Journées thématiques du Réseau Semi-conducteurs IN2P3-IRFU.
Méthodes de test orientées simulation

Radiation Damage Effects: Characterization Techniques and Numerical Modelling

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Outline

- Motivation / Radiation damage effects in silicon sensors
- TCAD radiation damage modelling approach.
- **Surface damage effects**: Simulations vs. Measurements
  - ☐ Test structures / measurements and parameters extraction.
  - ☐ DC (steady-state) -> Diodes / Gate Controlled Diodes.
  - ☐ AC (small-signals) -> MOS Capacitors.
- “**New Perugia model**” - Comprehensive Bulk + Surface TCAD damage modelling scheme
  - ☐ Leakage current.
  - ☐ Electric field profile.
  - ☐ Charge Collection Efficiency.
  - ☐ Model Application in the prediction of complex devices behavior (e.g. LGAD).

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Motivations

- √ Given the expected radiation levels at future collider experiments, the radiation-tolerance of the detectors is of the utmost importance. Need of numerical models to predict the behavior of heavily irradiated devices.
- √ 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 considered 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 SYNOPSYS®

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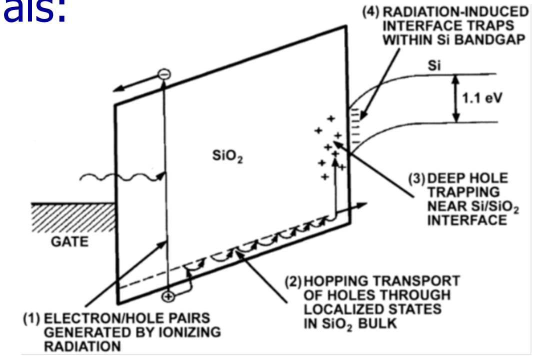
Radiation damage effects

Two main types of radiation damage in detector materials:

√ SURFACE damage ← Ionizing Energy Loss (IEL)

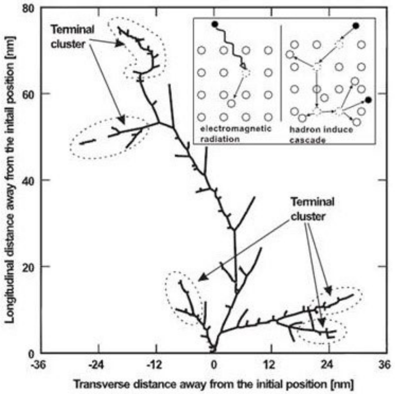
- build-up of trapped charge within the oxide;
- bulk oxide traps increase;
- interface traps increase;
- Q_{OX}, N_{IT}.



T. R. Oldham, F. B. McLean, *Total Ionizing Dose Effects in MOS Oxides and Devices*, IEEE Trans. on Nuclear Science, vol. 50, no. 3, June 2003

√ BULK damage ← Non-Ionizing Energy Loss (NIEL)

- silicon lattice defect generations;
- point and cluster defects;
- deep-level trap states increase;
- change of effective doping concentration;
- N_T.



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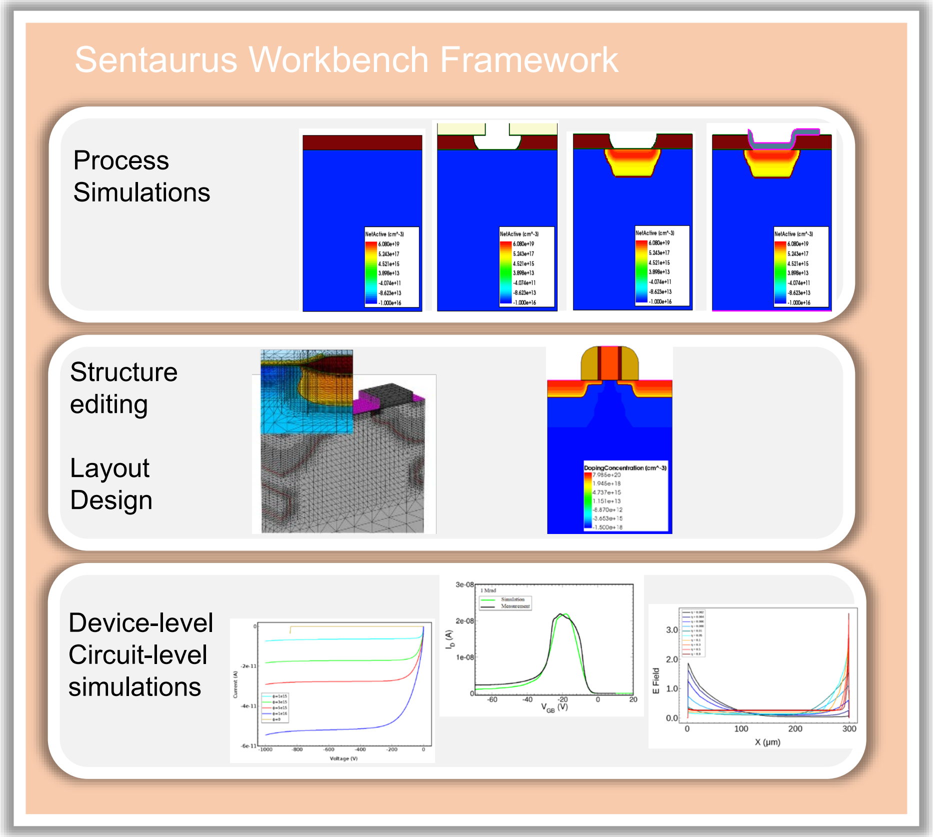
The Technology-CAD modelling approach


Sentaurus Workbench Framework

Process Simulations

Structure editing

Layout Design

Device-level Circuit-level simulations

- √ 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.
- ✓ Synopsys© Sentaurus TCAD

$$
\begin{cases}
\nabla\cdot\left(-\varepsilon_s\nabla\varphi\right)=q\left(N_D^+-N_A^-+p-n\right) & \text{Poisson} \\
\dfrac{\partial n}{\partial t}-\dfrac{1}{q}\nabla\cdot\vec{J}_n=G-R & \text{Electron continuity} \\
\dfrac{\partial p}{\partial t}+\dfrac{1}{q}\nabla\cdot\vec{J}_p=G-R & \text{Hole continuity}
\end{cases}
$$

$$\vec{J}_n=-q\mu_n n\nabla\varphi+qD_n\nabla n$$

$$\vec{J}_p=-q\mu_p p\nabla\varphi-qD_p\nabla p$$

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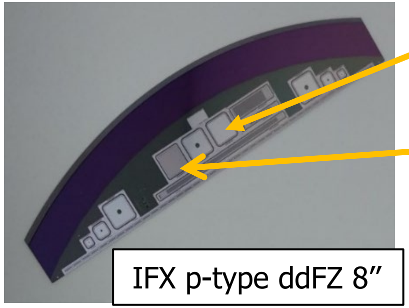
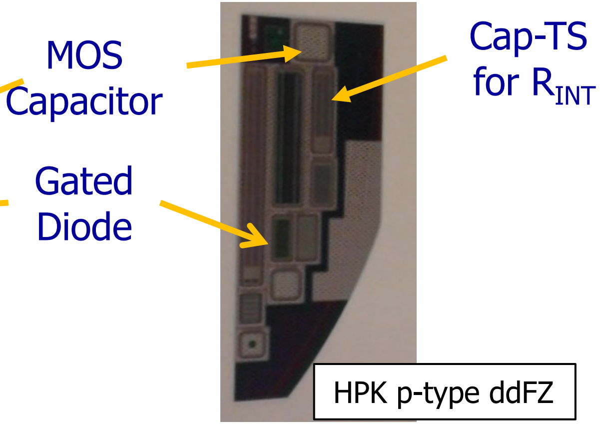
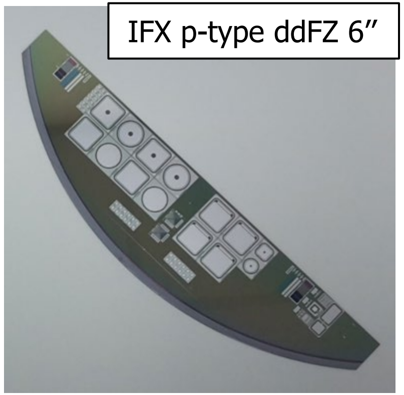
The main test structures at hand

√ Test structures…


IFX p-type ddFZ 8″

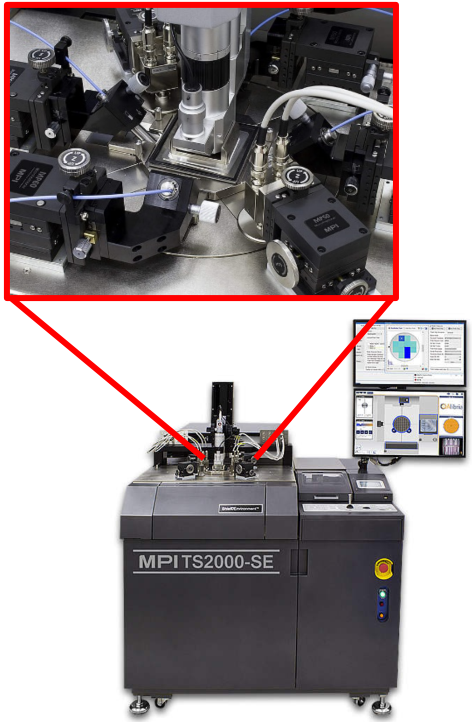


HPK p-type ddFZ


IFX p-type ddFZ 6″

- √ X-ray irradiation in Padova (IT).
- √ Dose range: 0.05 ÷ 100 Mrad(SiO_2).
- √ Dose rate: 0.8 Mrad/hour.
- √ Measurements after irradiation / annealing at 80°C for 10 min.
- √ different processes and thermal budget / p-stop or p-spray isolation options.

