A Comparative study by TCAD Simulation for two different planar n-on-p silicon particle detectors with different guard ring implant type

S Oussalah, M Mekheldi, W Filali, and E Garoudja
Centre de Développement des Technologies Avancées, 20 août 1956, Baba Hassen, 16081 Algiers, Algeria

E-mail: soussalah@cdta.dz

Abstract. In this paper, we compare two multi-guard ring geometries for n-on-p silicon particle detectors for high luminosity applications. One structure has p-type guard rings while the other has n-type guard rings with p-stop isolation between n+ implants. The pre-irradiation performance of the guard ring structures are studied as a function of oxide charge. It is found that for both structures, there is a value of oxide charge for which the breakdown voltage is maximum. The post-irradiation performance of the structures are evaluated with simulations up to a radiation fluence of $1 \times 10^{16}$ neq/cm$^2$ using an existing three-level trap model for p-type FZ silicon. TCAD simulation has been used to simulate I-V characteristics, charge carrier concentration, electric field, and potential distribution.

1. Introduction
Pixelated silicon particle detectors are widely used in high energy physics (HEP) experiments as those at the Large Hadron Collider (LHC) and its proposed upgrade to the HL-LHC [1-2]. The application of this type of silicon detectors in the ATLAS (A Toroidal LHC ApparatuS) experiment at CERN (European Organization for Nuclear Research) in Geneva requires a reliable performance in adverse radiation conditions, which is the main test for these detectors [3-4]. The level of radiation damage expected during the detector lifetime implies very high bias voltages for the detector operation to maximize the signal and reduce the charge collection time [5-6]. In almost all experiments at LHC, multi-guard ring structures are used for silicon strips and pixel detectors. Planar pixel structures use guard rings to redistribute the electric field over a larger distance along the detector edge, thus preventing breakdown along the detector edge at high bias voltages [7-12]. The detector is thus operated at much larger biases than the initial full depletion voltage.

N-on-n technology is already the preferred choice for the highly irradiated inner regions of ATLAS. Planar pixel sensor based on n-type substrate technology, the junction moves to the front-side after space charge sign inversion (SCSI) caused by radiation-induced negative space charges and, therefore, the high electric field is on the side of the readout electrodes. An inconvenient of this technology is that sensors must be produced with a double sided technology. Silicon detectors with p-type substrate are considered as a strong candidate among the scientific community and is expected to be more radiation hard than detectors with n-type substrate technology [10]. The main advantage of the p-type devices is that they are easy to produce and handle due to the single sided processing. Nevertheless these devices are more complex as they need a good isolation between n-type implants. This is
because the positive charge present in SiO$_2$ [13] induces a thin electron accumulation layer at the Si/SiO$_2$ interface that would short out n$^+$ implants if no isolation mechanism were introduced. This insulation is achieved by two kinds of blank surface implant, named p-spray or p-stop [14-15]. P-spray is a lightly doped layer over the wafer surface and p-stop is a heavily doped p$^+$ implants between the n-type implants. Until now, no standard guard ring design for the n-on-p technology has been established yet. Koybasi et al. [11] have proposed an interesting new guard ring geometry for p-substrate silicon particle detectors for high luminosity applications.

In this work, we present a comparative study for two different n-on-p silicon particle detectors in the purpose of evaluating the electric behavior for high luminosity applications. The two structures based on the n-on-p technology [11] with and without p-stop isolation between guard rings have been simulated on high resistivity silicon wafers with and without radiation damage using Silvaco™ Technology Computer Assisted Design (TCAD) simulation software. The bulk radiation damage model used in this analysis is based on the so called Perugia three level traps model [16], where irradiation generates two acceptor levels, positioned slightly above the mid band gap, and one donor level, located below the mid band gap.

2. Simulation conditions

2.1. Multi-guard rings structures

Detector structures are based on p-type silicon substrate with a uniform doping concentration of 5x10$^{11}$ cm$^{-3}$ and thickness of 300 µm. As shown in figure 1, the last pixel is surround by eight guard rings with different width and spacing between them as detailed in reference [11]. The pixel is n$^+$ - implanted area with a peak concentration of 1x10$^{18}$ cm$^{-3}$ and a junction depth equal to 1.5 µm. The oxide thickness is fixed to 1 µm and the oxide charge density varies from 5x10$^{10}$ cm$^{-2}$ to 1x10$^{12}$ cm$^{-3}$.

