Simulations of radiation hard detectors for timing applications

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(3) DI, University of Perugia, Perugia, Italy
(4) INFN Torino, Torino, Italy
(5) University of Torino, Torino, Italy
(6) University of Trento, Trento, Italy

AIDAinnova - Motivations

INFN and University of Perugia are involved in WP6 Task 6.2

Simulations of surface and bulk radiation damage for 4D (tracking+timing) detectors toward more radiation tolerant solutions

Calibration/extension of the previously developed simulation models

Calibration/extension of the previously developed models ("New University of Perugia TCAD model" and its recent upgrade) by comparing the simulation findings with measurements carried out on dedicated test structures as well as on different classes of 3D and LGAD detectors.

Study the effect of surface and bulk radiation damage with reference to 4D (tracking+timing) detectors toward more radiation resistance solutions.

The proposed activity will focus specifically on disentangling the effects of the two main radiation damage mechanisms, e.g., the surface damage due to ionizing effect and the bulk damage due to atomic displacement, with reference to 4D detectors toward more radiation resistance solutions.

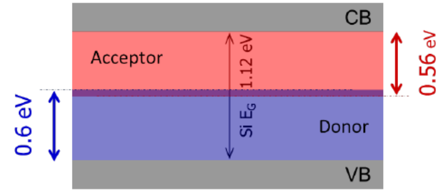
Extension of the Radiation Damage Model

"PerugiaModDoping"[3]

"Perugia0" Bulk/Surface Radiation Damage Model [1]

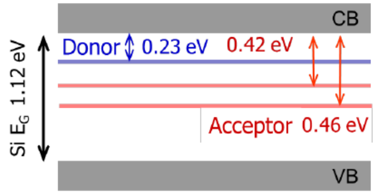
Surface damage (+ Q_{ox})

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	$D_{IT} = D_{IT}(\Phi)$



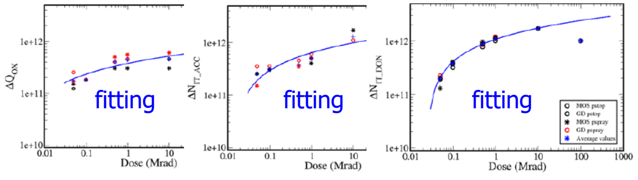
Bulk damage

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}



- ✓ **Bulk damage → Traps concentrations** dependence upon the introduction rate **η** (defects concentration) and the **fluence** (**~ η×Φ**)
- ✓ **Surface damage → Traps** (N_{IT} interface trap density) and **oxide charge** (**Q_{OX}**) **concentrations** dependence upon the **fluence** as follow

$$Q_{OX}(\phi) = Q_{OX}(0) + \Delta Q_{OX}(\phi)$$
$$N_{IT_{acc}} = N_{IT_{acc}}(0) + \Delta N_{IT_{acc}}(\phi)$$
$$N_{IT_{don}} = N_{IT_{don}}(0) + \Delta N_{IT_{don}}(\phi)$$



(a) ΔQ_{OX} (b) ΔN_{IT_ACC} (c) ΔN_{IT_DON}

Torino analytical parameterizations [2]

- **Gain Layer** (Acceptor Removal)

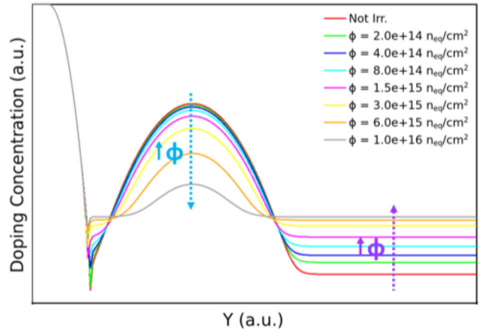
$$N^{peak}_{A,GL}(\Phi) = N_{A,GL}(0) \cdot e^{-c \cdot \Phi}$$

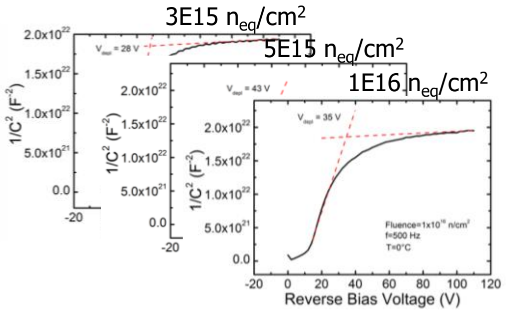
- **Bulk** (Acceptor Creation)
  - ✓ if $0 < \Phi \le$ 3e15 n_{eq}/cm^2

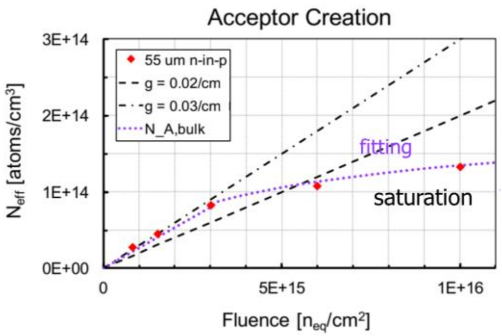
$$N_{A,bulk}(\Phi) = N_{A,bulk}(0) + g_c \cdot \Phi$$

  - ✓ if $\Phi >$ 3e15 n_{eq}/cm^2

$$N_{A,bulk}(\Phi) = 4{,}17e13 \cdot \ln(\Phi) - 1{,}41e15$$







[1] A. Morozzi et. al, PoS (Vertex2019) 050
[2] M. Ferrero et. al, 34th RD50 Workshop, Lancaster, UK (2019)
[3] P. Asenov et. al, Nucl. Instrum. Meth. A 1040 (2022) 167180

TCAD simulation of **LGAD** device

- ✓ In collaboration with *INFN Torino*: **calibration/extension** of the previously developed models **by comparing** the **simulation findings** with **measurements** carried out on different classes of **LGAD** detectors.
- ✓ **Comparison** with **experimental data**, **before** and **after irradiation** (UFSD2 production, by FBK)

"**PerugiaModDoping**"

- **Torino analytical parameterization**
  - **Gain Layer** (Acceptor Removal)
  - **Bulk** (Acceptor Creation)
- "**Perugia0**" Bulk/Surface Radiation Damage 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

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}
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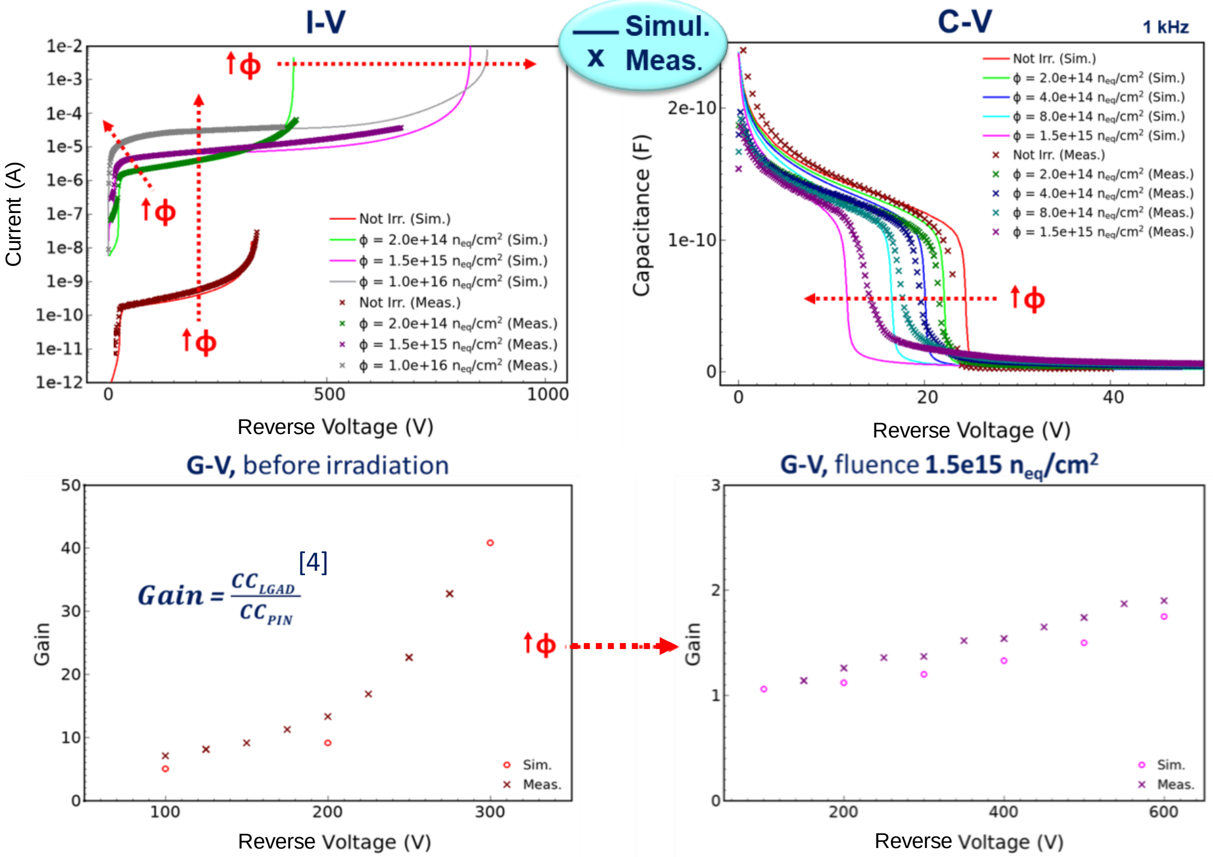

[4] V. Sola et al., *First FBK production of 50 μm ultra-fast silicon detectors*, Nucl. Instrum. Methods Phys. Res. A, 2019.

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

Massey model. Temperature **300 K** [5]. Electrical contact area **1 x 1 mm²**

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SIMULATED C-V & 1/C²-V – HPK2, Split 1 & 2

✓ Pre & Post-irr.

SINGLE

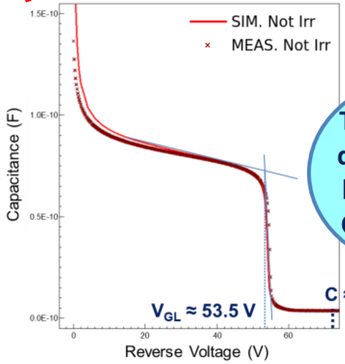
Pad size:
1,25 x 1,25 mm²

Edge distance:
300 µm

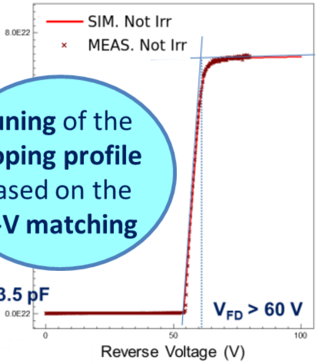
M. Ferrero et al., 1st ed., CRC Press (2021).
https://doi.org/10.1201/9781003131946

Split 1

C-V, pre-irr.



1/C²-V, pre-irr.



Tuning of the **doping profile** based on the **C-V matching**

"PerugiaModDoping"

- **Torino analytical parameterization**
  - **Gain Layer** (Acceptor Removal)
  - **Bulk** (Acceptor Creation)
- "**Perugia0**" Bulk/Surface Radiation Damage Model

Surface damage (+ Q_{ox})

Type	Energy (eV)	Band width (eV)	Conc. (cm⁻²)
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Bulk damage

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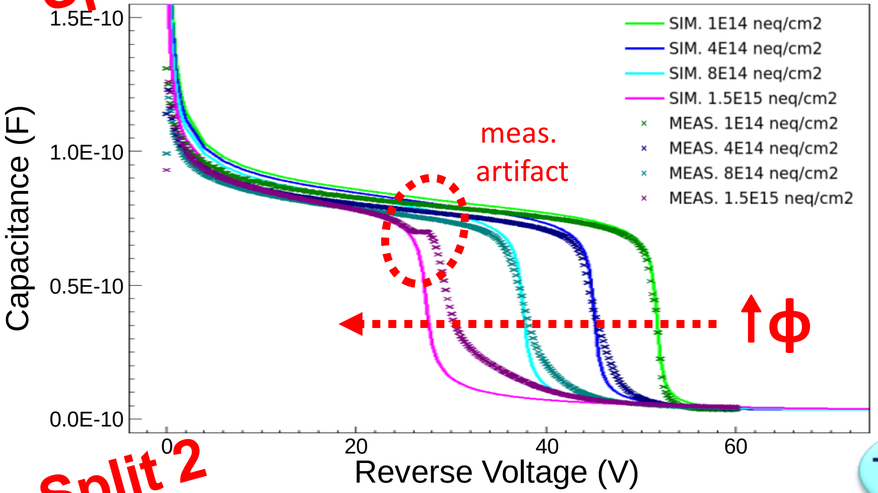
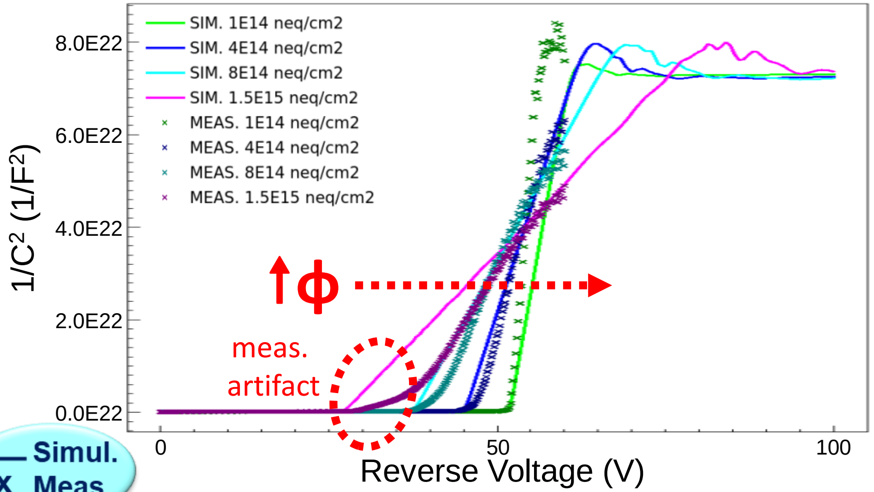
Acceptor	E_C - 0.42	1.6	1×10^{-15}	1×10^{-14}
Acceptor	E_C - 0.46	0.9	7×10^{-14}	7×10^{-13}

Split 1

C-V, post-irr.

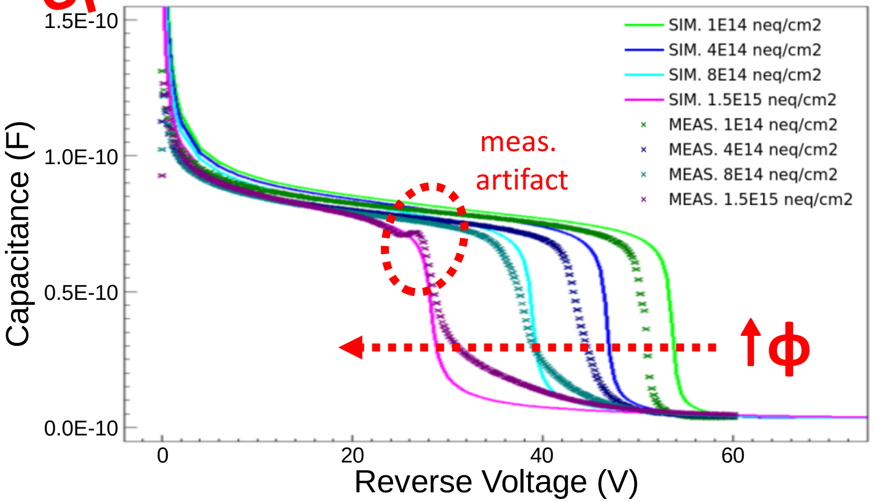


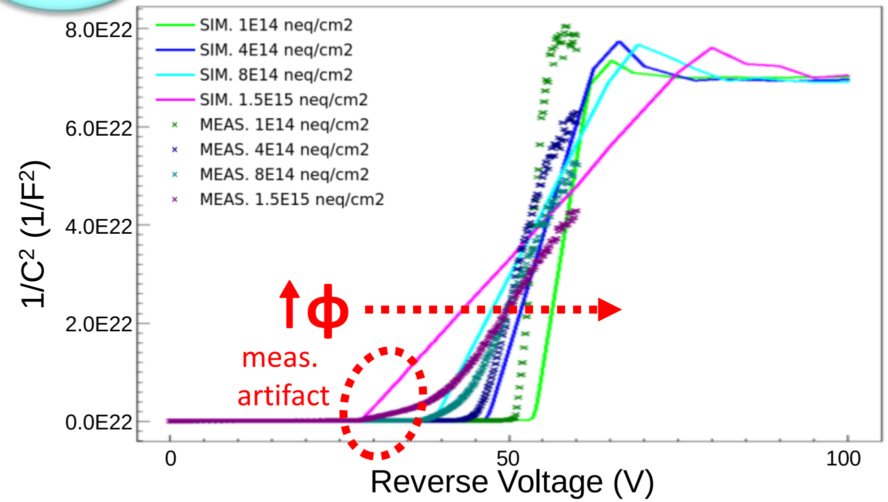
1/C²-V, post-irr.



— Simul.
x Meas.

Split 2





Temperature **300 K**. Frequency **1 kHz**. Electrical contact area **1,25 x 1,25 mm²**

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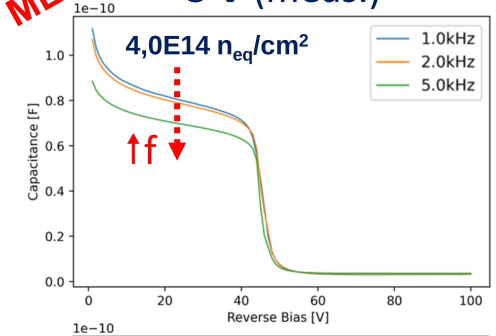
MEASURED C-V & 1/C²-V – HPK2, Split 1

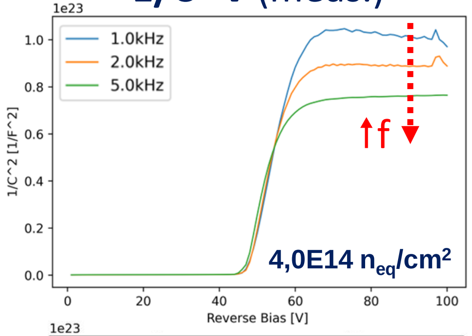
✓ Post-irr.

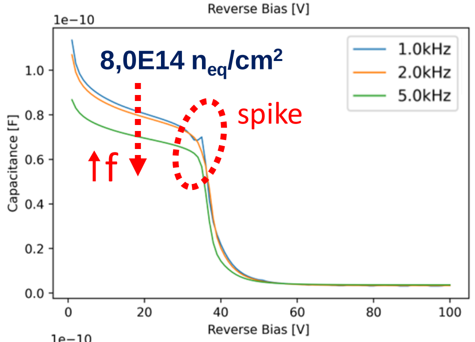
MEAS.

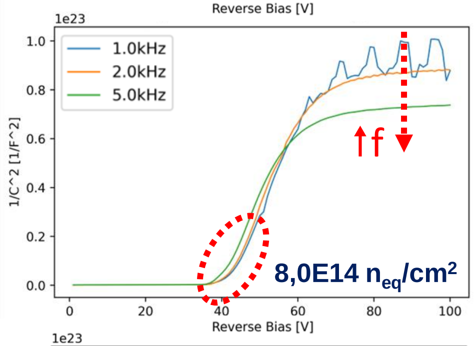
C-V (meas.)

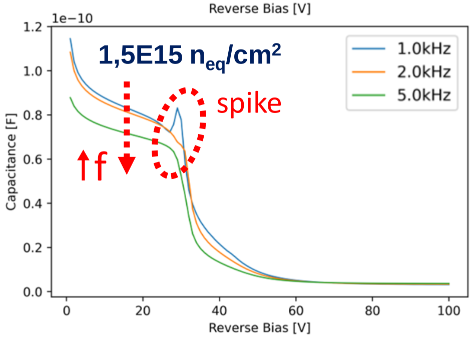


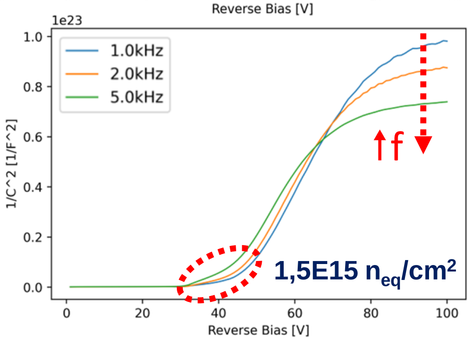
1/C²-V (meas.)





