A Versatile Analysis of Surface and Bulk Radiation Damage Effects

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\textsuperscript{f} TIFPA INFN, via Sommarive 14, 38123 Trento, Italy
\textsuperscript{g} HEPHY, Austrian Academy of Sciences, 1050 Wien, Austria
Outline

• Motivations

• Experimental Measurements (X-rays irradiations)
  • Different test-structures (Gated Diodes, MOS capacitors, MOSFETs)
  • Different providers (FBK, HPK, IFX) and substrates (p-type, n-type)

• Simulation Results

• Comparison with experimental data
  • Update of the TCAD Si/SiO₂ interface damage model
  • Combined surface and bulk damage model

• Conclusions
Motivations and goals

- Simulate the effects of radiation damage on silicon devices at very high fluences (HL-LHC operation greater than $2 \times 10^{16} \text{ 1MeV } n_{eq}/\text{cm}^2$).

- Extension of the predictive capability of the past “University of Perugia” numerical TCAD model to these very high fluences:
  - Physically-grounded parametrization,
  - Keep low the number of traps (e.g. avoiding fitting),
  - No over-specific modelling (e.g. device and technology independent)
  - Compatibility with the already developed bulk damage model
  - Deep understanding of physical device behavior.

- Extraction from simple test structures of relevant parameters to be included within the model

- Validation of the new modeling scheme through comparison with measurements of different test structures before and after irradiation.
New “University of Perugia” model

- Modelling the effects of the radiation damage.
- Predictive insight of the behaviour of detectors, aiming at their performance optimization.
Test Structures

Measurement Campaign: X-ray irradiation
- carried out in Padova (IT)
- doses range: 0.05 ÷ 20 Mrad(SiO₂)
Test structures IFX and HPK

- MOS capacitors
- 1 gated diode (called GCD)
- Strip structures for Rint measurements

√ Measurement Campaign: X-ray irradiation
  - carried out in Padova (IT)
  - doses range: $0.05 \div 20$ Mrad(SiO$_2$)
New “University of Perugia” model

TEST STRUCTURE MEASUREMENTS

MODEL

PARAMETERS EXTRAPOLATION

MODEL VALIDATION

DETECTOR OPTIMIZATION
FBK - MOS Capacitors: measurements

- $n$-type substrate
- HF measurements at 100 kHz with a small signal amplitude of 15 mV.
- The QS characteristics were measured with delay times of 0.7 s using a voltage step of 100 mV.
- Effective oxide charge density $N_{\text{EFF}}$ obtained from $V_{\text{FB}}$ measurements.
- Unbiased devices during the irradiation steps.
The interface trap density ($D_{IT}$) was estimated by using the C-V High-Low method.

Donor interface trap states evaluation from $p$-type substrates

Accepter interface trap states evaluation from $n$-type substrates
FBK – Gated Diodes

- Unbiased devices during the irradiation steps.
- From I-V measurements the surface velocity $s_0$ was evaluated as a function of the dose.

$$s_0 = \frac{I_s}{n_i q A_G}$$

$$s_0 = \frac{\pi}{2} \sigma_s v_{th} D_{it} k_B T$$
FBK - MOSFETs

- $V_{th} = -0.8 \div 0.1$ V (unirradiated)
- Unbiased devices during the irradiation steps
- Radiation $\rightarrow$ interface traps ($N_{IT}$) + trapped-oxide ($N_{Ox}$) $\rightarrow$ $V_{th}$ shift ($\Delta V_{th}$).
- $\Delta V_{th}$ is separated into a contribution due to $N_{IT}$ and due to $N_{Ox}$, from $I_{DS}$-$V_{GS}$ of MOSFET (method proposed in McWorther Applied Physics Letters 48, 133 (1986))

\[
\Delta V_{th} = \Delta V_{N_{IT}} + \Delta V_{N_{Ox}}
\]
FBK Summary of measurements – p-type

Effective oxide charge density ($N_{\text{EFF}}$)

Integrated interface trap density ($N_{\text{IT}}$)

Describe the Donor trap state characteristics as INPUT PARAMETERS to the TCAD tool
FBK Summary of measurements – n-type

Effective oxide charge density ($N_{\text{EFF}}$)

Integrated interface trap density ($N_{\text{IT}}$)

Describe the Acceptor trap state characteristics as INPUT PARAMETERS to the TCAD tool.
IFX p-type MOS CV Measurements after X-ray

- $V_{FB} \approx -10$ V at 50 krad
- $V_{FB} \approx -17$ V at 100 krad (not shown in this figure)
- $V_{FB} \approx -30$ V at 500 krad
- $V_{FB} \approx -42$ V at 1 Mrad krad
- $V_{FB} \approx -50$ V at 10-20 Mrad
HPK and IFX p-type Summary of measurements

P-type substrate

- Very similar values between two vendors
IFX and HPK p-type GCD after X-ray irradiation

- Annealing 80°C 10 min
- Surface velocity $s_0$ evaluated as a function of the dose
- Area $11.71$ mm$^2$

Area $6.14$ mm$^2$
Interstrip resistance after X-ray irradiation

**IFX**

![Graph showing interstrip resistance vs. V_{SUB} for different radiation doses.]