Figure 1 shows the structure proposed in reference [11] that has p-type guard rings while the figure 2 shows a structure with n-type guard rings that contains p-type implants commonly called p-stop between the guard rings [17]. The n-type implants (GRs) in the last structure must be electrically isolated from each other to prevent their being shorted by the accumulation layer present at the Si-SiO$_2$ interface. In this study, the first structure is called p-GRs while the second one is called n-GRs, referring to the type doping of the guard rings.

![Figure 1. A cross-sectional schematic of p-type substrate silicon detector structure simulated in this work with p-type guard rings [11].](image)
2.2. TCAD simulation

2.2.1. Physical models. Numerical simulation is a powerful tool to understand the physics of electronic devices and materials. It is also a cheap and effective tool to optimize the semiconductor device conception and operating mode. Simulation results presented in this paper are carried out using Atlas from Silvaco’s TCAD software [18]. Atlas is a 2D and 3D finite element device simulator that performs DC, AC, and transient analysis for silicon and other semiconductor material-based devices. Atlas enables the characterization and optimization of semiconductor devices under electrical, optical, and thermal constraints for a wide range of technologies. Thus device takes a grid mesh made of discrete elements as an input structure and solves the Poisson’s equation (equation (1)) along with carrier continuity and drift-diffusion equations for electrons (equation (2)) and holes (equation (3)) at every grid point of the mesh to calculate electrical properties such as current and capacitance and physical quantities such as electric field distribution and carrier mobility inside the device. For the transient mode, the displacement current is calculated (equation (4)). The set of equations which are solved inside the simulator are given by [19]:

\[-\nabla^2 V = \nabla \cdot \vec{E} = \frac{\rho - Q_T}{\varepsilon}\]  

\[\frac{dn}{dt} = \nabla \cdot D_e \nabla n - \nabla \cdot (n\mu_e \vec{E}) + G_e - R_e\]  

\[\frac{dp}{dt} = \nabla \cdot D_h \nabla p + \nabla \cdot (p\mu_h \vec{E}) + G_h - R_h\]  

\[\vec{J}_{disp} = \varepsilon \frac{d\vec{E}}{dt}\]  

Figure 2. A cross-sectional schematic of p-type substrate silicon detector structure simulated in this work with n-type guard rings and p-stop isolation between n+ implants.
where \( n \) and \( p \) are electron and hole concentrations respectively in (cm\(^{-3}\)), \( D \) and \( \mu \), their respective diffusion coefficient in (cm\(^2\)s\(^{-1}\)) and mobility in (cm\(^2\)V\(^{-1}\)s\(^{-1}\)). \( G \) and \( R \) are the generation rate and recombination rate in (cm\(^{-3}\)s\(^{-1}\)), respectively. The \( e \) and \( h \) subscript respectively refer to electrons and holes. \( \rho \) is the net charge density in (C/cm\(^3\)) and \( Q_T \) is the charge due to traps and defects in (C/cm\(^2\)) present in the bulk of the semiconductor device, where \( C \) is Coulomb. \( J_{\text{disp}} \) is the displacement current density in (Acm\(^{-2}\)) and \( \varepsilon \) is the material dielectric constant. \( \rho \) is expressed by the equation (5).

\[
\rho = n - p + N_{D^+} - N_{A^-}
\]

(5)

\( N_{D^+} \) and \( N_{A^-} \) are the ionized donor and acceptor impurity concentrations in (cm\(^{-3}\)), respectively.

