Simulations of radiation hard detectors for timing applications

F. Moscatelli[2,1], T. Croci[1], D. Passeri[3,1], A. Morozzi[1], A. Fondacci[3], M. Menichelli [1], G.M. Bilei[1], V. Sola[5,4], M. Ferrero[4], F. Siviero[5], L. Lanteri[5], J. Ye[6], A. Boughedda[6], G.-F. Dalla Betta[6]

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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.

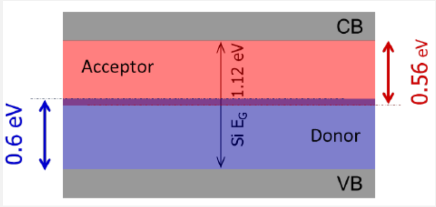
Extension of the Radiation Damage Model

"PerugiaModDoping" [1]

"**New University of Perugia**" Radiation Damage Model [2]

Surface damage (+ Q_{ox})

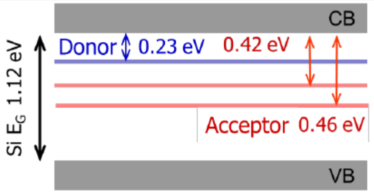
Type	Energy (eV)	Band width (eV)	Conc. (cm^{-2})
Acceptor	$E_C \le E_T \le E_C$-0.56	0.56	$D_{IT} = D_{IT}(\Phi)$
Donor	$E_V \le E_T \le E_V$+0.6	0.60	$D_{IT} = D_{IT}(\Phi)$



+

Bulk damage

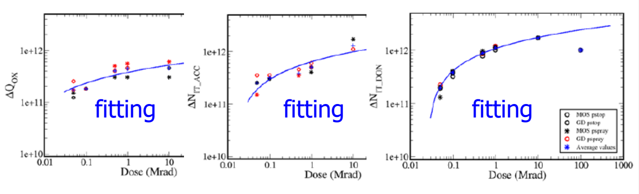
Type	Energy (eV)	η (cm^{-1})	σ_n (cm^2)	σ_h (cm^2)
Donor	E_C - 0.23	0.006	2.3×10^{-14}	2.3×10^{-15}
Acceptor	E_C - 0.42	1.6	1×10^{-15}	1×10^{-14}
Acceptor	E_C - 0.46	0.9	7×10^{-14}	7×10^{-13}



✓ **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:

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



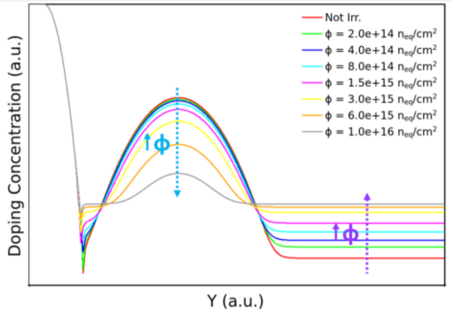
(a) ΔQ_{OX} (b) ΔN_{IT_ACC} (c) ΔN_{IT_DON}

+

Torino doping analytical parameterizations [3]

- **Gain Layer** (Acceptor Removal)

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

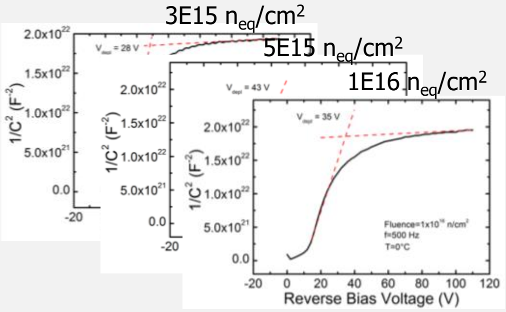


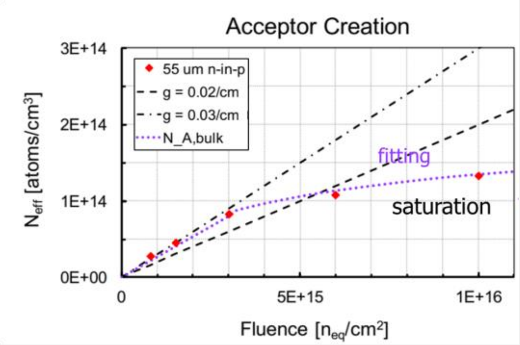
- **Bulk** (Acceptor Creation)
  - ✓ if $0 < \Phi \le 3e15\ n_{eq}/cm^2$

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

  - ✓ if $\Phi > 3e15\ n_{eq}/cm^2$

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





[1] P. Asenov et. al, NIM. A 1040 (2022) 167180; **[2]** A. Morozzi et. al, PoS (Vertex2019) 050; **[3]** M. Ferrero et. al, CRC Press (2021).

TCAD simulation of **LGAD** device - **FBK**

✓ 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 run, by FBK)

"PerugiaModDoping"

- **Torino analytical parameterizations**
  - **Gain Layer** (Acceptor Removal)
  - **Bulk** (Acceptor Creation/Damage Saturation)
- "**New UNIPG**" TCAD 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	$D_{IT} = D_{IT}(\Phi)$

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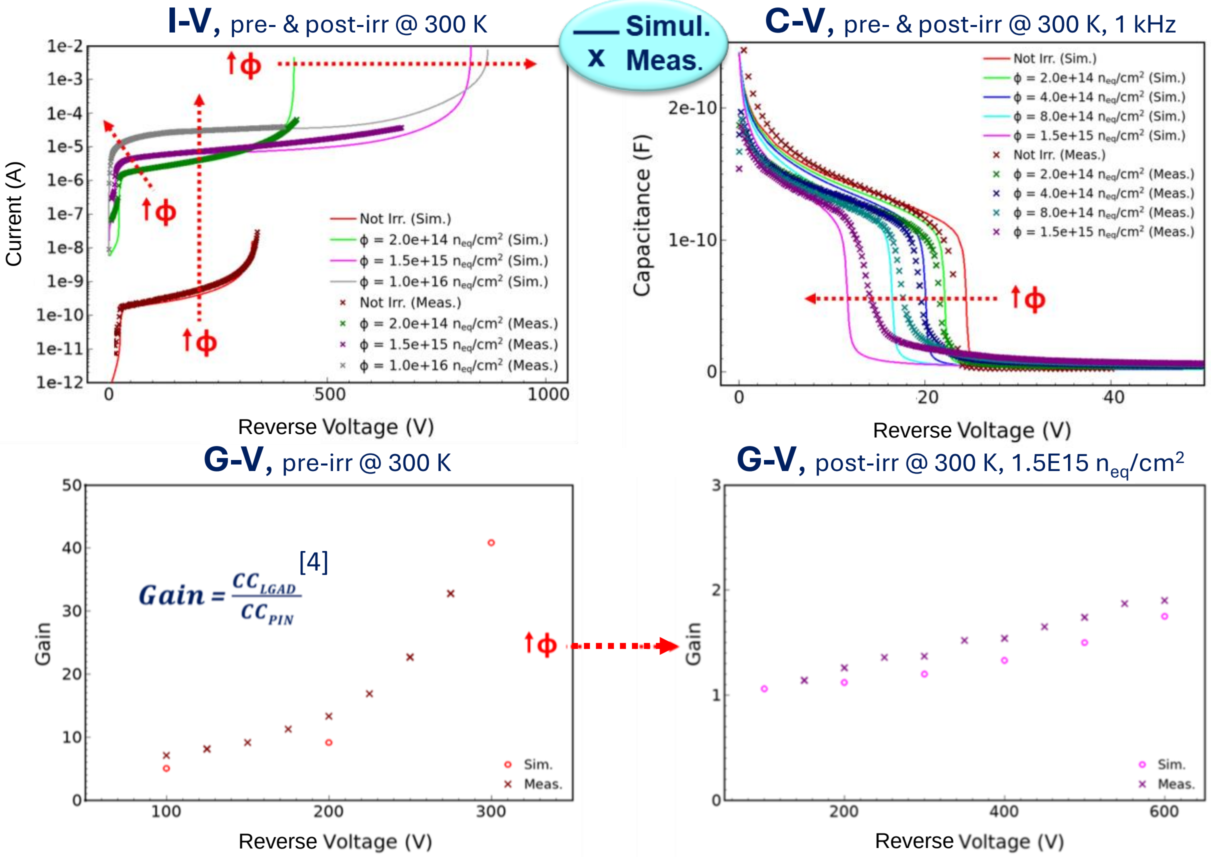

Massey avalanche model. Temperature **300 K** [5]. Electrical contact area **1 x 1 mm²**

[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.

TCAD simulation of **LGAD** device - **HPK**

- ✓ 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** (HPK2 production run, by HPK)

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"PerugiaModDoping"

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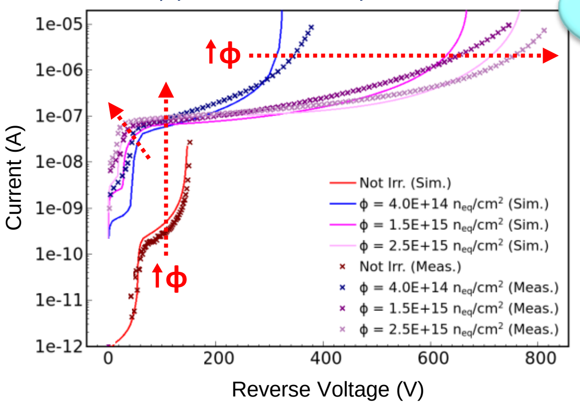
[6] R. V. Overstraeten et al., *Measurement of the ionization rates in diffused silicon p-n junctions*, SSE. 13, 1970.

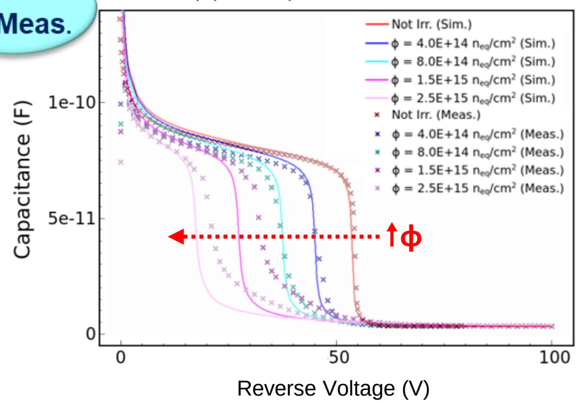
[7] E. C. Rivera, *Study of Impact Ionization Coefficients in Silicon With Low Gain Avalanche Diodes*, IEEE TED 70, 2023.

I-V, pre-irr @ 290 K, post-irr @ 248 K

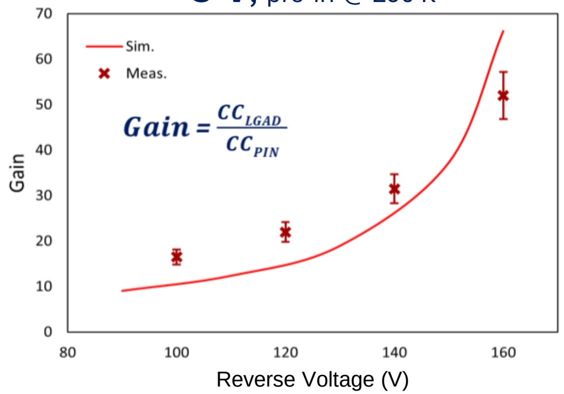


— Simul.
x Meas.

