Characterization of irradiated p-type silicon detector for TCAD surface radiation damage model validation

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Motivations.

TCAD radiation damage modelling approach.

Test structures / measurements and parameters extraction.

Measurements and simulation results comparison:

- different vendors (Infineon Technologies IFX, Hamamatsu Photonics HPK) and process recipes (p-stop vs. p-spray, thermal budget, 6” vs. 8”,...).

- DC (steady-state) -> Diodes / Gate Controlled Diodes.

- AC (small-signals) -> MOS Capacitors.

Conclusions.
Outline

√ Motivations.
√ TCAD radiation damage modelling approach.
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Motivations

✓ Modern TCAD simulation tools\(^{(1)}\) at device/circuit level offer a wide variety of approaches, characterized by different combinations among physical accuracy and comprehensiveness, application versatility and computational demand.

✓ A number of different physical damage mechanisms actually may interact in a non-trivial way. Deep understanding of physical device behavior therefore has the utmost importance, and device analysis tools may help to this purpose.

✓ Bulk and surface radiation damage have been taken into account by means of the introduction of deep level radiation induced traps whose parameters are physically meaningful and whose experimental characterization is feasible.

✓ Within a hierarchical approach, increasingly complex models have been considered, aiming at balancing complexity and comprehensiveness.

\(^{(1)}\) Sentaurus Device
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The modeling approach

√ Modelling the effects of the radiation damage.
√ Predictive insight of the behaviour of detectors, aiming at their performance optimization.
The **Technology CAD** modeling approach

√ TCAD simulation tools solve fundamental, physical partial differential equations, such as **diffusion** and **transport equations** for discretized geometries (finite element meshing).

√ This deep **physical approach** gives TCAD simulation **predictive accuracy**.

\[
\nabla \cdot \left( -\varepsilon_s \nabla \phi \right) = q \left( N_D^+ - N_A^- + p - n \right) \\
\frac{\partial n}{\partial t} - \frac{1}{q} \nabla \cdot \overline{J}_n = G - R \\
\frac{\partial p}{\partial t} + \frac{1}{q} \nabla \cdot \overline{J}_p = G - R \\
\overline{J}_n = -q \mu_n n \nabla \phi + q D_n \nabla n \\
\overline{J}_p = -q \mu_p p \nabla \phi - q D_p \nabla p
\n\]
Radiation damage effects

- Electrons
- Protons
- Neutrons
- Si⁺, etc.

Particles

High-Energy Photons

- gamma-rays

Low-Energy Photons

UV, visible X-rays

Displacement

Ionization

Small amount

Varying amounts

Long-term Effects

- Increased defect concentration
- Increased junction leakage current
- Decreased carrier lifetime and mobility
- Decreased carrier concentration
- Local disorder (cluster defects)

Transient Effects

- Rapid annealing of minority carrier lifetime, ...

Long-term Effects

- Charge excitation
  - altered population of traps
- Charge transport
- Bonding changes
- Decomposition

Transient Effects

- Photocurrents leading to transient voltage changes
- Latching
- Breakdown effects (abnormally high local currents)
Radiation damage effects

- **Ionization** -> **SURFACE damage**
  - build-up of trapped charge in the oxide;
  - increase in the number of bulk oxide traps;
  - increase in the number of interface traps;
  - $Q_{OX}$, $N_{IT}$

- **Atomic Displacement** -> **BULK damage**
  - silicon lattice defect generations;
  - point and cluster defects;
  - increase of deep-level trap states;
  - $N_T$
Radiation damage effects

√ Ionization -> SURFACE damage
- build-up of trapped charge in the oxide;
- increase in the number of bulk oxide traps.
- increase in the number of interface traps;
- $Q_{OX}$, $N_{IT}$

“God made the bulk, the surface was invented by the devil.”

W. Pauli
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The main test structures at hand

√ Test structures...

MOS Capacitor
Gated Diode
Cap-TS for $R_{\text{INT}}$
HPX

IFX 2S 8” wafer

√ X-ray irradiation in Padova (IT).
√ Doses range: 0.05 ÷ 100 Mrad(SiO$_2$).
√ Dose rate: 0.8 Mrad/hour.
√ Measurements after irradiation / annealing at 80°C for 10 min.
Parameter extraction procedure

√ From C-V measurements of MOS capacitors:

- $D_{IT}$ is assessed by using the C-V High-Low method.
- High-Frequency (HF) measurements are carried out at 100 kHz with a small signal amplitude of 25 mV.
- Quasi-Static (QS) characteristics measured with delay times of 0.5 sec using a voltage step of 100 mV.
- $N_{EFF}$ is obtained from $V_{FB}$ measurements.

√ From I-V measurements of MOSFETs:

- After X-ray irradiation $\Delta V_{th}(V_{FB}) = \Delta V_{N_{it}} + \Delta V_{Q_{ox}}$
- $\Delta V_{th}$ is due to two contributions ascribed to $N_{IT}$ and $Q_{OX}$, which can be evaluated from $I_{DS} - VG_S$ of MOSFETs using the method proposed in [1].

