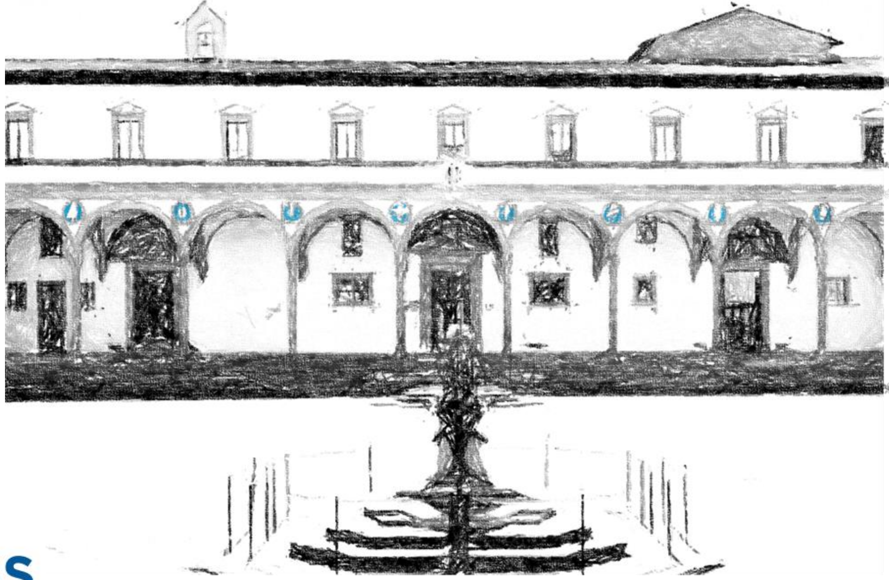


IFAE 2024

Frontiera Energia
Frontiera Intensità
Cosmologia ed Astroparticelle
Nuove Tecnologie

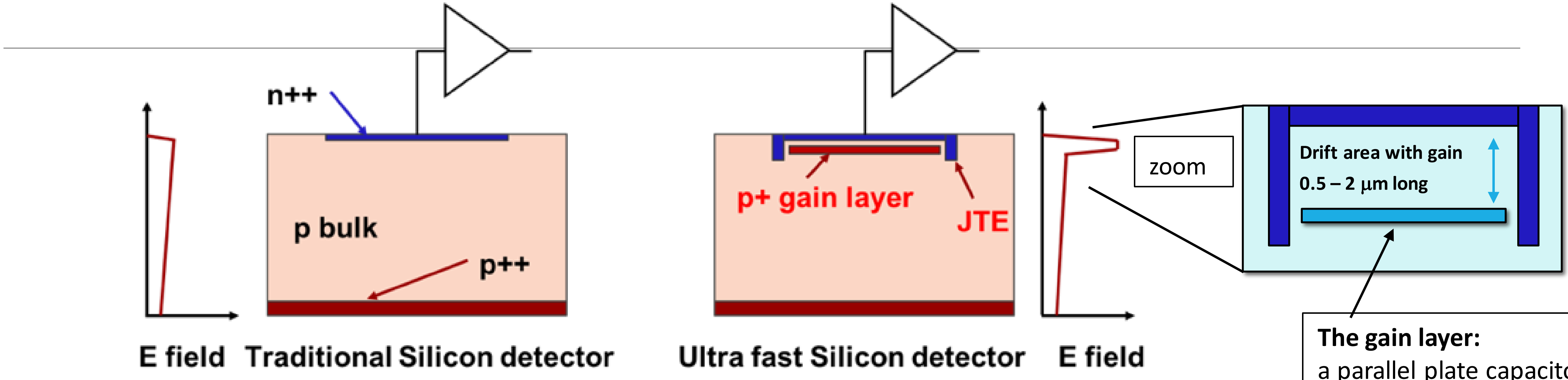
Firenze, 3-5 Aprile 2024
Istituto degli Innocenti, Piazza SS Annunziata

Sensori al silicio per l'alta intensità

F. Moscatelli, IOM-CNR e INFN di Perugia

V. Sola, G. Paternoster, A. Morozzi, L. Anderlini, R. Arcidiacono, M. Barozzi, G. Borghi, M. Boscardin, N. Cartiglia, M. Centis Vignali, M. Costa, T. Croci, M. Ferrero, F. Ficorella, A. Fondacci, S. Giordanengo, O. Hammad Ali, C. Hanna, L. Lanteri, L. Menzio, D. Passeri, N. Pastrone, F. Siviero, R.S. White

First design innovation: low gain avalanche diode (LGAD)



The gain layer:
a parallel plate capacitor
with high field

The LGAD sensors, as proposed and first manufactured by CNM

(National Center for Micro-electronics, Barcelona):

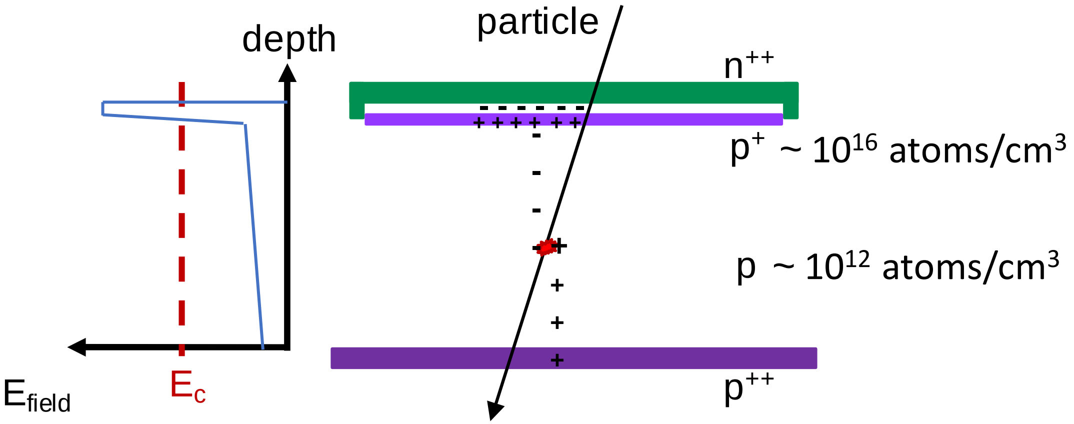
High field obtained by adding an extra doping layer

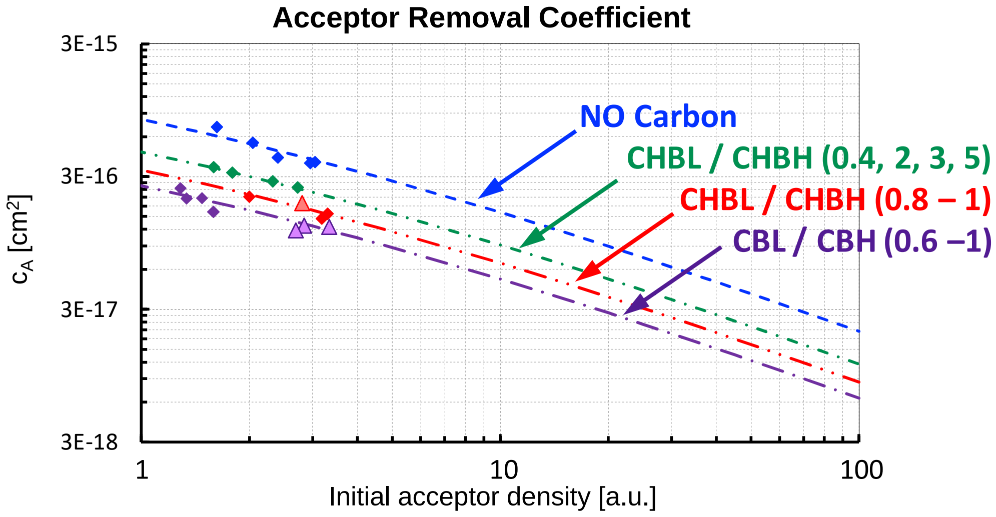
E ~ 300 kV/cm, closed to breakdown voltage

- The low-gain mechanism, obtained with a moderately doped p-implant, is the defining feature of the design.