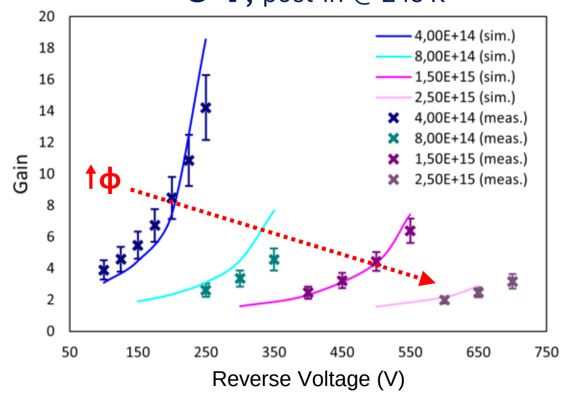
C-V, pre- & post-irr @ 298 K, 2 kHz



G-V, pre-irr @ 290 K



G-V, post-irr @ 248 K

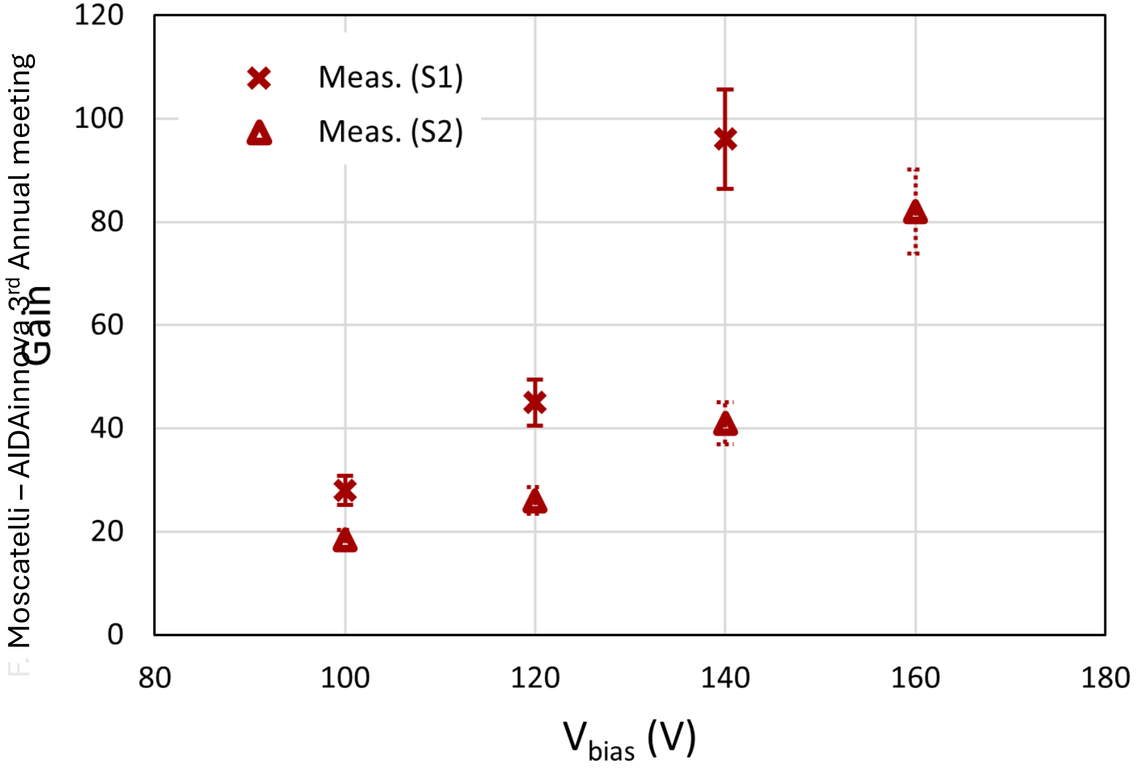


vOv [6] & **Opt. vOv** [7] avalanche models. Electrical contact area **1,25 x 1,25 mm²**

MEASURED G-V – HPK2, Split 1 vs. Split 2

Pre-irradiation (TCT setup @ Torino)

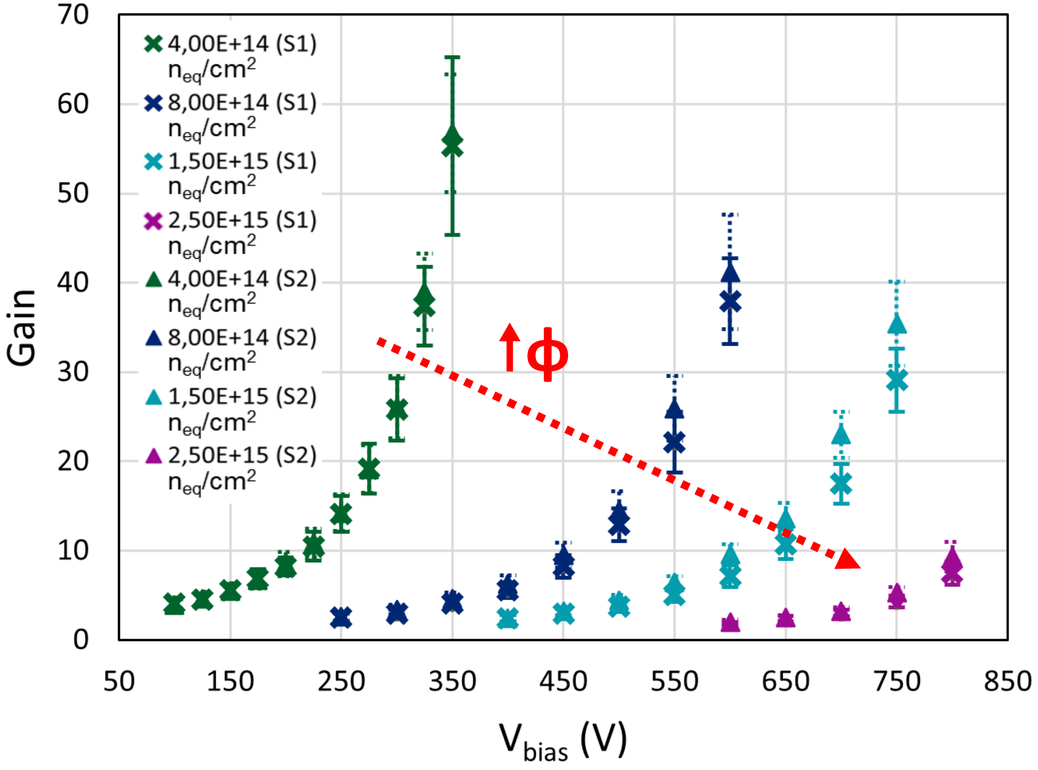
Gain-Voltage @ RT, ~ 1 MIP



$Gain_{S1} > Gain_{S2}$

Post-irradiation (β-source setup @ Torino)

Gain-Voltage @ 248 K, 1 MIP



$Gain_{S1} \approx Gain_{S2}$

L. Lanteri, F. Siviero

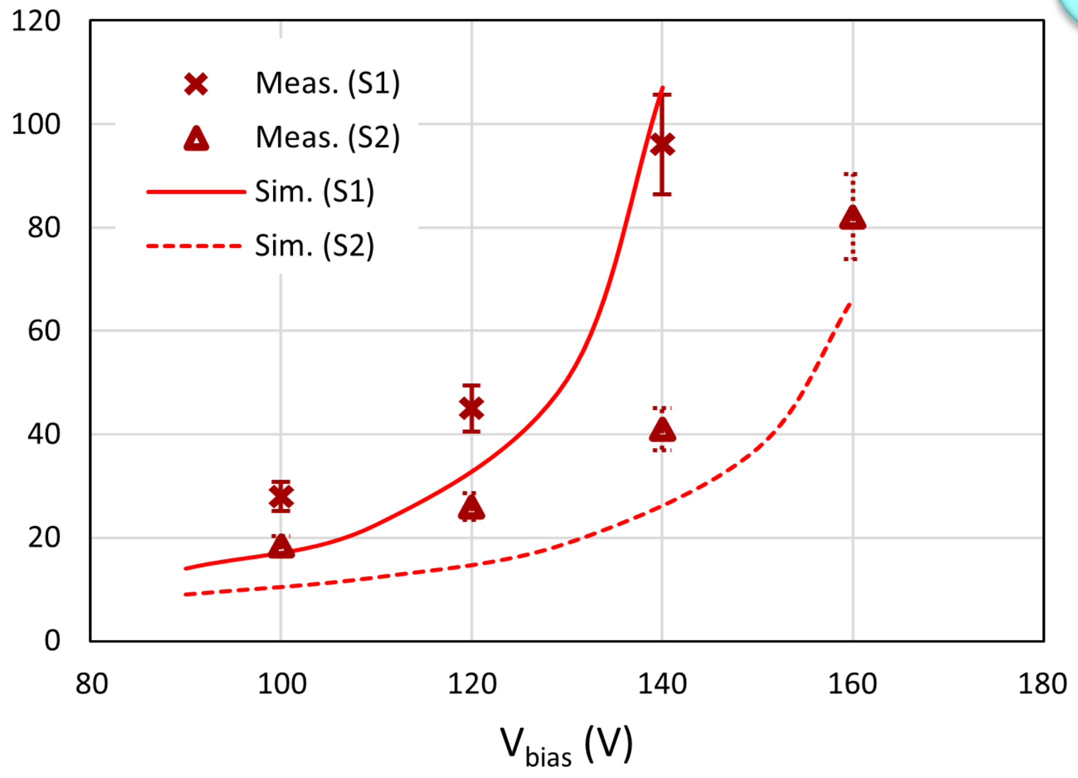
SIM. vs. MEAS. G-V – HPK2, Split 1 vs. Split 2

Pre-irradiation (TCT setup @ Torino)

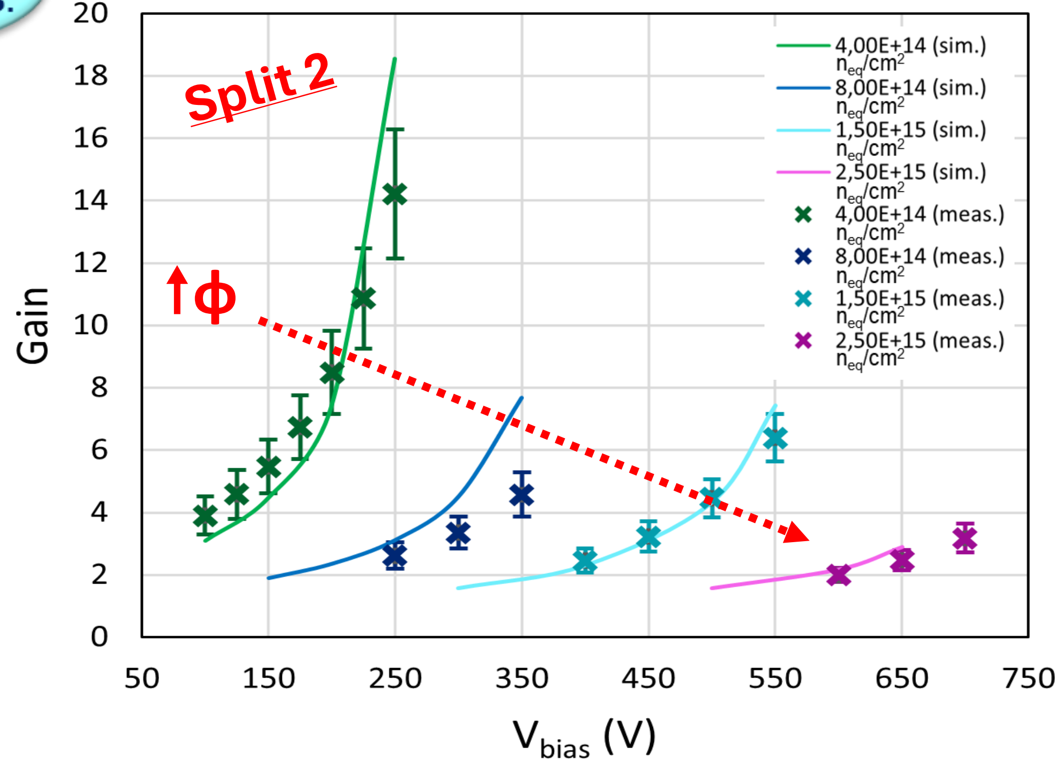
Post-irradiation (β-source setup @ Torino)

— Simul.
x Meas.