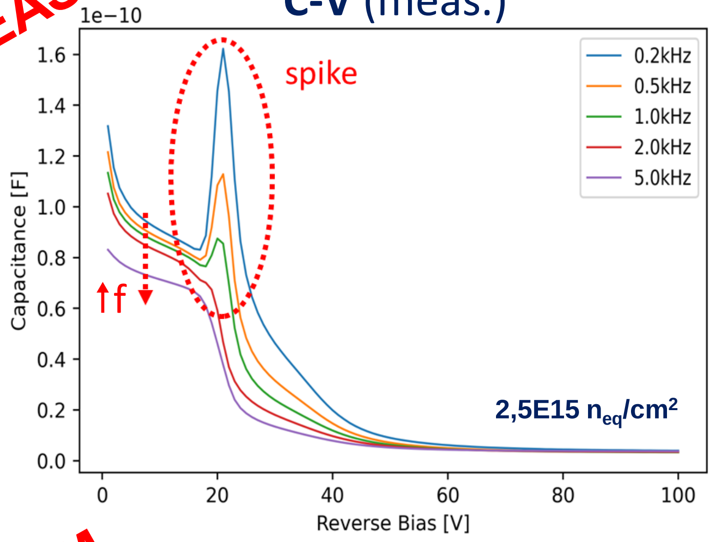




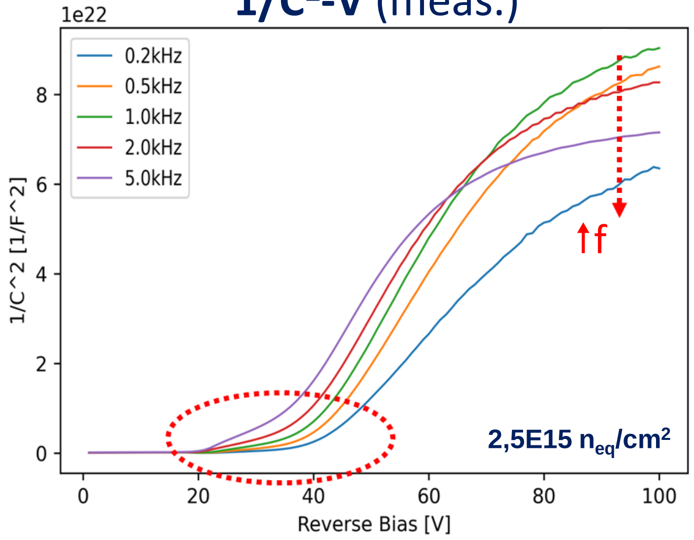


MEAS.

C-V (meas.)

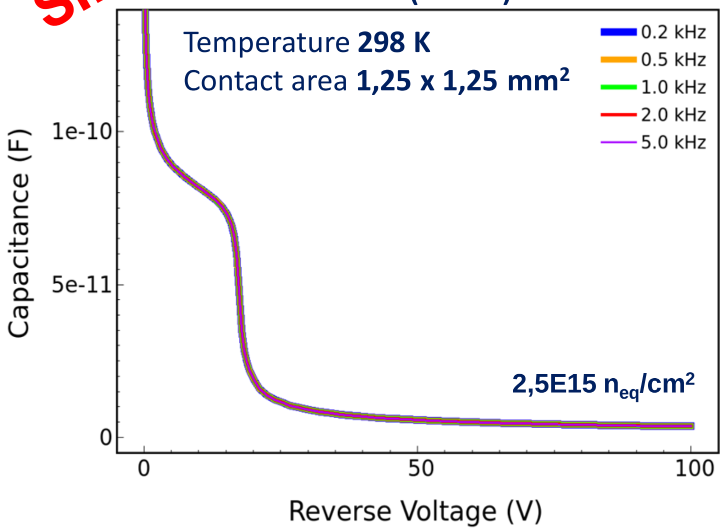


1/C²-V (meas.)

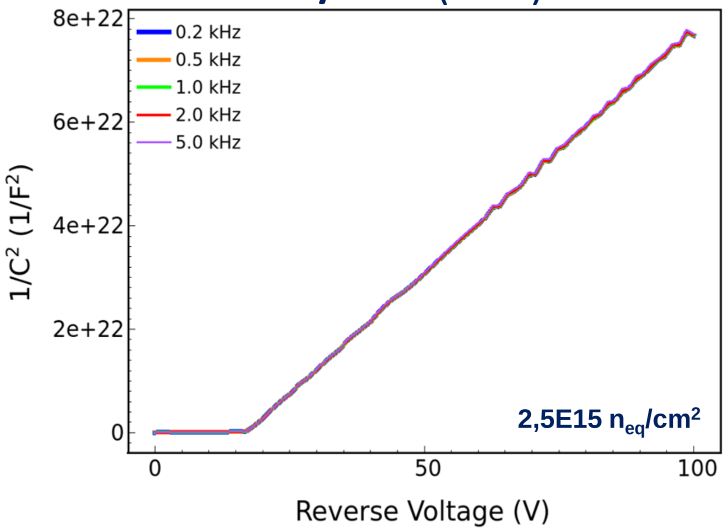


SIM.

C-V (sim.)



1/C²-V (sim.)



SIMULATED C-V & I-V – HPK2, Split 2

✓ Pre-irr.

Split 2

❑ Massey Model

$$\alpha(F_{ava}) = a\exp\left(-\frac{b}{F_{ava}}\right)$$

implemented via **C++ routine**[6]

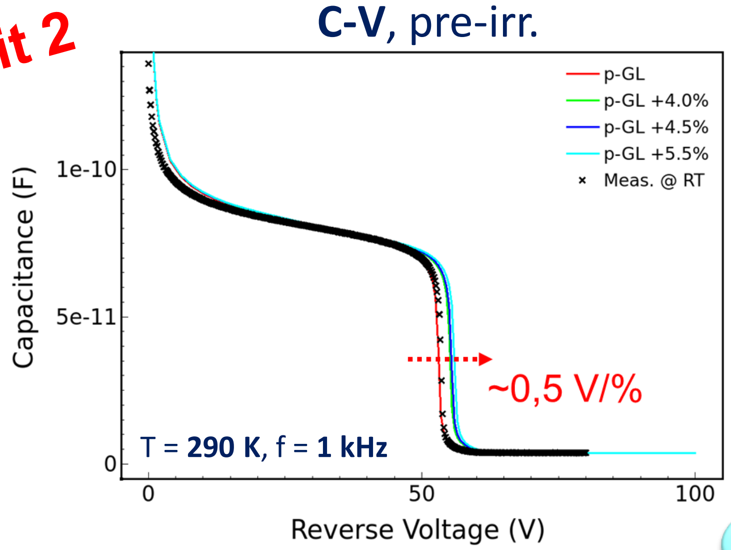
	Massey default	
Parameter	electrons	holes
A (cm^{-1})	4.43×10^5	1.13×10^6
C ($V{\cdot}cm^{-1}$)	9.66×10^5	1.71×10^6
D ($V{\cdot}cm^{-1}K^{-1}$)	4.99×10^2	1.09×10^3

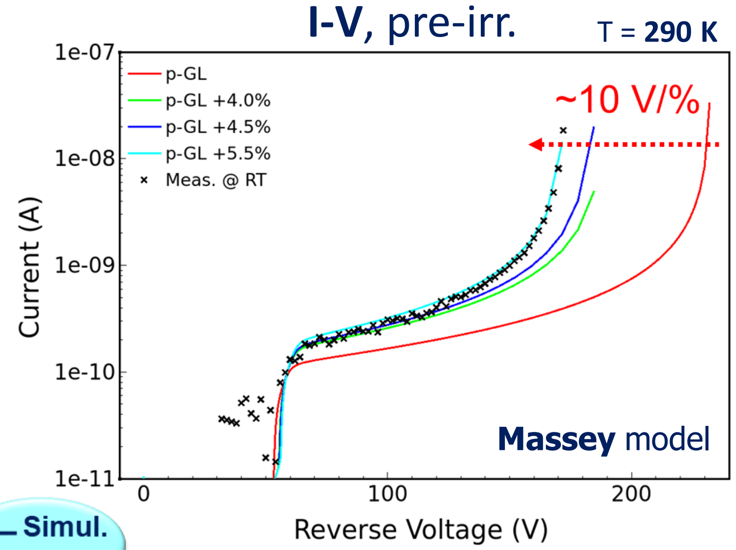
[6] M. Mandurrino et. al, IEEE NSS/MIC, Atlanta, USA (2017)

❑ van Overstraeten - de Man Model

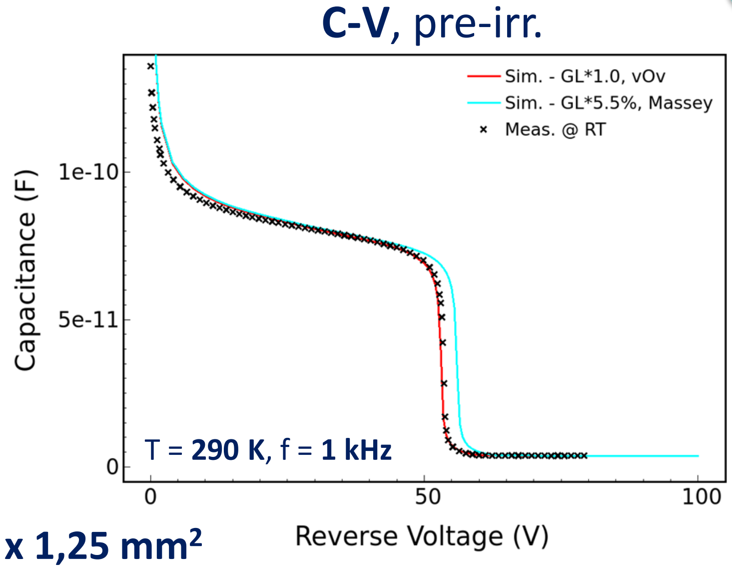
$$\alpha(F_{ava}) = \gamma a\exp\left(-\frac{\gamma b}{F_{ava}}\right) \qquad \gamma = \frac{\tanh\left(\frac{\hbar\omega_{op}}{2kT_0}\right)}{\tanh\left(\frac{\hbar\omega_{op}}{2kT}\right)}$$

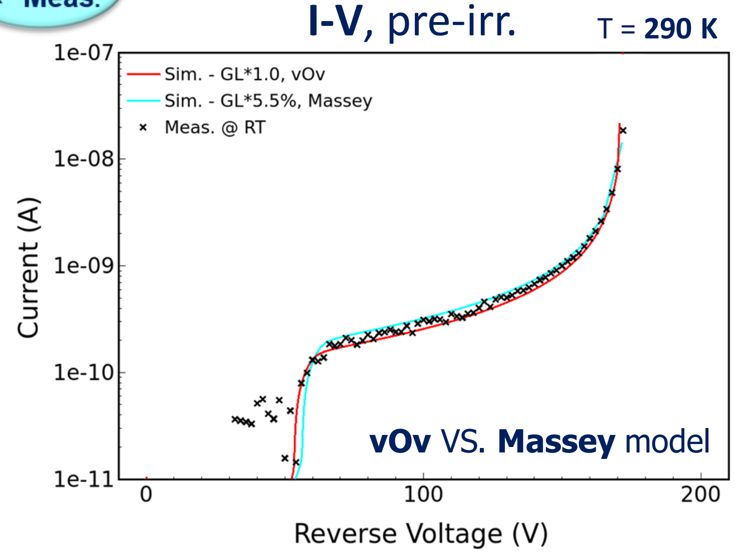
	Van Overstraeten default	
Parameter	electrons	holes
A (cm^{-1})	7.03×10^5	1.582×10^6
B ($V{\cdot}cm^{-1}$)	1.231×10^6	2.036×10^6
$\hbar\omega_{op}$ (eV)	0.063	0.063





— Simul.
x Meas.





Electrical contact area **1,25 x 1,25 mm²**

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SIMULATED I-V – HPK2, Split 1

"PerugiaModDoping"

AIDA innova

✓ Post-irr. (1/2)

Split 1

❑ Massey Model

$$\alpha(F_{ava}) = a\exp\left(-\frac{b}{F_{ava}}\right)$$

implemented via **C++ routine**[6]

[7]

	Massey default		Massey optimized	
Parameter	electrons	holes	electrons	holes
A (cm^{-1})	4.43×10^5	1.13×10^6	1.186×10^6	2.250×10^6
C (V·cm^{-1})	9.66×10^5	1.71×10^6	1.020×10^6	1.851×10^6
D (V·cm$^{-1}K^{-1}$)	4.99×10^2	1.09×10^3	1.043×10^3	1.828×10^3

[6] M. Mandurrino et. al, IEEE NSS/MIC, Atlanta, USA (2017)

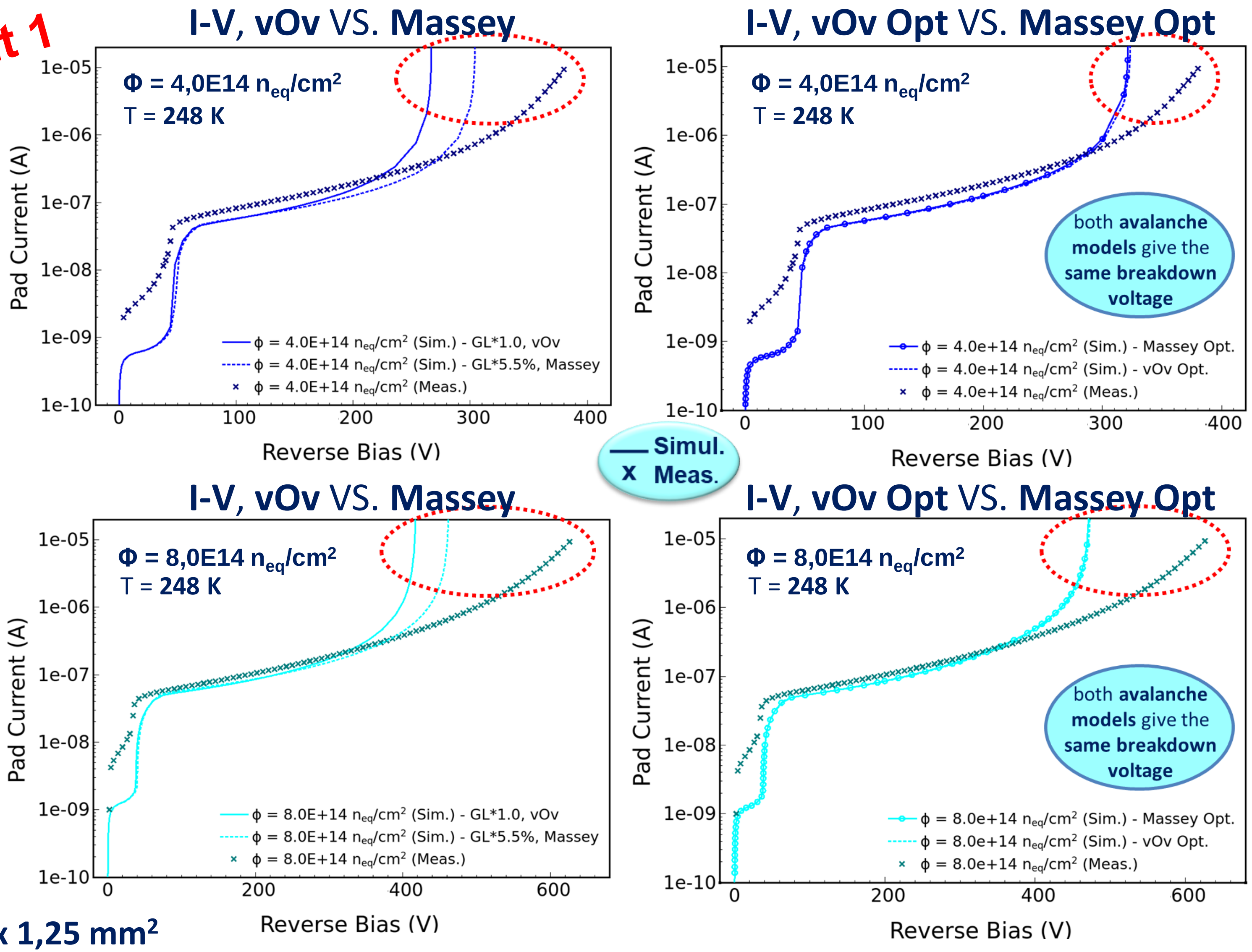
[7] E. Curras et. al, 41st RD50 Workshop, Seville, Spain (2022)

❑ van Overstraeten - de Man Model

$$\alpha(F_{ava}) = \gamma a\exp\left(-\frac{\gamma b}{F_{ava}}\right) \qquad \gamma = \frac{\tanh\left(\frac{\hbar\omega_{op}}{2kT_0}\right)}{\tanh\left(\frac{\hbar\omega_{op}}{2kT}\right)}$$

[7]

	Van Overstraeten default		Van Overstraeten optimized	
Parameter	electrons	holes	electrons	holes
A (cm^{-1})	7.03×10^5	1.582×10^6	1.149×10^6	2.519×10^6
B (V·cm^{-1})	1.231×10^6	2.036×10^6	1.325×10^6	2.428×10^6
$\hbar\omega_{op}$ (eV)	0.063	0.063	0.0758	0.0758



Electrical contact area **1,25 x 1,25 mm²**

SIMULATED I-V – HPK2, Split 1

"PerugiaModDoping"

AIDA innova

✓ Post-irr. (2/2)

Split 1

❑ Massey Model

$$\alpha(F_{ava}) = a\exp\left(-\frac{b}{F_{ava}}\right)$$

implemented via **C++ routine** [6]

[7]

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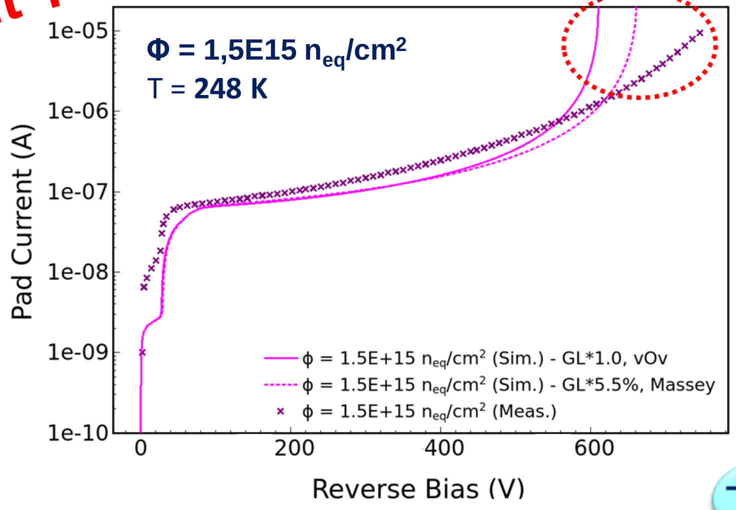
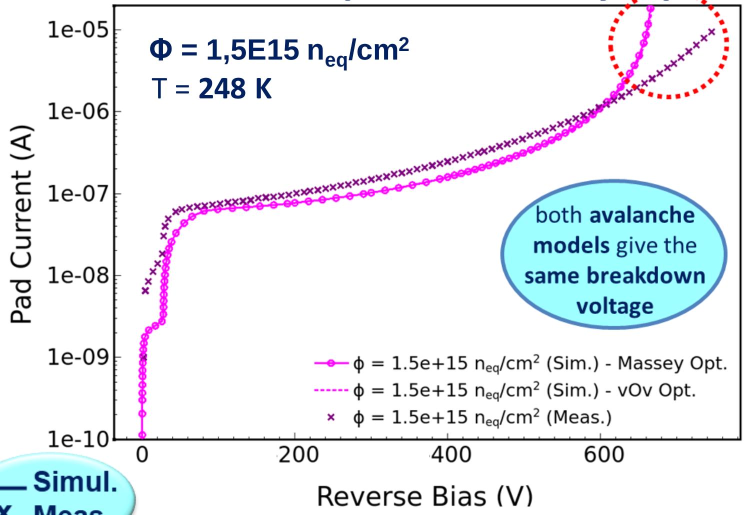
I-V, vOv VS. Massey

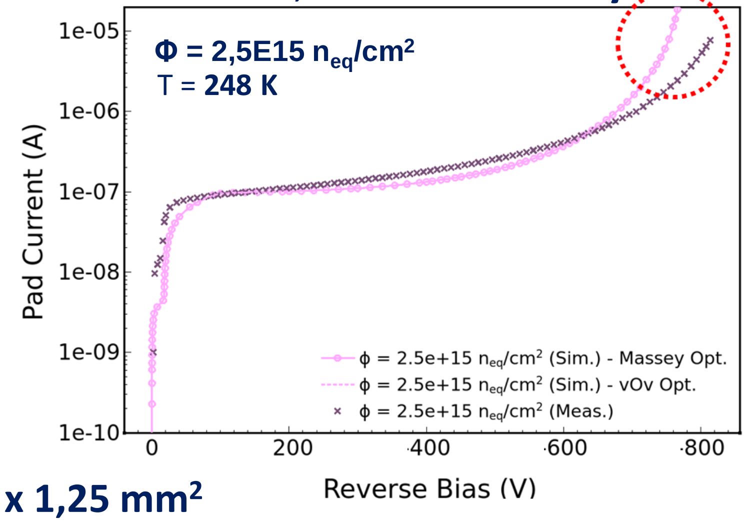


I-V, vOv Opt VS. Massey Opt

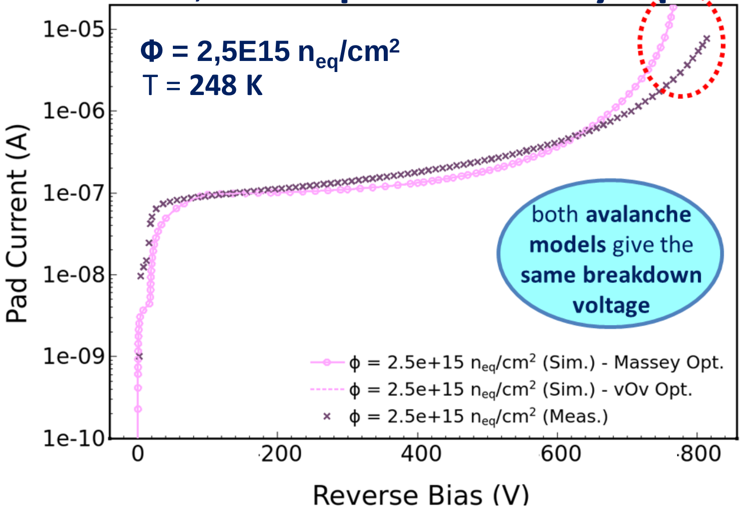


— Simul.
x Meas.

