Combined effect of bulk and surface damage on strip insulation properties of proton irradiated n⁺-p silicon strip sensors

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ABSTRACT: Silicon sensors in next generation hadron colliders will face a tremendously harsh radiation environment. Requirement to study rarest reaction channels with statistical constraints has resulted in a huge increment in radiation flux, resulting in both surface damage and bulk damage. For sensors which are used in a charged hadron environment, both of these degrading processes take place simultaneously. Recently it has been observed in proton irradiated n⁺-p Si strip sensors that n⁺ strips had a good inter-strip insulation with low values of p-spray and p-stop doping densities which is contrary to the expected behaviour from the current understanding of radiation damage. In this work a simulation model has been devised incorporating radiation damage to understand and provide a possible explanation to the observed behaviour of irradiated sensors.

KEYWORDS: Si microstrip and pad detectors; Radiation-hard detectors; Detector modelling and simulations II (electric fields, charge transport, multiplication and induction, pulse formation, electron emission, etc)

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1 Introduction

In the last few decades, extensive experimental and simulation studies have been carried out to understand the mechanisms of radiation damage in Si sensors [1–18]. The detailed insight obtained from these studies has been helpful to establish Si sensors as one of the most important ingredients of present generation of high energy physics experiments and they are expected to prevail their dominance in future also [19]. During the sensor operation, the high fluence of radiation introduces defects, both in Si substrate causing bulk damage and at Si-SiO$_2$ interface causing surface damage. Bulk damage [1–4] impacts on the detector operation by introducing acceptor and donor type trap levels. This leads to higher leakage current, change in effective space charge concentration of the substrate and lowering of charge collection efficiency.

On the other hand, surface damage can create positive surface oxide charge density ($Q_F$) and interface traps around the Si-SiO$_2$ interface. The value of $Q_F$ increases with increase in surface damage and saturates around 2–3 $\times$ 10$^{12}$ cm$^{-2}$ [20, 21]. The high value of $Q_F$ creates a sustainable electron accumulation layer under the Si-SiO$_2$ interface, shorting the n$^+$-strips in n$^+$-p type Si strip sensors. The accumulation layer provides a conduction channel which causes the charge produced by the ionizing particle to spread over many strips degrading the position resolution. Modern strip sensors have integrated coupling capacitors and polysilicon biasing resistors with a typical value of $\sim$1–2 MΩ. The interstrip resistance ($R_{int}$) is one of the parameter to ascertain strip insulation. A strip insulation is considered good if the value of the $R_{int}$ is in the range of $\sim$100 MΩ.

The usual method to maintain the strip insulation in n$^+$-p strip sensors is to introduce p-type layers of various geometries and doping concentrations between the strips. The promising ones are p-stop [22–30] which consists of high dose p-type implant between readout strips and p-spray [29–34] which consists of a uniform low concentration p-type implant, and their combination. It has been established in various experimental and simulation studies [29, 30, 35] that the required peak doping density of p-stop/p-spray which can ensure strip insulation should be, at least, of the order of 1 $\times$ 10$^{17}$ cm$^{-3}$ (equivalent to implanted boron dose of about 4.1 $\times$ 10$^{12}$ cm$^{-2}$ assuming 1.5 µm deep Gaussian profile), the exact value being dependent on the details of the doping profile of the insulation structure.
In case of proton irradiated sensors, both surface and bulk radiation damage are expected to take place together. Hence, for $n^+\cdot p$ sensors without any p-stop/p-spray or with p-stop/p-spray having insufficient doping density, strip insulation between $n^+$ strips is expected to be lost. However, contrary to this expectation, in recent measurements on $n^+\cdot p$ sensors, it was observed that a good strip insulation exists with very low p-stop/p-spray doping densities even after irradiation with proton fluence of more than $1 \times 10^{15}$ cm$^{-2}$ [36]. Particularly, a p-spray peak doping density of $\sim 1 \times 10^{15}$ cm$^{-3}$ (corresponding to implanted boron dose of about $5.4 \times 10^{10}$ cm$^{-2}$) and a p-stop doping density of $\sim 4 \times 10^{15}$ cm$^{-3}$ (corresponding to implanted boron dose of about $2.0 \times 10^{11}$ cm$^{-2}$), which are almost 50 times lower than values commonly used [28], seem to provide strip insulation in proton irradiated sensors after high fluence. Even more striking was the observation of good strip insulation, after irradiation with a proton fluence of $7 \times 10^{14}$ cm$^{-2}$, in $n^+\cdot p$ sensors having no insulation structure at all [9]. It was shown that, before irradiation, the strip insulation for Si sensors without any insulating structure was very poor up to a reverse bias of 1000 V which got improved after irradiation and a very good strip insulation was achieved for reverse bias of $\sim 500$ V [9].

