A comprehensive numerical simulation of heavily irradiated p-type and n-type silicon detectors

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Abstract
In the framework of the CERN-RD50 Collaboration, the adoption of p-type substrates has been proposed as a suitable mean to improve the radiation hardness of silicon detectors up to fluences of 1016n/cm2. In this work the simulated electrical characteristics of irradiated p-type and n-type detectors are reported, for comparison with experimental measurements collected from the literature. The behaviour of the silicon devices at a fluence of 1016n/cm2 shows better results in term of charge collection efficiency using a p-type silicon detector.

Keywords
type, p, detectors, irradiated, silicon, heavily, simulation, numerical, comprehensive, n

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Marco Petasecca, Francesco Moscatelli, Daniele Passeri, Giorgio Umberto Pignatel, Carlo Scarpello, Giovanni Caprai

Abstract – In the framework of the CERN-RD50 Collaboration, the adoption of p-type substrates has been proposed as a suitable mean to improve the radiation hardness of silicon detectors up to fluences of $10^{14}$ n/cm$^2$.

In this work the simulated electrical characteristics of irradiated p-type and n-type detectors are reported, for comparison with experimental measurements collected from the literature.

The behaviour of the silicon devices at a fluence of $10^{16}$ n/cm$^2$ shows better results in term of charge collection efficiency using a p-type silicon detector.

Index Terms—device simulation, particle physics, radiation damage effects.

I. INTRODUCTION

Silicon microstrip detectors are planned to be used as particle trackers in the high energy physics (HEP) experiments planned at the large Hadron Collider (LHC), CERN - CH. The future upgrade of LHC to a luminosity of $10^{33}$ cm$^{-2}$s$^{-1}$ [1] poses serious demands to the radiation hardness of silicon devices.

The macroscopic effects of radiation damage in silicon detectors are: an increase of leakage current, the increase of charge trapping and full depletion voltage, a change in the effective doping concentration [2]. Recently, in the framework of the RD50 collaboration, the use of p-type silicon has been proposed as a suitable mean to improve the radiation hardness of the detectors [1].

In the present study we report preliminary results, carried out by means of the SINOPSIS – TCAD DESSIS [3] simulation tool, concerning p-type and n-type silicon devices. In particular we have highlighted the dependence of depletion voltage and charge collection efficiency on the neutron-equivalent radiation fluence $\Phi_{eff}$.

II. THE RADIATION DAMAGE MODEL

Radiation damage in silicon is simulated by means of a model based on the introduction of deep levels in the forbidden energy gap of the semiconductor.

This approach provides an insight into the microscopic phenomena which is fundamental for understanding the macroscopic behavior of the detector and hence for its optimization. As a matter of fact, numerical device simulation has emerged to be a practical means for the design of radiation-hardened devices, because calculations allow fast and relatively inexpensive predictions of detector performance in various radiation environments.

A. n-type silicon

In the past, we have developed, for n-type silicon detectors, a so-called “three-level model” [4-6], which is able to reproduce, the increase of the leakage current, the degradation
of the charge collection efficiency and the variation of $N_{ef}$ at fluences of the order of $10^{14}$ (1MeV) neutrons/cm$^2$.

The most relevant defects have been identified to be the divacancy (V$\text{}_2$) and the carbon-oxygen (C$_2$O$_2$) complex on account of their high introduction rates and relative proximity to mid-gap. These two defects play an important role in determining the macroscopic behaviour of radiation damaged devices, including type-inversion and the increase in leakage current. A third important defect has an energy level $E_c-0.50eV$ and is probably related to the divacancy-oxygen (V$\text{}_2$O) complex.

At the end of a heavy recoil track, the non-ionizing interactions become dominant and dense defect agglomerations are formed, resulting in disordered regions often referred to as “clusters” [7]. These very small regions (whose typical diameter is of the order of ≈10nm) contain extremely high defect concentrations ($=10^{19}$cm$^{-3}$), which makes possible direct charge exchange between deep levels.

The SRH recombination statistics does not allow to predict the direct charge exchange, underestimating the increase of leakage current as a function of the fluence [8]. A technique to compensate this effect is to consider that the divacancy is the defect level related to the presence of clusters [9], and so, for both n and p type silicon, we have adopted a divacancy introduction rate greater than what measured on irradiated diodes [2].

