16th (Virtual) Workshop on Advanced Silicon Radiation Detectors
Trento, Italy. February 16-18 2021

TCAD numerical simulation of irradiated Low-Gain Avalanche Diodes

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Outline

- Motivations
- TCAD simulation of LGAD devices
  - ☐ Layout and doping profile
  - ☐ Physical models (e.g. avalanche) and parameters
- Methodology
  - ☐ Static (DC) and small-signal (AC) behavior
  - ☐ Transient response
- Application of the developed model (e.g. thin LGADs)

Motivations

- ✓ **L**ow-**G**ain **A**valanche **D**iode (**LGAD**)
- ✓ The **intrinsic multiplication of the charge** allows **to improve the signal to noise ratio**

  => limitation of its drastic **reduction with fluence**.
- ✓ Most promising devices **to cope with the high fluences** expected **in the future HEP experiments.**
- ✓ **Device-level simulation tools**[1] **for predicting** the electrical behaviour and the charge collection properties **up to the highest particle fluences**.
- ✓ **Implementation** of a proper **radiation damage model** within the simulation environment.

[1] Synopsys© Sentaurus TCAD

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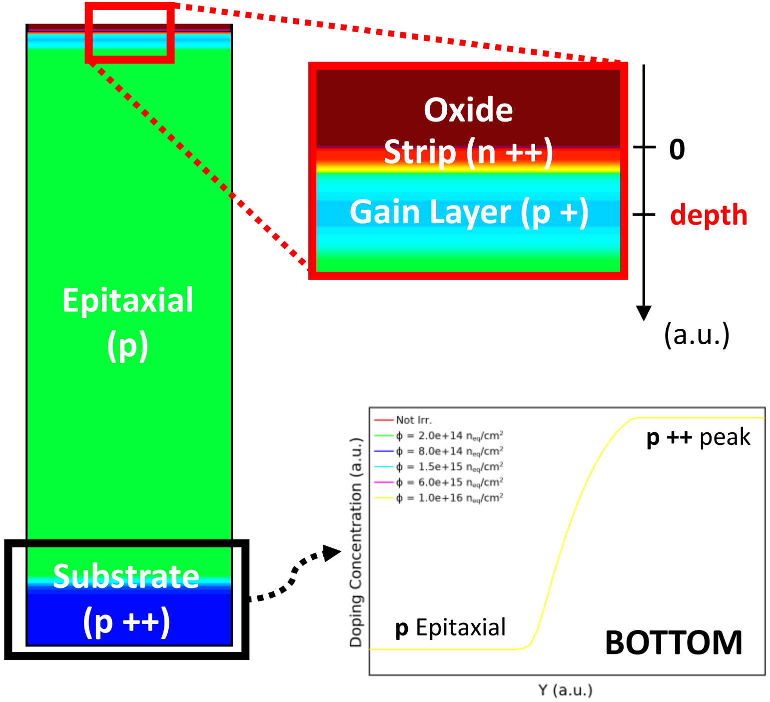
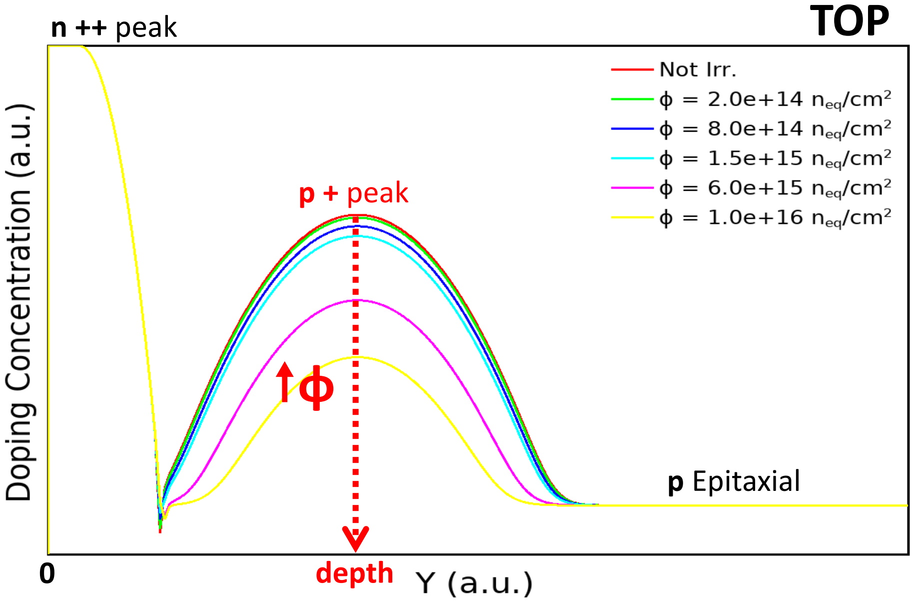
TCAD simulation of LGAD devices (1/2)

✓ **Layout** and **doping profile**





TCAD simulation of LGAD devices (2/2)

- ✓ Physical models
- ✓ **Generation/Recombination rate**
  - Shockley-Read-Hall (SRH), Band-To-Band Tunneling (BTBT), Auger
  - **Avalanche Generation**
    => impact ionization models, such as *van Overstraeten-de Man*, *Okuto-Crowell*, *Massey*[2], *UniBo*
- ✓ **Carriers mobility variation** doping and field dependent
- ✓ **Physical parameters**
  - e-/h+ recombination lifetime
  - surface recombination velocity

- ✓ Radiation damage models
- ✓ **“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

- **G**ain **L**ayer (**GL**)
- **c**, removal rate, evaluated using the **Torino parameterization**[4]

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[2] M. Mandurrino et al., *Numerical Simulation of Charge Multiplication in Ultra-Fast Silicon Detectors (UFSD) and Comparison with Experimental Data*, IEEE, 2017

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

[4] see M. Ferrero talk

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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
- **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

Transient analysis

- For each DC bias step, one **Time-Variant (TV)** simulation of impinging particle (**MIP**), following the **"HeavyIon" model**
  - instant of penetration, 1ns
  - impinging point, 10 µm
  - through the whole device
  - Linear Energy Transfer (LET)

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

where

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

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

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**

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

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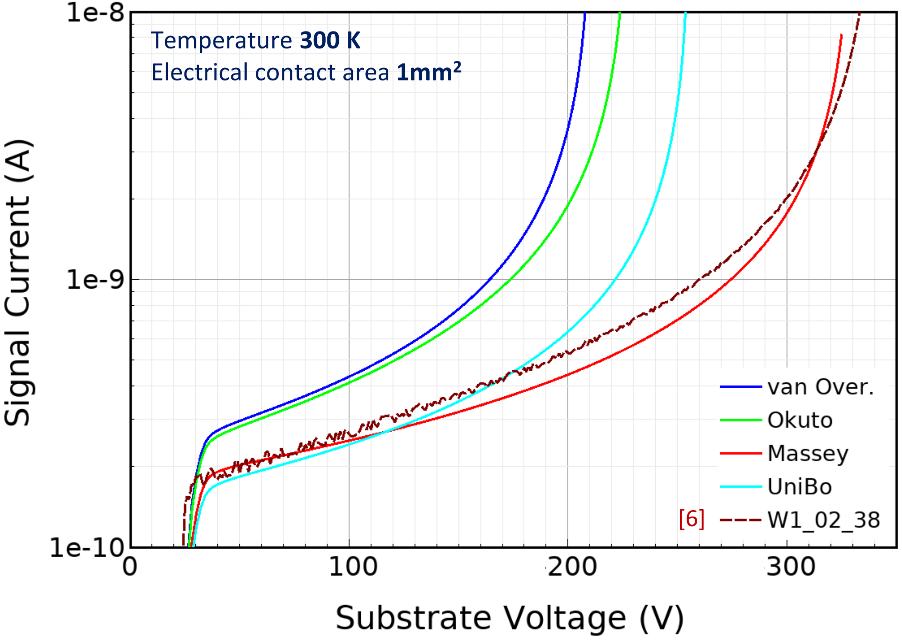
[5] S. Meroli et al., *Energy loss measurement for charged particles in very thin silicon layers*, JINST 6 P06013, 2011