In device simulations, bulk damage is incorporated by introducing various trap levels within the band gap. A trap level is characterized by various parameters like energy, introduction rate ($g_{int}$) and capture cross-sections for electrons ($\sigma_e$) and holes ($\sigma_h$). By varying the number of trap levels and their parameters, simulations have been able to explain some of the experimental results [10–17]. It is to be noted that the success of these models is governed by their ability to explain experimental results for which the models are proposed. Hence several sets of such trap levels are incorporated in the literature to explain the measurements, like leakage current, full depletion voltage ($V_{FD}$), charge collection efficiency etc [10–17]. In this work a five level trap model is used which, while explaining the measurements like leakage current, effective doping concentration, interstrip capacitance ($C_{int}$) and $R_{int}$, also provides an insight for the possible mechanism to explain the above described puzzling $R_{int}$ measurements. It is expected that properties like $C_{int}$ and $R_{int}$ are mainly governed by the surface effects (near the interstrip region), and hence a complete radiation damage model should be able to incorporate both bulk and surface damage simultaneously. In order to develop a reliable model, we started working with the EVL model [10] which basically is a three trap model with one deep acceptor level, one donor level and one trap to produce the right amount of leakage current. To avoid using a trap level which generates only current, we modified the original EVL model in which the third trap producing leakage current is removed. In the modified EVL model with two trap levels, the parameters like electron and hole capture cross-sections and introduction rates were tuned to reproduce the leakage current as well as the double peak electric field profile at high fluences [37]. However, using this modified EVL two trap model (referred to as EVL4 in ref. [17] and [37]) for irradiated sensors, the interstrip capacitance results are found to match with measurements only for extremely small values of oxide charge density [17], which is unrealistic from the physics point of view. When we incorporated higher values of oxide charge density as expected in irradiated sensors, the modified EVL two trap model was not able to reproduce the measured values of $C_{int}$. Furthermore, the developed model could not explain the observed interstrip insulation behaviour. Therefore, we extended the damage model by adding three more defect levels to the modified EVL model. This model is implemented using device simulation program, 2-D Atlas (Silvaco) TCAD tool [38]. The simulation results show that
the accumulation layer, which is expected to be formed due to ionizing radiation, is suppressed in proton irradiated sensors thus giving an explanation for the above mentioned puzzling measurement results on irradiated strip sensors.

2 Combined bulk and surface damage model and TCAD simulations

Proton irradiation results in bulk damage, creating deep acceptor and donor like traps, leading to significant leakage current [39]. In a reverse biased n$^+$-p strip sensor, electrons drift toward n$^+$ strips while holes move toward p$^+$ backside. During operation of a sensor, the electron density near the n$^+$ strip side and the hole density near the p$^+$ side are therefore higher in comparison to the center of the device. After irradiation, the acceptor states trap electrons near the n$^+$ strips, thus, creating negative space charge. The formation of a very dense negative space charge near n$^+$ strips has been directly established by Edge-TCT measurements of irradiated sensors [40]. The build-up of a very high electric field near n$^+$ strips with irradiation is a clear signature of a dense negative space charge. Similarly, holes are trapped in donor states near the p$^+$ contact leading to the formation of positive space charge. The complete mechanism is well explained by double junction models [10–12].

In this work, we treat only proton damaged devices. Proton irradiation does not only create bulk damage in Si but can also create electron-hole pairs in the SiO$_2$. Depending on the ionization density and the electric field, a fraction of electron-holes recombine, but the remaining electrons and holes can move in SiO$_2$, by drift and diffusion mechanisms, escaping the initial recombination [21]. Due to very different mobility of electrons ($\sim 20$ cm$^2$/V·s) and holes ($< 10^{-5}$ cm$^2$/V·s) most of the free electrons leave the SiO$_2$, whereas holes get trapped in the SiO$_2$, mainly in a layer of a few nano-meter depth close to the Si-SiO$_2$ interface, leading to the formation of a layer of positive oxide charge density. Another important surface effect of irradiation, though not considered in present simulations, is generation of interface traps with energy levels distributed in the Si band gap [21].