√ N_{IT}/D_{IT} evaluation (from C_{HF} - C_{QS} measurements).

Donor interface trap states from \( p \)-type substrates

Accepter interface trap states from \( n \)-type substrates

Relatively low interface trap state density region

Non negligible interface trap state density
IFX test structures wrap-up

- Noticeable differences among three processes in terms of $N_{EFF}$ and $N_{IT}$ (process variability).
- Higher differences at lower doses.

![Graph showing the comparison of $N_{EFF}$ and $N_{IT}$ across different processes.](image-url)
HPK test structures wrap-up

- Reduced variability due to different technology options in terms of radiation hardness.
- Similar values of $N_{\text{EFF}}$ and $N_{\text{IT}}$ for HPK devices with different p-stop/p-spray isolation structures.
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✓ Conclusions.
Gate Controlled Diode

✓ Non-irradiated structures (Hamamatsu).
Gate Controlled Diode

√ Irradiated structures (Hamamatsu).

![Graph showing current versus voltage for different irradiation levels (50 krad, 100 krad, 500 krad, 1 Mrad, 10 Mrad, Not-irrad). The graph includes both measurements and simulations.](image-url)
√ 2S process.

Measurements
Simulations

\[
\begin{align*}
C_{\text{Cox}} & = \text{ACC} \\
C_{\text{HF}} & = \text{DEPL} \\
C_{\text{LF}} & = \text{INV}
\end{align*}
\]

\[V_{\text{GATE}} (V)\]
√ 2S process.
√ PS-S process.

Measurements
Simulations

\[ \frac{C}{C_\text{ox}} \]

\[ V_{\text{GATE}} \text{ (V)} \]

- Not irrad.
- 50 krad
- 100 krad
- 500 krad
- 1 Mrad
- 10 Mrad
- 100 Mrad
HPK MOS capacitor

√ p-stop process.

Measurements
Simulations

\[ C/C_{ox} \]

\[ V_G (V) \]

1 Mrad
10 Mrad
100 Mrad
√ p-stop implant isolation.
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Conclusions.
The “New Perugia” model

√ Surface damage (+ $Q_{OX}$)

<table>
<thead>
<tr>
<th>Type</th>
<th>Energy (eV)</th>
<th>Band width (eV)</th>
<th>Conc. (cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptor</td>
<td>$E_C \leq E_T \leq E_C - 0.56$</td>
<td>0.56</td>
<td>$D_{IT} = D_{IT}(\Phi)$</td>
</tr>
<tr>
<td>Donor</td>
<td>$E_V \leq E_T \leq E_V + 0.6$</td>
<td>0.60</td>
<td>$D_{IT} = D_{IT}(\Phi)$</td>
</tr>
</tbody>
</table>

√ Bulk damage

<table>
<thead>
<tr>
<th>Type</th>
<th>Energy (eV)</th>
<th>$\eta$ (cm$^{-1}$)</th>
<th>$\sigma_n$ (cm$^2$)</th>
<th>$\sigma_h$ (cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Donor</td>
<td>$E_C - 0.23$</td>
<td>0.006</td>
<td>$2.3 \times 10^{-14}$</td>
<td>$2.3 \times 10^{-15}$</td>
</tr>
<tr>
<td>Acceptor</td>
<td>$E_C - 0.42$</td>
<td>1.6</td>
<td>$1 \times 10^{-15}$</td>
<td>$1 \times 10^{-14}$</td>
</tr>
<tr>
<td>Acceptor</td>
<td>$E_C - 0.46$</td>
<td>0.9</td>
<td>$7 \times 10^{-14}$</td>
<td>$7 \times 10^{-13}$</td>
</tr>
</tbody>
</table>


Charge Collection for silicon strips.

Conclusions

✓ Modelling radiation damage effects is a tough task!

✓ Radiation damage modelling scheme (bulk + surface), suitable for commercial TCAD tools (e.g. Synopsys Sentaurus).

✓ Predictive capabilities extended to high doses (fluences).

✓ Validation with experimental data comparisons → model refinement.

✓ Application to the optimization of advanced (pixel) detectors (3D detectors, LGADs, ...).

✓ Increasing significance of surface/interface related radiation damage effects for future e+/e- colliders...

✓ ... becoming more relevant if sensitive parts of the sensor chip are placed underneath or close to oxide layers (e.g. in LGAD and HV-CMOS sensors).
Backup slides
MOS Capacitor Measurements

- Different measurement campaigns with X-rays @ Padova (IT)
- Doses range $0.05 \div 100$ Mrad(SiO$_2$)

![Graph showing capacitance vs. gate voltage with different measurement campaigns and doses.]

$\text{Area}_{\text{GATE}} = 0.1717(\text{MOS1}) \ 0.0998(\text{MOS2}) \quad \text{C}_{\text{LF}}$ (solid), $\text{C}_{\text{HF}}$ (dashed)