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

Analysis of different avalanche models

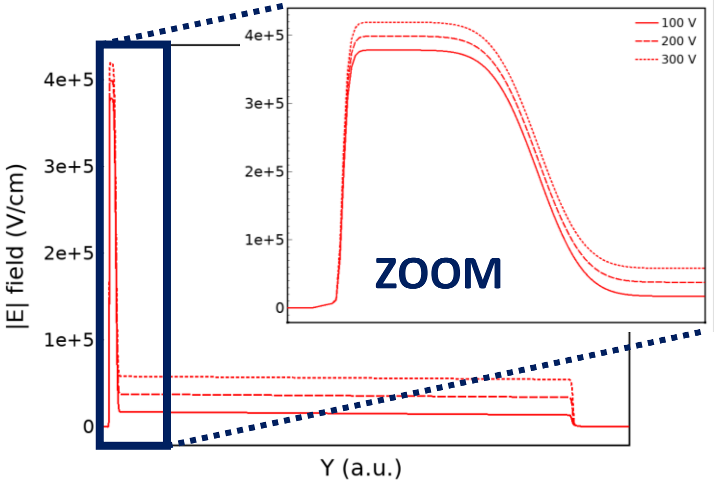
- ✓ **Simulation** results, **before irradiation**

I-V



Good agreement
with experimental **data**
for **Massey model**

Cut of the electric field for different V_{bias}

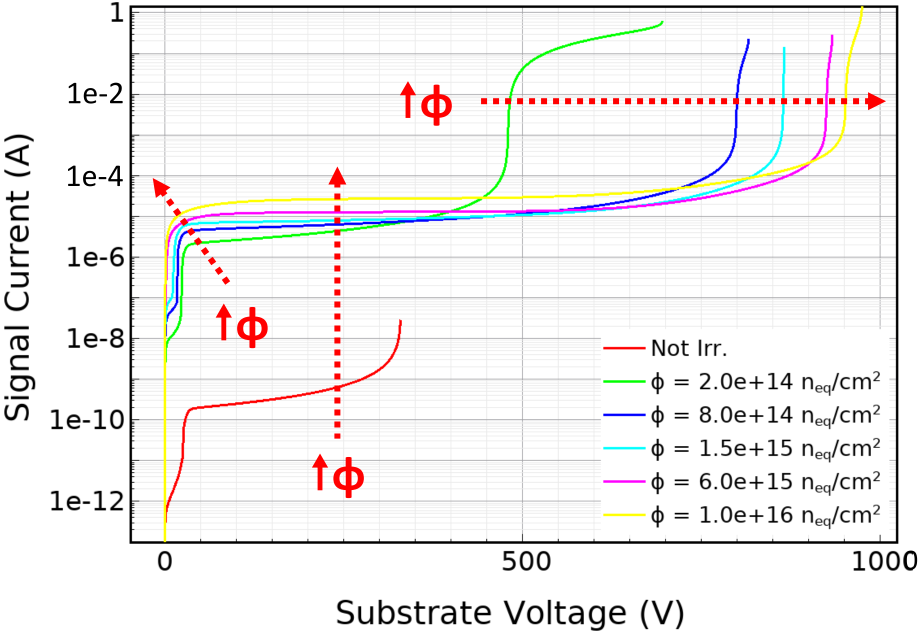


[6] V. Sola et al., *First FBK production of 50 μm ultra-fast silicon detectors*, Nucl. Instrum. Methods Phys. Res. A, 2019

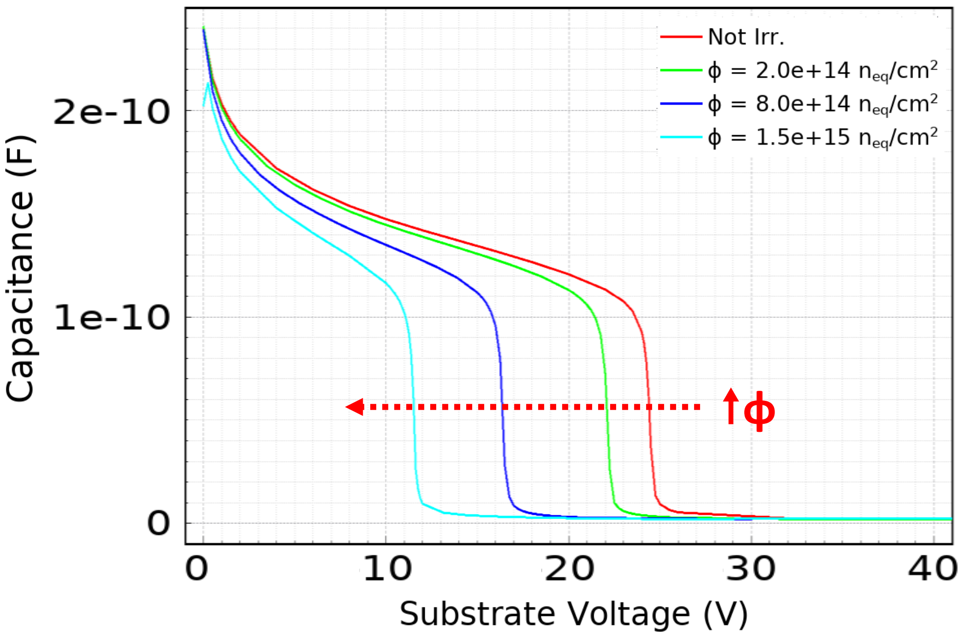
Static (DC) and small-signal (AC) behavior (1/6)

- ✓ **Simulation** results, **before** and **after irradiation**

I-V



C-V



Massey model. Temperature **300 K**. Electrical contact area **1mm²**

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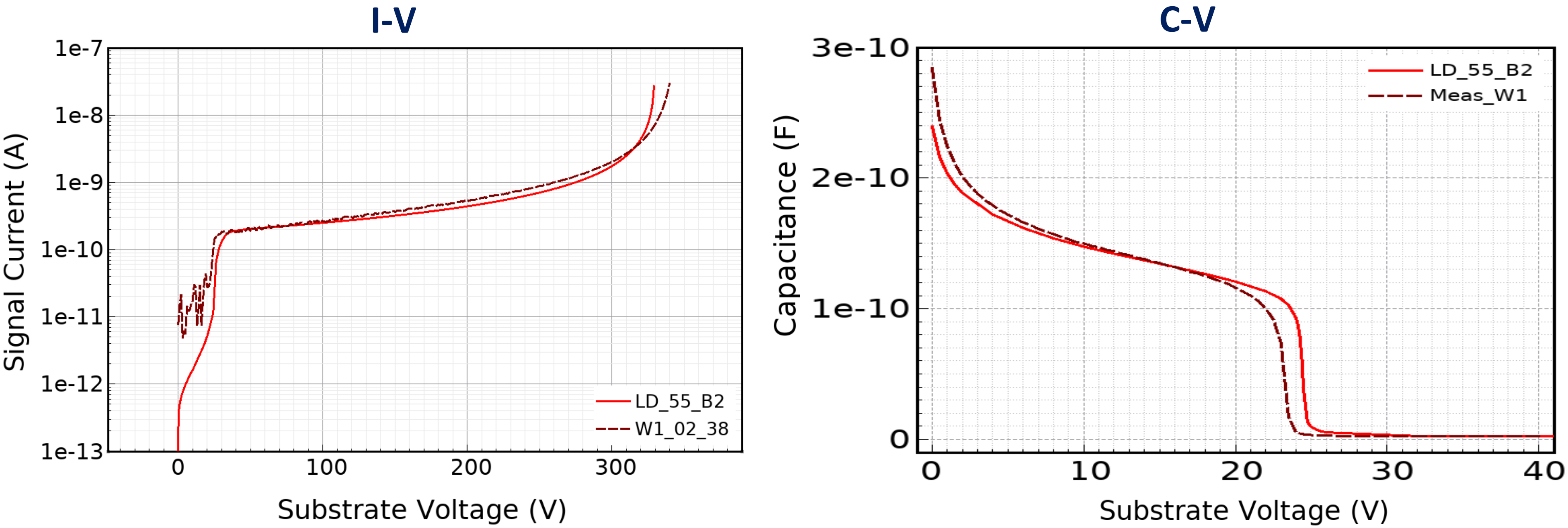
Static (DC) and small-signal (AC) behavior (2/6)

- ✓ **Comparison** with **experimental data, before irradiation**

Good agreement!