Irradiation with X-rays increases the positive oxide charge density near Si-SiO$_2$ interface. The amount of bulk damage is negligible which is reflected by insignificant increase in the leakage current of the sensor [39].

On the other hand, in proton irradiation case, both bulk and surface damage take place simultaneously. During the operation of a sensor, the build-up of a dense negative space charge near n$^+$ strips due to bulk damage and a positive charge layer in SiO$_2$, near Si-SiO$_2$ interface, due to surface damage take place together. In this work, it is proposed that because of the presence of this negative space charge, the formation of a dense mobile electron accumulation layer under Si-SiO$_2$ interface is suppressed and hence the strip insulation is preserved in sensors with very low p-stop/p-spray doping densities and even without any insulation structure as observed in the recent measurements on n$^+$-p sensors [9, 36]. Device simulations are performed to understand this mechanism further. At first, the effect of surface damage on the $R_{int}$ is studied, which corresponds to the case of X-ray irradiation. Further, the effect of bulk damage is incorporated additionally to study the effect of proton irradiation.

The simulations are carried out using 2-D Atlas (Silvaco) TCAD tool [38]. Atlas solves Poisson’s equation and continuity equation for holes and electrons. The default parameters were
used for the concentration dependent lifetime, Shockley-Read-Hall (SRH) recombination and for concentration and field dependent mobility models. The Selberherr impact ionization model is included in the simulation. The trap assisted tunnelling is also switched on in the simulations in order to include the change in effective lifetime of trapped carriers at high values of electric field within the detector. Calculations are performed using a triangular grid generated by the program. Surface damage is characterized as a positive charge-sheet located at the Si-SiO$_2$ interface with a uniform distribution along the interface. Reflecting Neumann conditions are imposed at the outer edges of the structure and also on the top of SiO$_2$.

### 2.1 Simulation structure

Simulations are performed on p-type $<100>$ oriented Si substrate with a uniform doping concentration of $3 \times 10^{12}$ cm$^{-3}$ and a thickness of 320 $\mu$m with $n^+$ strips 18 $\mu$m wide and with pitch equal to 80 $\mu$m. The $n^+$ implants have a Gaussian profile with a peak concentration of $5 \times 10^{18}$ cm$^{-3}$ and a junction depth equal to 2 $\mu$m. It is assumed that the lateral junction width at the curvature of the implanted $n^+$ regions is equal to 0.7 times the vertical depth. The SiO$_2$ thickness below the metal overhang and between the electrodes is 700 nm, and 1 $\mu$m respectively. A double p-stop structure is introduced between the $n^+$ implants. The width of each p-stop is 4 $\mu$m with a depth of 1.5 $\mu$m and they are separated by 6 $\mu$m. The backside $p^+$ contact is implemented by using a depth (where concentration is equal to bulk $p^-$) of 30 $\mu$m and a doping concentration as that of $n^+$. A schematic of the structure used in this work is shown in figure 1. It shows one central strip, named anode2, and two neighboring half strips, which are shorted together, named anode1. For the $R_{\text{int}}$ simulations, a small 0.2 V bias is given to anode2 electrode while reverse bias is provided from backside electrode. $R_{\text{int}}$ is calculated from the difference in anode1 and anode2 currents. This approach for $R_{\text{int}}$ simulation is similar to $R_{\text{int}}$ measurements technique used in [41, 42]. Further, $R_{\text{int}}$ values are normalized for strip length equal to 1 cm.
Table 1. Two trap level model parameters [17, 37].

| No. | Trap   | Energy Level | $g_{int}$ (cm$^{-1}$) | $\sigma_e$ (cm$^{-2}$) | $\sigma_h$ (cm$^{-2}$) |
|-----|--------|--------------|-----------------------|------------------------|------------------------|
| 1.  | Accepter | $E_c - 0.525$ eV | 0.8                   | $4 \times 10^{-14}$    | $4 \times 10^{-14}$    |
| 2.  | Donor   | $E_v + 0.48$ eV   | 0.8                   | $4 \times 10^{-14}$    | $4 \times 10^{-14}$    |

