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Impact of annealing of trapping times on charge collection in irradiated silicon detectors ☆

G. Kramberger[a,*], V. Cindro[a], I. Mandić[a], M. Mikuž[a,b]

[a]Institute Jožef Stefan, Jamova 39, SI-1111 Ljubljana, Slovenia
[b]Department of Physics, University of Ljubljana, SI-1000 Ljubljana, Slovenia

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Abstract

The evolution of effective trapping times with time in position sensitive silicon detectors at the experiments at Large Hadron Collider (LHC) has been calculated for envisaged operation scenario. The trapping probability of holes will increase by 30% when compared to the value at the end of beneficial annealing for the same total fluence. The effective trapping probability of electrons on the other hand will decrease by around 15%. Possible operation scenarios for an upgrade of LHC (SLHC) were investigated and the differences in terms of charge trapping were compared. The simulation confirms the observations that at fluences $\Phi_{eq} > 2 \times 10^{15}\,cm^{-2}$ the long term annealing does not affect much the CCE of highly segmented n^+-p devices.

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Keywords: Effective carrier trapping time; Silicon detectors; Charge collection efficiency

1. Introduction

Most of the recent experiments in high energy physics use position sensitive silicon detectors for tracking of charged particles. At the Large Hadron Collider (LHC) high collision rates and track multiplicities will cause substantial radiation damage of silicon detectors [1]; even more is envisaged after a possible increase of the LHC luminosity by a factor of 10 to $10^{35}\,cm^{-2}\,s^{-1}$ (SLHC) [2]. Consequently, fluences received by the detectors at SLHC will range from $10^{14}\,n_{eq}\,cm^{-2}$ at outer silicon tracker at $r = 100\,cm$ to the $10^{16}\,n_{eq}\,cm^{-2}$ for the innermost layer of the pixel detector at $r = 4\,cm$. At small radii the damage is dominated by fast charged hadrons (mostly pions), while for $r > 20\,cm$ the neutrons originating from the calorimeter prevail. The radiation damage reflects in an increase of: effective dopant concentration (N_{eff}), leakage current and effective trapping probabilities ($1/\tau_{eff,e,h}$) of the drifting electrons and holes [3]. The latter determines the charge collection efficiency (CCE) and consequently the performance of irradiated silicon detectors. The defects in the Si-lattice which are responsible for the degradation of the detector performance change with time after the irradiation. Annealing of the defects responsible for changes of N_{eff} were studied in details by RD48 collaboration [3]. Much scarce are on the other hand the annealing studies of $1/\tau_{eff,e,h}$. So far, for most of the samples evolution of $\tau_{eff_{e,h}}(t)$ was measured at certain temperature [4–6] and only recently systematic annealing studies were performed at different temperatures [7]. This procedure enables the scaling of the annealing time constants to close to the operation temperatures and by that the prediction of the $\tau_{eff,e,h}$ evolution during the LHC lifetime.

Moreover, at highest SLHC fluences the annealing of $\tau_{eff_{e,h}}$ could explain small effect of long term annealing on charge collection in highly segmented n^+-p devices observed in Ref. [8]. Due to short trapping times loss of the depletion depth does not affect CCE so much as at lower fluences.

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*Corresponding author. Tel.: + 386 1 477 3512; fax: + 386 1 425 7074.
E-mail address: Gregor.Kramberger@ijs.si (G. Kramberger).

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2. Simulation procedure

The effective trapping probability scales linearly with fluence as

$$1/\tau_{\mathrm{eff}_{e,h}} = \beta_{e,h}(t,T)\Phi_{eq} \tag{1}$$

where $\beta_{e,h}$ is the proportionality constant depending on time after irradiation t and operation temperature T. Most of the β measurements performed so far were done after the completion ($t_{\min}$) of beneficial annealing of N_{eff}. The average of measurements taken from Ref. [4–7,9,10] and scaled to $T=-10\,^{\circ}\mathrm{C}$ are given in the Table 1.

The changing of trapping times with time can be modeled by the decay of the dominant electron or hole trap into another stable one. The resulting ansatz is

$$\beta_{e,h}(t) = \beta_{0_{e,h}} \cdot \mathrm{e}^{-t/\tau_{e,h}} + \beta_{\infty_{e,h}} \cdot (1-\mathrm{e}^{-t/\tau_{e,h}}) \tag{2}$$

with $\beta_{0_{e,h}}$ and $\beta_{\infty_{e,h}}$ the trapping constants at early ($t \to 0$) and late ($t \to \infty$) annealing times, respectively. The parameters of the model are gathered in the Table 2, together with the activation energy used for scaling trapping times to lower temperatures (Arrhenius relation) [7]. For the relevant temperatures $\beta_{e,h}(t_{\min}) \approx \beta_{0_{e,h}}$. It is worth mentioning that values for $(\beta_0-\beta_\infty)/\beta_0$ are obtained as average not only from Transient Current Technique (TCT) measurements [4–7] but also from ATLAS pixel test-beam data [11]. It is assumed here that the $(\beta_0-\beta_\infty)/\beta_0$ does not depend on irradiation particle type.

