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

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

## 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

## Disciplines

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# A Comprehensive Numerical Simulation of Heavily Irradiated p-type and n-type Silicon Detectors

Marco Petasecca, Francesco Moscatelli, Daniele Passeri, Giorgio Umberto Pignatelli, 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  $10^{16}$  n/cm<sup>2</sup>.

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<sup>2</sup> 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  $10^{35}$  cm<sup>-2</sup>s<sup>-1</sup> [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 SINOPSYS – 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  $\Phi_{\text{eff}}$ .

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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.

## II. THE RADIATION DAMAGE MODEL

Irradiation significantly alters the electrical properties of silicon detectors. It leads to changes in the effective doping concentration ( $N_{\text{eff}}$ ) and consequently in the full depletion voltage ( $V_{\text{dep}}$ ), in the leakage current  $I_{\text{leak}}$ , and in the charge collection efficiency (CCE) [2]. The simulation of these effects can be carried out by means of a model developed with a general purpose technology CAD tool. The model is based on a generalized Shockley-Read-Hall (SRH) expression which is applied to the case of multiple trap levels, located deeply into the semiconductor bandgap.

Highly-energetic ionising particles crossing the detector interact with bulk silicon and generate along their path electron-hole pairs which can be collected at the electrodes of an inversely biased junction. If these particles have high enough energy, a lattice atom can be displaced from its original position (Primary Knock-on Atom or PKA) and two defects are generated in the silicon lattice, namely an interstitial atom and a vacancy (referred to as a Frenkel pair).

Along the path of the recoiling atom, the energy loss consists of two competing contributions, the first due to ionisation and the second caused by further displacements. Even at room temperature, most of the generated interstitials and vacancies quickly recombine because of their very high mobility, but a significant proportion of them can interact with impurities to produce electrically active defects, whose energy is located within the forbidden gap. These defects behave as recombination centres and act as traps for carriers.

### 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  $N_{eff}$  at fluencies of the order of  $10^{14}$  (1MeV) neutrons/cm<sup>2</sup>,

The most relevant defects have been identified to be the divacancy ( $V_2$ ) and the carbon-oxygen ( $C_iO_i$ ) 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  $E_C-0.50\text{eV}$  and is probably related to the divacancy-oxygen ( $V_2O$ ) 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  $\approx 10\text{nm}$ ) contain extremely high defect concentrations ( $\approx 10^{19}\text{cm}^{-3}$ ), 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  $E70^{0/-}$  and the  $V2^{0/-}$  states. However, the device simulator is not able to model this phenomenon at fluencies above  $10^{14}\text{n/cm}^2$ .

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.II): two acceptor levels located at  $E_C-0.42\text{eV}$  and  $E_C-0.50\text{eV}$  assigned to a divacancy ( $V_2$ ) and to the divacancy-oxygen ( $V_2O$ ) complex respectively [6], and a donor level  $E_V+0.36\text{eV}$ , 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.

TABLE I  
THE THREE LEVELS RADIATION DAMAGE MODEL FOR N-TYPE

Level	Ass.	$\sigma_n$ [cm <sup>-2</sup> ]	$\sigma_p$ [cm <sup>-2</sup> ]	$\eta$ [cm <sup>-1</sup> ]
$E_C-0.42\text{eV}$	$VV^{(-0)}$	$2.2\text{e-}15^{**}$	$1.2\text{e-}14$	13
$E_C-0.50\text{eV}$	VVO	$4\text{e-}15^{**}$	$3.5\text{e-}14$	$0.08^{**}$
$E_V+0.36\text{eV}$	$C_iO_i$	$2\text{e-}18^{**}$	$2.5\text{e-}15^{**}$	$1.1^{**}$

### 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  $E_C-0.46\text{eV}$  and the effect of the divacancy located at  $E_C-0.42\text{eV}$ , which have been described in papers [10,11]. The presence of the  $V_3$  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 a irradiated detector.