Low gain is the key ingredient to good temporal resolution

Gain Removal Mechanism in LGADs





The acceptor removal mechanism deactivates the p^+-doping of the **gain implant** with irradiation as

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

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

$\Phi_0 = 1/c_A$ ~ the fluence at which multiplication power of the gain implant reaches unity

▲ thin sensors from the EXFLU1 batch

[R.S. White, 43rd RD50 Workshop (2023) CERN]

⇒ Is it possible to reduce c_A further?

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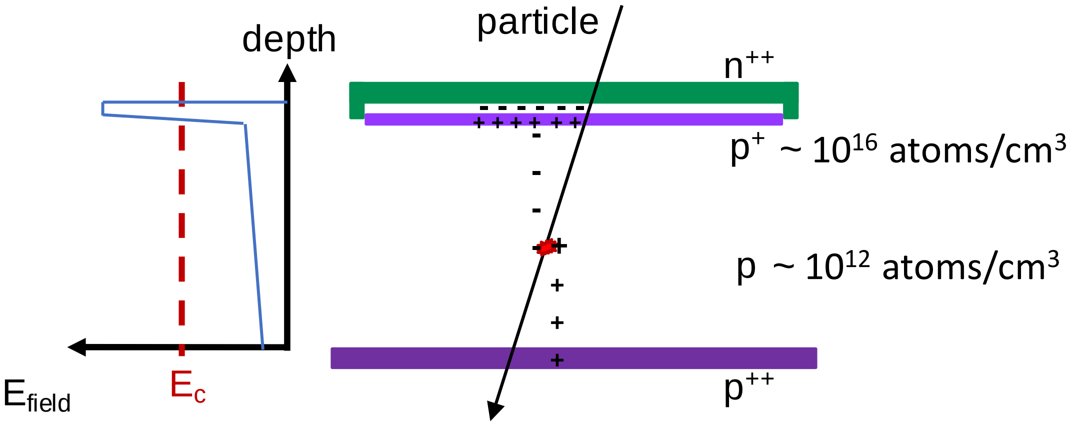
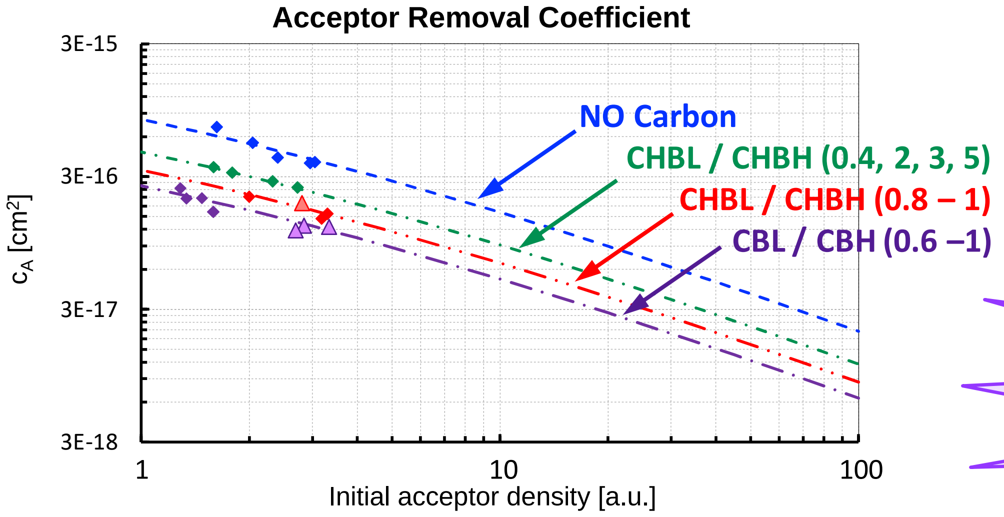
Gain Removal Mechanism in LGADs





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[R.S. White, 43rd RD50 Workshop (2023) CERN]

⇒ Is it possible to reduce c_A further?

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Towards a Radiation Resistant Design

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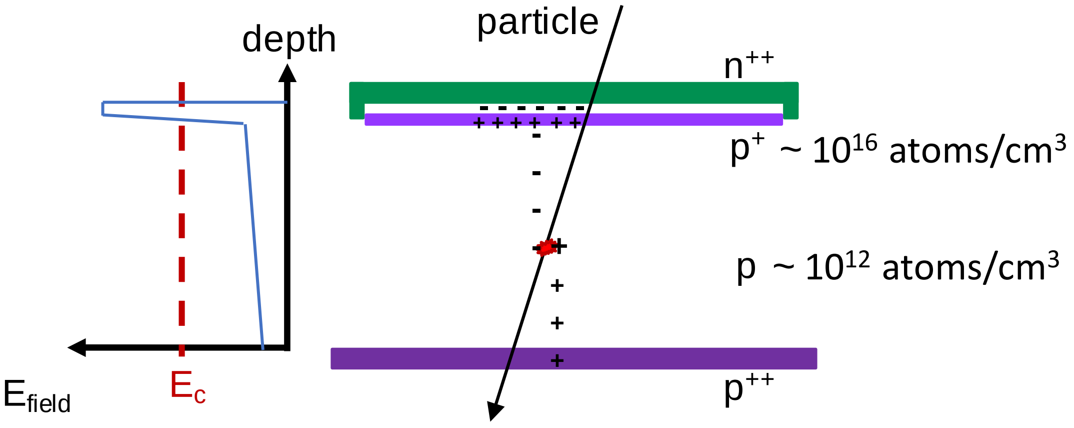
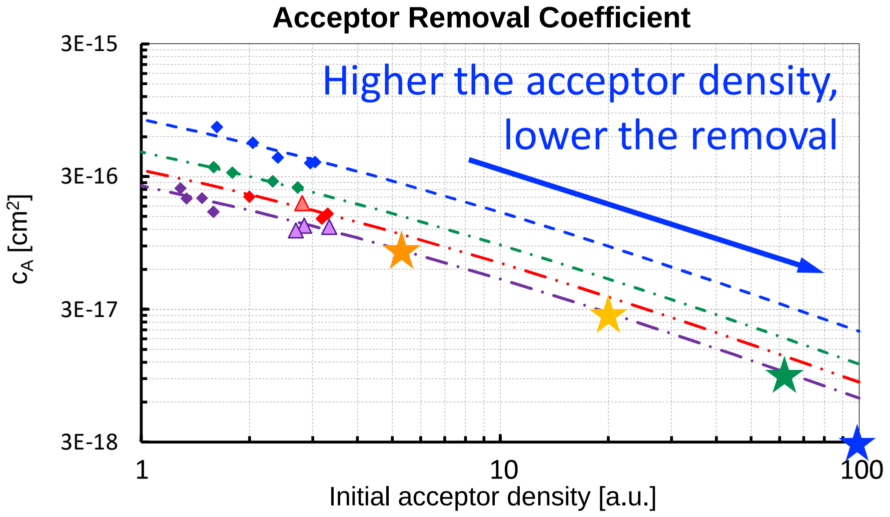