I-V **C-V**



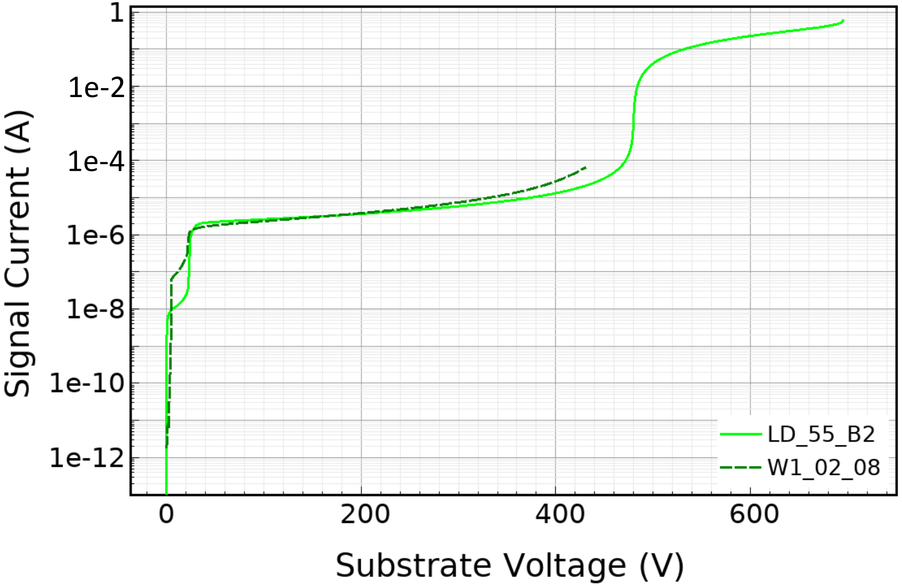
Massey model. Temperature **300 K**. Electrical contact area **1mm²**

Static (DC) and small-signal (AC) behavior (3/6)

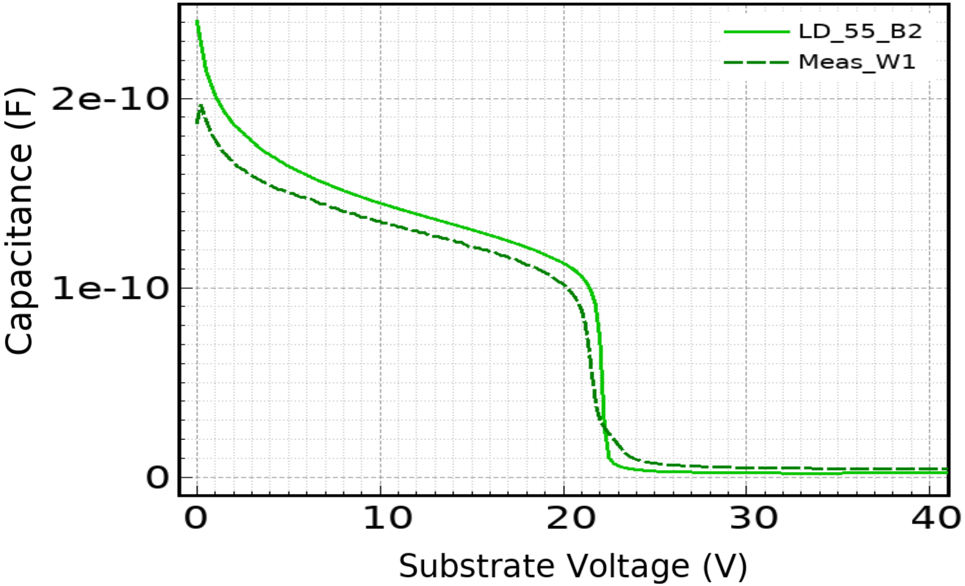
✓ **Comparison** with **experimental data**, fluence **2.0e14 n_{eq}/cm^2**

Good agreement!

I-V



C-V



Massey model. Temperature **300 K**. Electrical contact area **$1mm^2$**

INFN

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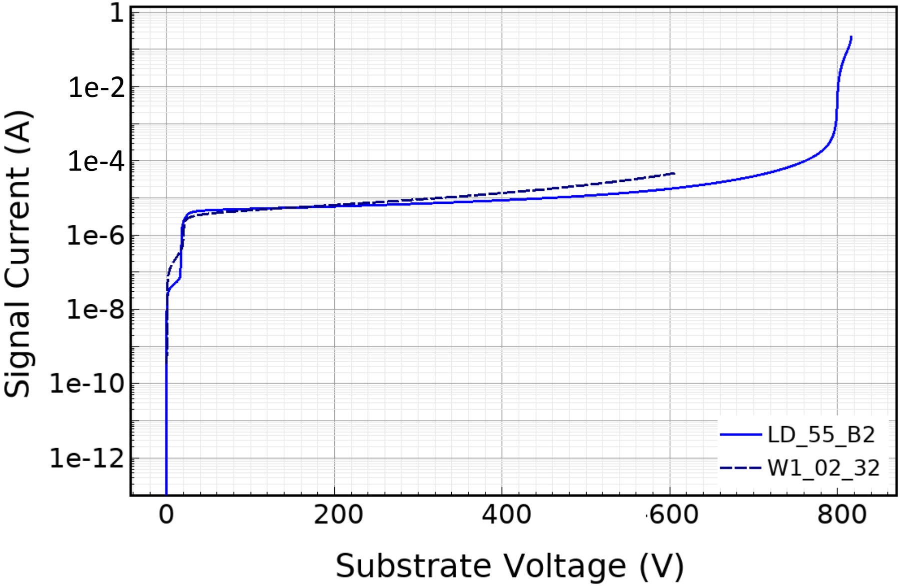
Static (DC) and small-signal (AC) behavior (4/6)

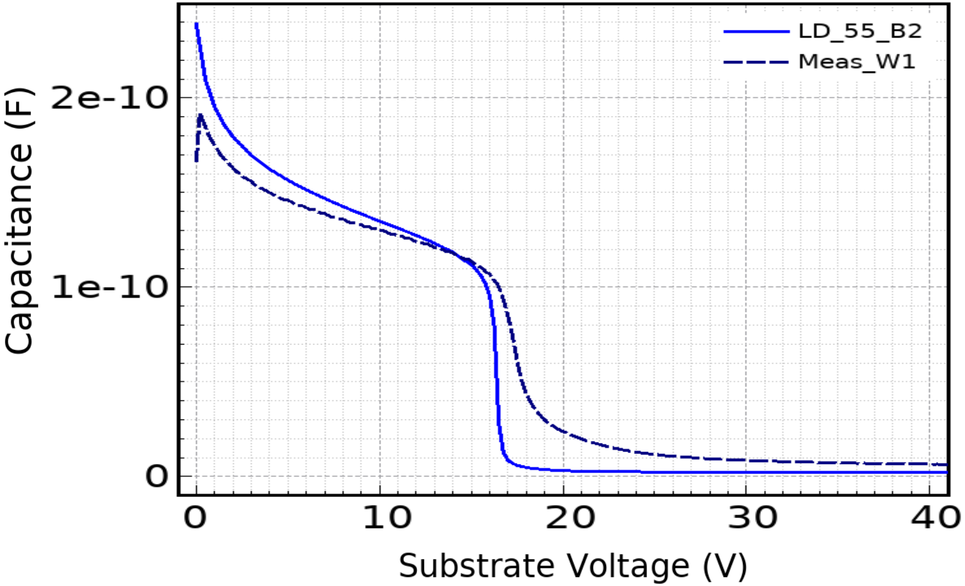
✓ **Comparison** with **experimental data**, fluence **8.0e14 n_{eq}/cm^2**

Good agreement!