TABLE II  
THE TWO LEVELS RADIATION DAMAGE MODEL FOR P-TYPE

Level	Ass.	$\sigma_n$ [cm <sup>-2</sup> ] Exp.[xx]	$\sigma_p$ [cm <sup>-2</sup> ] Exp.[1,2]	$\sigma_n$ [cm <sup>-2</sup> ]	$\sigma_p$ [cm <sup>-2</sup> ]	$\eta$ [cm <sup>-1</sup> ]
$E_C-0.42\text{eV}$	$VV^{(-0)}$	$2\cdot 10^{-15}$	$2\cdot 10^{-15}$	$2\cdot 10^{-15}$	$2\cdot 10^{-14}$	1.613
$E_C-0.46\text{eV}$	$VVV^{(-0)}$	$5\cdot 10^{-15}$	$5\cdot 10^{-15}$	$5\cdot 10^{-15}$	$5\cdot 10^{-14}$	0.9

## 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  $N_{A/D}\approx 10^{12}\text{cm}^{-3}$  corresponding to a resistivity of about  $6\text{k}\Omega\text{cm}$ . A  $1\mu\text{m}$  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,  $300\mu\text{m}$  thick,  $40\mu\text{m}$  wide, separated by  $15\mu\text{m}$  from a  $6\mu\text{m}$  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<sub>2</sub> interface under irradiation is taken into account by defining a different charge oxide concentration in non-irradiated ( $4\cdot 10^{11}\text{cm}^{-3}$ ) and irradiated ( $1\cdot 10^{12}\text{cm}^{-3}$ ) devices respectively. Each defect level is characterized by four parameters: the energy level  $E_i$  [eV], the introduction rate  $\eta$  [cm<sup>-1</sup>], and the cross section of electrons and holes [cm<sup>-2</sup>] respectively.

#### 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  $\alpha=3.75 \cdot 10^{-17} \text{ A/cm}$ , which is in satisfactory agreement with the reported value of  $3.99 \pm 0.03 \cdot 10^{-17} \text{ A/cm}$  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).

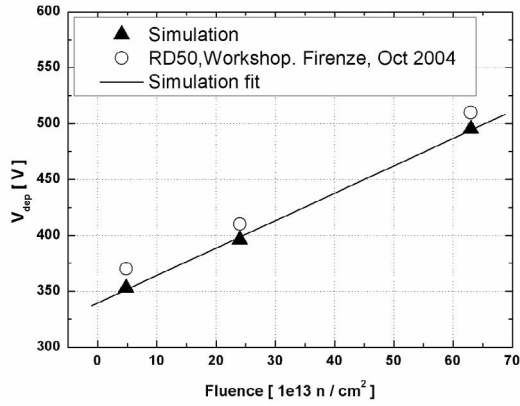


Fig. 1. Simulated and measured values of the Full Depletion Voltage as a function of the fluence for p-type detectors

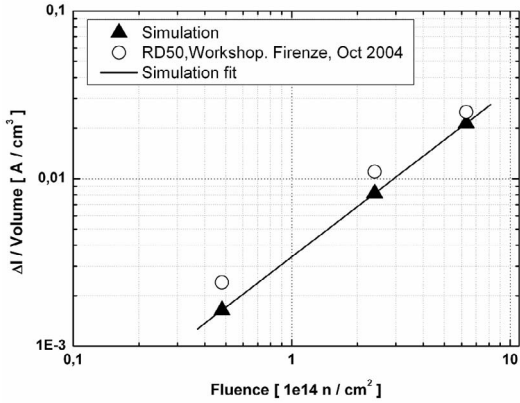


Fig. 2. Simulation of the Leakage Current Density as a function of the fluence for p-type detectors compared with experimental data.

##### 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 fluencies up to  $1 \cdot 10^{15} \text{ n/cm}^2$ .

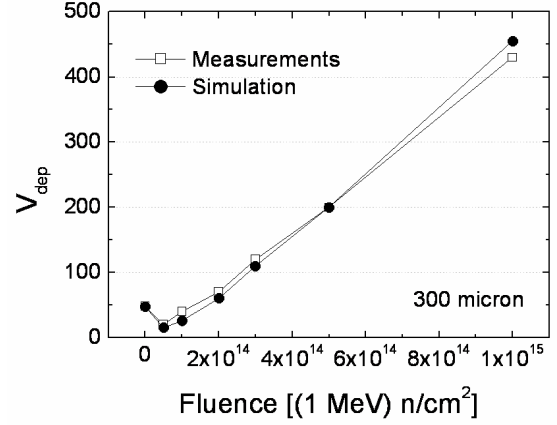


Fig. 3. Comparison between simulation and experimental data of the full depletion voltage as a function of the fluence for n-type detectors.