I-V, vOv VS. Massey



I-V, vOv Opt VS. Massey Opt



Electrical contact area **1,25 x 1,25 mm²**

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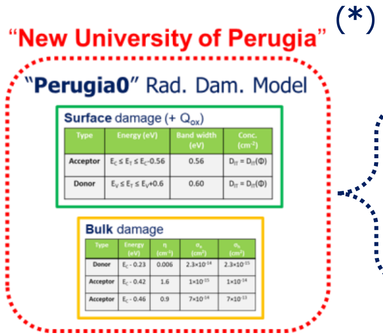
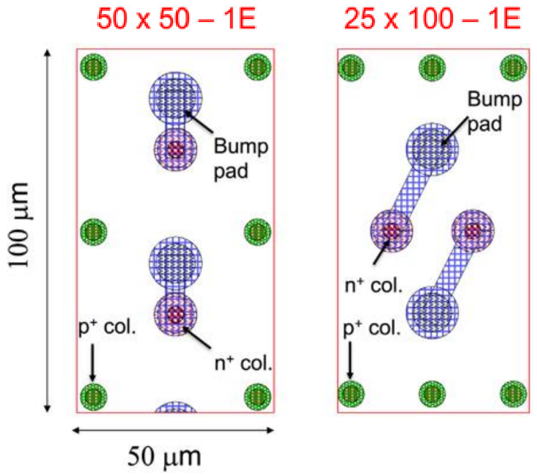
TCAD simulation of **3D** device

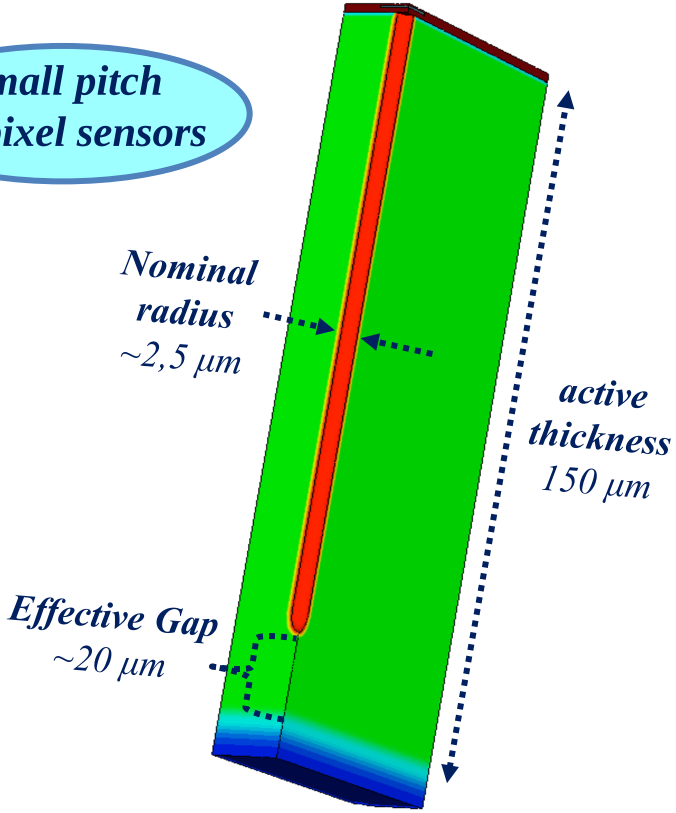
- ✓ In collaboration with the *University of Trento*: **validation** of the previously developed model (*) **by comparing** the **simulation findings** with **measurements** carried out on different classes of **3D** detectors.
- ✓ **Comparison** with **experimental data**, **before** and **after irradiation** (FBK R&D, Batch 3)



Model Used	*Temp*
Perugia Surface *Damage Model* [8]	*-25 °C*
Perugia Bulk *Damage Model* [1]	*-25 °C*
CERN Bulk *Damage Model* [9]	*-38 °C*



Small pitch 3D pixel sensors

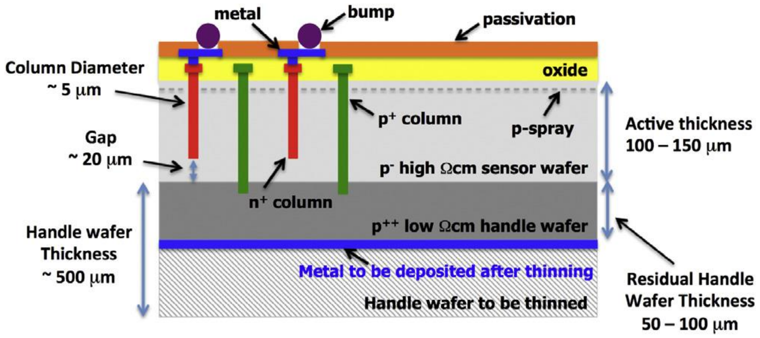


Simulation domain
25 ⨯100-1E

[8] A. Morozzi et al., *TCAD modeling of surface radiation damage effects: a state-of-the-art review*, Front. Phys. 9 (2021) 617322.

[9] A. Folkestad et al., *Development of a silicon bulk radiation damage model for Sentaurus TCAD*, NIMA 874 (2017) 94.

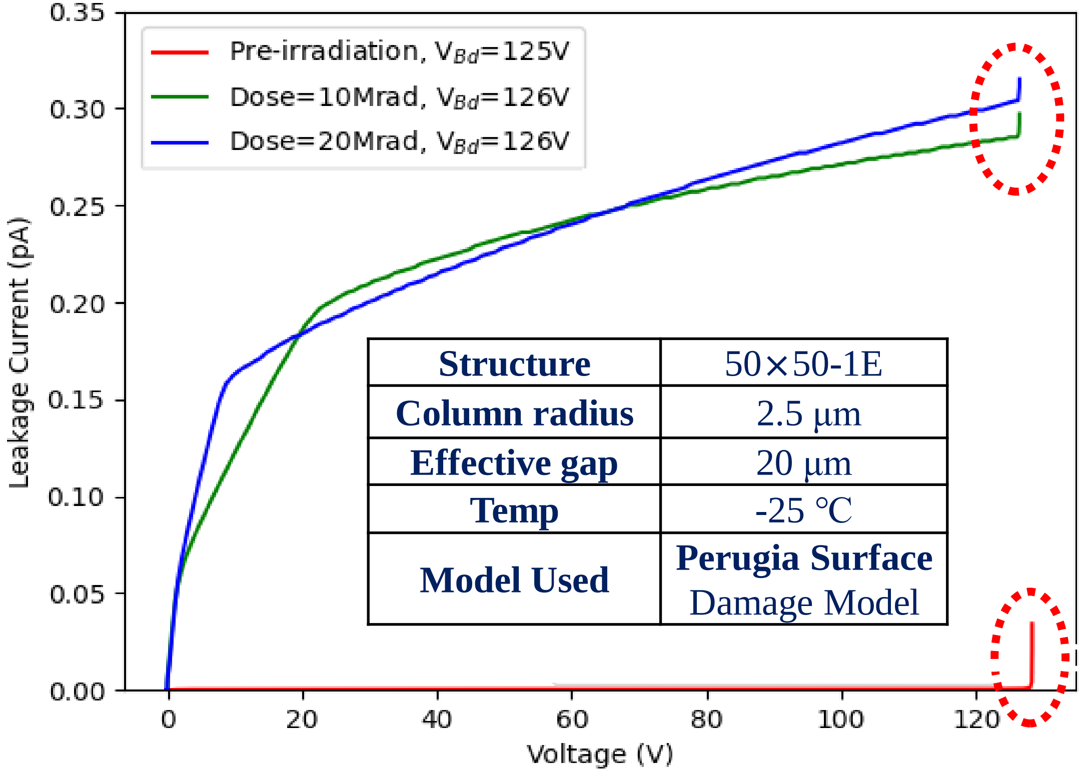
NB: simulation based on the CERN Bulk Damage Model used -38 °C, the leakage current was then scaled to -25 °C using the SRH model.



SIMULATED I-V – *Surface* Damage Model

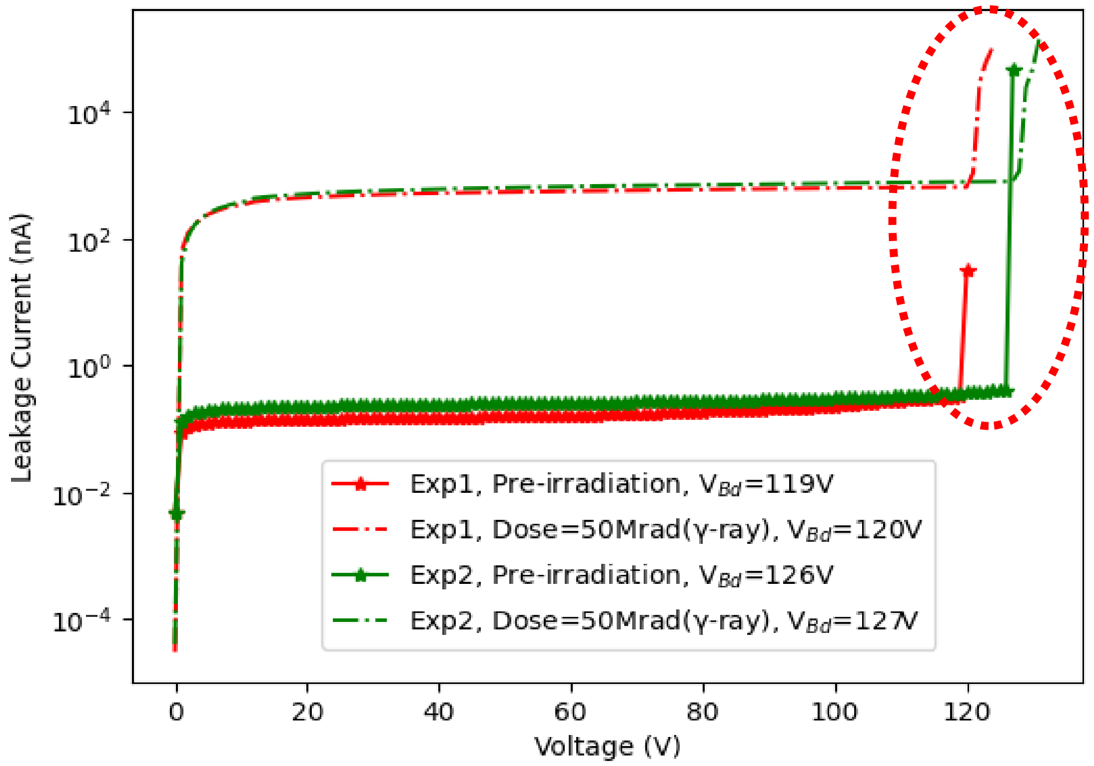
✓ Pre & Post-irr.

I-V (sim.)



Structure	50×50-1E
Column radius	2.5 µm
Effective gap	20 µm
Temp	-25 °C
Model Used	Perugia Surface Damage Model

I-V (meas.)



— Simul.
—✱— Meas.

van Overstraeten - de Man model. Temperature **248 K**

SIMULATED I-V – *Bulk* Damage Model

AIDA innova

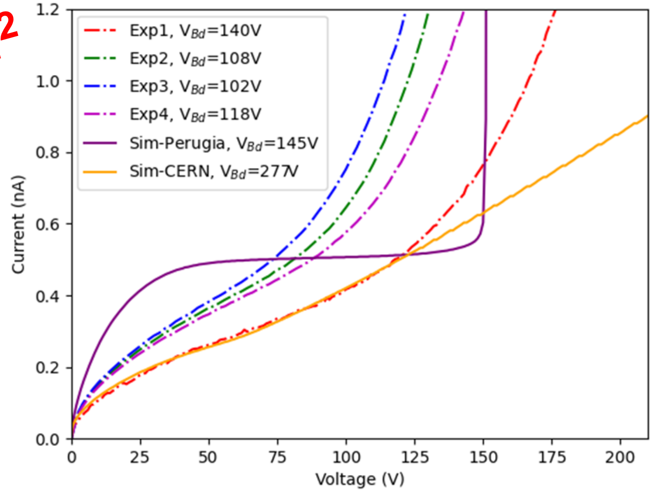
✓ Post-irr.

1,0E16 n_{eq}/cm^2

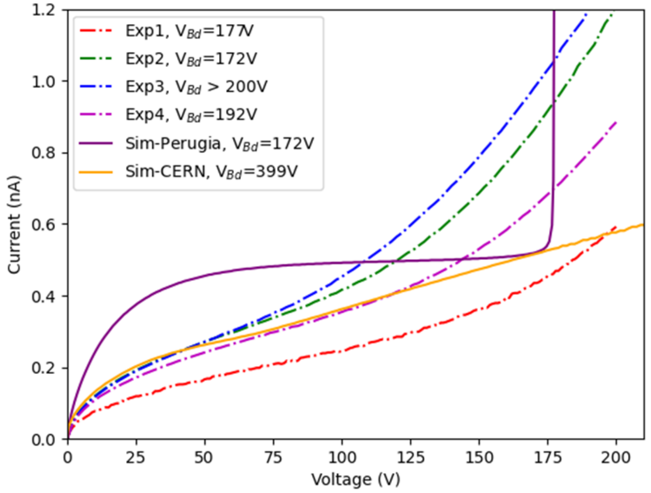
Calculated Damage Rate at V_b=100V, T=20°C

Structure	α^* Experiment (10^{-17}A/cm)	α^* Perugia Model (10^{-17}A/cm)	α^* CERN Model (10^{-17}A/cm)
50×50-1E	6.92±1.14	5.92	4.90
25×100-1E	4.25±0.91	5.74	4.22

I-V, 50x50-1E

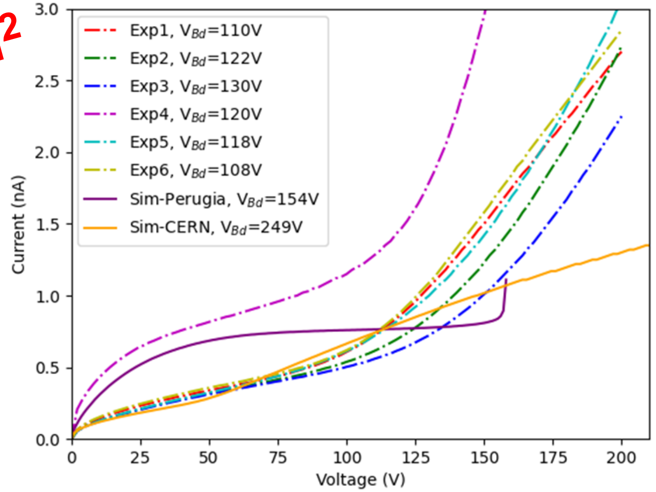


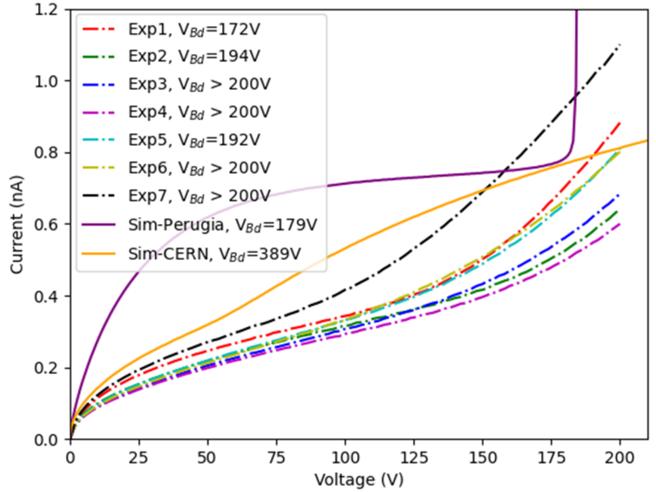
I-V, 25x100-1E



1,5E16 n_{eq}/cm^2

Structure	α^* Experiment (10^{-17}A/cm)	α^* Perugia Model (10^{-17}A/cm)	α^* CERN Model (10^{-17}A/cm)
50×50-1E	4.41± 0.36	5.91	5.14
25×100-1E	3.87±0.43	5.54	4.09





van Overstraeten - de Man model. Temperature **248 K**

— Simul.
····· Meas.