### 2.2 Simulation model for bulk damage

There is an uncertainty in the introduction rates for various trap levels along with correct electron/hole capture cross sections due to irradiation. Moreover, it is very difficult to accommodate cluster defects properly and for several point defects the introduction rates depend on impurity content such as Oxygen or Carbon. Finally, the ratio between point and cluster defects depends on the particle type and energy used for the irradiation experiment. Keeping the above facts into consideration, we have devised an ad-hoc simulation model incorporating a set of trap levels which can account correctly for some measurements but are not based on data originating from experimental defect characterization studies. The simulations in this work are compared to experimental data obtained after proton irradiation. All fluences and introduction rates are normalized to the 1 MeV neutron equivalent fluence following the NIEL (Non Ionizing Energy Loss) hypothesis.

As mentioned earlier, the effect of surface damage in device simulation is incorporated by using different values of $Q_F$ at the Si-SiO$_2$ interface. We have used the expected surface oxide charge density for the surface damage for different fluences. The use of oxide charge density to approximate the surface damage have been used in many simulation studies [28–30, 43] and had been found useful. To simulate the more realistic effect of surface damage, interface traps should also be included in the simulations. However, measurements are not available for proton irradiated sensors to ascertain the interface trap parameters to be incorporated in the simulations. Moreover it is really challenging to define sufficient mesh points near the Si-SiO$_2$ interface.

It is important to note that usual flat band voltage measurements of MOS structures, which are successfully used for $Q_F$ measurements in photon irradiation cases, are not useful in heavily proton irradiated sensors [41, 42] though for low irradiation cases MOS measurements clearly indicate expected build up of surface oxide charges. Moreover, along with radiation damage, oxide charge density is a complex function of fabrication process, annealing steps, humidity etc. Hence, instead of taking one value of $Q_F$, for a given fluence of proton irradiation, a range of $Q_F$ is considered in the simulations presented in this work.

The simplest approach to incorporate bulk damage in device simulation is by incorporating two deep trap energy levels, one acceptor and one donor [10–13]. More than two trap levels are also considered elsewhere [14–16, 18]. As mentioned earlier, we have incorporated modified EVL model based on two deep trap levels, to incorporate bulk damage. However, as shown in a previous work [17, 37] parameters like electron and hole capture cross-sections and introduction rates have to be modified as given in table 1, with respect to the original EVL model, in order to obtain more realistic leakage currents and to obtain double peak electric field profiles at high fluences. Even after these modifications, we found that the simulation results for interstrip capacitance, interstrip resistance and electric field show discrepancies with respect to measurements.

Thus, three additional trap levels, i.e. two acceptor levels and one donor level with high introduction rates, are introduced in this work which allows to describe the experimental measurements.
Table 2. Radiation induced trap level model used in the simulations.

| No. | Trap    | Energy Level | $g_{int}$ (cm$^{-1}$) | $\sigma_e$ (cm$^{-2}$) | $\sigma_h$ (cm$^{-2}$) |
|-----|---------|--------------|-----------------------|------------------------|------------------------|
| 1.  | Acceptor| $E_c - 0.525$ eV | 3.0                   | $1 \times 10^{-14}$    | $1.4 \times 10^{-14}$  |
| 2.  | Acceptor| $E_c - 0.45$ eV  | 40                    | $8 \times 10^{-15}$    | $2 \times 10^{-14}$    |
| 3.  | Acceptor| $E_c - 0.40$ eV  | 40                    | $8 \times 10^{-15}$    | $2 \times 10^{-14}$    |
| 4.  | Donor   | $E_v + 0.50$ eV  | 0.6                   | $4 \times 10^{-15}$    | $4 \times 10^{-15}$    |
| 5.  | Donor   | $E_v + 0.45$ eV  | 20                    | $4 \times 10^{-15}$    | $4 \times 10^{-15}$    |

Figure 2. Variation of leakage current vs. fluence for a diode using the five trap model in simulation and its comparison with theoretical expectation for annealing of 10 minutes at 80°C. The value of damage coefficient $\alpha = 8.8 \times 10^{-19}$ cm$^{-1}$ at 253 K is used to evaluate the expected value of leakage current.