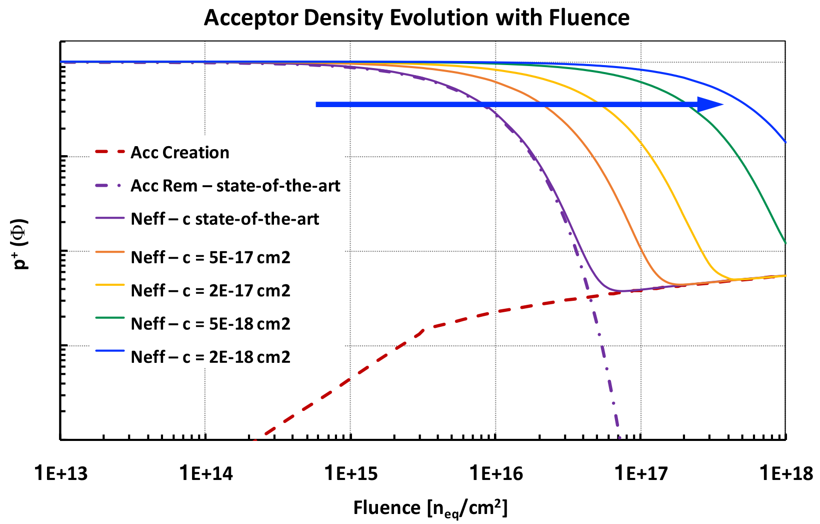
The acceptor removal mechanism deactivates the p^+-doping of the **gain implant** with irradiation as

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

where c_A is the acceptor removal coefficient

To substantially reduce c_A, it is necessary to increase $p^+(0)$, the initial acceptor density

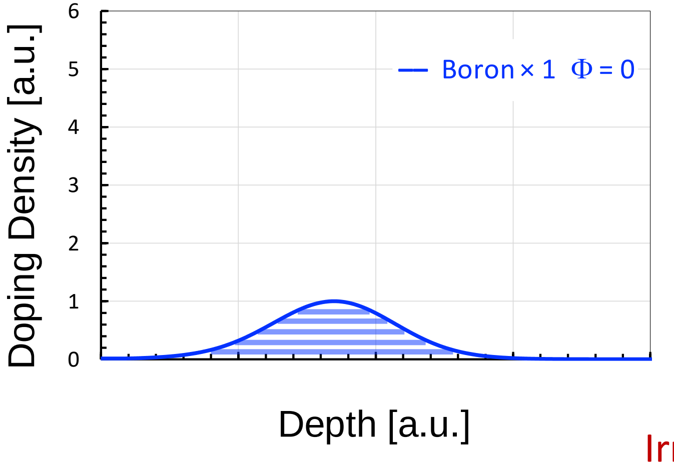




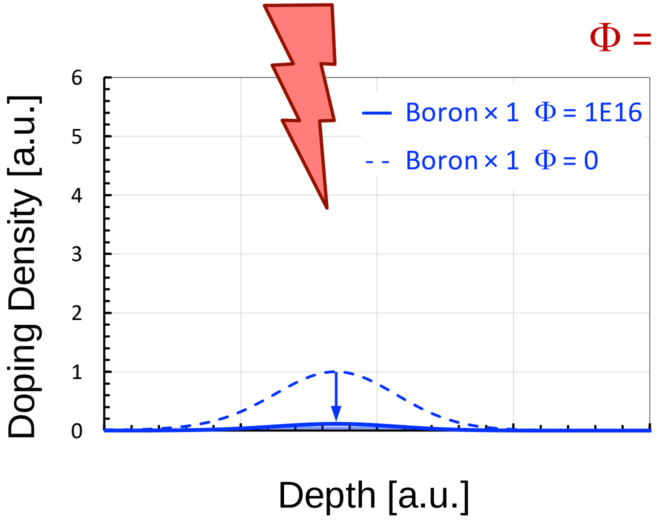
Lowering c_A can extend the gain layer survival up to $\Phi \geq 10^{17}$ n_{eq}/cm²

A new Paradigm – Compensation

Doping Profile – Standard LGAD



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



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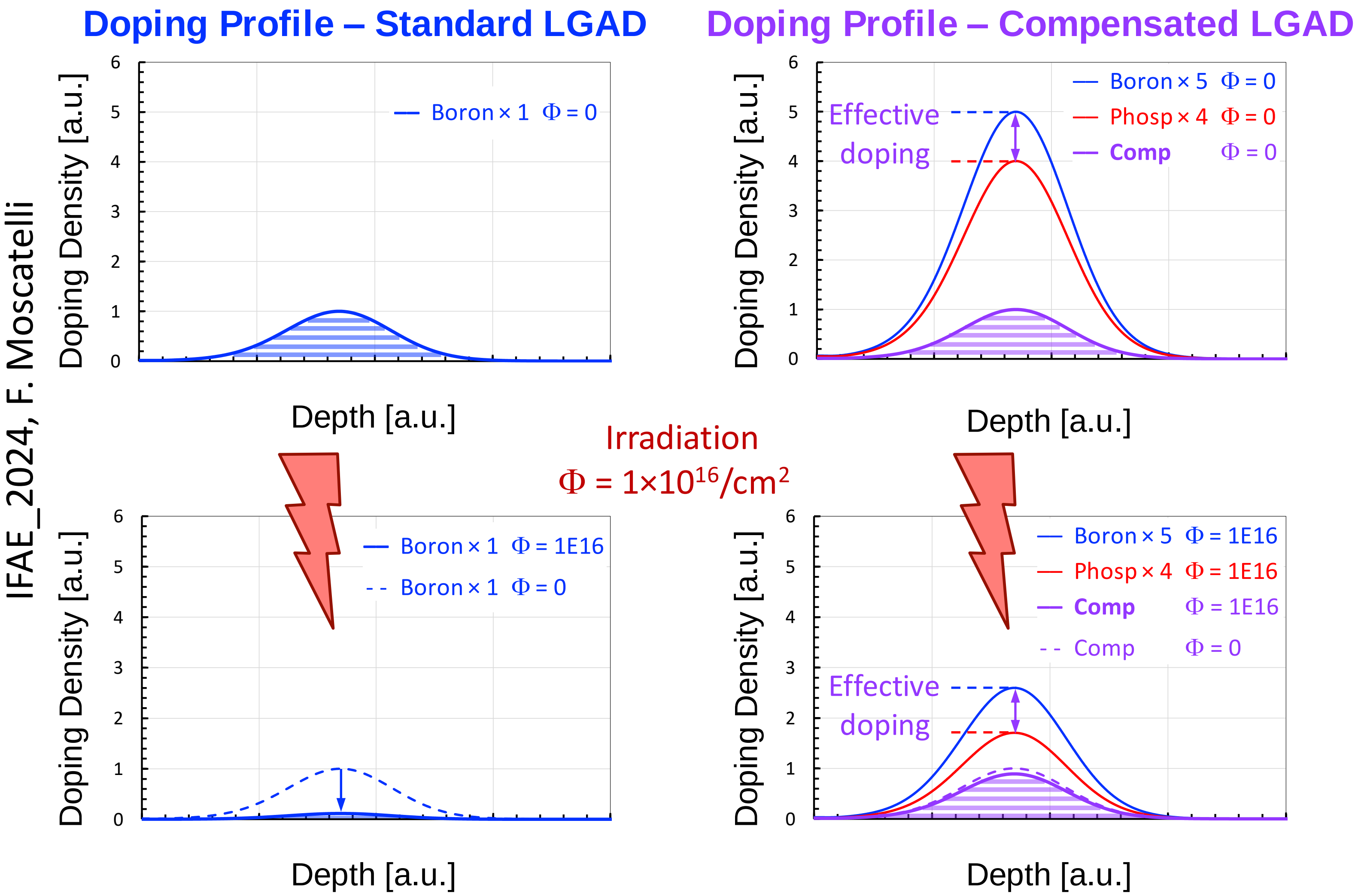
A new Paradigm – Compensation



