Total Ionizing Dose, Random Dopant Fluctuations, and its combined effect in the 45 nm PDSOI node

Eleni Chatzikyriakou, William Redman-White, C.H. De Groot

Department of Electrical and Computer Science, University of Southampton

Abstract

Total Ionizing Dose and Random Dopant Fluctuation simulations in 45 nm Partially Depleted Silicon-on-Insulator nMOSFETs are presented. Calibration is done according to the commercial IBM 45 nm technology node. The importance of the bottom corner parasitic transistor to the Total Ionizing Dose response is shown with the use of ultra shallow junctions. Simulation of irradiation in two-dimensional slices of the device reveal that the majority of the charge is trapped around the silicon film and at the bottom of the Buried OXide in the case of a positive gate bias. Random Dopant Fluctuations are examined using the Sano and the Impedance Field Method. The simulation results of the two methods are in good agreement. Dopant fluctuations do not produce significant response variation pre-irradiation, but they affect post-irradiation results introducing statistical deviations and aggravating Total Ionizing Dose effects. This effect is more pronounced during weak inversion of the parasitic transistor.

Keywords:
Simulation, Finite Elements Method, Total Ionizing Dose, Partially Depleted, Silicon-on-Insulator, Random Dopant Fluctuations

1. Introduction

Partially-Depleted Silicon-on-Insulator (PDSOI) nMOSFETs of sub-100 nm gate lengths have been shown to exhibit increased hardness against Total Ionizing Dose (TID) due to the high body doping incorporated to suppress short channel effects [1, 2] and the use of a thick silicon film that mitigates electrostatic coupling between the front gate transistor and any parasitic channels induced in the device after irradiation [3]. Furthermore, the Buried OXide (BOX) insulates the active silicon region from charge collected in the bulk making them less susceptible to Single Event Effects [4]. To this end, the 45 nm commercial SOI node is a good candidate for aerospace and aviation applications.

TID-induced degradation in these devices is manifested as increase in the off-state current ($I_{off}$) that results from the formation of parasitic transistors at the sidewall of the active silicon region adjacent to the Shallow Trench Isolation (STI) and at the back interface of the top silicon layer with the BOX [5–10]. Threshold voltage shifts induced by gate oxide charge are less pronounced due to the increased probability of the charges tunnelling out of these thin oxides [11–14].

Variations in the TID response of bulk sub-100nm MOSFETs such as that caused by STI topology and stress have been studied previously [15, 16] on the premise that identical devices from the same lot have exhibited similar pre-irradiation and different post-irradiation response [17]. In this work, Random Dopant Fluctuations (RDF) arising as a result of the low total number of dopant atoms implanted in the small volume of the active silicon region, are examined. The commercial simulation software Synopsys Sentaurus is used for this purpose.

RDFs as a source of variability become significant in deca-nanometer technologies. It has been suggested that at 45 nm
Table 1: 45 nm device characteristics as measured experimentally [20] and simulated (this work).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>IBM 45 nm node</th>
<th>This work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical (L_g) (nm)</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>EOT (nm)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(I_{35}) (nm)</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td>(I_{1240}) ((\mu)A/(\mu)m)</td>
<td>1200</td>
<td>1220</td>
</tr>
<tr>
<td>(I_{200}) (nA/(\mu)m)</td>
<td>200</td>
<td>4</td>
</tr>
<tr>
<td>(V_i) (V)</td>
<td>0.35</td>
<td>0.36</td>
</tr>
<tr>
<td>(V_{dd}) (V)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

they approach 50% of total variability [18]. In [19], it is shown that random discrete dopants can have a significant effect in device response when also taking into account traps located at the channel region and created due to device degradation. Our current focus is on the effects that changes in the number and position of dopant atoms can have on the TID response of the device taking into account that such effects require a large number of devices to be measured. Furthermore, using simulation tools, the variations due to RDFs can be measured separately from other variation sources.

2. Simulation details

A floating body 45 nm PDSOI nMOSFET was constructed in Sentaurus process (Figure 1). The steps are similar to the gate-first flow in [22]. Important device characteristics and structural parameters are shown in conjunction with those in [20] and [23] in Table 1. \(I_d-V_g\) results of the simulation are compared to the experimental results from [21] in Figure 2. The doping profile in two directions inside the silicon film is shown in Figure 3. The doping level in the device is between \(3 \times 10^{18}\) cm\(^{-3}\) and \(5.4 \times 10^{18}\) cm\(^{-3}\). The doping profile is constant in the third dimension as our device was first created in 2D and then extruded to 3D. This assured that the same doping level extends to the STI sidewalls.