Gain-Voltage @ 290 K, 1 MIP



Gain-Voltage @ 248 K, 1 MIP



$Gain_{S1} > Gain_{S2}$

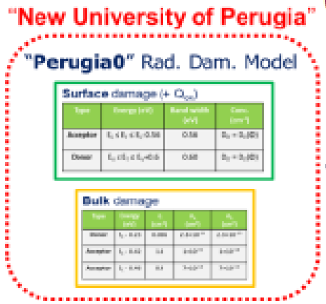
$Gain_{S1} \approx Gain_{S2}$

vOv [6] avalanche model. Electrical contact area **1,25 x 1,25 mm²**

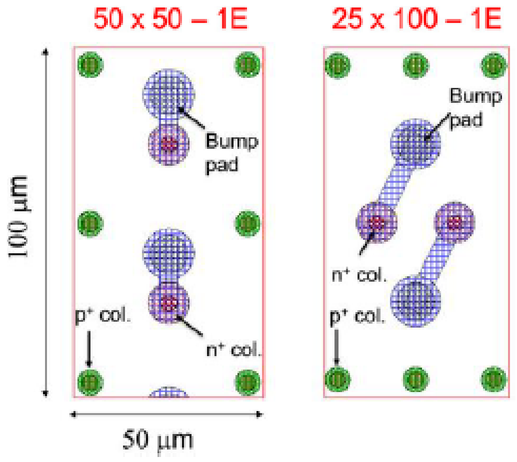
Simulation of 3D devices

- ✓ 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)

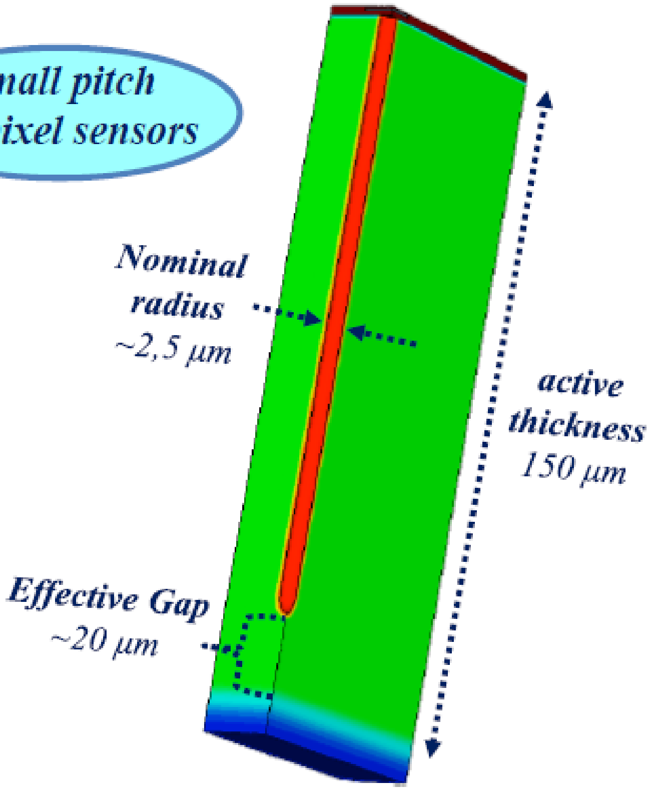
(*)

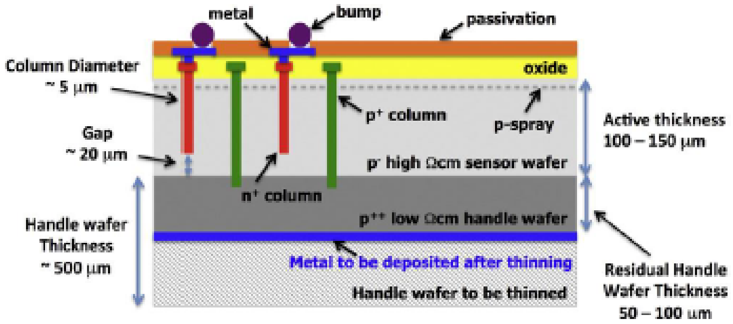


Model Used	*Temp*
Perugia Surface Damage Model [8]	*-25 °C*
Perugia Bulk Damage Model [1]	*-25 °C*
CERN Bulk Damage Model [9]	*-38 °C*



Small pitch 3D pixel sensors





[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 – *Bulk* Damage Model

✓ Post-irr.

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

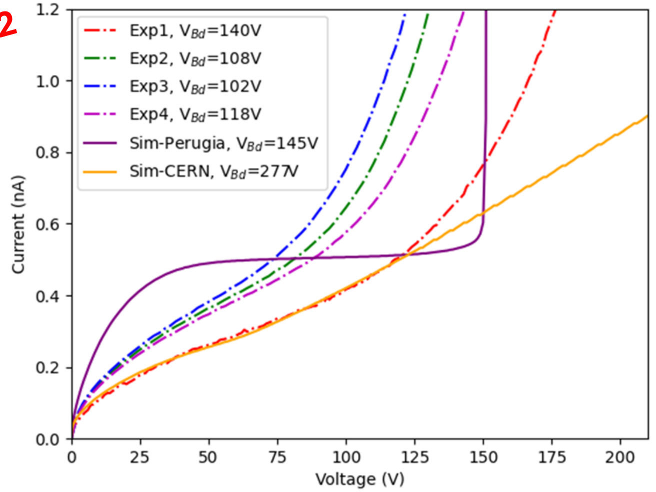
Calculated Damage Rate at V_b=100V, T=20°C

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

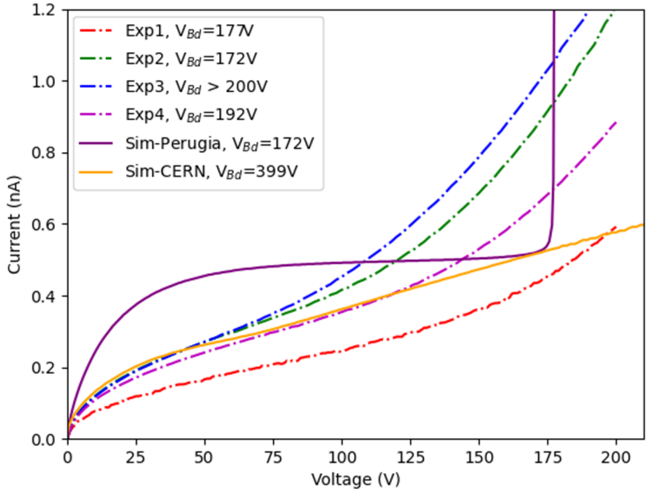
1,5E16 n_{eq}/cm^2

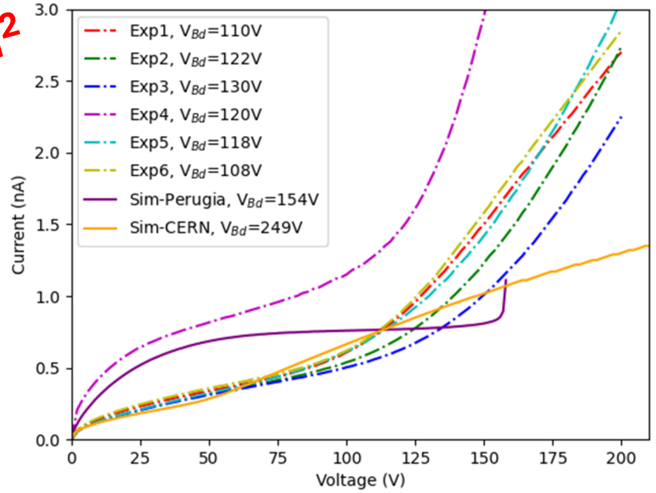
Structure	α^* Experiment (10^{-17}A/cm)	α^* Perugia Model (10^{-17}A/cm)	α^* CERN Model (10^{-17}A/cm)
50×50-1E	4.41± 0.36	5.91	5.14
25×100-1E	3.87±0.43	5.54	4.09

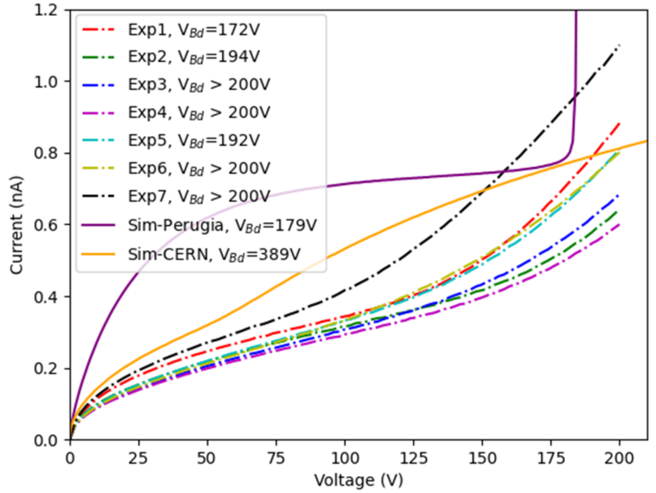
I-V, 50x50-1E



I-V, 25x100-1E







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

—— Simul.
····· Meas.

Impact of varying the sigma acceptor 1

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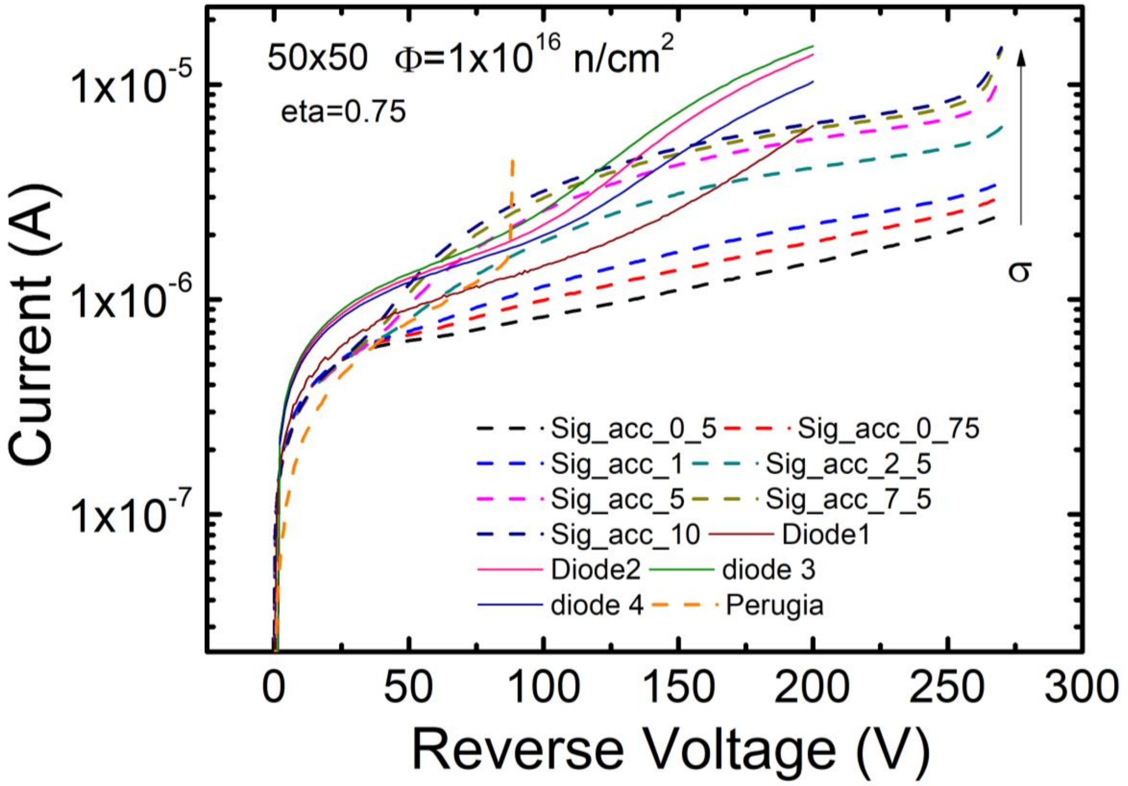