**HPK**

![Graph showing interstrip resistance vs. Bias Voltage for different radiation doses.]

- **R_{INT}(Ω)**
  - 1E11
  - 1E10
  - 1E9
  - 1E8
  - 1E7

- **V_{SUB} (V)**
  - 0
  - 100
  - 200
  - 300
  - 400
  - 500

- **Resistance (Ω)**
  - 1x10^10
  - 1x10^9
  - 1x10^8
  - 1x10^7
  - 1x10^6

- **Bias Voltage (V)**
  - 0
  - 100
  - 200
  - 300
  - 400
  - 500

- **Radiation Doses:**
  - 50 krad
  - 100 krad
  - 500 krad
  - 1 Mrad
  - 20 Mrad
  - 100 krad
  - 500 krad
  - 1 Mrad
  - 10 Mrad
  - 20 Mrad
New “University of Perugia” model
### Surface Damage Model: Gaussian

#### Interface trap state energy modelling

<table>
<thead>
<tr>
<th>Type</th>
<th>Peak Energy (eV)</th>
<th>Density (cm(^{-2}))</th>
<th>(\sigma) (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptor</td>
<td>(E_C - 0.40)</td>
<td>40% of acceptor (N_{IT}) ([1]) ((N_{IT} = M \cdot N_{OX}))</td>
<td>0.07</td>
</tr>
<tr>
<td>Acceptor</td>
<td>(E_C - 0.60)</td>
<td>60% of acceptor (N_{IT}) ([1]) ((N_{IT} = M \cdot N_{OX}))</td>
<td>0.07</td>
</tr>
<tr>
<td>Donor</td>
<td>(E_V + 0.70)</td>
<td>100% of donor (N_{IT}) ((N_{IT} = M \cdot N_{OX}))</td>
<td>0.07</td>
</tr>
</tbody>
</table>

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F. Moscatelli et al., HSTD11 & SOIPIX2017, 11 December 2017
# Surface Damage Model: Uniform Bands

## Interface trap state energy modelling

![Diagram showing the energy levels of the bands](image)

### Band Diagram

- **Conduction Band**
  - **E_C**
  - **Acceptor Band**
  - **Donor Band**
- **Valence Band**
  - **E_V**
  - **E_C - 0.56 eV**
  - **E_V + 0.6 eV**
  - **E_V + 0.3 eV**

## Band Properties

<table>
<thead>
<tr>
<th>Type</th>
<th>Energy (eV)</th>
<th>Band width (eV)</th>
<th>Concentration (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>( \text{Dit} = \text{Dit}(\Phi) )</td>
</tr>
<tr>
<td>Donor</td>
<td>( E_V + 0.3 \leq E_T \leq E_V + 0.6 )</td>
<td>0.30</td>
<td>( \text{Dit} = \text{Dit}(\Phi) )</td>
</tr>
</tbody>
</table>
Gated Controlled Diode – surface damage

- I-V measurements compared to simulations at different doses.
- Surface velocity $s_0 \rightarrow$ agreement between simul. and meas. 
  ($s_0 \neq$ fitting parameter, $s_0 =$ simul. output)

![Diode Diagram]

- 450 µm active layer
- $n_{-sub}=6 \cdot 10^{11}$ cm$^{-3}$
- $p^+=1 \cdot 10^{19}$ cm$^{-3}$

**Measurements**

**Simulations**

- $S_0 = 88.1$ cm/sv
- $S_0 = 107$ cm/s
- $S_0 = 65.2$ cm/s
- $S_0 = 69.6$ cm/s
FBK MOS Capacitors – Model validation

@ 20 Mrad

✓ Irradiated FBK structures n-type.
✓ C-V measurements compared to simulations at different doses.
→ Good agreement!

@ 50 krad

@ 100 krad

@ 10 Mrad

@ 20 Mrad
HPK p-type MOS capacitors: simulations

- Irradiated structures HPK p-type.
- C-V measurements compared to simulations at different doses.