Another radiation damage effect, so called “donor removal”, consists in a reaction of defects with the shallow dopants to form neutral complexes, which decrease the active doping concentration.

For example, in n-type silicon, the most important reaction occurs between phosphorus atoms and vacancies: the phosphorus is neutralised and some of the shallow donors can be considered as having been removed.

In our model we have considered the donor removal mechanism according with the work of Moll [2].

In previous studies [12], we have also developed a four-level model for n-type silicon, in which it is possible to implement direct charge exchange between the E70$^{dc}$ and the V2$^{bc}$ states. However, the device simulator is not able to model this phenomenon at fluences above $10^{14}$n/cm$^2$.

These multiple effects produce a complicated picture of radiation damage. The implementation of a comprehensive modelling scheme, featuring an exhaustive set of defects, is prevented by computational limitations: a simplified approach is therefore necessary. In particular, only a set of dominant defects has been considered. We have therefore reverted to the three-level model [6].

In conclusion, the adopted radiation damage model for n-type substrates includes three defect levels (Tab.I): two acceptor levels located at Ec-0.42eV and Ec-0.50eV assigned to a divacancy (V$\text{}_2$) and to the divacancy-oxygen (V$\text{}_2$O) complex respectively [6], and a donor level Ev+0.36eV, assigned to the carbon-oxygen complex. All these defects play an important role in determining the macroscopic behaviour of radiation damaged devices, including type-inversion and the increase in leakage current.

### B. p-type silicon

For p-type substrate we have used a Two-Level model (Tab.I) which takes into account the effect of the tri-vacancy complex defect located at Ec-0.46eV and the effect of the divacancy located at Ec-0.42eV, which have been described in papers [10,11]. The presence of the V$\text{}_2$ defect allows us to use a more realistic introduction rate for the divacancy. It is worth noting that the adopted cross section for holes is one order of magnitude greater than the experimental values, in order to compensate the absence of many others defects, present in an irradiated detector.

### III. Simulation setup

To analyze p-type and n-type substrate behavior, we consider two dimensional n$^+$/p/p$^+$ and p$^+$/n/n$^+$ structures with a substrate doping concentration $N_{d,SiO_2}$=$10^{13}$cm$^{-3}$ corresponding to a resistivity of about 6kΩcm. A 1μm deep n$^+$ (or p$^+$) implant (Gaussian profile) has been adopted for the n$^+$ (or p$^+$) guard ring. The simulated structure consists of a simple diode, 300μm thick, 40μm wide, separated by 15μm from a 6μm wide guard ring which is necessary to obtain a uniform electric field distribution underneath the diode junction. The effect of charge build up at the Si/SiO$_2$ interface under irradiation is taken into account by defining a different charge oxide concentration in non-irradiated ($4·10^{13}$cm$^{-3}$) and irradiated ($1·10^{13}$cm$^{-3}$) devices respectively. Each defect level is characterized by four parameters: the energy level $E_i$ [eV], the introduction rate $\eta$ [cm$^{-1}$], and the cross section of electrons and holes [cm$^2$] respectively.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>THE THREE LEVELS RADIATION DAMAGE MODEL FOR N-TYPE</th>
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</thead>
<tbody>
<tr>
<td>Level</td>
<td>Ass.</td>
</tr>
<tr>
<td>Ec-0.42eV</td>
<td>VV$^{(10)}$</td>
</tr>
<tr>
<td>Ec-0.50eV</td>
<td>VVO</td>
</tr>
<tr>
<td>Ev+0.36eV</td>
<td>CiOi</td>
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</table>

<table>
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<tr>
<th>TABLE II</th>
<th>THE TWO LEVELS RADIATION DAMAGE MODEL FOR P-TYPE</th>
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<tbody>
<tr>
<td>Level</td>
<td>Ass.</td>
</tr>
<tr>
<td>Ec-0.42eV</td>
<td>VV$^{(10)}$</td>
</tr>
<tr>
<td>Ec-0.46eV</td>
<td>VV$^{(10)}$</td>
</tr>
</tbody>
</table>

**References:**

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IV. DEPLETION VOLTAGE AND LEAKAGE CURRENT

In this section we report the results obtained with the two levels model for the p-type silicon and the three levels radiation damage model for n-type, respectively.

All simulations are carried out at room temperature.

A. p-type detectors

The two levels p-type model reproduces the experimental [13] variation of the full depletion voltage as a function of the fluence (Fig.1) fairly well. The deviation between simulated and experimental data is less than 5%.