I-V



C-V



Massey model. Temperature **300 K**. Electrical contact area **1mm²**

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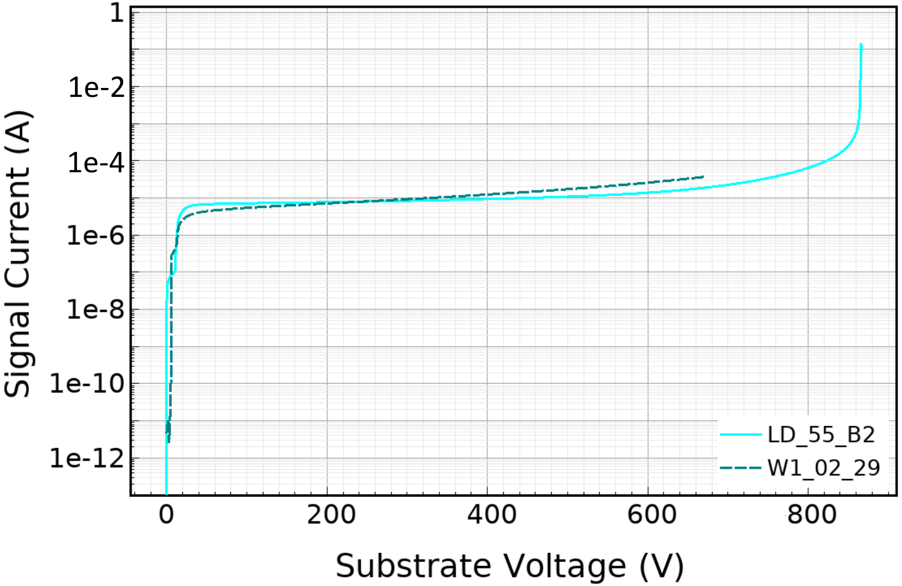
Static (DC) and small-signal (AC) behavior (5/6)

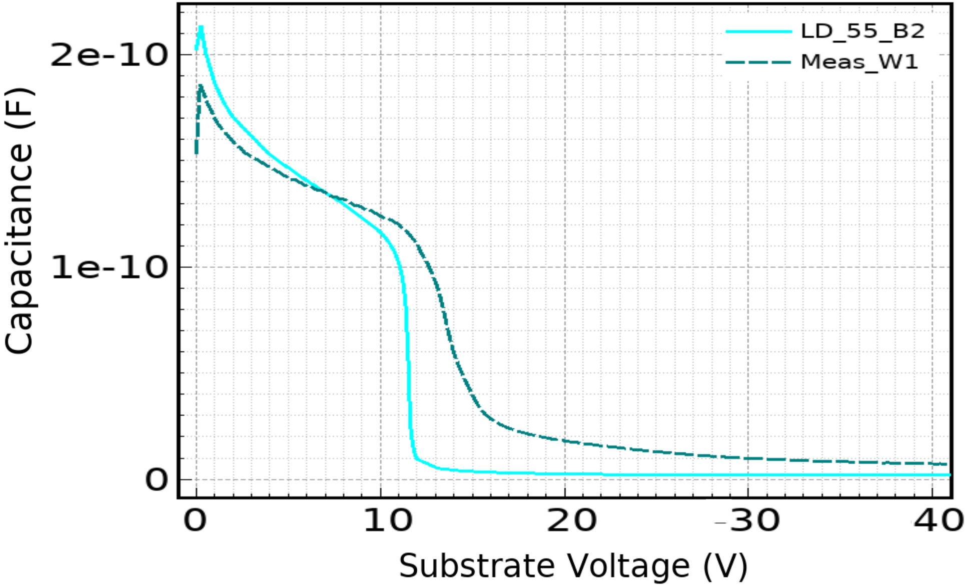
✓ **Comparison** with **experimental data**, fluence **1.5e15 n_{eq}/cm^2**

Good agreement!

I-V



C-V



Massey model. Temperature **300 K**. Electrical contact area **1mm^2**

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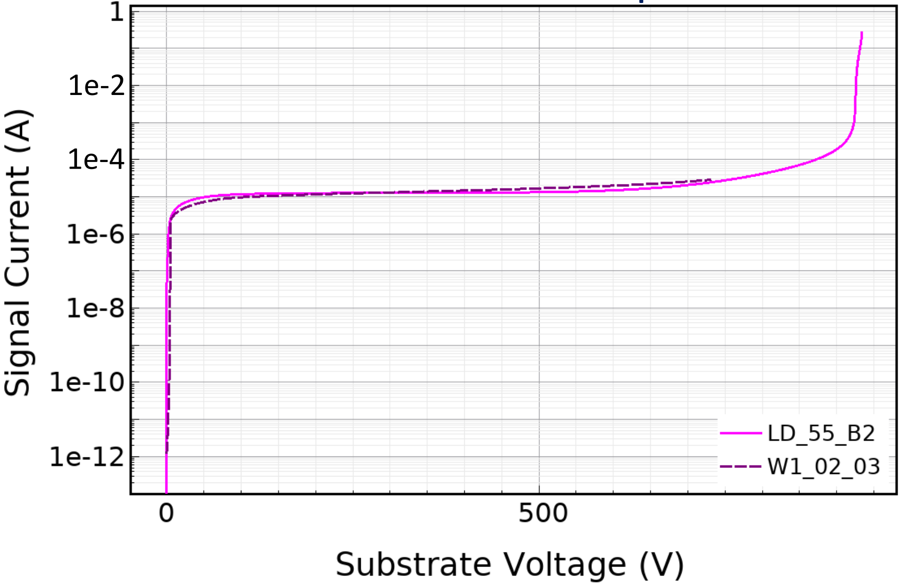
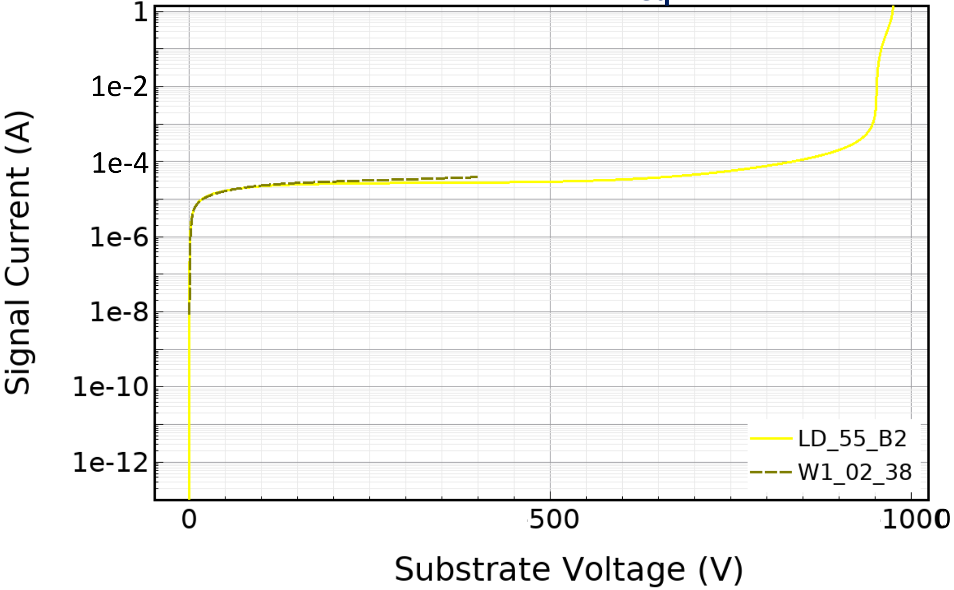
Static (DC) and small-signal (AC) behavior (6/6)

✓ **Comparison** with **experimental data, after irradiation**

Good agreement!



