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Prediction of the performances of finely segmented Si detector for tracking applications in future super-colliders after severe radiation damage

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Abstract

The effect of hadron irradiation on segmented silicon detectors is known to severely affect their performances and to lead to their failure after a certain dose is accumulated. The dose at which this failure happens is strongly dependent on the geometry and on the required performances of the devices. In the various scenarios predicted for the CERN Large Hadron Collider (LHC) detector trackers, the deterioration of the full depletion voltage (V_{fd}) has been used as a measure of the capability of the sensors to survive a certain level of irradiation. This concept can be regarded as a simplification, and a discussion of its limits is presented here.
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1. Introduction

The silicon trackers presently being constructed for the general purpose experiments in Large Hadron Collider (LHC) (CMS, ATLAS [1,2]) are based on silicon microstrip detectors made with p-strips implanted on n-type silicon bulk (p^+-in-n), capacitevely coupled to fast (25 ns shaping time) electronics. Silicon detectors used in high radiation environments will degrade their performances and eventually fail. The ability to predict the fluence at which this failure occurs is a fundamental information for the design of the tracker detectors for high-energy physics experiments where high radiation levels are involved. A possible upgrade of the LHC to about ten times higher luminosity (sLHC) is being considered [3]. The tracker sensors in the upgraded machine will have to withstand an order of magnitude higher radiation damage than the present LHC detectors. If silicon detectors are to be used in the upgraded tracker, with different geometries at different radii, it will be necessary to predict the radiation doses that every particular sensor can survive. A discussion of the criteria needed to guide this prediction is proposed here.

2. Macroscopic effects of the radiation damage

The hadron irradiation introduces electrically active defects in the silicon bandgap, which changes several key properties of the devices. The effects that mainly influence the operation of detectors are the increase in the leakage current and the full depletion voltage (see e.g. [4–6]) along with higher trapping of the charge carriers generated by ionising particles passing through the detectors. The increase in reverse current as a function of the fluence is parameterised by

$$I_{\mathrm{r}} = \alpha\phi V \tag{1}$$

where ϕ is the hadron fluence, V is the volume of the detector and α the current damage factor. The reverse current has also a strong dependence on the temperature, expressed by

$$I_{\mathrm{r}}(T) \propto T^2 \exp\left(-\frac{E_{\mathrm{g}}}{2k_{\mathrm{B}}T}\right) \tag{2}$$

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where E_g is the silicon bandgap (1.12 eV), k_B the Boltzmann constant and T the absolute temperature.

The reverse-bias voltage required to remove the free carriers from the active volume of the detector (full depletion voltage, V_{fd}) is proportional to the effective doping concentration, N_{eff}. The defects introduced by irradiation act predominantly as acceptor (p-type). The introduction of p-type defects in n-type silicon at first reduces N_{eff}. After a few times, 10^{13} hadrons cm^{-2}, N_{eff} (therefore V_{fd}) reaches its minimum. Further irradiation will cause the linear increase of V_{fd} with fluence, with the effective space charge of the detector being inverted to p-type. The change of N_{eff} as a function of fluence can be parameterised, in the case of n-type detectors, by

$$N_{eff} = N_{eff}(0)e^{-c\phi} - \beta\phi \tag{3}$$

where $N_{eff}(0)$ is the initial effective doping concentration, c the constant of donor removal and β the introduction rate of acceptor-like defects.

This has to be considered an effective parameterisation. It is in fact now well accepted that the irradiation introduces both type of defects, donor and acceptor-like, with these latter being predominant. Nonetheless, the presence of donor-like radiation defects allows the explanation of the shape of the electric field in irradiated silicon detectors, as discussed below.

