Design, simulation and characterization of innovative Low-Gain Avalanche Diodes for High Radiation Environments

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Outline

- Motivations
- TCAD simulation of LGAD devices
  - Layout and doping profile
  - Physical models and parameters
- Methodology (DC, AC and transient response)
- Application of the developed model
  - Compensated LGAD

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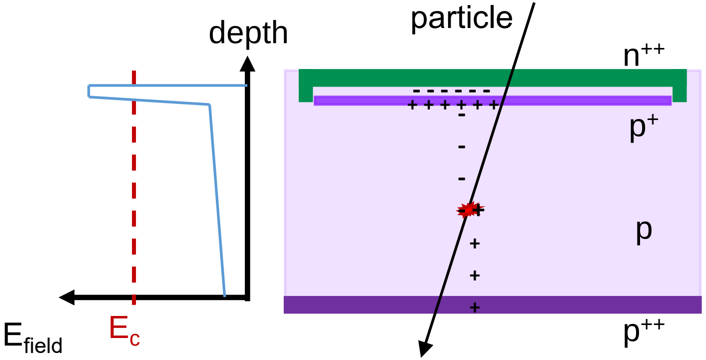
Motivations

✓ **LGADs** are **n-in-p silicon** sensors
Operated in **low-gain regime** (20 – 30)
Critical electric field ~ 20 – 30 V/µm



✓ The **acceptor removal mechanism**[1] deactivates the p^+-doping of the **gain layer** with irradiation

✓ **Device-level simulation tools**[2] **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] [M. Ferrero et al., doi:10.1016/j.nima.2018.11.121] **[2]** Synopsys© Sentaurus TCAD

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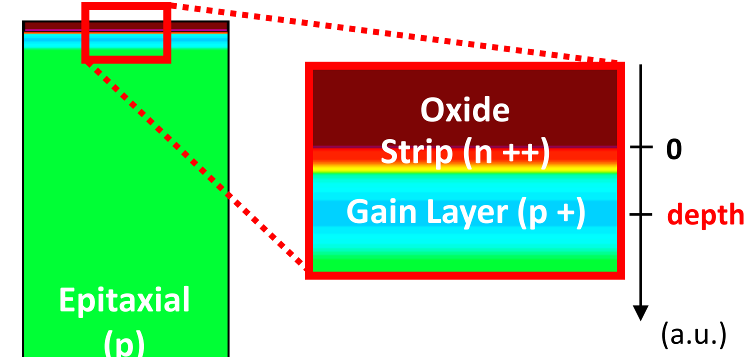
TCAD simulation of LGAD devices (1/2)

✓ **Layout** and **doping profile**



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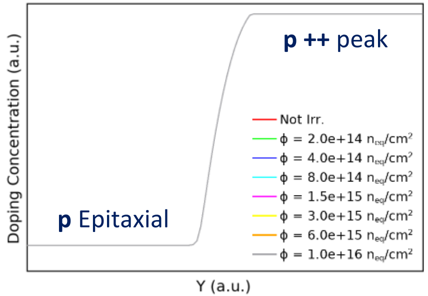

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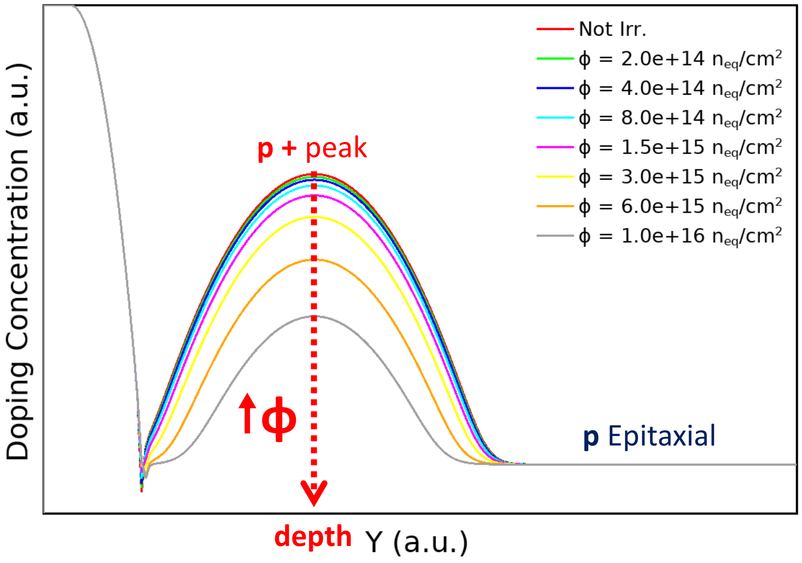


Gaussian Gain Layer **profile**

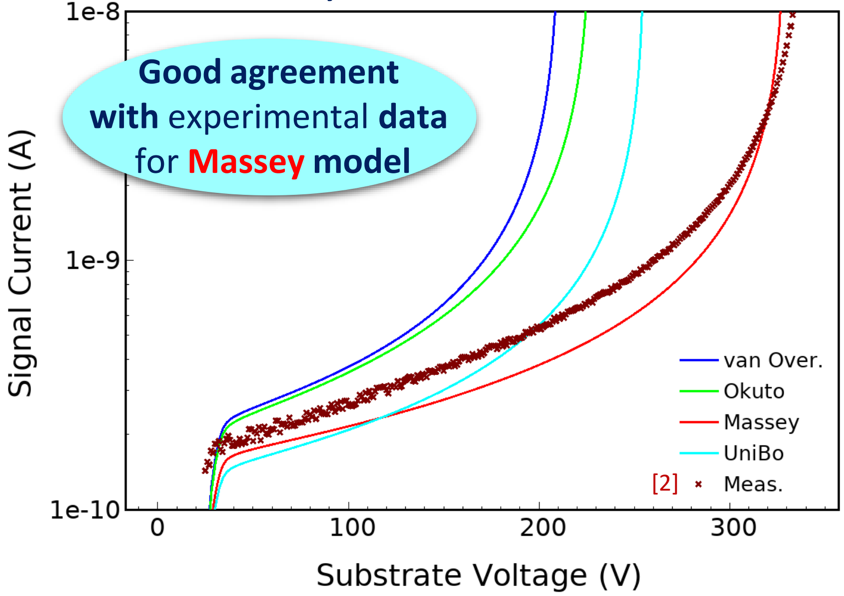
TCAD simulation of LGAD devices (2/2)

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

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

- ✓ **Physical parameters**
  - e-/h+ recombination lifetime

I-V, before irradiation



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

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

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

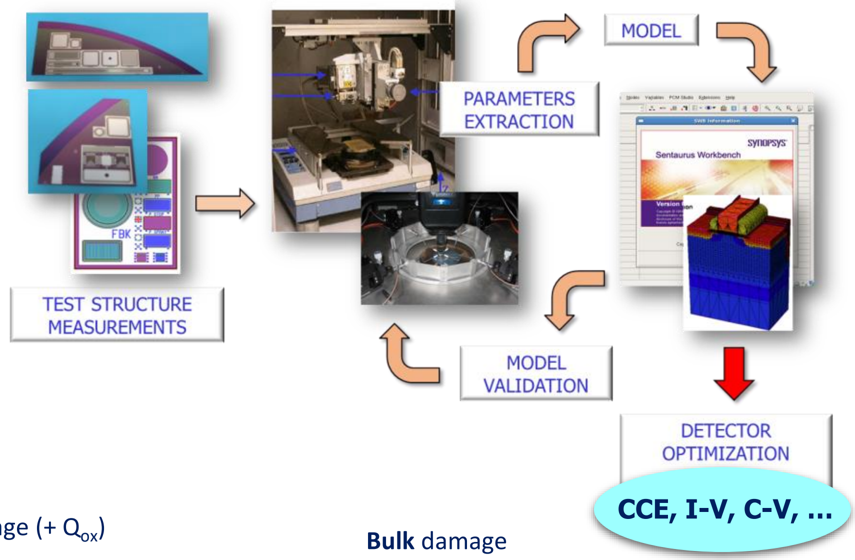
TCAD radiation damage models used

- **"New University of Perugia model"**
  - ✓ **Combined surface and bulk** TCAD damage modelling scheme[1]
  - ✓ 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 **Torino parameterization**[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}

[1] AIDA2020 report, *TCAD radiation damage model - CERN Document Server*
[2] M. Ferrero et al., *Radiation resistant LGAD design*, Nucl. Inst. And Meth. In Phys. Res. A, November 30, 2018.