Another parameter of interest is the effective doping concentration which is extracted from full depletion voltage of the pad diodes. The full depletion voltage is extracted from the capacitance-
Figure 3. Comparison of effective bulk concentration vs fluence against experimental measurements for both n and p type pad detectors of 320 µm thickness [36]. The measurement of $V_{FD}$ is carried out for pad diodes irradiated with 23 MeV protons after annealing of 10 minutes at 80°C.

voltage characteristics of the diodes by plotting $1/C^2$ (C being the diode capacitance) over bias voltage. This method works well for non-irradiated sensors, but is not very accurate for irradiated sensors [36] and hence one can expect to compare general trend in simulation with measurement, which is observed in figure 3. The measurements are done on Fz pad sensors, 320 µm thick, both p type and n type, irradiated to different fluences with 23 MeV protons at ZAG, Germany [36]. The simulations are performed on pad sensors of dimension 1 µm $\times$ 1 µm $\times$ 320 µm.

In a recent work, it is shown that the simulation results for interstrip capacitance ($C_{int}$) matches well with the experimental values for non-irradiated Si strip sensors [17]. Also, for irradiated sensors, using a two trap model the $C_{int}$ results are found to match with measurements for low values of $Q_F$ [17]. This can also be seen from figure 4, which shows the comparison of the $C_{int}$ simulated using a two trap model [17] and the five trap model for different values of $Q_F$ along with the measurement for sensors irradiated with a proton fluence of $5 \times 10^{14}$ cm$^{-2}$. Both measurements and simulations are performed at a temperature of 253 K. When realistic values of the $Q_F$ (after radiation damage) is incorporated, like $Q_F = 5 \times 10^{11}$ cm$^{-2}$ the corresponding results differ significantly from the experimental values for the two trap model. On the other hand, using the five trap model, a better agreement with experimental result is obtained even for higher values of $Q_F$ as seen in figure 4.

Figure 5 shows the variation of $R_{int}$ with fluence using the two trap and the five trap models for different values of $Q_F$ at applied reverse bias voltage of 600 V. It is found that using the two trap model the $R_{int}$ of sensors decreases drastically with respect to non-irradiated sensors and strip insulation is lost with irradiation for higher values of $Q_F$. In contrast, by incorporating the five trap model the simulated $R_{int}$ values are consistent with the measurements [36, 42].

The above observed behaviour of $C_{int}$ and $R_{int}$ is due to difference in the electric field behaviour around the surface region as shown in figure 6. The two trap model gives significantly lower values of the peak electric field near n$^+$ strips as compared to the five trap model and hence is unable to account for the surface damage appropriately. On the other hand the 5 trap model is able to simultaneously account for the bulk (figure 2 and 3) and surface properties (figure 4 and 5).
Figure 4. Variation of $C_{\text{int}}$ vs. reverse bias voltage for two trap and five trap models for different values of $Q_F$.

Figure 5. Variation of $R_{\text{int}}$ vs. fluence for two trap and five trap model for different values of $Q_F$ at applied reverse bias voltage of 600 V. The measured $R_{\text{int}}$ values are taken from [36].

2.3 Simulation of $R_{\text{int}}$ without bulk damage

The value of $R_{\text{int}}$ was computed for structures with p-stops (see figure 1) and also without any p-type insulation between the strips. A doping density of $5 \times 10^{15} \text{ cm}^{-3}$ (corresponding to implanted boron dose of about $2.4 \times 10^{11} \text{ cm}^{-2}$) was assumed for the p-stop. A range of $Q_F$ values between $5 \times 10^{10} \text{ cm}^{-2}$ and $5 \times 10^{11} \text{ cm}^{-2}$ was considered, representing non-irradiated sensors with initial values of $Q_F$ due to fabrication induced imperfections, to photon irradiated sensors with higher values of $Q_F$. $R_{\text{int}}$ as a function of reverse bias voltage, are presented in figure 7(a) and figure 7(b) for a structure with p-stops and without one, respectively. It can be seen from figure 7(a) that $R_{\text{int}}$ vs. reverse bias voltage qualitatively can be broadly categorized in three different behaviors. For low values of $Q_F$, good strip insulation is obtained even for low reverse bias voltages. For intermediate values of $Q_F$, strip insulation is very poor at low reverse bias voltages, but improves with higher
variation of electric field along the device at applied reverse bias voltage of 500 V. The $n^+$ strip is on the left and backside $p^+$ is on the right.