3. Uniform profile results

3.1. Fixed oxide charge

Initially, the devices were solved with uniform bulk fixed oxide charges and a uniform doping profile. The \(I_d-V_g\) results for...
The location of the parasitic inversion charge occurs mainly at the bottom silicon corner, with the holes trapped in the field oxides acting as lateral gates in the top silicon film.

![Figure 4](image-url)

**Figure 4**: Id-Vg results of 45nm PDSOI with uniform doping profile and uniform bulk field oxide charges

Different densities of charge trapped in the BOX, the STI and both the BOX and STI are shown in Figure 4. These results are similar to another 45 nm technology examined both computationally and experimentally in [31].

![Figure 5](image-url)

**Figure 5**: Depletion region width and off-state current density at Vg=0 V, Vds=0.05 V through Cut B of Fig. 1. The white line indicates the boundaries of the depletion region.

Specifically, the increased areal charge required to invert the parasitic channel is attributed to the high body doping we have used in our technology calibration and the distribution of the doping profile in the device. For the BOX only case, very minimal conduction of the parasitic structure is observed at 5×10^{12} cm^{-2}, while the threshold voltage shift observed for this structure due to STI charge of the same density is 10 mV. It is clear that even though the S/D implants do not extend to the BOX, radiation affects off-state current significantly. This, however, only happens when both the BOX and STI charges are included. The width of the depletion regions and the current density is shown in Figure 5 for the cases of no charge and uniform oxide charge of 5×10^{12} cm^{-2}. The location of the parasitic inversion charge occurs mainly at the bottom silicon corner.

![Figure 6](image-url)

**Figure 6**: Electric field lines in the field oxides.

Figure 6 shows the electric field lines in the field oxides. Their direction further confirms that the bottom corner transistor takes place in our device. Holes created in the STI and BOX follow the direction of the electric field lines and get trapped in defect centers (E_{γ}' and E_{δ}') [32]. According to the theory, the trapped charge density will be higher towards the end of the lines at the interface with the silicon, as the hole flux there will be higher. Ionic hydrogen (H^+) originating from the oxide also follows the same path. At the Si/SiO_{2} interface, hydrogen can de-passivate dangling bonds creating either interface traps, or introducing fixed positive charge [33]. In our device, the field lines have a similar distribution as that in over-etched STI 0.2 μm PDSOI MOSFETs [28], moving from the STI to the BOX and from the BOX towards the silicon and the bottom silicon corner [34].

### 3.2. Radiation simulations

Radiation simulations were further performed in a two-dimensional cut of the PDSOI structure in order to quantify the amount of bulk charge trapped in the BOX and STI as well as its distribution. The radiation generation model of Sentaurus device was used for this purpose, which has been well-calibrated previously in [35, 36]. Drift-diffusion was used for the transport of the carriers in the oxide. Hydrodynamic transport is disabled for both the silicon and the oxide. The simulation parameters used for the carrier generation, transport and trapping are shown in Table 2 [12, 35]. Holes are assumed to be trapped in defects (E_{γ}' and E_{δ}') in the field oxides.

Donor traps with uniform concentration and a deep effective activation energy of 4 eV above the valence band, representing deep traps that remained filled the longest after irradiation are assumed. For trapping, the drift motion of the carriers is fully taken into account, and diffusion is completely neglected. For both electrons and holes, the degeneracy factor of the gap energy states is unity and the constant emission rate is zero.

