VERTEX 2019

TCAD Advanced Radiation Damage Modelling in Silicon Detectors

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AIDA 2020

INFN Istituto Nazionale di Fisica Nucleare

iom Istituto Officina dei Materiali

Outline

- Motivation / Radiation damage effects in silicon sensors
- Test structures / measurements and parameters extraction.
- TCAD radiation damage modelling approach.
- Surface damage effects: **Simulations vs. Measurements**
  - Different vendors (IFX, 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.
- **“New Perugia model”** - Comprehensive Bulk + Surface TCAD damage modelling scheme
  - Leakage current
  - Electric field profile
  - Charge Collection Efficiency

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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 SYNOPSYS®

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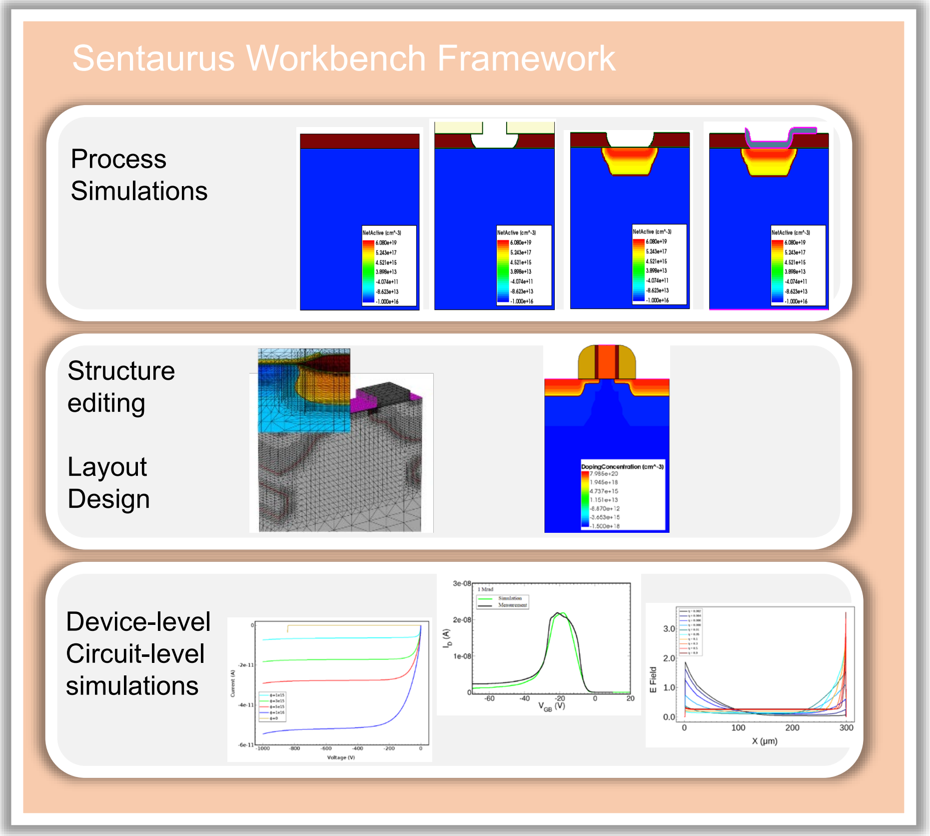
The Technology-CAD modelling approach



- √ 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.
- ✓ Synopsys© Sentaurus TCAD

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

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

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

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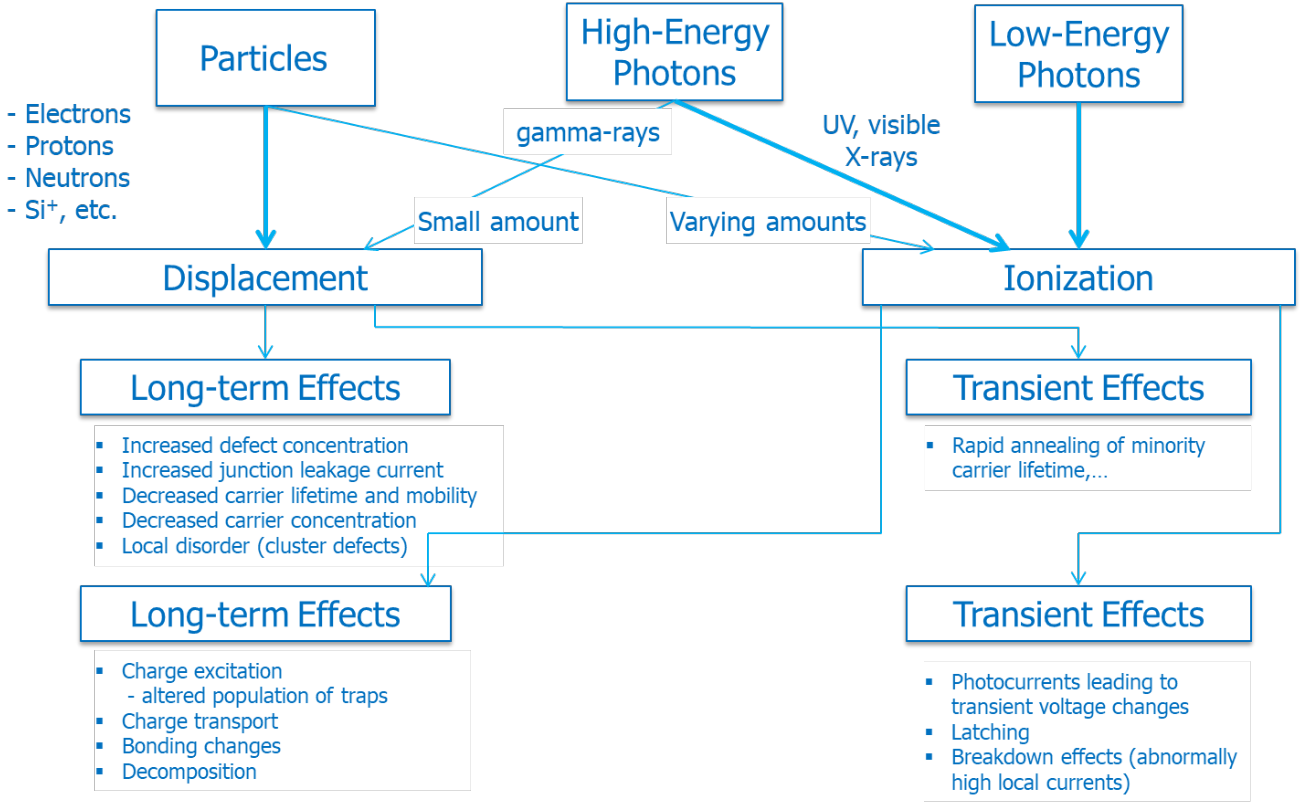
Radiation damage effects



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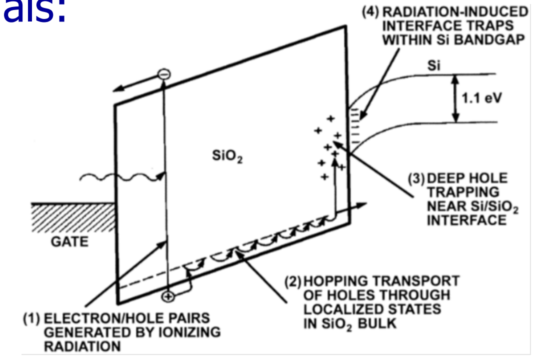
Radiation damage effects

Two main types of radiation damage in detector materials:

√ SURFACE damage ← Ionizing Energy Loss (IEL)

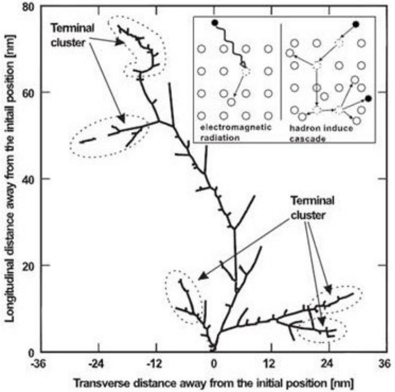
- build-up of trapped charge within the oxide;
- bulk oxide traps increase;
- interface traps increase;
- Q_{OX}, N_{IT}.