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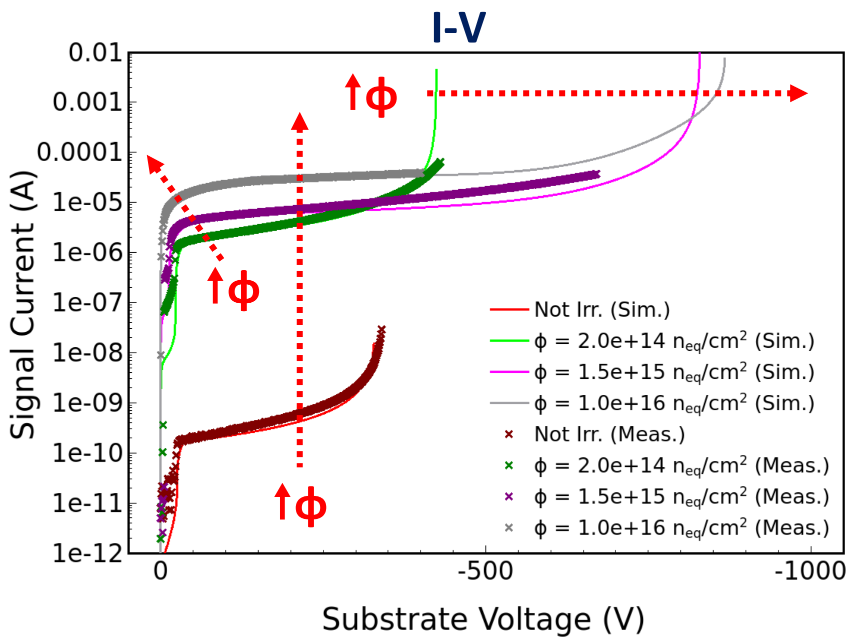
Static (DC) and small-signal (AC) behavior: FBK

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

Good agreement!



— Simul.
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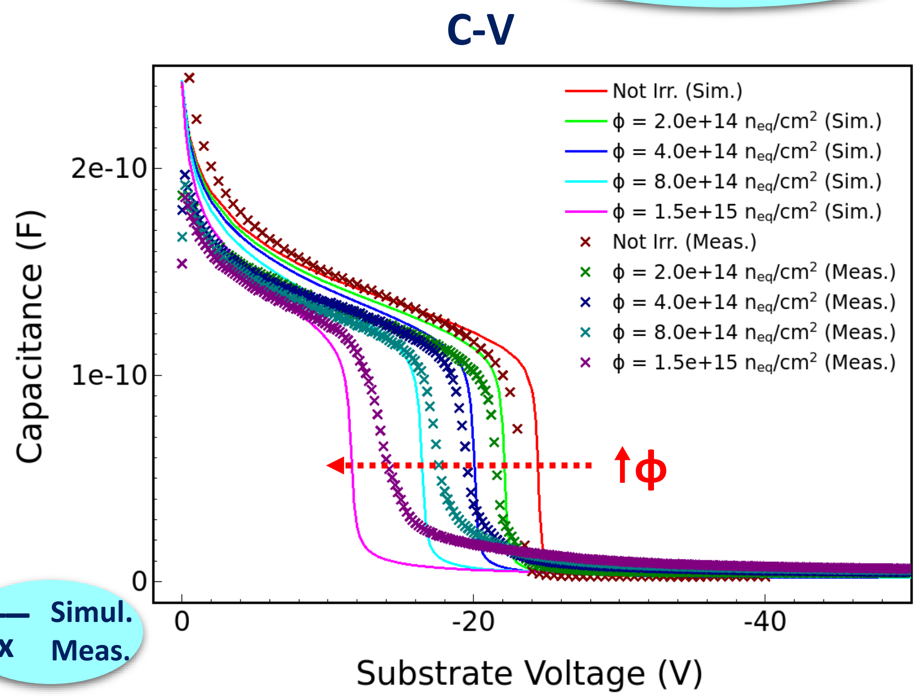
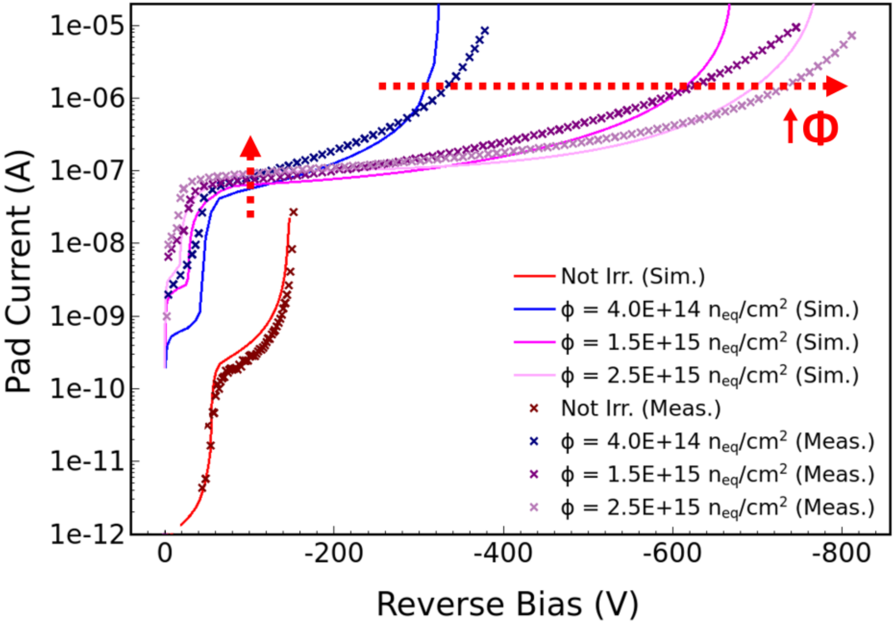
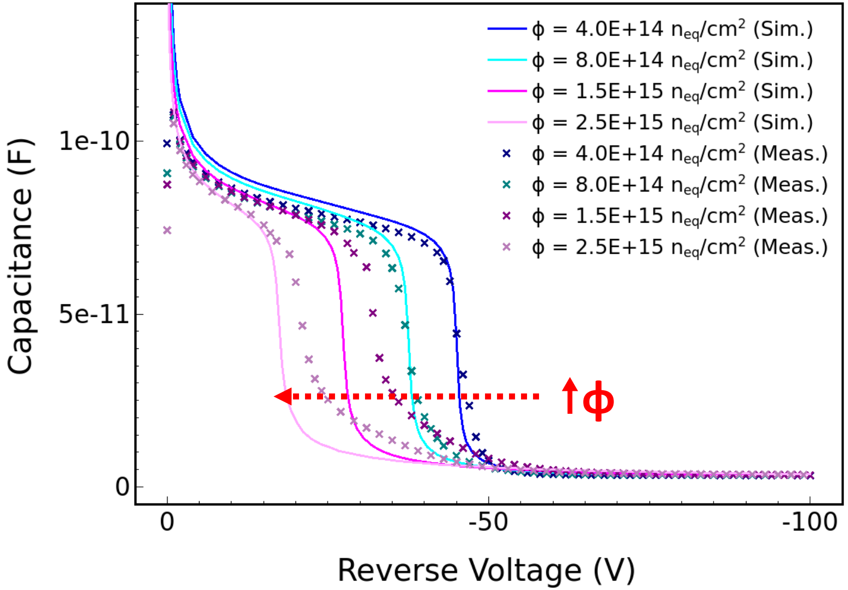


Avalanche model: **Massey**. Frequency **1 kHz** for **C-Vs**. Electrical contact area **1mm^2**