√ Measurements: I-V, C-V, R_{INT}



Parameter extraction procedure

√ From C-V measurements of MOS capacitors:

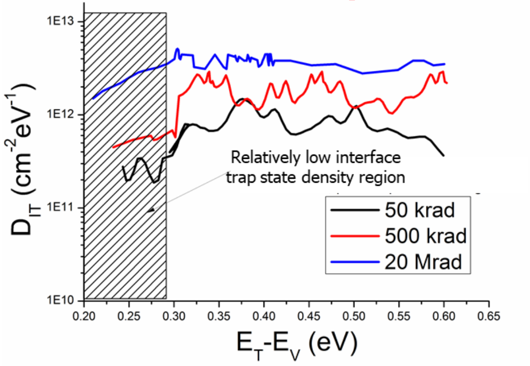
- D_{IT} is assessed by using the C-V High-Low method.
- High-Frequency (HF) measurements are carried out at 100 kHz with a small signal amplitude of 25 mV.
- Quasi-Static (QS) characteristics measured with delay times of 0.5 sec using a voltage step of 100 mV.
- N_{EFF} is obtained from V_{FB} measurements.

$$\mathrm{C_{IT}} = \left(\frac{1}{C_{LF}} - \frac{1}{C_{OX}}\right)^{-1} - \left(\frac{1}{C_{HF}} - \frac{1}{C_{OX}}\right)^{-1}$$

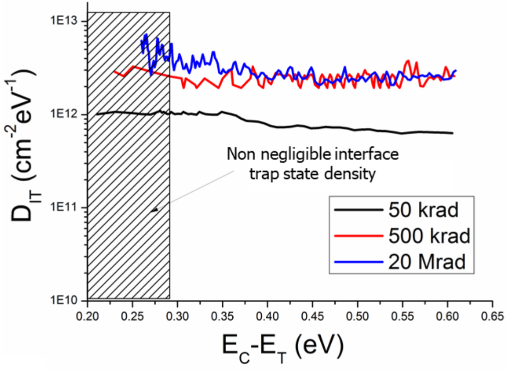
$$\mathrm{D_{IT}} = \frac{\mathrm{C_{IT}}}{\mathrm{q \times A}}$$

$$\mathrm{N_{IT}} = D_{IT}\frac{\mathrm{E_g}}{2}$$

Donor interface trap states (p-type subs)



Acceptor interface trap states (n-type subs)



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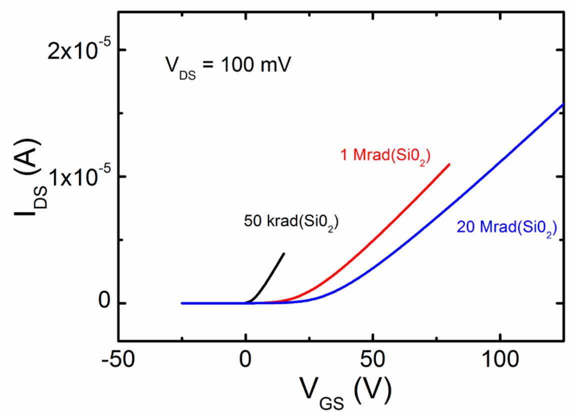
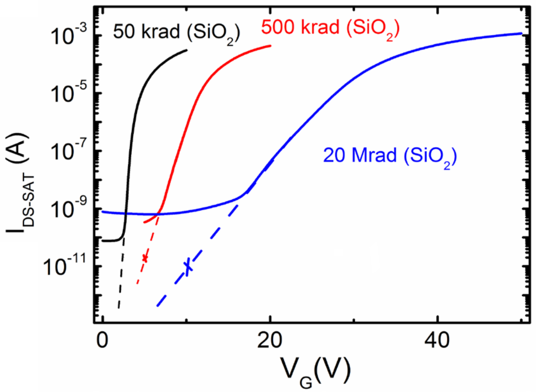


nMOSFET

√ From I-V measurements of MOSFETs:

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

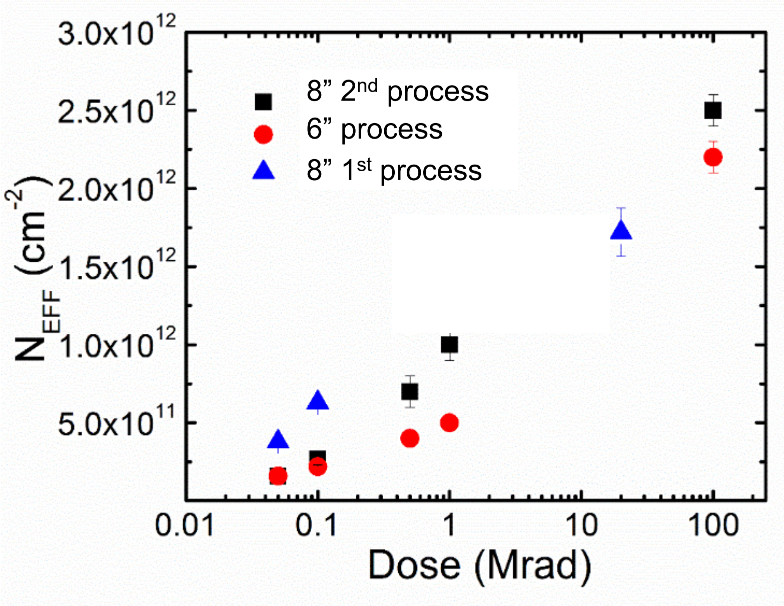


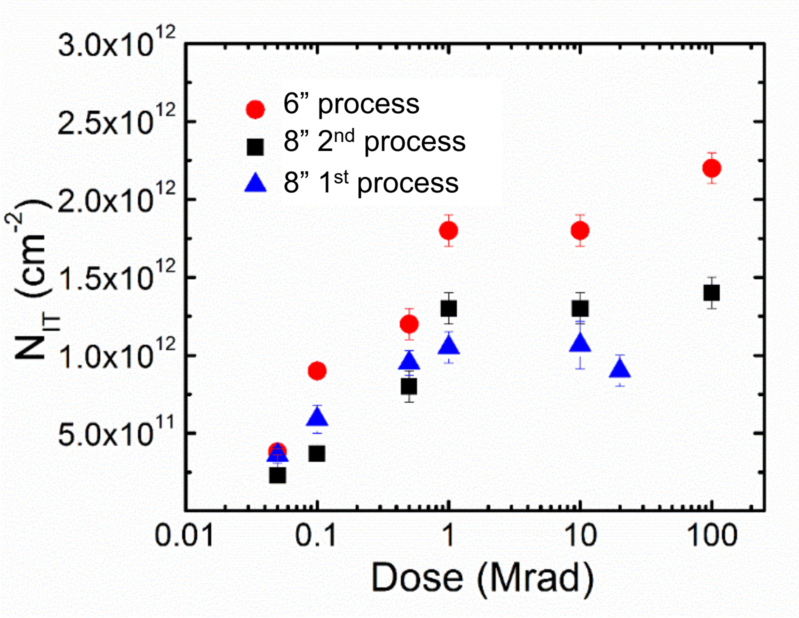
pMOSFET

[1] P. J. McWhorter and P. S. Winokur, *Appl. Phys. Lett. 48*, 133 (1986).

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.





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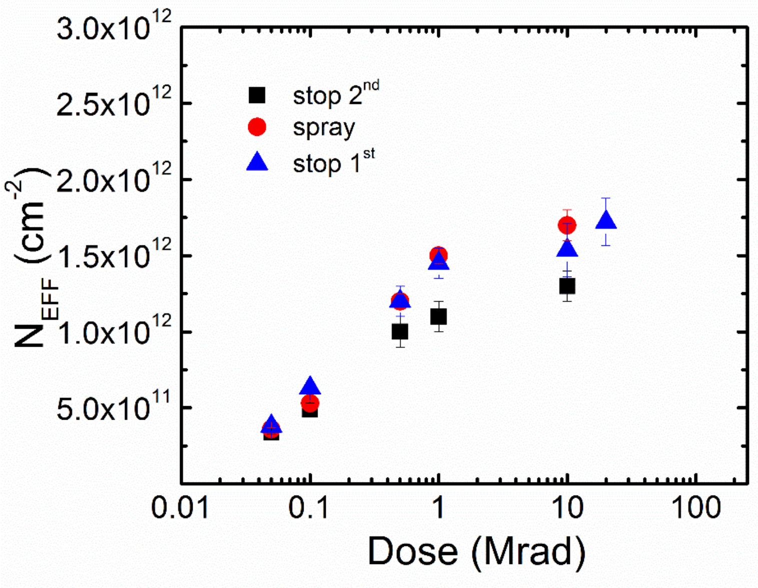
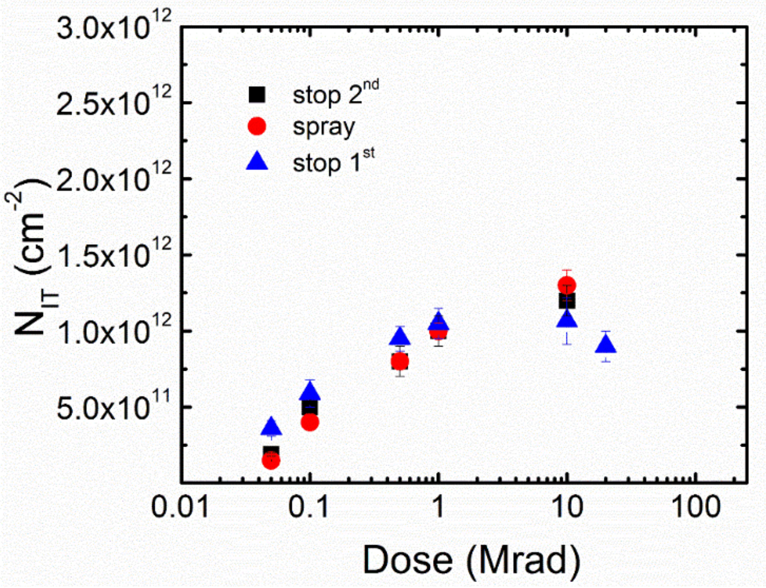
HPK test structures wrap-up

- √ Reduced variability due to different technology options in terms of radiation hardness.
- √ Similar values of N_{EFF} and N_{IT} for HPK devices with different p-stop/p-spray isolation structures.





