TCAD simulations of rad-hard sensors

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on behalf of INFN and University of Perugia (Italy), CNR-IOM,
and INFN and University of Torino (Italy) groups

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Outline

- Motivations and Challenges
- Radiation damage effects in silicon sensors
- TCAD radiation damage modeling approaches
- TCAD modeling of rad-hard sensors
  - LGAD
  - Compensated LGAD
  - DC-RSD
- Conclusions

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Motivations and Challenges

- Semiconductor detectors will face increasing radiation levels
  - $>1\text{x}10^{16}$ 1MeV n_{eq}/cm^2 (HL-LHC);
  - $>5\text{x}10^{17}$ 1MeV n_{eq}/cm^2 (FCC-hh);
    - detectors used at LHC cannot be operated after such irradiation.

- New requirements lead to new detector technologies
  - Need to be optimized for radiation hardness and/or 4D tracking capabilities.

- Modern TCAD simulation tools can have a crucial role in radiation-hard device design
  - Reducing costly and time-consuming physical testing.
  - Deep understanding of physical device behavior.
  - Combined Bulk and surface radiation damage can be considered.
    - deep-level radiation-induced traps whose parameters are physically meaningful and whose experimental characterization is feasible.
  - Within a hierarchical approach, increasingly complex models can be considered, by balancing complexity and comprehensiveness.

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Radiation damage effects

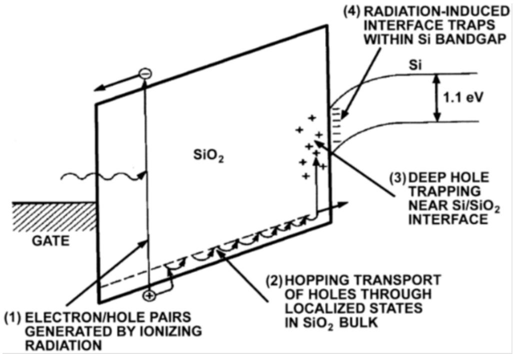
Two main types of radiation damage in detector materials:

√ 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}.

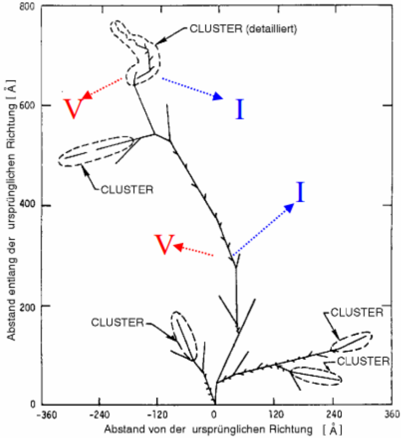
√ BULK damage ← Non-Ionizing Energy Loss (NIEL)

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



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

van Lint 1980



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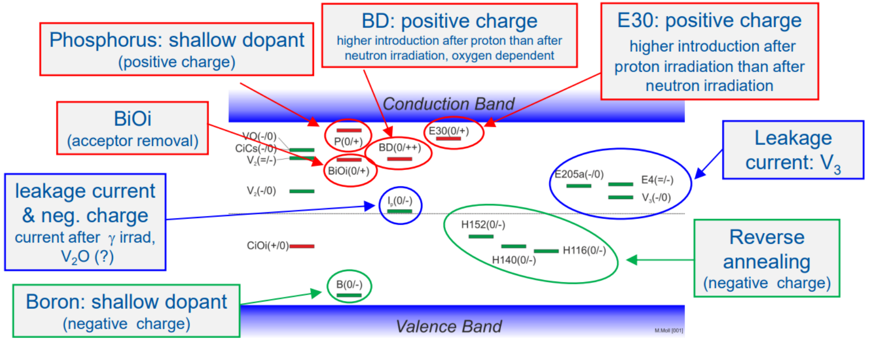
TCAD models - an overview

Different approaches to TCAD radiation damage modeling:

✓	EVL Model	(2 levels)
✓	Delhi-2014	(2 levels)
✓	KIT (Eber)	(2 levels)
✓	New Univ. Of Perugia Bulk+Surface	(3 levels)
✓	Folkestad (CERN model)/LHCb	(3 levels)
✓	Hamburg Penta Trap Model (HPTM)	(5 levels)

Different modeling approaches (traps, energy levels and related parameters), often tailored to specific datasets and devices.



Phosphorus: shallow dopant
(positive charge)

BD: positive charge
higher introduction after proton than after neutron irradiation, oxygen dependent

E30: positive charge
higher introduction after proton irradiation than after neutron irradiation

BiOi
(acceptor removal)

Leakage current: V_3

leakage current & neg. charge
current after γ irrad, V_2O (?)

Reverse annealing
(negative charge)

Boron: shallow dopant
(negative charge)

RD50 map of most relevant defects for device performance near RT

GOAL: General purpose TCAD model

- Not over specific
  → set of "effective" defects within the semiconductor bandgap.
- Accounts for different irradiation levels and particle types.

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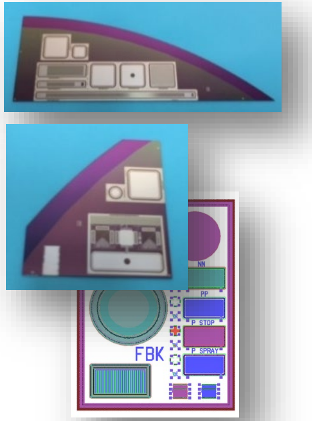
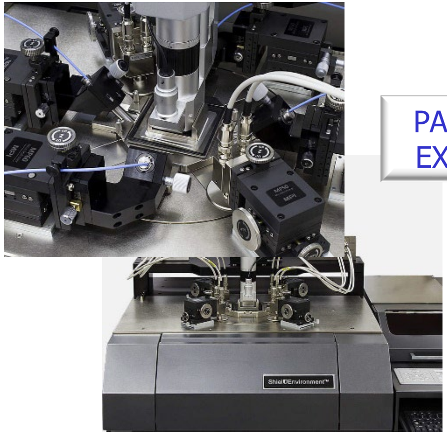
New University of Perugia model

The overall modelling approach pursued

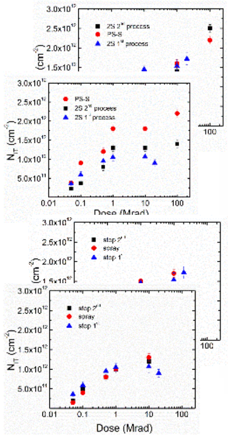


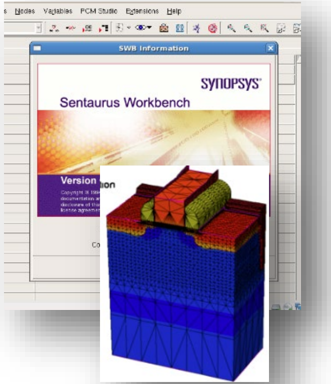
TEST STRUCTURE MEASUREMENTS



PARAMETERS EXTRACTION

MODEL





MODEL VALIDATION

DETECTOR OPTIMIZATION

CCE, I-V, C-V, …

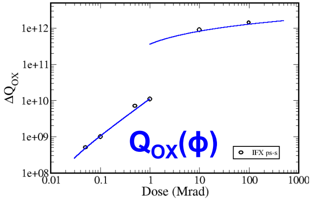
√ Modeling the effects of the radiation damage.

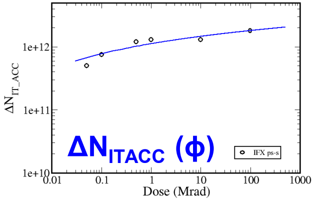
√ Predictive insight into the behavior of detectors, aiming at their performance optimization.

Application of TCAD surface radiation model

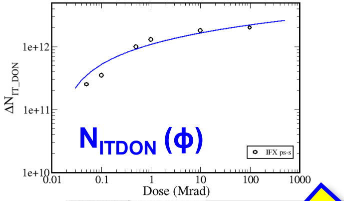
INPUT

Developed TCAD radiation damage effects model



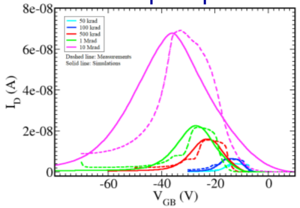


$$Q_{OX}(\Phi) = Q_{OX}(0) + \Delta Q_{OX}(\Phi)$$
$$N_{ITacc}(\Phi) = N_{ITacc}(0) + \Delta N_{ITacc}(\Phi)$$
$$N_{ITdon}(\Phi) = N_{ITdon}(0) + \Delta N_{ITdon}(\Phi)$$

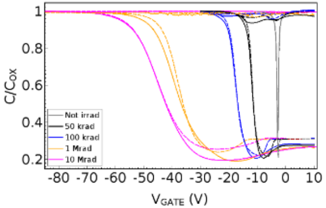


OUTPUT (I-V, C-V, R_{INT})