Static (DC) and small-signal (AC) behavior: HPK

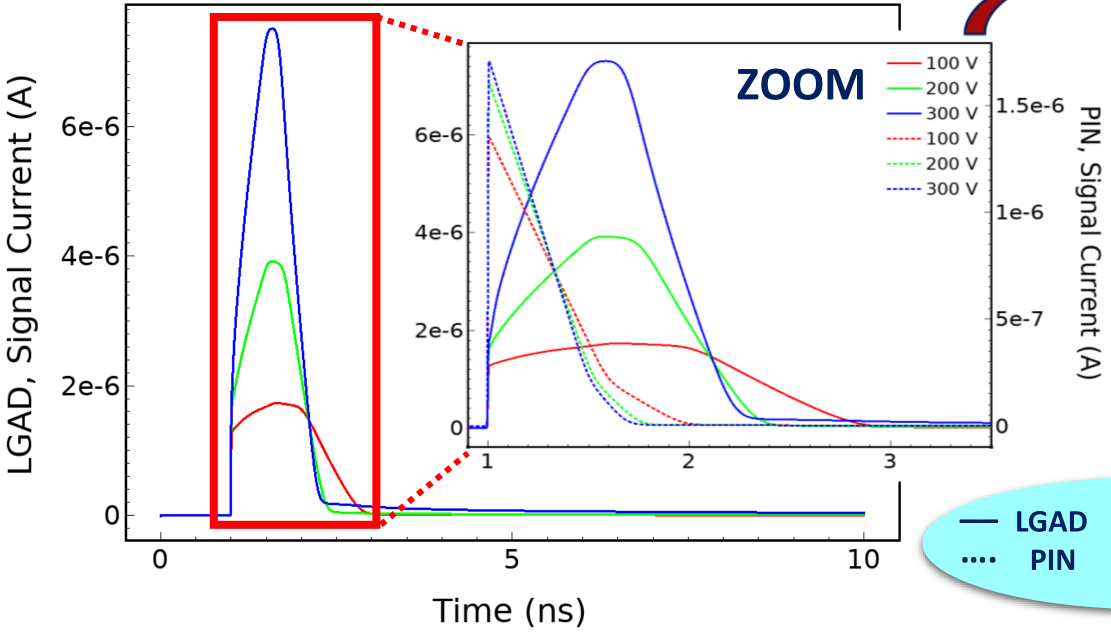




Transient response

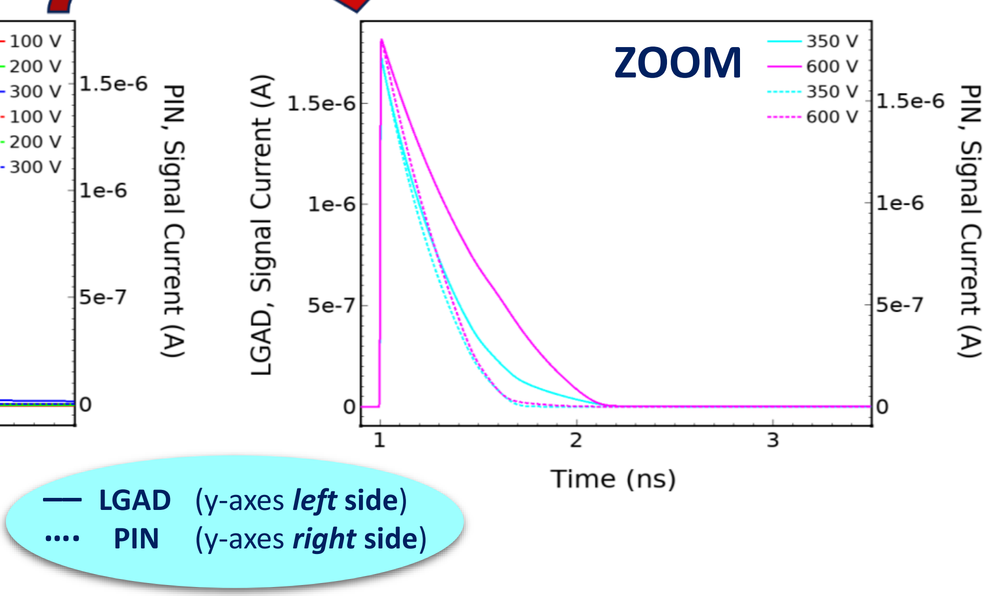
- ✓ **Comparison** between **LGAD** and **PIN** response to the **MIP** for different V_{bias}

I-t, before irradiation



↑ϕ

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



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

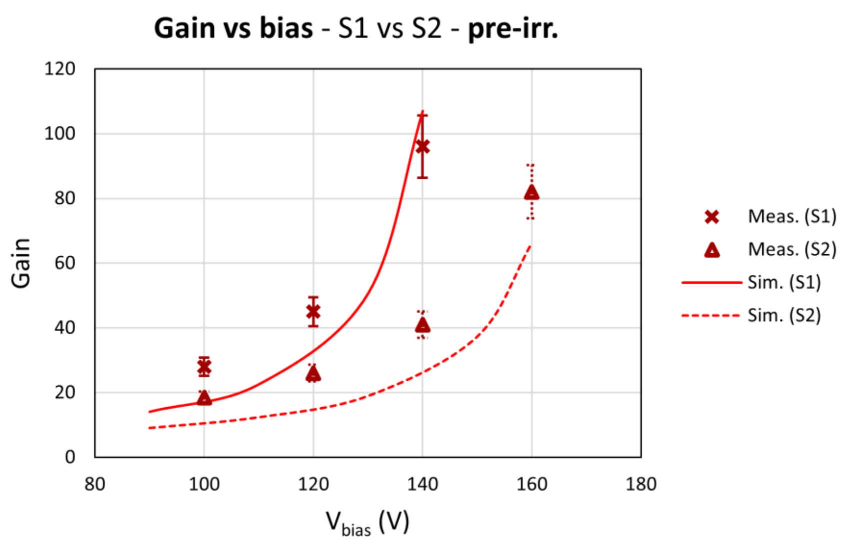
Gain calculation: HPK

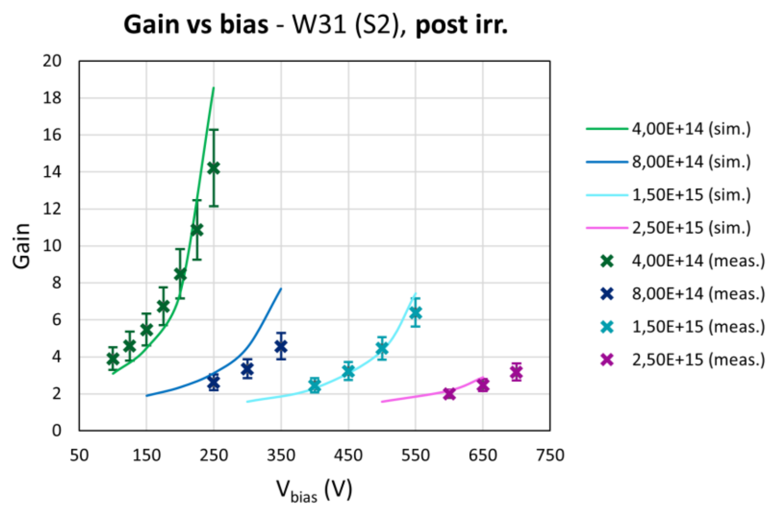
- ✓ Estimated **error** on **data ±10 %**

$$Gain = \frac{CC_{LGAD}}{CC_{PIN}} [1]$$

G-V, before irradiation

Good agreement!





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

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LGAD for extreme fluences

✓ **Difficult to operate silicon sensors above 10^{16} n_{eq}/cm^2 due to**:

– defects in the silicon lattice structure → increase of the dark current

– trapping of the charge carriers → decrease of the charge collection efficiency

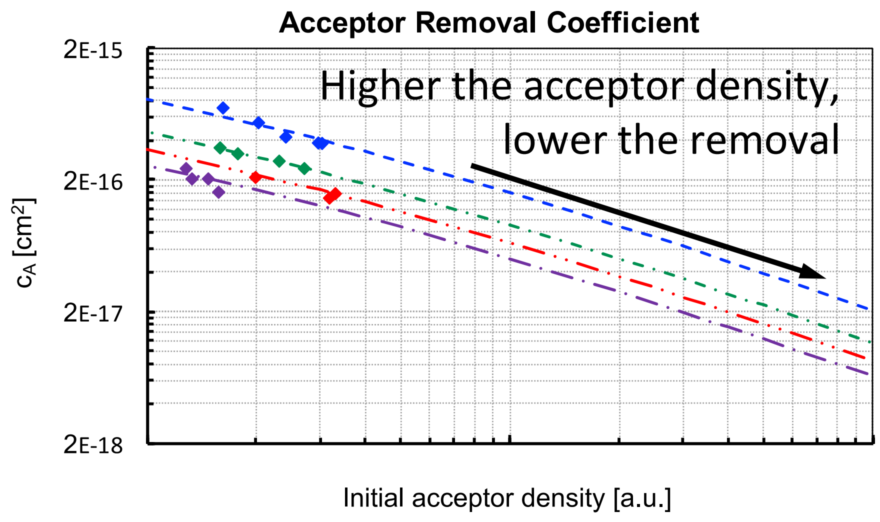
– change in the bulk effective doping → impossible to fully deplete the sensors

- For LGAD acceptor removal mechanism

✓ **The options to overcome the present limits above 10^{16} n_{eq}/cm^2 are:**

1. **saturation** of the radiation damage effects above $5 \cdot 10^{15}$ n_{eq}/cm^2
2. the use of **thin** active substrates (20 – 40 μm)
3. **extension** of the charge carrier multiplication up to 10^{17} n_{eq}/cm^2

Towards a Radiation Resistance Design



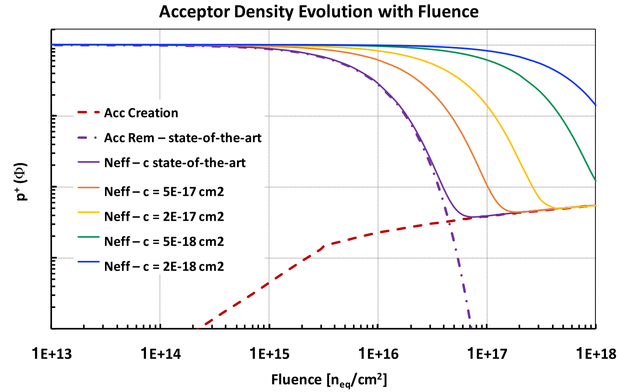
The acceptor removal mechanism deactivates the p^+-doping of the **gain layer** with irradiation according to

$$p^+(\Phi) = p^+(0)\cdot e^{-c_A\Phi}$$

where c_A is the acceptor removal coefficient

c_A depends on the initial acceptor density, $p^+(0)$, and on the defect engineering of the gain layer atoms