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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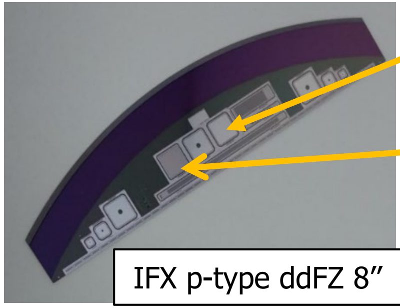
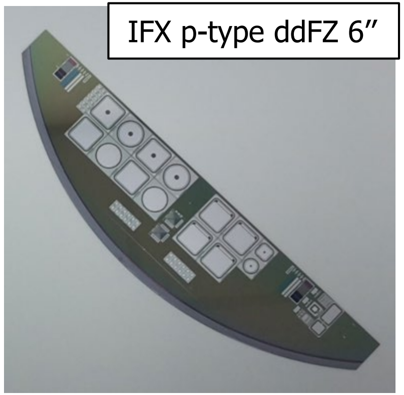
The main test structures at hand

√ Test structures…



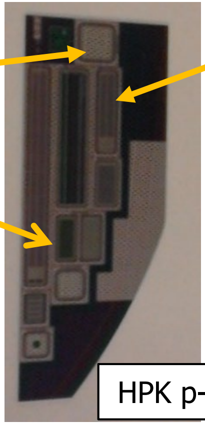
IFX p-type ddFZ 8”



IFX p-type ddFZ 6”

MOS Capacitor

Gated Diode



HPK p-type ddFZ

Cap-TS for R_{INT}

√ Measurements: I-V, C-V, R_{INT}

√ 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.

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Parameter extraction procedure

√ From C-V measurements of MOS capacitors:

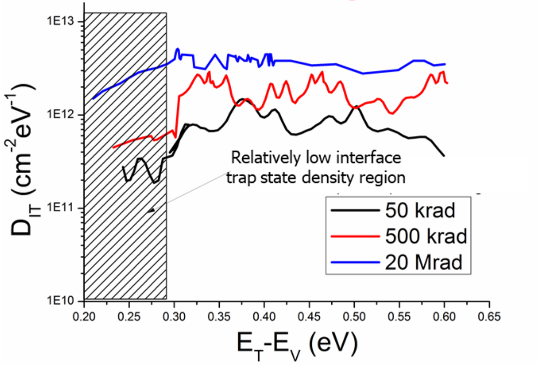
- D_{IT} is assessed by using the C-V High-Low method.
- High-Frequency (HF) measurements are carried out at 100 kHz with a small signal amplitude of 25 mV.
- Quasi-Static (QS) characteristics measured with delay times of 0.5 sec using a voltage step of 100 mV.
- N_{EFF} is obtained from V_{FB} measurements.

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

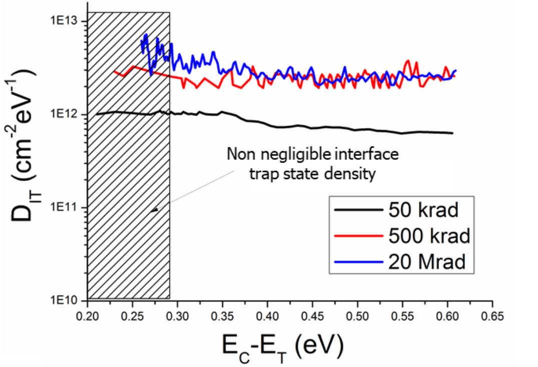
$$\mathrm{D_{IT}} = \frac{\mathrm{C_{IT}}}{\mathrm{q} \times \mathrm{A}}$$

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

Donor interface trap states (p-type subs)



Acceptor interface trap states (n-type subs)



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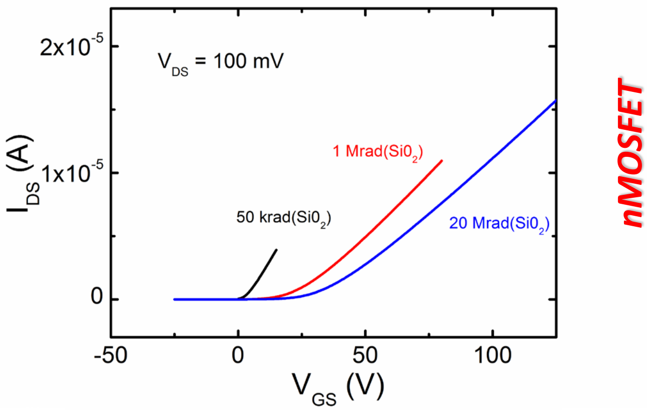
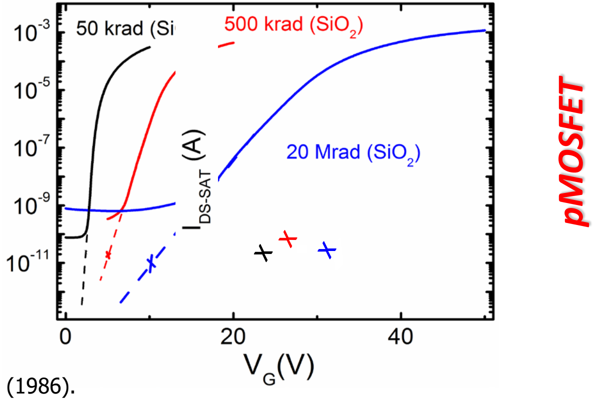


√ From I-V measurements of MOSFETs:

- After X-ray irradiation →
- 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].

$$\Delta V_{th}(V_{FB}) = \Delta V_{N_{it}} + \Delta V_{Q_{ox}}$$



[1] P. J. McWhorter and P. S. Winokur, "Simple technique for separating the effects of interface traps …", *Appl. Phys. Lett. 48*, 133 (1986).

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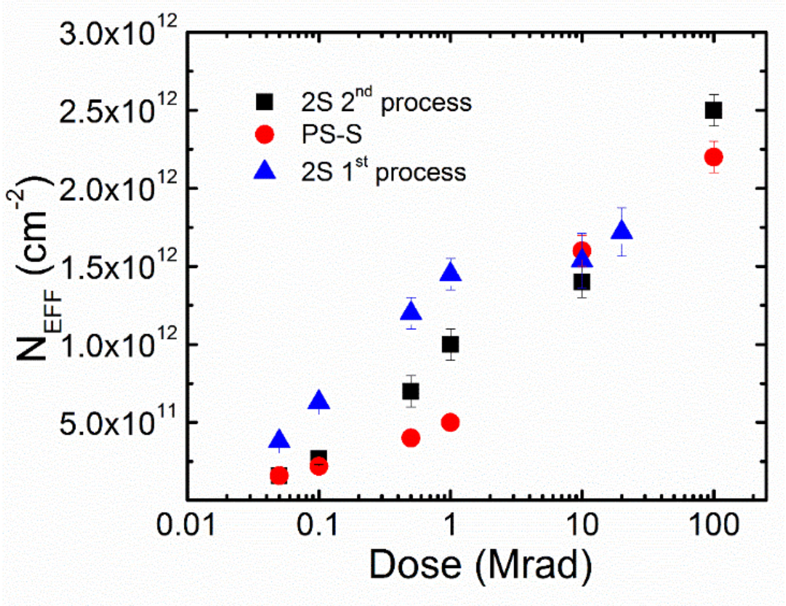
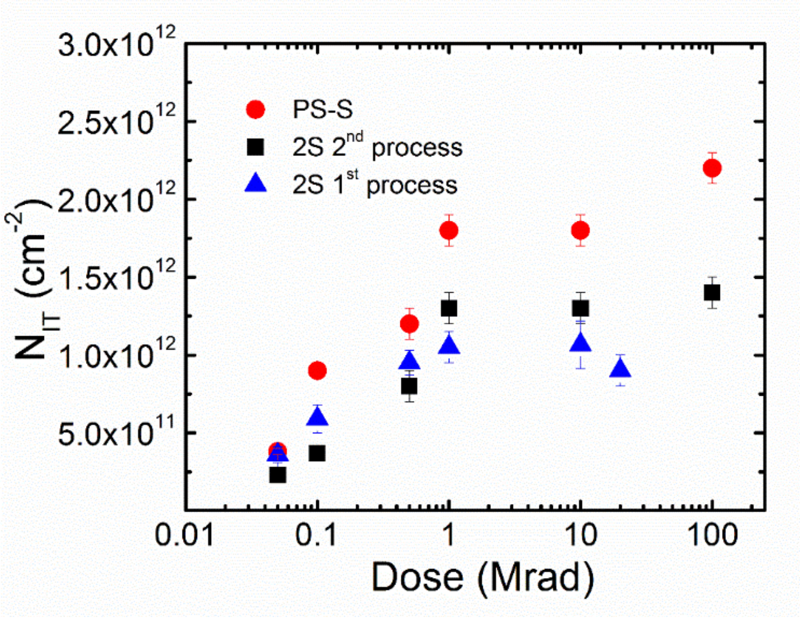
IFX test structures wrap-up

√ Noticeable differences among three processes in terms of N_{EFF} and N_{IT} (process variability).