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Conclusions & Next steps

- ✓ Recent upgrade of the *Perugia radiation damage model* → "**PerugiaModDoping**"
  - **Traps** parameterization (New University of Perugia TCAD model)
  - **Gain Layer** and **Bulk** effective **doping evolution** with Φ (Torino analytical parameterization)

- ✓ The new **model** has been **verified** for **LGAD devices,** by comparing TCAD simulations w/ measurements
  - **UFSD2** production (FBK): static (DC), small-signal (AC) and gain behavior well reproduced
  - **HPK2** production (HPK): DC and AC behavior well reproduced (but **pay attention** to the **impact ionization model**)
    - **to measure** (w/ β source) and **to simulate**: **gain behavior** before and after irradiation

- ✓ **Validation** of the "**New University of Perugia TCAD model**" with **3D detectors** (in collaboration **with Trento group** for 3D detectors modelling)
  - **Perugia Bulk Damage Model** can predict the breakdown quite accurately, despite the shape of the I-V curves is quite different from the measured ones
  - **CERN Bulk Damage Model** is better at predicting the leakage current, but largely overestimates the breakdown voltage
  - **To measure**: **DC behavior** and **laser response** of **3D** and **trenched-3D** detectors, before and after irradiation (up to the fluence of 2,5E15 n_{eq}/cm^2)
  - **To validate** the new model "**PerugiaModDoping**" against the already-in-house and new measurements

BACKUP

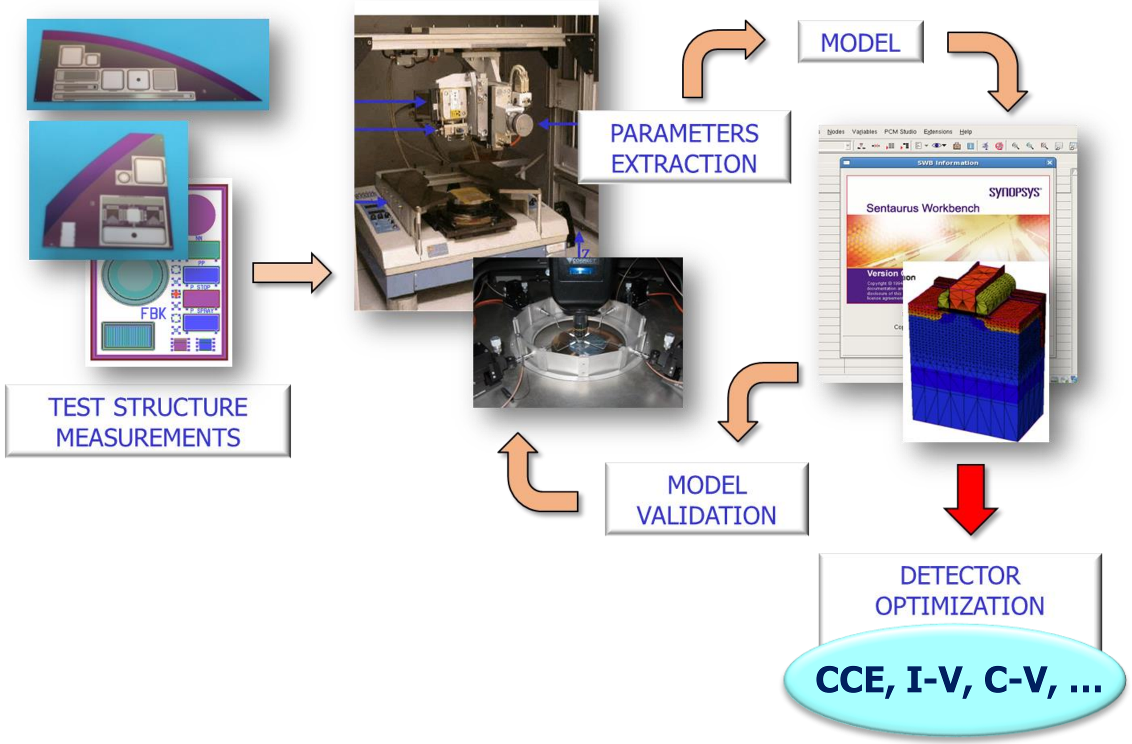
TCAD radiation damage model used

- **"New University of Perugia model"**
  - ✓ **Combined surface and bulk** TCAD damage modelling scheme[3]
  - ✓ Traps generation mechanism
- **Acceptor removal mechanism**

$$N_{GL}(\phi) = N_A(0)e^{-c\phi}$$

where

- **Gain Layer (GL)**
- **c**, removal rate, evaluated using the **Torino parameterization**[4]



[3] AIDA2020 report, *TCAD radiation damage model - CERN Document Server*
[4] M. Ferrero et al., *Radiation resistant LGAD design*, Nucl. Inst. And Meth. In Phys. Res. A, November 30, 2018. doi: 10.1016/j.nima.2018.11.121

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

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}

Acceptor Removal – the c formula

- **Acceptor removal mechanism**

$$N_{GL}(\phi) = N_A(0)e^{-c\phi}$$

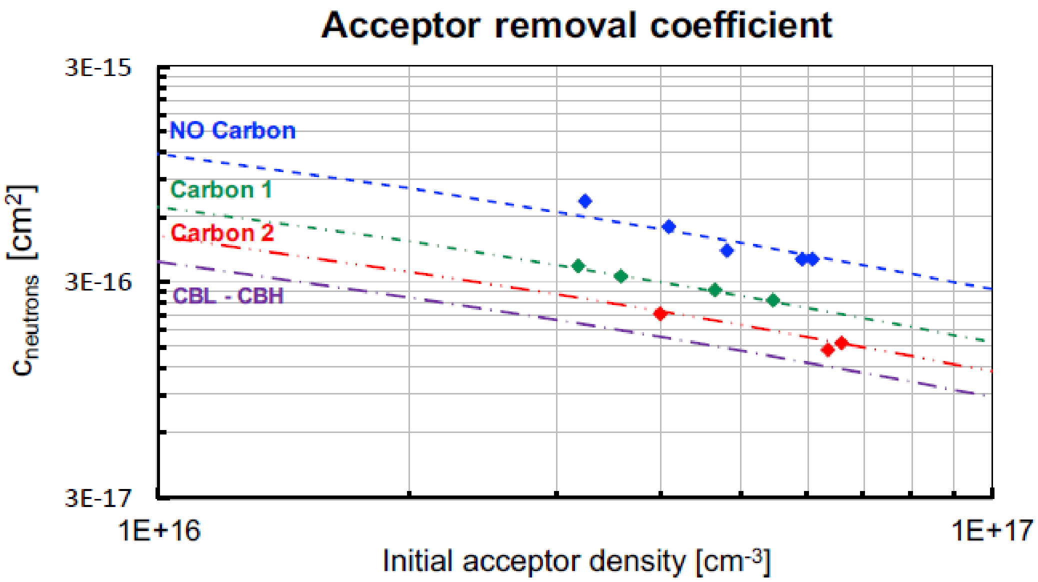
where

- **Gain Layer (GL)**
- **c**, removal rate, evaluated using the **Torino parameterization**[4]

$$c = \frac{N_{Si} \cdot \sigma_{Si}}{C_{par} \cdot N_A(0)} \cdot D_2$$

$$D_2 = \frac{1}{1 + \left(\frac{N_{A0}}{N_A(0)}\right)^{\frac{2}{3}}}$$

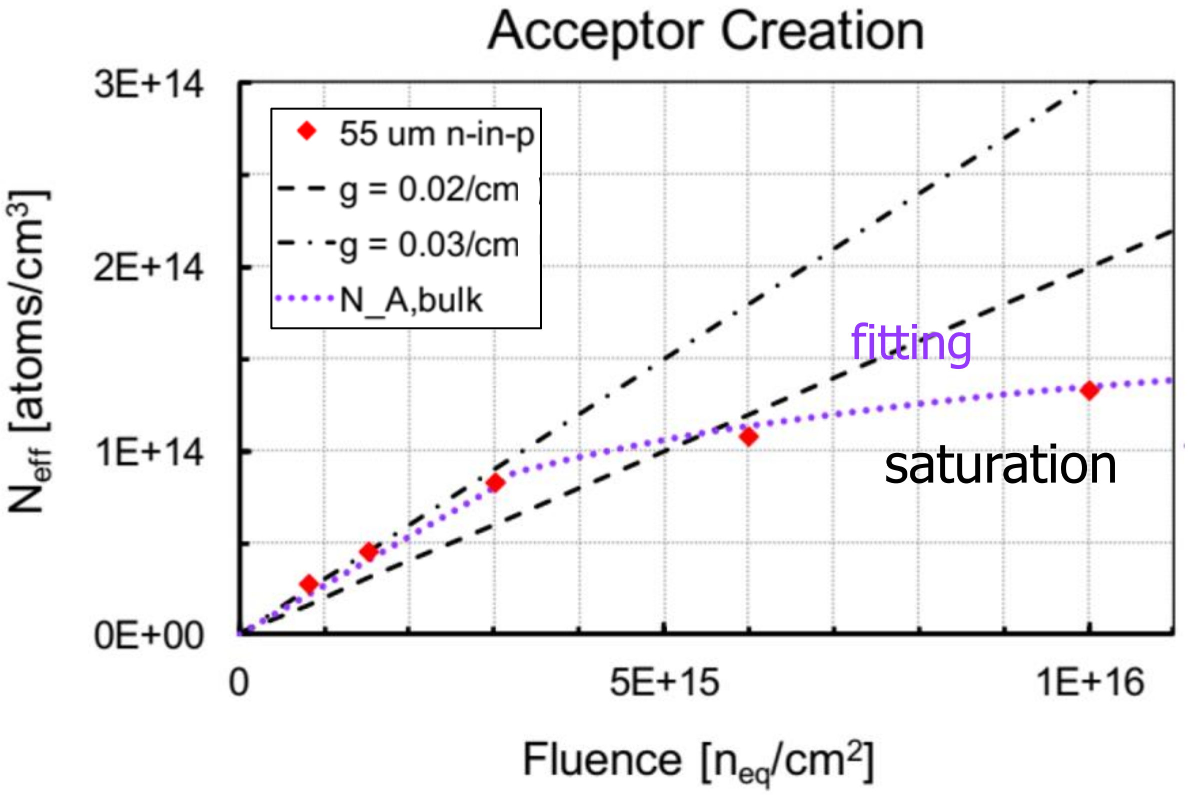
$N_{Si} = 5 \cdot 10^{22}\ cm^{-2}$
$\sigma_{Si} = 7.5 \cdot 10^{-22}\ cm^2$
$N_{A0} \equiv \rho_{A0} = 4.5 \cdot 10^{16}\ cm^{-3}$
$N_A(0) \equiv \rho_A(0)$
$C_{par} = 0.63 / k_{cap}$



[4] M. Ferrero et al., *Radiation resistant LGAD design*, Nucl. Inst. And Meth. In Phys. Res. A, November 30, 2018. doi: 10.1016/j.nima.2018.11.121

Acceptor Doping Evolution with Φ

✓ **Bulk** effective acceptor doping



- Torino **Bulk analytical parameterization** (Acceptor Creation)
  - ✓ if $0 < \Phi \leq 3e15\ n_{eq}/cm^2$

    $$\mathbf{N_{A,bulk}(\Phi) = N_{A,bulk}(0) + g_c \cdot \Phi}$$

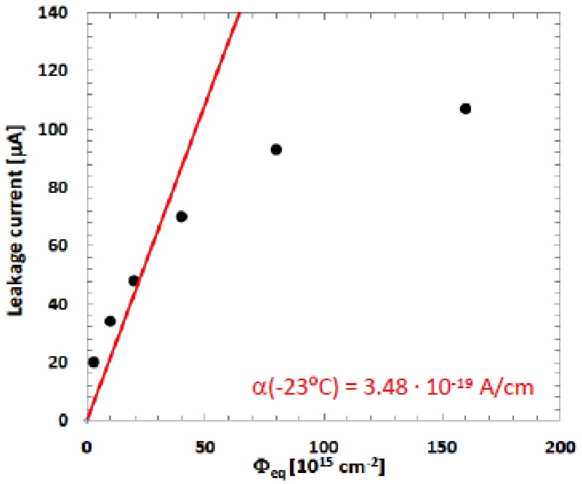
    where g_c = 2,37e-2 cm^{-1}
  - ✓ if $\Phi > 3e15\ n_{eq}/cm^2$

    $$\mathbf{N_{A,bulk}(\Phi) = 4{,}17e13 \cdot \ln(\Phi) - 1{,}41e15}$$

[M. Ferrero et. al, *Recent studies and characterization on **UFSD sensors***, 34th RD50 Workshop, Lancaster, UK (2019)]

SATURATION

✓ Saturation of radiation effects **observed @ Φ > 5E15 n_{eq}/cm^2**

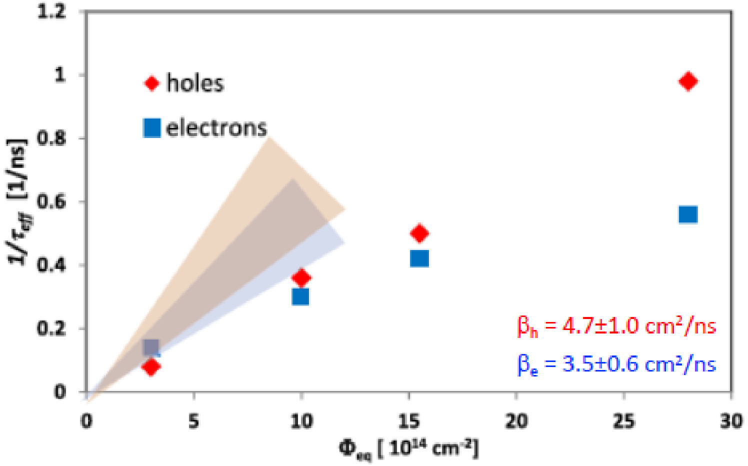


[G. Kramberger et al., doi:10.1088/1748-0221/8/08/P08004]

Leakage current saturation

$I = \alpha V \Phi$

α from linear to logarithmic

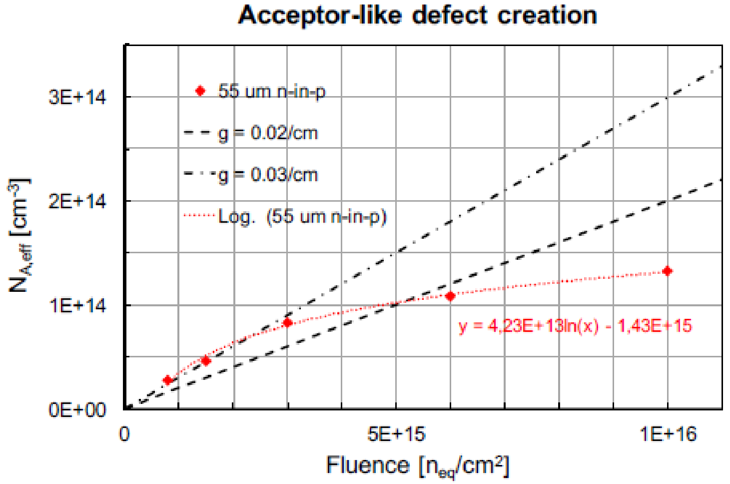


[G. Kramberger et al., doi:10.1016/j.nima.2018.08.034]

Trapping probability saturation

$1/\tau_{eff} = \beta\Phi$

β from linear to logarithmic



[M. Ferrero et al., 34th RD50 Workshop, Lancaster, UK]

Acceptor creation saturation

$N_{A,eff} = g_c\Phi$

g_c from linear to logarithmic

Silicon detectors irradiated @ Φ 1E16 – 1E17 n_{eq}/cm^2 behave better that expected

New series of Perugia models

	etaA1 (cm^-1)	etaA2 (cm^-1)	etaD (cm^-1)	EmidA1 (eV)	EmidA2 (eV)	EmidD (eV)	hxA1 (cm^2)	hxA2 (cm^2)	exD (cm^2)
Case 1	1.6	0.9	0.006	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 2	1.6	0.9	0.006	0.42	0.545	0.23	1.00E-14	1.00E-14	2.30E-14
Case 3	1.6	0.9	0.2	0.42	0.545	0.23	1.00E-14	1.00E-14	2.30E-14
Case 4	1.6	0.9	0.2	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 5	1.6	0.9	0.02	0.42	0.545	0.23	1.00E-14	1.00E-14	2.30E-14
Case 6	1.6	0.9	0.02	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 7	1.6	0.9	0.01	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 8	1.6	0.9	0.015	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 9	1.6	0.9	0.015	0.42	0.46	0.23	1.00E-14	1.40E-12	2.30E-14
Case 10	1.6	0.9	0.015	0.42	0.46	0.23	5.00E-14	7.00E-13	2.30E-14
Case 11	1.6	1.5	0.015	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 12	2	0.9	0.015	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 13	2.5	0.9	0.015	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 14	3	0.9	0.015	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 15	5	0.9	0.015	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 16	10	0.9	0.015	0.42	0.46	0.23	1.00E-14	7.00E-13	2.30E-14
Case 17	10	0.9	0.015	0.42	0.46	0.23	1.00E-14	4.00E-13	2.30E-14
Case 18	10	1.2	0.015	0.42	0.46	0.23	1.00E-14	4.00E-13	2.30E-14

"New University of Perugia TCAD model"[2]

We always have **two acceptor levels** (A_1, A_2) and **one donor level** (D)

eta: introduction rate;
Emid: mid-energy level of uniformly distributed band of traps;
hx/ex: capture cross sections for holes/electrons;
exA = hxA/10, hxD = exD/10

BEST CASE: the one for which the sum of squares of relative differences between simulated and experimental values of all important parameters is minimized

[2] AIDA2020 report, *TCAD radiation damage model - CERN Document Server.*

TCAD simulation of **PIN** device

- ✓ In collaboration with *INFN Torino*: **calibration/extension** of the previously developed models **by comparing** the **simulation findings** with **measurements** carried out on different classes of **PIN** detectors.
- ✓ **Comparison** with **experimental data**, **before** and **after irradiation** (UFSD2/UFSD3.2 production, by FBK)

"PerugiaModDoping" [3]

- **Torino analytical parameterization**
  - **Bulk** (Acceptor Creation)
- "**Perugia0**" Bulk/Surface Radiation Damage 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

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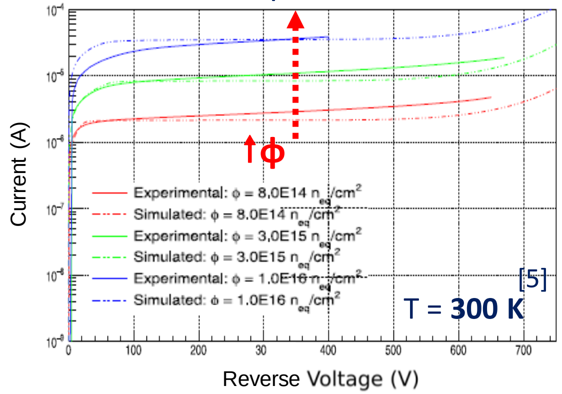
[3] P. Asenov et. al, Nucl. Instrum. Methods Phys. Res. A 1040 (2022) 167180.

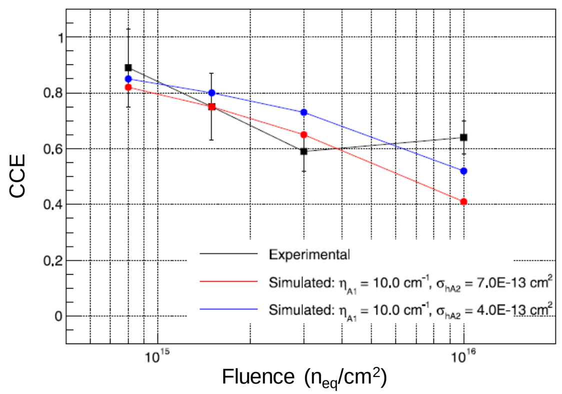
[4] V. Sola et al., *First FBK production of 50 µm ultra-fast silicon detectors*, Nucl. Instrum. Methods Phys. Res. A, 2019.

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

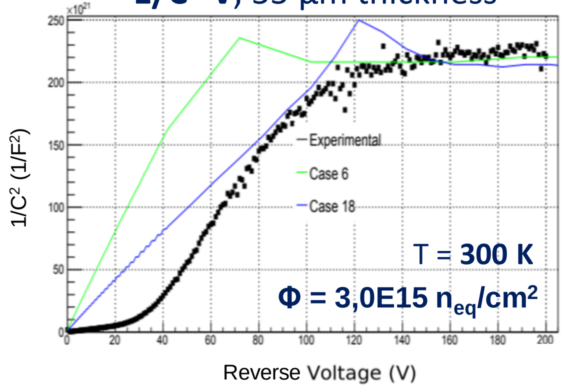
I-V, 55 µm thickness



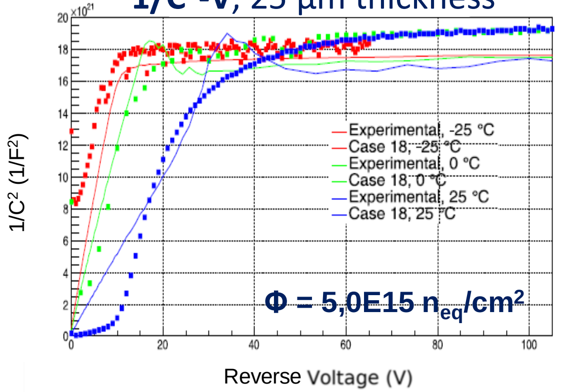
CCE, 55 µm thickness



1/C²-V, 55 µm thickness



1/C²-V, 25 µm thickness



Massey model. Electrical contact area **1 x 1 mm²**

HPK2

- ✓ 2nd sensor **HPK production**
- ✓ R&D for the ATLAS and CMS timing detectors
- ✓ Deep and narrow multiplication layer
- ✓ High-resistivity bulk
- ✓ 4× splits of p-gain dose (1, 2, 3 and 4)

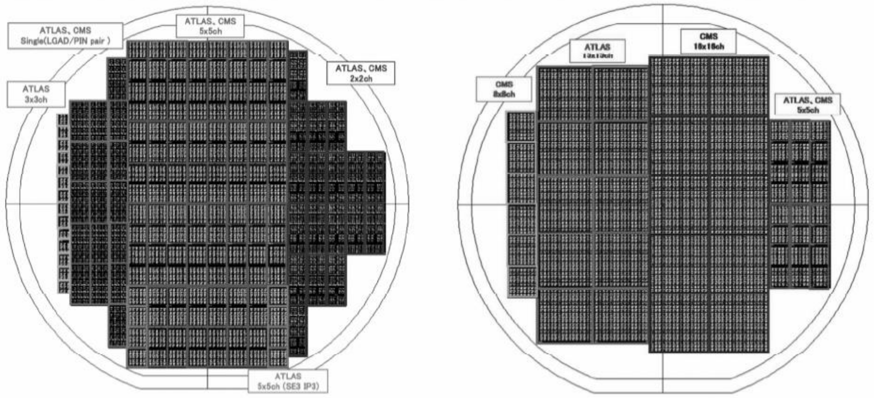


Figure A.9 HPK2 wafer layouts. *Left*: small sensors. *Right*: large sensors [110].