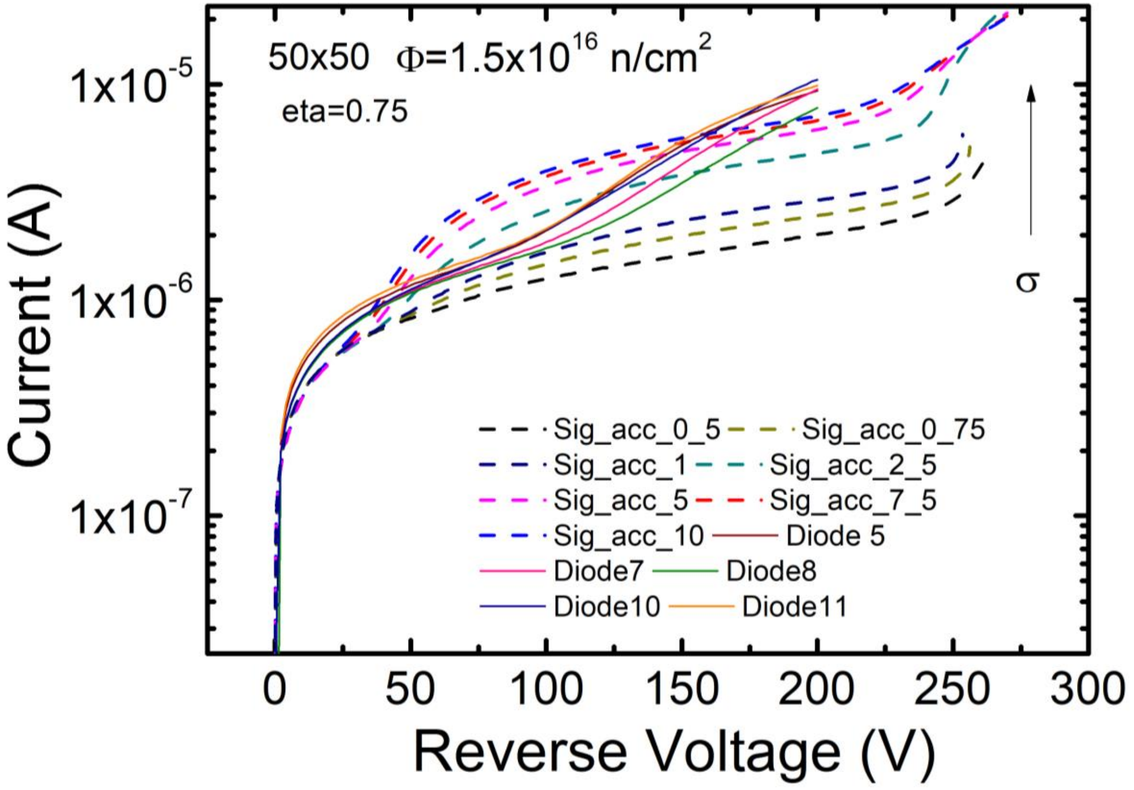
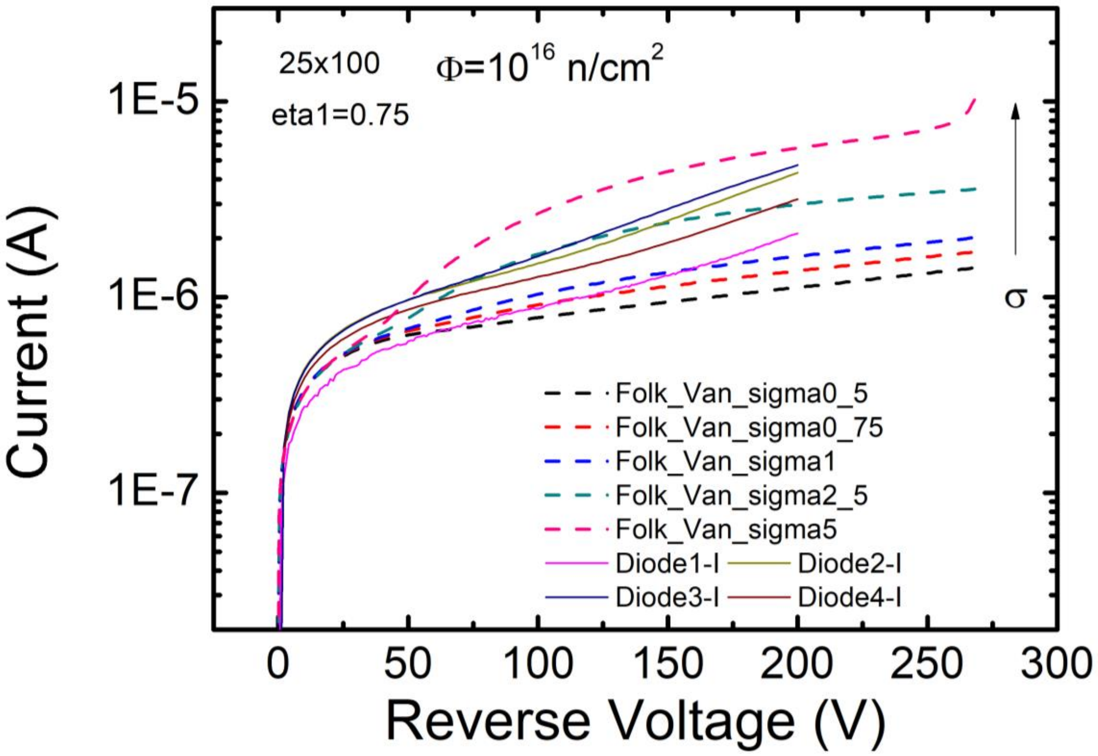


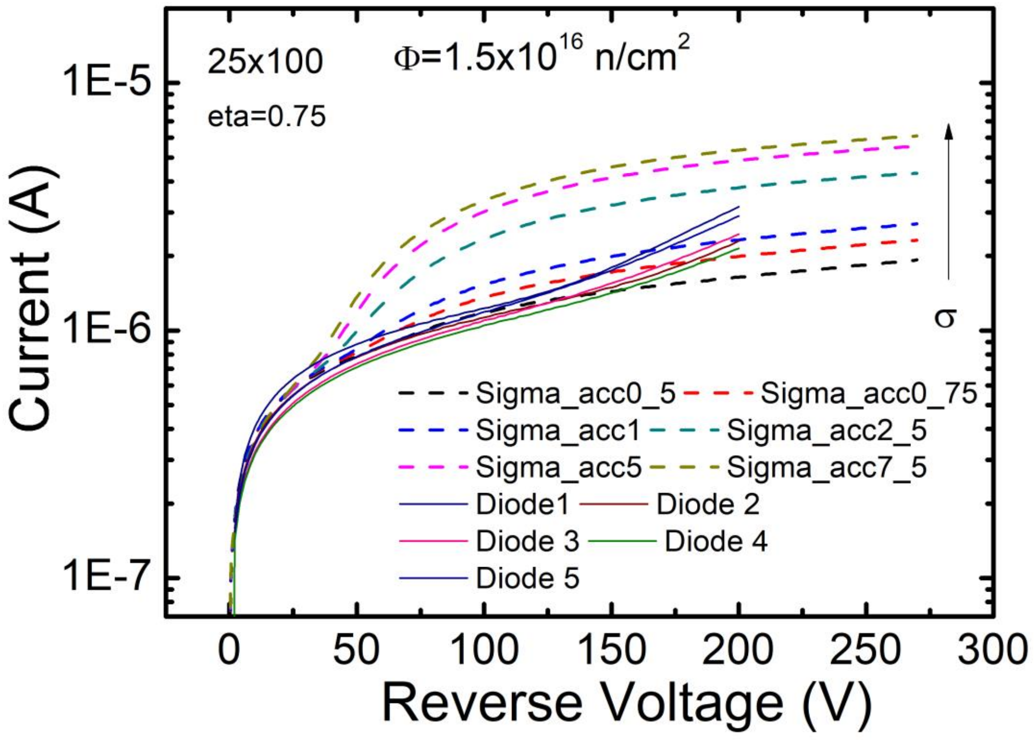
Table 2

Parameters of the proposed radiation damage model. The energy levels are given with respect to the valence band (E_V) or the conduction band (E_C). The model is intended to be used in conjunction with the Van Overstraeten–De Man avalanche model.

Defect number	Type	Energy level [eV]	σ_e [cm^{-2}]	σ_h [cm^{-2}]	η [cm^{-1}]
1	Donor	$E_V + 0.48$	2×10^{-14}	1×10^{-14}	4
2	Acceptor	$E_C - 0.525$	5×10^{-15}	1×10^{-14}	0.75
3	Acceptor	$E_V + 0.90$	1×10^{-16}	1×10^{-16}	36