The 2D cut is taken as shown in Figure 1c. The contact of the oxide with the metal gate is defined as Schottky. The bottom of the BOX has a silicon region adjacent to it. A substrate bias is applied to fix the electrostatic potential to that of the three
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiation term</td>
<td>$g \cdot 7.6 \times 10^{12}$ cm$^{-3}$Rad(SiO$_2$)</td>
</tr>
<tr>
<td>Dose Rate</td>
<td>$D \cdot 38.6$ Rad(SiO$_2$)/s</td>
</tr>
<tr>
<td>Electron Mobility</td>
<td>$\mu_n \cdot 20$ cm$^2$ V$^{-1}$s$^{-1}$</td>
</tr>
<tr>
<td>Hole Mobility</td>
<td>$\mu_p \cdot 10^{-5}$ cm$^2$ V$^{-1}$s$^{-1}$</td>
</tr>
<tr>
<td>Electron thermal velocity</td>
<td>$v_n \cdot 2.042 \times 10^7$ cm/s</td>
</tr>
<tr>
<td>Hole thermal velocity</td>
<td>$v_p \cdot 1.562 \times 10^7$ cm/s</td>
</tr>
<tr>
<td>Electron capture cross section</td>
<td>$\sigma_n \cdot 10^{-12}$ cm$^2$</td>
</tr>
<tr>
<td>Hole capture cross section</td>
<td>$\sigma_p \cdot 6.8 \times 10^{-14}$ cm$^2$</td>
</tr>
<tr>
<td>Effective density of states in conduction band</td>
<td>$N_C \cdot 8.867 \times 10^{18}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Effective density of states in valence band</td>
<td>$N_V \cdot 1.931 \times 10^{20}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Energy of donor traps</td>
<td>$E_{\text{trap}} \cdot E_V + 4$ eV</td>
</tr>
<tr>
<td>Donor traps density</td>
<td>$p_t \cdot 5 \times 10^{15}$ cm$^{-3}$</td>
</tr>
</tbody>
</table>

Table 2: Parameters used for radiation simulations

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Figure 7: 2D simulation results of positive trapped charge density in the STI and BOX (cm$^{-3}$). The cut is taken in the direction as shown in Figure 1c.

The 2D simulation results under two different bias conditions ($V_g = 0$ V and $V_g = 1$ V) are shown in Figure 7. The highest density of the trapped charge is aggregated around the silicon film. At $V_g = 1$ V, the trapped charge density is increased at the bottom of the BOX as well, as the holes are pushed towards it by the positive gate bias. This reduces the amount of holes trapped underneath the silicon film with increasing radiation, a process that is also dependent on the annealing time of the positive trapped charge.

Trapped charge as a function of distance from the bottom silicon corner for both bias conditions is shown in Figure 8. At $V_g = 1$ V, the high density of trapped holes at the bottom of the BOX is observed more clearly (Figure 8b). There exists a peak of trapped charge concentration at the bottom silicon corner at 100 KRad(SiO$_2$). Beyond that, the density starts decreasing under the influence of the holes trapped at the bottom of the BOX. Charge is then pushed to the STI sidewalls. Similarly, the charge trapped at the bottom of the silicon film at $V_g = 0$ V is affected by the charge trapped at the bottom of the BOX (Figure 8d). In this case, holes are pushed towards the substrate under the influence of the positive charge trapped at the bottom of the silicon film. In both cases, the electric field is reduced in the middle of the BOX between the two interfaces with the silicon, causing less electron-hole pairs to be generated, a process described as ‘electric field collapse’ [37].

The highest value of areal trapped charge at the bottom of the silicon corner for $V_g = 0$ V occurs above 400 KRad(SiO$_2$) with $9.4 \times 10^{11}$ cm$^{-2}$ in the X direction and $7.5 \times 10^{11}$ cm$^{-2}$ in the Z direction. At $V_g = 1$ V, the highest areal trapped charge density is at 300 KRad(SiO$_2$) with $5.6 \times 10^{11}$ cm$^{-2}$ in the X direction and $4.3 \times 10^{11}$ cm$^{-2}$ in the Z direction. All values are below the value required for parasitic channel inversion, as was shown in the fixed charge simulations, indicating that a higher density of traps would be needed to reach inversion of the parasitic transistor.
3.3. Interface traps

To examine the effects of traps located at the interface of the BOX and STI with the top silicon film, the simulations shown in Figure 9 were performed. Donor and acceptor interface traps were examined separately with areal concentrations up to $10^{13}$ cm$^{-2}$. The activation energies of the traps are 0.45 eV from the silicon conduction band for the acceptors traps and 0.45 eV from the valence band for the donor traps, that represent the worst case scenario.