Lowering c_A extends the gain layer survival up to the highest fluences



Compensation

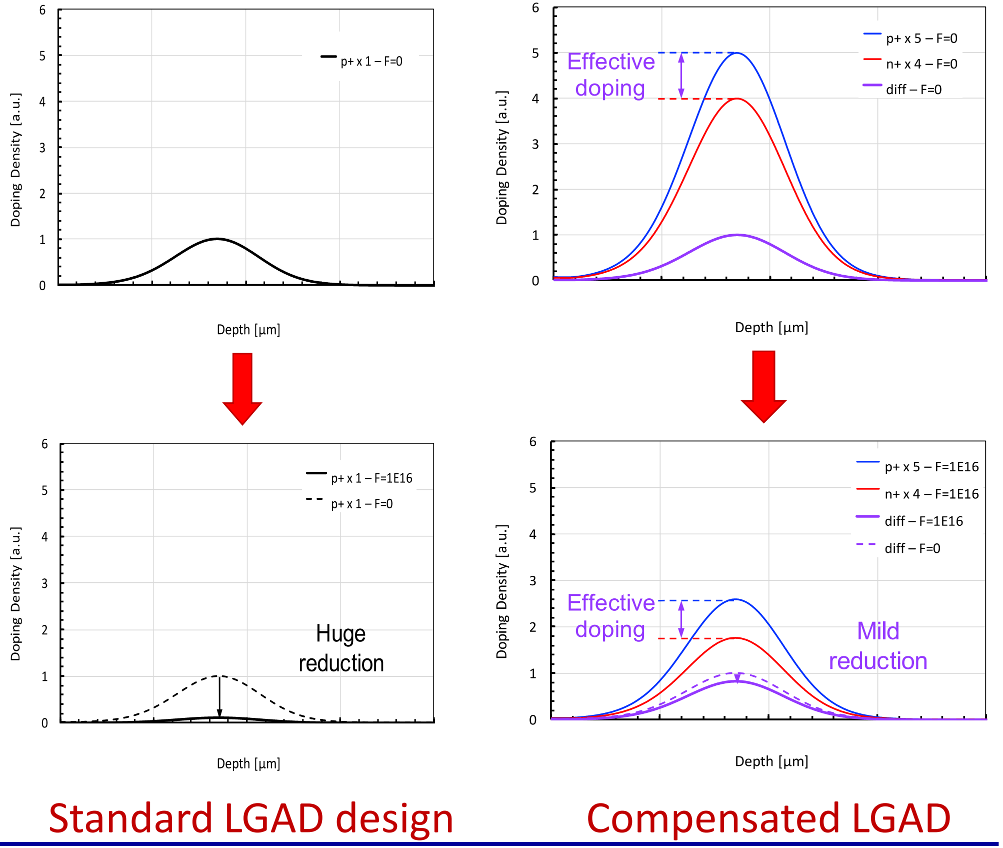
Impossible to reach the design target with the present design of the gain layer

Use the interplay between acceptor and donor removal to keep a constant gain layer active doping density

Many unknown:

- donor removal coefficient, from $n^{+}(\Phi) = n^{+}(0)\cdot e^{-cD\Phi}$
- interplay between donor and acceptor removal ($\mathbf{c_D}$ vs $\mathbf{c_A}$)
- effects of substrate impurities on the removal coefficients

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



Compensation – doping evolution with fluence

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

1. $c_A \sim c_D$

   p^+ & n^+ difference will remain constant $\Rightarrow$ unchanged gain with irradiation

   $\rightarrow$ **This is the best possible outcome**

2. $c_A > c_D$

   effective doping disappearance is slower than in the standard design

   $\rightarrow$ **Co-implantation of Carbon** atoms mitigates the removal of p^+-doping

3. $c_A < c_D$

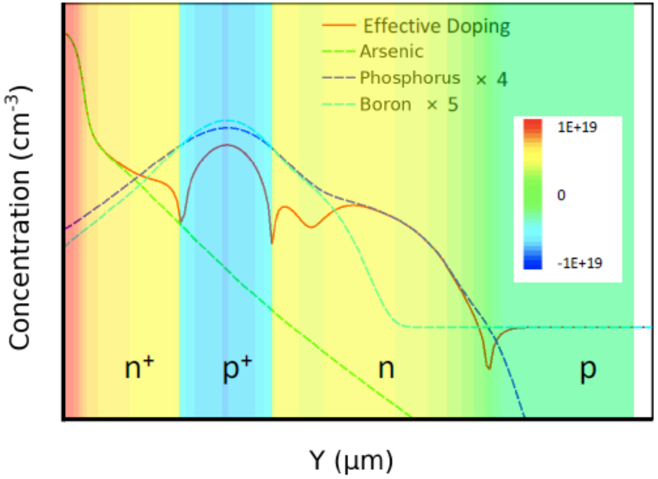
   n^+-atoms removal is faster $\Rightarrow$ increase of the gain with irradiation

   $\rightarrow$ **Co-implantation of Oxygen** atoms might mitigate the removal of n^+-doping

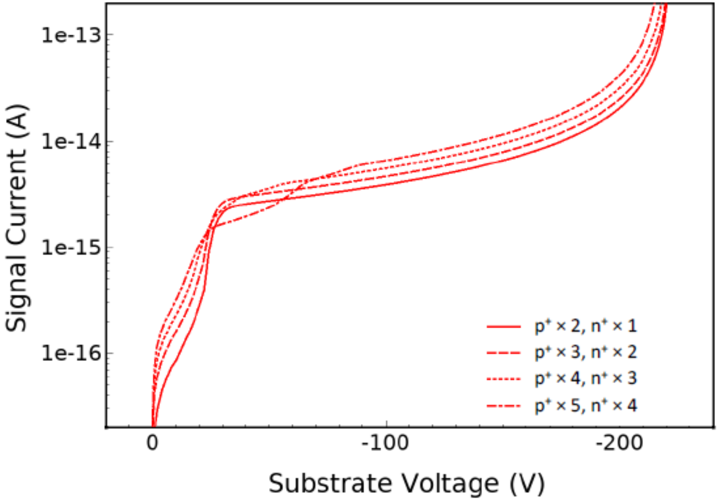
Compensation - simulation

Process simulations of Boron (p^+) and Phosphorus (n^+) implantation and activation reveal the different shape of the two profiles (TCAD Silvaco)

Doping Profiles from Process Simulation



I-V from Simulation



→ The simulation of the electrostatic behaviour show that it is possible to reach similar multiplication for different values of initial compensation (TCAD Synopsys)

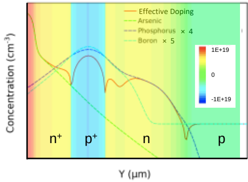
Compensated Gain Layer Design – Split Table

Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
7	30	2 b	1	
8	30	2 b	1	
9	30	2 c	1	
10	30	3 a	2	
11	30	3 b	2	
12	30	3 b	2	
13	30	3 b	2	1.0
14	30	3 c	2	
15	30	5 a	4	

[a < b < c]

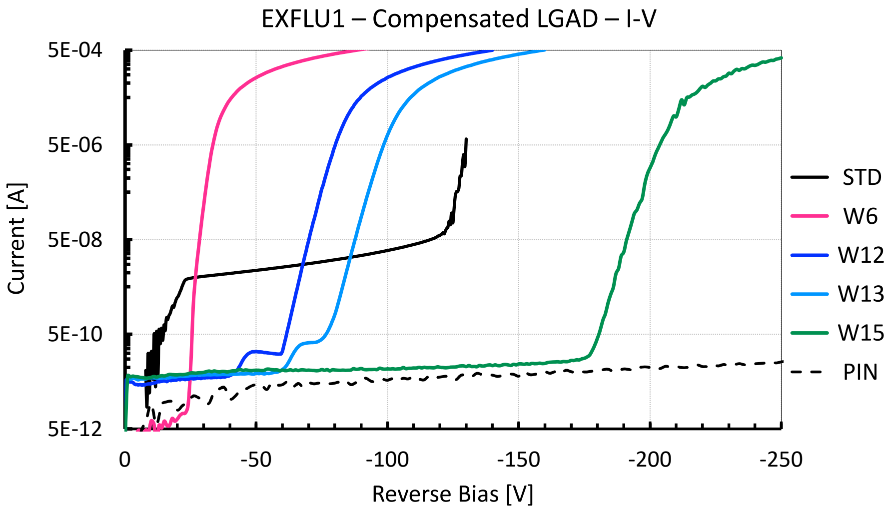
3 different combinations of $p^+ - n^+$ doping: 2 – 1, 3 – 2, 5 – 4

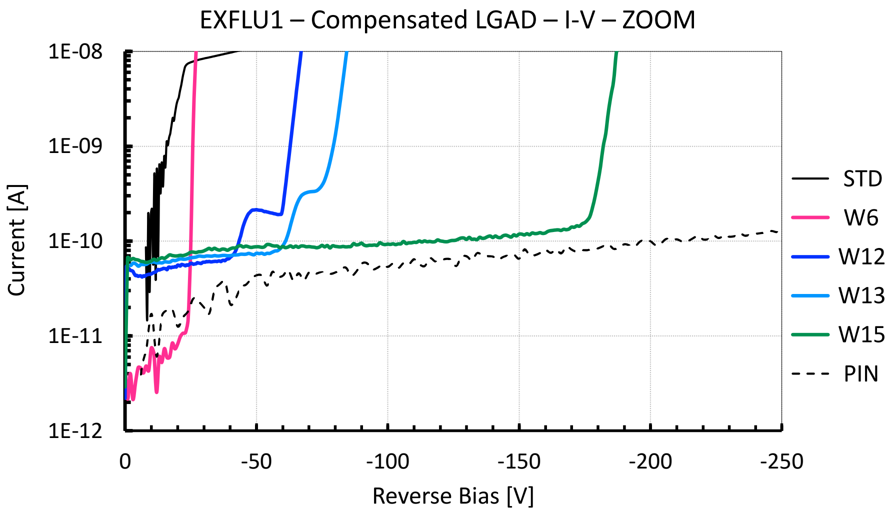
Compensated LGAD – I-V



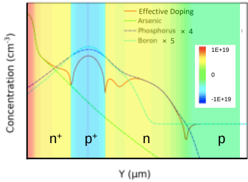
Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
12	30	3 b	2	
13	30	3 b	2	1.0
15	30	5 a	4	