The radiation damage constant calculated with this model is \( \alpha = 3.75 \times 10^{-17} \text{A/cm} \), which is in satisfactory agreement with the reported value of \( 3.99 \pm 0.03 \times 10^{-17} \text{A/cm} \) at room temperature [11]. The difference between the simulated and the experimental leakage current for all the considered fluencies is less than 10% (Fig.2).

Fig. 1. Simulated and measured values of the Full Depletion Voltage as a function of the fluence for p-type detectors.

Fig. 2. Simulation of the Leakage Current Density as a function of the fluence for p-type detectors compared with experimental data.

B. n-type detectors

The simulations of depletion voltage (Fig.2) and leakage current density (Fig.3) of the n-type material using the three-levels radiation damage model, nicely reproduces the experimental values [15] for fluences up to \( 1 \times 10^{15} \text{n/cm}^2 \).

The detector behavior at the fluence of \( 10^{16} \text{n/cm}^2 \) is reported in Fig.6. The estimated collected charge at \( 10^{16} \) of fluence, with a bias voltage of 900V, is about 5000 electrons corresponding to an efficiency of about 20%.

V. CHARGE COLLECTION EFFICIENCY

A. p-type detectors

The two level radiation damage model for p-type substrate is not able to reproduce the experimental charge collection efficiency (CCE). To overcome this problem a third level at the energy of \( E_v + 0.3 \text{eV} \) was introduced.

This defect, generally assigned to a C\textsubscript{v}O\textsubscript{v} complex, has no effect on the depletion voltage and the leakage current, but allows to fit well (deviation less than 7%) the experimental data reported on p-type silicon pad detectors [14] up to fluencies of \( 5 \times 10^{15} \text{n/cm}^2 \).

In this case the radiation damage constant \( \alpha_{\text{simulated}} = 3.3 \times 10^{-17} \text{A/cm}^2 \) is in the range of \( 2 \pm 10 \times 10^{-17} \text{A/cm}^2 \), typical of the experimental values reported for n-type silicon (Fig.5). The current density at the same fluence is comparable between n and p type.

Fig. 3. Comparison between simulation and experimental data of the full depletion voltage as a function of the fluence for n-type detectors.

Fig. 5. Simulation of the leakage current density as a function of the fluence for n-type detectors.

Fig. 6. Comparison between simulation and experimental data of the full depletion voltage as a function of the fluence for n-type detectors.
B. n-type detectors

The CCE as a function of the fluence of the n-type detectors has been obtained using the three level radiation damage model. In Fig.7, a comparison between measured [16] and simulated data performed for fluence up to $1 \times 10^{15}$ n/cm$^2$ and simulated data is described: each simulated point is in a fairly good agreement with experimental data (average deviation less than 7.5%).

The collected charge estimated at the fluence expected for sLHC, for a n-type detector biased at 900V, is less than 3000 e-h pairs corresponding to a CCE of 12%.

VI. CONCLUDING REMARKS

In this work, numerical simulation techniques have been used to validate a modelling technique for p-type and n-type detectors irradiated up to $1 \times 10^{16}$ n/cm$^2$ (1MeV neutron equivalent). The simulation results are compared with experimental data obtained in the framework of the RD50 CERN Collaboration.

For p-type substrate, the two level damage model (acceptors at 0.42eV and 0.46eV) fits measured data well with a deviation (in comparison with experimental data) of less than the 10% on the full depletion voltage and leakage current as a function of the fluence. A third defect level (donor at Ev+0.36eV) is necessary to simulate the experimental decrease of CCE as a function of the fluence.

The n-type detector behaviour is simulated by a three level radiation damage model. The model is composed of two acceptors and a donor: the introduction rate and cross section are dimensioned to take into account the cluster contribution and the presence of many other defects.

A first comparison (Fig.8) between the expected collected charge, at fluence of $10^{16}$ n/cm$^2$ and at the same depletion bias voltage of 900V, shows that p-type substrate has a fairly better efficiency than the n-type. This is probably due to the higher mobility of the electrons with respect to the mobility of holes.

However, it must be considered that detectors realized on a p-type substrate, exhibit a higher depletion voltage for fluence of $10^{16}$ n/cm$^2$. A further analysis of trapping in n-type and p-type material is foreseen.

REFERENCES

[3] ISE TCAD Manuals