Acceptor traps remained unoccupied based on the electrostatic potential at the Si/SiO$_2$ interface. Donor traps with concentration of $10^{13}$ cm$^{-2}$ created a $V_t$ shift of 12 mV and $\Delta I_{\text{off}} = 1.82 \times 10^{10}$ A/$\mu$m in the case where no bulk charge ($N_{\text{ox}}$) was considered. Under weak inversion of the parasitic transistor ($N_{\text{ox}} = 3.5 \times 10^{15}$ cm$^{-2}$), further increase of leakage current when compared to the device with bulk oxide charge, $\Delta I_{\text{off}} = 3.93 \times 10^{10}$ A/$\mu$m, was observed.

The net effect of donor interface traps when combined with bulk oxide charge is a negative threshold voltage shift of the parasitic transistor. Leakage current is therefore observed in lower values of bulk oxide charge.

4. Random Dopant Fluctuations

Two different methods were used for the RDF simulations: The Sano method and the Impedance Field Method (IFM). Uniform fixed oxide charge was used in both cases.

4.1. Sano Method

Using the Sano method in Sentaurus mesh, the doping concentration in the device is first translated to a total number of atoms, then, both their number and position is randomized and re-assigned to the mesh. The number density of the discrete dopant is given by the long range part of the Coulomb potential,

$$n(r) = \frac{k_c^3}{2\pi^2} \sin(k_c r) - (k_c r) \cos(k_c r)$$

where $k_c$ is the screening factor and $r$ is the distance from the atom. One method of calculating the screening length is the Conwell-Weisskopf model [38, 39] defined as,

$$\frac{1}{k_c} \approx \frac{1}{2 \times N_{\text{ac}}^{1/3}} = 3 \times 10^{-7} \text{cm}$$

for doping density $N_{\text{ac}} = 4.6 \times 10^{18}$ cm$^{-3}$ extracted from the simulator. In Sentaurus mesh, the oscillatory function is cut-off at the first occurrence of zero. The normalized doping density as a function of distance from the atom is shown in Figure 10. Simulations were performed to test the effects of the screening length on the spread of $I_{\text{off}}$. This is shown in Figure 11. $\sigma I_{\text{off}}$ showed negligible change in a screening length range of 1.5 nm to 10 nm. Therefore, the Conwell-Weisskopf model can be safely used.

Only the silicon volume directly underneath the gate was randomized (Figure 12). The total number of atoms encountered in the randomized profile devices had a range of 544 - 700. The frequency distribution of devices with dopant atoms within a specific range is shown in Figure 13. For 100 samples that were produced, the mean is just above the nominal device which has 600 atoms. There is also a tail towards the maximum.

$I_{\text{off}}$-$V_f$ results of the devices with the randomized doping profiles for the cases of combined BOX and STI charge are shown in Figure 14. It is observed that the spread in $I_{\text{off}}$ is higher at $3.5 \times 10^{12}$ cm$^{-2}$. At this areal charge, the parasitic transistor is at the point of weak inversion. Beyond that, the parasitic transistor is completely turned on and the spread reduces to its minimum.
Figure 12: Active silicon region where RDFs are applied

Figure 13: Frequencies of devices with total number of atoms in the region where randomization was performed as labelled in X axis

Figure 14: RDF $I_d$-$V_g$ results of 45nm PDSOI MOSFET. Fixed oxide charge is included in both the BOX and STI. Shown in red is the device with uniform doping profile.

It is also observed that the nominal device shows lower values than the mean. This could potentially be a result of the $V_t$ lowering of the parasitic transistor caused due to randomizing the position and number of the dopant atoms. The electrons can thus find the easiest routes through the channel [40]. The tail in the distribution of the count of devices with dopant atoms within a specific range (Figure 13) is directly translated to the devices showing the highest resistance to TID during parasitic channel inversion. $\sigma V_t$ remains constant for all cases of oxide charge examined, as shown in Figure 15.

4.2. Impedance Field Method

RDFs are also examined using the IFM in Sentaurus device. This method uses only one solution to a reference device, and then calculates the effect of the variation as a linear response to a perturbation of the contact characteristics. The Green’s function is solved once, for the reference device, for each contact. For the case of contact current, the perturbation due to RDFs at location $x$ will result in the following response,

$$\delta I_c = \int G(x) \delta N_\xi(x) \, dx$$

(3)

where the integral is for the whole device, $c$ is the contact node, $G(x)$ is Green’s function and $N_\xi$ is the equation that involves the doping concentration term [41, 42]. Using a Poisson distribution, the probability to find $k$ dopant atoms in a box volume $V_i$ (cm$^{-3}$) with average doping concentration $N_i$ (cm$^{-3}$) at a vertex $i$ of the mesh is,

$$P_i(k) = \frac{(N_i V_i)^k}{k!} \exp(-N_i V_i)$$

(4)

Both donor and acceptor atoms are taken into account and are treated as separate, uncorrelated sources of variation.