- 2–1 is more doped than standard LGAD
- 3–2 & 5–4 exhibit a flat behaviour followed by an abrupt increase of the current



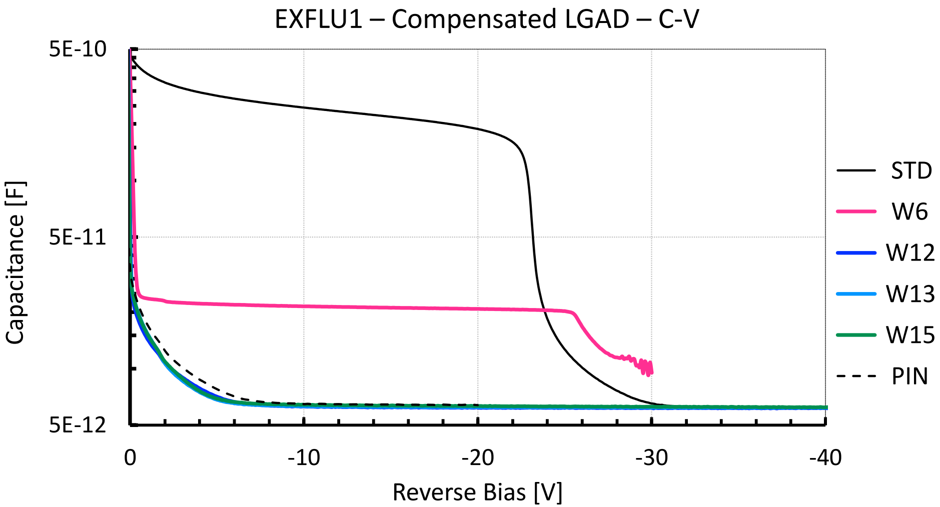


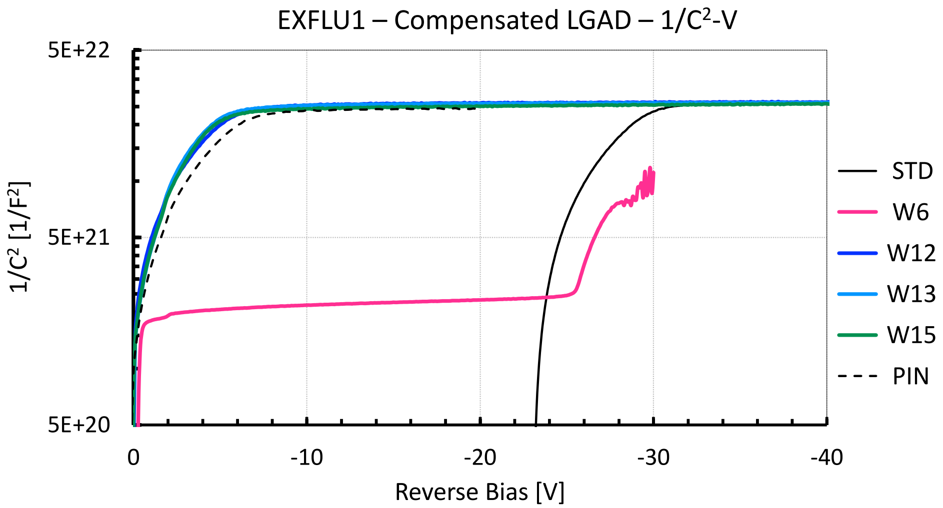
Compensated LGAD – C-V



Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
12	30	3 b	2	
13	30	3 b	2	1.0
15	30	5 a	4	

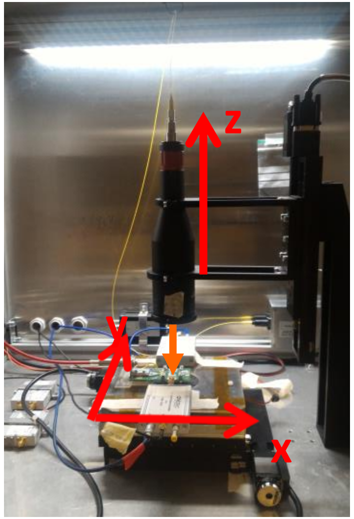
- □ 2–1 is more doped than standard LGAD
- □ 3–2 & 5–4 exhibit a capacitance lower than PIN





IR Laser Stimulus on Compensated LGAD 2–1

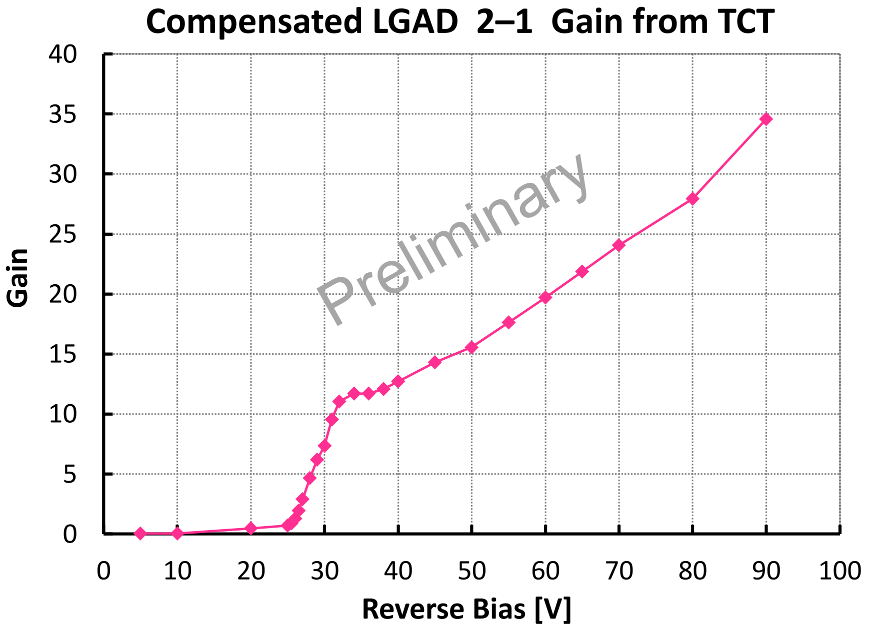
TCT Setup from Particulars
Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
Room temperature



$$\text{Gain} = \frac{Q_{LGAD}}{Q_{PiN}}$$

Laser intensity
~ 10 MIPs

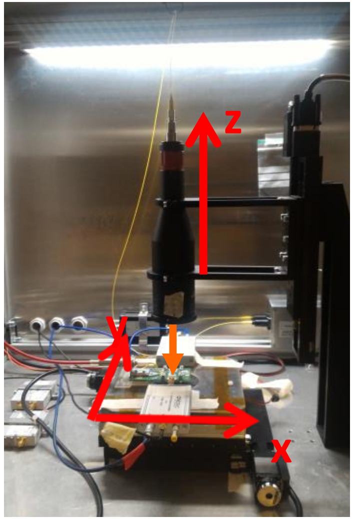
Laser stimulus on a LGAD-PiN structure from W6 (2 – 1)



→ Good transient behaviour of 2 – 1 compensated LGAD sensors

IR Laser Stimulus on Compensated LGAD 5–4

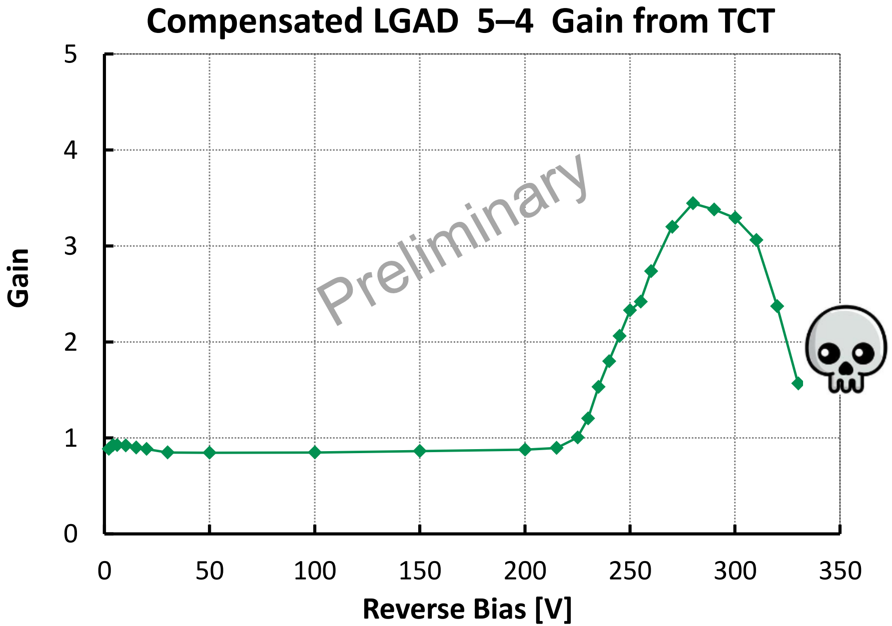
TCT Setup from Particulars
Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
Room temperature



$$\text{Gain} = \frac{Q_{LGAD}}{Q_{PiN}}$$

Laser intensity
~ 90 MIPs

Laser stimulus on a LGAD-PiN structure from W6 (5 – 4)



→ **Not optimal behaviour of 5 – 4 compensated LGAD sensors**

Conclusions

- ✓ **Strategy** for TCAD numerical simulation of LGAD devices.
- ✓ **Results** obtained under **different operating 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 analysis of **different innovative options in particular Compensated LGAD=> optimization** for their **use in the future HEP experiments**.
- ✓ **Ongoing comparison** between **simulation findings** and **new experimental data** of real devices

  => new guidelines for **future production** of **radiation-resistant LGADs**.