A new Paradigm – Compensation

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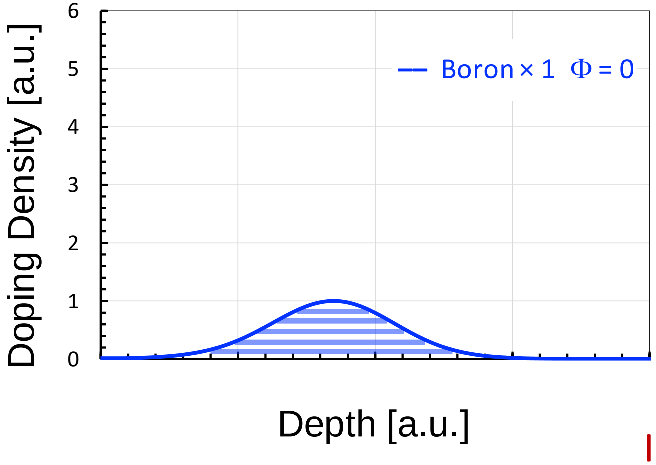
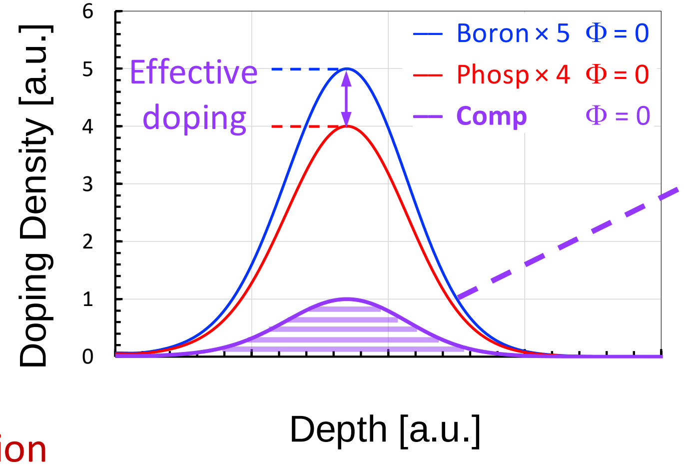
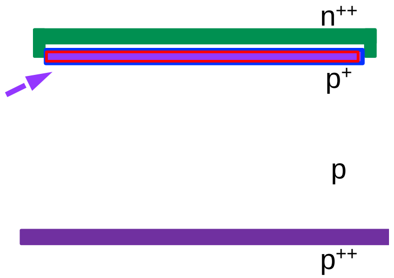
Doping Profile – Standard LGAD



Doping Profile – Compensated LGAD

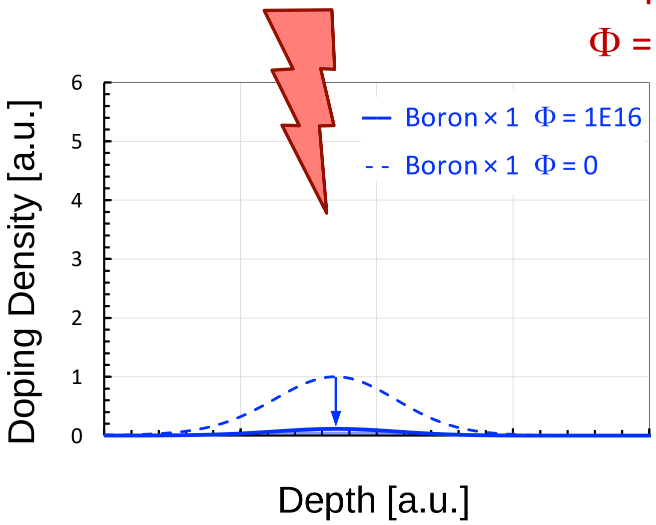


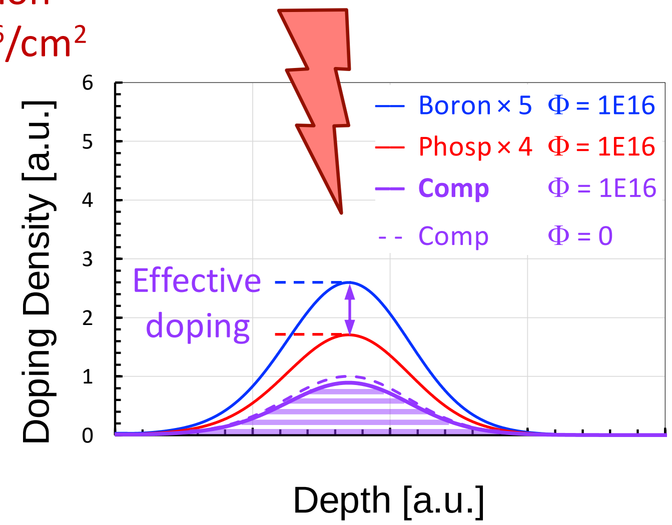


Compensated LGAD

Irradiation

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





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

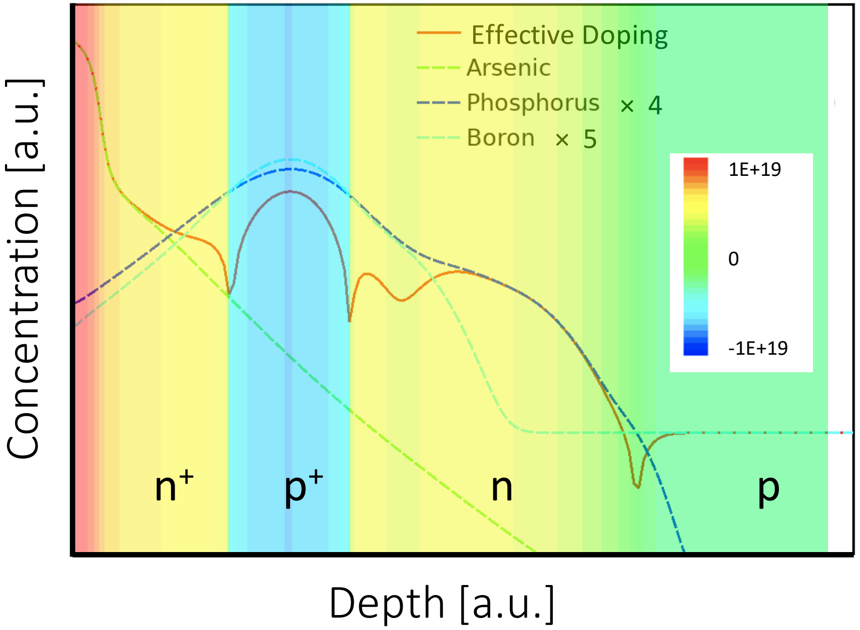
Many unknowns:

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

Compensation from Simulation

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

Doping Profiles from Process Simulation



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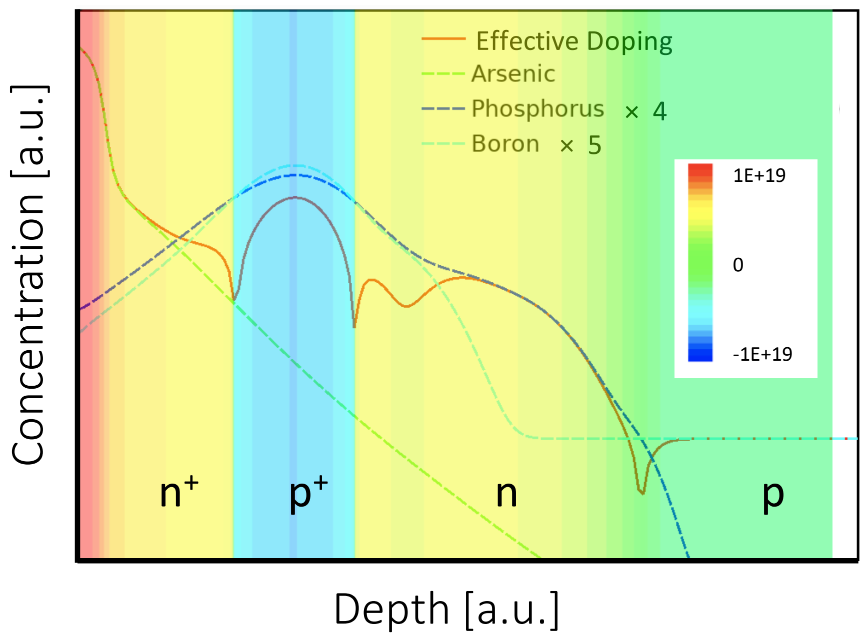
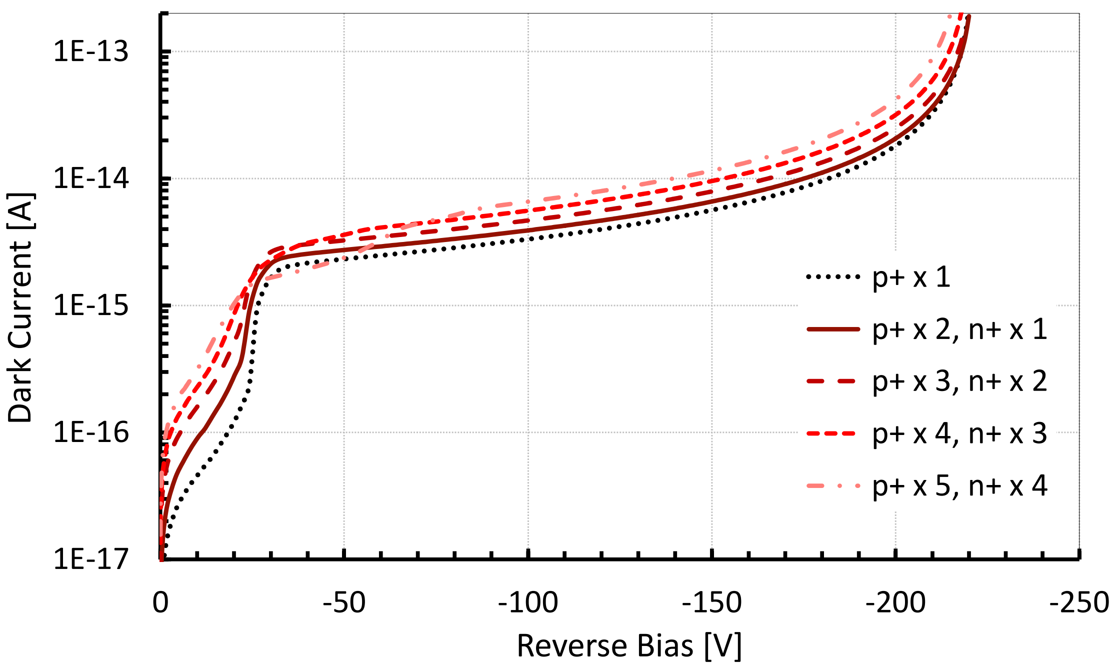
Compensation from Simulation

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

Doping Profiles from Process Simulation



Compensated LGAD – I-V from Simulation



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→ The simulation of the electrostatic behaviour shows that it is possible to reach similar multiplication for different initial concentrations of p^+ and n^+ dopants

First Compensated LGADs – EXFLU1

First compensated LGAD sensors have been released by FBK in the framework of the EXFLU1 batch

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Other R&D paths pursued by the EXFLU1 batch to extend the radiation tolerance of the LGAD sensors:

- new guard ring design
- decrease of the acceptor removal – carbon shield
- thin substrates (15–45 µm)

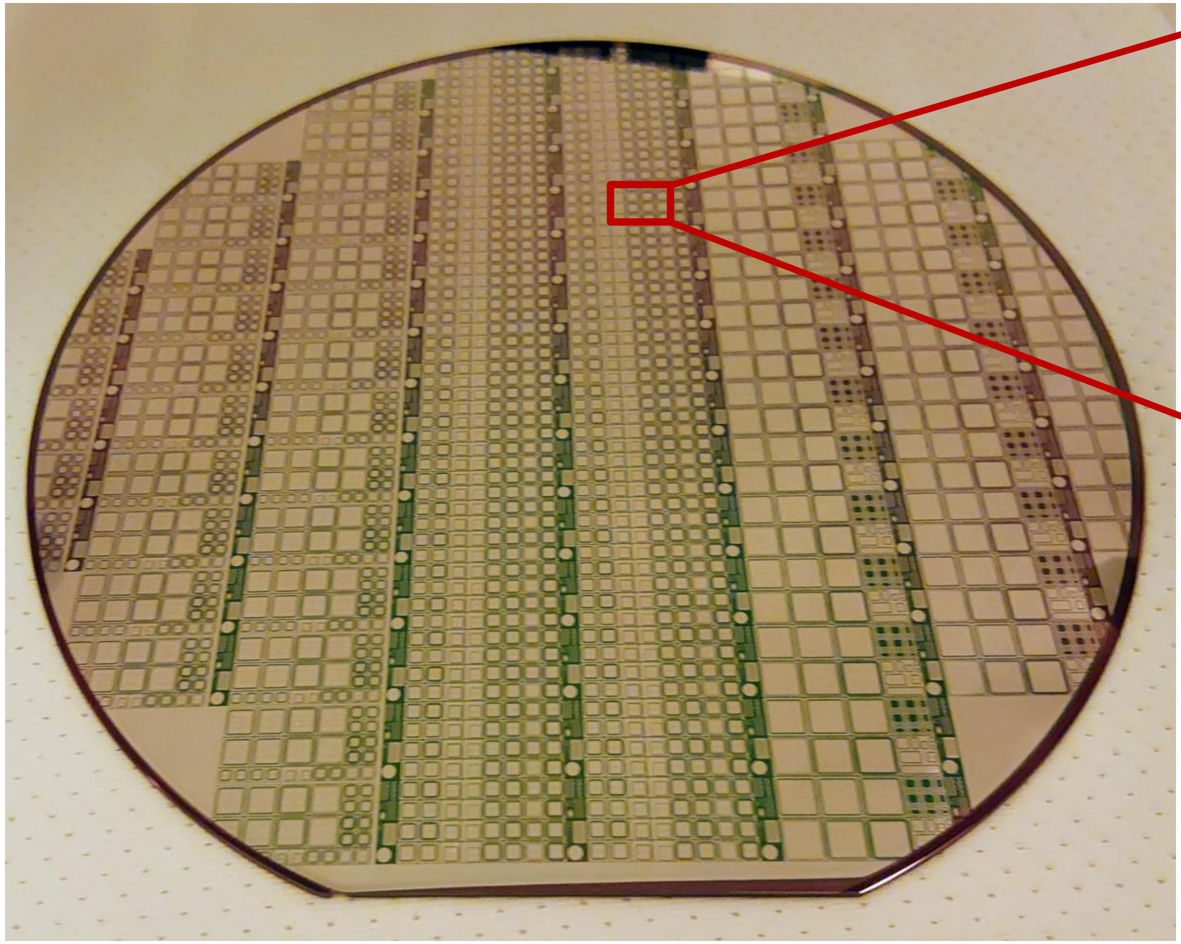
Design and preparatory studies have been performed in collaboration with the **Perugia group**

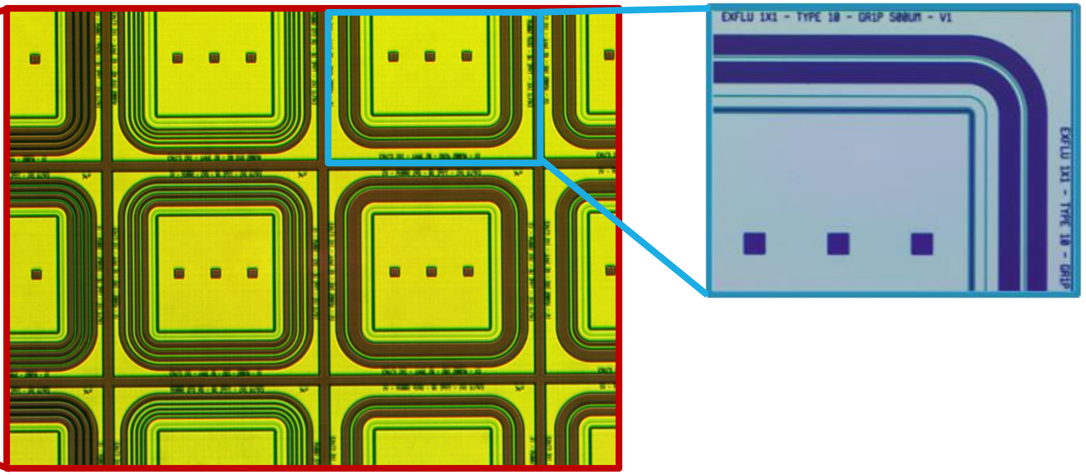
→ The EXFLU1 wafers exited the FBK clean room at the end of 2022