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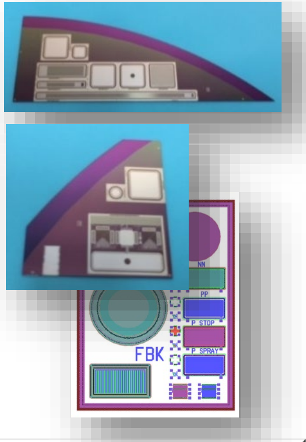
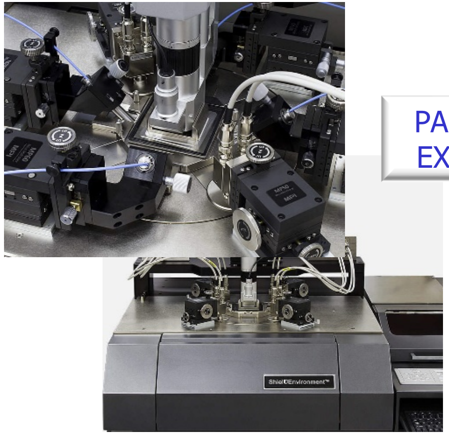
The overall modelling approach pursued

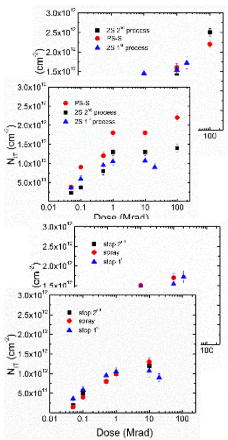


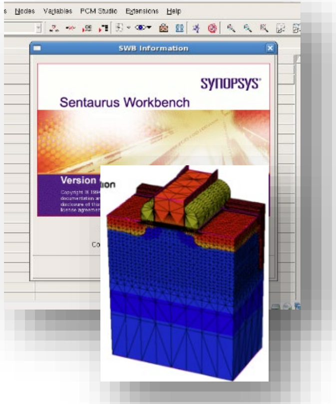
TEST STRUCTURE MEASUREMENTS



PARAMETERS EXTRACTION

MODEL





DETECTOR OPTIMIZATION

CCE, I-V, C-V, …

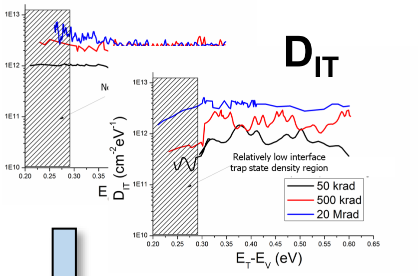
MODEL VALIDATION

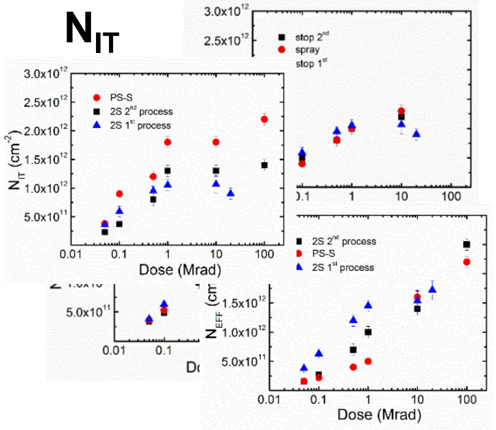
√ Modelling the effects of the radiation damage.

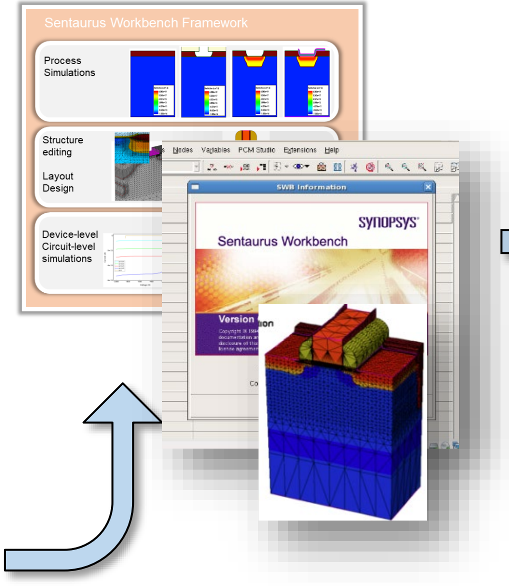
√ Predictive insight of the behaviour of detectors, aiming at their performance optimization.

Development of TCAD surface radiation model

INPUT

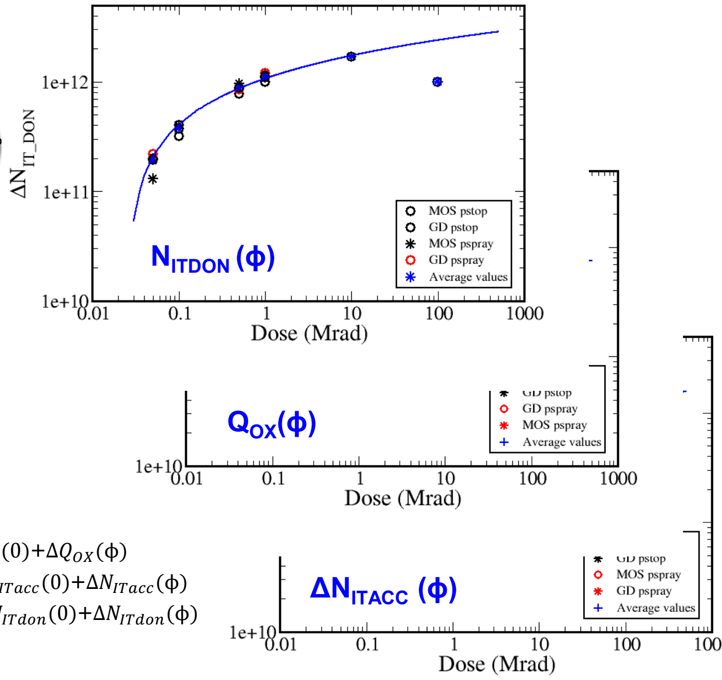






OUTPUT

HPK pspray/pstop



$$Q_{OX}(\phi) = Q_{OX}(0) + \Delta Q_{OX}(\phi)$$
$$N_{ITacc}(\phi) = N_{ITacc}(0) + \Delta N_{ITacc}(\phi)$$
$$N_{ITdon}(\phi) = N_{ITdon}(0) + \Delta N_{ITdon}(\phi)$$

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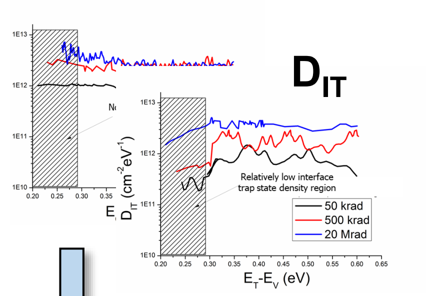
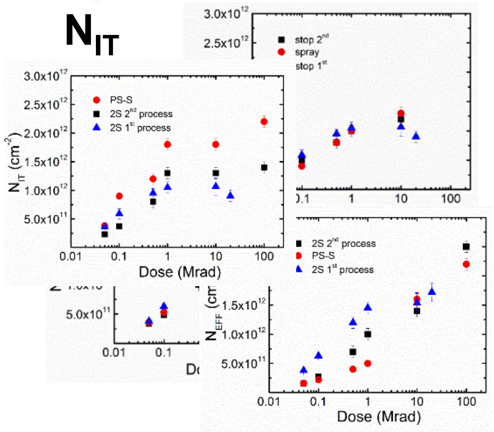
Development of TCAD surface radiation model