√ Higher differences at lower doses.





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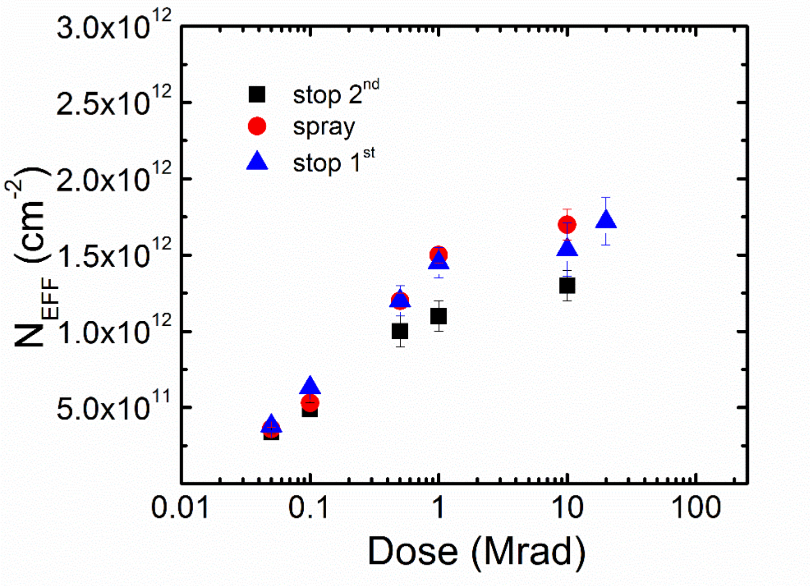
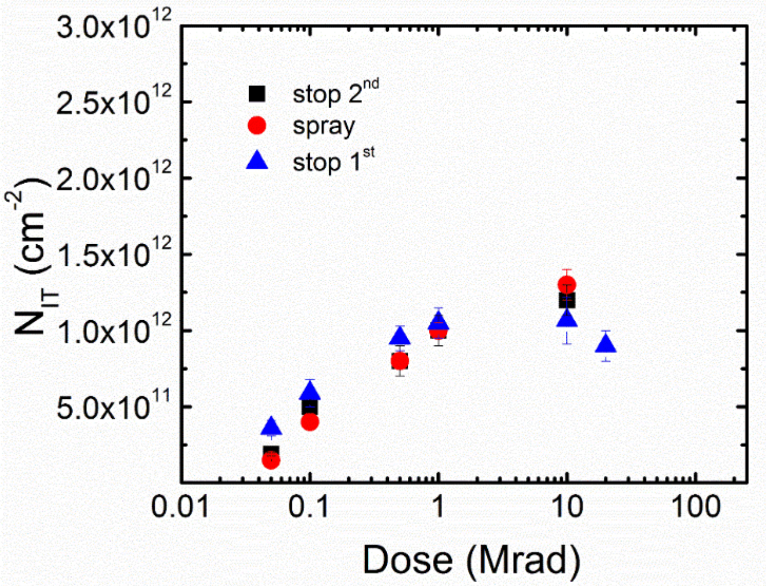
HPK test structures wrap-up

√ 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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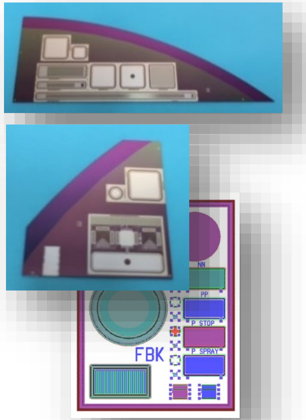
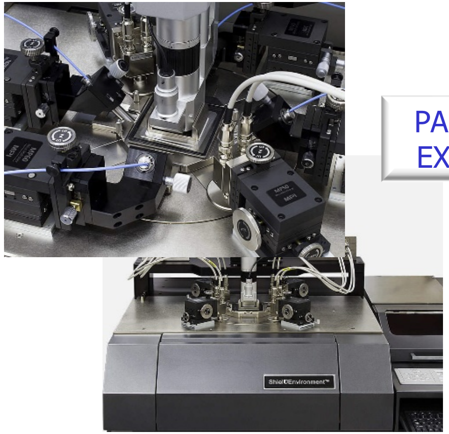
The overall modelling approach pursued

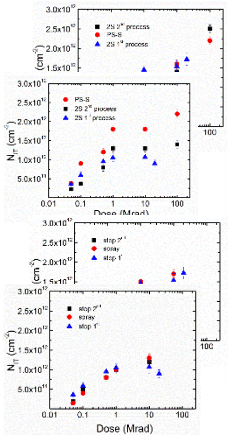


TEST STRUCTURE MEASUREMENTS



PARAMETERS EXTRACTION

MODEL



MODEL VALIDATION

DETECTOR OPTIMIZATION

CCE, I-V, C-V, …

√ Modelling the effects of the radiation damage.

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

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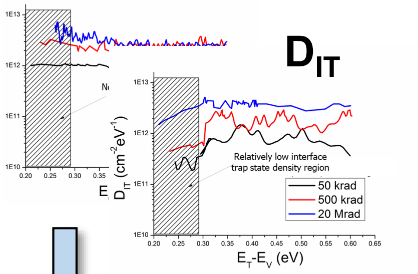
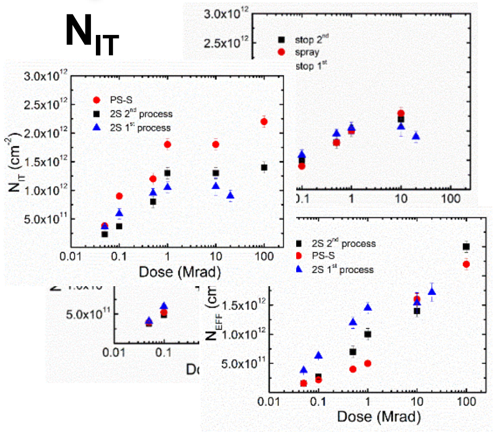
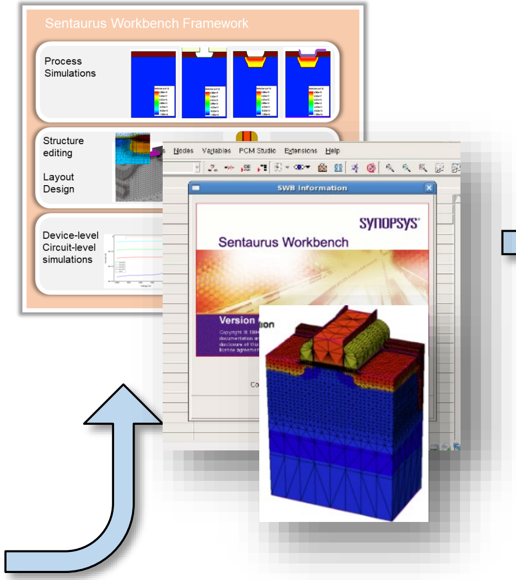
Development of TCAD surface radiation model