[V. Sola, TREDI 2023, Trento]

First Compensated LGADs – EXFLU1

6” Wafer





⇒ An extensive testing campaign on compensated LGADs started 1 year ago and is still ongoing

Compensated Gain Layer Design – Split Table

Active thickness 30 μm

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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 on wafer

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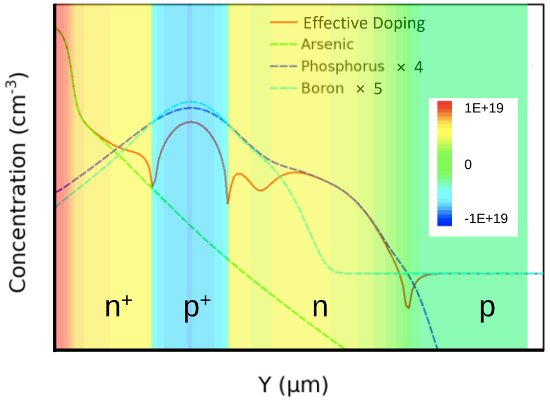
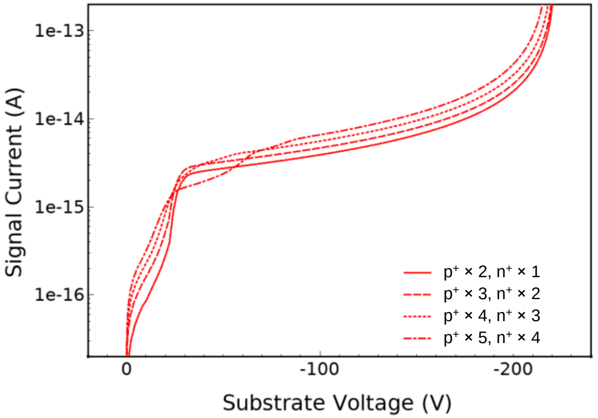
Simulation





Compensated LGAD – I-V on wafer

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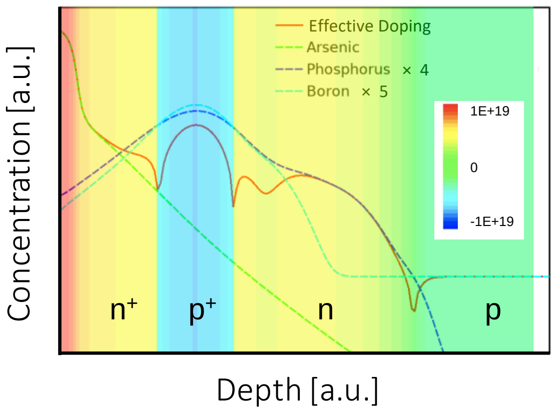
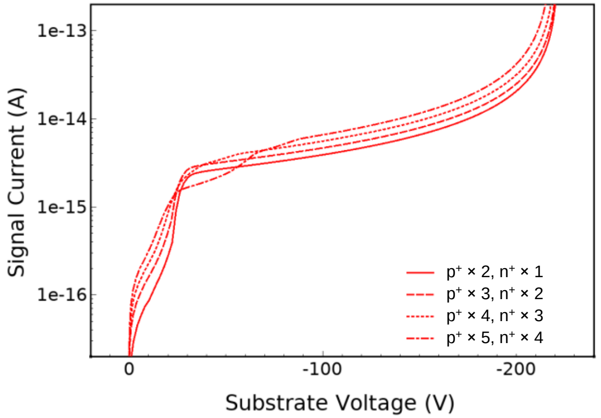
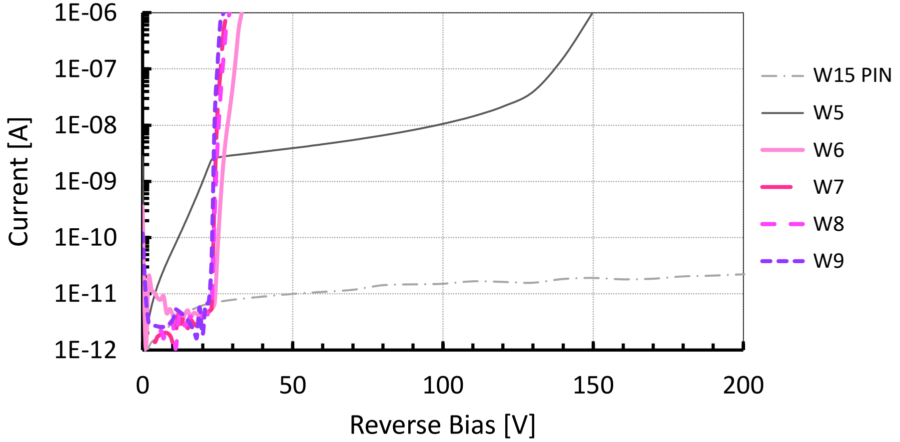
Simulation