Impact of varying the sigma acceptor 1





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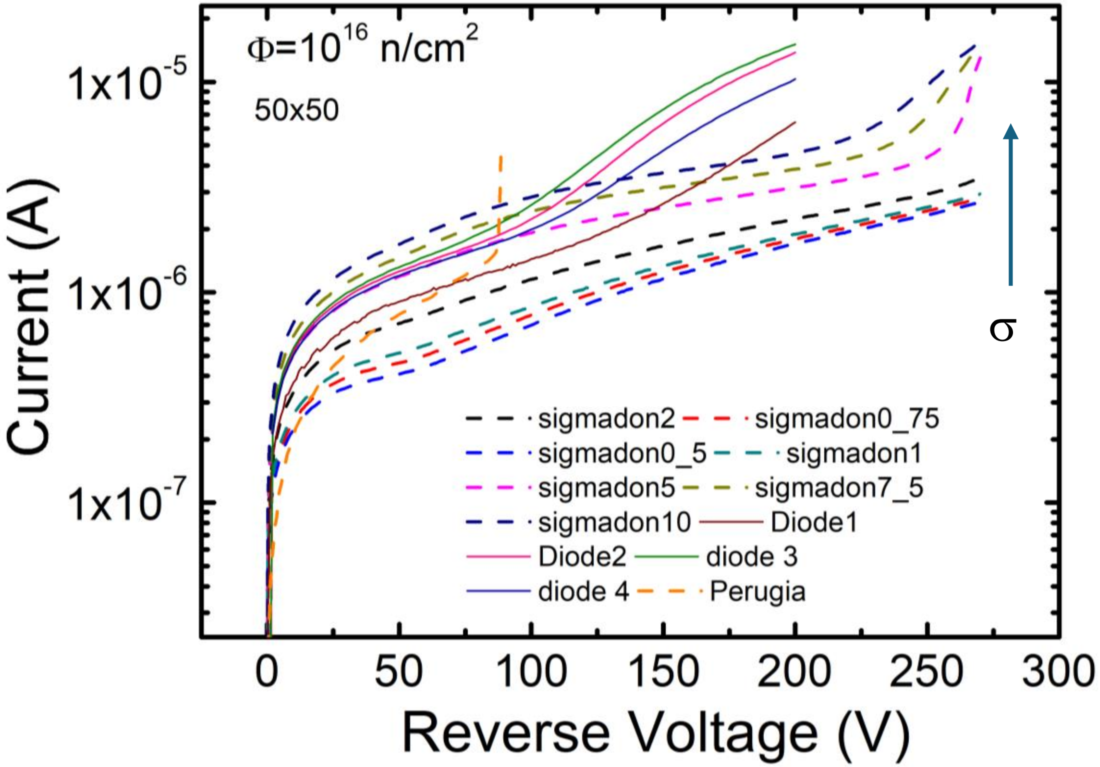
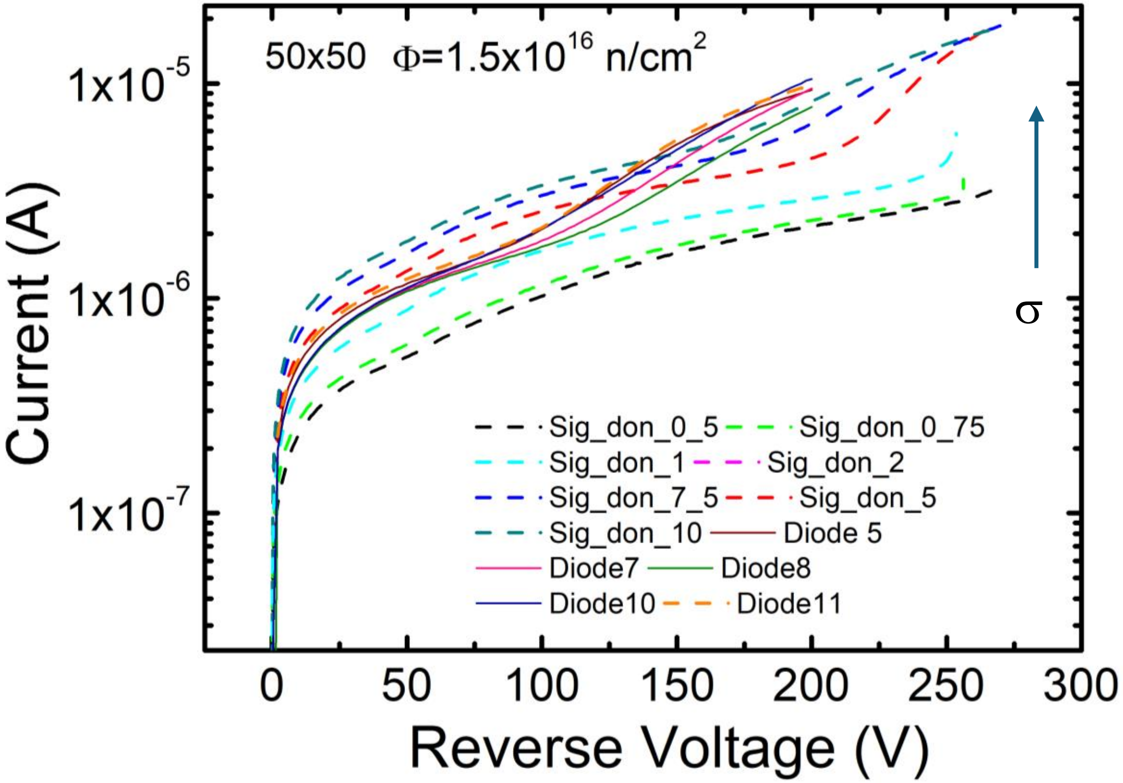
Impact of sigma donor





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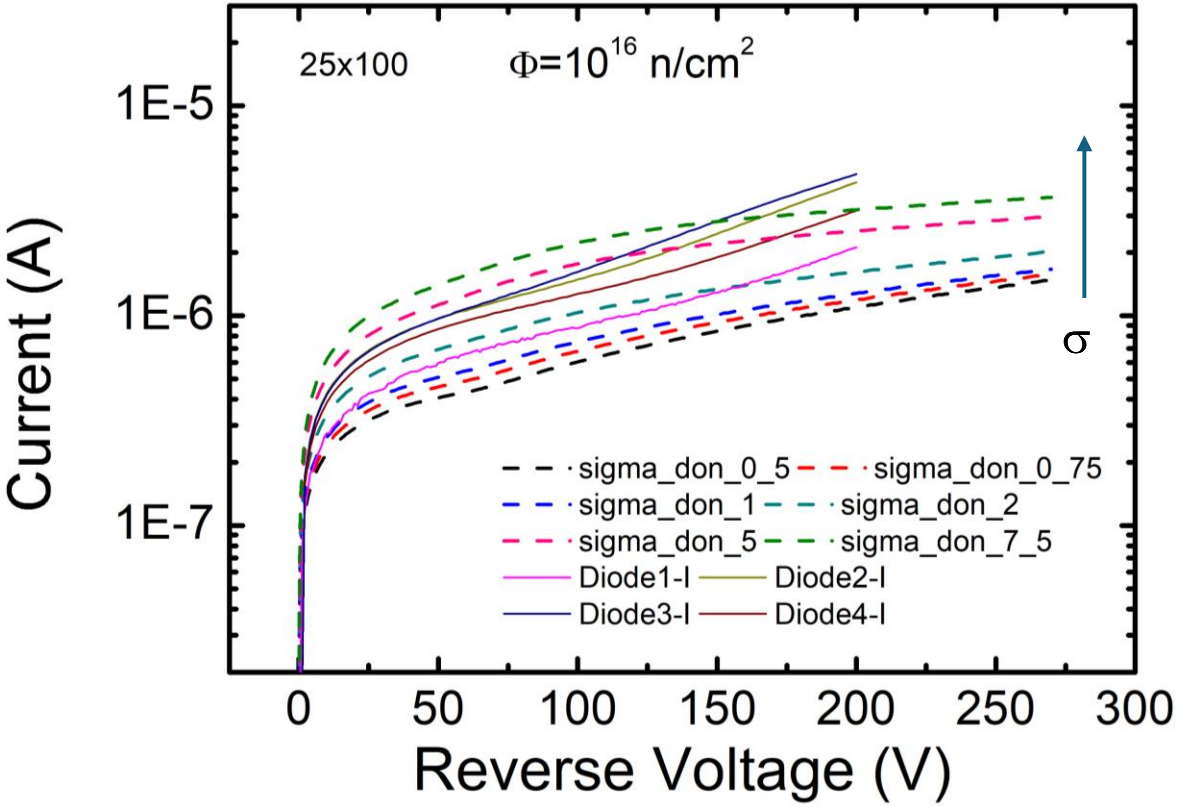
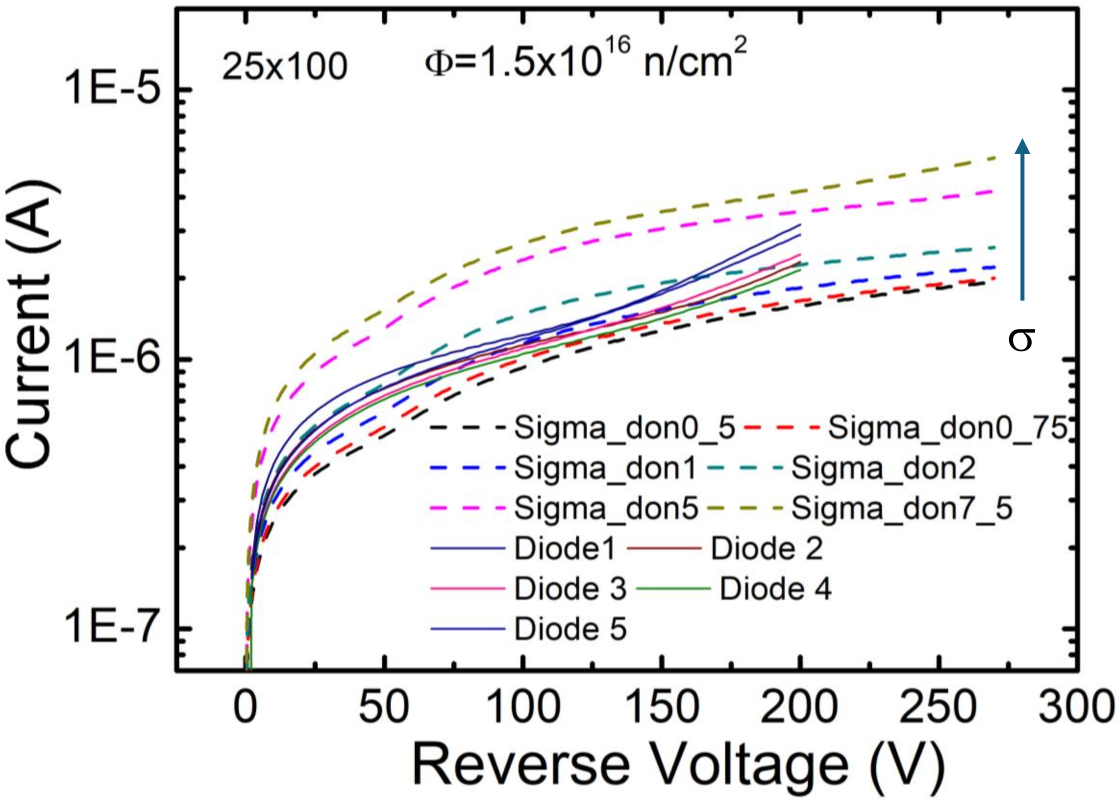
Impact of sigma donor: 25x100