Table A.10
Wafers of the HPK2 Production

Wafer #	Wafer layout	Split of p-gain dose	Target breakdown voltage [V] @ RT
25, 28	Small	1 (highest p-dose)	160
31, 33	Small	2	180
36, 37	Small	3	220
42, 43	Small	4 (lowest p-dose)	240

- ☐ I-V and C-V meas. curves, pre-irr.
- ☐ C-V meas. curves, post-irr. **w/ neutrons**
- ☐ I-V and C-V meas. curves, pre and post-irr. **w/ neutrons**

Table A.11
Devices in the HPK2 Production

Layout	Device geometry	Edge	Inter-pad
Small	Single pad	SE3	-
	2 × 2	SE3	IP3
	2 × 2	SE3	IP4
	2 × 2	SE3	IP5
	2 × 2	SE3	IP7
	2 × 2	SE5	IP5
	3 × 3	SE3	IP5
	5 × 5	SE3	IP3
	5 × 5	SE3	IP4
	5 × 5	SE3	IP5
	5 × 5	SE3	IP7
	5 × 5	SE5	IP7
Large	5 × 5	SE3	IP4
	5 × 5	SE3	IP5
	5 × 5	SE3	IP7
	5 × 5	SE5	IP7
	8 × 8	SE5	IP7
	15 × 15	SE3	IP7
	16 × 16	SE5	IP7
	30 × 15	SE3	IP7
	32 × 16	SE5	IP7

Pad size:
1,25 x 1,25 mm²

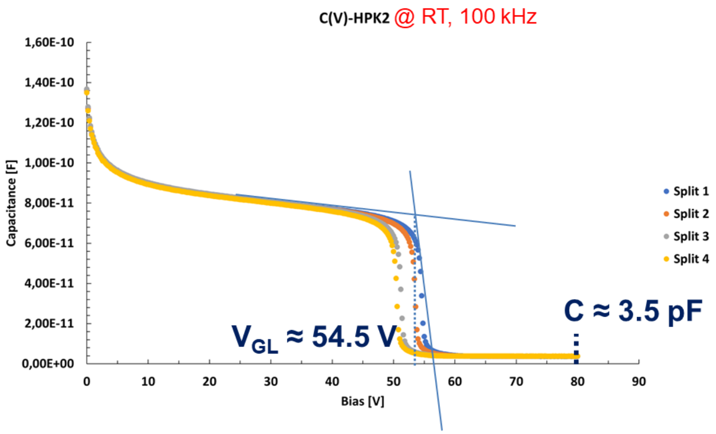
Edge distance:
300 µm

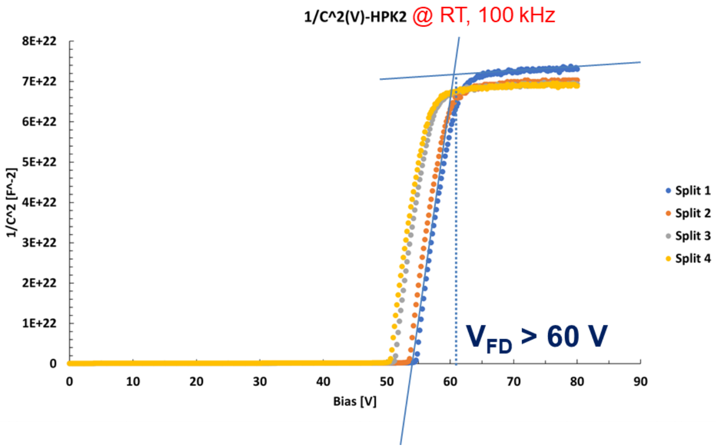
SINGLE

M. Ferrero et al., *An Introduction to Ultra-Fast Silicon Detectors*, 1st ed., CRC Press (2021).

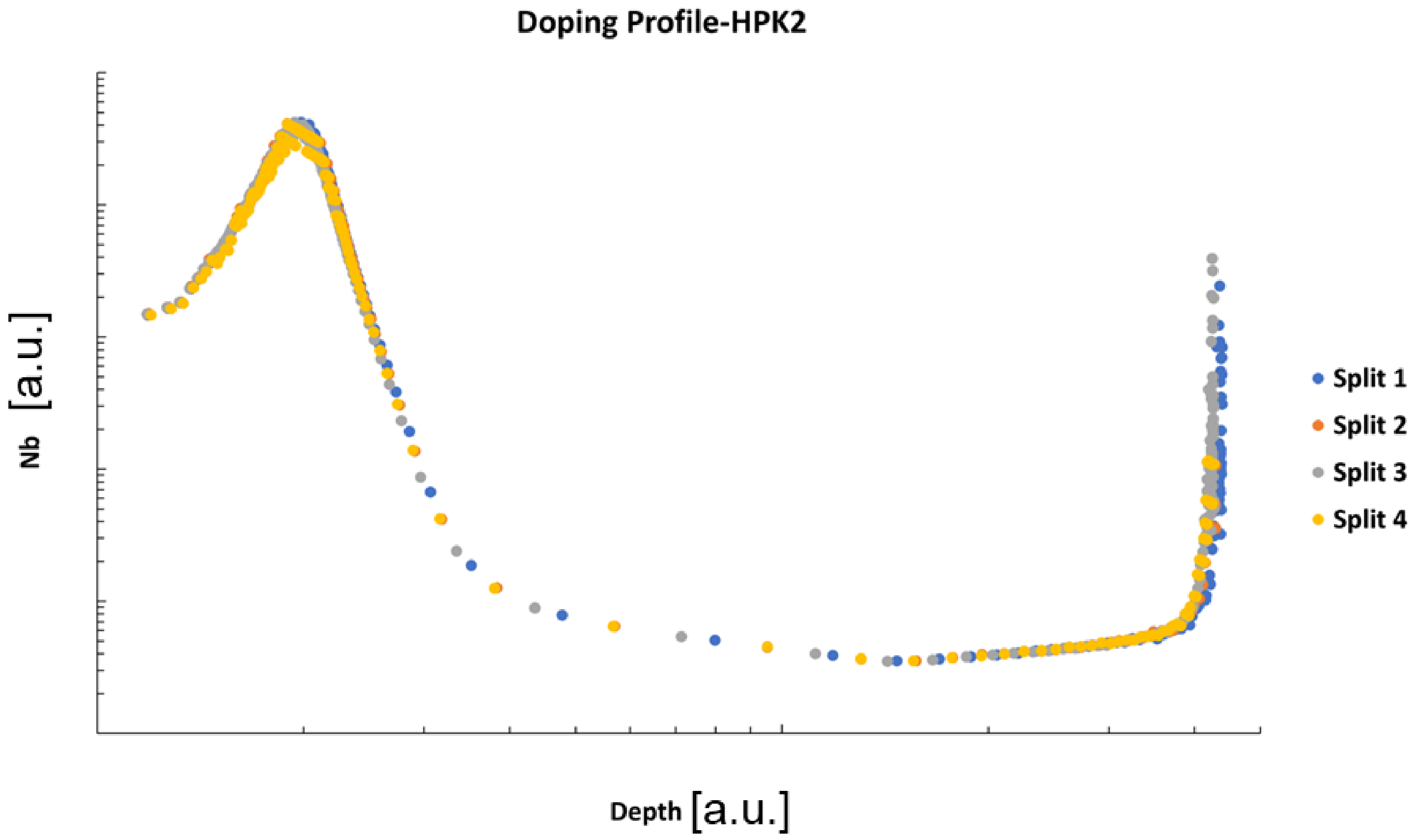
MEASURED C-V and 1/C²-V – HPK2

✓ Pre-irr.





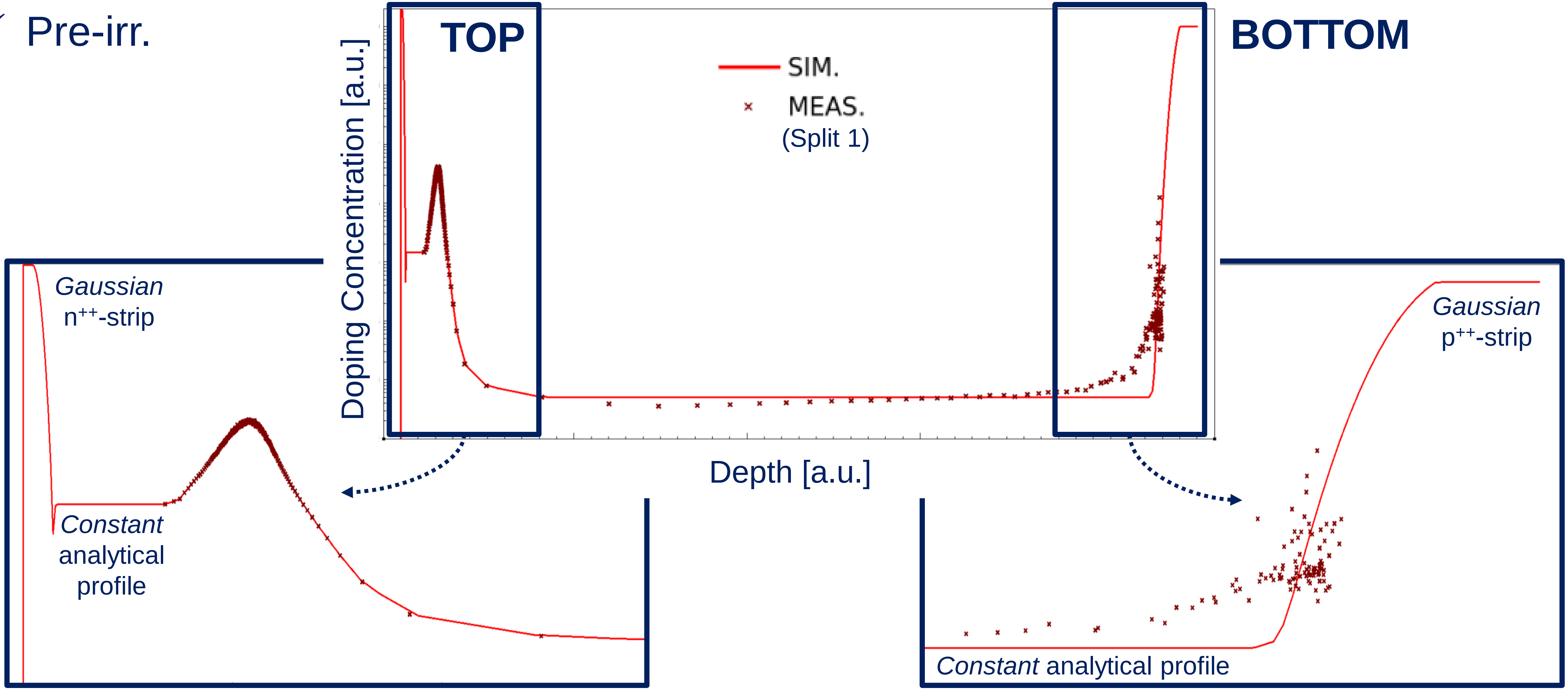
CALCULATED



M. Ferrero et al.

SIMULATED doping profiles – HPK2, Split 1

- ✓ Pre-irr.



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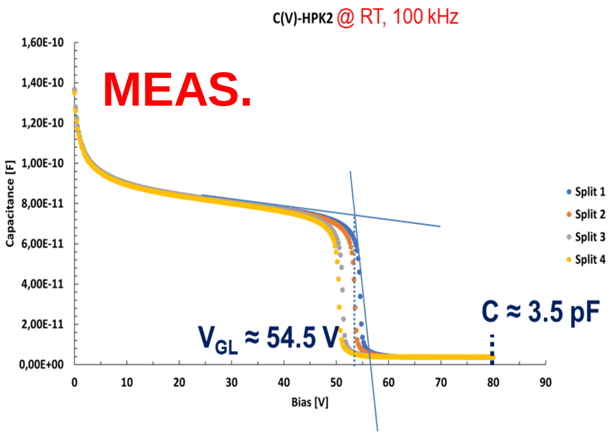
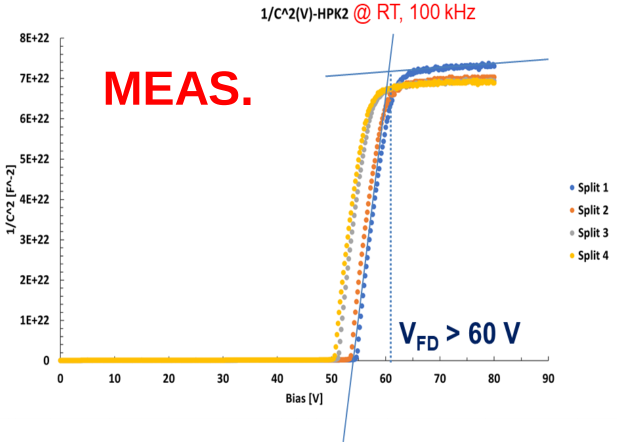
SIMULATED C-V and 1/C²-V – HPK2, Split 1

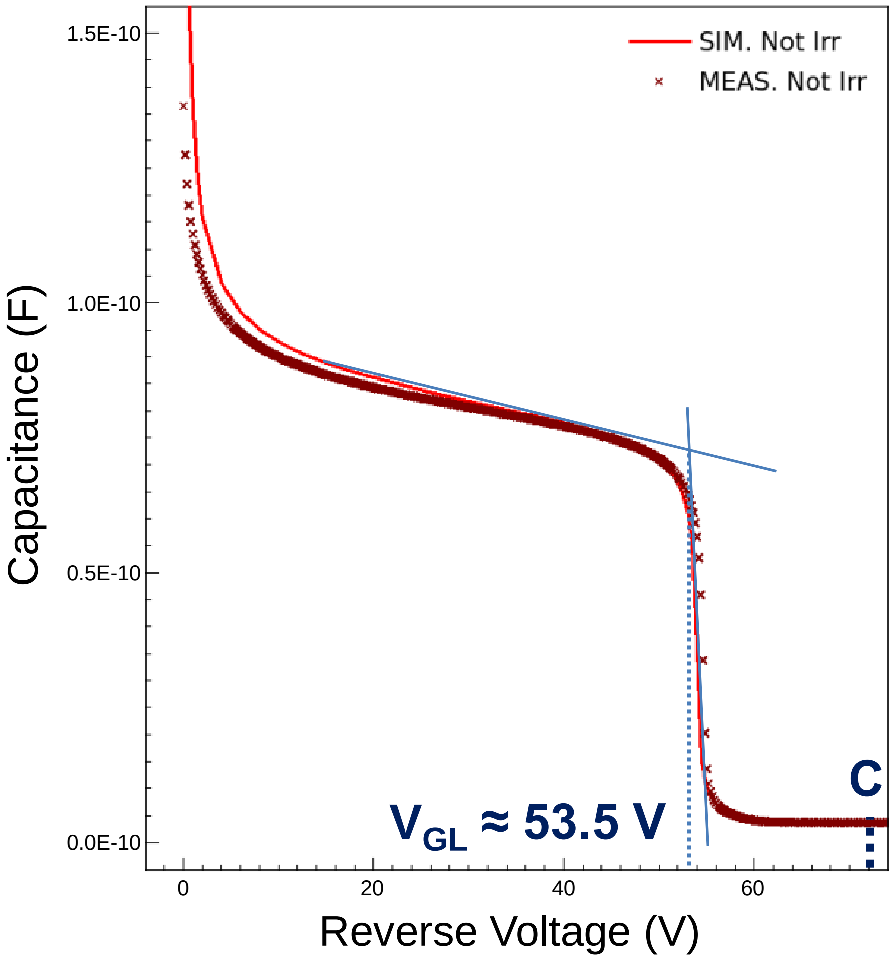
AIDA innova

✓ Pre-irr.

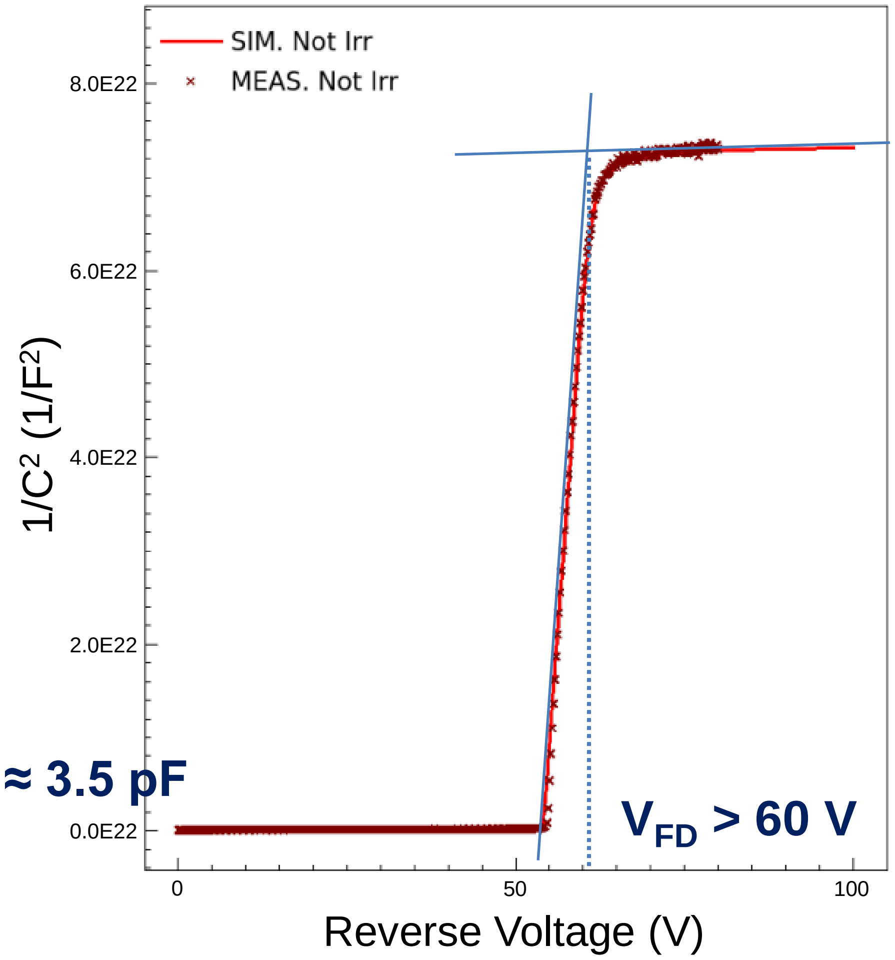




SIM vs. MEAS.



SIM vs. MEAS.