BACKUP SLIDES

Low-Gain Avalanche Diodes (LGADs)

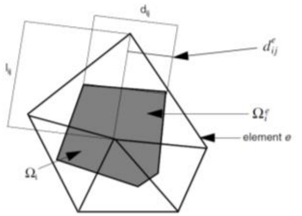
- Most promising devices to cope with the high spatial density of particles hits due to the increasing radiation fluence expected in the HL-LHC at CERN.
- **LGAD structure**: pin diode with the additional inclusion of a p+-type layer just below the n-contact, which is commonly called *multiplication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

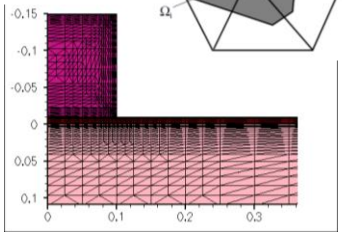
$$\mathrm{G}_{\mathrm{aval}} = \boldsymbol{\alpha_n} n v_n + \boldsymbol{\alpha_p} p v_p \qquad\qquad \boldsymbol{\alpha} = \frac{E}{E_{th}} e^{-\frac{E_i}{E}}$$

- 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**

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**





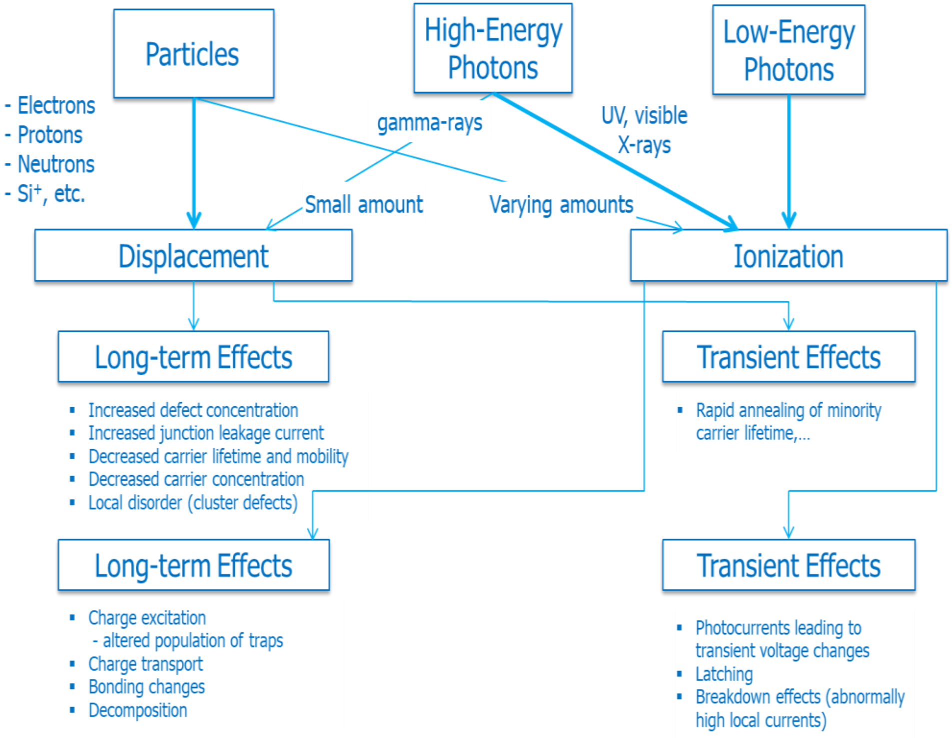
$$\begin{cases} \nabla \cdot (-\varepsilon_s \nabla \phi) = q \; (N_D^+ - N_A^- + p - n) & \text{Poisson} \\ \dfrac{\partial n}{\partial t} - \dfrac{1}{q} \nabla \cdot \vec{J}_n = U_n & \text{Electron continuity} \\ \dfrac{\partial p}{\partial t} + \dfrac{1}{q} \nabla \cdot \vec{J}_p = U_p & \text{Hole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

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

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

Radiation damage effects (1/2)

✓ in **silicon sensors**



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.

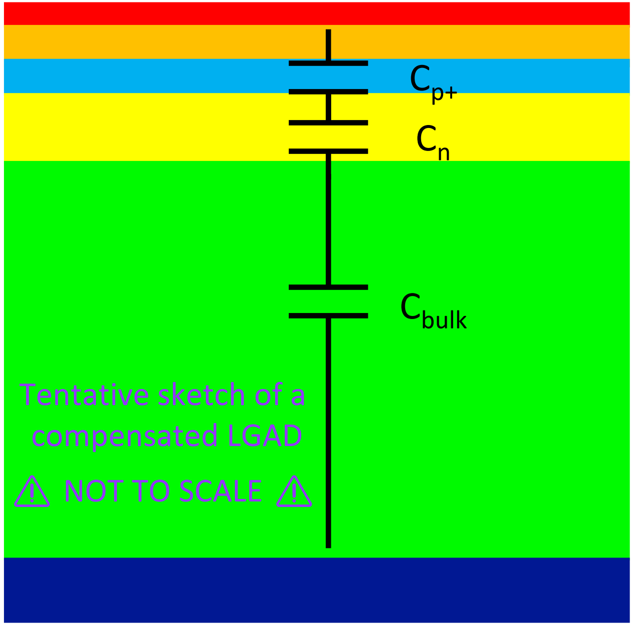
[1] G. Kramberger, M. Baselga et al., J. Inst., vol. 10, no. 7, p. P07006, 2015
[2] G. D. Watkins, *Defects and Their Structure in Non-metallic Solids*, B. Henderson and A. E. Hughes, Eds. New York: Plenum, 1975

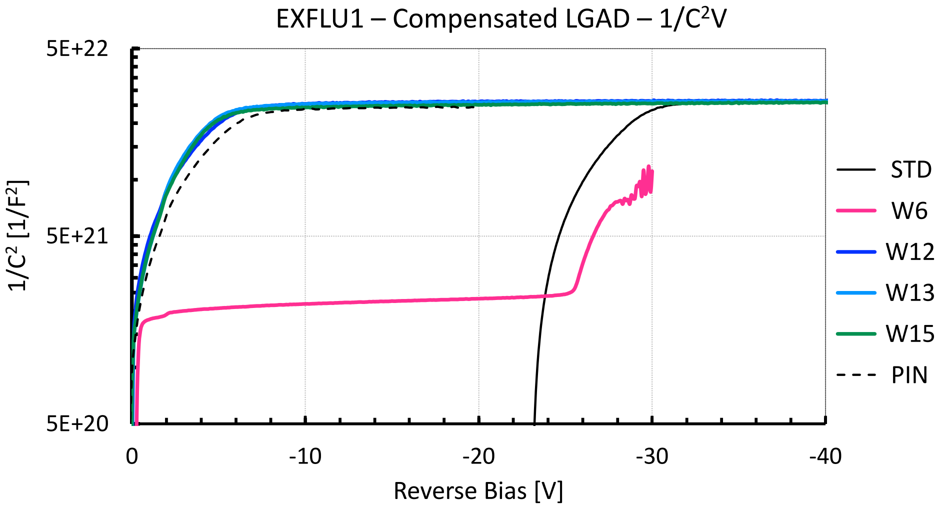
Methodology

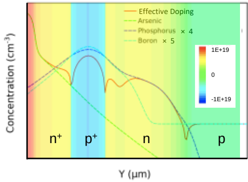
DC / AC analysis	Transient analysis	Gain calculation
• **DC biasing (static)** ○ n cathode: 0 V ○ p anode: *sweep* ✓ start = 0 V ✓ step = - 25 V (from 100 V) ✓ stop = - 1000 V ○ Temperature ✓ 300 K for not irr., 253 K for irr. [7] • **AC biasing (small-signal)** ○ For each DC bias step, superimposition of a 1 V_{pp}, 1 kHz sinusoid ○ Impedance matrix for each node of the discretized grid ○ Temperature 300 K for not irr. / irr.	• 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] $E_{LOSS} = 0{,}027\, log(y) + 0{,}126\ \frac{keV}{\mu m}$	• 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** $Gain = \frac{CC_{LGAD}}{CC_{PIN}}$ [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.