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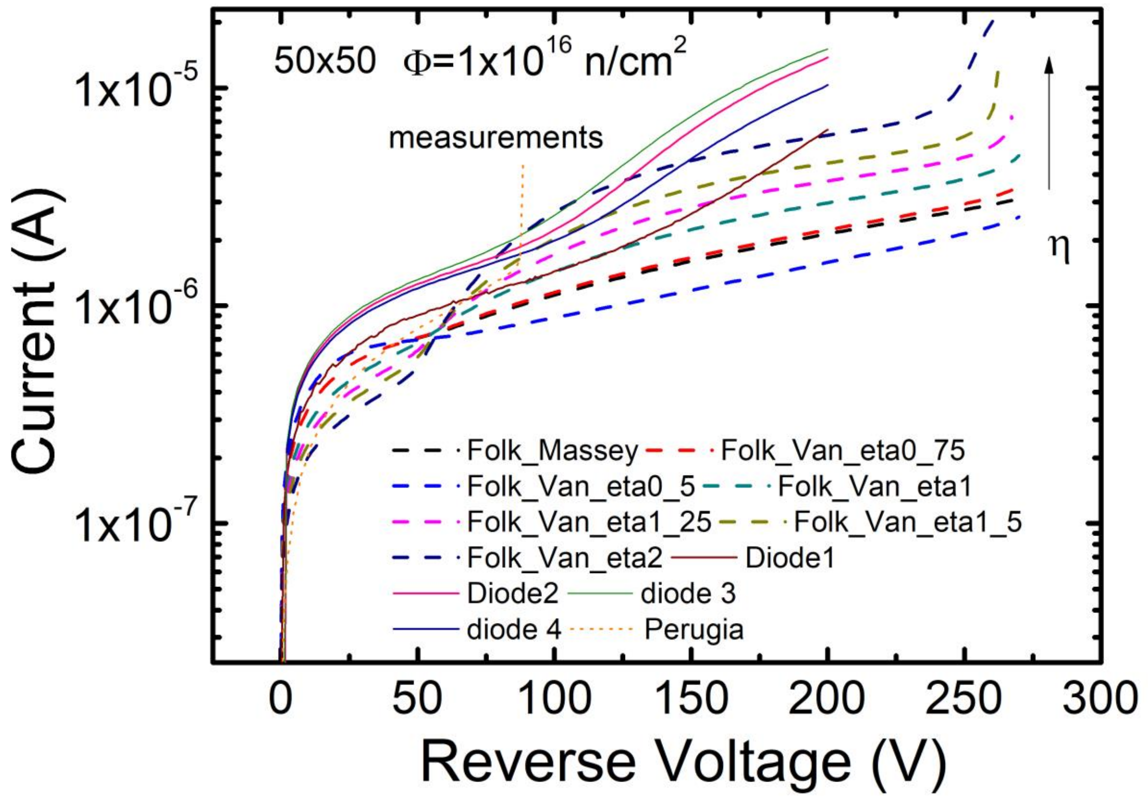
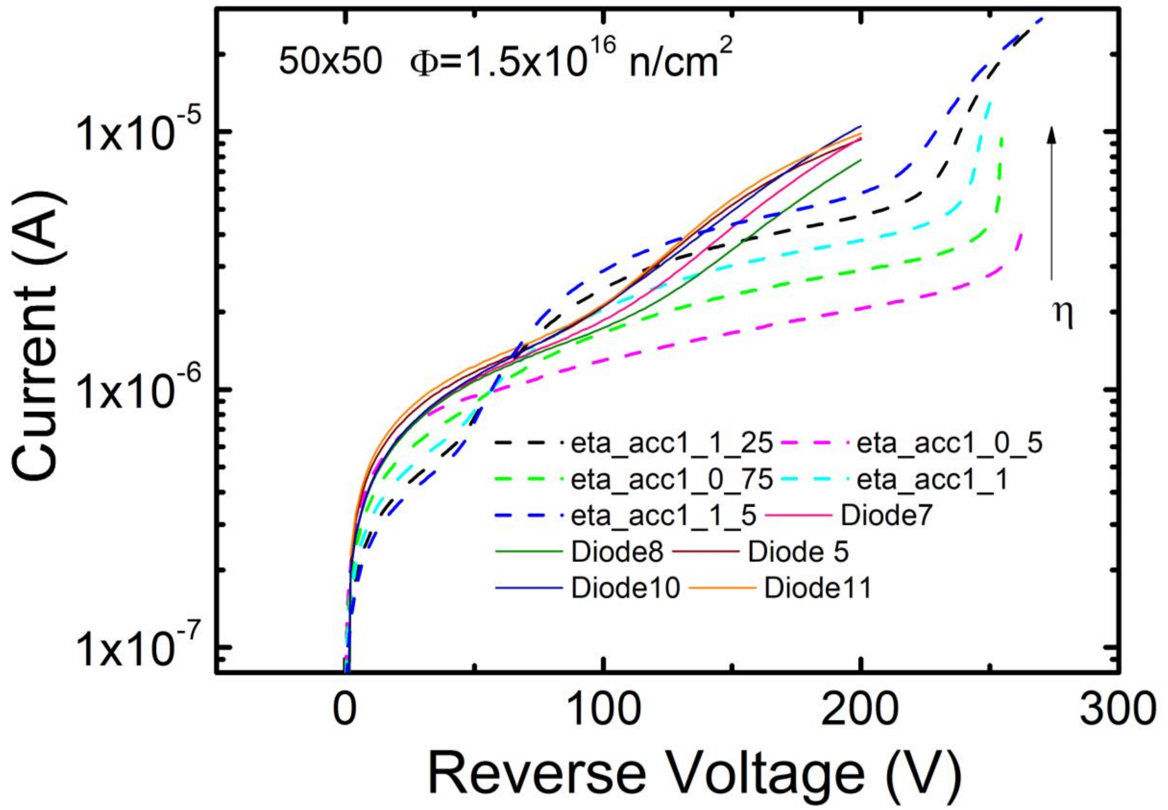
Impact of introduction rate Acc1





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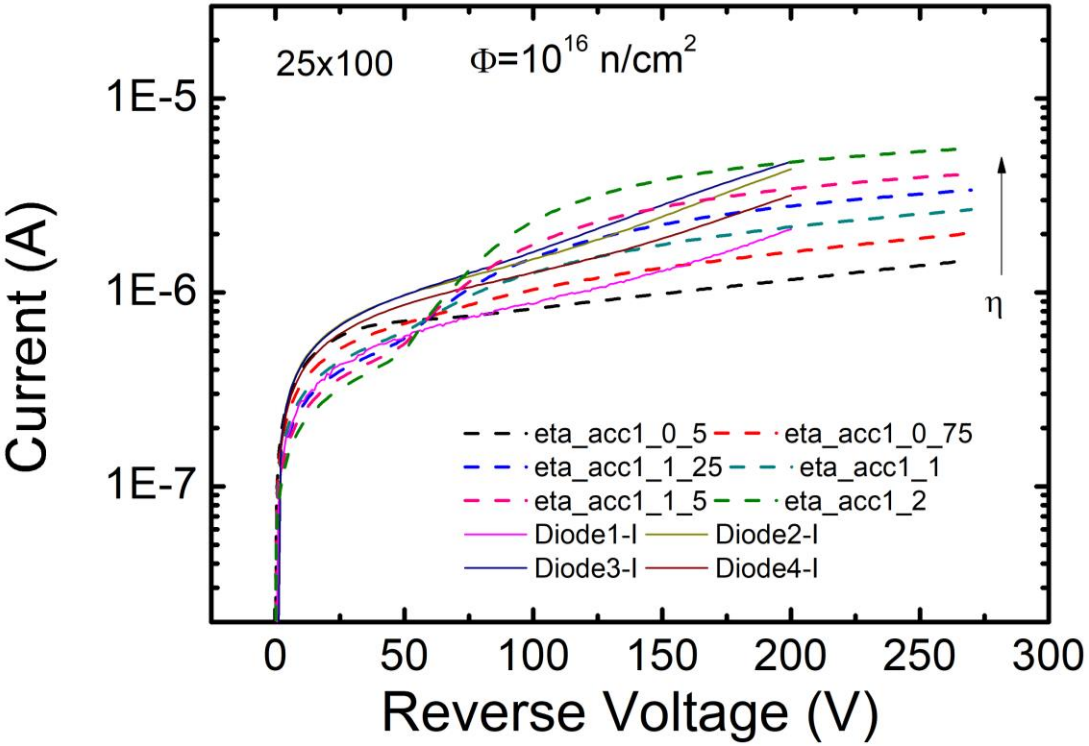
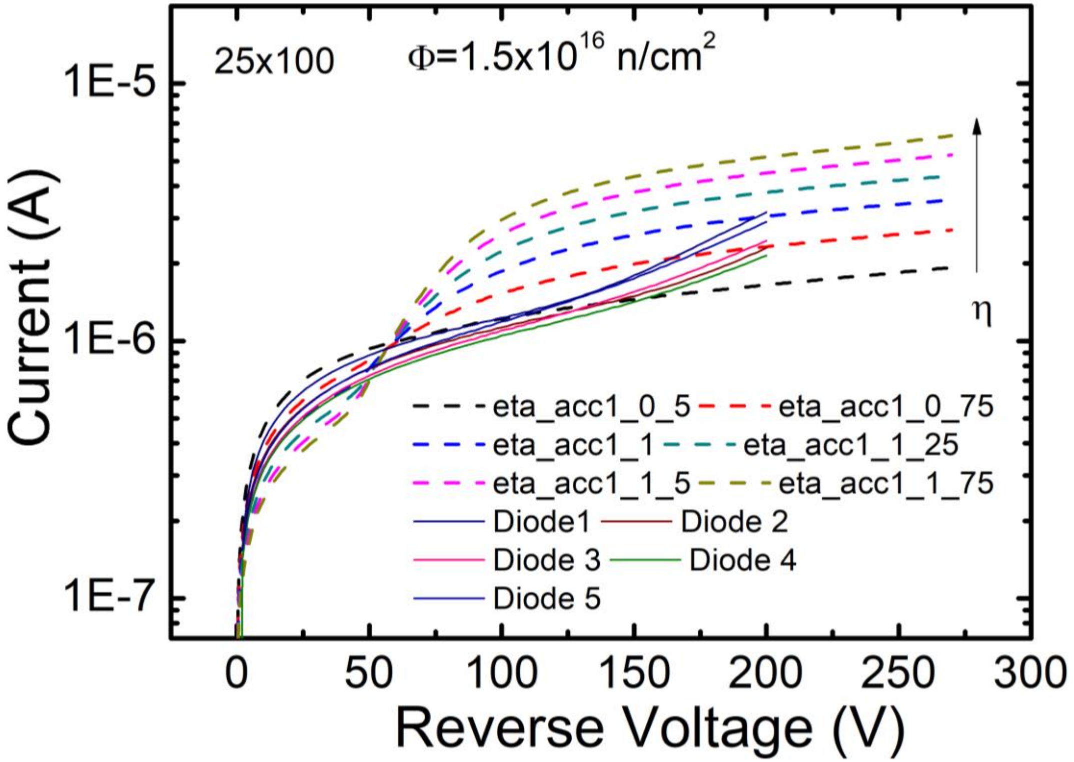
Impact of ntroduction rate Acc1:25x100





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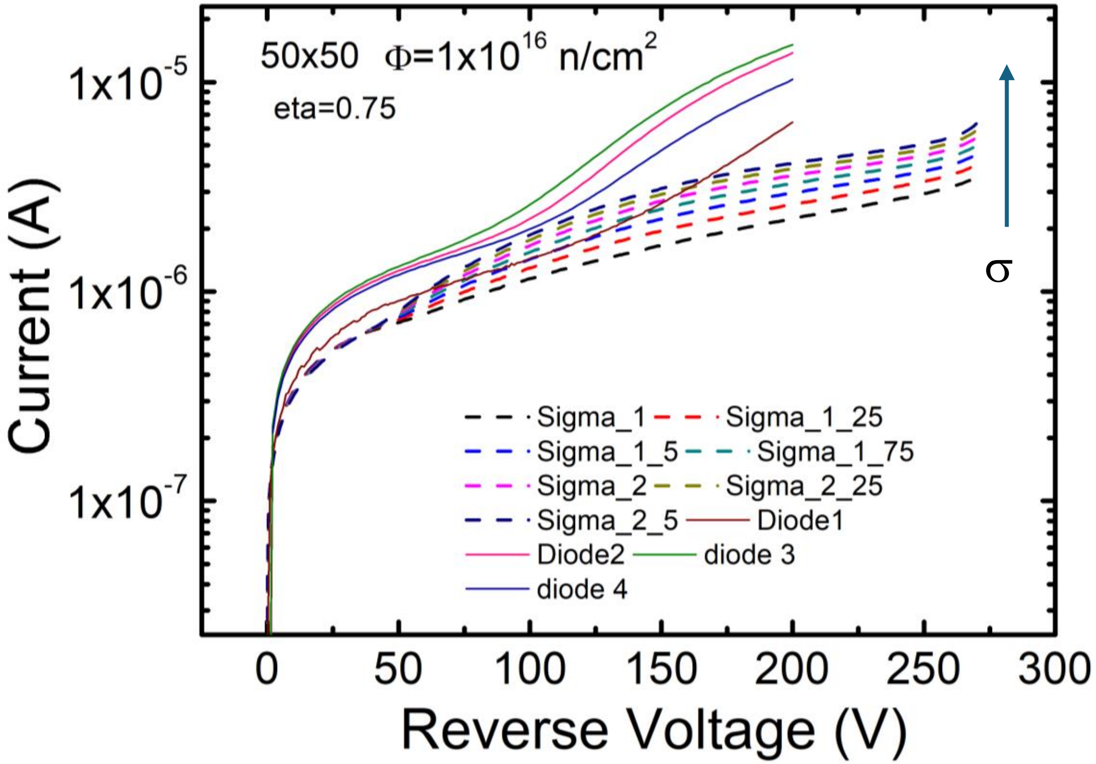
Impact of sigma acceptor 1: refine