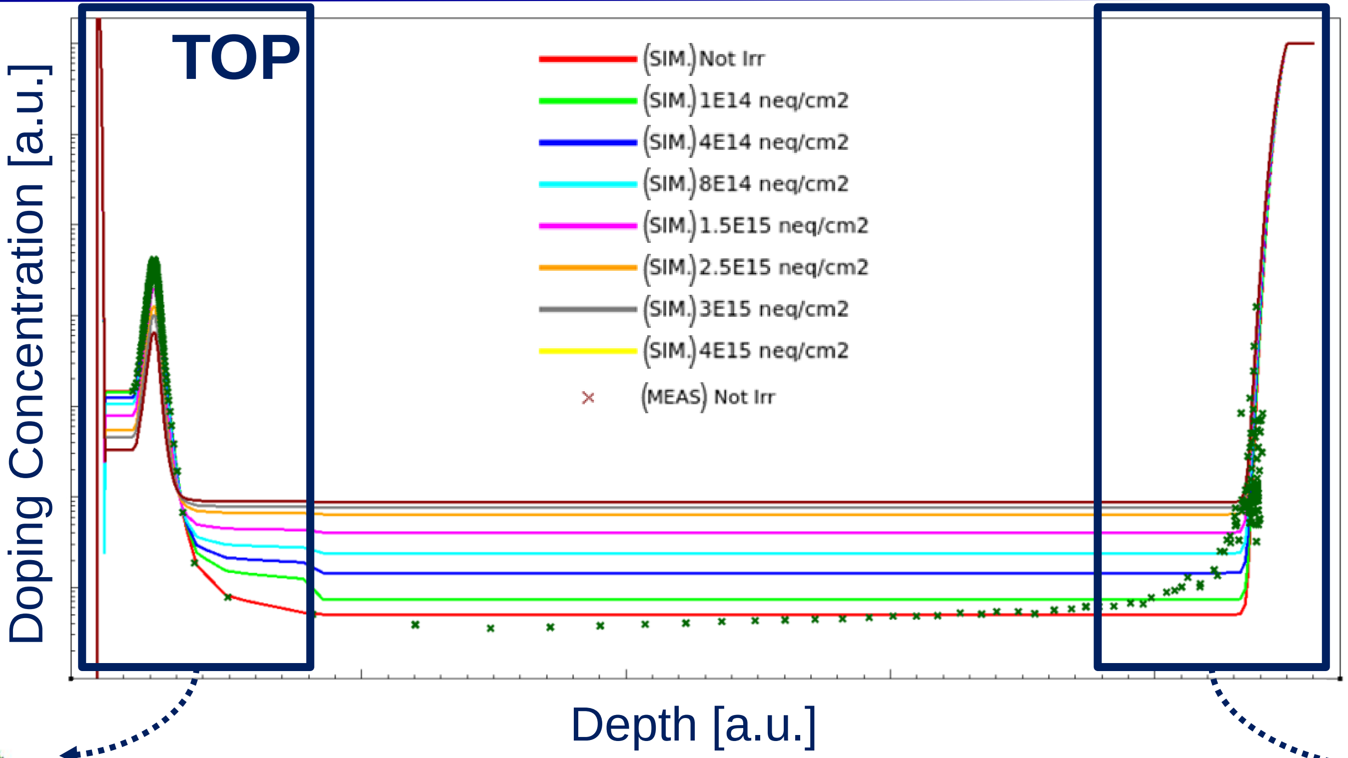


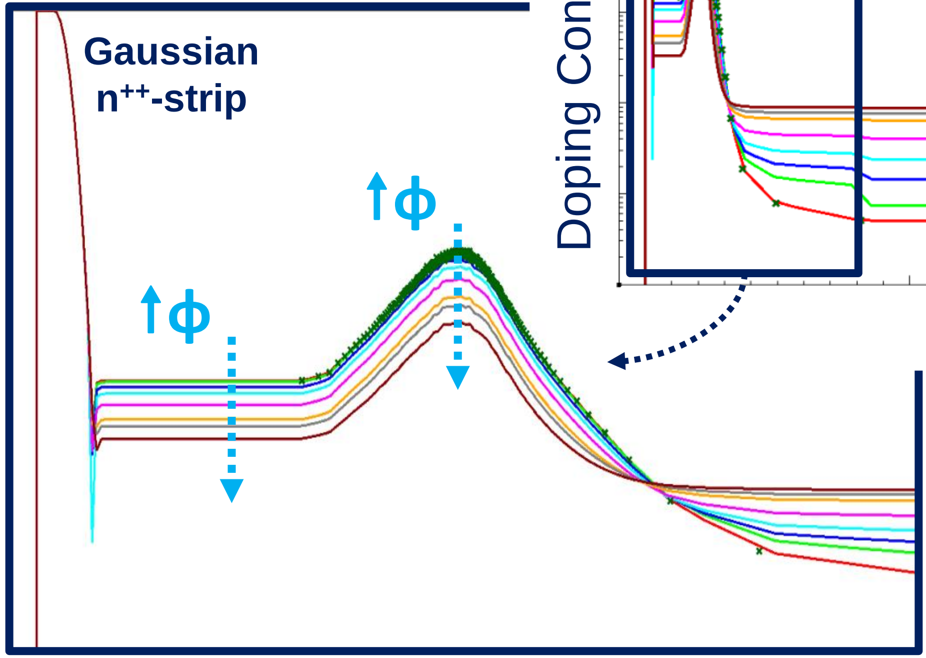
Avalanche model: **Massey**. Temperature **300 K**. Frequency **1 kHz**. Electrical contact area **1,25 x 1,25 mm²**

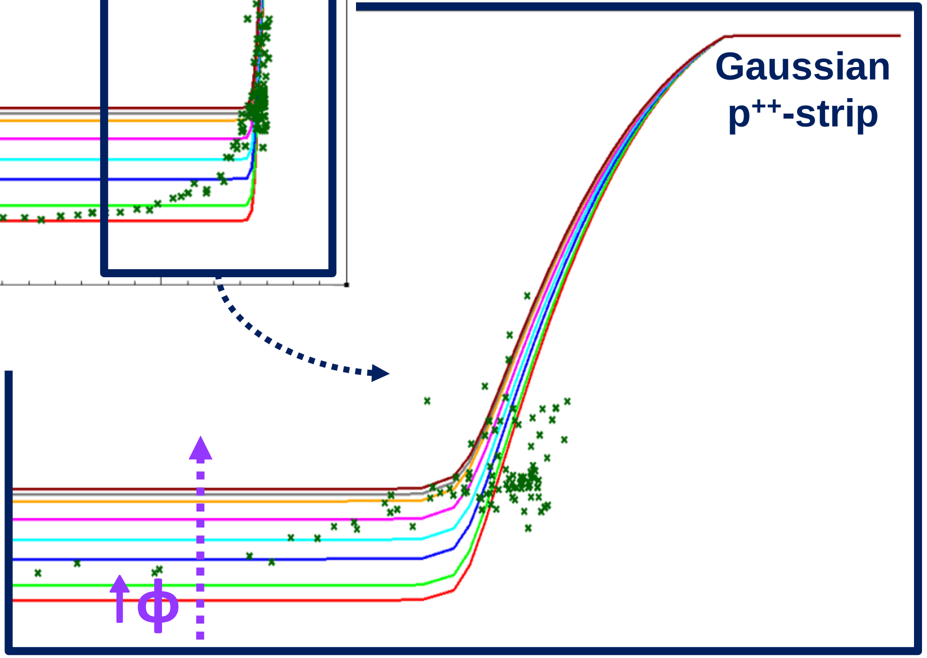
SIMULATED doping profiles – HPK2, Split 1

AIDA innova

✓ Pre & post-irr.







"PerugiaModDoping"

- **Torino analytical parameterization**
  - **Gain Layer** (Acceptor Removal)
  - **Bulk** (Acceptor Creation)
- "**Perugia0**" Bulk/Surface Radiation Damage Model

Surface damage (+ Q_{ox})

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Bulk damage

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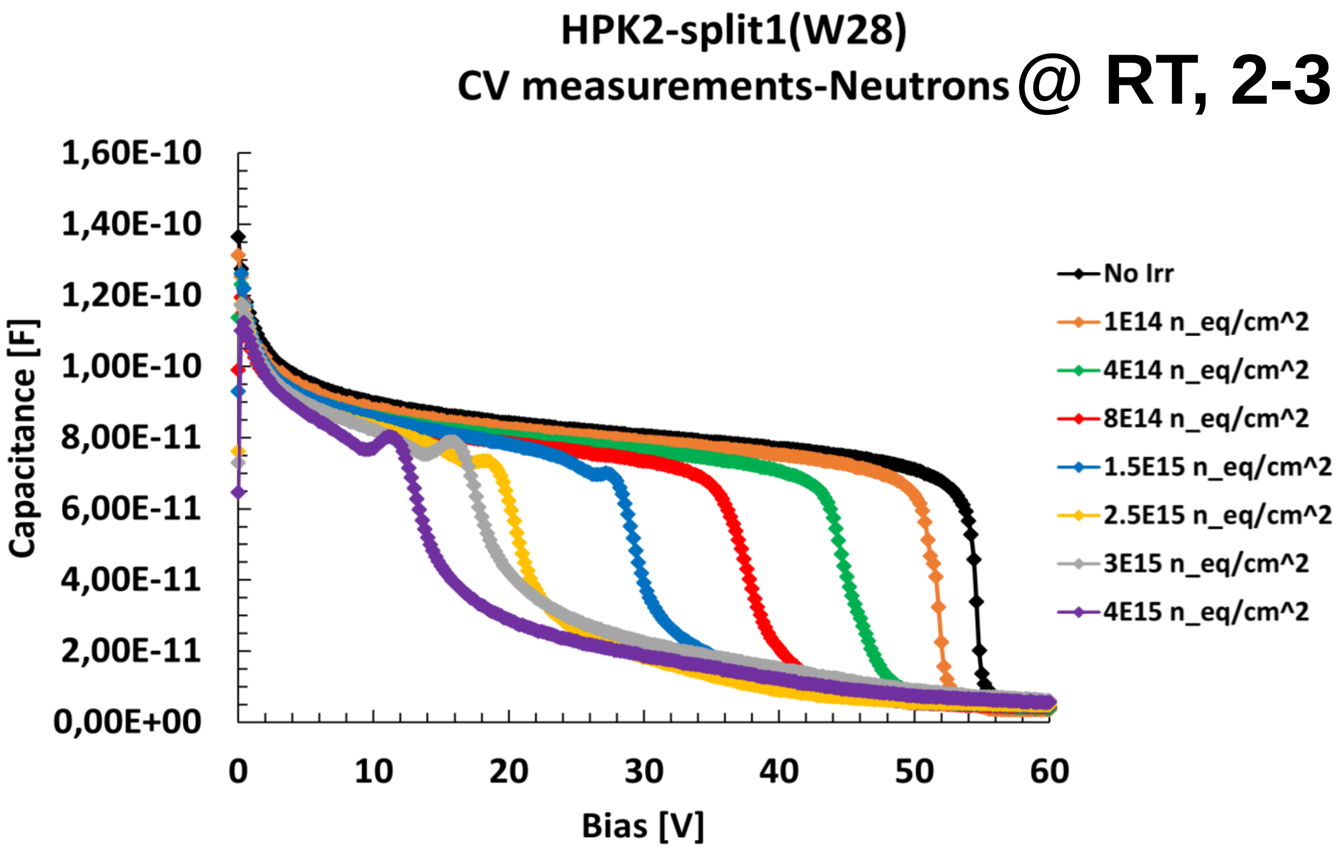
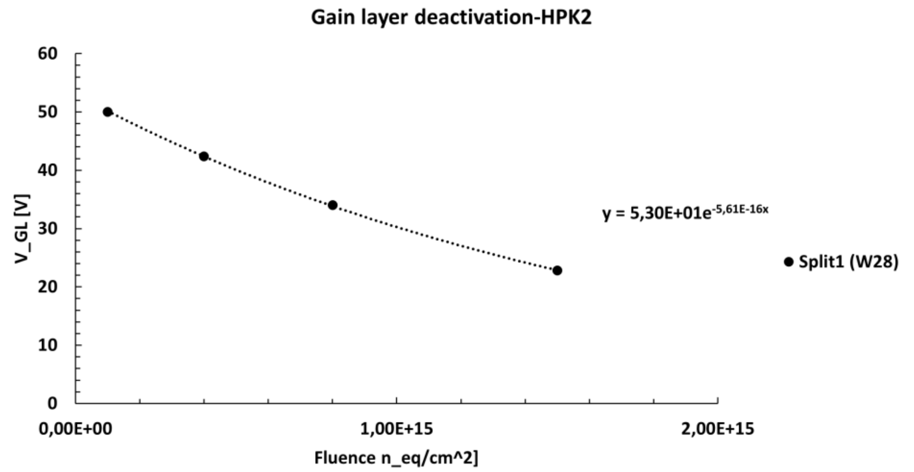
Acceptor	E_C - 0.42	1.6	1×10^{-15}	1×10^{-14}
Acceptor	E_C - 0.46	0.9	7×10^{-14}	7×10^{-13}

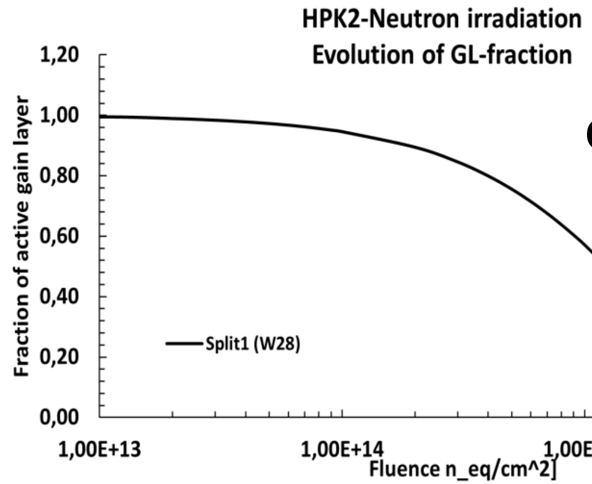
MEASURED C-Vs – HPK2, Split 1, W28

✓ Post-irr. w/ neutrons

@ RT, 2-3 kHz







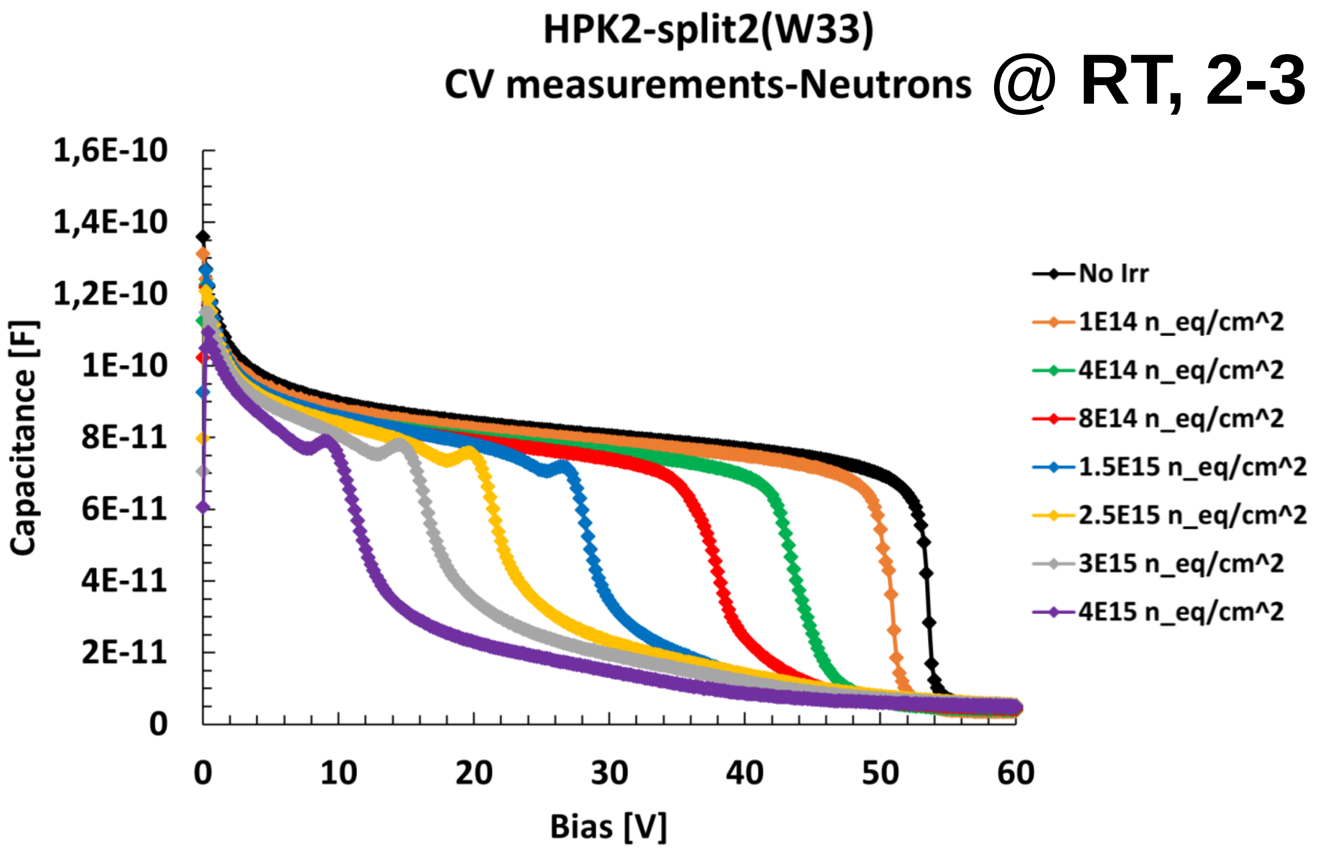
c = 5,61E-16

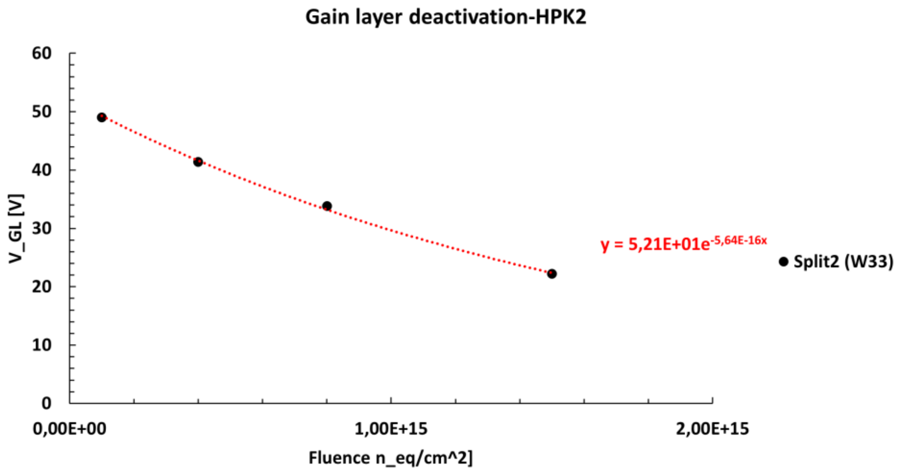
M. Ferrero et al.