→ Using the same model good agreement between simulation and experimental data.
IFX p-type MOS capacitors: simulations

- Irradiated structures IFX p-type.
- C-V measurements compared to simulations at different doses, using the same model.

Good agreement for IFX devices!

50 krad

1 Mrad

20 Mrad
The new “University of Perugia” model

√ For fluences up to $2.2 \times 10^{16}$ 1 MeV $n_{eq}/cm^2$)

√ Surface damage

<table>
<thead>
<tr>
<th>Type</th>
<th>Energy Band</th>
<th>Concentration (cm$^{-2}$)</th>
<th>Oxide Charge density (cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptor</td>
<td>$E_C \leq E_T \leq E_C - 0.56$</td>
<td>$D_{IT_{acc}} = D_{IT} (\Phi)$</td>
<td>$N_{OX} = N_{OX}^{\text{pre-xray}} + \Delta N_{OX}(\Phi)$</td>
</tr>
<tr>
<td>Donor</td>
<td>$E_V + 0.3 \leq E_T \leq E_V + 0.6$</td>
<td>$D_{IT_{don}} = D_{IT} (\Phi)$</td>
<td></td>
</tr>
</tbody>
</table>

√ Bulk damage ($\rho$-type) *

<table>
<thead>
<tr>
<th>Type</th>
<th>$E$ (eV)</th>
<th>$\sigma_e$ (cm$^2$)</th>
<th>$\sigma_h$ (cm$^2$)</th>
<th>$\eta$ (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptor</td>
<td>Ec-0.42</td>
<td>$1.0 \times 10^{-15}$</td>
<td>$1.0 \times 10^{-14}$</td>
<td>1.6</td>
</tr>
<tr>
<td>Acceptor</td>
<td>Ec-0.46</td>
<td>$0.1 \times \sigma_h (\Phi)$</td>
<td>$\sigma_h (\Phi)$</td>
<td>0.9</td>
</tr>
<tr>
<td>Donor</td>
<td>Ev+0.36</td>
<td>$3.2 \times 10^{-13}$</td>
<td>$3.2 \times 10^{-14}$</td>
<td>0.9</td>
</tr>
</tbody>
</table>

√ Avalanche ON: Van Overstraeten–De Man (default)

Overhang effect at high fluences

Fluence $2 \times 10^{16}$ n/cm$^2$

Different particle hit
Overhang effect at high fluences: CCE

At high fluences charge multiplication effect for particle hit interesting the high-field regions
Effect of w/p ratio

Decreasing w/p ratio, the electric field at the strip corners increases.

w=40 µm p=80 µm

w=20 µm p=80 µm
Conclusions

✓ Extensive measurements campaign on dedicated FBK p-on-n and n-on-p, IFX and HPK n-on-p test structures before and after irradiation with X-rays.

✓ Surface radiation damage effects have been deeply investigated aiming at the extraction of the most relevant parameters:

✓ cross-check of $N_{OX}$, $N_{IT}$, $D_{IT}$ evaluated by different methodologies from different test structures and for different vendors (FBK, HPK and IFX).

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

✓ No over-specific modelling

✓ Application to the analysis and optimization of different classes of silicon detectors to be used in the future HEP experiments.
Backup slides
Two different irradiation conditions: without/with biasing the devices.
Comparison of Simulators - Perugia
Irradiated structure – IV curves

- compare IV curves from both simulators at different temperatures
- small difference between the two
- current lower in Synopsys
- constant ratio – difference could be due to temperature scaling

Evaluation of the current related damage rate $\alpha$ at 20 C (no rescale for temperature needed) gives:

<table>
<thead>
<tr>
<th>Tool</th>
<th>Silvaco</th>
<th>Synopsys</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ [$10^{-17}$ A/cm]</td>
<td>4.2±0.1</td>
<td>3.5±0.1</td>
</tr>
</tbody>
</table>
Charge Collection Efficiency

✓ Charge collection: simulations vs. measurements at different biasing voltages (T = 248 K)
  - bulk + surface model

MOS Capacitors – surface damage

- Non-Irradiated structures.
- C-V measurements compared to simulations at different doses.

