau_i). \qquad (3)$$

It is reassuring that this improved analysis does not significantly deviate from the previously published results [8]. It should be emphasized that even for higher fluences above type conversion the annealing function is not changed for $t > 1$ h. Therefore under real operating conditions with a flux of about 10^7 n/cm^2 s the deviation at short times is expected to be washed out completely.

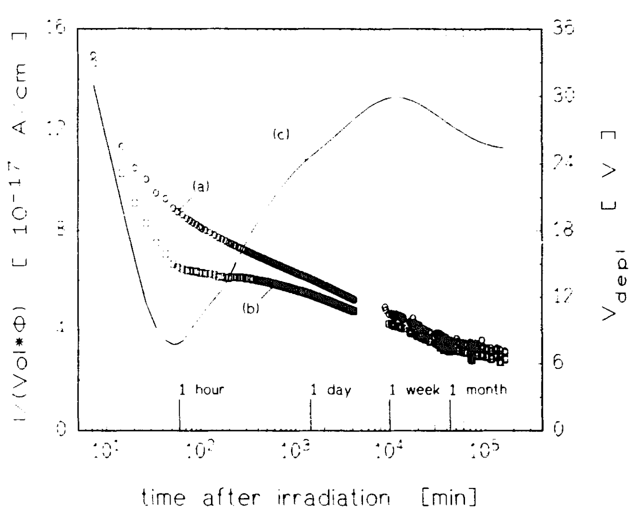

Fig. 8. Room temperature annealing of reverse current after irradiation with 3.92×10^{12} n/cm^2. (a): at a fixed bias (50 V), (b): at time dependent depletion voltage as given by (c).

5. Irradiation effects under bias

In a first attempt to study effects of detectors irradiated with applied bias as under real operating conditions we exposed two identical small pads with a diode area of 5.8 mm^2 and an electrode overlapping the oxide of 1.6 mm^2 each placed on the same detector.

Table 3
Time constants τ_i and relative amplitudes A_i for the annealing of the bulk generation current obtained from fitting the data given in fig. 9

Time constant τ_i [min]	Relative amplitude A_i
$(1.78 \pm 0.17) \times 10^1$	0.156 ± 0.038
$(1.19 \pm 0.03) \times 10^2$	0.116 ± 0.003
$(1.09 \pm 0.01) \times 10^3$	0.131 ± 0.002
$(1.47 \pm 0.01) \times 10^4$	0.201 ± 0.002
$(6.70 \pm 0.01) \times 10^5$	0.396 ± 0.001

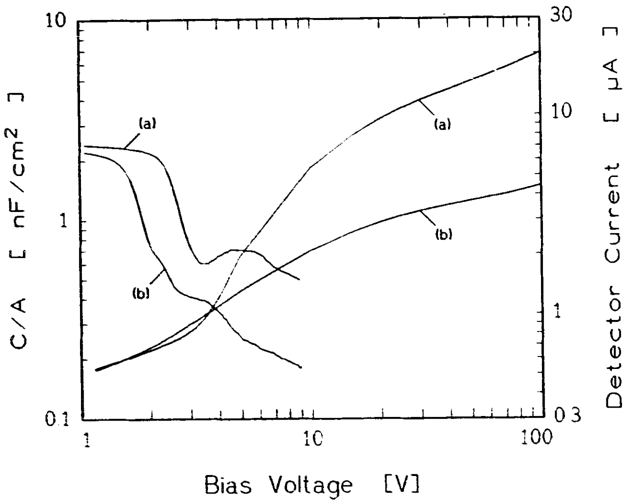

Fig. 10. Comparison between I/V and C/V characteristics for two identical detectors irradiated with 7.6×10^{12} n/cm^2; (a) under bias, (b) without bias.

One of these pads was biased at 100 V, the other one floating. Immediately after irradiation both I/V and C/V characteristics were measured (fig. 10). From the difference in these curves we clearly can see the additional influence of the SiO_2–Si interface. For the biased detector the flat band voltage is shifted to a higher value which is caused by increased fixed oxide charges and interface states. In correlation with the flat band voltage we observed also a sharper increase of the detector current probably due to these interface states [11]. Systematic studies of these effects have still to be performed.

6. Conclusions

Previous radiation hardness studies of silicon detectors have been extended to neutron fluences of 10^{15} n/cm^2. Emphasis was given on the change in the effective impurity concentration. It is demonstrated that the depletion voltage extracted from C/V-characteristics is identical with that from measurements of the response for alpha particles. The shape of the C/V-curve is shown to be independent of the fluence if plotted as function of the thickness of the depleted zone ($x/d \propto \sqrt{V/V_{depl}}$), a physical model for a better understanding has still to be devised.

After a proper correction for self annealing the radiation induced change of the effective impurity concentration can best be explained by a removal of both original donors (P) and acceptors (B) as well as a fluence proportional generation of acceptor like centers which may be correlated with neutron induced cluster defects. The time dependence of the room temperature self annealing was carefully measured and analysed, resulting in a universal function which saturates at about one third of its value immediately after irradiation.

It is also shown that for the accurate extraction of the bulk current and its annealing the time depending depletion voltage has to be taken into account. Again the fluence normalised currents are following a universal behaviour. These improved data are in very good agreement with previously reported results. Even above the conversion of the silicon from n- to p-type no change of the long term annealing function was observed. These results may already serve as a tool for the change of the detector performance expected under real operating conditions. Systematic investigations for irradiations under bias and at lower temperatures have recently been started. First experiments show that in addition to the bulk damage surface effects have to be taken into account.

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