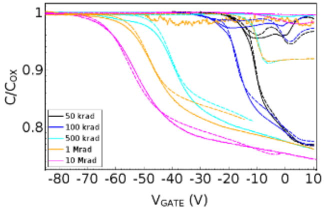
HPK GD p-stop



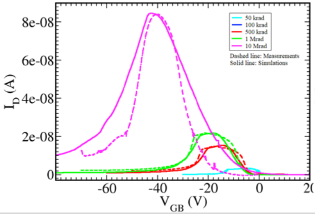
HPK MOS Cap p-stop



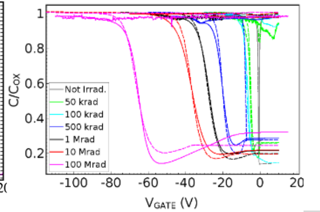
HPK MOS Cap p-spray



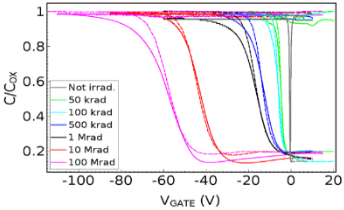
HPK GD p-spray

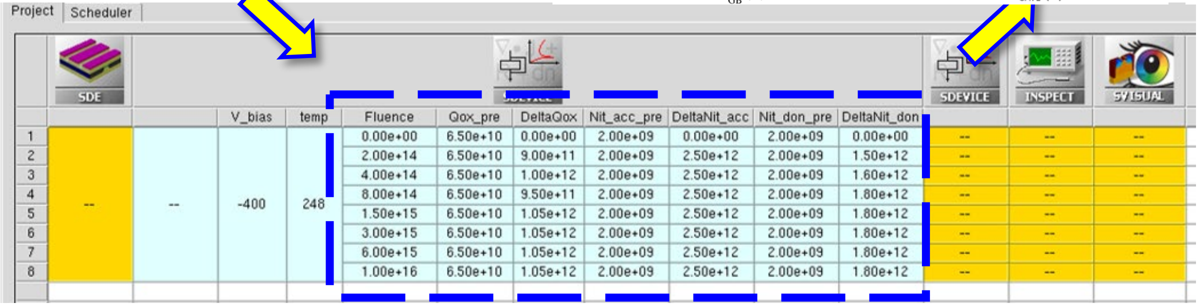


IFX MOS Cap 8" process.



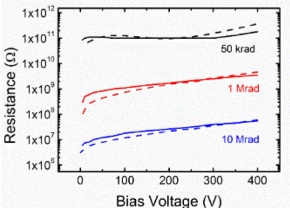
IFX MOS Cap 6" process.





	SDE		V_bias	temp	Fluence	Qox_pre	DeltaQox	Nit_acc_pre	DeltaNit_acc	Nit_don_pre	DeltaNit_don	SDEVICE	INSPECT	SVISUAL
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	--	--	--

HPK p-stop



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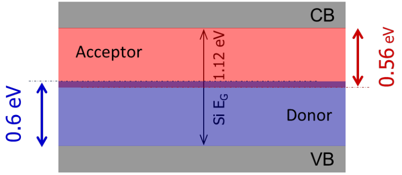
The “New Univ. of Perugia” model

√ Surface damage (+ Q_{OX})

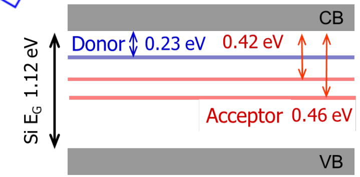
Type	Energy (eV)	Band width (eV)	Conc. (cm^{-2})
Acceptor	$E_C \leq E_T \leq E_C$-0.56	0.56	$D_{IT} = D_{IT}(\Phi)$
Donor	$E_V \leq E_T \leq E_V$+0.6	0.60	$D_{IT} = D_{IT}(\Phi)$



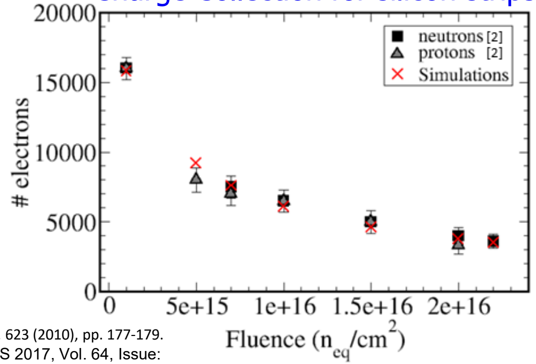
√ Bulk damage

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}

Avalanche ON:
Van Overstraeten–De Man
(default)

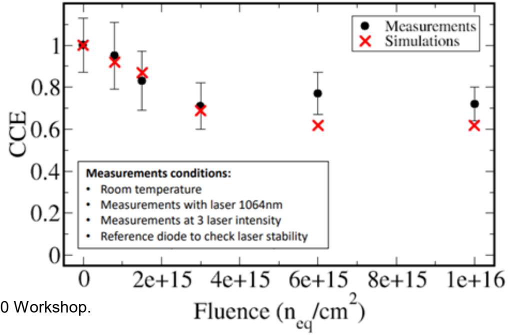


Charge Collection for silicon strips.



[2] A. Affolder et al., NIMA Vol. 623 (2010), pp. 177-179.
F. Moscatelli et al., IEEE TNS 2017, Vol. 64, Issue: 8, 2259 – 2267.

Charge Collection for PiN diodes.



M. Ferrero, 34th RD50 Workshop.

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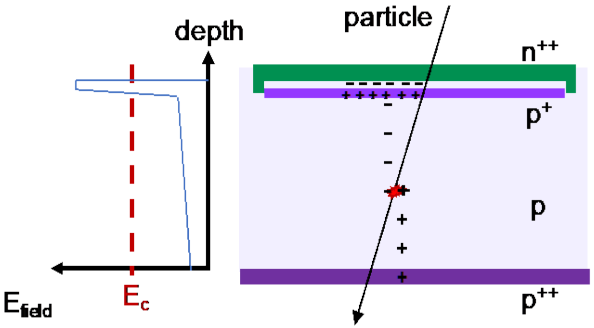
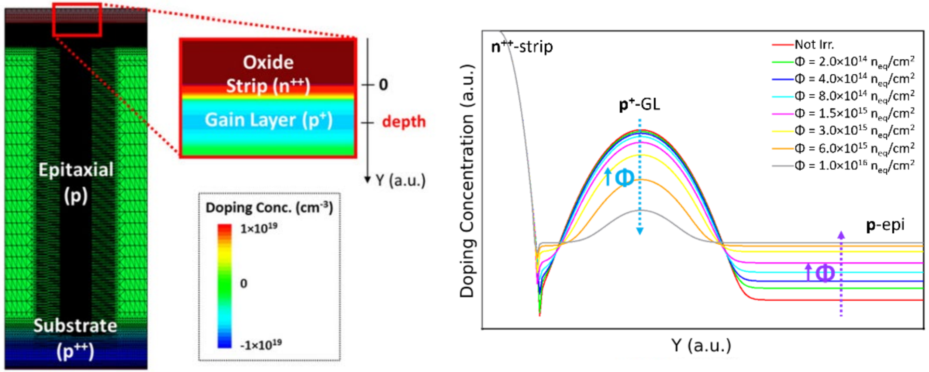
Low Gain Avalanche Diodes

- **Low-Gain Avalanche Diode (LGAD)**
  - **n-in-p silicon** sensors
  - Operated in **low-gain regime** (20 – 30)
  - **Critical electric field ~ 20 – 30 V/µm**
  - Good candidate for **4D tracking**
  - Mitigation of the radiation damage effects by exploiting the **controlled charge multiplication** mechanism.



- **Advanced TCAD** modeling
  - **Radiation damage effects** model implementation
  - Accounts for the acceptor removal mechanism[5] which deactivates the p^+-doping of the gain layer with irradiation.
  - Electrical behavior **prediction/ performance optimization** up to the highest fluences.

Layout and **doping profile**



[5] [M. Ferrero et al., doi:10.1016/j.nima.2018.11.121]

TCAD simulation of LGAD devices

✓ **Physical models**

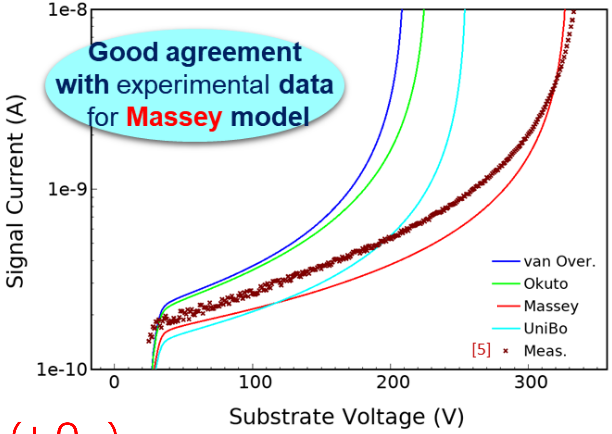
- **Generation/Recombination rate**
  - Shockley-Read-Hall, Band-To-Band Tunneling, Auger
  - **Avalanche Generation => impact ionization models,** *van Overstraeten-de Man, Okuto-Crowell, Massey*[1], *UniBo*
- **Fermi-Dirac statistics**
- **Carriers mobility variation** doping and field-dependent
- **Physical parameters**
  - e-/h+ recombination lifetime

✓ **Radiation damage models: "PerugiaModDoping"**

- **"New University of Perugia model"**
  - **Combined surface and bulk** TCAD damage modeling scheme[2]
  - Traps generation mechanism
- **Acceptor removal mechanism** => $N_{GL}(\phi) = N_A(0)e^{-c\phi}$
  - where
    - **Gain** Layer (**GL**), **c** removal rate (**Torino parameterization**[3])
- **Acceptor creation**

$$N_{A,bulk} = \begin{cases} N_{A,bulk}(0) + g_c\phi, & 0 < \phi < 3E15\, n_{eq}/cm^2 \\ 4.17E13 \cdot \ln(\phi) - 1.41E15, & \phi > 3E15\, n_{eq}/cm^2 \end{cases}$$

where g_c = 0.0237 cm^{-1} (**Torino acceptor creation**)



Good agreement with experimental data for Massey model

Surface damage (+ Q_{OX})

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[1] M. Mandurrino et al., https://doi.org/ 10.1109/NSSMIC.2017.8532702.
[2] D. Passeri, AIDA2020 report, CERN Document Server.
[3] M. Ferrero et al., https://doi.org/ 10.1016/j.nima.2018.11.121.
[4] V. Sola et al., https://doi.org/10.1016/j.nima.2018.07.060.