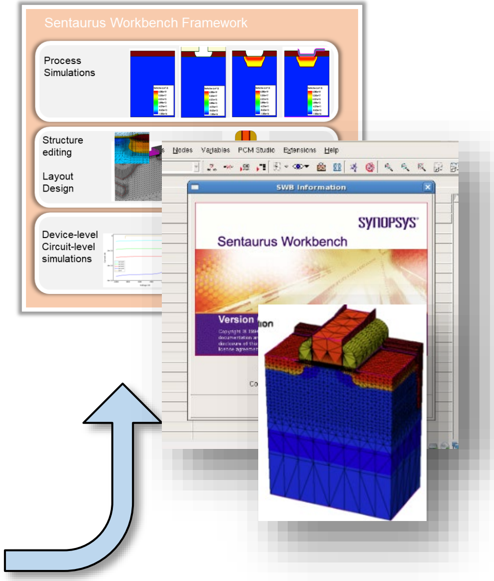
INPUT



D_{IT}

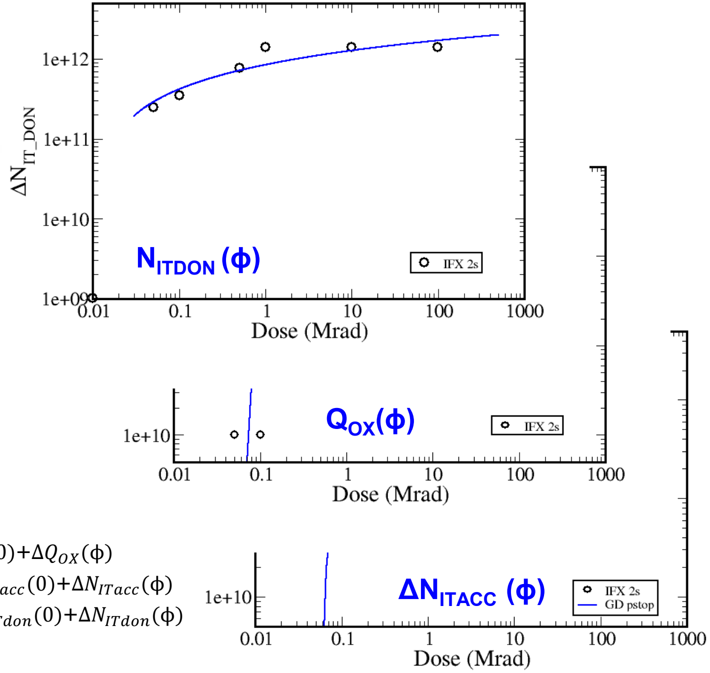
N_{IT}





OUTPUT

IFX 8” process



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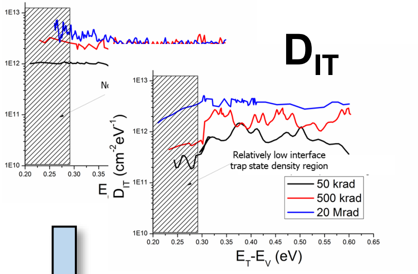
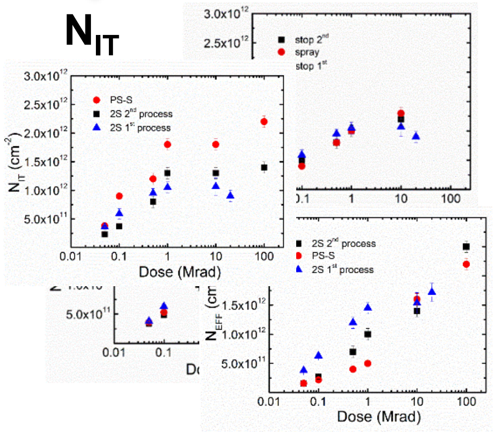
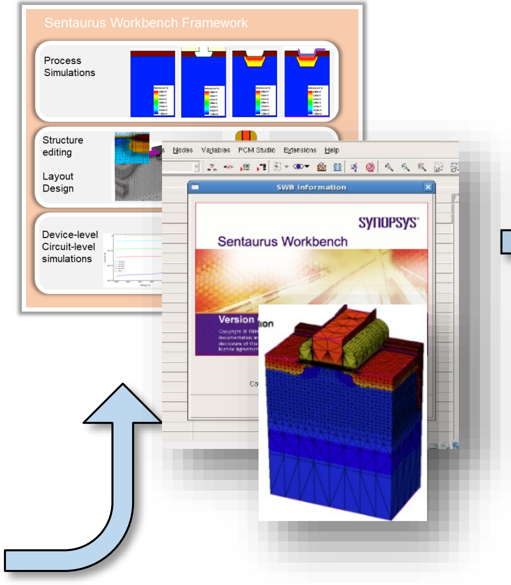


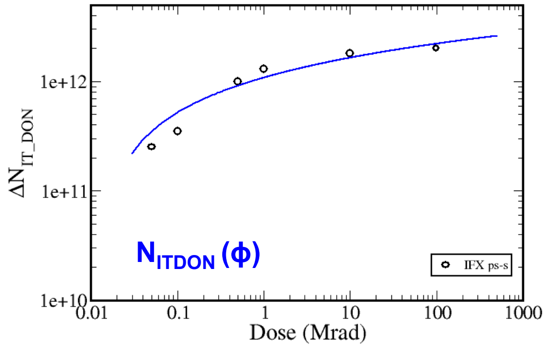
N$_{IT}$

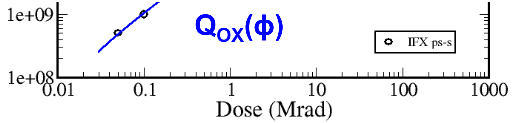




OUTPUT

IFX 6" process





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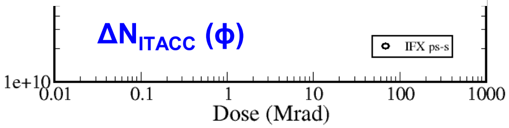

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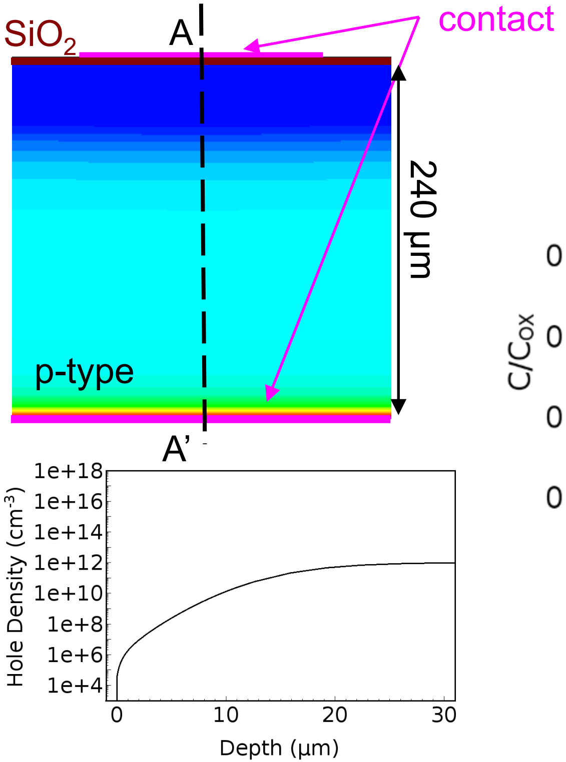
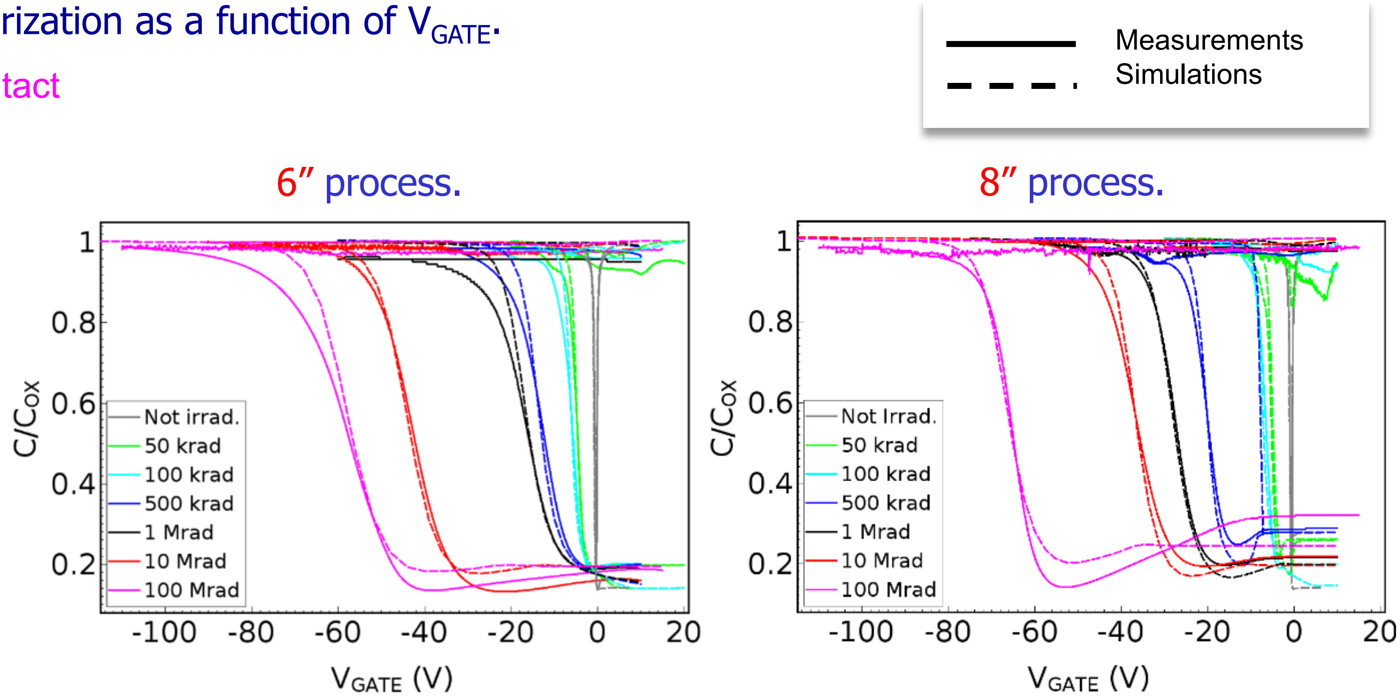
Surface model validation: IFX MOS Capacitors

- √ MOS capacitors characterization as a function of V_{GATE}.





6″ process.

8″ process.