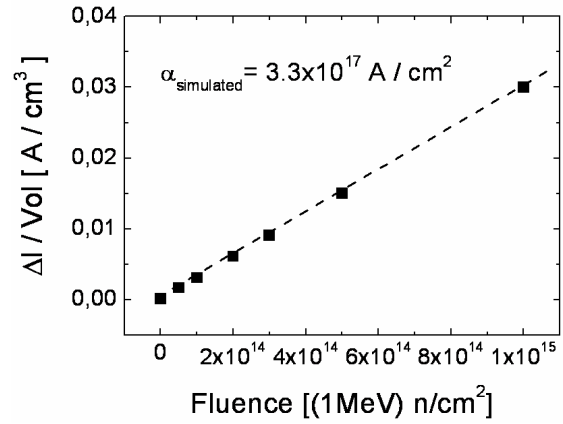


Fig. 5. Simulation of the leakage current density as a function of the fluence for n-type detectors.

In this case the radiation damage constant  $\alpha_{\text{simulated}}=3.3 \cdot 10^{-17} \text{ A/cm}^2$  is in the range of  $2 \div 10 \cdot 10^{-17} \text{ A/cm}^2$ , 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.

#### 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  $\text{Ev}+0.36\text{eV}$  was introduced.

This defect, generally assigned to a  $\text{C}_i\text{O}_i$  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  $5 \cdot 10^{15} \text{ n/cm}^2$ .

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%.

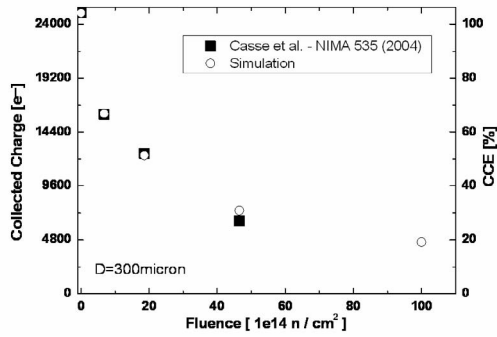


Fig. 6. Comparison between the CCE of the measured [14] and simulated data for p-type substrates.

### 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  $1 \cdot 10^{15} \text{ n/cm}^2$  and simulated data is described: each simulated point is in a fairly good agreement with experimental data (average deviation less than 7.5%).

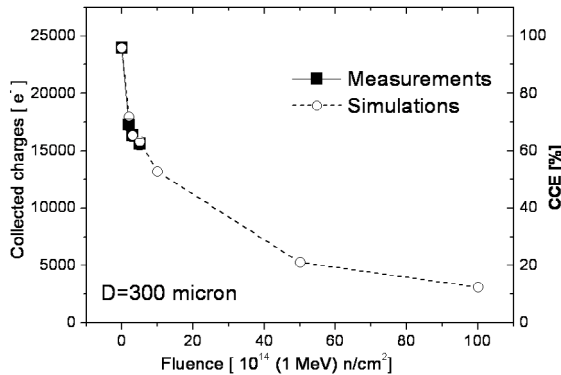


Fig. 7. Comparison between the CCE of the measured [16] and simulated data for n-type substrates.

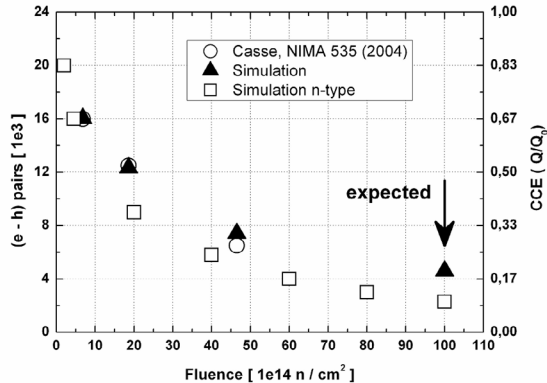


Fig. 8. Comparison between the simulations of n-type and p-type charge collection efficiency as a function of the fluence.

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  $1 \cdot 10^{16} \text{ n/cm}^2$  (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  $E_v + 0.36 \text{ eV}$ ) 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  $10^{16} \text{ n/cm}^2$  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  $10^{16} \text{ n/cm}^2$ . A further analysis of trapping in n-type and p-type material is foreseen.

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