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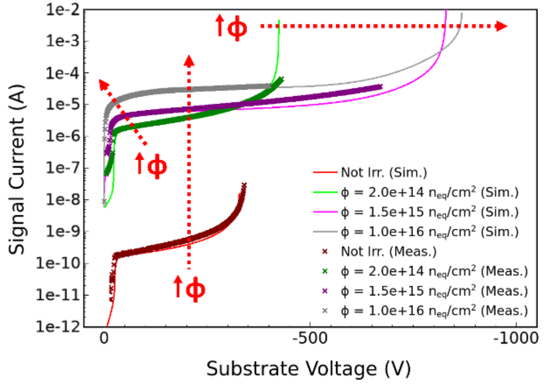
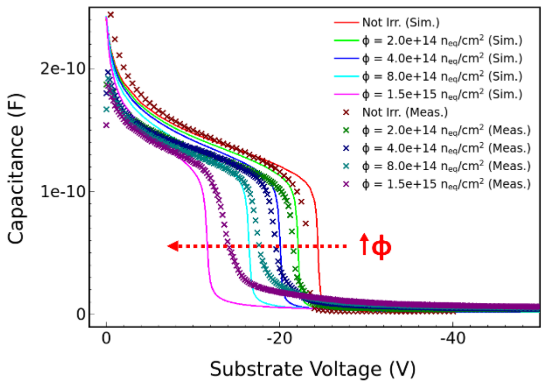
LGAD: Electrical behavior investigation (1)

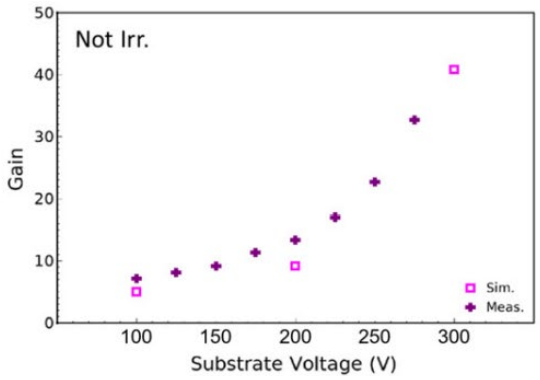
- ❑ **FBK LGADs** (UFSD2, W1)
  - ❑ 55 µm thick

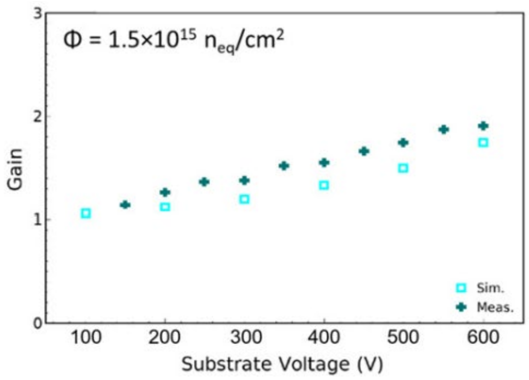
- ❑ Simulations-Measurements comparison for not irradiated and irradiated devices.

- ❑ TCAD settings:
  - ❑ "PerugiaModDoping"
  - ❑ Massey avalanche model.
  - ❑ Temperature sets as per experimental measurements (RT not irrad, 248 K irrad).
  - ❑ Electrical contact area 1mm^2.
  - ❑ Frequency 1 kHz for C-Vs.









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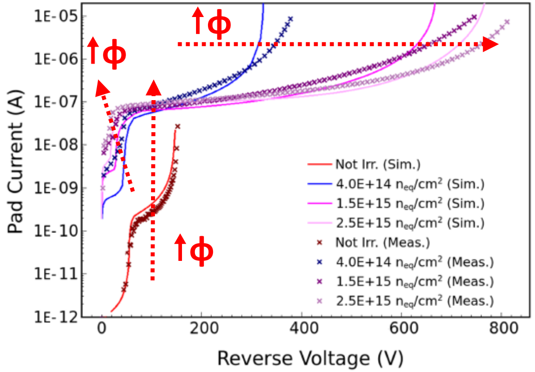
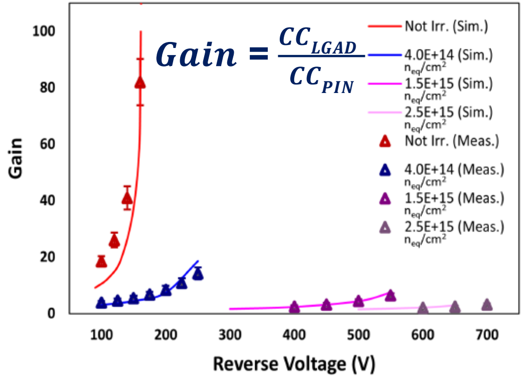
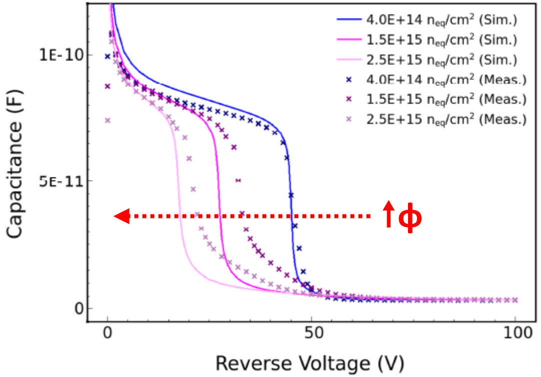
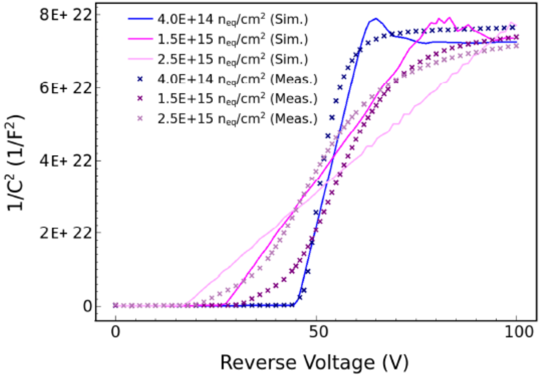
LGAD: Electrical behavior investigation (2)

- **HPK LGADs** (HPK2, split 1-2)
    - 50 μm thick
- Simulations-Measurements comparison for not irradiated and irradiated devices.
- TCAD settings:
    - ”PerugiaModDoping”
    - vOv avalanche model.
    - Temperature sets as per experimental measurements (RT not irrad, 248 K irrad).
    - Electrical contact area 1.3×1.3 mm^2.
    - Frequency 2 kHz for C-Vs.









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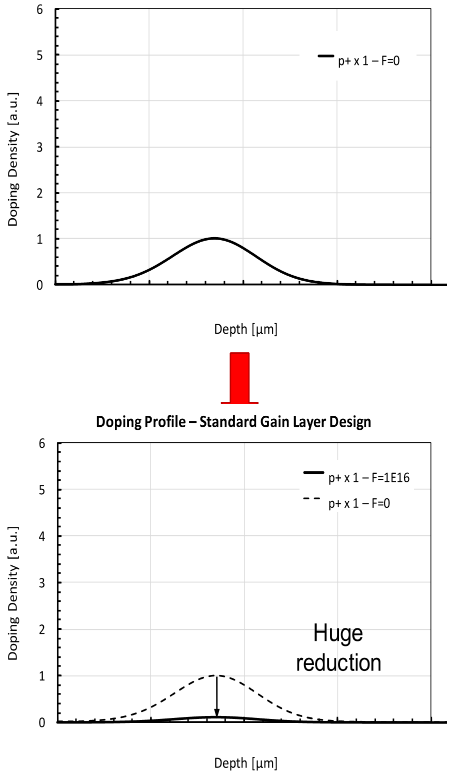
Compensated LGAD: innovation for extreme fluences

- Difficult to operate silicon sensors above 10^{16} n_{eq}/cm^2 due to:
    - defects in the silicon lattice structure → dark current increase
    - trapping of the charge carriers → charge collection efficiency decrease
    - change in the bulk effective doping → impossible to fully deplete the sensors
- In standard LGAD
    - acceptor removal mechanism → $\Phi > 1–2 \cdot 10^{15}$ n_{eq}/cm^2 lose the multiplication power and behave as standard n-in-p sensors .
- Overcome the present limits above extreme fluences[6]:
    - saturation of the radiation damage effects above $5 \cdot 10^{15}$ n_{eq}/cm^2
    - the use of thin active substrates (20 – 40 mm)
    - extension of the charge carrier multiplication up to $5 \cdot 10^{17}$ n_{eq}/cm^2