Figure 7. Variation of $R_{\text{int}}$ vs. reverse bias voltage for a structure with double p-stop structure (a), and without any insulation structure (b), for different values of $Q_F$ for sensors without bulk damage.

reverse bias, as the electrons from accumulation layer are progressively removed, resulting in a higher $R_{\text{int}}$. But for $Q_F = 5 \times 10^{11} \text{ cm}^{-2}$, $R_{\text{int}}$ remains very low up to 800 V. A p-stop doping density of $5 \times 10^{15} \text{ cm}^{-3}$ is not sufficient to maintain insulation between strips with an oxide charge density of this order and higher. Similarly, it can be inferred from figure 7(b) that without any insulating structure, strip insulation is compromised even for $Q_F = 3 \times 10^{11} \text{ cm}^{-2}$ below 800 V.

2.4 Simulation of $R_{\text{int}}$ after proton irradiation

Simulation of proton damaged devices is carried out using the bulk damage model represented by the defect properties in table 1 along with the expected range of $Q_F$ values. Simulations of $R_{\text{int}}$ are carried out for three values of fluence, $1 \times 10^{14} \text{ cm}^{-2}$, $5 \times 10^{14} \text{ cm}^{-2}$ and $1 \times 10^{15} \text{ cm}^{-2}$, respectively. In order to understand the effect of bulk damage on strip insulation, figure 8, figure 9 and figure 10 show the simulated $R_{\text{int}}$ as a function of reverse bias voltage for a structure with p-
Figure 8. Variation of $R_{\text{int}}$ vs. reverse bias voltage for a structure with double p-stop structure (a), and without any insulation structure (b), for different values of $Q_F$ for sensors irradiated with proton to a fluence of $1 \times 10^{14}$ cm$^{-2}$.

Figure 9. Variation of $R_{\text{int}}$ vs. reverse bias voltage for a structure with double p-stop structure (a), and without any insulation structure (b), for different values of $Q_F$ for sensors irradiated with proton to a fluence of $5 \times 10^{14}$ cm$^{-2}$.

It is observed that for $Q_F = 5 \times 10^{11}$ cm$^{-2}$, the inter-strip resistance was below 100 $\Omega$. For higher charge densities, though, no insulation is visible even for reverse bias voltage up to 800 V.

Figure 9 presents the $R_{\text{int}}$ as a function of reverse bias for the same structures considered irradiated with proton to $5 \times 10^{14}$ cm$^{-2}$, $Q_F$ is varied between $5 \times 10^{11}$ cm$^{-2}$ and $1.2 \times 10^{12}$ cm$^{-2}$. It is observed that for $Q_F = 5 \times 10^{11}$ cm$^{-2}$, for which the inter-strip resistance was below 100 $\Omega$...
Figure 10. Variation of $R_{\text{int}}$ vs. reverse bias voltage for a structure with double p-stop structure (a), and without any insulation structure (b), for different values of $Q_F$ for sensors irradiated with proton to a fluence of $1 \times 10^{15}$ cm$^{-2}$.

before irradiation (see figure 5), values of the order of G$\Omega$ are obtained for voltages above 600 V for both the structures. For higher oxide charge densities the $R_{\text{int}}$ increases with reverse bias voltage, but does not reach saturation below 800 V.

The effect of bulk damage on strip insulation is even more pronounced for a proton fluence of $1 \times 10^{15}$ cm$^{-2}$. Simulated $R_{\text{int}}$ are plotted in figure 10. The range of $Q_F$ used in simulation is from $8 \times 10^{11}$ cm$^{-2}$ to $2 \times 10^{12}$ cm$^{-2}$. The simulated value of $R_{\text{int}}$, in general, increases with increase in reverse bias voltage but for lower $Q_F$, $R_{\text{int}}$ first increases with reverse bias voltage and then it decreases slightly at higher reverse bias voltage. One can see that even for the highest value of $Q_F$, an inter-strip resistance of above 2 M$\Omega$ is obtained at high voltages.