Compensated LGAD – C-V

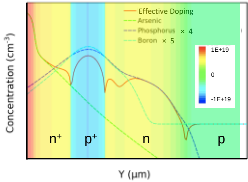




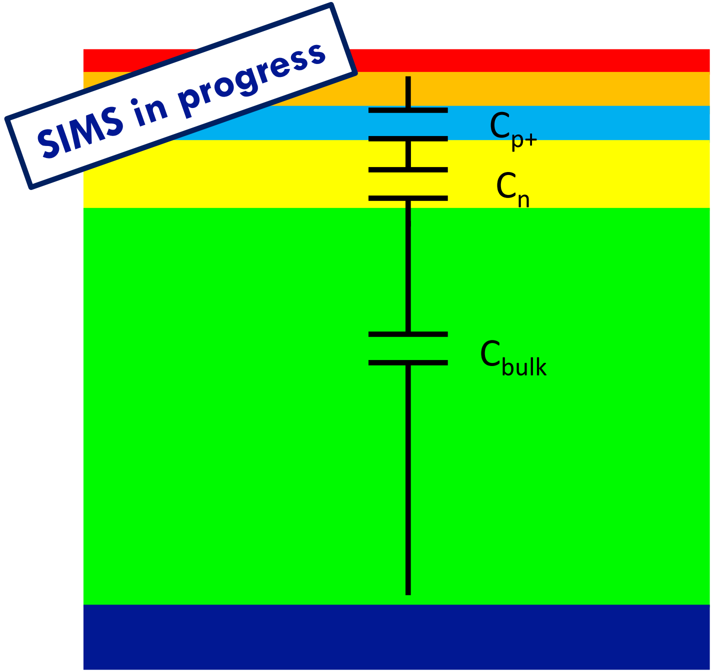


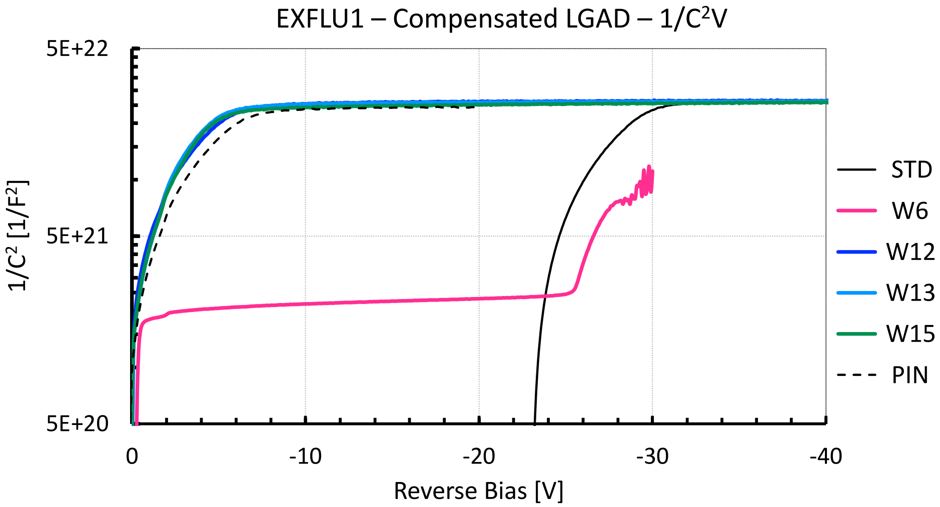
3–2 & 5–4 C-V measurements appear as the series of two different p-n junctions, and the sensor depletion starts from the n-bulk junction

Hypothesis: the concurrent activation of Boron and Phosphorus may reduce the lateral diffusion of Boron



Compensated LGAD – C-V





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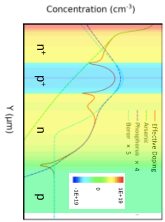
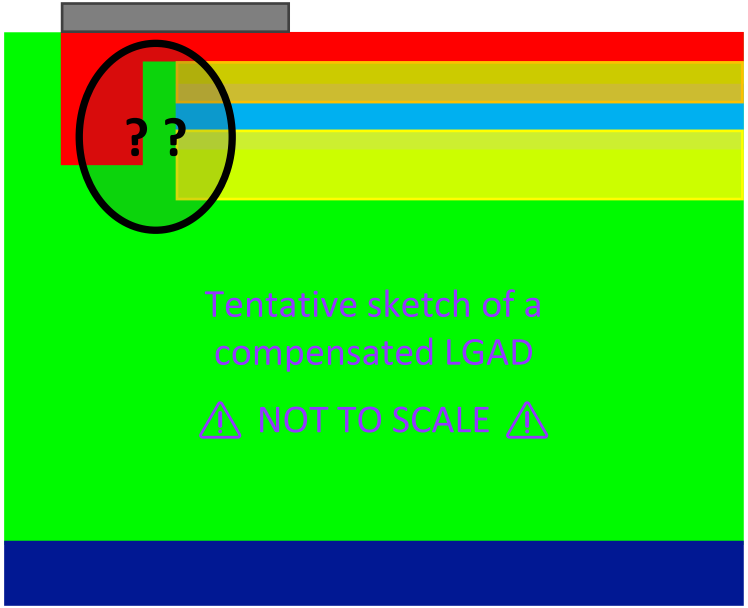
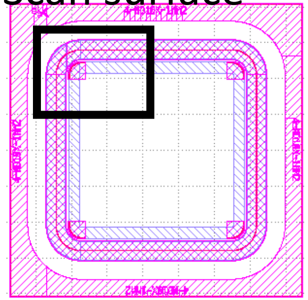


Compensated LGAD – 2D Scan with IR Laser

Ongoing characterisation: investigate with IR laser the edge of the compensated gain implants



Scan surface



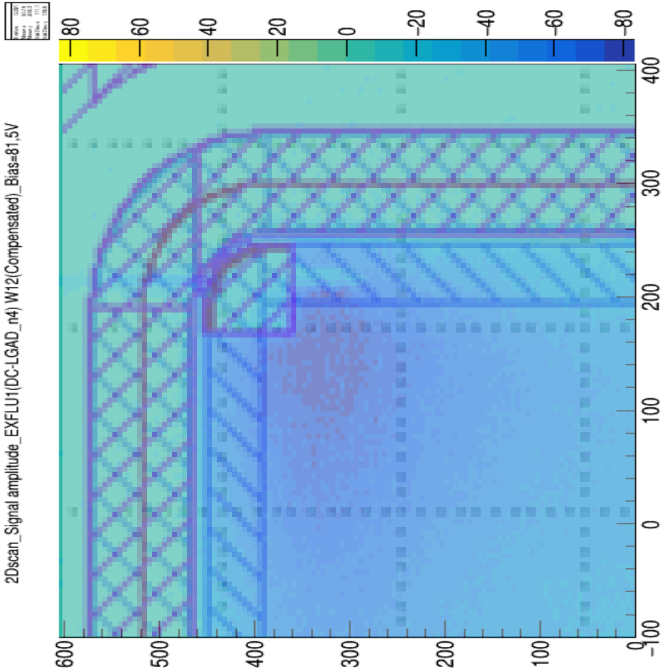
TCT scan with IR laser

Laser spot ~ 10 μm

Sensor from W12 (3–2)