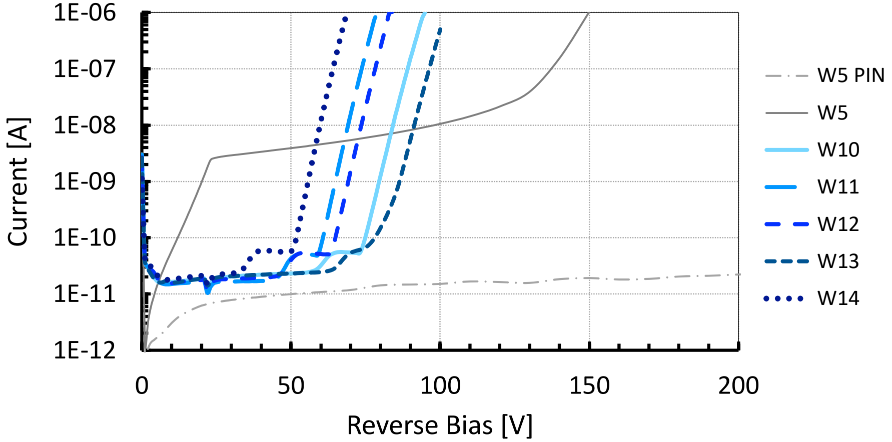
EXFLU1 – Compensated LGAD 2–1 – I-V



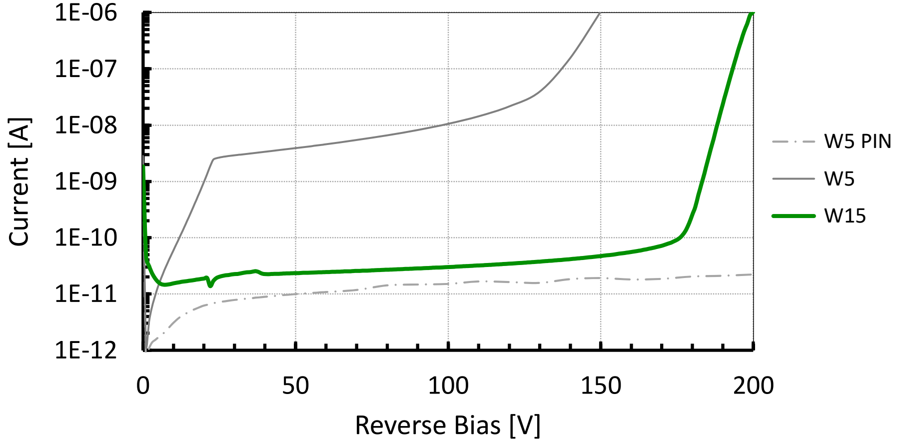
2 – 1

EXFLU1 – Compensated LGAD 3–2 – I-V

3 – 2

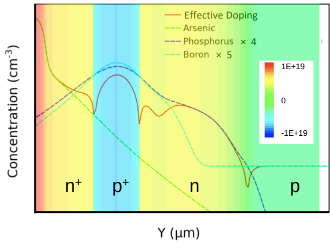


EXFLU1 – Compensated LGAD 5–4 – I-V



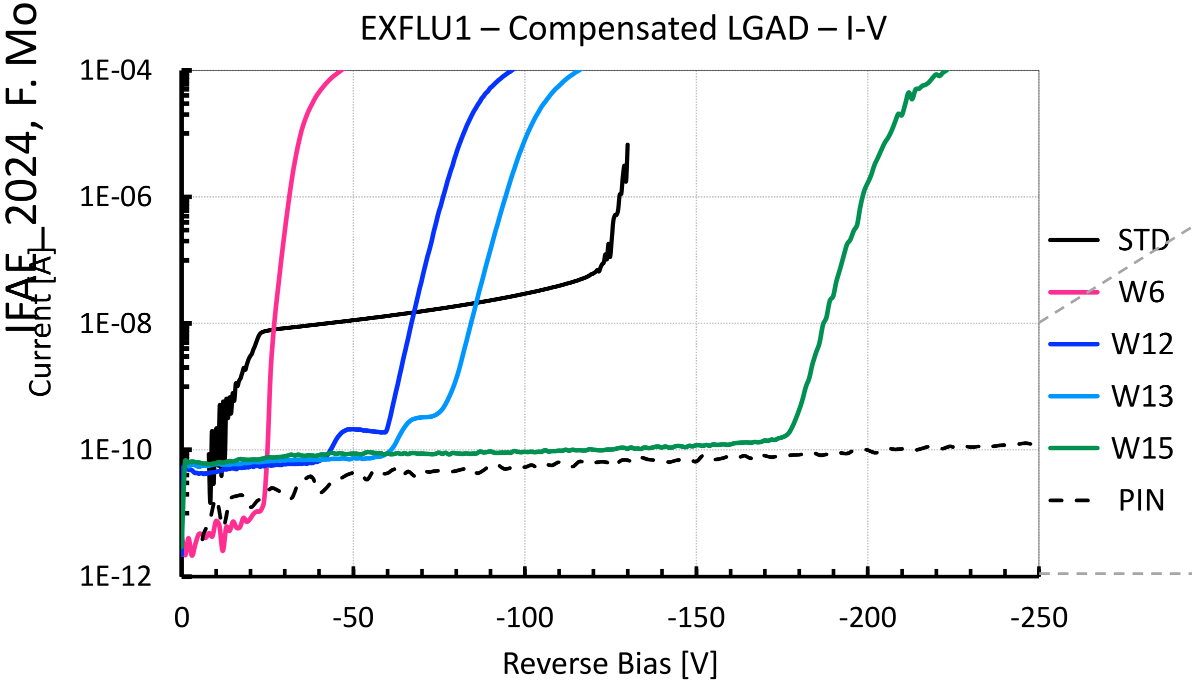
5 – 4

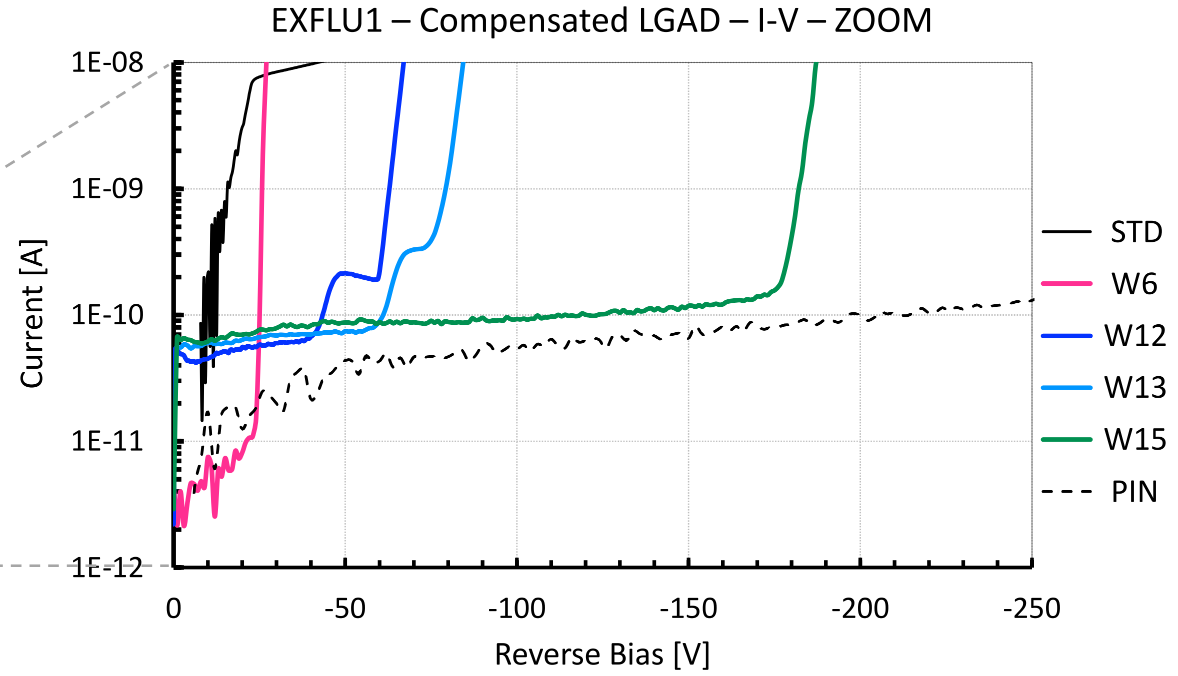
Compensated LGAD – I-V



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**

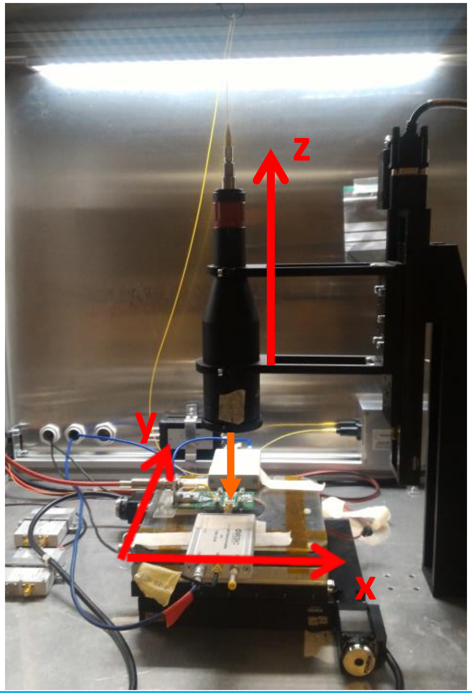




IR Laser Stimulus on Compensated LGAD 2–1

IFAE_2024, F. Moscatelli

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