3. Results and discussion

In terms of trapping probability the long term annealing is non-beneficial for holes and beneficial for electrons (see Table 2). This has an important consequence. Unlike in diodes the contribution of electrons (Q_e) and holes (Q_h) to the total induced charge Q differs and depends on geometry [12]. In segmented device the larger fraction of the signal comes from the type of carriers drifting to the sensing electrodes. For example for tracks going through the center of the ATLAS strip detector (thickness = 280 μm, pitch = 80 μm, implant width = 18 μm) the ratio is $Q_h/Q = 0.81$. Approximately the same ratio $Q_e/Q = 0.83$ is obtained for a 280 μm thick ATLAS pixel detector (pixel size $50\times 400\,\mu\mathrm{m}^2$). It is evident that even if electric field is high enough to allow to reach the saturation velocity in the entire detector volume (ideal case) the performance of detectors with p^+ readout (strip detectors) will not only be significantly lower after irradiation, but it will also degrade with time. On the contrary the performance of the detectors with highly segmented n^+ readout (pixel detectors) will improve.

Table 1
Trapping time damage constants for neutron and hadron irradiated silicon detectors

$t_{\min}$, $T=-10\,^{\circ}\mathrm{C}$	β_h ($10^{-16}\mathrm{cm}^2\,\mathrm{ns}^{-1}$)	β_e ($10^{-16}\mathrm{cm}^2\,\mathrm{ns}^{-1}$)
Reactor neutrons	5.7 ± 1	3.7 ± 0.6
Fast charged hadrons	6.6 ± 0.9	5.4 ± 0.4

Table 2
Parameters used to model annealing of effective trapping times

	τ (min at 60 °C)	$(\beta_0-\beta_\infty)/\beta_0$	E_{ta} (eV)
Electrons	650 ± 250	0.35 ± 0.15	1.06 ± 0.1
Holes	530 ± 250	-0.4 ± 0.2	0.98 ± 0.1

The evolution of effective trapping times was simulated using the ATLAS-SCT operation scenario: 100 days operation at −7 °C, 2 days at 20 °C, 14 days at 17 °C and for remaining of the year at −7 °C. The results are shown in Fig. 1 for detector located at $r = 26$ cm (first layer of strip detectors in ATLAS) from the interaction point where contributions from fast charged hadrons and neutrons are approximately equal [1]. For comparison also effective trapping probabilities are shown as obtained after annealing for 4 min at 80 °C which is often used to account for the maintenance period when the detectors are kept at ambient temperature. The $1/\tau_{\mathrm{eff}}$ at the end of operation is around 30% higher for holes and 15% lower for electrons.

Although the time constants in Eq. (2) are comparable with the one for reverse annealing of N_{eff} [3], the activation energies are not. Smaller activation energies result in shorter time constants than those of the N_{eff} annealing at relevant temperatures (−10 to 20 °C). As a consequence at the end of LHC lifetime N_{eff} increases for about a 20% of the reverse annealing amplitude [1] and $1/\tau_{\mathrm{eff}}$ changes up to more than half of its annealing amplitude.

Evolution of effective trapping probabilities is governed by the first order process, hence the simulations shown for ATLAS-SCT (see Fig. 1) can be scaled to any detector (i.e. fluence) with an equivalent running scenario (time at given temperature). The scaling factor is calculated from the difference in equivalent fluence and irradiation particles composition (see Table 1).

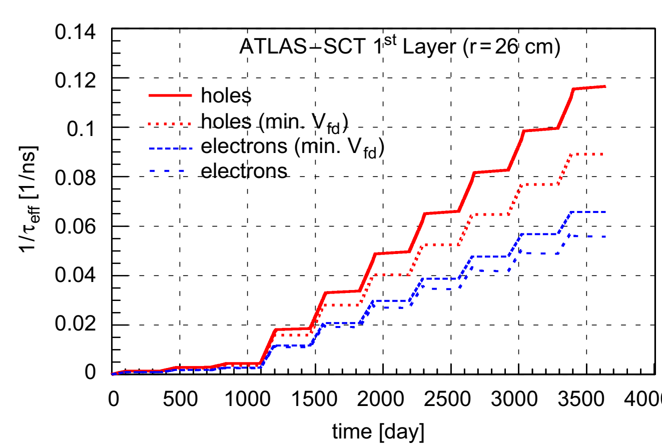

Fig. 1. Evolution of effective trapping probabilities in ATLAS experiment at the location of the first SCT layer. The neutron contribution to the total fluence of $2\times10^{14}\,n_{eq}\,\mathrm{cm}^{-2}$ was assumed to be 50%.