I-V, fluence **6.0e15 n_{eq}/cm^2**



I-V, fluence **1.0e16 n_{eq}/cm^2**

Massey model. Temperature **300 K**. Electrical contact area **1mm²**

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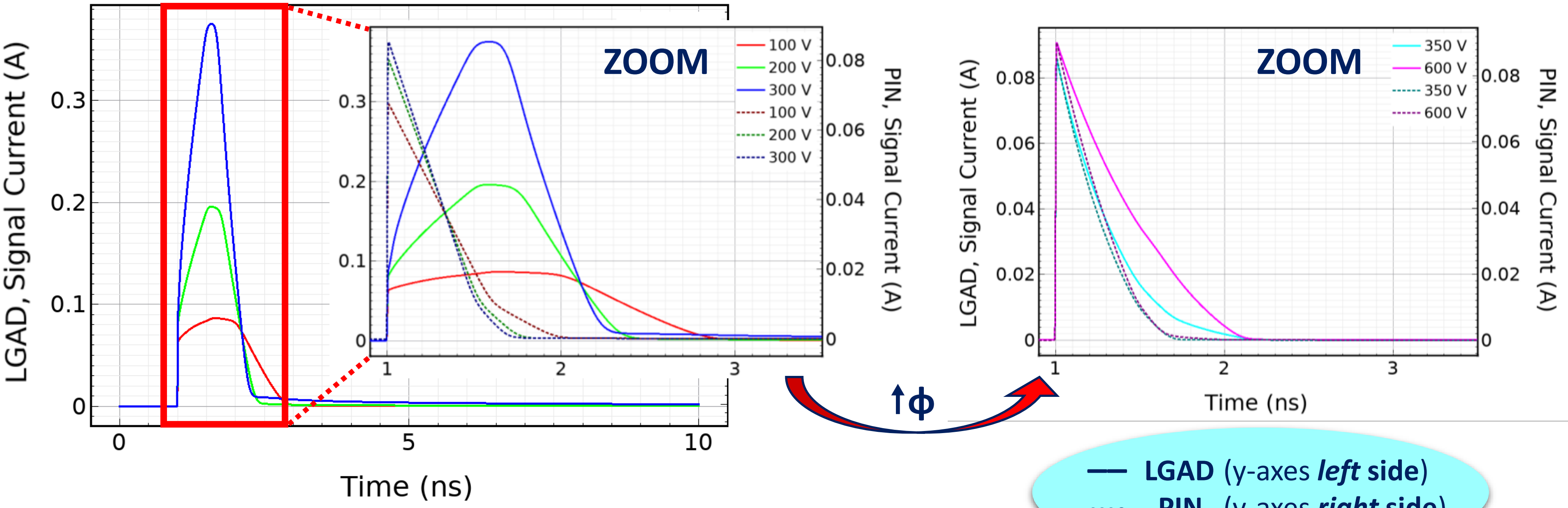
Transient response

- ✓ **Comparison** between **LGAD** and **PIN** response to the **MIP** for different V_{bias}

I-t, before irradiation

I-t, fluence **1.5e15 n_{eq}/cm^2**



—— **LGAD** (y-axes ***left*** **side**)
···· **PIN** (y-axes ***right*** **side**)

Massey model. Temperature **300 K**. Electrical contact area **1mm²**

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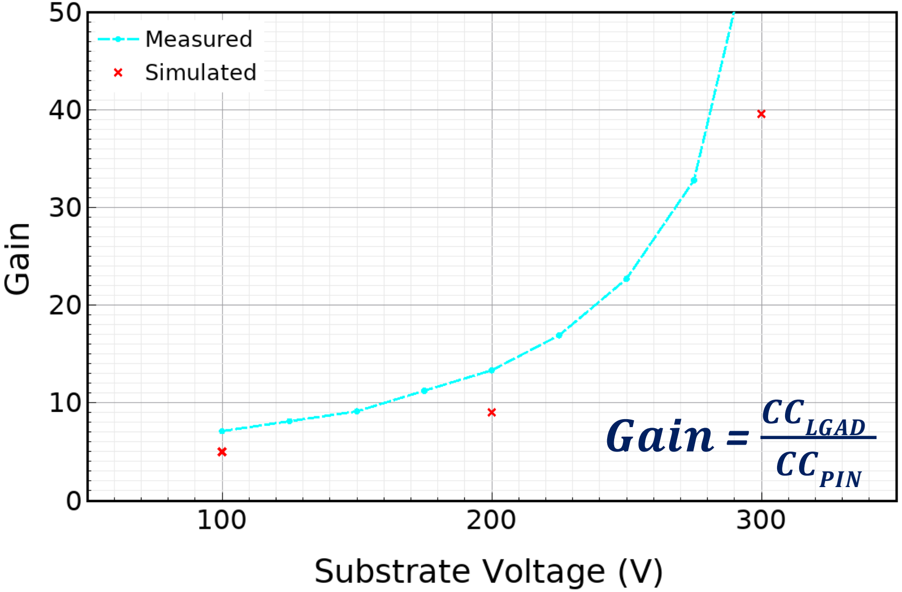
Gain calculation

- ✓ Estimated **error** on **data ±10 %**

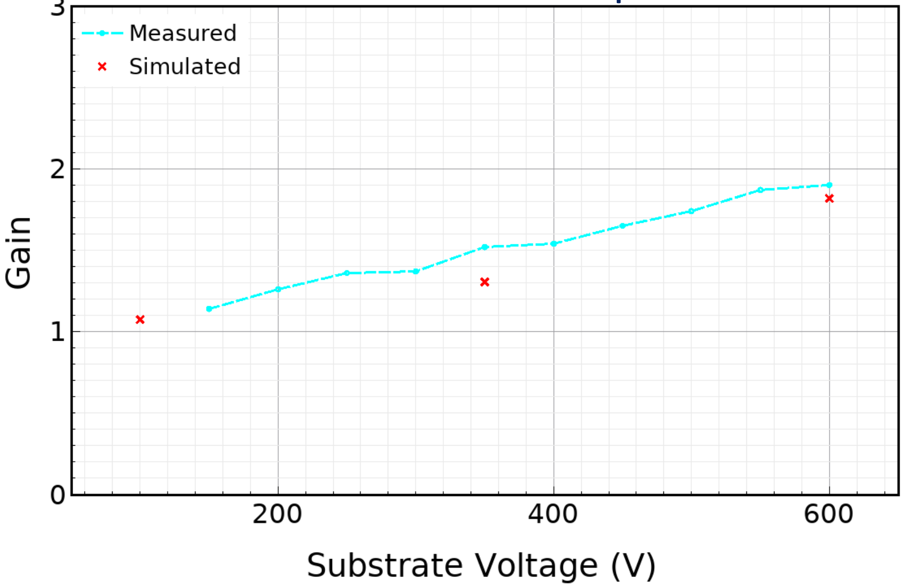
Good agreement!