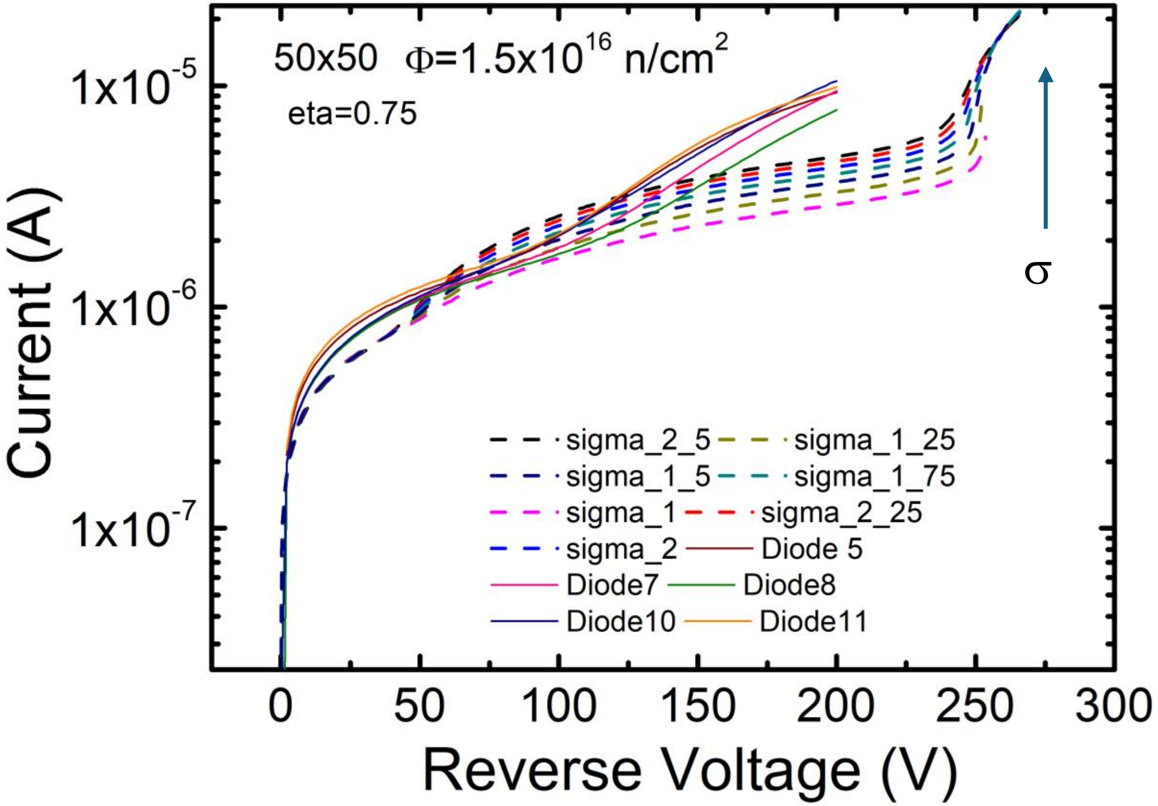
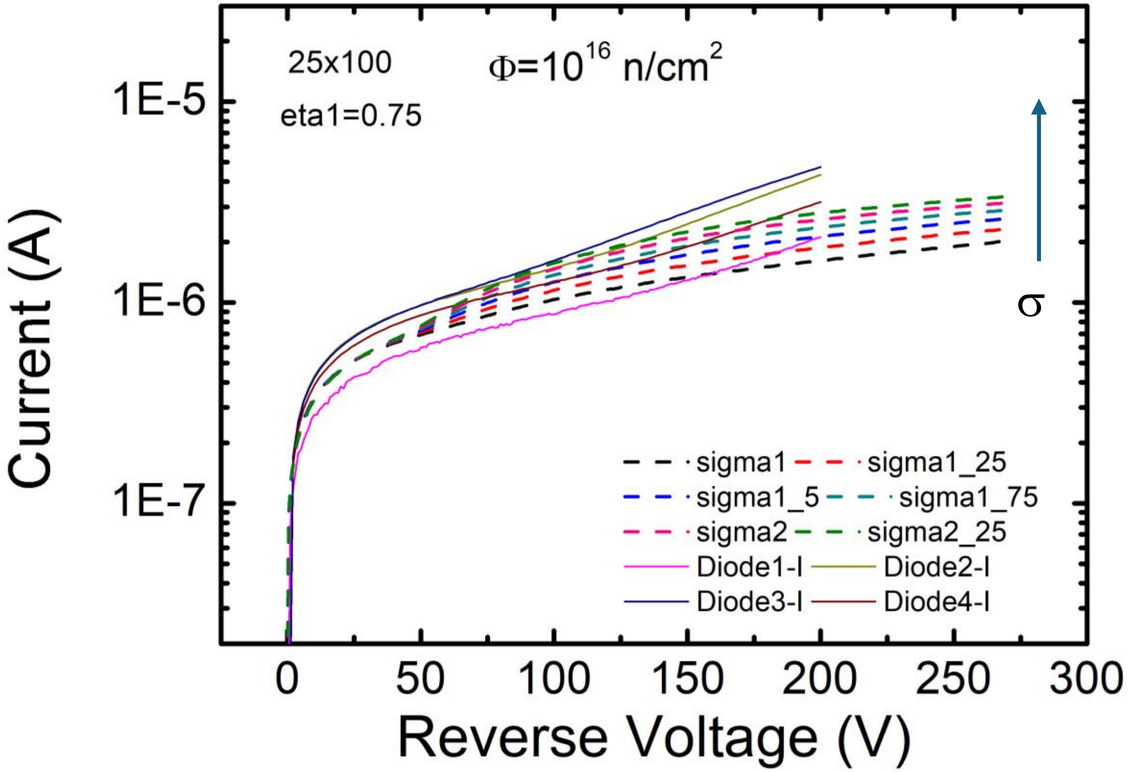
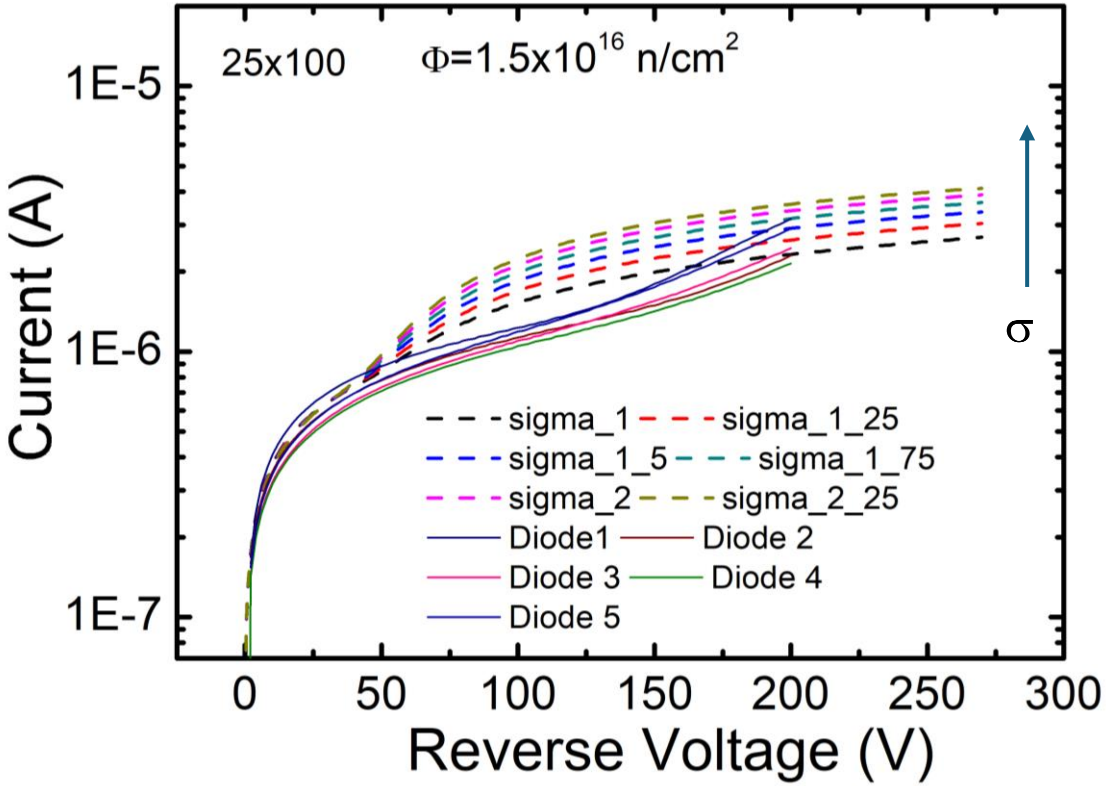


Table 2
Parameters of the proposed radiation damage model. The energy levels are given with respect to the valence band (E_V) or the conduction band (E_C). The model is intended to be used in conjunction with the Van Overstraeten–De Man avalanche model.

Defect number	Type	Energy level [eV]	σ_e [cm^{-2}]	σ_h [cm^{-2}]	η [cm^{-1}]
1	Donor	$E_V + 0.48$	2×10^{-14}	1×10^{-14}	4
2	Acceptor	$E_C - 0.525$	5×10^{-15}	1×10^{-14}	0.75
3	Acceptor	$E_V + 0.90$	1×10^{-16}	1×10^{-16}	36

Impact of sigma acceptor 1 refine





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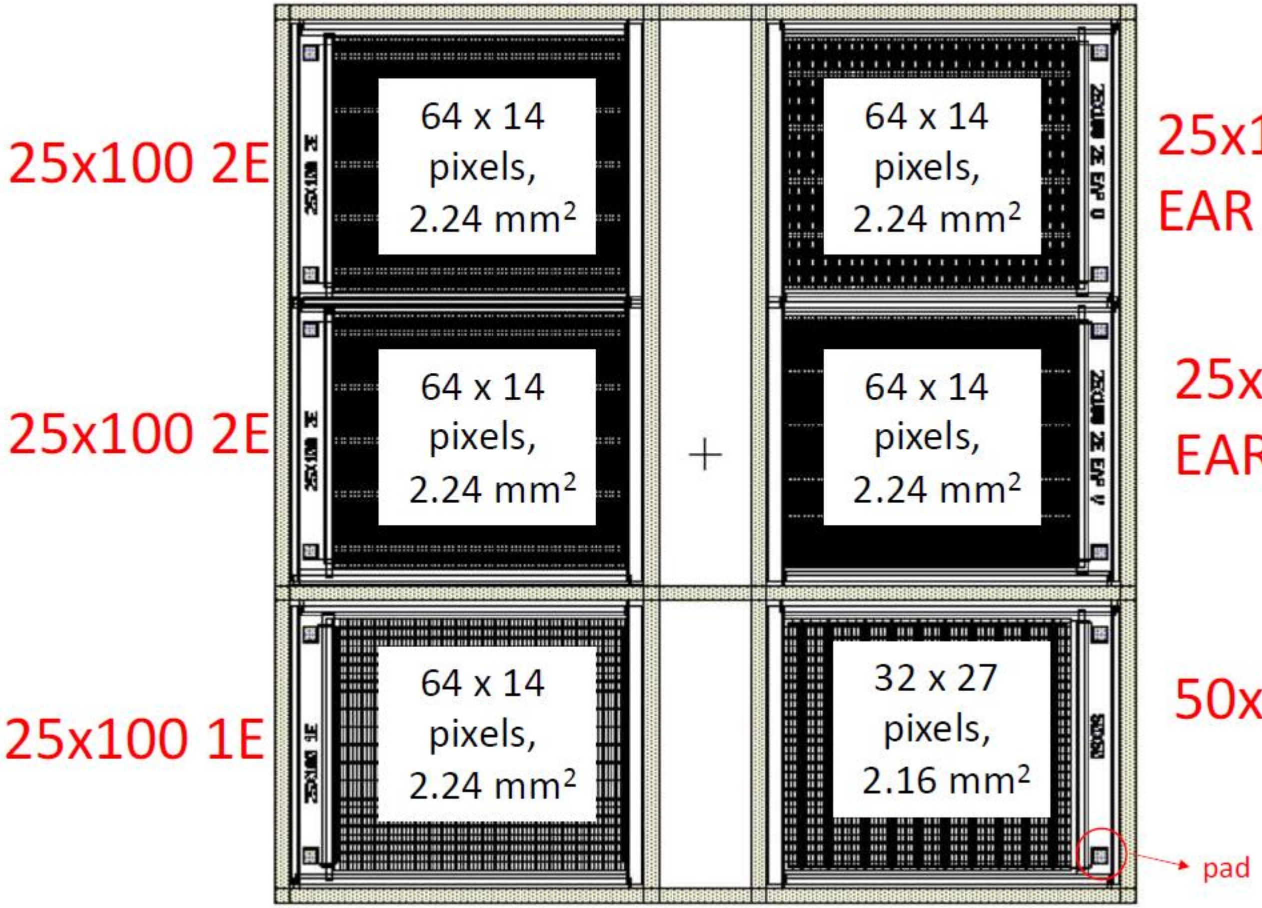
3D diodes from Trento