INPUT

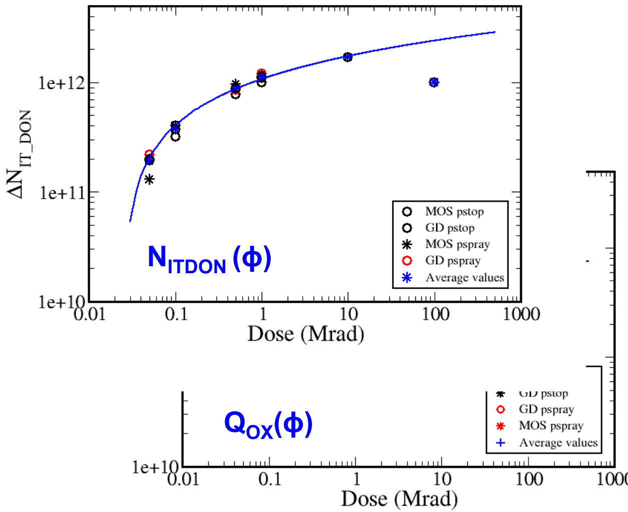






OUTPUT

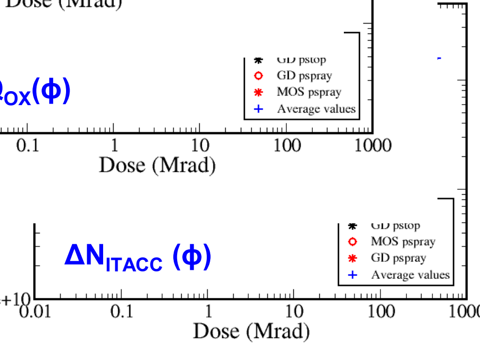
HPK pspray/pstop



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

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

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



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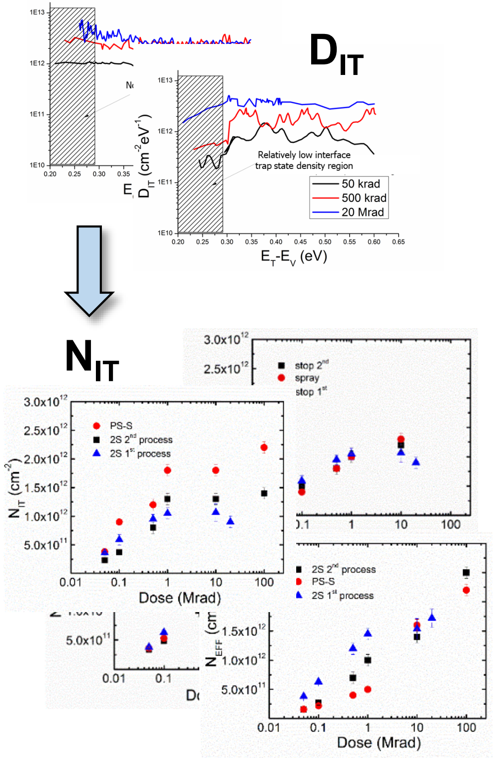
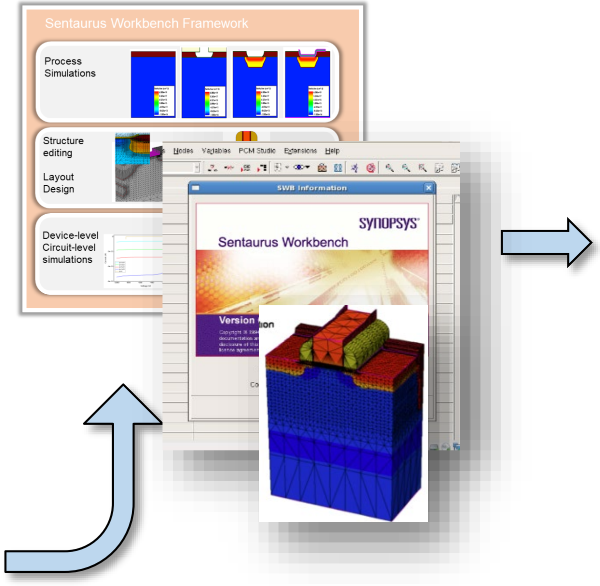
Development of TCAD surface radiation model

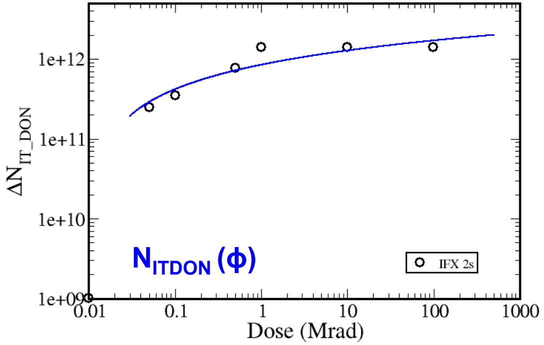
INPUT

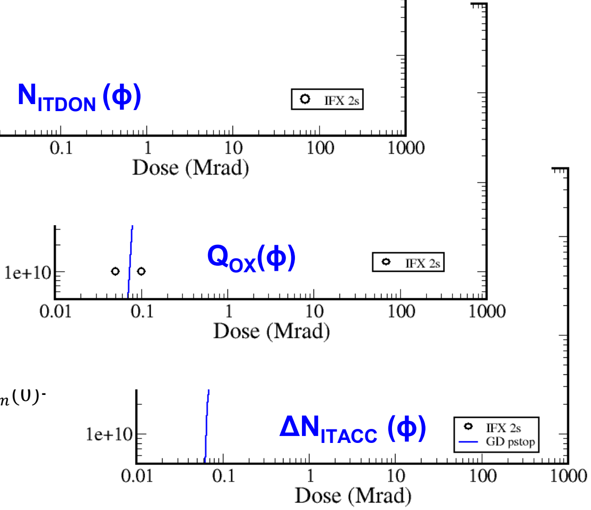




OUTPUT

IFX 8" process





$Q_{OX}(\phi) = Q_{OX}$

$N_{ITacc}(\phi) = N_{I}$

$N_{ITdon}(\phi) = N_{ITdon}(\upsilon)$-

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Development of TCAD surface radiation model

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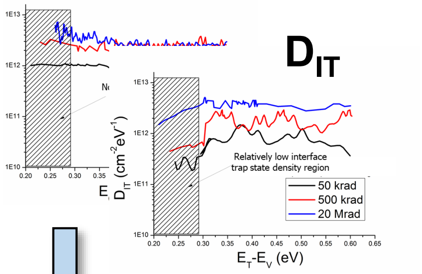
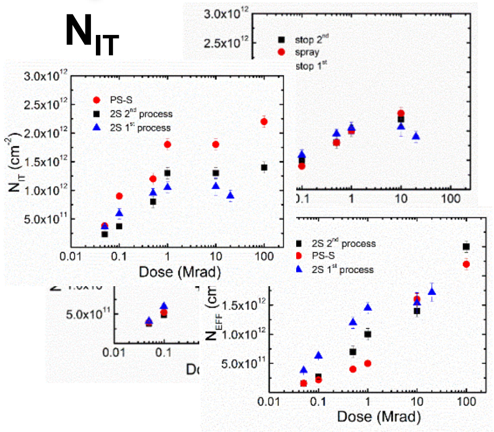
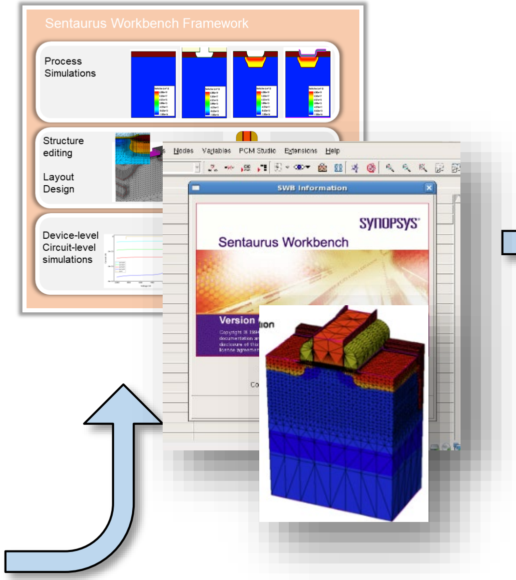
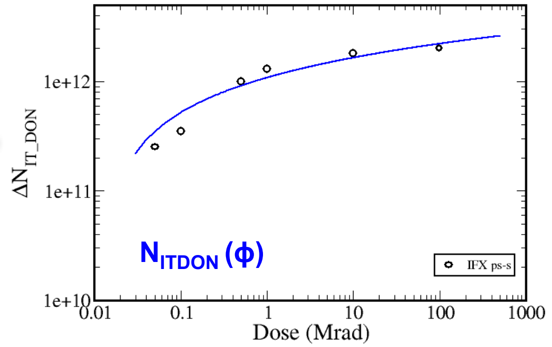