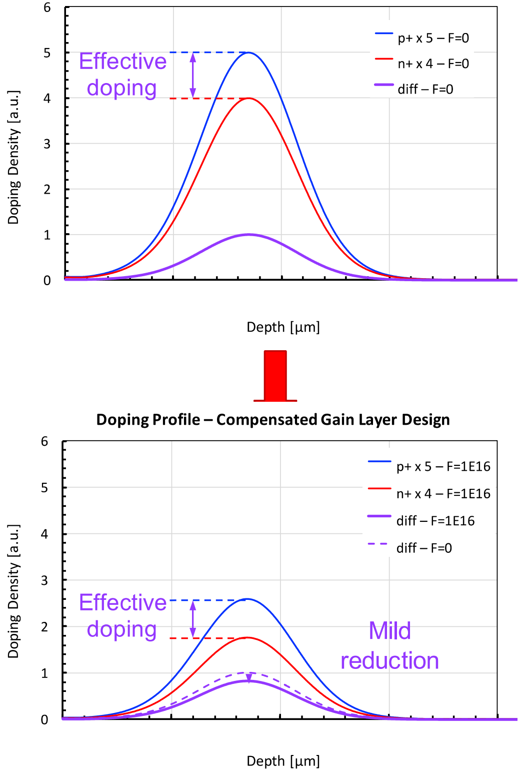


Standard LGAD design

[6] V. Sola et al, "A compensated design of the LGAD gain layer", NIMA 1040 (2022) 167232

Compensated LGAD: innovation for extreme fluences

- **Goal**: extreme fluences $\Phi = 5 \cdot 10^{17}\ n_{eq}/cm^2$
- Impossible to reach the design target with the present design of the gain layer.
- Use the interplay between acceptor and donor removal to keep a constant gain layer active doping density.
  Compensated LGAD: Technology under development (FBK EXFLU1 R&D)
- Many unknowns:
  - donor removal coefficient,
  - interplay between donor and acceptor removal (c_D vs c_A)
  - effects of substrate impurities on the removal coefficients



Compensated LGAD

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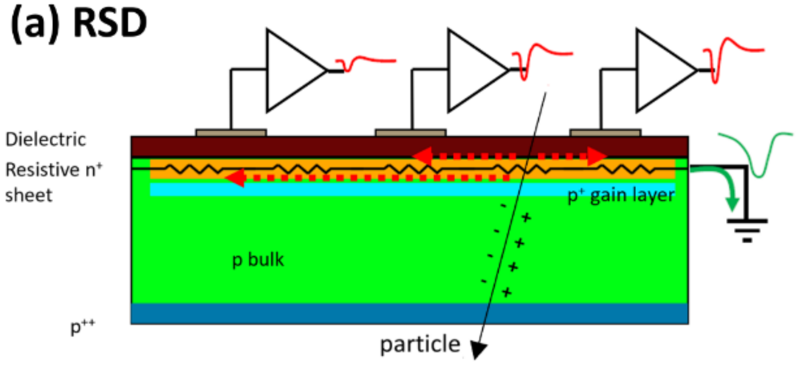
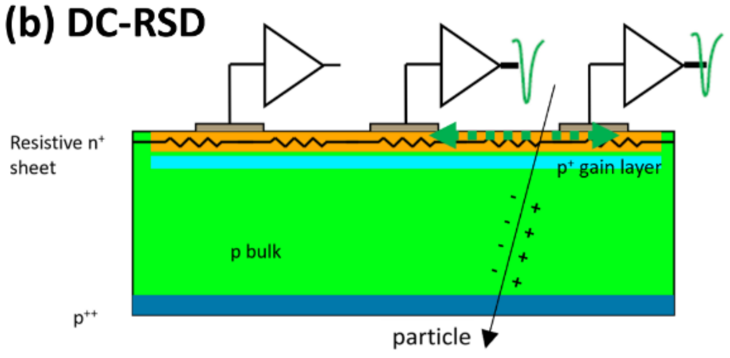
Resistive Silicon Detector: AC-RSD and DC-RSD





- ✓ This design has been manufactured in several productions by FBK, BNL, and HPK.
- ✓ A single diode, instead of many p-n diodes.
- ✓ The n-doped implant is resistive and acts as a signal divider.
- ✓ Very uniform electric and weighing fields, good geometry for timing.

- ✓ This design is presently under development by FBK.
- ✓ The main advantage of the DC-RSD design is to limit the signal spread;
- ✓ A promising solution to simultaneously meet all the specifications required for the next generation of colliders;
- ✓ Evaluation of different layouts and technologies for future DC-RSD production using TCAD tools;

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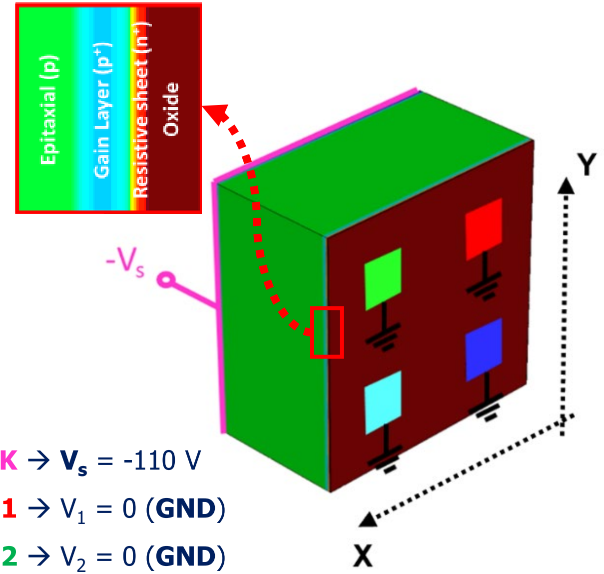
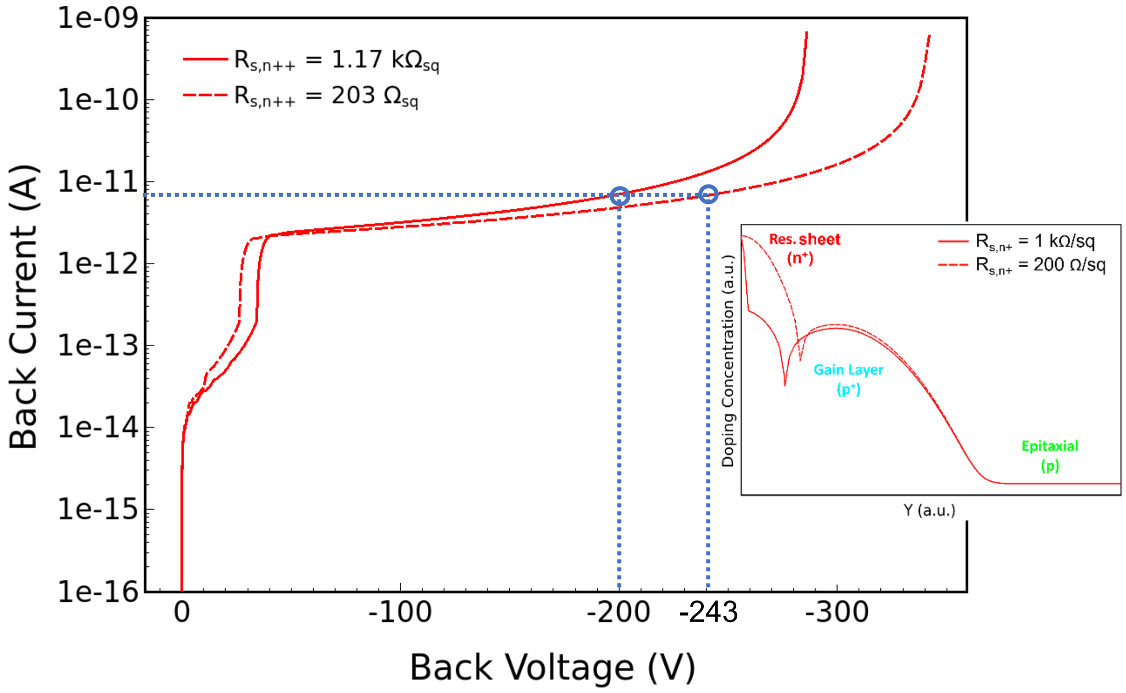
Different n^{++} layer resistance

✓ 3D structure, 2x2 PADs => LGAD



- ☐ **BACK** → $\mathbf{V_s}$ = -110 V
- ☐ **PAD1** → V_1 = 0 (**GND**)
- ☐ **PAD2** → V_2 = 0 (**GND**)
- ☐ **PAD3** → V_3 = 0 (**GND**)
- ☐ **PAD4** → V_4 = 0 (**GND**)

I-V, not irr.