Dedicated R&D programs (CERN-RD48 and RD50 [7,8]) have been devoted to the radiation hardening of silicon detectors, that is reducing α, β and the charge trapping constant. The intention [7] was to achieve the goal through material engineering, with the introduction of selected impurity in the silicon crystal. Those impurities can react with the primary radiation-induced defects (vacancies, interstitials and clusters) and influence the defect dynamics to reduce the concentration of electrically active centres. The various silicon crystals produced by RD48 with added impurities (C, O) have shown no changes of the parameter α ; therefore, no control on the reverse current is available through this technique. A lower value of the parameter β can though be achieved by increasing the oxygen concentration to more than 10^{17} cm^{-3} in the high-grade float zone silicon used for detector processing [9]. A simple technique to enhance the oxygen concentration has been developed [10] and it is now being used by several silicon detector manufacturers. Both I_r and N_{eff} also change with time after irradiation. The reverse current decreases after irradiation according to

$$\Delta I_r(t) = \Delta I_r(t=0) \times \sum_i d_i \exp\left(-\frac{t}{\tau_i}\right) \tag{4}$$

where d_i are the relative amplitudes of the various annealing components with lifetime τ_i [6,9]. A different evolution with time is found for N_{eff} (therefore V_{fd}) that decreases for ~10 days at room temperature to reach a minimum (*beneficial annealing*), than starts to increase again (*reverse annealing*). This behaviour can be described by [6,9]

$$\Delta N_{eff}(t, \Phi) = \Phi \times \sum_i g_{a,i} \exp\left(-\frac{t}{\tau_{a,i}}\right) + N_c(\Phi) + N_{y,\infty} \times \left(1 - \frac{1}{1 + t/\tau_y}\right) \tag{5}$$

where $g_{a,i}$ are the relative amplitudes of the beneficial annealing with lifetimes $\tau_{a,i}$, N_c is a term independent on the time after irradiation and proportional to the fluence, and $N_{y,\infty}$ is the amplitude of the reverse annealing, weighted by a time-dependent empiric function with constant τ_y. The annealing has a strong dependence on the temperature: for example it can be accelerated by a factor >7300 or retarded by a factor ~50, relative to 20 °C (RT), if the detectors are kept at 80 or 0 °C, respectively. Fig. 1 shows the changes of N_{eff} (V_{fd}) at room temperature, according to Eq. (5), for a detector irradiated to 7.5×10^{15} p cm^{-2}.

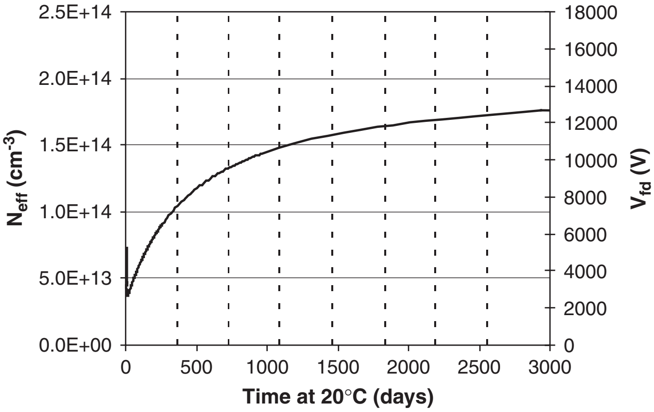

Fig. 1. Changes of N_{eff} (V_{fd}) with time after irradiation at room temperature for silicon detector irradiated to 7.5×10^{15} p cm^{-2}.

The high density of radiation-induced trapping centres also reduces the charge carrier lifetime. The trapping probability of a charge carrier during its drift through the detector is proportional to the ratio of the collection time t_c to the trapping time constant $\tau_{tr}(\phi)$. For long t_c, the amount of trapped charge, which is effectively removed from the signal, can be significant.

3. Changes of the electric field in irradiated detectors

The description of the charge collection properties of the detectors requires the knowledge of the electric field profile in the active volume. The electric field of non-irradiated silicon diodes is proportional to the depth coordinate with the slope determined by N_{eff} (Fig. 2). The naïve approach of considering the electric field of the detector after inversion as simply mirrored with the junction (and therefore the high field) located on the opposite side (Fig. 2) is contradicted by experimental measurements. This simple model is not able to explain documented behaviours of the irradiated detectors, like the *double-junction*

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