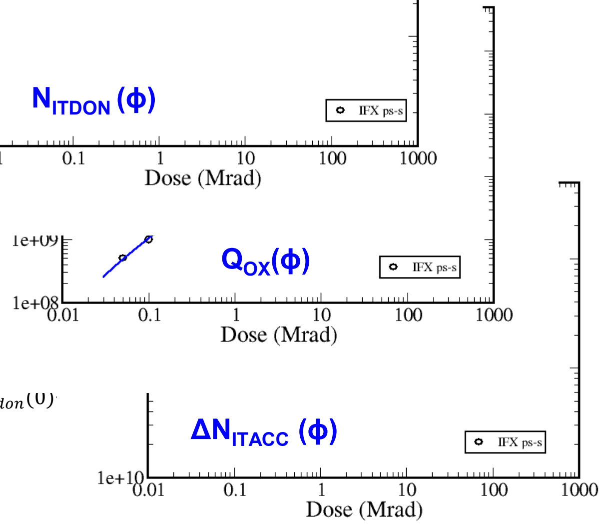




OUTPUT

IFX 6" process





$Q_{OX}(\Phi) = Q_{O}$
$N_{ITacc}(\Phi) = N$
$N_{ITdon}(\Phi) = N_{ITdon}(0)$

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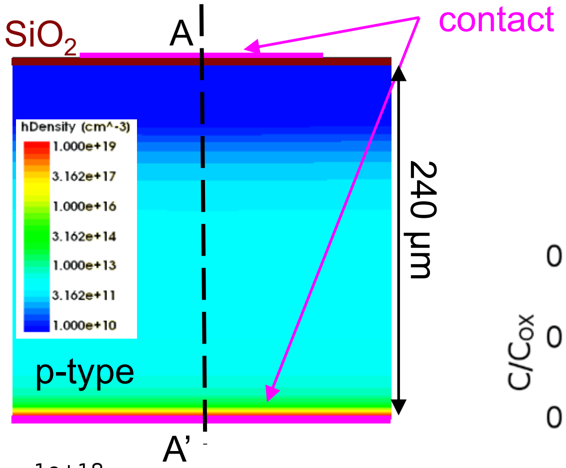
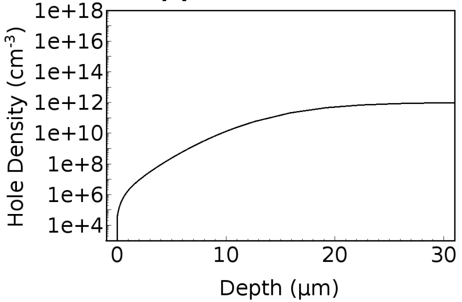
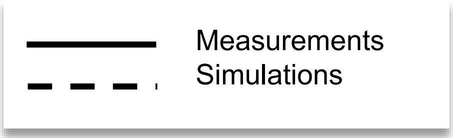
Surface model validation: IFX MOS Capacitors

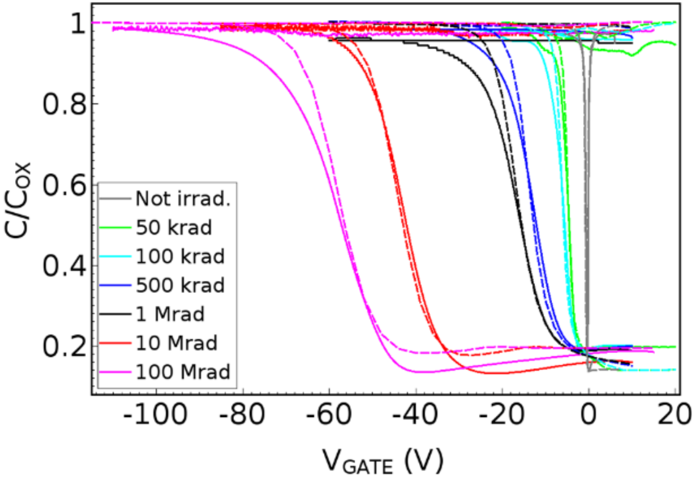
√ MOS capacitors characterization as a function of V_{GATE}.



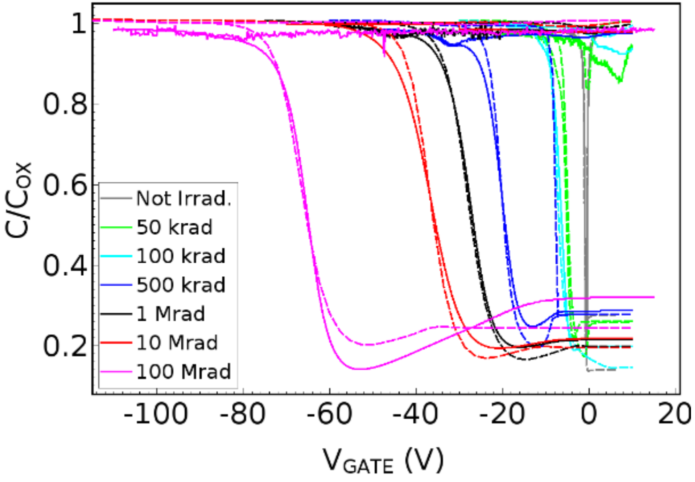




6″ process.



8″ process.



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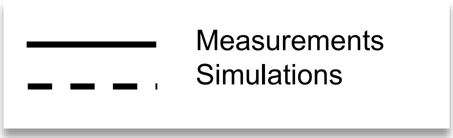
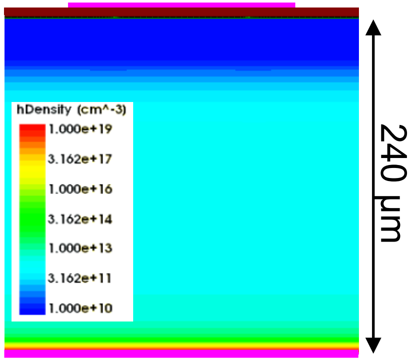
Surface model validation: HPK MOS Capacitors

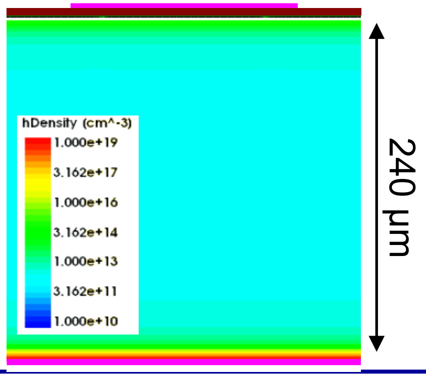
√ MOS capacitors characterization as a function of V_{GATE}.



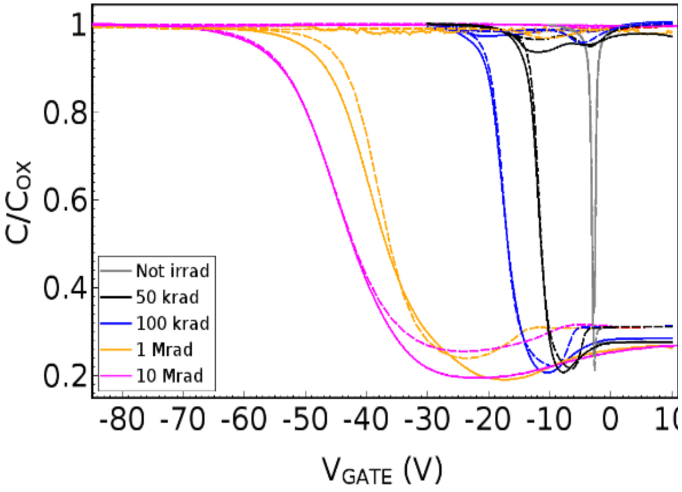
p-stop process.



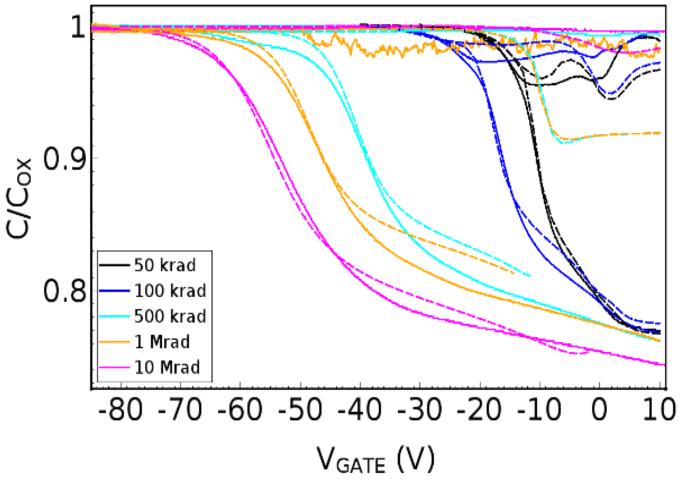
p-spray process.



p-stop process.



p-spray process.