Avalanche model: **Massey**. Temperature **300 K**

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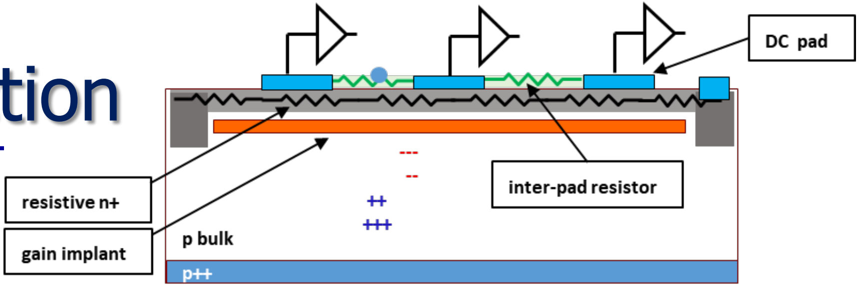
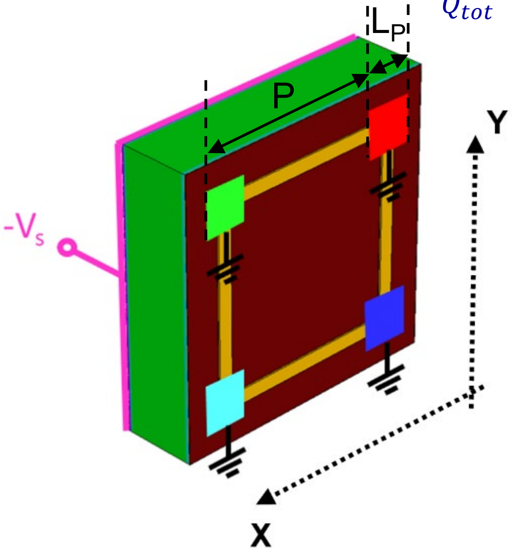
DC-RSD with strips: reconstruction



- ✓ Stimulus MIP
- ✓ The position is reconstructed using the charge imbalance

$$x_i = \frac{Q_{top\,right} + Q_{bottom\,right} - Q_{top\,left} - Q_{bottom\,left}}{Q_{tot}}$$

$$z_i = \frac{Q_{top\,right} + Q_{top\,left} - Q_{bottom\,left} - Q_{bottom\,right}}{Q_{tot}}$$



$L_P = 15\ \mu m$

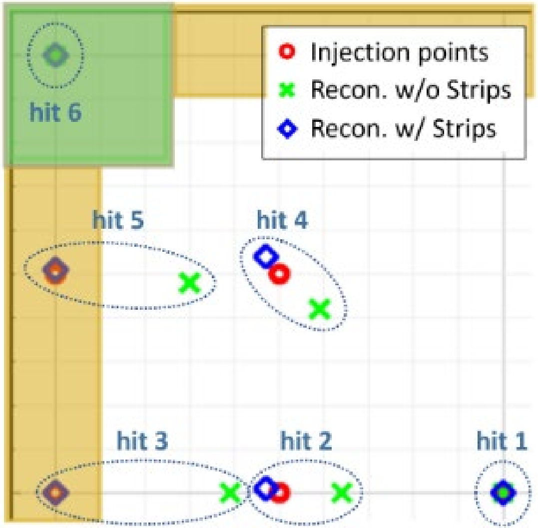
$P = 105\ \mu m$

@ $V_{Back} = -110\ V$

$R_{s,n++} \approx 721\ \Omega_{sq}$

$R_{s,strip} \approx 15\ m\Omega/\mu m$

Results from *TCAD* simulations



Avalanche model: **Massey**. Temperature **300 K**

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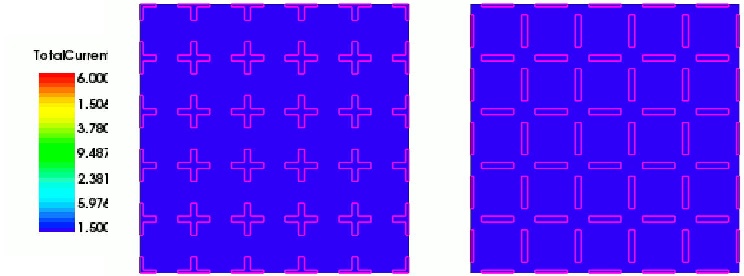
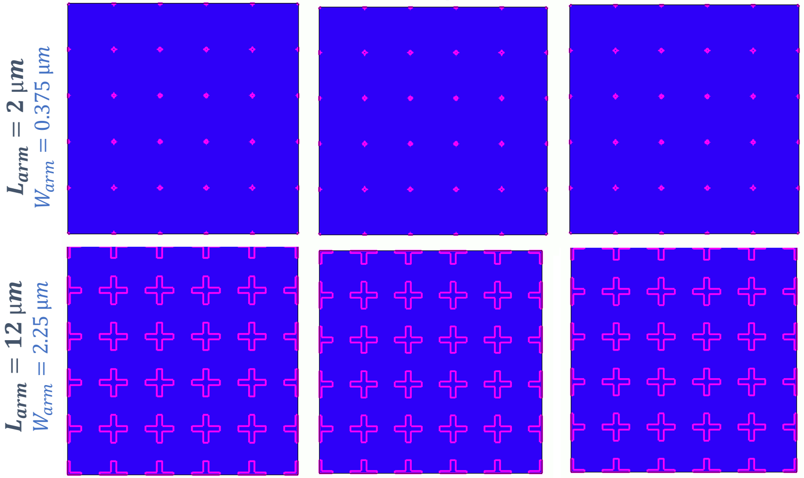
Charge sharing and signal confinement

- ☐ Investigation of the signal confinement within the TCAD environment.
- ☐ Minimum Ionizing Particle (MIP): various hit points considered.
- ☐ Different pad geometries
  - Cross or bar-shaped;
  - Better confinements in larger pads;
  - Error in reconstruction by associating any point covered by metal with the center of the pad;
  - Need **small**, **circular-shaped** electrodes and a strategy to confine the signal (e.g., trenches);

Cross- vs bar-shaped pads



Three hit points



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Conclusions

- ✓ Strategy for TCAD numerical simulation of rad-hard devices
  - Bulk + Surface radiation damage effects need to be considered in the modeling scheme.
  - “New University of Perugia Model” + Acc removal/creation mechanism→ “PerugiaModDoping”
    - LGAD, compensated and RSD LGAD → optimization for their use in the future HEP experiments

- ✓ TCAD plays a pivotal role in the design/optimization of rad-hard devices
  - Modelling radiation damage effects is a tough task!
  - New guidelines for future production of radiation-resistant options.
  - Modeling dopant removals, impact ionization, carriers’ mobility, traps dynamics

- ✓ A General-purpose TCAD modeling scheme for extreme fluences doesn’t exist yet
  - Predictive capabilities to be extended $\Phi > 10^{16}\ n_{eq}/cm^2$.
  - Application to the optimization of advanced (pixel) detectors (3D detectors, LGADs, …)

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BACKUP SLIDES

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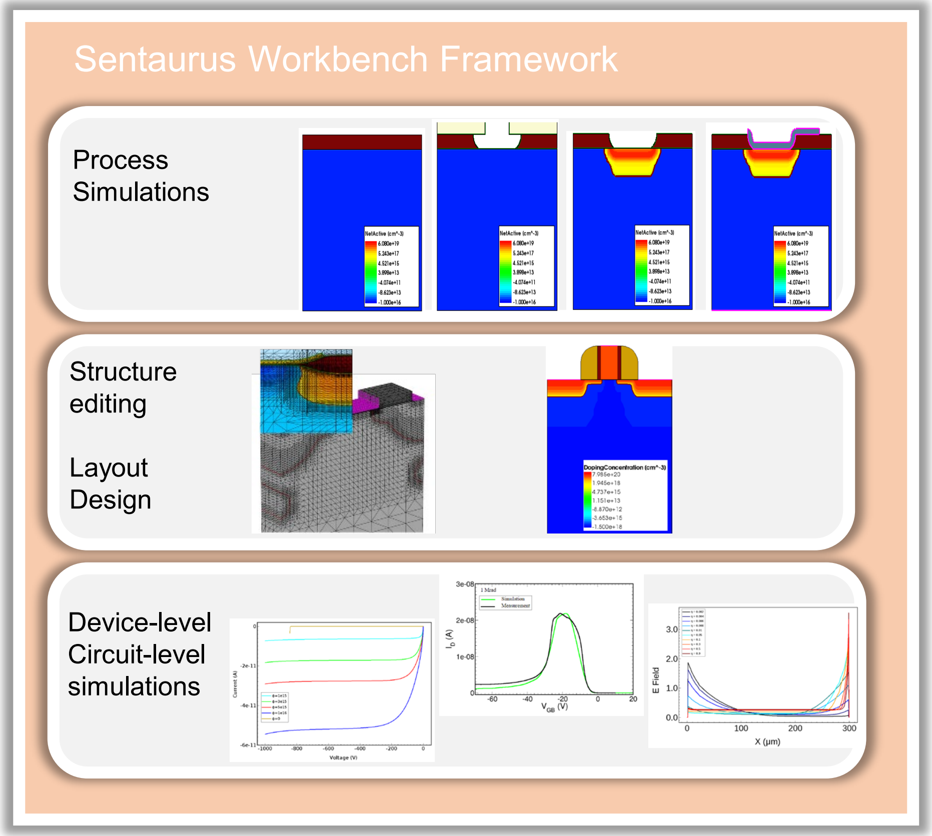
The Technology-CAD modeling approach



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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Low-Gain Avalanche Diodes (LGADs)

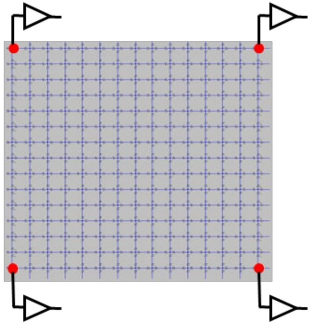
- Most promising devices to cope with the high spatial density of particles hits due to the increasing radiation fluence expected in the HL-LHC at CERN.
- **LGAD structure**: pin diode with the additional inclusion of a p+-type layer just below the n-contact, which is commonly called *multiplication layer.*
- By applying a reverse-bias, this layer is responsible for a **multiplication of carriers**.