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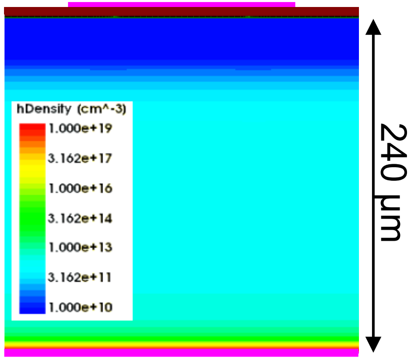
Surface model validation: HPK MOS Capacitors

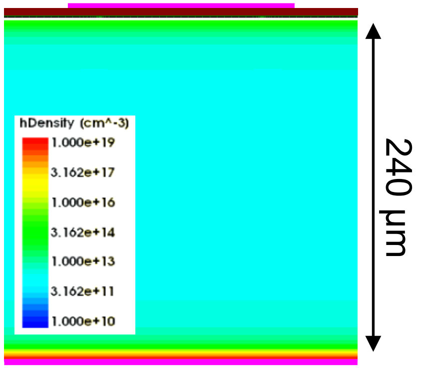
√ MOS capacitors characterization as a function of V_{GATE}.

— Measurements
- - - Simulations

p-stop process.



p-spray process.



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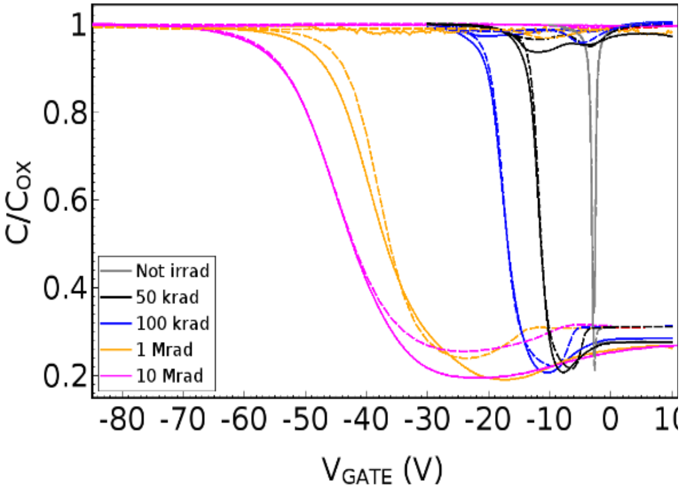

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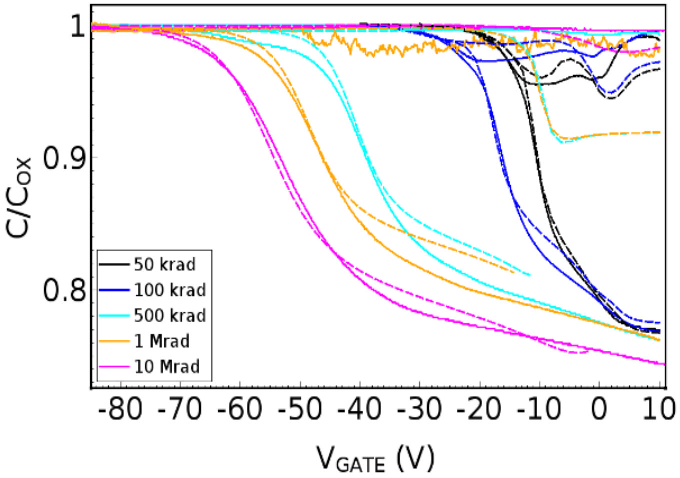
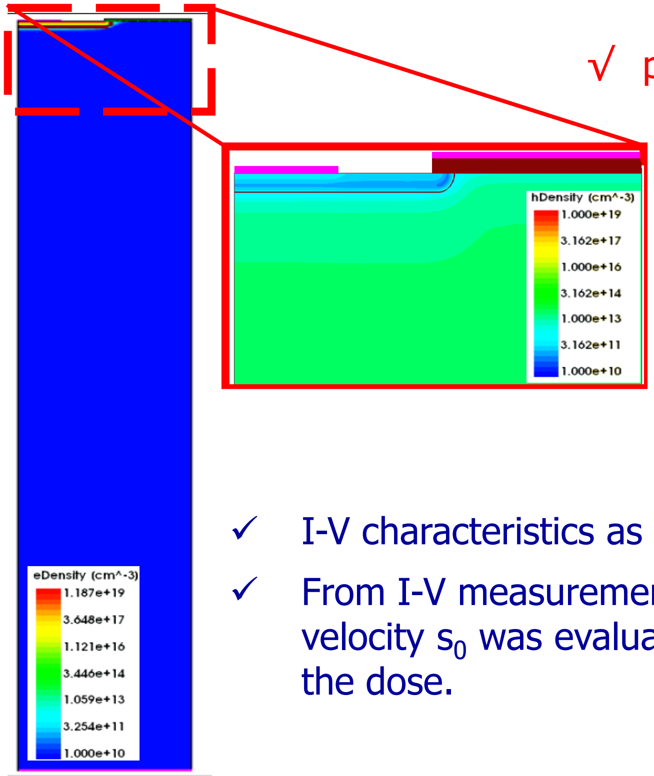
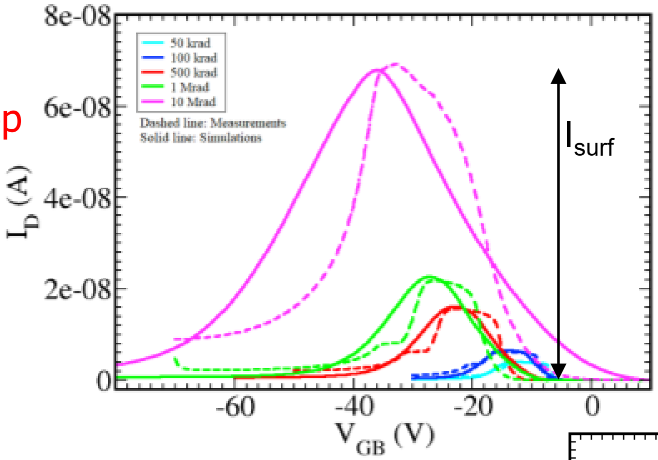


Surface model validation: HPK Gated Diodes



√ p-stop



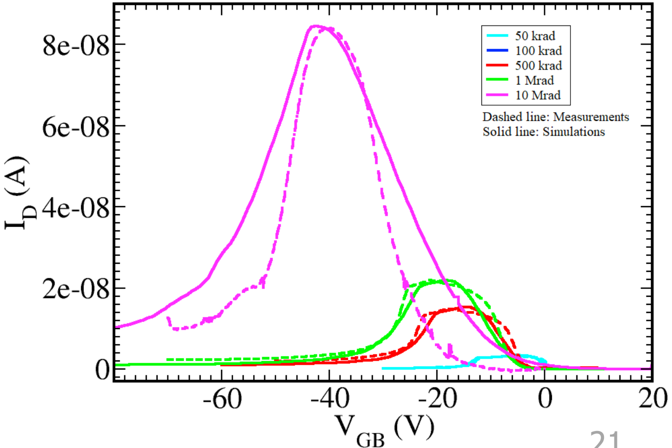
Measurements

Simulations

$$\boxed{s_0} = \frac{\boxed{I_{surf}}}{n_i q A_G}$$

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

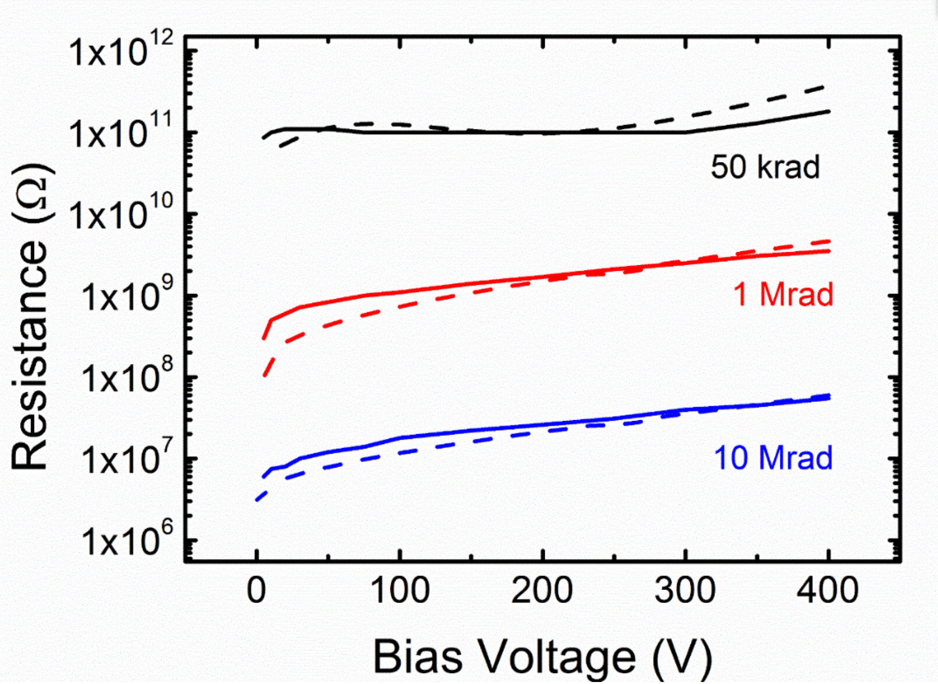
√ p-spray



- ✓ I-V characteristics as a function of V_{GATE}.
- ✓ From I-V measurements the surface velocity s_0 was evaluated as a function of the dose.