The physical models used in the simulation are included in the default bipolar model that contains different physical models such as Schokley-Read-Hall recombination, Auger recombination accounting for high-level injection effects, concentration dependent mobility, field dependent mobility, and band gap narrowing. Impact ionization is an important phenomena to be taken into account when semiconductor device works at high electric field. In Atlas, the Selberherr’s model [20] is used among other models to predict the impact ionization effect in semiconductor devices, which is the generation of free carriers (electrons, holes) mechanism resulting the avalanche breakdown. The avalanche breakdown is analysed by determining where and at what bias voltage the ionization integral exceeds unity that corresponds to infinite carrier multiplication. The junction breakdown voltage is accurately predicted and the junction curvature effects causing higher electric fields at the device corners are included in the program. The electric field lines, potential contours, current flow lines, and impact ionization generation rates can be plotted by Tonyplot. Thus, the location where the breakdown occurs can be precisely identified. In our simulation, the refined mesh was located at the pn junction and the silicon/SiO\(_2\) interface and p-n junctions with a maximum height of 0.2 and width of 0.5 µm to ameliorate the accuracy of the results. Moreover, the number of grid points was chosen as a compromise between computing time and precision. Figure 3 illustrates the mesh structure for n-type GRs.

![Figure 3. Illustration of the mesh structure of silicon detector with n-type GRs.](image-url)
2.2.2. Radiation physical model. The principle source of radiation damage in silicon detectors is from the non-ionizing-energy-loss (NIEL). It’s expressed in terms of 1 MeV neutron equivalent for silicon (1 MeV neq/cm²). Radiation damage introduce defects in the bulk of the silicon that modify its behaviour. The primary effects of the radiation bulk damage are the conversion of the substrate material from n- to p-type, an increase in leakage current, and a reduction of the charge collection efficiency due to increasing number of traps. Defect energy state distribution model exists to try to reproduce the behaviour of irradiated detector. Developing a TCAD radiation damage model consists in defining a set of defect states, characterized by their concentration and type (i.e. whether they are a donor or an acceptor), location (energy level) in the band gap, electron and hole capture cross-sections (σ_n, σ_p). A trap model has been proposed by the Petasecca et al. from the University of Perugia [16] to describe radiation damage caused by proton irradiation in p-type silicon substrate grown by the floating zone (FZ) technique. According to the model, the radiation generates two acceptor levels positioned slightly above the mid band gap and one donor level located far below the mid band gap. In the Perugia model, the density of traps is predicted to increase linearly with radiation fluence Φ, so for each trap an introduction rate (η) is defined as $\eta = N\Phi^{-1}$, where N is the trap concentration. The details of the trap model are presented in table 1.

### Table 1. Parameters of the three trap bulk radiation damage model proposed by University of Perugia used in our simulations. The energy levels are given with respect to the conduction band (E_c) or the conduction band (E_v).

| Defect type | Energy level (eV) | $\sigma_n$ (cm$^{-2}$) | $\sigma_p$ (cm$^{-2}$) | $\eta$ (cm$^{-1}$) |
|-------------|------------------|-----------------------|-----------------------|-------------------|
| Acceptor    | Ec-0.42          | 2x10$^{-15}$          | 2x10$^{-14}$          | 1.613             |
| Acceptor    | Ec-0.46          | 5x10$^{-15}$          | 5x10$^{-14}$          | 0.9               |
| Donor       | Ec+0.36          | 2.5x10$^{-14}$        | 2.5x10$^{-15}$        | 0.9               |

3. Results and discussion

3.1. Unirradiated sensors

A protective coating useful as a passivation layer for semiconductor devices incorporates a layer of several 100 nm of SiO$_2$ grown onto the silicon wafers in a high temperature oxygen atmosphere. However SiO$_2$ is positively charged due to technological processes (defects within the volume of the SiO$_2$ layer and defects at the interface between the silicon and the SiO$_2$). For a non-irradiated detectors the charge density is estimated about 5x10$^{-10}$ cm$^{-2}$ for a good quality of SiO$_2$ layer [13]. The charge density increases with the radiation dose, up to a level known as the “oxide saturation charge” about 10$^{12}$ cm$^{-2}$ depending on the oxide thickness and crystal orientation [21]. Values reported in literature are not very uniform due to strong process dependence. As a consequence, electrons are accumulated at the Si/SiO$_2$ interface of the silicon detectors due to this positive charge. Accordingly the n$^+$ implants can be shorted and the generated signal would spread over several pixels.