$$\mathrm{G}_{\mathrm{aval}} = \boldsymbol{\alpha}_{\boldsymbol{n}} n v_n + \boldsymbol{\alpha}_{\boldsymbol{p}} p v_p \qquad \boldsymbol{\alpha} = \frac{E}{E_{th}} e^{-\frac{E_i}{E}}$$

- By accurately chosing the **peak and shape of the implanted p+ profile**, it is possible to control the **avalanche mechanism** in order to obtain the required internal gain with a sufficiently high breakdown voltage.
- One of the best tools **for predicting the behaviour of the avalanche process** is **device-level simulation**

Reconstruction (3/3)

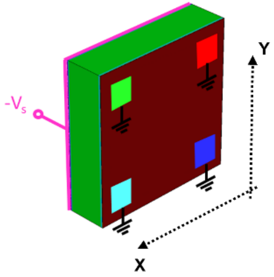
Results from *Spice* simulations **VS.** **Results** from *TCAD* simulations



AMPLITUDE imbalance

$$x_i = \frac{A_{top\ right} + A_{bottom\ right} - A_{top\ left} - A_{bottom\ left}}{A_{tot}}$$

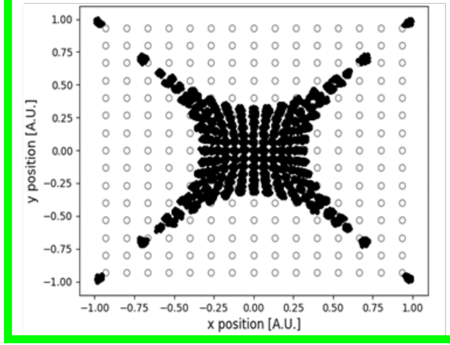
$$z_i = \frac{A_{top\ right} + A_{top\ left} - A_{bottom\ left} - A_{bottom\ right}}{A_{tot}}$$



CHARGE imbalance

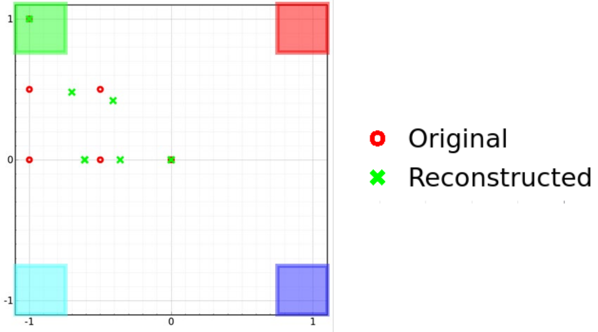
$$x_i = \frac{Q_{top\ right} + Q_{bottom\ right} - Q_{top\ left} - Q_{bottom\ left}}{Q_{tot}}$$

$$z_i = \frac{Q_{top\ right} + Q_{top\ left} - Q_{bottom\ left} - Q_{bottom\ right}}{Q_{tot}}$$



Empty circles: injection points

Filled circles: reconstructed points



From **L. Menzio et al.**, 17th ''TREDI'' Workshop 03/03/22.

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	$D_{IT} = D_{IT}(\Phi)$
Donor	$E_V \le E_T \le E_V$+0.6	0.60	$D_{IT} = D_{IT}(\Phi)$

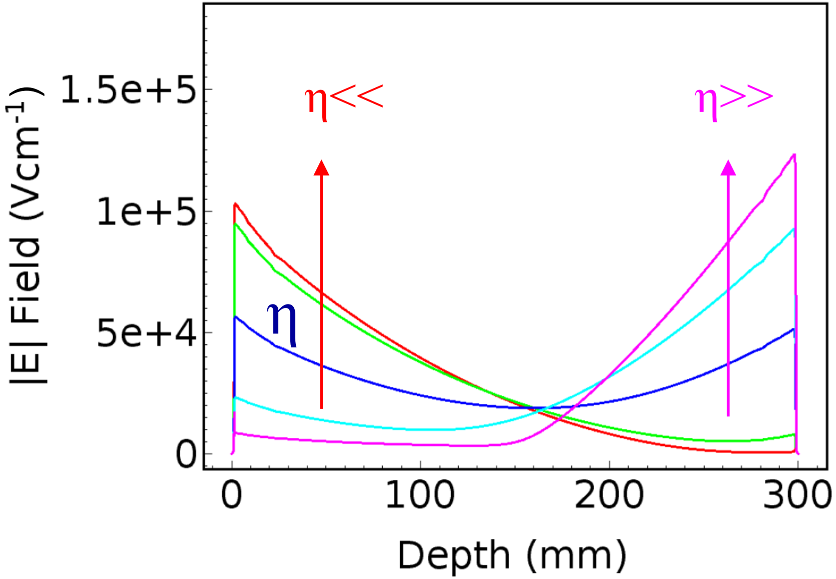
√ Bulk damage

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	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}

AIDA 2020

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



Methodology

DC / AC analysis

- **DC biasing (static)**
  - n cathode: 0 V
  - p anode: *sweep*
    - ✓ start = 0 V
    - ✓ step = - 25 V (from 100 V)
    - ✓ stop = - 1000 V
  - Temperature
    - ✓ 300 K for not irr., 253 K for irr. [7]
- **AC biasing (small-signal)**
  - For each DC bias step, superimposition of a 1 V_{pp}, 1 kHz sinusoid
  - Impedance matrix for each node of the discretized grid
  - Temperature 300 K for not irr. / irr.

Transient analysis

- For each DC bias step, one **Time-Variant (TV)** simulation of impinging particle (**MIP**), following the **"HeavyIon" model**
  - instant of penetration 1 ns
  - through the whole device
  - Linear Energy Transfer (LET)

$$LET_f = \frac{E_{LOSS}}{E} \frac{pC}{\mu m}$$

where

$$E = 3{,}68\ eV$$

[5] $$E_{LOSS} = 0{,}027\, log(y) + 0{,}126\ \frac{keV}{\mu m}$$

Gain calculation

- Leakage current calculation
  - instant = 0,9 ns
- Leakage current offset subtracted from the simulated I(t) curve
- Calculation of **Collected Charge (CC)** as the **integral of the current**

$$\boxed{Gain = \frac{CC_{LGAD}}{CC_{PIN}}}$$ [6]

[5] S. Meroli et al., *Energy loss measurement for charged particles in very thin silicon layers*, JINST 6 P06013, 2011

[6] V. Sola et al., *First FBK production of 50 µm ultra-fast silicon detectors*, Nucl. Instrum. Methods Phys. Res. A, 2019

[7] A. Chilingarov, *Temperature dependence of the current generated in si bulk*, JINST 8 P10003, 2013.

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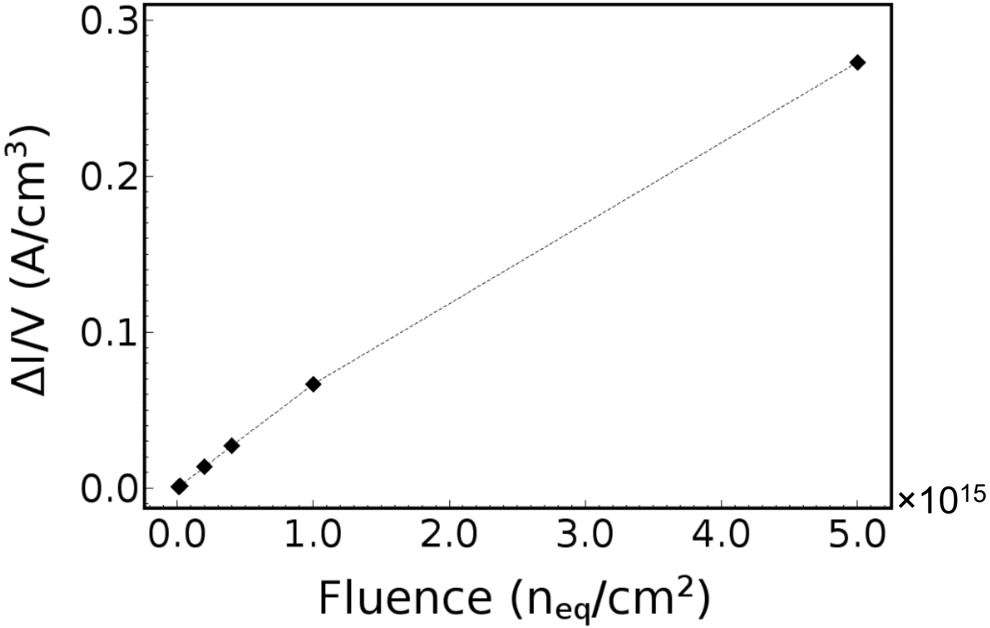
Leakage current vs fluence