Surface model validation: Interstrip resistance

- √ R_{INT} measurements.
- √ HPK p-stop implant isolation.



— Measurements
- - - Simulations

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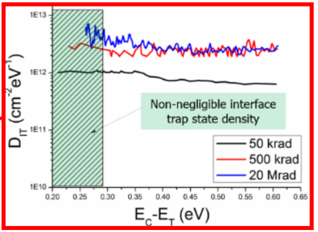
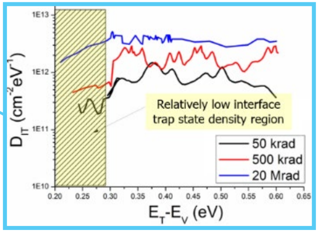
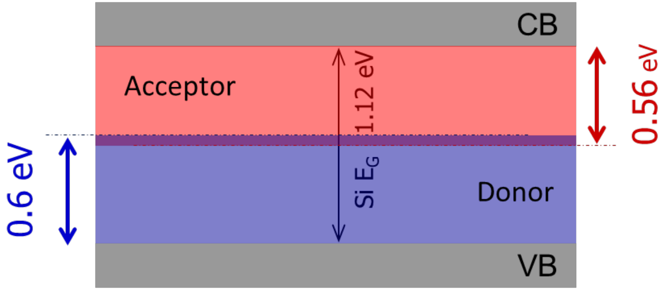
The “New Perugia” model

√ Surface damage (+ Q_{OX})

Type	Energy (eV)	Band width (eV)	Conc. (cm^{-2})
Acceptor	$E_C \leq E_T \leq E_C$-0.56	0.56	$D_{IT} = D_{IT}(\Phi)$
Donor	$E_V \leq E_T \leq E_V$+0.6	0.60	$D_{IT} = D_{IT}(\Phi)$

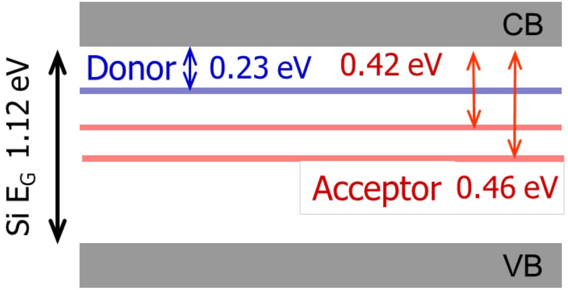






√ Bulk damage

Type	Energy (eV)	η (cm^{-1})	σ_n (cm^2)	σ_h (cm^2)
Donor	E_C - 0.23	0.006	2.3×10^{-14}	2.3×10^{-15}
Acceptor	E_C - 0.42	1.6	1×10^{-15}	1×10^{-14}
Acceptor	E_C - 0.46	0.9	7×10^{-14}	7×10^{-13}



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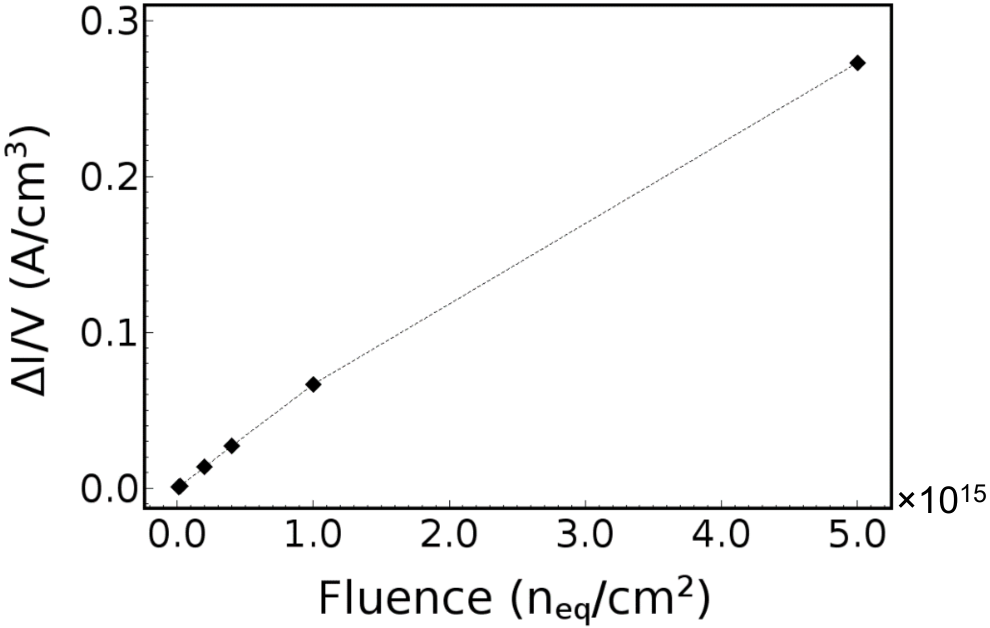
Leakage current vs fluence

- ✓ Leakage current measured/simulated at -20°C and scaled to +20°C [3].
- ✓ p-type susbstrate devices.
- ✓ Leakage current over a detector volume is proportional to the fluence with a proportionality factor α :
  - ✓ MEASUREMENTS: $\alpha \sim 4 \div 7 \times 10^{-17}$ A/cm^3 depending on the annealing time/temperature [4].
  - ✓ SIMULATIONS: $\alpha = 5.4 \times 10^{-17}$ A/cm^3.



$$\boxed{\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}}$$

[3] A. Chilingarov, Generation current temperature scaling, RD50 technical note.

[4] A. Dierlamm, KIT Status, CMS Outer tracker Meeting, March 2019.

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The “New Perugia” model

√ Surface damage (+ Q_{OX})

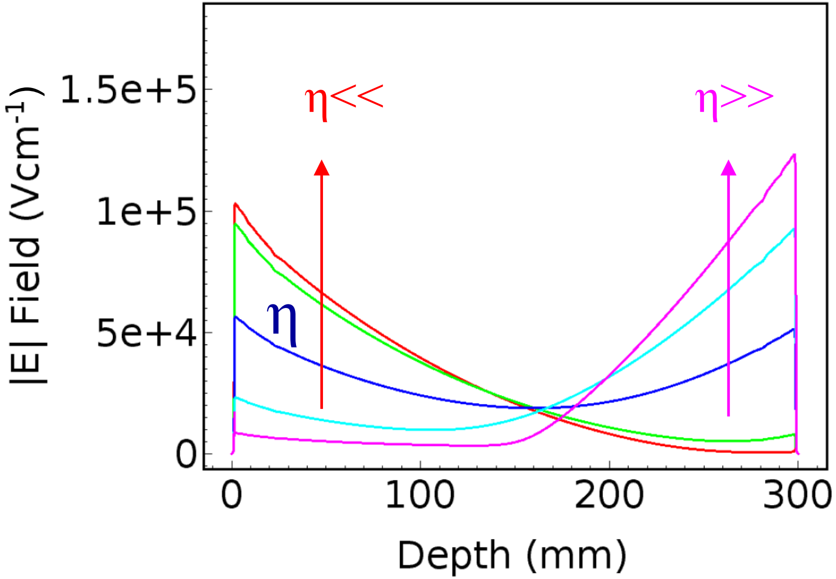
Type	Energy (eV)	Band width (eV)	Conc. (cm^{-2})
Acceptor	$E_C \leq E_T \leq E_C$-0.56	0.56	$D_{IT} = D_{IT}(\Phi)$
Donor	$E_V \leq E_T \leq E_V$+0.6	0.60	$D_{IT} = D_{IT}(\Phi)$

√ Bulk damage

Avalanche ON:
Van Overstraeten–De Man
(default)

Type	Energy (eV)	η (cm^{-1})	σ_n (cm^2)	σ_h (cm^2)
Donor	E_C - 0.23	$\boxed{0.006}$	2.3×10^{-14}	2.3×10^{-15}
Acceptor	E_C - 0.42	1.6	1×10^{-15}	1×10^{-14}
Acceptor	E_C - 0.46	0.9	7×10^{-14}	7×10^{-13}

- ✓ Traps concentrations dependence upon fluences ~ $\eta \times \phi$.
- ✓ Strong sensitivity to the introduction rate (defects concentration).
- ✓ @ 1.0×10^{16} n_{eq}/cm^2.



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The "New Perugia" model

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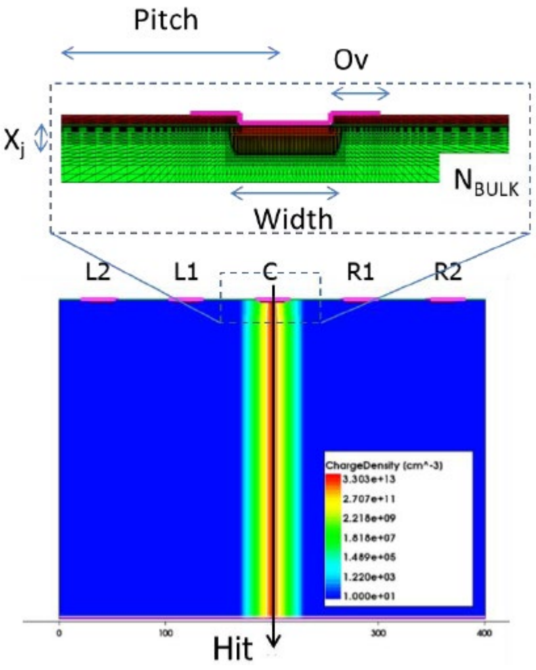
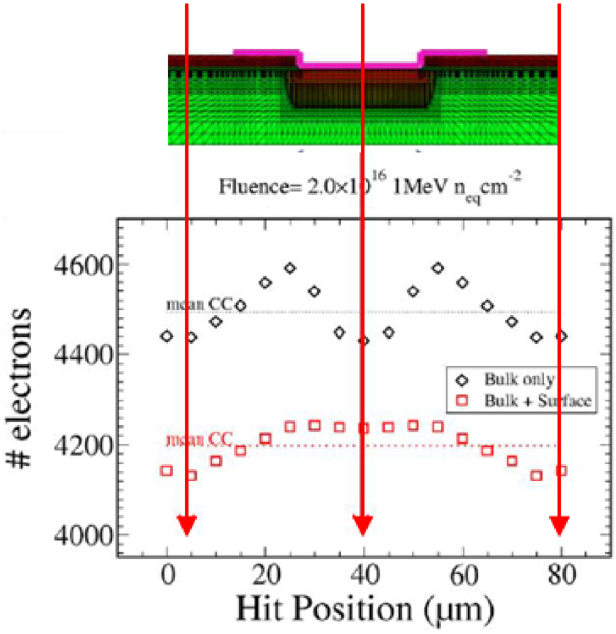


- ✓ Stimulus (MIP equivalent)
- ✓ Segmented sensors.