In our recent work [17], we compared the two structures for some geometrical parameters before irradiation. As one would expect, the substrate with the highest resistivity yields the highest breakdown voltage. When guard ring depth increases, breakdown voltage increases for p-GRs structure while it decreases for n-GRs structure. Oxide thickness has no influence on the breakdown voltage. For both structures we observed that breakdown voltage decreases as the deviation of oxide charge from a specific value increases. Leakage current versus reverse bias voltage characteristics of the multi-guard structures with different oxide charge density are shown in figures 4 and 5 for p-GRs and n-GRs structures, respectively.
Figure 4. Leakage current versus reverse bias voltage for different values of oxide charge for p-GRs structure. The breakdown voltage decreases as the deviation of oxide charge from $6 \times 10^{11}$ cm$^{-2}$ increases.

Figure 5. Leakage current versus reverse bias voltage for different values of oxide charge for n-GRs structure. The breakdown voltage decreases as the deviation of oxide charge from $4 \times 10^{11}$ cm$^{-2}$ increases.
We remark that p-GRs structure has better performance than n-GRs structure in term of breakdown voltage. For both structures breakdown voltage increases with oxide charge until a maximum value and then decreases. The maximum values of breakdown voltage are about 1200 V for p+GRs structure and 400 V for n-GRs structure attributed to the oxide charge density of $4 \times 10^{11}$ cm$^{-2}$ and $6 \times 10^{11}$ cm$^{-2}$, respectively. We note that simulation is performed with Synopsys TCAD in [11] for the p-type GRs structure that can explain the difference for the optimum value of oxide charge [22].

Figure 6 and figure 7 show the simulation results for the potential drop and the electric field distribution along the device surface at a depth of 0.1 µm from the Si/SiO$_2$ interface for p-GRs and n-GRs, respectively. At each figure two values of oxide charge density are presented $5 \times 10^{10}$ (left) and $1 \times 10^{12}$ (right) and the structures are reverse biased at 400 V and 250 V for p-GRs and n-GRs, respectively. With this potential distribution, p-GRs structure is able to sustain reverse biases exceeding 1100 V while n-GRs structure has a maximum breakdown voltage of 400 V as shown in figure 4 and figure 5, respectively. For lower or higher oxide charge density, the device structure performance are degraded.

At low oxide charges silicon surface conductivity is low and therefore the majority of the potential drops at the pixel and innermost guard rings. Figure 6(a) and figure 7(b) show that the maximum electric field is localized at the junction of the diode for both structures. As the surface conductivity increases the potential drop is distributed uniformly over the guard rings, which results in an increase in the slope of potential drop at each guard ring. When the optimum oxide charge value is reached corresponding to the maximum breakdown voltage the field distribution is uniform. A further increase in oxide charges makes the potential drop at each lateral p-/p+ boundaries steeper due to the interruption of the electron channel resulting in higher electric field peaks and therefore a lower breakdown voltage as shown in figures 8 and 9 for p-GRs and n-GRs structure, respectively. Higher values of breakdown voltage of p-GRs compared to n-GRs are due to the field distribution uniformity even at oxide charge saturation as shown in figure 6(b).

![Figure 6](image_url)

**Figure 6.** Simulated potential drop (black, left axis) and electric field (red, right axis) along a cut line parallel to the surface of p-GRs device at a depth of 0.1 µm from Si/SiO$_2$ interface for oxide charge density of (a) $5 \times 10^{10}$ cm$^{-2}$ and (b) $1 \times 10^{12}$ cm$^{-2}$. The detector is reverse biased at 400 V which is just below the breakdown voltage.
Figure 7. Simulated potential drop (black, left axis) and electric field (red, right axis) along a cut line parallel to the surface of n-GRs device at a depth of 0.1 µm from Si/SiO₂ interface for oxide charge density of (a) 5x10¹⁰ cm⁻² and (b) 1x10¹² cm⁻². The detector is reverse biased at 250 V which is just below the breakdown voltage.
Figure 8. Electron concentration (top) and electric field (bottom) distributions along to the surface of p-GRs structure for oxide charge density of $1 \times 10^{-12}$ cm$^{-2}$. The detector is reverse biased at 400 V which is just below the breakdown voltage.
Figure 9. Electron concentration (top) and electric field (bottom) distributions along to the surface of n-GRs structure for oxide charge density of $1 \times 10^{12}$ cm$^{-2}$. The detector is reverse biased at 400 V which is just below the breakdown voltage.