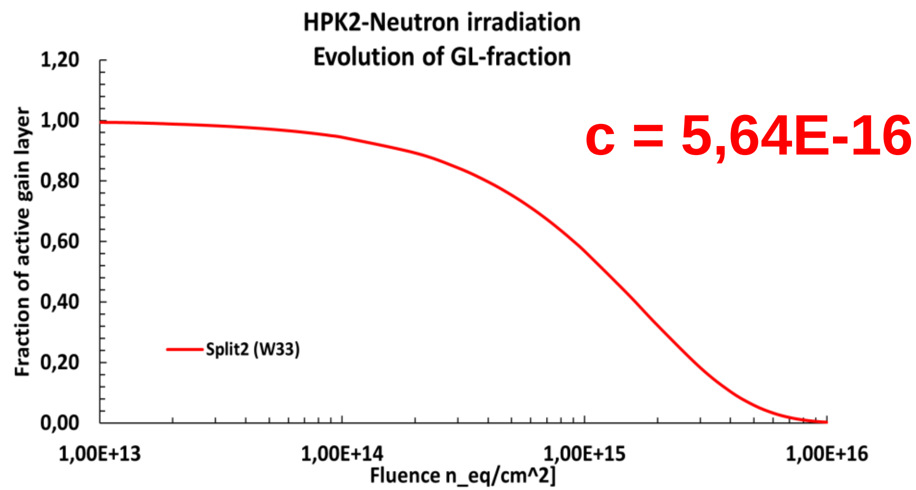
MEASURED C-Vs – HPK2, Split 2, W33

- ✓ Post-irr. w/ neutrons

@ RT, 2-3 kHz







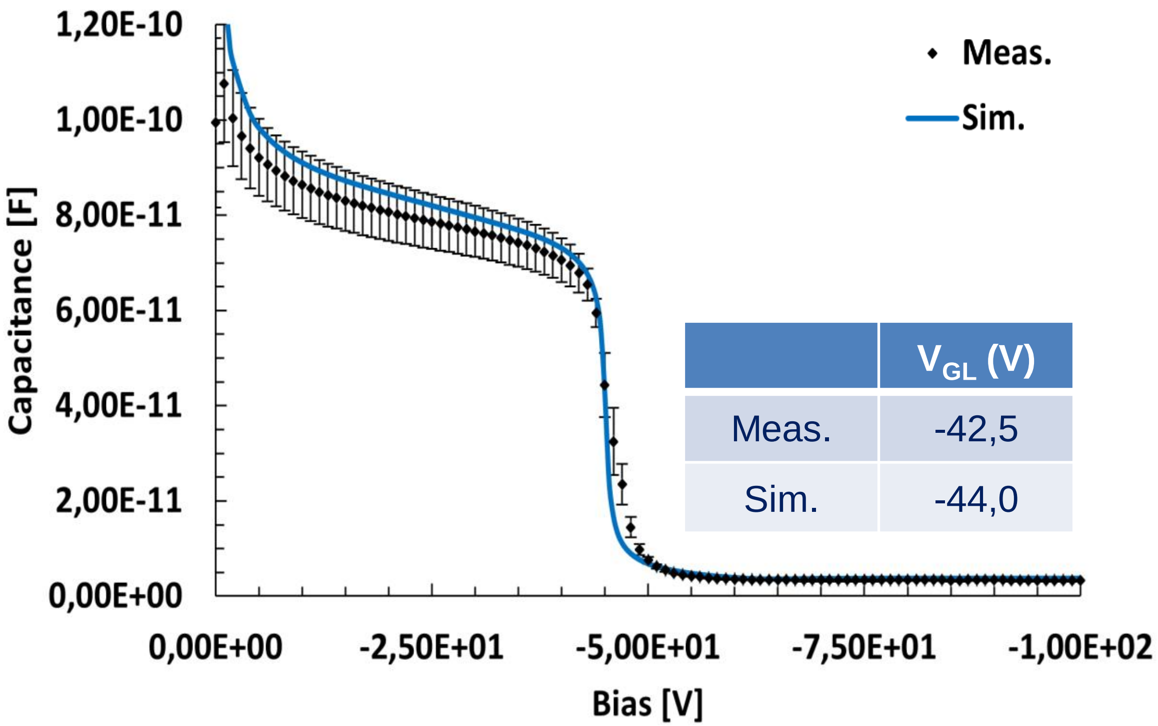
c = 5,64E-16

M. Ferrero et al.

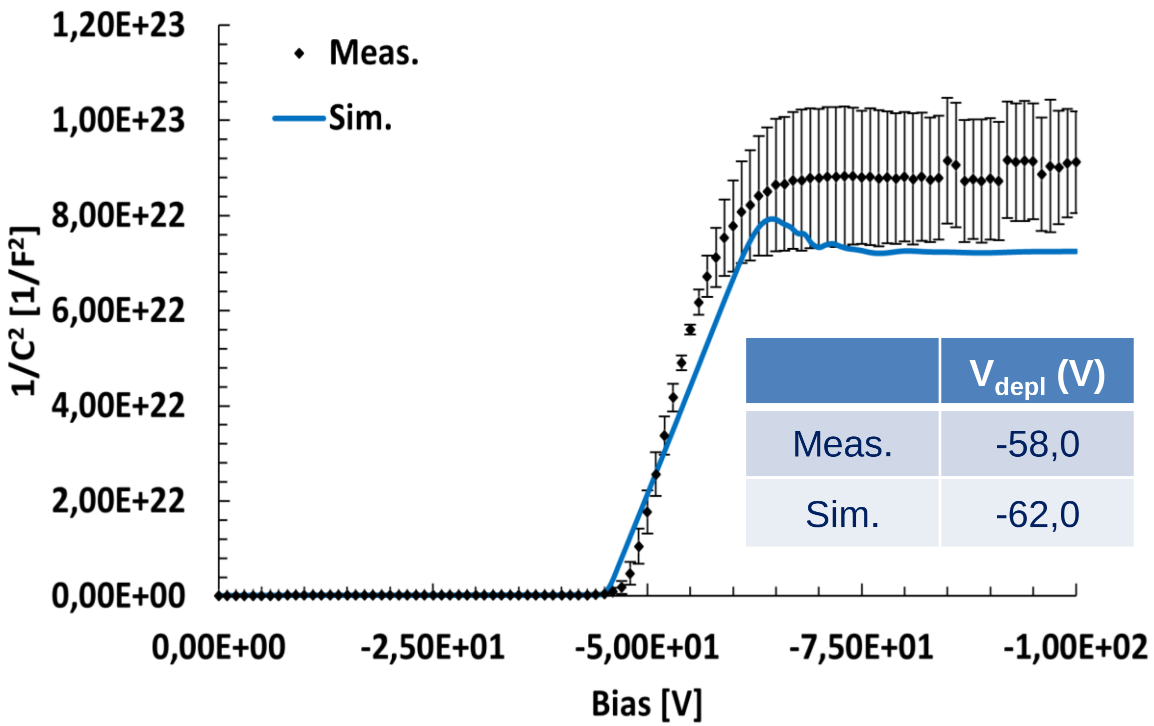
SIM. vs MEAS. C-V & $1/C^2$-V – HPK2, Split 1

- ✓ Post-irr. ($\Phi = 4{,}0E14\ n_{eq}/cm^2$)

Split 1



	V_{GL} (V)
Meas.	-42,5
Sim.	-44,0



	V_{depl} (V)
Meas.	-58,0
Sim.	-62,0

SIM vs. MEAS

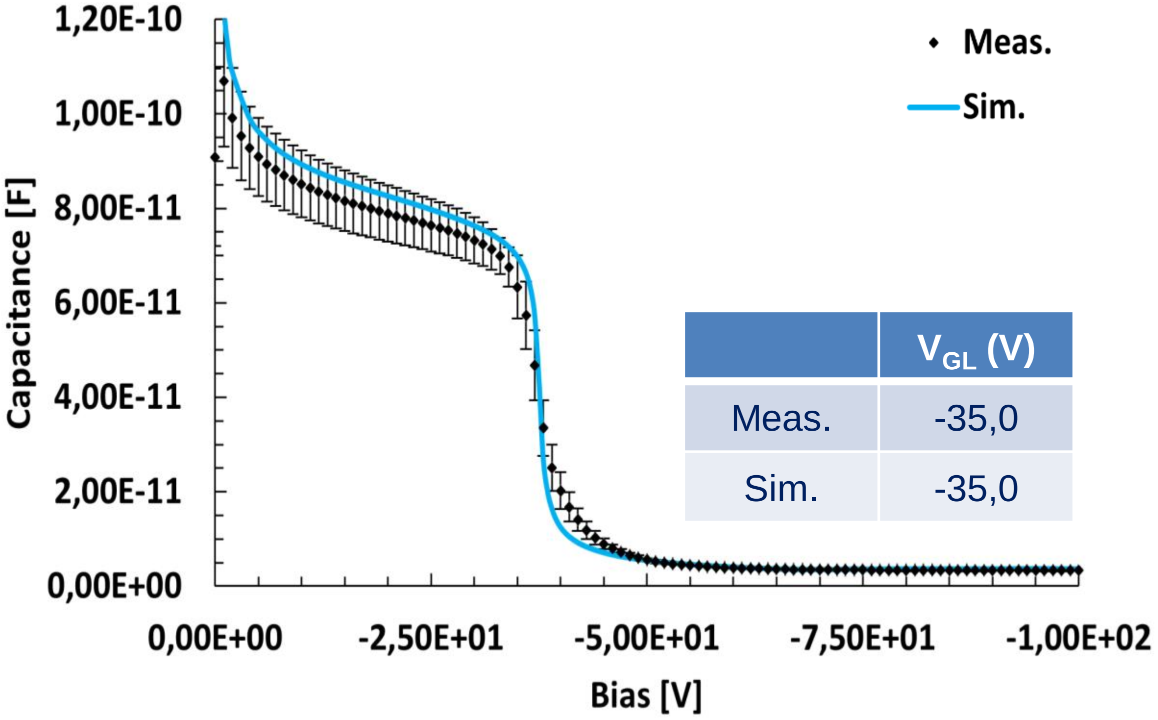
Temperature **298 K**. Frequency **2 kHz**. Electrical contact area **1,25 x 1,25 mm²**

SIM. vs MEAS. C-V & 1/C²-V – HPK2, Split 1

✓ Post-irr. (**Φ = 8,0E14 n_{eq}/cm²**)

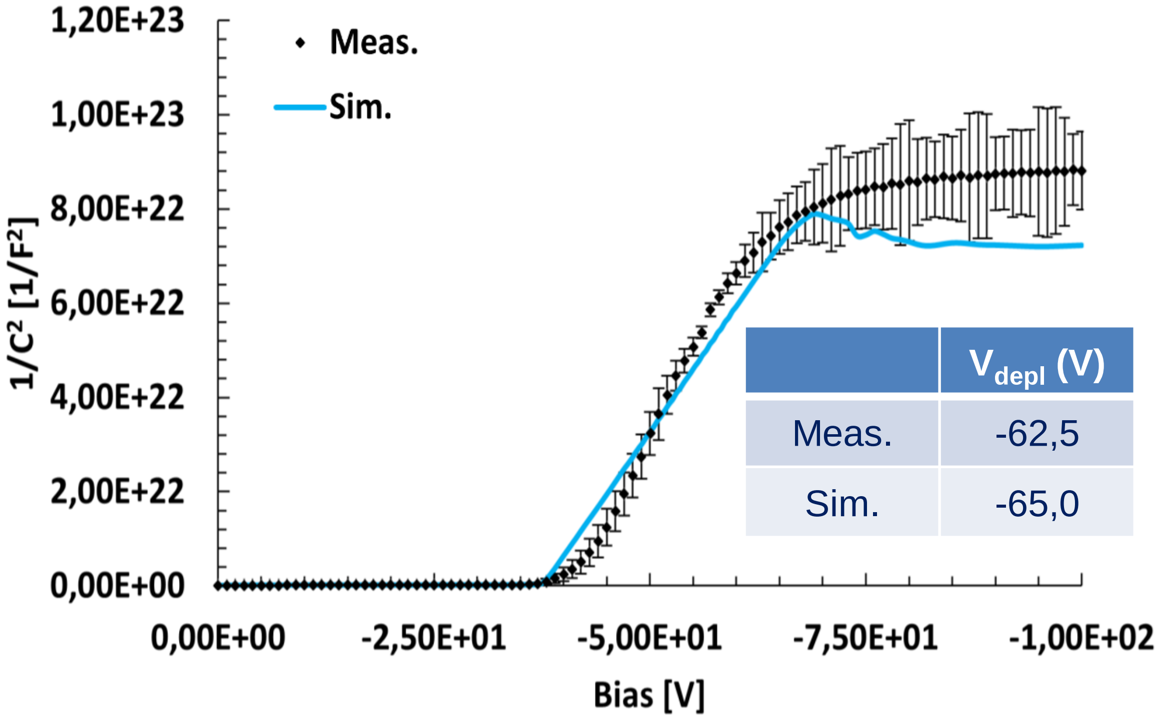
Split 1

C-V



	V_{GL} (V)
Meas.	-35,0
Sim.	-35,0

1/C²-V



	V_{depl} (V)
Meas.	-62,5
Sim.	-65,0

SIM vs. MEAS

Temperature **298 K**. Frequency **2 kHz**. Electrical contact area **1,25 x 1,25 mm²**

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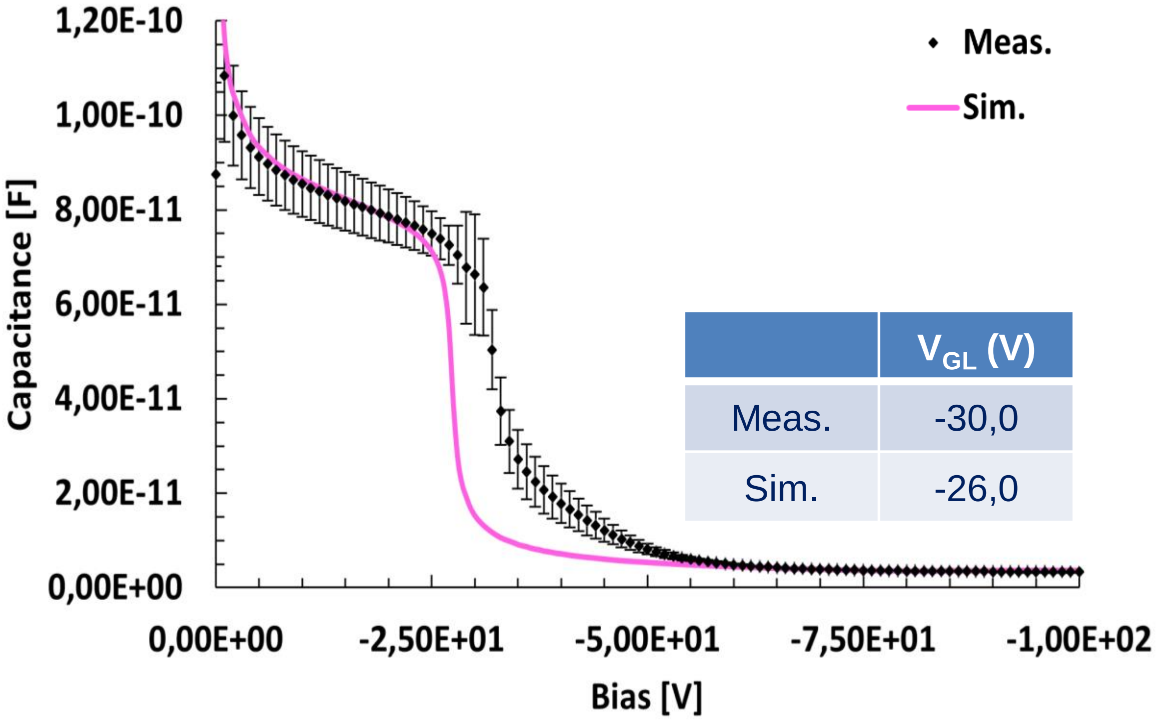
SIM. vs MEAS. C-V & 1/C²-V – HPK2, Split 1

✓ Post-irr. (**Φ = 1,5E15 n_{eq}/cm²**)

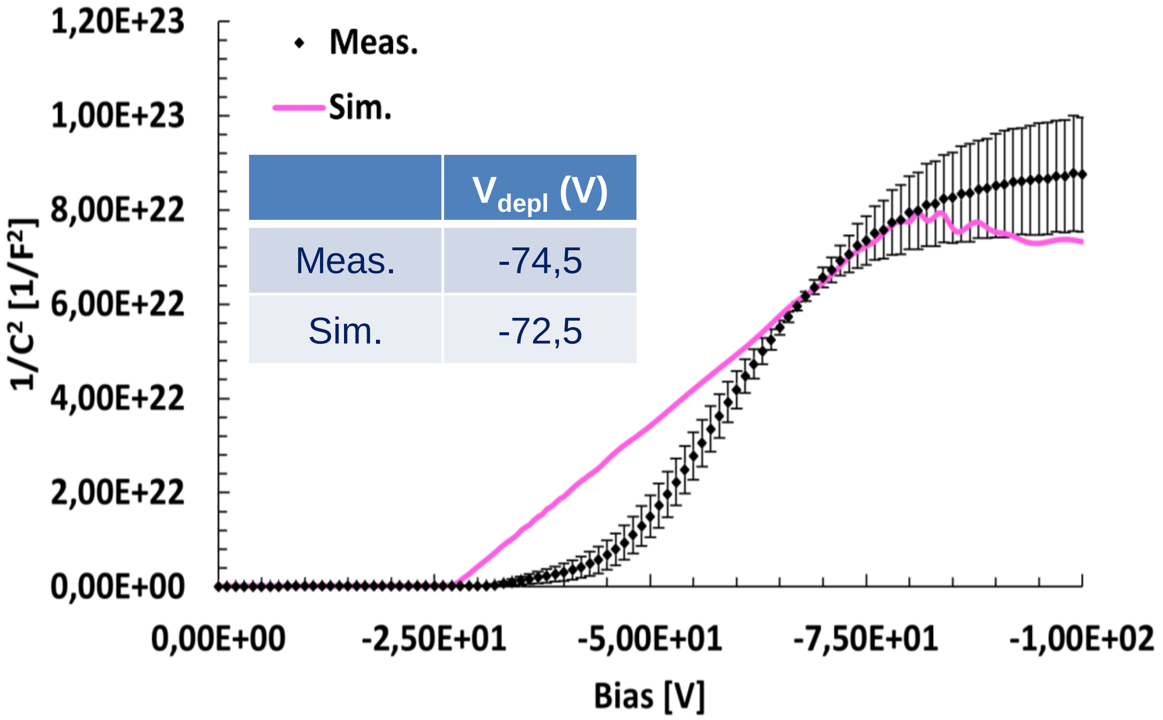
Split 1

C-V



	V_{GL} (V)
Meas.	-30,0
Sim.	-26,0

1/C²-V



	V_{depl} (V)
Meas.	-74,5
Sim.	-72,5

SIM vs. MEAS

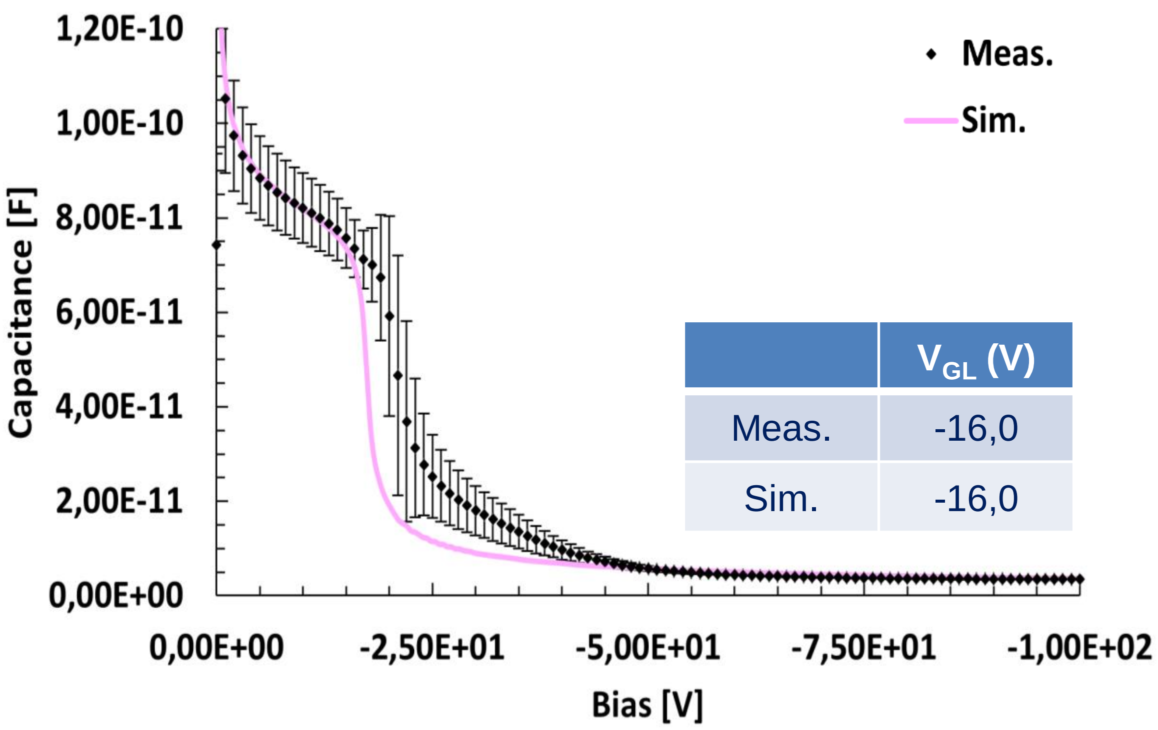
Temperature **298 K**. Frequency **2 kHz**. Electrical contact area **1,25 x 1,25 mm²**

SIM. vs MEAS. C-V & 1/C²-V – HPK2, Split 1

✓ Post-irr. (**Φ = 2,5E15 n_{eq}/cm²**)