The “New Perugia” model

√ Surface damage (+ Q_{OX})

Type	Energy (eV)	Band width (eV)	Conc. (cm^{-2})
Acceptor	$E_C \le E_T \le E_C$-0.56	0.56	$D_{IT} = D_{IT}(\Phi)$
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√ Bulk damage

Avalanche ON:
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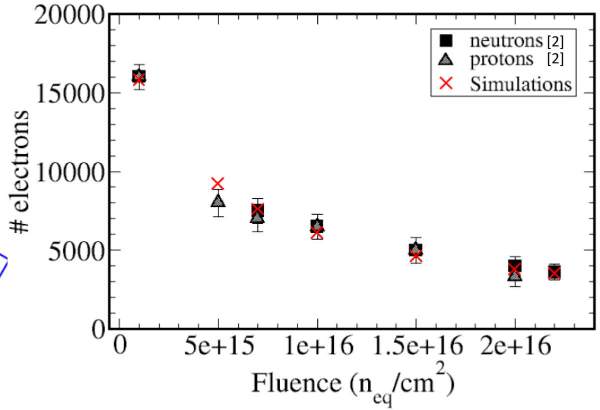
Acceptor	E_C - 0.46	0.9	7×10^{-14}	7×10^{-13}

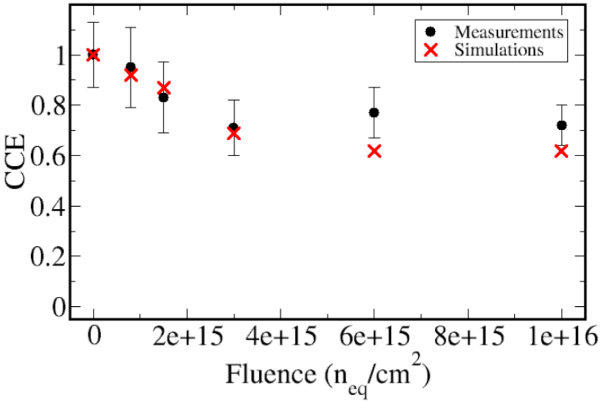
Charge Collection for silicon strips.



[2] A. Affolder et al., NIMA Vol. 623 (2010), pp. 177-179.

F. Moscatelli et al., *Effects of Interface Donor Trap States on Isolation Properties of Detectors Operating at High-Luminosity LHC*, IEEE Transactions on Nuclear Science, 2017, Vol. 64, Issue: 8, 2259 – 2267.

Charge Collection for PiN diodes.

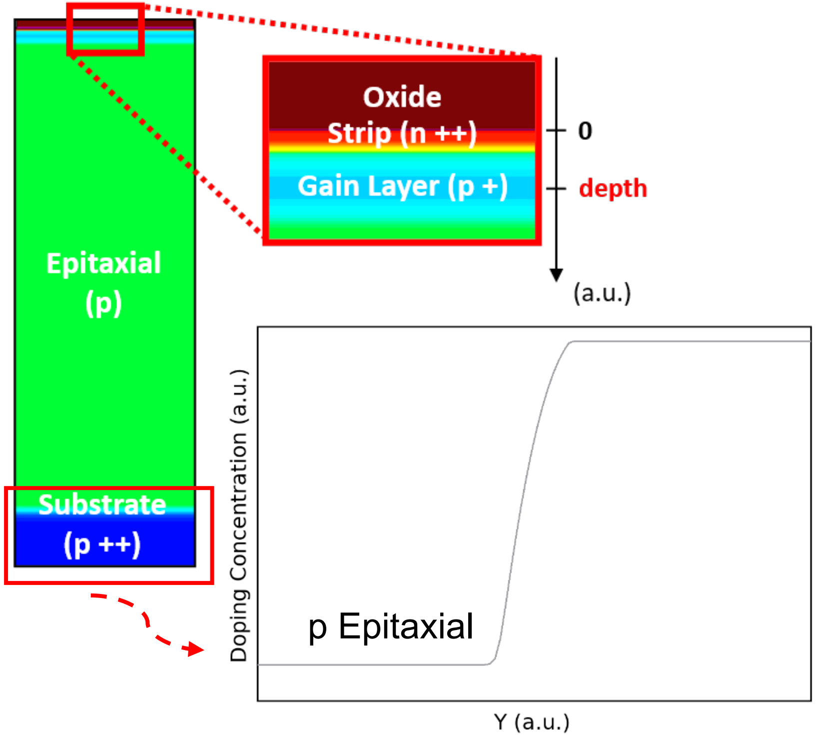


M. Ferrero, 34th RD50 Workshop, June 12-14 2019

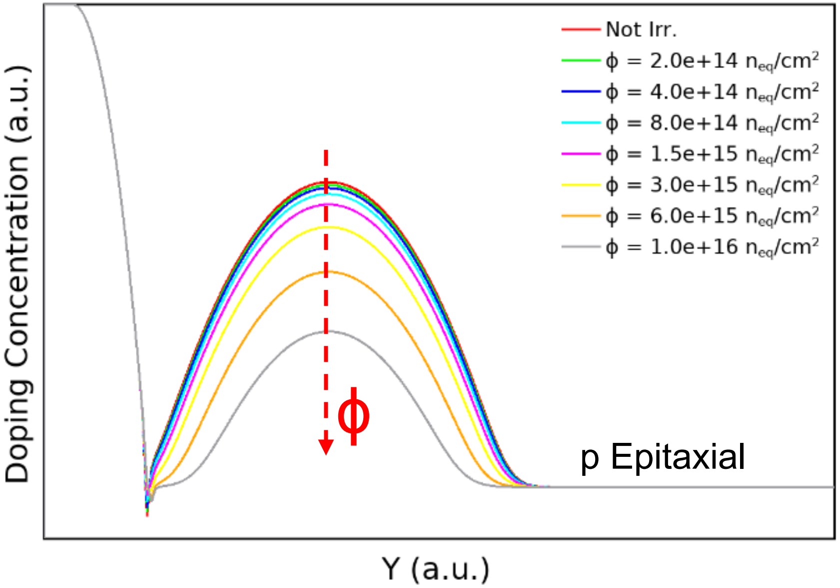
Measurements conditions:
- Room temperature
- Measurements with laser 1064nm
- Measurements at 3 laser intensity
- Reference diode to check laser stability

LGAD - Low Gain Avalanche Diode

✓ Layout and doping profile.



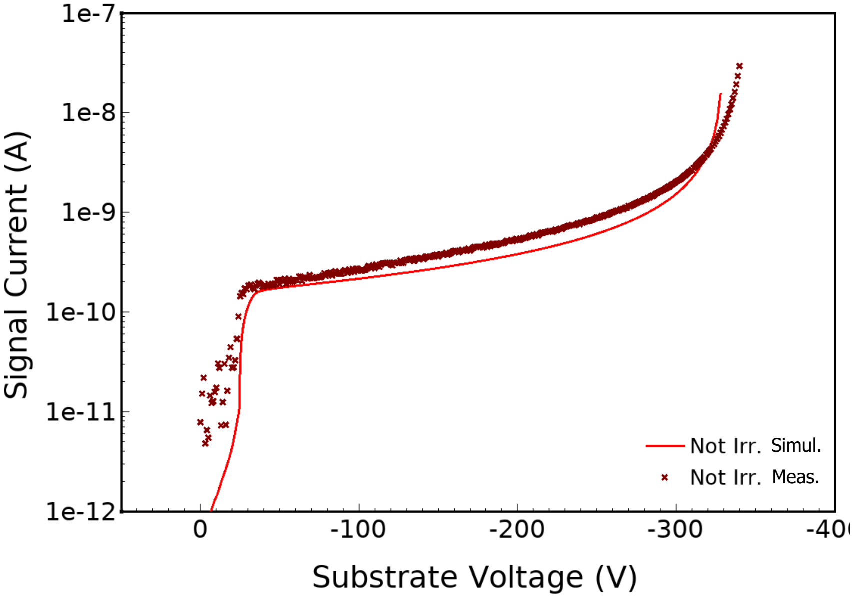
Gaussian Gain Layer profile



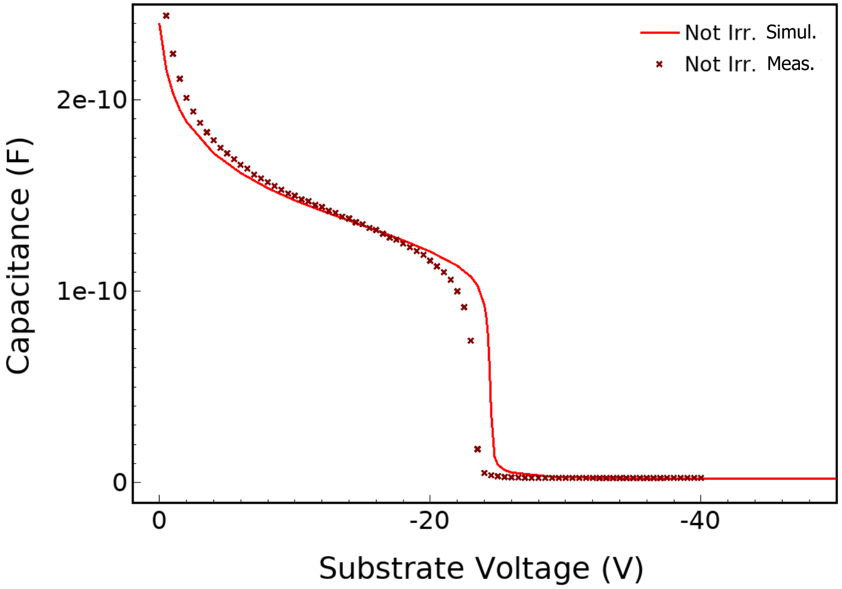
LGAD - I-V and C-V characterization (1/2)

✓ Comparison between measurements and simulations of not irradiated LGADs.