3.2. Irradiated sensors

The post irradiation performance of the multi-guard structures has been evaluated with simulations using the trap model presented in table 1. The simulation has been performed for fluences from $2 \times 10^{14}$ n$_{eq}$/cm$^2$ to $1 \times 10^{16}$ n$_{eq}$/cm$^2$ and for charge oxide density varying from $5 \times 10^{10}$ cm$^{-2}$ to $1 \times 10^{12}$ cm$^{-2}$.

Figure 10 shows the evolution of the breakdown voltage versus the oxide charge density as a function of fluence density. As one can see, the breakdown behavior degrades significantly with radiation. At a fluence of $1 \times 10^{16}$ n$_{eq}$/cm$^2$ and for an oxide charge of $1 \times 10^{12}$ cm$^{-2}$, the p-GRs structure is able to survive only up to bias voltage of 300 V while the n-GRs structure is able to sustain a reverse bias of 100 V. The breakdown voltages for both structures is not high enough for very high luminosity applications, so further improvements are needed.

Figure 11 shows for both structures the electron concentration distribution along to the surface at a depth of 0.1 µm from Si/SiO$_2$ interface at a fluence of $1 \times 10^{16}$ n$_{eq}$/cm$^2$ and for oxide charge density of $1 \times 10^{12}$ cm$^{-2}$. This can give us information on the isolation capacity between the pixel and the guard rings, for each structure. As we can see n-GRs structure presents lower concentration compared to p+GRs, about $10^5$ cm$^{-3}$ and $10^9$ cm$^{-3}$ for n-GRs and p-GRs structure, respectively. As shown in figure 12 n-GRs structure shows better behavior in term of leakage current than p-GRs structure when oxide charge saturation takes place.
Figure 10. Breakdown voltage versus oxide charge density as a function of fluence density for (a) p-GRs and (b) n-GRs structures, respectively.

Figure 11. Electron concentration distribution (cm$^{-3}$) along to the surface at a depth of 100 nm from Si/SiO$_2$ interface at a fluence of 1x10$^{-16}$ neq/cm$^2$ and for oxide charge density of 1x10$^{-12}$ cm$^{-2}$ for p-GRs structure (black line) and n-GRs structure (red line). The structures are reverse biased at 100 V.
4. Conclusion

In this work TCAD simulation was used to evaluate the electrical performances of two different high-voltage silicon detectors based on n-on-p technology dedicated to high-energy physics experiments. One structure has p-type guard rings while the other has n-type guard rings with p-stop isolation between n+ implants. For both structures, breakdown voltage increases with oxide charge until a maximum value and then decreases. Without radiation, at the optimum oxide charge density the structure featuring p-type guard rings can withstand reverse bias voltages above 1200 V while the structure featuring n-type guard rings can withstand only 400 V. It was found that with increasing radiation fluence density from $2 \times 10^{14}$ n$_{eq}$/cm$^2$ to $1 \times 10^{16}$ n$_{eq}$/cm$^2$ breakdown voltage decreases significantly for both structures. The structure with n-type guard rings shows better behavior in term of leakage current when oxide charge saturation takes place. Moreover, isolation between implants is more assured by n-type guard rings structure. Despite these results, future work is needed to improve electrical performances of the structures for very high luminosity applications. Further studies will explore the possibility of optimizing the structure design for high-voltage operation that features different doping profiles, guard ring dimensions and spacing, oxide thicknesses, and adding field plate lengths.

Acknowledgments

The authors gratefully acknowledge David Green from Silvaco, Inc. for his support on TCAD simulation.