- ✓ 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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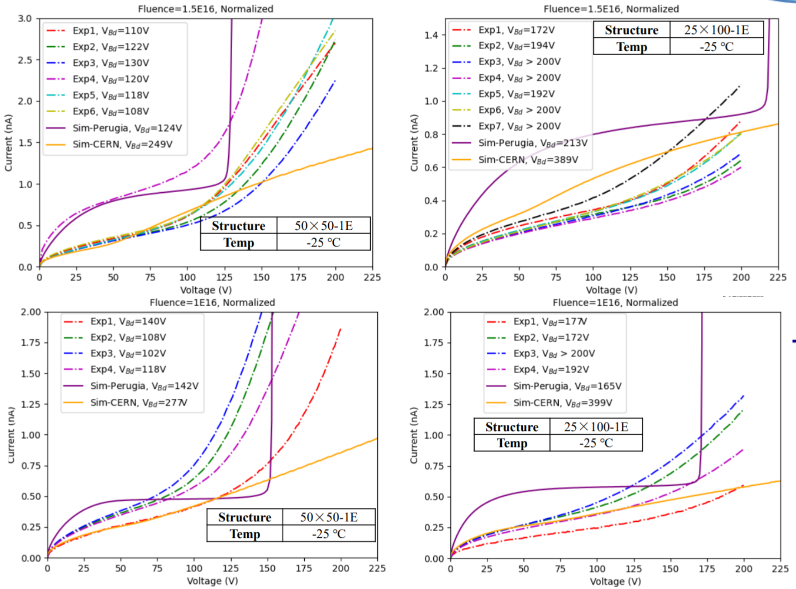
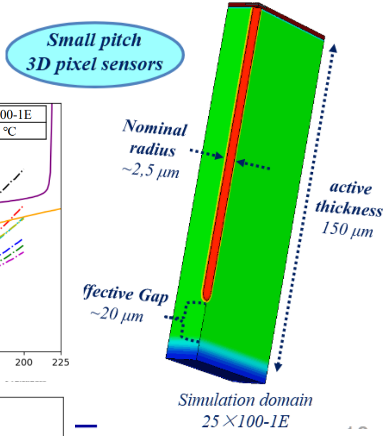
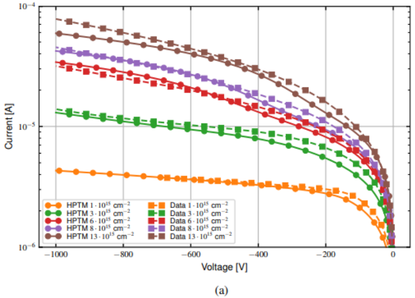
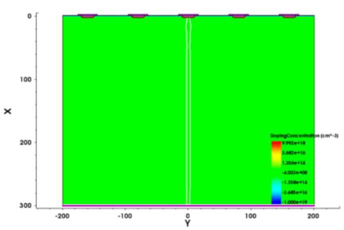
TCAD models - some applications

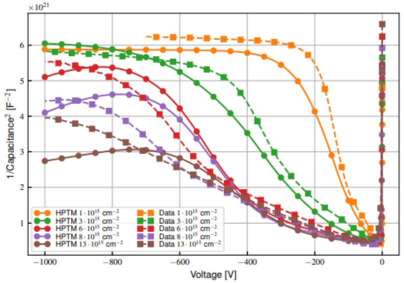






(a)





Simulation based on the **CERN Bulk Damage Model.**
Univ. of Trento Group.

Hamburg Penta Trap Model (**HPTM**).
Univ. of Hamburg group.

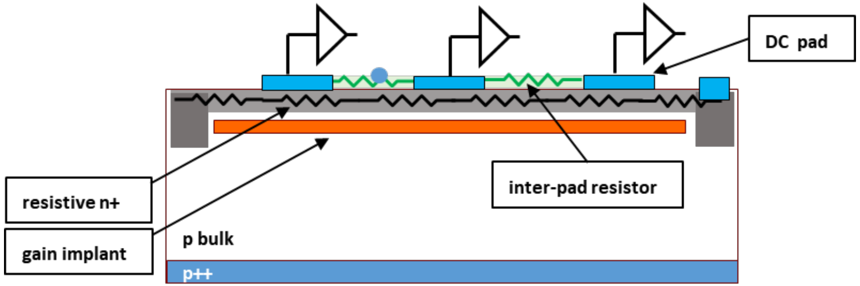
Ye, J.; Sensors 2023, 23, 4732, doi: 10.3390/s23104732

J. Schwandt et al., 2018 IEEE NSS/MIC, doi: 10.1109/NSSMIC.2018.8824412.

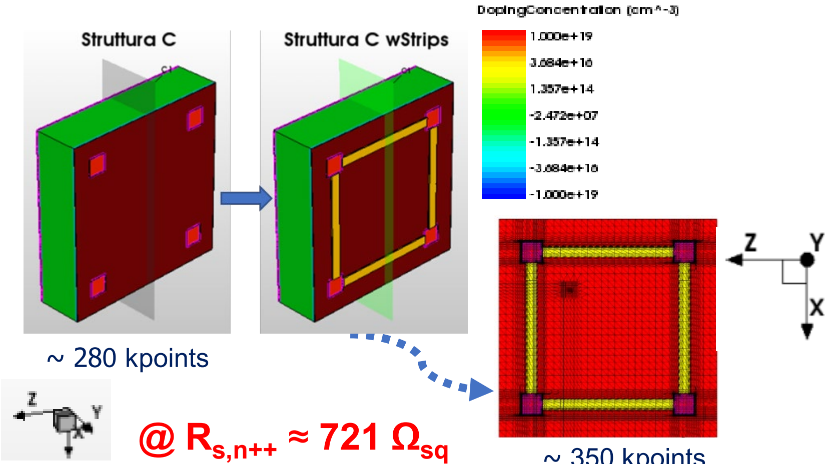
DC-RSD with strips

- The DC-RSD design can consider resistors between the read-out electrodes.

→ these resistors could improve the position resolution of the sensors



3D structure, **2x2 PADs** => **LGAD**

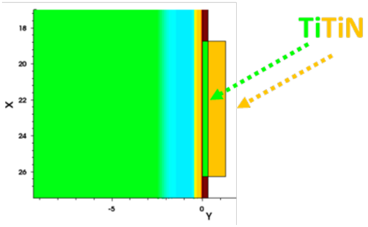


~ 280 kpoints

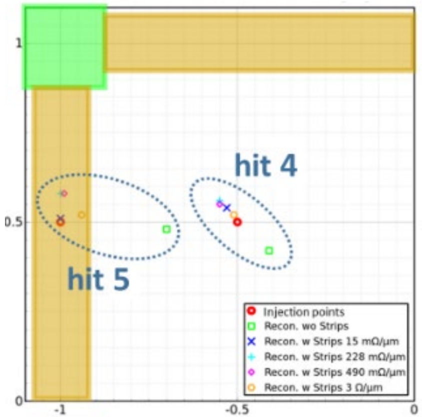
~ 350 kpoints

@ $R_{s,n++} \approx 721\ \Omega_{sq}$

Y-Cut



$$R_{TiTiN} \begin{cases} 3{,}06\ \Omega/\mu m \\ 228\ \ m\Omega/\mu m \\ 490\ \ m\Omega/\mu m \\ 15\ \ \ \ m\Omega/\mu m \end{cases}$$



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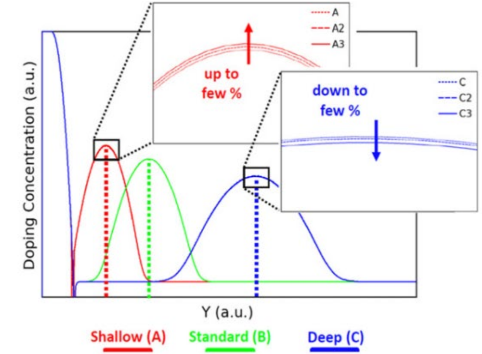
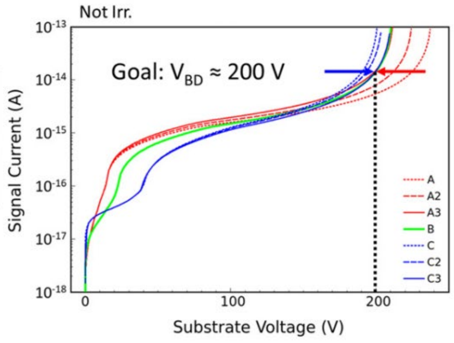
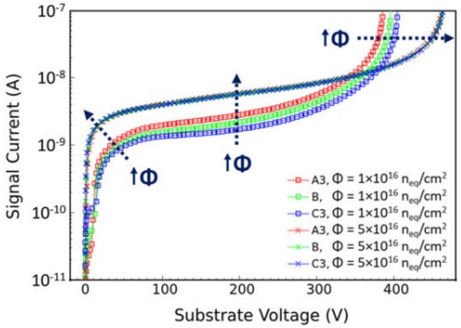
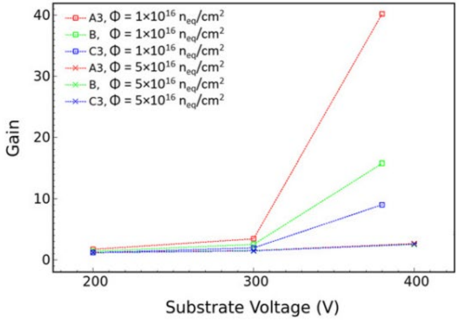
Gain layer sensitivity analysis

- Three different doping profiles considered
  - Shallow, Standard, Deep.
  - **Gain layer** peak: a variation of a few percentages affects the breakdown voltage (V_{BD}).
  - Effect on the gain layer depletion voltage.
  - **Predictive** analysis on sensor performance considering the **radiation damage effects**.