Irradiated with neutrons at:

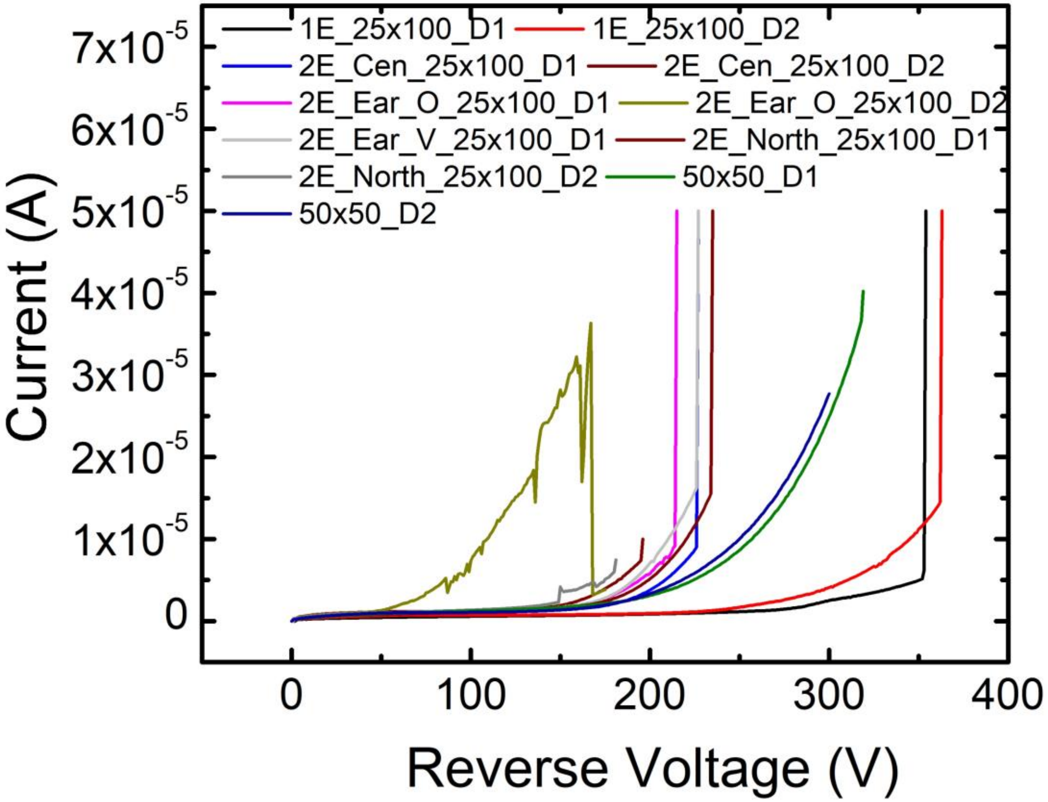
- $1x10^{16}$ n_{eq}/cm^2 (2 blocks)
- $2.5x10^{16}$ n_{eq}/cm^2 (6 blocks)

IV measurements 3D diodes

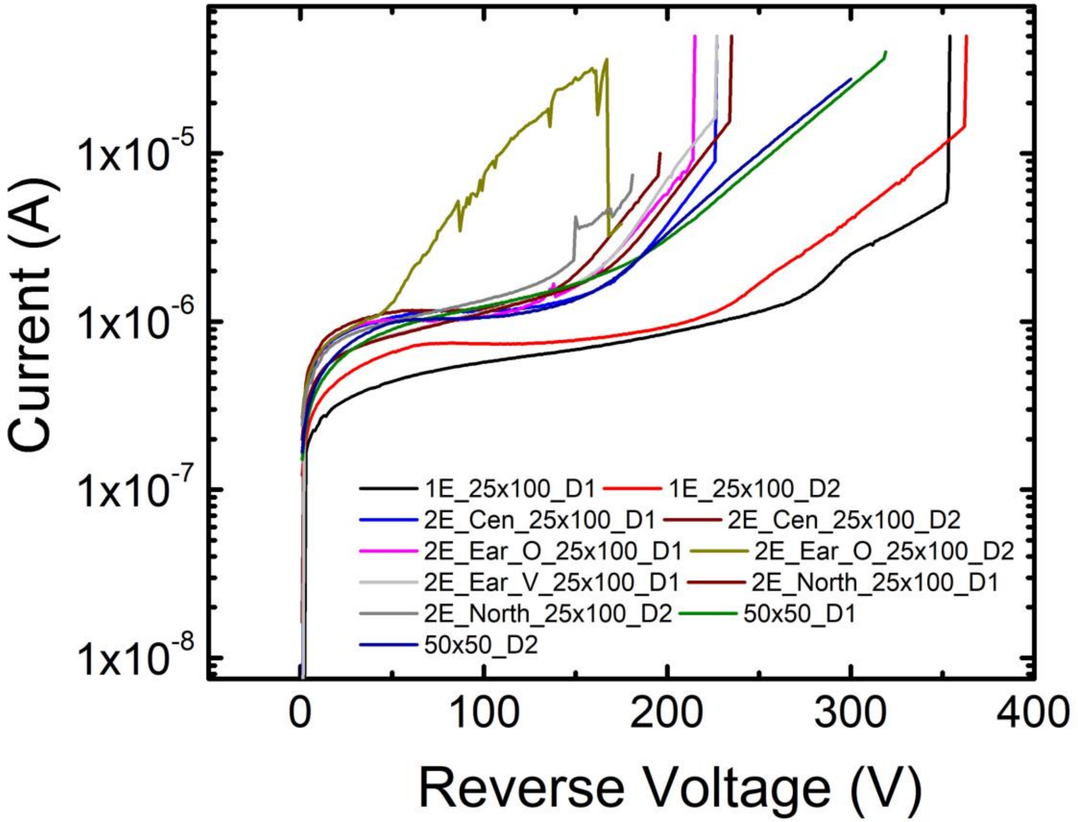
Step 1 V
Delay 2s
T=-25 °C
Compliance max=50 uA

$\Phi = 1\times10^{16}$ n/cm^2

Linear scale



Log scale

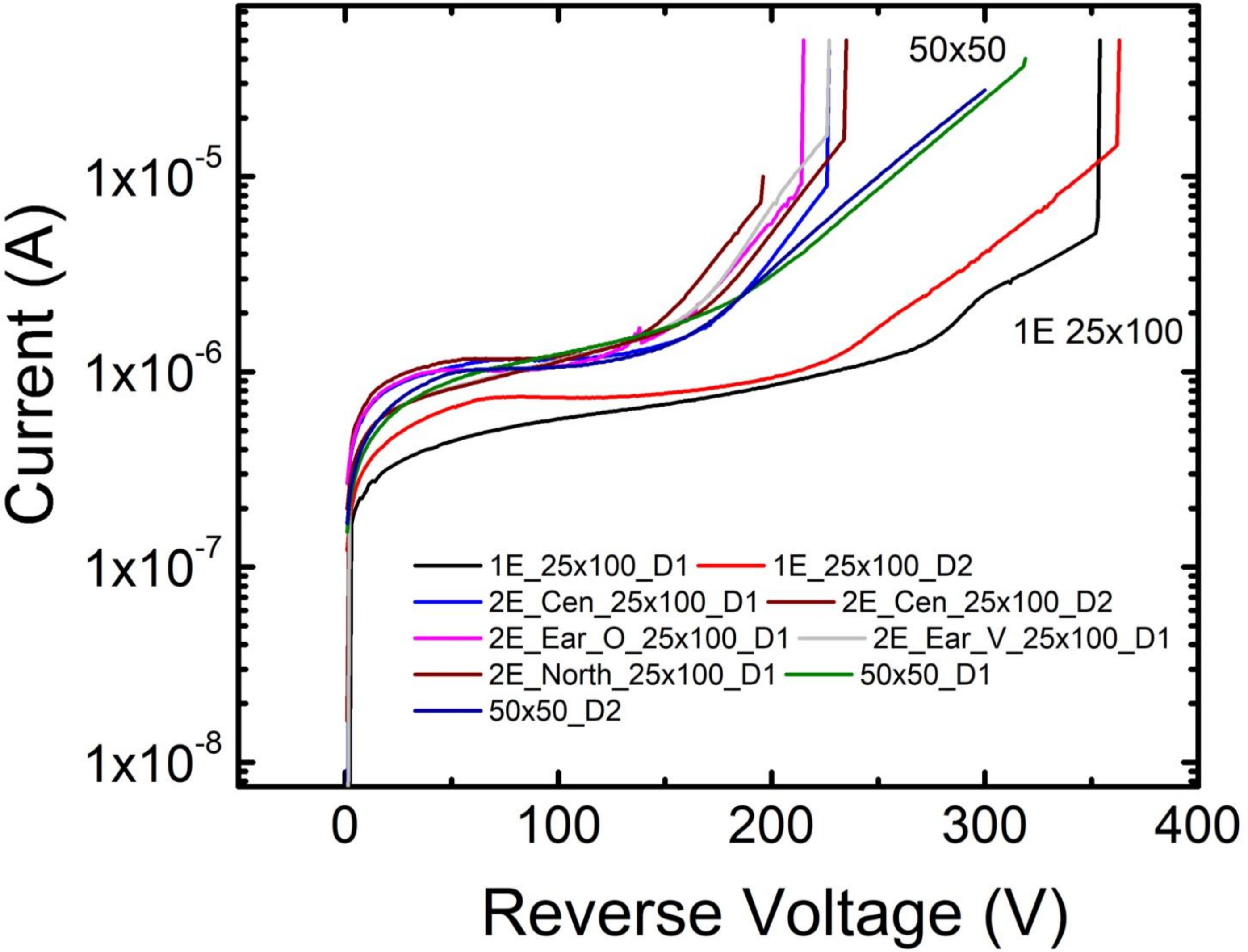


IV: 50x50 and 1 E 25x100 3D diodes

V_{BD} for 50x50 structures is over 300 V

V_{BD} for 1 E 25x100 structures is near 350 V.

$\Phi = 1 \times 10^{16}$ n/cm^2



Next steps: Test structures from Trento

I-V and C-V measurements to carry out in Perugia on different test structures (3D diode, 3D strip, 3D array)

Irradiated with neutrons at:

- $5x10^{16}$ n_{eq}/cm^2 (8 blocks), label "1984"
- $1x10^{17}$ n_{eq}/cm^2 (8 blocks), label "1985"

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 parameterizations)

- ✓ 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, AC and gain behavior well reproduced (but **pay attention** to the **impact ionization model**)

- ✓ **Simulation of 3D detectors** (in collaboration **with Trento group** for 3D detectors modelling)
  - **CERN model** seems able to reproduce the IV characteristics of measured 3D, with a little variation of the defect parameters.
  - New measurements in Perugia on 3D detectors and test structures in the range 1-2.5×10^{16} n/cm^2. New simulations to compare with experimental data.
  - **To measure**: **DC behavior** and **laser response** of **3D** and **trenched-3D** detectors, before and after irradiation (up to the fluence of 2,5E16 n_{eq}/cm^2)