References

[1] Jezequel S 2013 Prospects for the high-luminosity LHC Nuclear Physics B Proceedings Supplements 245 145
[2] Affolder A et al 2011 Silicon detectors for the sLHC Nuclear Instruments and Methods in Physics Research Section A 658 11
[3] Aad G et al. 2008 The ATLAS Collaboration Journal of Instrumentation 03 SO8003
[4] Evans L and Bryant P 2008 LHC Machine *Journal of Instrumentation* **03** 1

[5] Lindstrom G, Moll M and Fretwurst E 1999 Radiation hardness of silicon detectors - a challenge from high-energy physics *Nuclear Instruments and Methods in Physics Research Section A* **426** 1

[6] Affolder A, Allport P and Casse G 2009 Studies of charge collection efficiencies of planar silicon detectors after doses up to 10^{+15}\text{n}_{eq}\text{cm}^{-2} and the effect of varying diode configurations and substrate types *Nuclear Instruments and Methods in Physics Research Section A* **604** 250

[7] Beck G A, Carter A A, Carter J R, Greenwood N M, Lucas A D, Munday D J, Pritchard P W, Robinson D, Wilburn C D and Wyllie K H 1997 Radiation-tolerant breakdown protection of silicon detectors using multiple floating guard rings *Nuclear Instruments and Methods in Physics Research Section A* **396** 214

[8] Mishra V, Chandratre V B, Dixit M Y, Shrivastava V D, Topkara A, Kataria S K, Prabhakar Rao Y P and Shankarnarayan N P 2004 Studies on reducing leakage current and improving breakdown voltage of large-area silicon detectors: technology and results *Nuclear Instruments and Methods in Physics Research Section A* **527** 308

[9] Hadj Larbi F, Oussalah S, Belkhelfa N and Lounis A 2014 26th *Proc. Int. Conf. on Microelectronics* (Doha) (IEEE) p 29

[10] Benoit M, Lounis A and Dinu N 2009 Simulation of radiation damage effects on planar pixel guard ring structure for ATLAS inner detector upgrade *IEEE Transactions on Nuclear Science* **56** 3236

[11] Koybasi O, Bolla G and Bortoletto D 2010 Guard Ring Simulations for non-p Silicon Particle Detectors *IEEE Transactions on Electron Devices* **57** 2978

[12] Chmill V, Affolder A, Allport P P, Casse G, Huse T, Kendrick G and Tsurin I 2011 Study of various high voltage protection structures for reduction of the insensitive region of silicon sensors designed for extreme radiation tolerance *Journal of Instrumentation* **6** C01062

[13] Ma T P and Dressendorfer P V 1989 *Ionizing Radiation Effects in MOS Devices and Circuits* (New Jersey: Wiley-Interscience)

[14] Chatterji S, Singla M, Müller W F J and Heuser J M 2013 Exploring Various Isolation Techniques to Develop Low Noise, Radiation Hard Double-Sided Silicon Strip Detectors for the CBM Silicon Tracking System *IEEE Transactions on Nuclear Science* **60** 2254

[15] Mekheldi M, Oussalah S, Lounis A and Brihi N 2016 Comparison of electrical performances of two n-in-p detectors with different implant type of guard ring by TCAD simulation *Results in Physics* **6** 80

[16] Petasecca M, Moscatelli F, Passeri D and Pignatel G U 2006 Numerical simulation of radiation damage effects in p-type and n-type FZ silicon detectors *IEEE Transactions on Nuclear Science* **53** 2971

[17] Mekheldi M, Oussalah S, Lounis A and Brihi N 2019 Simulation of guard ring type effects on the electrical characteristics of n-on-p planar silicon detectors *Journal of Nano- and Electronic Physics* **11** 04008

[18] Silvaco Inc., ATLAS User's Manual Device Simulation Software (Santa Clara, CA: 2010)

[19] Sze S M and Lee M K 2012 *Semiconductor Devices Physics and Technology* (New York: Wiley-Interscience)

[20] Selberherr S 1984 *Analysis and Simulation of Semiconductor Devices* (New York: Springer)

[21] Rossi L, Fisher P, Rohe T and Wermes N 2006 *Pixel detectors: From Fundamentals to applications* (Berlin Heidelberg: Springer)

[22] Bomben M 2018 *Silicon trackers for high luminosity colliders* PhD Thesis Université Paris Diderot Paris 7 Sorbonne Paris