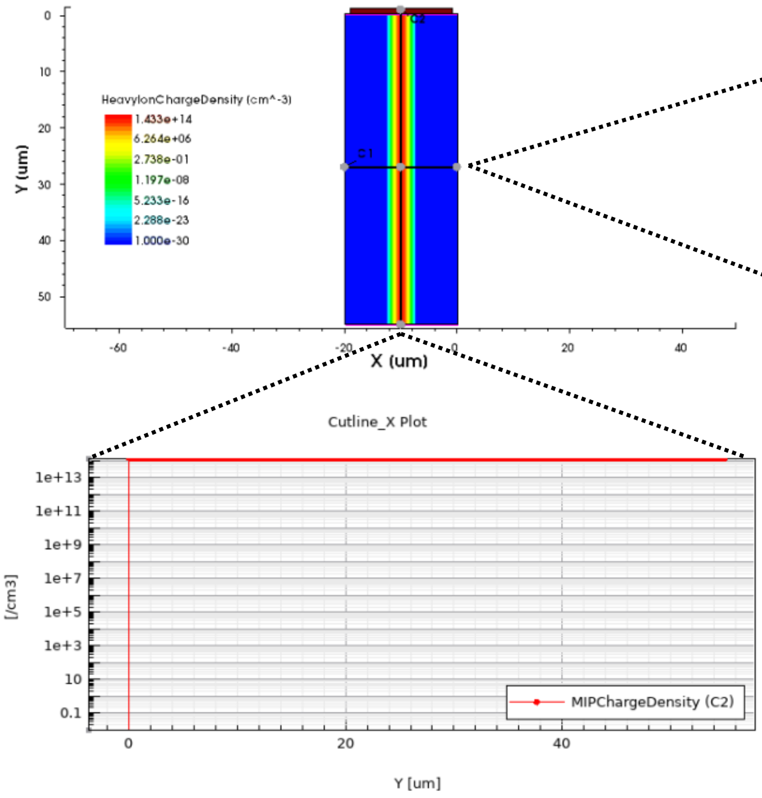
V_{bias} = 81 V

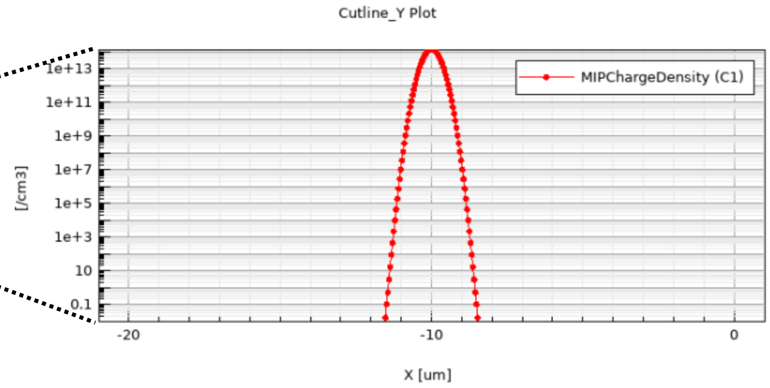
Very close to BD

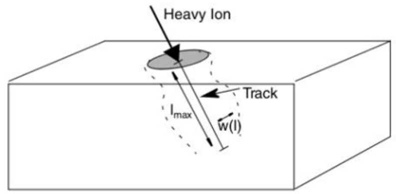


→ **No issues observed at the edge of the compensated gain implants**

Transient responce: “HeavyIon” model







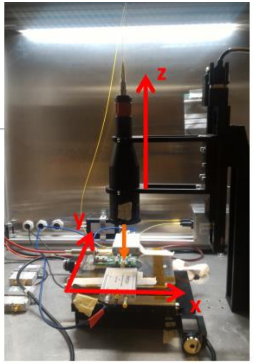
$$G(l, w, t) = G_{LET}(l)\, R(w, l)\, T(t)$$

→ **Gaussian**

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

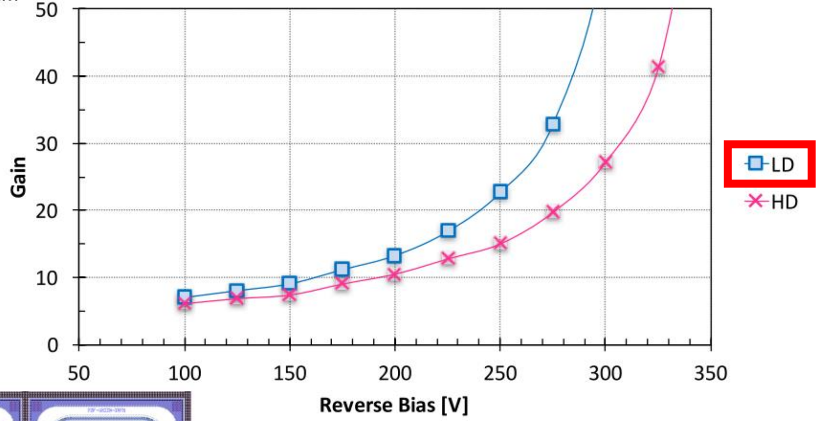
Pre-Irradiation: Experimental Data (FBK UFSD2 Production)

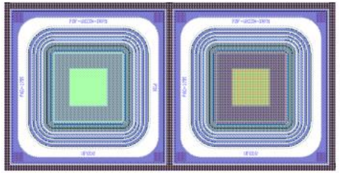
Gain Measurement – Φ=0



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)

LD peak: 6.1E16/cm³ => 6.4E16/cm³ (*)
HD peak: 4.0E16/cm³





GAIN = Charge LGAD / Charge PiN

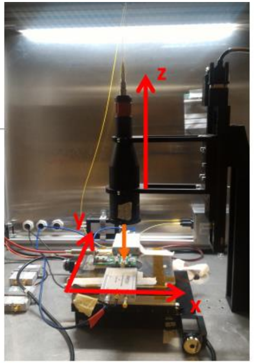
Bias [V]	Gain LD (W1)	Gain HD (W8)
100	7.1	6.1
125	8.1	6.9
150	9.1	7.4
175	11.2	9.1
200	13.3	10.5
225	16.9	12.8
250	22.7	15.1
275	32.8	19.8
300	61.8	27.2
325	248.8	41.3
350	-	82.3

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

V. Sola SIMULATION PLAN 2

Post-Irradiation: Experimental Data (FBK UFSD2 Production)

Gain Measurement – Irradiated LD



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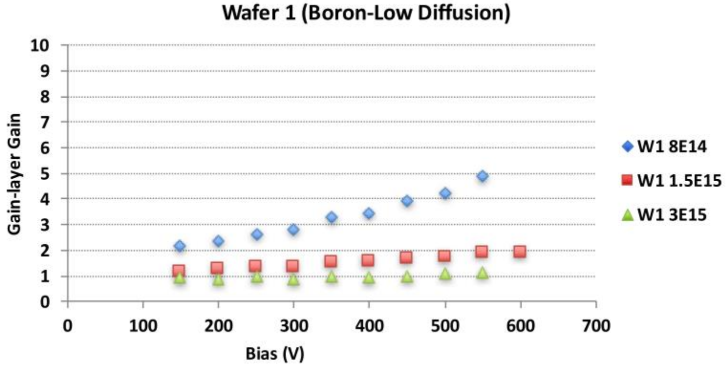


GAIN = Charge LGAD / Charge PiN
irradiated at the same fluence
→ gain from gain layer only

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

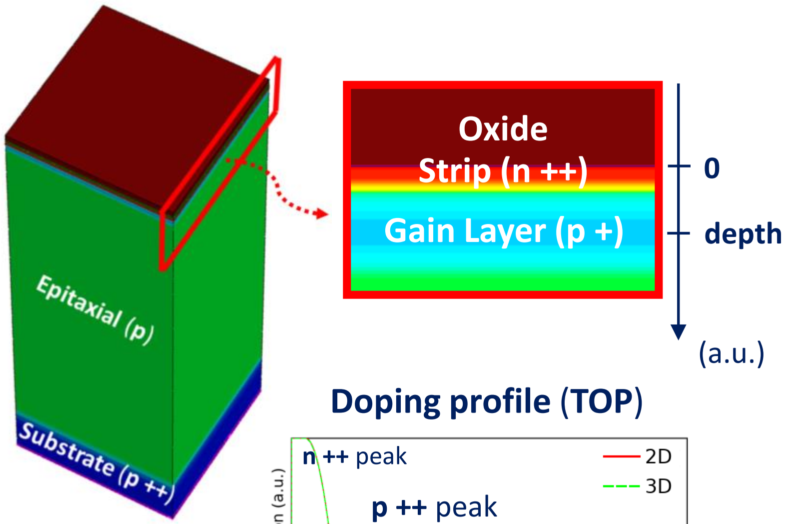
W1

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

V. Sola SIMULATION PLAN 3

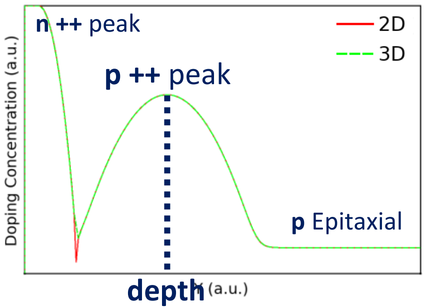
Gain calculation (3D)

✓ **Fully-3D** structure

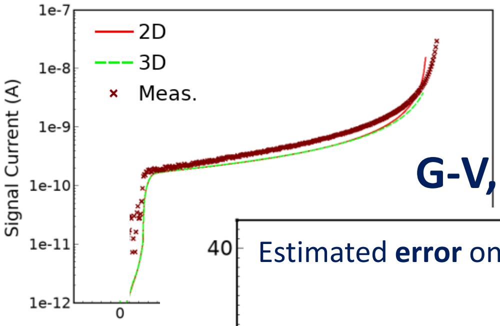


Doping profile (TOP)

Gaussian Gain Layer **profile**

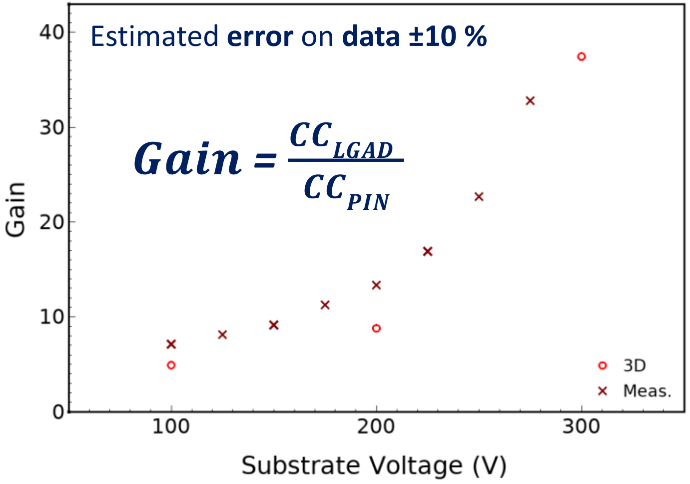


I-V, before irradiation



Good agreement!

G-V, before irradiation



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

Avalanche model: **Massey**. Temp. **300 K**. Electrical contact area **1mm²**