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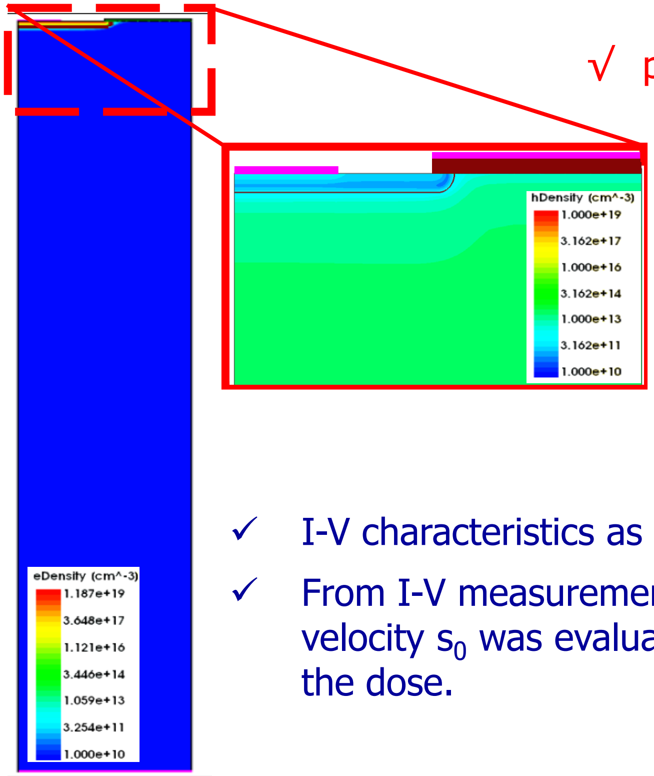
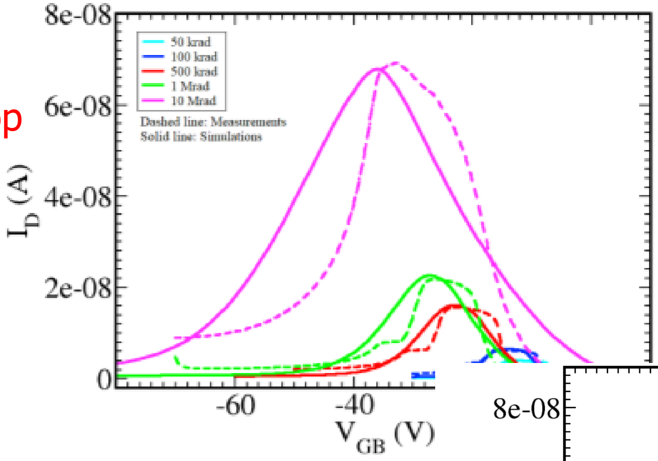
Surface model validation: HPK Gated Diodes



√ p-stop

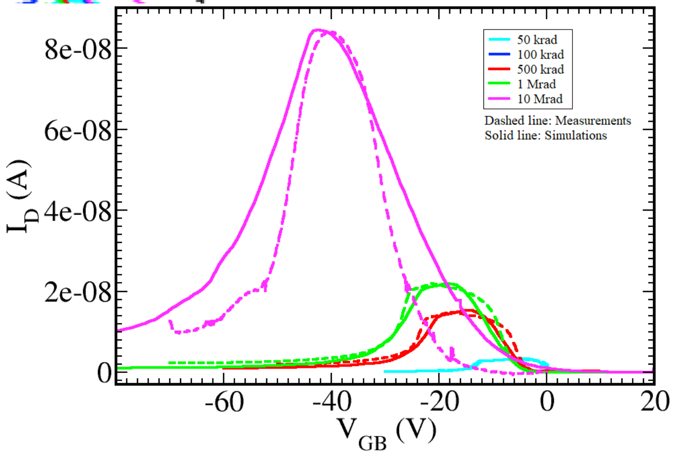


Measurements
Simulations

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

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

√ 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.

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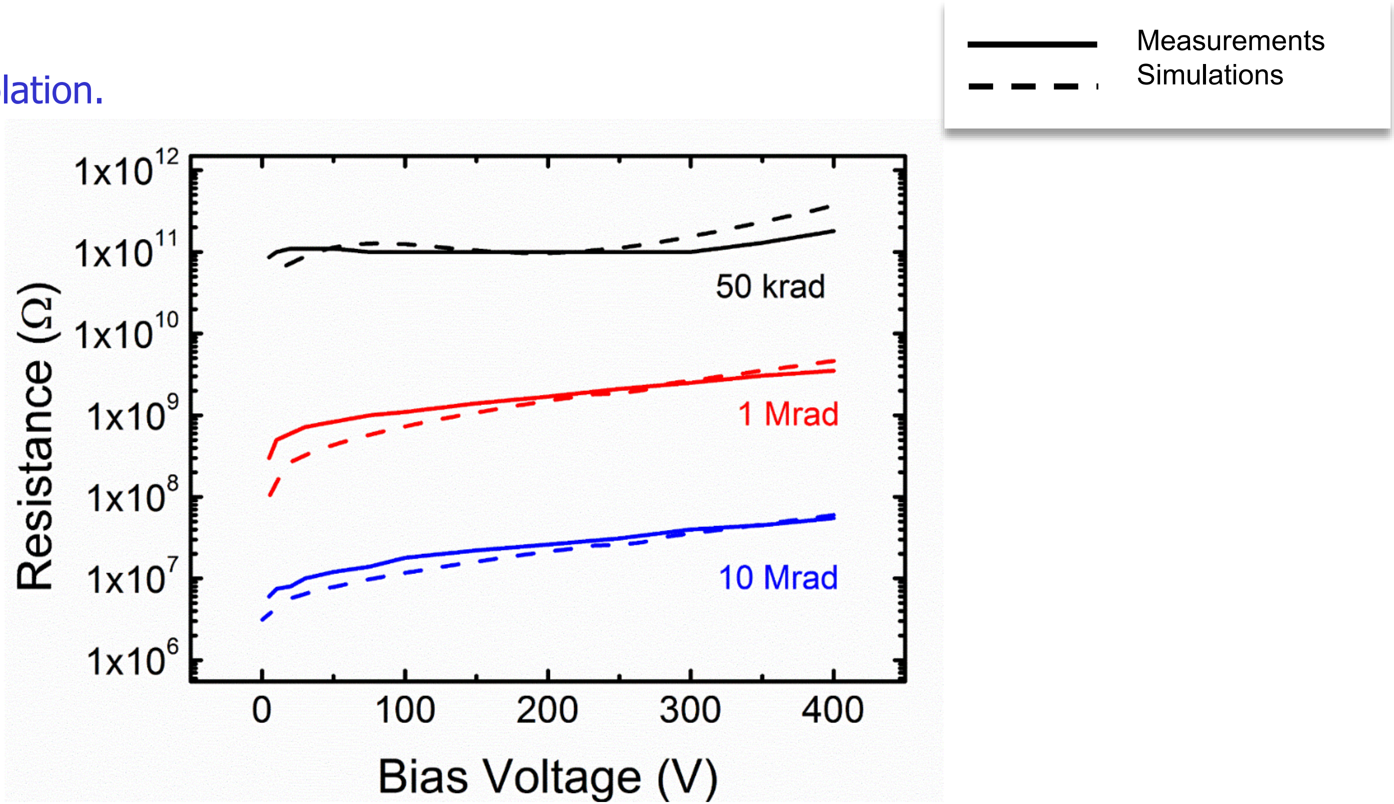
Surface model validation: Interstrip resistance

√ R_{INT} measurements.

√ HPK p-stop implant isolation.



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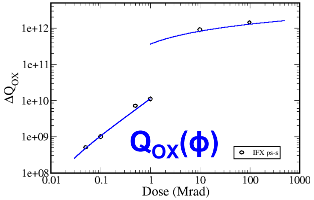
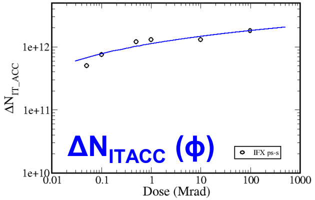
Application of TCAD surface radiation model

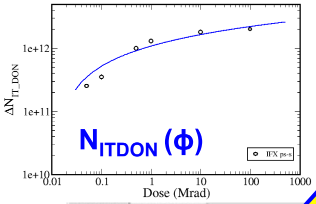
INPUT

Developed TCAD radiation damage effects model



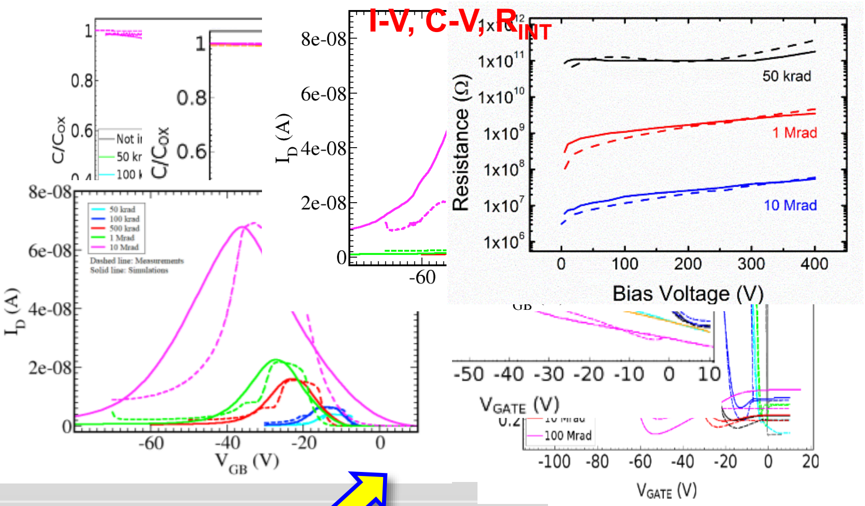


$$Q_{OX}(\phi) = Q_{OX}(0) + \Delta Q_{OX}(\phi)$$
$$N_{ITacc}(\phi) = N_{ITacc}(0) + \Delta N_{ITacc}(\phi)$$
$$N_{ITdon}(\phi) = N_{ITdon}(0) + \Delta N_{ITdon}(\phi)$$