G-V, before irradiation



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

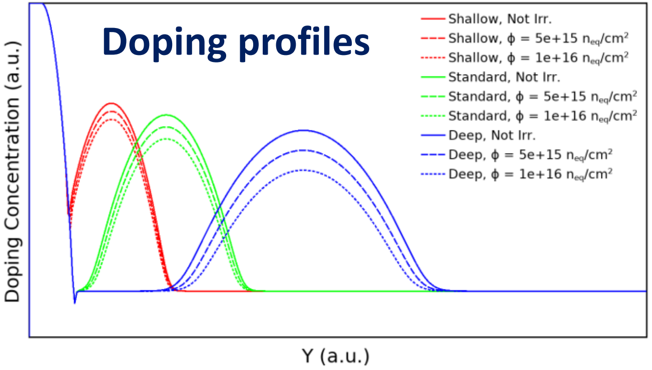
G-V, fluence **1.5e15** $\mathbf{n_{eq}/cm^2}$

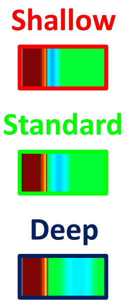


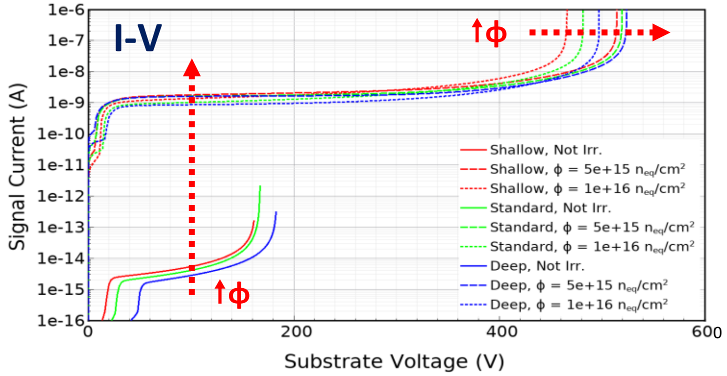
Massey model. Temperature **300 K**. Electrical contact area $\mathbf{1mm^2}$

Application of the developed model

- ✓ **Thin wafers** recently produced by **FBK**
  - thickness 25 and 35 µm [7]
- ✓ **TCAD simulations** very **useful to**
  - **compare** the **results with** the experimental **data**, **before** and **after irradiation** (irradiation campaign just completed at the Ljubljana JSI facility up to 1.0e17 n_{eq}/cm^2)
  - **designing** the **future productions** of **thin LGADs** for **extreme fluences**







Massey model, Temperature **300 K**.

[7] V. Sola et al., *First results from thin silicon sensors for extreme fluences*, 37th RD50 Workshop, Zagreb, Croatia, 2020

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Conclusions

- ✓ **Strategy** for the numerical simulation of LGAD devices.
- ✓ **Results** obtained under **different operative conditions** (device biasing, fluence).
- ✓ **Good agreement** between simulation predictions and experimental data **for both non-irradiated and irradiated** LGAD device.
- ✓ **Combination** of “new University of Perugia TCAD model” and the “acceptor removal” analytical model is used to simulate the **radiation damage effects**
  - **=>** successful **description** of the **decrease in gain with** an increase in **fluence**.
- ✓ **Application** of the validated simulation framework **for the prediction** of **different design options/detector geometries** (e.g. thin sensors) behavior
  - **=>** optimization for their **use in the future HEP experiments**.

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Thank you for the attention!

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Foto di Franco Vairtainer

BACKUP SLIDES

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**.

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

- 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**

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Technology-CAD simulations

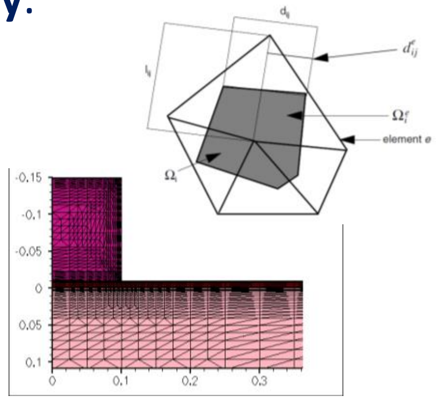
- **TCAD simulation tools** solve fundamental, physical partial differential equations, such as diffusion and transport equation for discretized geometries (finite element meshing).
- This deep physical approach gives TCAD simulation **predictive accuracy**.
- **Synopsys© Sentaurus TCAD**

$$\begin{cases} \nabla \cdot (-\varepsilon_s \nabla \phi) = q \ \ (N_D^+ - N_A^- + p - n) \\ \dfrac{\partial n}{\partial t} - \dfrac{1}{q} \nabla \cdot \vec{J}_n = \boxed{U_n} \\ \dfrac{\partial p}{\partial t} + \dfrac{1}{q} \nabla \cdot \vec{J}_p = \boxed{U_p} \end{cases}$$

Poisson

Electron continuity

Hole continuity



$$\vec{J}_n, \vec{J}_p$$

$$\boxed{U_{n,p} = G - R}$$

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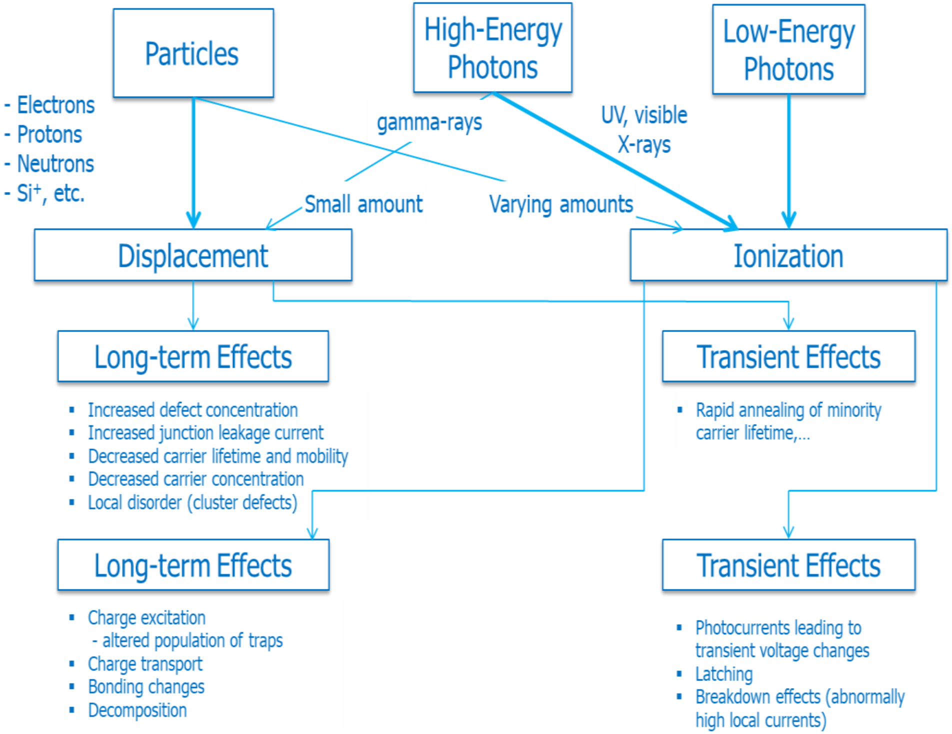
Radiation damage effects (1/2)

✓ **in silicon sensors**



Particles

- Electrons
- Protons
- Neutrons
- Si⁺, etc.

High-Energy Photons

Low-Energy Photons

gamma-rays

UV, visible X-rays

Small amount

Varying amounts

Displacement

Ionization

Long-term Effects

- Increased defect concentration
- Increased junction leakage current
- Decreased carrier lifetime and mobility
- Decreased carrier concentration
- Local disorder (cluster defects)

Transient Effects

- Rapid annealing of minority carrier lifetime,...

Long-term Effects

- Charge excitation
  - altered population of traps
- Charge transport
- Bonding changes
- Decomposition

Transient Effects

- Photocurrents leading to transient voltage changes
- Latching
- Breakdown effects (abnormally high local currents)

Two main **types of radiation damage** in detectors materials:

- **SURFACE damage** => Ionization
  - ✓ Build-up of trapped charge within the oxide;
  - ✓ Bulk oxide traps increase;
  - ✓ Interface traps increase;
  - ✓ Q_{ox}, N_{IT}.
- **BULK damage** => Atomic displacement
  - ✓ Silicon lattice defect generations;
  - ✓ Point and cluster defects;
  - ✓ Deep-level trap states increase;
  - ✓ Change of effective doping concentration;
  - ✓ N_T.

Radiation damage effects (2/2)

- ✓ **in LGAD devices**

- ➢ **Acceptor removal mechanism** [1]: the active (substitutionals) doping elements are partially removed from their lattice sites due to the ionizing radiation and then de-activated after a kick-out reaction (Watkins mechanism [2]) that produces ion-acceptor complexes (interstitials)
- ➢ Transformation of electrically active acceptors into defect complexes that no longer have dopant properties
- ➢ This has been recently suggested as a possible explanation for the significant degradation of gain (charge multiplication) observed on LGAD devices after irradiation.