I-V, not irradiated



C-V, not irradiated



Avalanche model: **Massey**. Temp: **300 K**. Electrical contact area **1 mm^2**.

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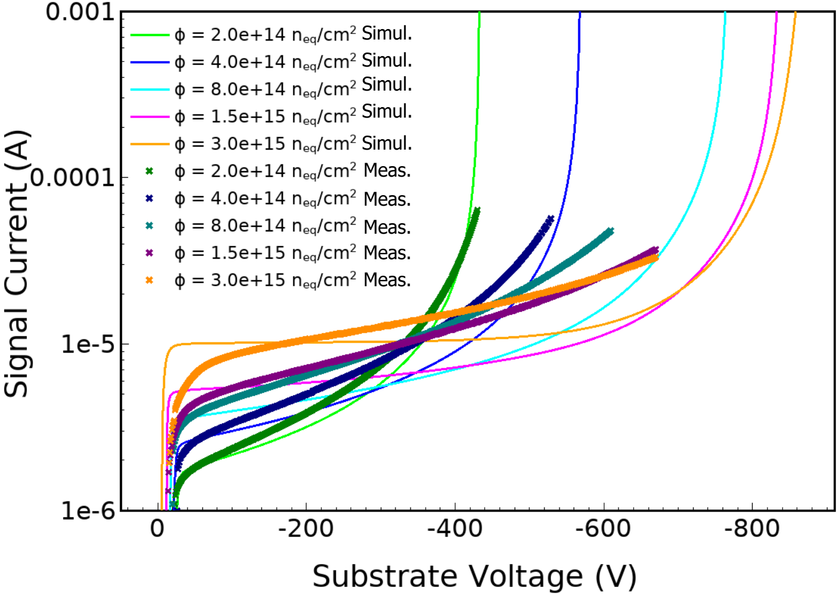
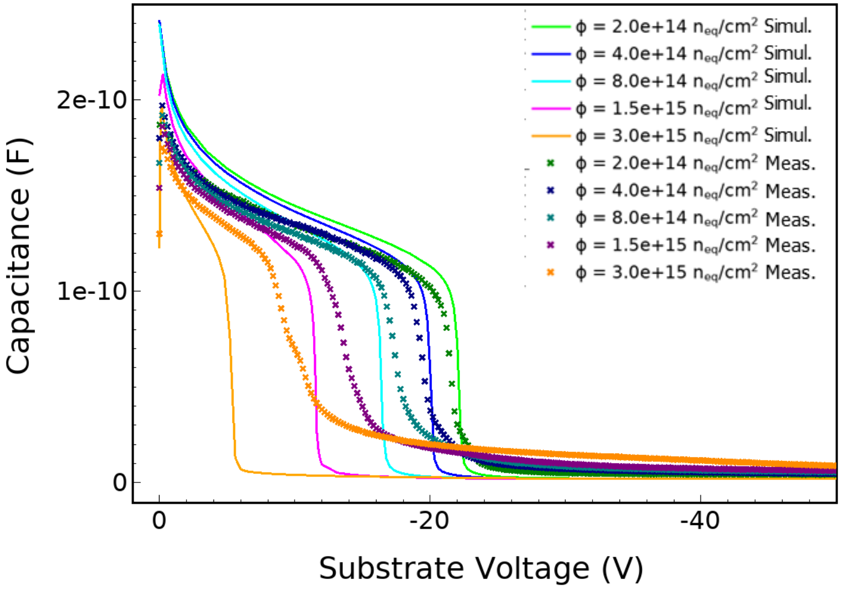
LGAD - I-V and C-V characterization (2/2)

✓ Comparison between measurements and simulations of not irradiated LGADs.

I-V at different fluences



C-V, at different fluences



Avalanche model: **Massey**. Temp: **253 K** for I-V (Chilingarov's formula [3]), **300 K** for C-V. Electrical contact area **1 mm^2**.

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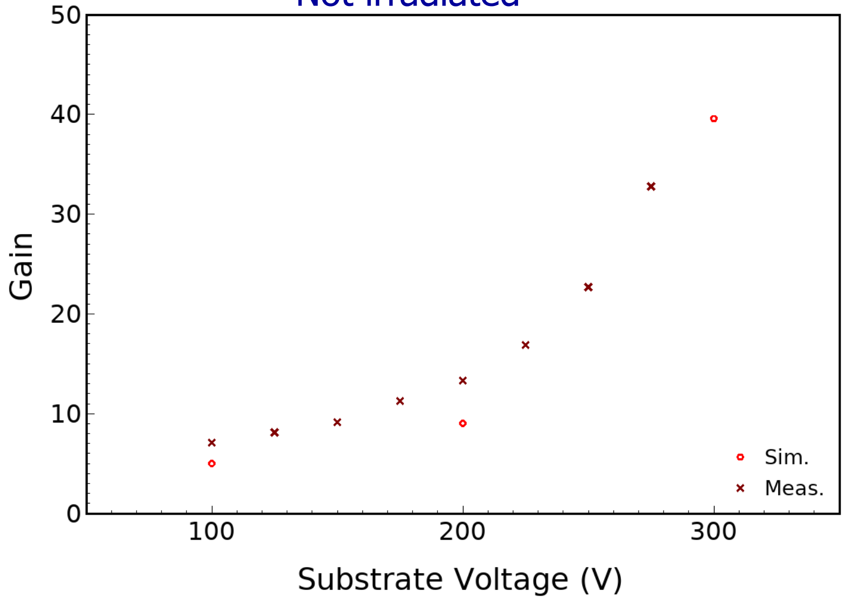
LGAD – Gain calculation

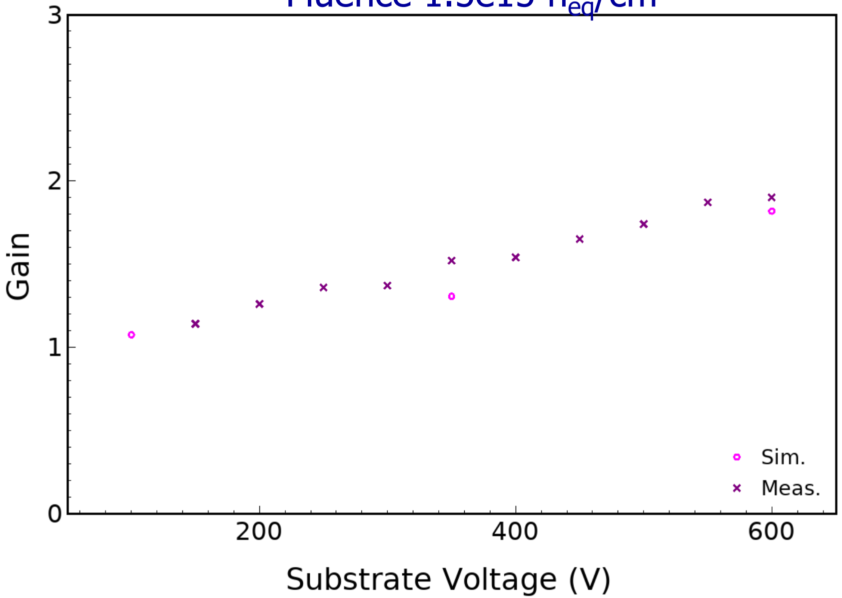
- ✓ Estimated error on data ±10%.
- ✓ Collected Charge (CC) as the integral of the current over time.

$$Gain = \frac{CC_{LGAD}}{CC_{PiN}}$$

Not irradiated



Fluence 1.5e15 n_{eq}/cm^2



Avalanche model: **Massey**. Temp: **300 K**. Electrical contact area **1 mm^2**.

Conclusions

- √ Modelling radiation damage effects is a tough task!
- √ Surface radiation damage effects modelling scheme.
  - √ Validated up to doses of 100 Mrad(SiO_2).
  - √ Different test structures / different technology (HPK, IFX, …).
- √ "University of Perugia Model" → "New Perugia Model"
  - √ TCAD general purpose BULK + SURFACE radiation effects modelling scheme.
  - √ Predictive capabilities extended up to ~10^{16} particles/cm^2.
  - √ suitable for commercial TCAD tools (e.g. Synopsys Sentaurus).
  - √ Validation with experimental data comparisons (I-V, C-V, Efield, CCE, …).
- √ 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).

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