![Graph showing C<sub>L</sub>F (solid), C<sub>HF</sub> (dashed)]
Effect of the Interface Trap density ($N_{IT}$)

✓ C-V simulations two case studies:
 ✓ Separate effect of $N_{ITacc}$ and $N_{ITacc}$

![Diagram](image)

- $N_{ITacc} = N_{ITdon}$
- $N_{ITacc} \approx 10 \cdot N_{ITdon}$
- $N_{ITdon} \approx 10 \cdot N_{ITacc}$
Effect of the Interface Trap density ($N_{IT}$)

- C-V simulations two case studies:
  - Separate effect of $N_{ITacc}$ and $N_{ITacc}$
  - $N_{ITacc} = N_{ITdon} = K$.

$C_LF$ highly depends on the $N_{IT}$

- $K = 1.0 \times 10^{10}$ cm$^{-2}$
- $K = 2.0 \times 10^{10}$ cm$^{-2}$
- $K = 6.0 \times 10^{10}$ cm$^{-2}$
Effect of the Oxide Charge density ($N_{ox}$)
Setting-up the measurements

✓ Measurement Campaign: X-ray irradiation
  • carried out in Padova (IT)
  • doses range:
    o 50 krad-10 Mrad (SiO$_2$)
    o 1 Mrad-20 Mrad (SiO$_2$)

✓ MOS capacitors, Gate-Controlled Diode (GCD), MOSFETs during irradiation steps.

✓ Measurements at 20°C
  • after irradiation / annealing 80°C 10 min (repeated minimum three times)

✓ Dry Nitrogen flux to maintain the relative humidity of the order of few percent
Simulation tools

Bulk damage

<table>
<thead>
<tr>
<th>Type</th>
<th>E (eV)</th>
<th>$\sigma_1$ (cm$^2$)</th>
<th>$\sigma_2$ (cm$^2$)</th>
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<td>0.1×$\sigma_1$ ($\Phi$)</td>
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Surface damage

<table>
<thead>
<tr>
<th>Type</th>
<th>Energy Band</th>
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<th>Oxide Charge density (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptor</td>
<td>Ec-0.3 ± 0.3 eV</td>
<td>$D_{trac} = D_{tr} (\Phi)$</td>
<td>$N_{ox} = \frac{\eta_{ox} \times 3 \times 4}{9} - \Delta N_{ox} (\Phi)$</td>
</tr>
<tr>
<td>Donor</td>
<td>Ev+0.15 ± 0.15 eV</td>
<td>$D_{trac} = D_{tr} (\Phi)$</td>
<td></td>
</tr>
</tbody>
</table>

Radiation damage model

Math

The Poisson's equation

$$\nabla \cdot (-\varepsilon_s \nabla \varphi) = q (N_D - N_A + p - n)$$

The continuity equations

$$\frac{\partial n}{\partial t} + \frac{1}{q} \nabla \cdot \vec{J}_n = G - R$$
$$\frac{\partial p}{\partial t} + \frac{1}{q} \nabla \cdot \vec{J}_p = G - R$$

Model VALIDATION

Device OPTIMIZATION

geometry
doping
mesh
layout
Surface Damage Model: Levels

- Interface trap state energy modelling

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Charge Collection Efficiency

✓ Charge collection: simulations vs. measurements at different biasing voltages (T = 248 K)
  - bulk + surface model

![Graph showing collected charge vs. fluence for neutrons, protons, and simulated surface plus bulk models with uniform, levels, and Gaussian distributions.]
Transient Analysis: MIP Response

✓ Central hit strip vs. lateral hit (in between two strips)

\[ V_{BIAS} = 900 \, V \]

\[ \Phi = 1 \cdot 10^{15} \, n/cm^2 \]
<table>
<thead>
<tr>
<th>Dose (rad)</th>
<th>$S_0$ (cm/s)</th>
<th>$V_{bulk}$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>measured</td>
<td>simulated</td>
</tr>
<tr>
<td>50 k</td>
<td>65.2</td>
<td>69.6</td>
</tr>
<tr>
<td>100 k</td>
<td>88.1</td>
<td>107</td>
</tr>
<tr>
<td>500 k</td>
<td>311</td>
<td>260</td>
</tr>
<tr>
<td>1 M</td>
<td>466</td>
<td>480</td>
</tr>
<tr>
<td>10 M</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 M</td>
<td></td>
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</tr>
</tbody>
</table>
### Bulk damage

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</table>

(7.0×10$^{15}$ ÷ 1.5×10$^{16}$ n/cm$^2$)

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<th>$\sigma_h$ (cm$^2$)</th>
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</tr>
</tbody>
</table>

(1.6×10$^{16}$ ÷ 2.2×10$^{16}$ n/cm$^2$)

w/p ratio

- \( W \) vs. \( P \)
- \( W < P \)
- \( W \ll P \)

Increased \( \vec{E} \)