(1) G. Kramberger, M. Baselga et al., J. Inst., vol. 10, no. 7, p. P07006, 2015
(2) G. D. Watkins, *Defects and Their Structure in Non-metallic Solids*, B. Henderson and A. E. Hughes, Eds. New York: Plenum, 1975

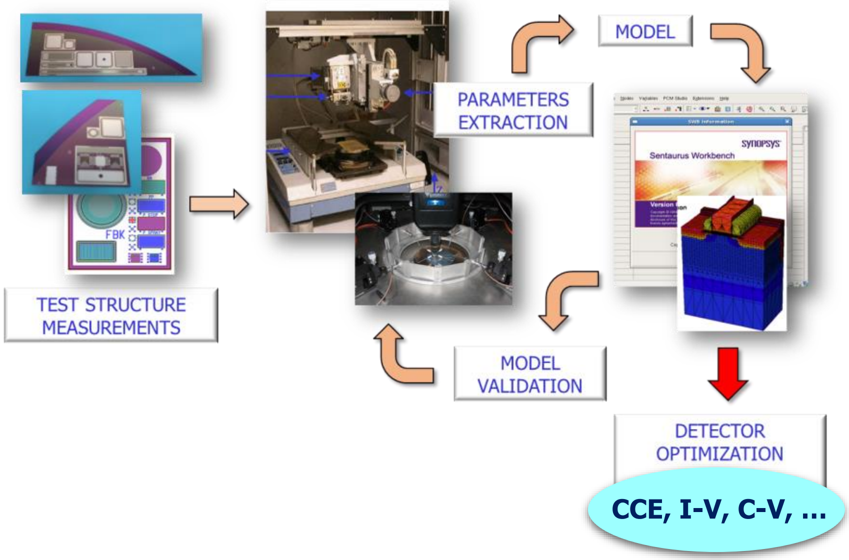
TCAD radiation damage models used

- **“New University of Perugia model”**
  - ✓ **Combined surface and bulk** TCAD damage modelling **scheme**
  - ✓ Traps generation mechanism
- **Acceptor removal mechanism**

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

where

- **G**ain **L**ayer (**GL**)
- **c**, removal rate, evaluated using the **Turin parameterization**


TEST STRUCTURE MEASUREMENTS

PARAMETERS EXTRACTION

MODEL

MODEL VALIDATION

DETECTOR OPTIMIZATION

CCE, I-V, C-V, …

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}

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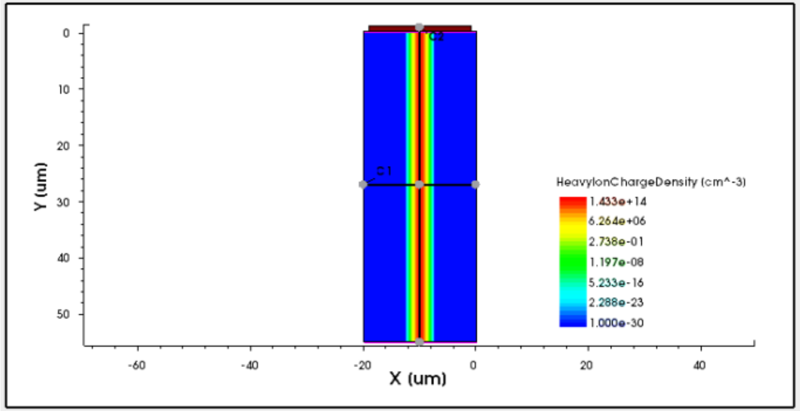
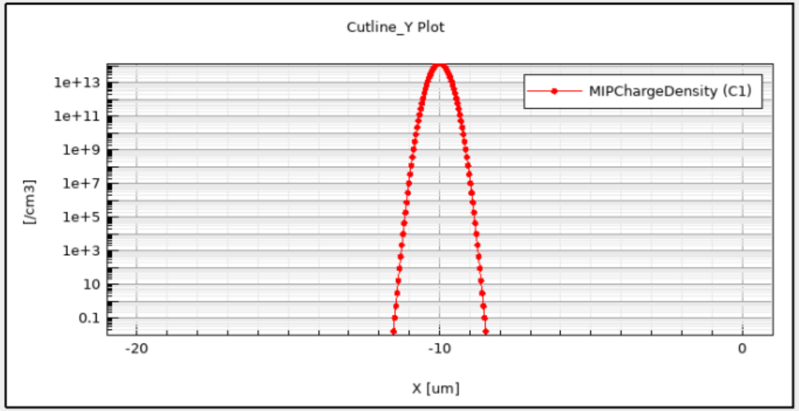
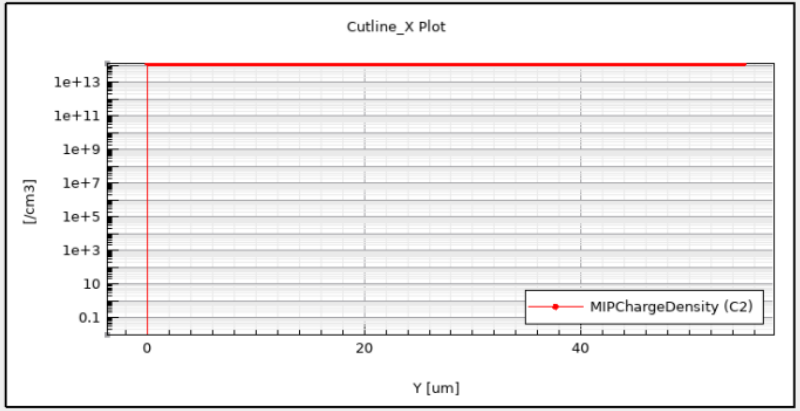
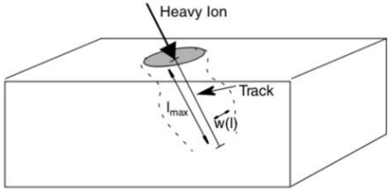
Transient responce: “HeavyIon” model









$$G(l,w,t) = G_{LET}(l)\,\underline{R(w,l)\,T(t)} \longrightarrow \text{Gaussian}$$

$$G_{LET}(l) = a_1 + a_2 l + a_3 e^{a_4 l} + k'\,[c_1 (c_2 + c_3 l)^{c_4} + LET\_f(l))$$