As mentioned in section 2, the acceptors states introduced during proton irradiation trap electrons thus creating a negative space charge, which reduces the electrons at the interface. Figure 11(a) shows the simulated electron density just below Si-SiO$_2$ interface plotted as a function of distance across the strips for different proton fluences. The simulation was done for $Q_F = 5 \times 10^{11}$ cm$^{-2}$ and at a reverse bias of 500 V. One can see that before the irradiation, fluence $= 0$, the assumed p-stop doping density of $5 \times 10^{15}$ cm$^{-3}$ is not sufficient to remove the accumulation layer electrons and a significant density of electrons exist even inside the p-stops. It decreases dramatically after an irradiation to $1 \times 10^{14}$ cm$^{-2}$ and is further reduced for higher fluences. In fact, for highly irradiated sensors, a higher $Q_F$ may act as stabilising factor because it can actually reduce the maximum electric field near the curvature of the n$^+$ strip. This can be visualised from figure 11(b), where the electric field is plotted as a function of distance across the strips, parallel to Si-SiO$_2$ interface, and passing through the curvature region of n$^+$ strip. The simulation was done for different values of $Q_F$ and it is found that the maximum value of electric field decreases as the $Q_F$ is increased from $5 \times 10^{11}$ cm$^{-2}$ to $1.2 \times 10^{12}$ cm$^{-2}$. Further, increase in the value of $Q_F$ does not help in reducing the electric field further as the curve for $Q_F = 2 \times 10^{12}$ cm$^{-2}$ lays over the curve for $Q_F = 1.2 \times 10^{12}$ cm$^{-2}$.
Figure 11. Density of the electron accumulation layer, just under Si-SiO$_2$ interface (0.1 µm below it) for different fluences and for $Q_F = 5 \times 10^{11}$ cm$^{-2}$ at 500 V (a) and Electric field across the strips parallel to Si-SiO$_2$ interface and 1.3 µm below it for a fluence of $1 \times 10^{15}$ cm$^{-2}$, for different values of $Q_F$ and at 500 V (b).

Figure 12. $R_{int}$ vs. Reverse Bias for different p-stop doping densities (a) and Electric field across the strips for different p-stop doping densities, parallel to Si-SiO$_2$ interface and 0.1 µm below it, for fluence of $1 \times 10^{15}$ cm$^{-2}$ & for $Q_F = 1.2 \times 10^{12}$ cm$^{-2}$ (b). P-stop peak doping densities of $5 \times 10^{16}$ cm$^{-3}$ and $5 \times 10^{17}$ cm$^{-3}$ correspond to implanted boron dose of $2.1 \times 10^{12}$ cm$^{-2}$ and $1.9 \times 10^{13}$ cm$^{-2}$ respectively.

Further, $R_{int}$ is a function of p-stop doping density also. The simulated $R_{int}$ vs. reverse bias for different p-stop doping densities is plotted in figure 12(a). These trends have also been observed experimentally [45, 46]. Higher values of p-stops doping density can also lead to build up of very high electric field near curvature of p-stops as shown in figure 12(b), which can lead to micro-discharge or breakdown near p-stop curvature. It must be mentioned that for low p-stop doping densities ($\sim 5 \times 10^{15}$ cm$^{-3}$) maximum electric field is near n$^+$ curvature region (figure 11(b)) which has been observed experimentally also [29].
3 Summary and conclusions

It is generally expected that the strip insulation in n⁺-p Si strip sensors require some minimum value of the p-stop/p-spray doping density below which strip insulation is lost and further irradiation should adversely affect the insulating properties. However, recent measurements on proton irradiated n⁺-p Si strip sensors show an interesting trend of good strip insulation, using low values of the p-stop/p-spray density and even without having any insulating structure between n⁺ strips at all. In this work, a bulk damage model is first developed such that the device simulation results match well with the measurements of different parameters like leakage current, effective doping concentration, interstrip capacitance and interstrip resistance. Further, incorporating the bulk damage model together with the surface damage the otherwise unexpected $R_{\text{int}}$ measurement results are explained. It is found that the detrimental effect of increasing $Q_F$ (because of surface damage) on $R_{\text{int}}$ is compensated by the increasing defect concentration in the sensor bulk such that at high proton fluence values, the n⁺ strips are insulated even in the absence of any insulating structure. In view of its importance for n⁺-p Si detector designs for future hadron collider upgrades and new experiments, this may need to be supplemented with more measurements and improved defect parameters for the simulations. However, the device simulation performed in this work provides an insight into the strip insulation properties of the n⁺-p Si sensor and thus provides a possible explanation for the existing measurements by taking into account both bulk and surface damage simultaneously.

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