The linear current response $\delta I_d$ is linked to the nodal drain current $dI_d$ and the gate voltage $dV_g$ variations through the boundary condition,

$$dI_d = \delta I_d + y_{d,g} dV_g$$

(5)

where,

$$y_{d,g} = \frac{\partial I_{ref,d}}{\partial V_g}$$

(6)
and \( I_{\text{ref},d} \) is the drain current of the reference device.

There are numerous techniques for extracting the \( I_d-V_g \) characteristics of the randomized profile devices produced with the IFM. These techniques are appropriate either for the on state of the transistor, weak inversion or leakage current. None of them, however, completely covers the situations examined in this work. Namely, it is not just the state of the front gate transistor that is recorded in the \( I_d-V_g \) results, but also the state of the parasitic transistor.

The final characteristics of the randomized profile devices are shown in Figure 16. Up to oxide charges of \( 3.0 \times 10^{12} \, \text{cm}^{-2} \), the ‘exp’ method is used, while the ‘dI’ method is used for the remaining charges examined. The trends are similar to those in the results of the Sano method with the randomized profile devices exhibiting higher \( I_{\text{off}} \) spread as we approach the parasitic channel weak inversion and then reducing as the parasitic channel is completely turned on. The artefacts in the saturation region are due to the extraction method chosen.

\[
I_{v,d} = I_{\text{ref},d} \exp\left( \frac{dI_{v,d}}{I_{\text{ref},d}} \right) \quad (7)
\]

and is appropriate only for transistor leakage current. This is due to the breaking of the linearity assumption that results in non-Gaussian distribution in other bias regimes. Therefore, the ‘dI’ method is used for the cases where the parasitic transistor is off. The drain current in this case is given by,

\[
I_{v,d} = I_{\text{ref},d} \left( V_{\text{ref},g} \right) + dI_{v,d} \quad (8)
\]

For the cases where non-physical, negative results occurred during the parasitic channel weak inversion, the ‘exp’ method was used to represent those specific \( I_d-V_g \) results.

The RDF results of the device for the case that radiation has created interface traps are shown in Figure 18. The randomized doping profile devices were constructed using the IFM. The densities and activation energies of the traps were chosen so as the highest contribution to \( I_{\text{off}} \) occurs. The results are similar to the case where radiation has created no interface traps. The parasitic transistor weak inversion now occurs at a lower value of areal charge (\( 3.0 \times 10^{12} \, \text{cm}^{-2} \)). This is due to the added effect of the interface traps.

Overall, RDFs have reduced the TID hardness of the device.
by increasing $I_{dd}$ values and are virtually negligible when the parasitic transistor is completely turned on.

5. Conclusions

The combined effects of Total Ionizing Dose and Random Dopant Fluctuations have been examined in the 45 nm PDSOI nMOSFET node. The post-irradiation device response is primarily dictated by the electric field at the bottom silicon corner, even in the case where there is no contact of the S/D junctions to the BOX. The existence of the bottom corner parasitic conduction channel is confirmed with transient radiation simulations where it is shown that the majority of the holes are trapped around the silicon film, creating the effect of lateral gates in the PDSOI nMOSFET.

However, radiation simulations also show that the areal trapped charge required to invert the parasitic transistor is not reached even at a total dose of 600 KRads(SiO2) and a total trap density of 5×10^{13} cm^{-2}. A threshold was also observed for the charge trapped close to the silicon film as holes trapped there create an electrostatic fence that prevents further movement of holes towards that direction. Donor traps introduced at the silicon interface with the BOX and STI further increased $I_{dd}$, mostly during the parasitic transistor weak inversion.

RDFs create significant response deviation but only in post-irradiation results. In pre-irradiation, the contribution of RDFs is minimal. The post-irradiation device response can deviate significantly, and therefore a greater number of measurements needs to be taken to account for the statistical error. RDFs, generally, aggravate post-irradiation response decreasing the dose level at which the device is hardened against. However, the effect is also more pronounced during weak inversion of the parasitic transistor.

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References