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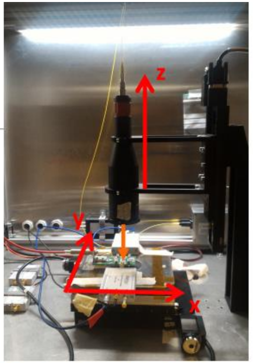
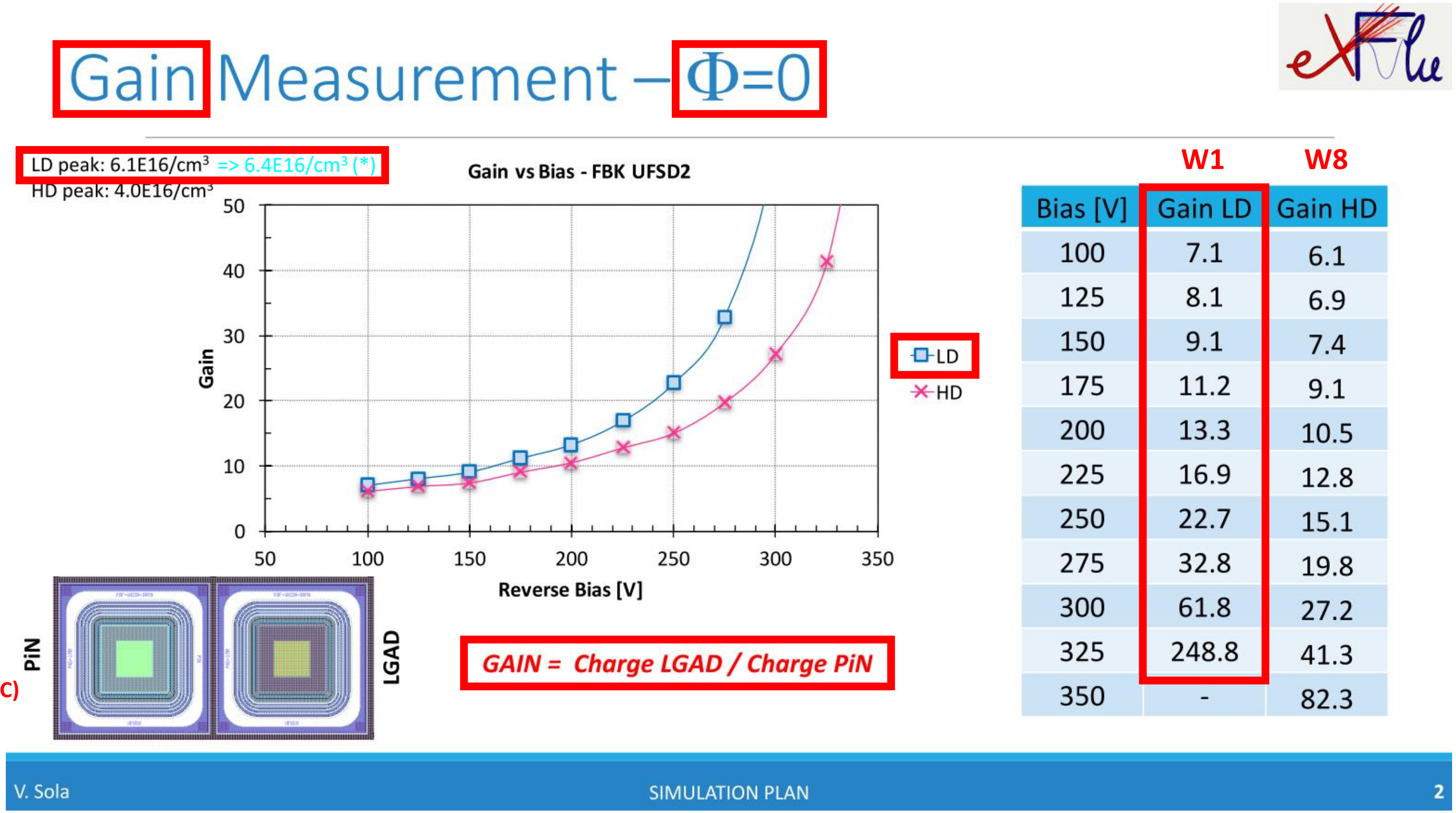
Pre-Irradiation: Experimental Data (FBK UFSD2 Production)



TCT Setup from Particulars
Pico-second IR laser at 1064 nm
Laser spot diameter ~ 50 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope Lecroy 640Zi
Room temperature
Laser attenutation 82% (3 MIP 150 fC)



Gain Measurement – $\Phi=0$

LD peak: 6.1E16/cm^3 => 6.4E16/cm^3 (*)
HD peak: 4.0E16/cm^3

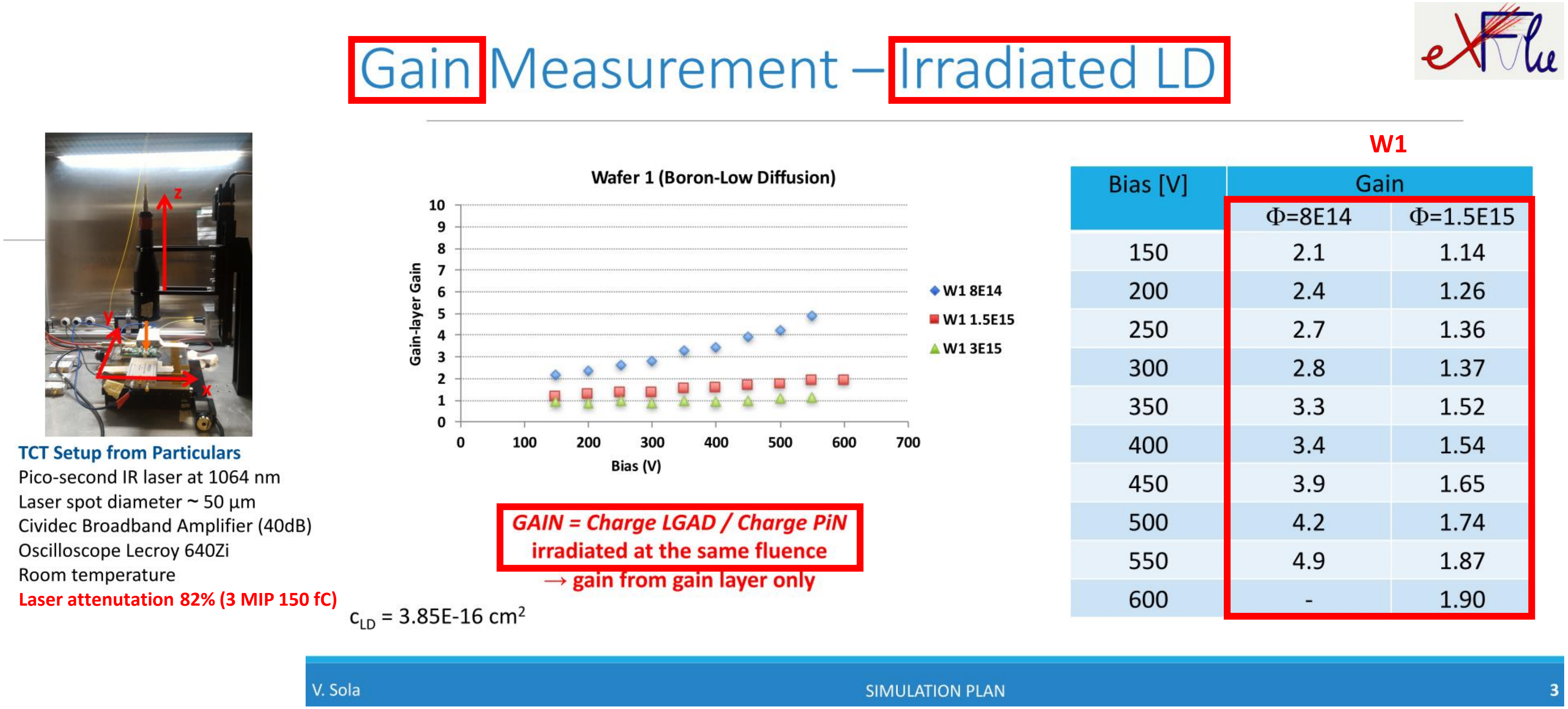
	W1	W8
Bias [V]	Gain LD	Gain HD
100	7.1	6.1
125	8.1	6.9
150	9.1	7.4
175	11.2	9.1
200	13.3	10.5
225	16.9	12.8
250	22.7	15.1
275	32.8	19.8
300	61.8	27.2
325	248.8	41.3
350	-	82.3

GAIN = Charge LGAD / Charge PiN

V. Sola SIMULATION PLAN 2

(*) values updated to the latest measurements – V. Sola, 20/10

Post-Irradiation: Experimental Data (FBK UFSD2 Production)



Gain Measurement – Irradiated LD

TCT Setup from Particulars
Pico-second IR laser at 1064 nm
Laser spot diameter ~ 50 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope Lecroy 640Zi
Room temperature
Laser attenutation 82% (3 MIP 150 fC)

GAIN = Charge LGAD / Charge PiN
irradiated at the same fluence
→ gain from gain layer only

c_{LD} = 3.85E-16 cm^2

W1

Bias [V]	Gain	
	Φ=8E14	Φ=1.5E15
150	2.1	1.14
200	2.4	1.26
250	2.7	1.36
300	2.8	1.37
350	3.3	1.52
400	3.4	1.54
450	3.9	1.65
500	4.2	1.74
550	4.9	1.87
600	-	1.90

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