Measurements and Simulations of Surface Radiation Damage Effects on IFX and HPK Test Structures

F. Moscatelli\textsuperscript{a,b}, A. Morozzi\textsuperscript{b,c}, D. Passeri\textsuperscript{b,c}, S. Mattiazzo\textsuperscript{d}, G.-F. Dalla Betta\textsuperscript{e,f}, V. Hinger\textsuperscript{g} and G. M. Bilei\textsuperscript{b}

\textsuperscript{a} CNR-IOM of Perugia, via Pascoli 1, 06123, Perugia, Italy
\textsuperscript{b} INFN of Perugia, via Pascoli 1, 06123, Perugia, Italy
\textsuperscript{c} Department of Engineering – University of Perugia, via G. Duranti 93, 06125, Perugia, Italy
\textsuperscript{d} Dipartimento di Fisica e Astronomia e INFN di Padova, via Marzolo 8, 35131 Padova, Italy
\textsuperscript{e} DII University of Trento, via Sommarive 9, 38123, Trento, Italy
\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 (MOS capacitors, Gated Diodes, Interstrip resistance test structures)
  • Different providers (HPK, IFX) and processes

• TCAD Simulation Results

• Model validation: comparison between simulation findings and experimental data

• Conclusions and future developments
Motivations and goals

- Study the effects of surface damage on silicon devices at high doses (HL-LHC operation greater than 50 Mrad for Outer Tracker and 1 Grad for Inner Tracker).

- Surface damage can strongly influence the breakdown, the inter-electrode isolation, the dark current and the charge collection efficiency of the sensor.

- Extension of the predictive capability of the past “University of Perugia” numerical TCAD model to these very high doses:
  - Physically-grounded parametrization,
  - Keep low the number of traps (e.g. avoiding fitting),
  - No over-specific modelling (e.g. device and technology independent)
  - 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 manufactured by different vendors with different processes before and after irradiation.
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). Dose rate 0.8 Mrad/hour
  - doses range: 0.05 ÷ 100 Mrad(SiO₂)
  - Measurements after irradiation / annealing 80°C 10 min.
IFX devices

1\textsuperscript{st} campaign 0.05-20 Mrad
IFX 8-inch 2S run
MOS
GCD
Rint

2\textsuperscript{nd} campaign
IFX 8-inch 2S run
MOS

2\textsuperscript{nd} campaign
IFX 6-inch PS-S run
MOS
FET
MOS Capacitors: measurements

- $p$-type substrate.
- HF measurements at 100 kHz with a small signal amplitude of 25 mV.
- The QS characteristics were measured with delay times of 0.5 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. Dry N flux during measurements.
IFX 2S 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
- $V_{FB} \approx -50$ V at 10-20 Mrad
IFX 2S MOS CV after X-ray 2nd campaign

- $V_{FB} \approx -5$ V at 50 krad
- $V_{FB} \approx -7$ V at 100 krad
- $V_{FB} \approx -18$ V at 500 krad
- $V_{FB} \approx -23$ V at 1 Mrad
- $V_{FB} \approx -35$ V at 10 Mrad
- $V_{FB} \approx -65$ V at 100 Mrad
IFX PS-S CV after X-rays

- $V_{FB} \approx -4$ V at 50 krad
- $V_{FB} \approx -5$ V at 100 krad
- $V_{FB} \approx -11$ V at 500 krad
- $V_{FB} \approx -15$ V at 1 Mrad
- $V_{FB} \approx -40$ V at 10 Mrad
- $V_{FB} \approx -55$ V at 100 Mrad
HPK CV after X-rays

Process p-stop (no implant under the oxide)  P-spray
IFX - MOSFETs

- $V_{th} = -0.1$ (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))

$$\Delta V_{th} = \Delta V_{N_{it}} + \Delta V_{N_{ox}}$$
IFX p-type Summary of measurements

For $N_{\text{EFF}}$ :
- Differences among the three processes at low doses.
- At high doses similar results.
- PS-S has higher interface traps
HPK p-type Summary of measurements

As expected very similar values for HPK devices
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 mm²
- Area 6.14 mm²
Interstrip resistance after X-ray irradiation

Interstrip resistance values are similar between the two campaigns
New “University of Perugia” model

- TEST STRUCTURE MEASUREMENTS
- PARAMETERS EXTRAPOLATION
- MODEL OPTIMIZATION
- MODEL VALIDATION
- DETECTOR OPTIMIZATION

F. Moscatelli et al., VCI 2019
### 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>σ (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>

Surface Damage Model: Uniform Bands

- Interface trap state energy modelling

<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>Dit = 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>Dit = Dit($\Phi$)</td>
</tr>
</tbody>
</table>

F. Moscatelli et al: “Analysis of surface radiation damage effects at HL-LHC fluences: Comparison of different technology options”, NIMA
https://doi.org/10.1016/j.nima.2018.07.081
IFX 2S MOS capacitors: simulations

- Irradiated structures IFX 2S 1\textsuperscript{st} campaign.
- C-V measurements compared to simulations at different doses.

→ Good agreement for IFX devices!
IFX 2S 2nd campaign MOS capacitors

- Irradiated structures IFX 2S 2nd campaign.
- C-V measurements compared to simulations at different doses with measured \( N_{IT} \) and \( N_{OX} \) of 2S wafer.
IFX PS-S MOS capacitors

- Irradiated structures IFX PS-S 2\textsuperscript{nd} campaign.
- Low $N_{OX}$ at low doses
- Higher $N_{IT}$
HPK p-type MOS capacitors: simulations

- Irradiated structures HPK p-type without p-spray.
- C-V measurements compared to simulations at different doses.

→ Using the same model with measured $N_{OX}$ and $N_{IT}$ good agreement between simulation and experimental data.
HPK MOS capacitors with p-spray: simulations

✓ Irradiated structures HPK p-type with p-spray.
Gated diodes

- p-type substrate
- Irradiated structures IFX p-type.
Interstrip resistance HPK

Good agreement using the same model used to simulate MOS capacitors
Conclusions

✓ Extensive measurements campaign on 5 different 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, for different vendors (HPK and IFX) and different processes.

✓ Development of the radiation damage modelling scheme, suitable for commercial TCAD tools (e.g. Synopsys Sentaurus), with a good agreement between measurements and simulations

✓ Application to the analysis and optimization of different classes of silicon detectors to be used in the future HEP experiments.
Future developments

- Bias the IFX and HPK devices during X-rays irradiation
- Irradiate new HPK batches FZ290 and thFZ240
- Irradiate test structures first with X-rays and then with neutrons to combine surface and bulk damage
Backup slides
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))

$$\Delta V_{th} = \Delta V_{N_{it}} + \Delta V_{N_{ox}}$$

\[ \begin{align*}
\text{pMOSFET} & \quad 50 \text{ krad (SiO}_2\text{)} \\
\quad & \quad 500 \text{ krad (SiO}_2\text{)} \\
\text{nMOSFET} & \quad 20 \text{ Mrad (SiO}_2\text{)} \\
\end{align*} \]
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.
Two different irradiation conditions: without/with biasing the devices.