Numerical simulation of radiation damage effects in p-type silicon detectors

Petasecca M.\textsuperscript{1,3}, Moscatelli F.\textsuperscript{1,2,3}, Scarpello C.\textsuperscript{1}, Passeri D.\textsuperscript{1,3}, Pignatel G.U.\textsuperscript{1,3}

\textsuperscript{1}DI EI - Università di Perugia, via G.Duranti, 93 - Italy
\textsuperscript{2}IM-CNR sez.di Bologna, via Gobetti 101 - Italy
\textsuperscript{3}INFN sez. Perugia - via Pascoli, 10 - Italy

6\textsuperscript{th} RD50 Workshop

Helsinki, 2-4 June. 2005
OUTLINE

- development of the radiation damage model for p-type silicon
- simulation of the Leakage Current and Depletion Voltage as a function of the Fluence
- simulation of the Charge Collection Efficiency (CCE) on irradiated silicon detectors as a function of the Fluence
Simulation tool:
ISE-TCAD – discrete time and space solution of drift/diffusion and continuity equations

Damage modelling:
- Deep levels: $E_t$, $\sigma_n$ and $\sigma_p$
- SRH statistics
- Uniform density of defect concentration

Radiation damage Effects to simulate:
- The increasing of the Leakage Current
- The increasing of the Full Depletion Voltage
- The decreasing of the Charge Collection Efficiency
Simulation setup

Simulated device structure and parameters:

- Doping profiles:
  - P doped substrates \((7 \times 10^{11} \text{ cm}^{-3}) \rightarrow 6\text{k}\Omega\text{cm}\).
  - Charge concentration at the silicon-oxide interface of:
    - \(4 \times 10^{11} \text{ cm}^{-3}\) pre-irradiation
    - \(1 \times 10^{12} \text{ cm}^{-3}\) post-irradiation
- Optimized variable mesh definition
- Temperature = 300 K
- \(D\) (thickness) = 300 um
The \textit{p-type} One-Level Radiation Damage Model


<table>
<thead>
<tr>
<th>Level*</th>
<th>Ass.</th>
<th>$\sigma_n$ [cm$^{-2}$] Experimental*</th>
<th>$\sigma_p$ [cm$^{-2}$] Experimental*</th>
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<tbody>
<tr>
<td>$E_c$ -0.42eV</td>
<td>VV(-/0)</td>
<td>2·10$^{-15}$</td>
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** 2 order of magnitude higher

\[\beta [\text{cm}^{-1}] \]
- simulated: $3.72 \cdot 10^{-3}$
- experimental: $4.0 \pm 0.4 \cdot 10^{-3}$

Measures extracted from [M. Lozano, et al., RD50 workshop, Firenze, Oct 2004]

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Measurements extracted from [M. Lozano, et al., RD50 workshop, Firenze, Oct 2004]

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\[ \alpha [\text{A/cm}] \\ \begin{array}{l} \text{simulated} \\ 6.6 \cdot 10^{-17} \end{array} \]

\[ \alpha [\text{A/cm}] \\ \begin{array}{l} \text{experimental} \\ 4.0 \pm 0.11 \cdot 10^{-17} \end{array} \]
The p-type Two-Level Radiation Damage Model


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** Measures extracted from [M. Lozano, et al., RD50 workshop, Firenze, Oct 2004]

** $eta$ [cm$^{-1}$]

- simulated: $3.98 \cdot 10^{-3}$
- experimental: $4.0 \pm 0.4 \cdot 10^{-3}$
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Measures extracted from [M. Lozano, et al., RD50 workshop, Firenze, Oct 2004]
The p-type Three-Level Radiation Damage Model:
no improvement for the Vdep and Leakage Current due to the donor defect level

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<td>0.9</td>
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<tr>
<td>$E_{v} + 0.36$ eV</td>
<td>C$<em>{v}$O$</em>{i}$</td>
<td>$2.5 \cdot 10^{-14}$</td>
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Measures extracted from [M. Lozano, et al., RD50 workshop, Firenze, Oct 2004]

$\beta$ [cm$^{-1}$] simulated: $3.98 \cdot 10^{-3}$

$\beta$ [cm$^{-1}$] experimental: $4.0 \pm 0.4 \cdot 10^{-3}$

$\alpha$ [A/cm] experimental: $4 \pm 0.11 \cdot 10^{-17}$

$\alpha$ [A/cm] simulated: $3.75 \cdot 10^{-17}$
CCE Simulation

\[ Q = \int I(t) dt \]

MIP: 80 e-h pairs/ \( \mu m \)  
cylinder diameter = 2\( \mu m \)
CCE Simulation

The recombination implemented in DESSIS simulator is based on a model called Scharfetter/Auger Trapped Assisted (TAA) recombination.

\[
R^{SRH} = \frac{np - n_{i,\text{eff}}^2}{1 + \frac{\tau_{p}^{SRH}}{\tau_{TAA}^{p}}} \left( n + n_{i,\text{eff}}^2 \frac{E_{\text{trap}}}{kT} \right) + \frac{\tau_{n}^{SRH}}{1 + \frac{\tau_{n}^{SRH}}{\tau_{TAA}^{n}}} \left( p + p_{i,\text{eff}}^2 \frac{E_{\text{trap}}}{kT} \right)
\]

\[
\tau_{n/p}^{SRH} = \tau_{dop} F(T, E)
\]

\[
\tau_{dop} (N_{\text{eff}}) = \tau_{\text{min}} + \frac{\tau_{\text{max}} \text{e/h} - \tau_{\text{min}}}{1 + \left( \frac{N_{\text{eff}}}{N_{\text{REF}}} \right)^\gamma}
\]

\[
\frac{1}{\tau_{TAA}^{n/p}} = c_{n/p}^{TAA} (n + p)
\]

\[
\frac{1}{\tau_{\text{eff}}} = \beta_{e/h} \cdot \Phi_{eq}
\]

From RD50 status Report (2004):

<table>
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<th>[10^{-16} \text{ cm}^2/\text{ns}]</th>
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<td>5.16 + 0.16</td>
<td>5.04 + 0.16</td>
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CCE vs Fluence for p-type silicon device

Simulation data well reproduce experimental* measure:

Simulations obtained using the **three-level radiation damage model**:
the donor defect level allows to reduce numerical convergence problems of the transient simulations.

Expected CCE at a fluence of $1\cdot10^{16}$ n/cm$^2$ is <4200 (probably over-estimated) e-h pairs!

* Measurements from Casse et al. NIMA 535 (2004)
Conclusions

- Irradiated diodes have been analyzed considering a three levels simulation model for p-type Si substrates:

  - The two-level model for the p-type fits experimental data for the Leakage Current and Full Depletion Voltage

  - The C_iO_j donor level for p-type silicon seems to be un-influential (at Room Temperature) to simulate the leakage current and the full depletion voltage as a function of the fluence, but has an important function for the transient simulations stability (CCE simulation).

  - The three-level for p-type fits CCE experimental data for fluences up to $4.85 \cdot 10^{15} \text{n/cm}^2$ at the full depletion voltage.

- Next step is to develop a technique to solve the problems to simulate the CCE vs BIAS voltage (up to $1 \cdot 10^{16} \text{n/cm}^2$) for p and n type Si substrates partially undepleted.