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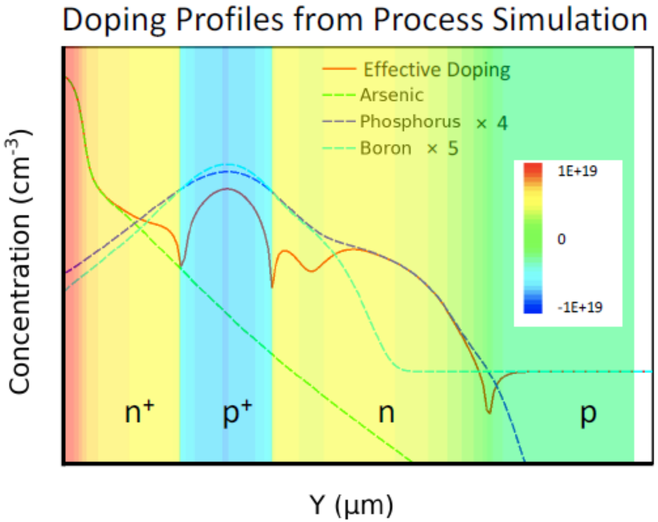
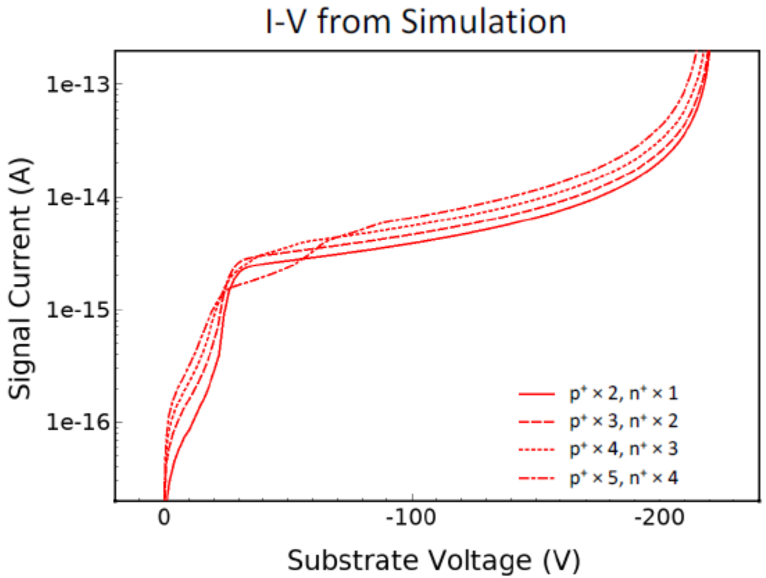
Compensation - simulation

- ☐ Process simulations of Boron (p+) and Phosphorus (n+) implantation and activation reveal the different shapes of the two profiles (TCAD Silvaco).





- ☐ The simulation of electrostatic behavior illustrates that attaining similar multiplication is achievable with diverse initial compensation values (TCAD Synopsys).

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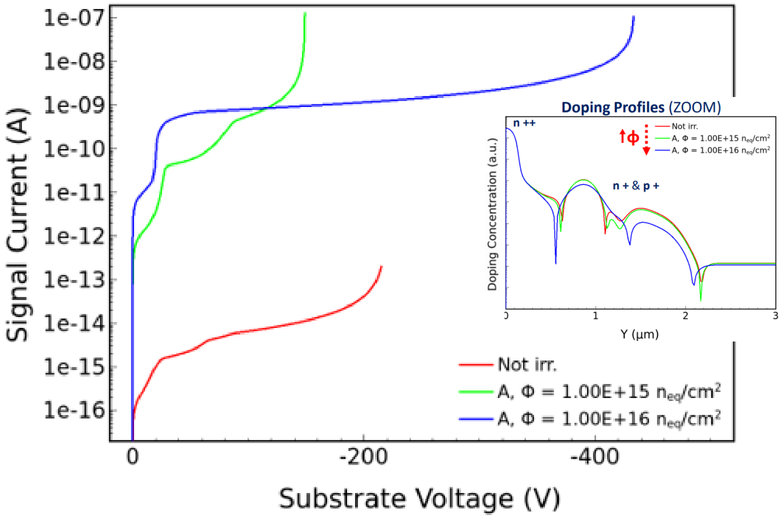
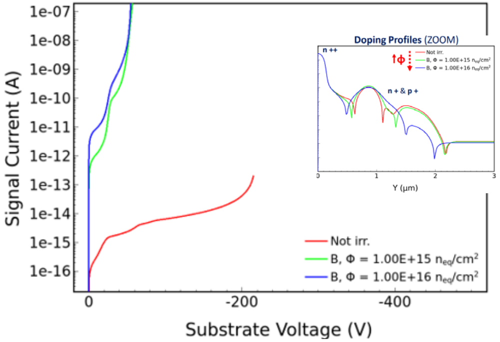
Compensation – doping evolution with fluence

- Three scenarios of net doping evolution are possible, according to the acceptor and donor removal interplay:

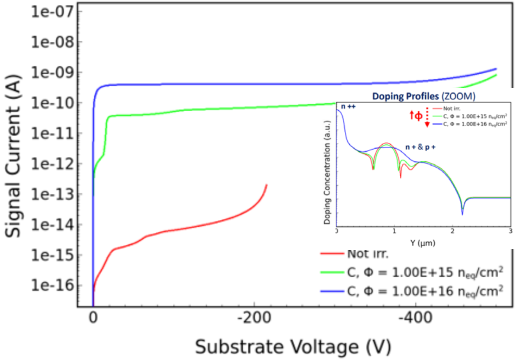
1. $c_A \sim c_D$
   p+-n+ effective doping remains almost constant → unchanged gain with irradiation.



2. $c_A < c_D$
   rapid increase of the net p+-doping → the gain increases with irradiation.
   Co-implantation of oxygen might mitigate the donor deactivation rate.



3. $c_A > c_D$
   effective doping disappearance is slower than in the standard design.
   Co-implantation of carbon atoms can mitigate the p+-doping removal.



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Parameter extraction procedure

√ From C-V measurements of MOS capacitors:

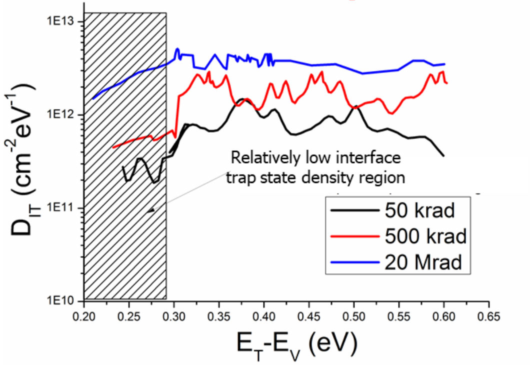
- D_{IT} is assessed by using the C-V High-Low method.
- High-Frequency (HF) measurements are carried out at 100 kHz with a small signal amplitude of 25 mV.
- Quasi-Static (QS) characteristics measured with delay times of 0.5 sec using a voltage step of 100 mV.
- N_{EFF} is obtained from V_{FB} measurements.

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

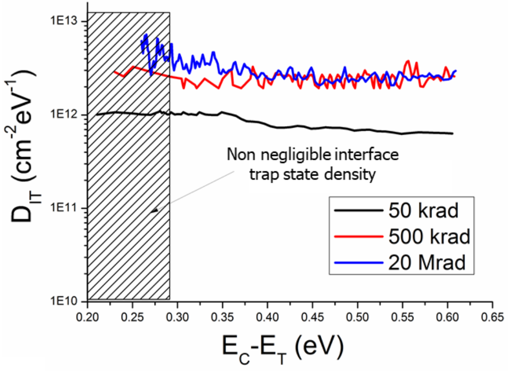
$$\mathrm{D_{IT}} = \frac{\mathrm{C_{IT}}}{\mathrm{q} \times \mathrm{A}}$$

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

Donor interface trap states (p-type subs)



Acceptor interface trap states (n-type subs)



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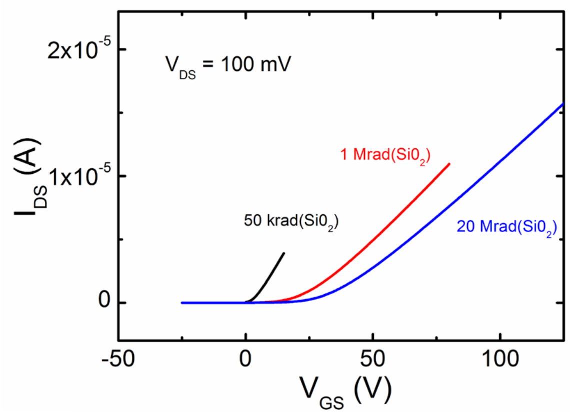
- N_{EFF} is obtained from V_{FB} measurements.

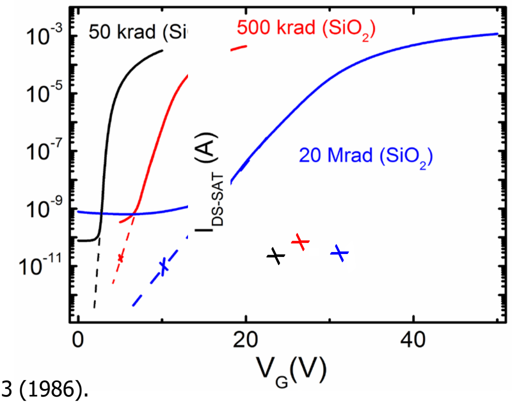


nMOSFET

√ 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].

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



pMOSFET

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