OUTPUT

I-V, C-V, R_INT



Project | Scheduler

SDE | SDEVICE | SDEVICE | INSPECT | SVISUAL

			V_bias	temp	Fluence	Qox_pre	DeltaQox	Nit_acc_pre	DeltaNit_acc	Nit_don_pre	DeltaNit_don			
1	--	--	-400	248	0.00e+00	6.50e+10	0.00e+00	2.00e+09	0.00e+00	2.00e+09	0.00e+00	--	--	--
2					2.00e+14	6.50e+10	9.00e+11	2.00e+09	2.50e+12	2.00e+09	1.50e+12	--	--	--
3					4.00e+14	6.50e+10	1.00e+12	2.00e+09	2.50e+12	2.00e+09	1.60e+12	--	--	--
4					8.00e+14	6.50e+10	9.50e+11	2.00e+09	2.50e+12	2.00e+09	1.80e+12	--	--	--
5					1.50e+15	6.50e+10	1.05e+12	2.00e+09	2.50e+12	2.00e+09	1.80e+12	--	--	--
6					3.00e+15	6.50e+10	1.05e+12	2.00e+09	2.50e+12	2.00e+09	1.80e+12	--	--	--
7					6.00e+15	6.50e+10	1.05e+12	2.00e+09	2.50e+12	2.00e+09	1.80e+12	--	--	--
8					1.00e+16	6.50e+10	1.05e+12	2.00e+09	2.50e+12	2.00e+09	1.80e+12	--	--	--

INFN
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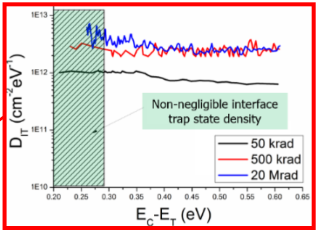
Outline

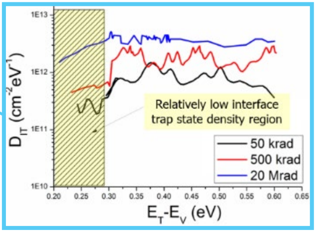
- Motivation / Radiation damage effects in silicon sensors
- Test structures / measurements and parameters extraction.
- TCAD radiation damage modelling approach.
- Surface damage effects: **Simulations vs. Measurements**
  - Different vendors (IFX, HPK) and process recipes (p-stop vs. p-spray, thermal budget, 6" vs. 8",…).
  - DC (steady-state) -> Diodes / Gate Controlled Diodes.
  - AC (small-signals) -> MOS Capacitors.
- **"New Perugia model"** - Comprehensive Bulk + Surface TCAD damage modelling scheme
  - Leakage current
  - Electric field profile
  - Charge Collection Efficiency

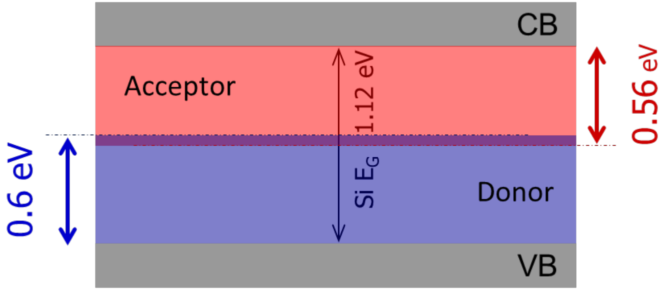
The "New Perugia" model

√ 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	$D_{IT} = D_{IT}(\Phi)$

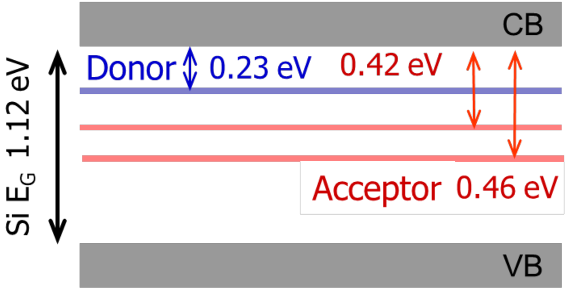






√ Bulk damage

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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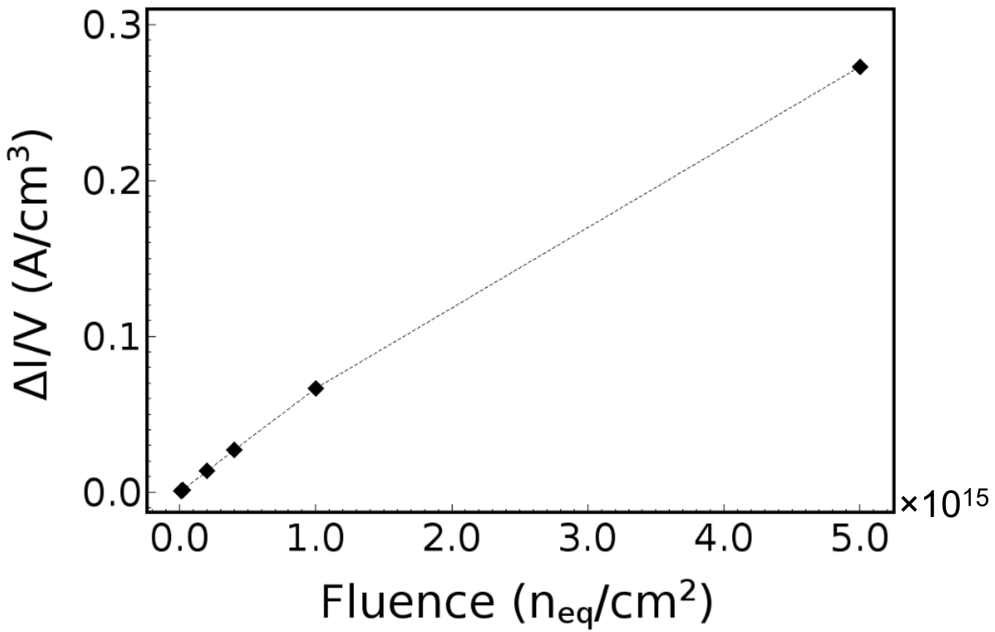
Leakage current vs fluence

- ✓ 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: $\alpha = 5.4 \times 10^{-17} A/cm^3$.



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

[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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√ Bulk damage

Avalanche ON: Van Overstraeten–De Man (default)

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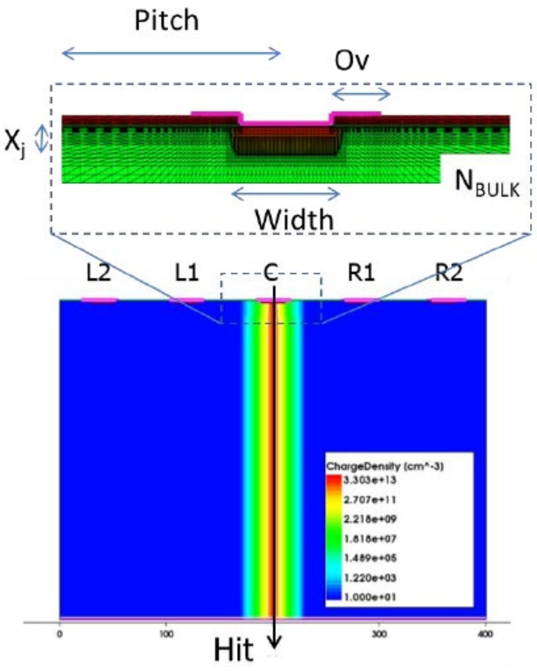
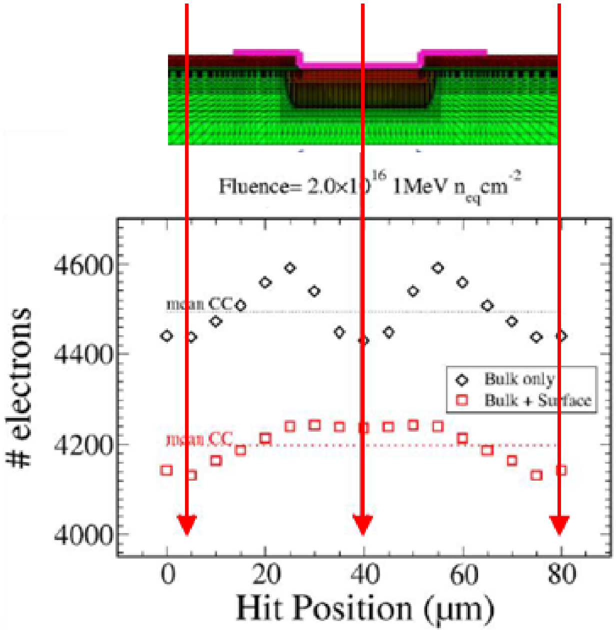


- ✓ Stimulus (MIP equivalent)
- ✓ Segmented sensors.