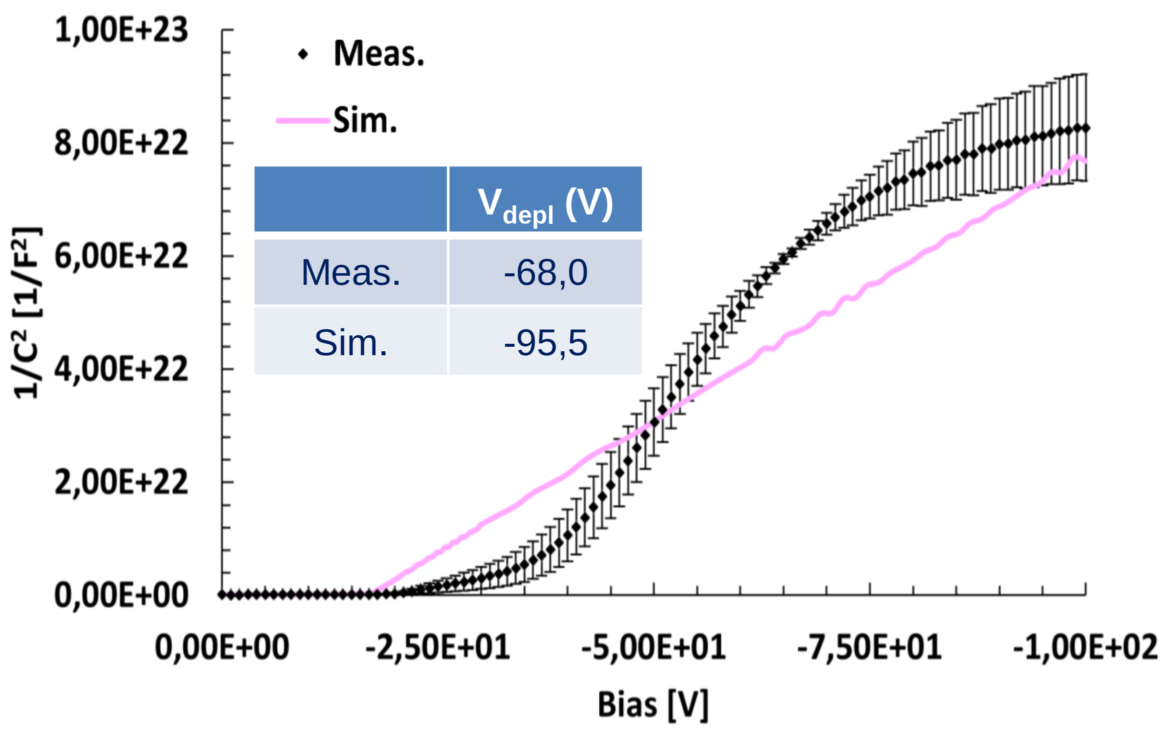
Split 1

C-V



	V_{GL} (V)
Meas.	-16,0
Sim.	-16,0

1/C²-V



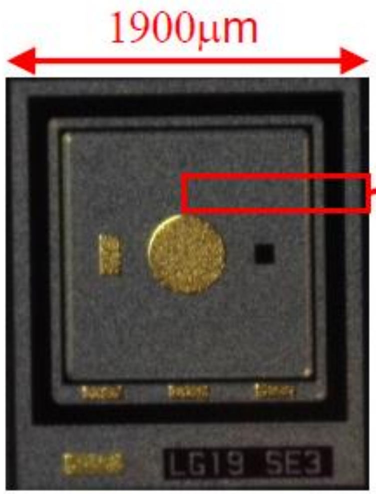
	V_{depl} (V)
Meas.	-68,0
Sim.	-95,5

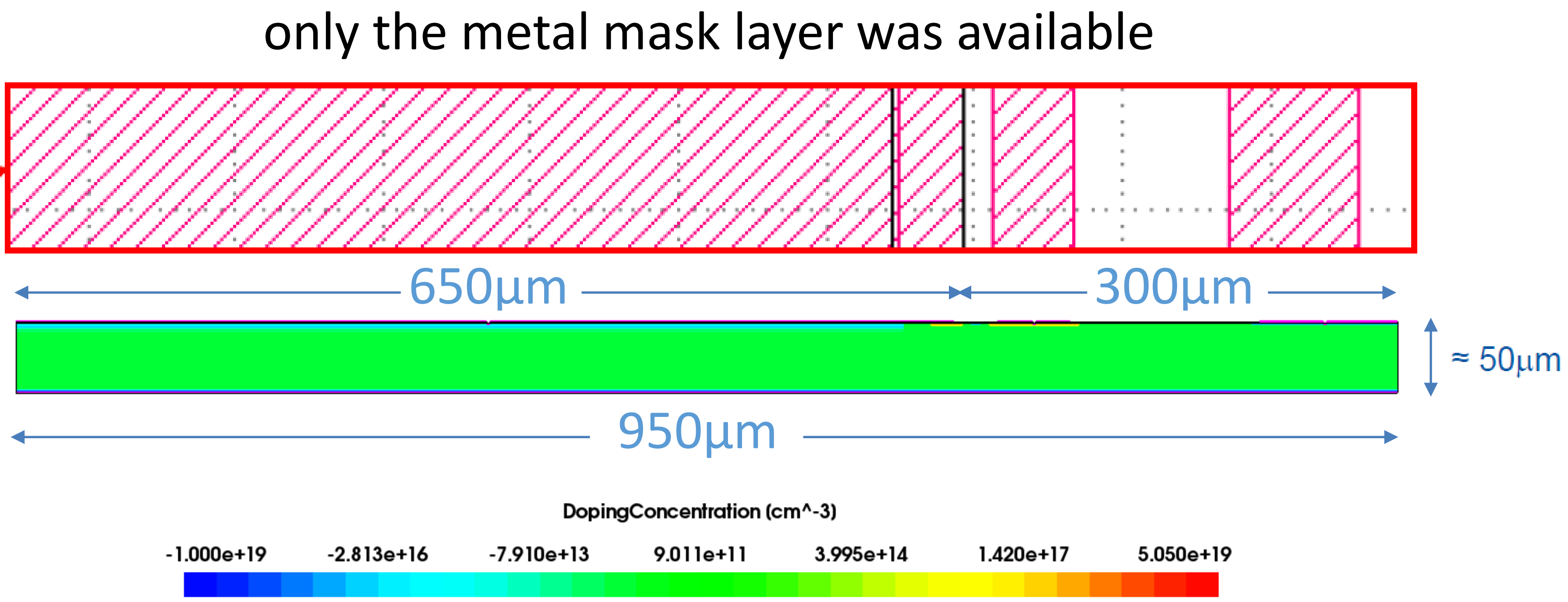
SIM vs. MEAS

Temperature **298 K**. Frequency **2 kHz**. Electrical contact area **1,25 x 1,25 mm²**

SIMULATED structure – HPK2

✓ Pre-irr.





2D simulation

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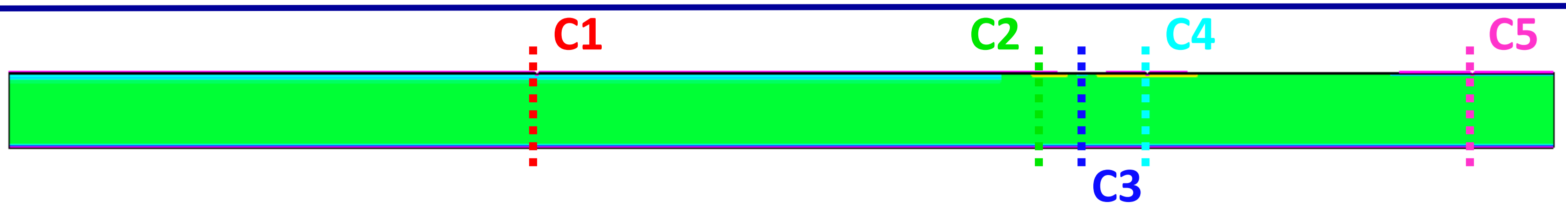
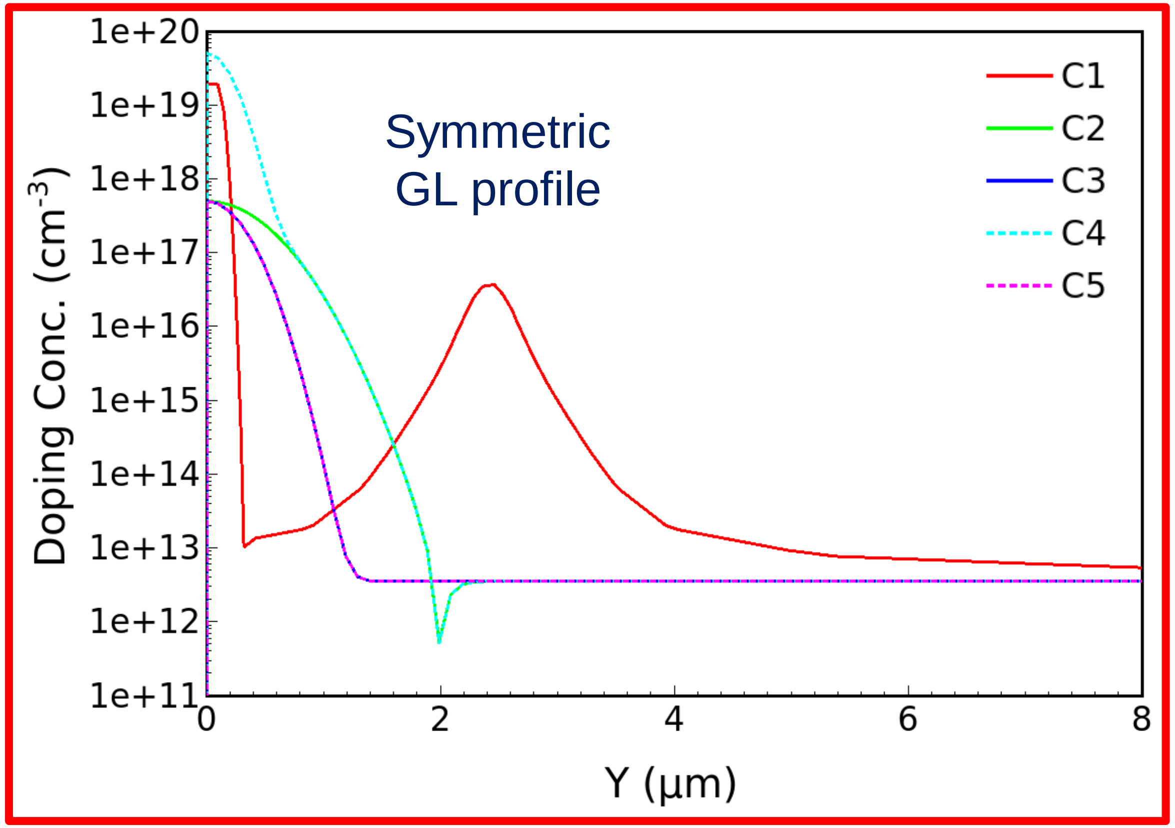
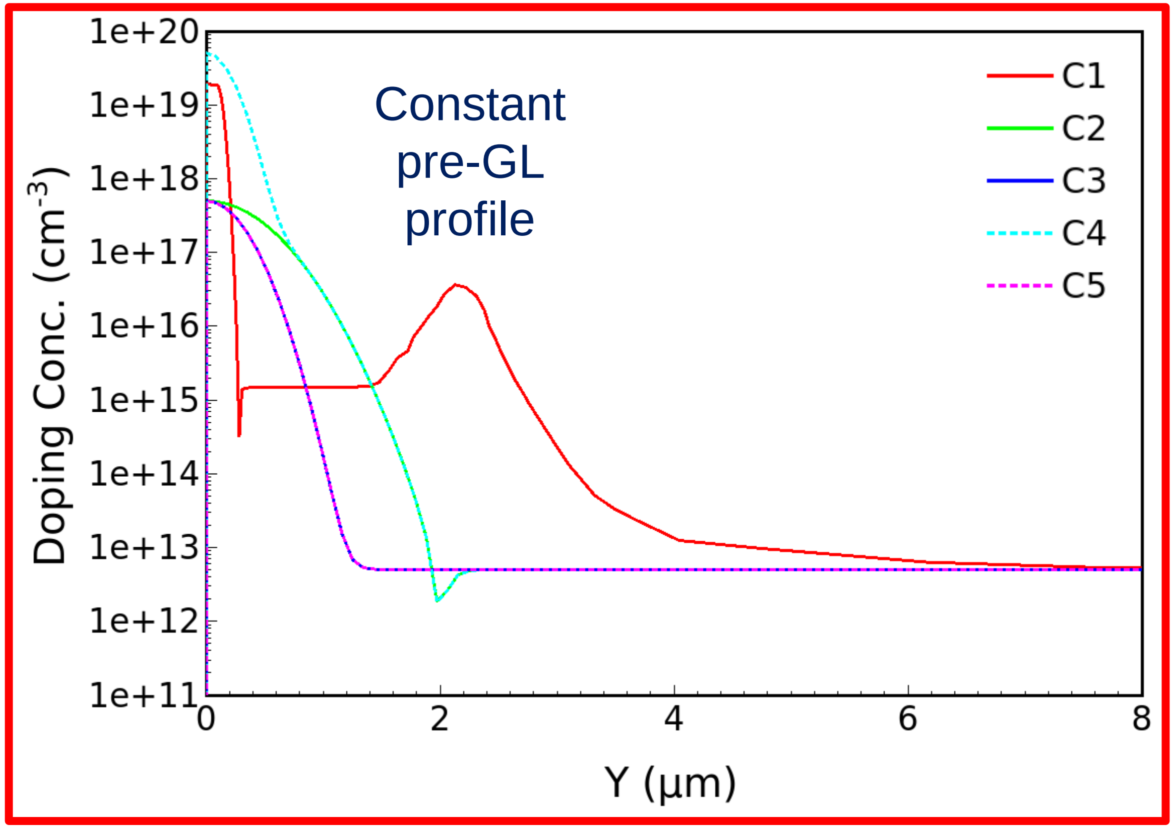
SIMULATED doping profiles – HPK2

- ✓ Pre-irr.







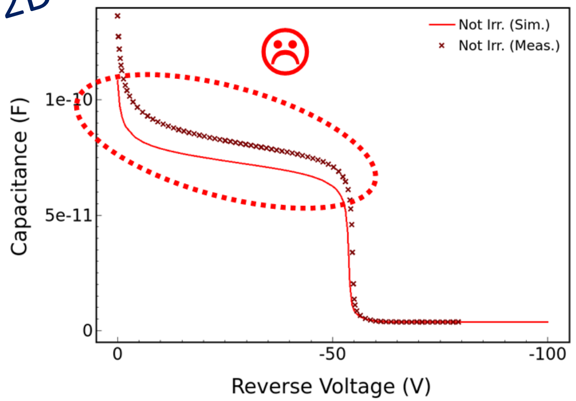
2D simulation

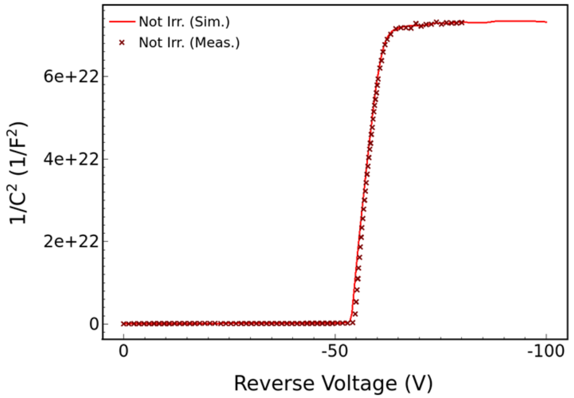
SIMULATED C-V and 1/C²-V – HPK2, pre-irr.

SIM vs. MEAS.

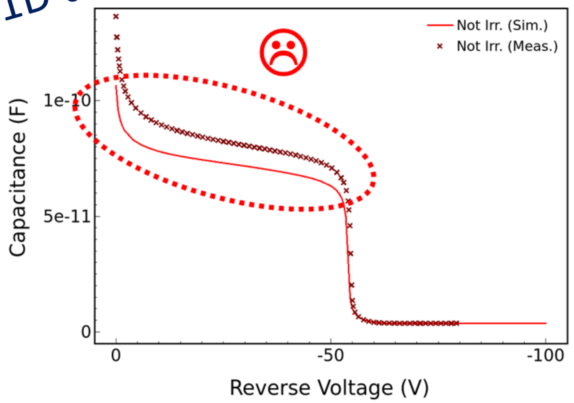
Symmetric GL profile

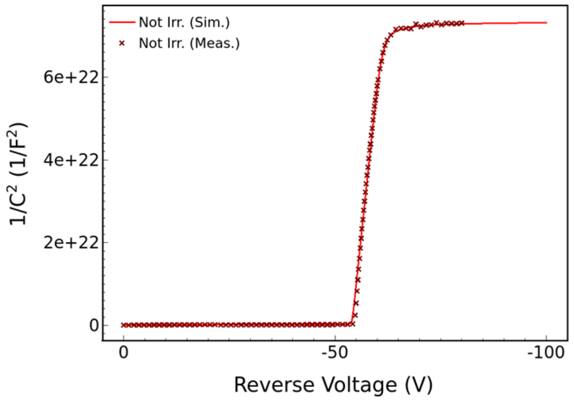
2D domain





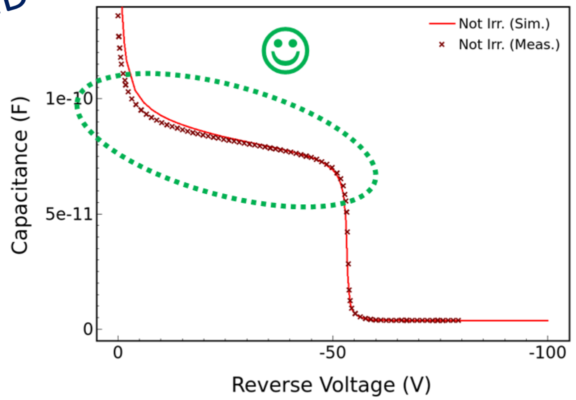
1D domain

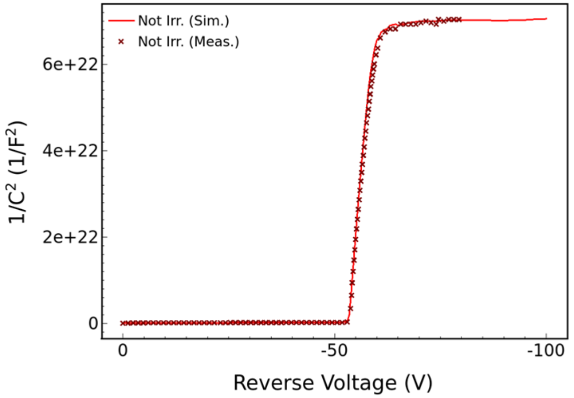




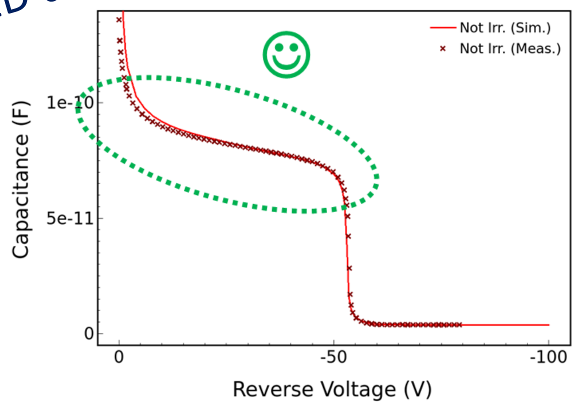
Constant pre-GL profile

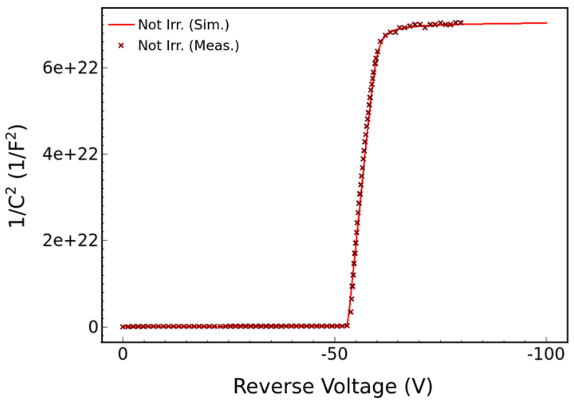
2D domain





1D domain





Temperature **290 K**. Frequency **1 kHz**. Electrical contact area **1,25 x 1,25 mm²**

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