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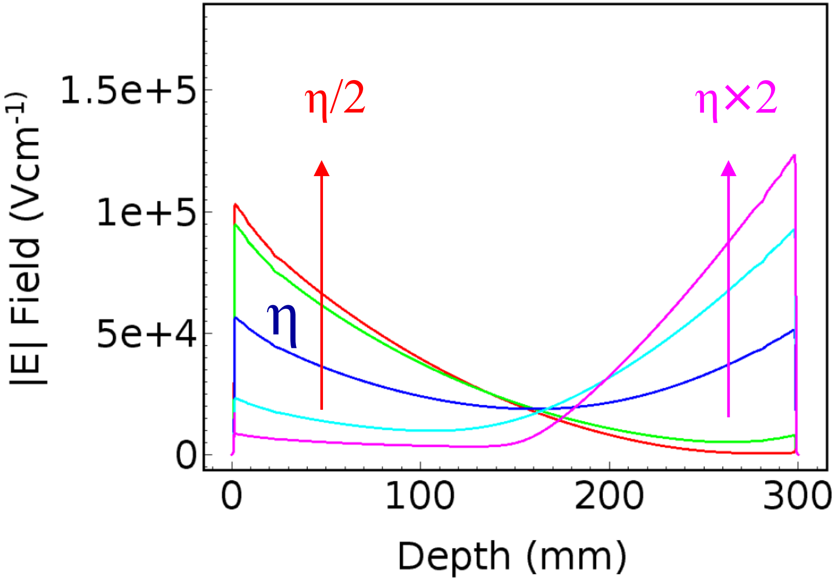
- ✓ Traps concentrations dependence upon fluences $\sim \eta \times \phi$.
- ✓ Strong sensitivity to the introduction rate (defects concentration).
- ✓ @ $1.0\times10^{16}\ n_{eq}/cm^2$.



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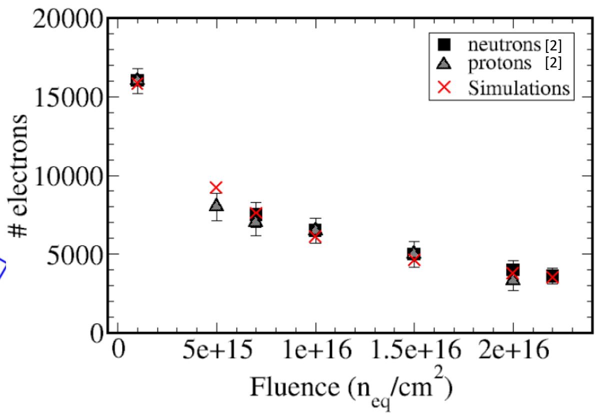
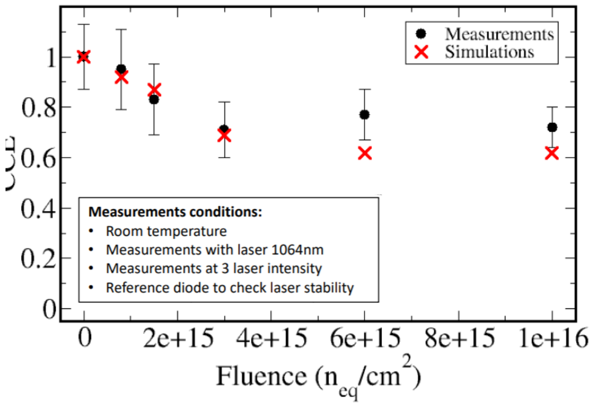
Charge Collection for silicon strips.



[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.

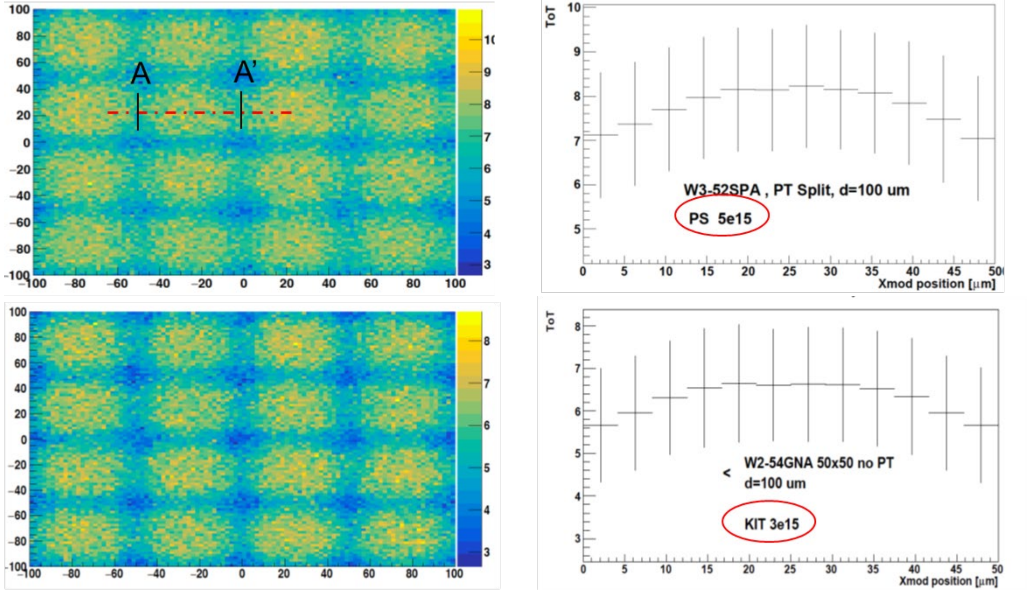


M. Ferrero, 34th RD50 Workshop, June 12-14 2019

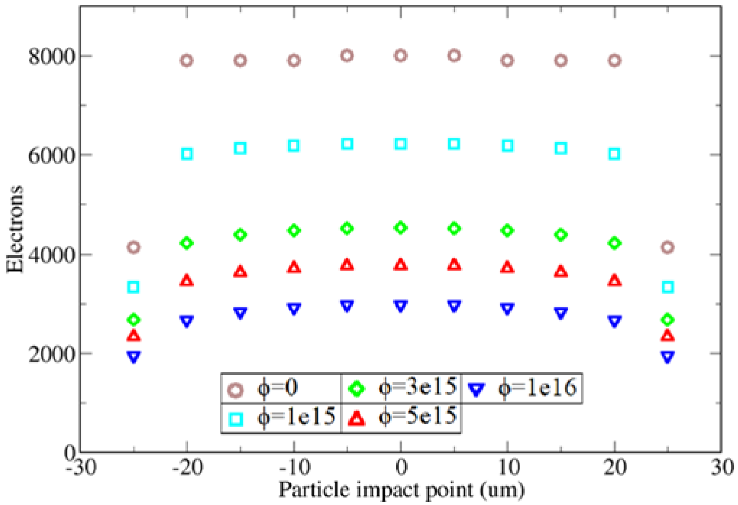
The "New Perugia" model:ToT and CCE maps

- ✓ Sensors produced by the Semiconductor Laboratory of the Max-Planck society (HLL)
- ✓ 16 pixel cells: irradiation at
  - ✓ PS at CERN (up to 5×10^{15} n_{eq}/cm^2) (top).
  - ✓ KIT (up to 3×10^{15} n_{eq}/cm^2) (bottom).

Measurements



Simulations



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Conclusions

- √ Modelling radiation damage effects is a tough task!
- √ Surface radiation damage effects modelling scheme
  - √ Validated up to doses of 100Mrad (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 $\sim 10^{16}$ particles/cm^2
  - √ suitable for commercial TCAD tools (e.g. Synopsys Sentaurus).
  - √ Validation with experimental data comparisons (I-V, Efield, CCE, …)
    → Increasing significance of surface/interface related radiation damage effects for future e+/e- colliders…
- √ Application to the optimization of advanced (pixel) detectors (3D detectors, LGADs, …).
  - √ … 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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