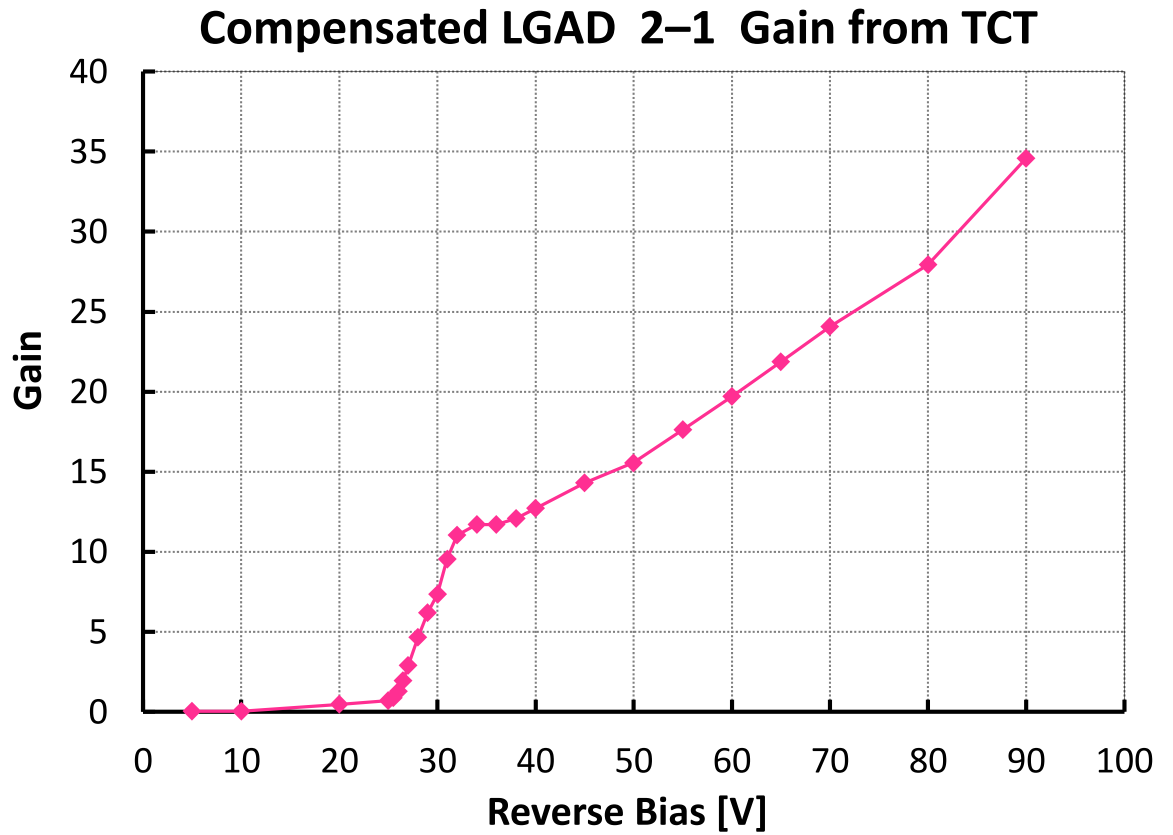


$$\mathbf{Gain} = \frac{Q_{LGAD}}{< Q_{PiN} >}$$

Laser intensity
~ 10 MIPs

T = RT
Φ = 0

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 3–2+C

TCT Setup from Particulars
Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
T = -20ºC

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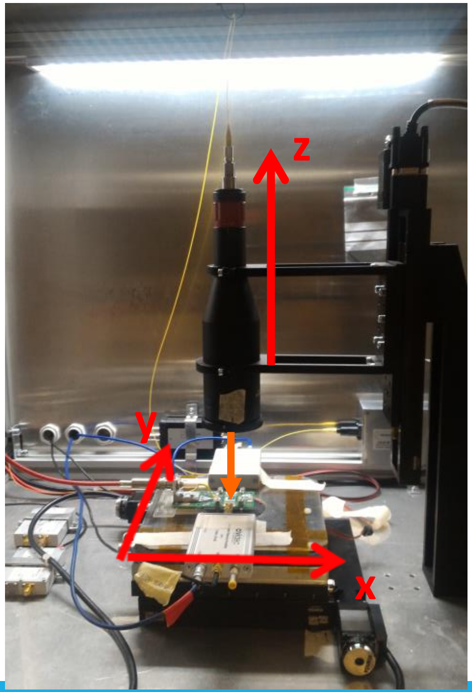
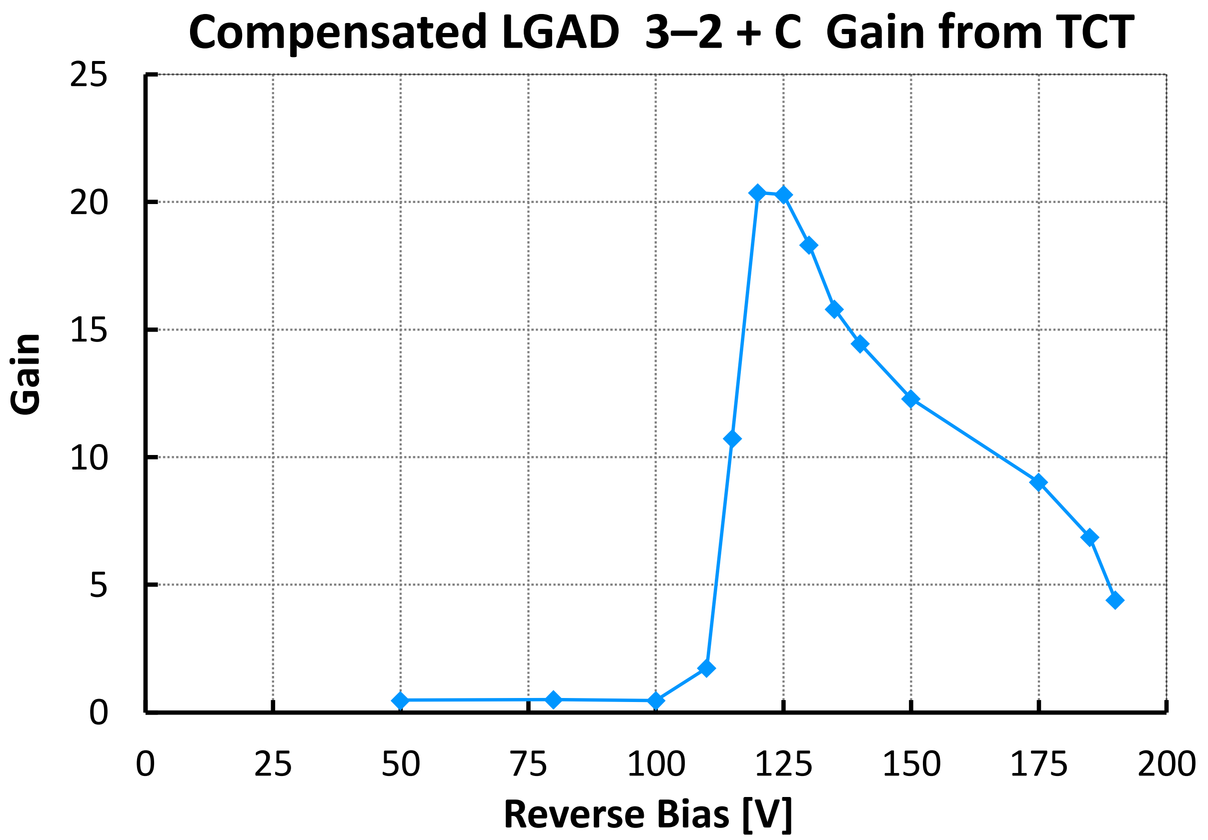


$$\text{Gain} = \frac{Q_{LGAD}}{\langle Q_{PiN} \rangle}$$

Laser intensity
~ 4 MIPs

$\Phi = 0$

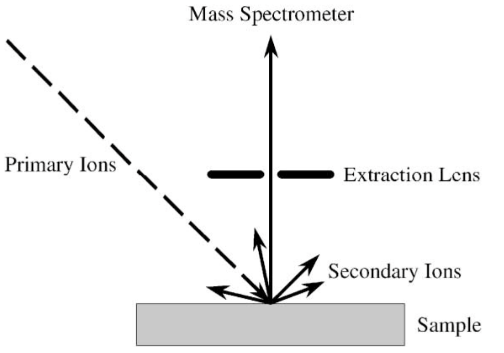
Laser stimulus on a LGAD-PiN structure from W13 (3 – 2 + C)



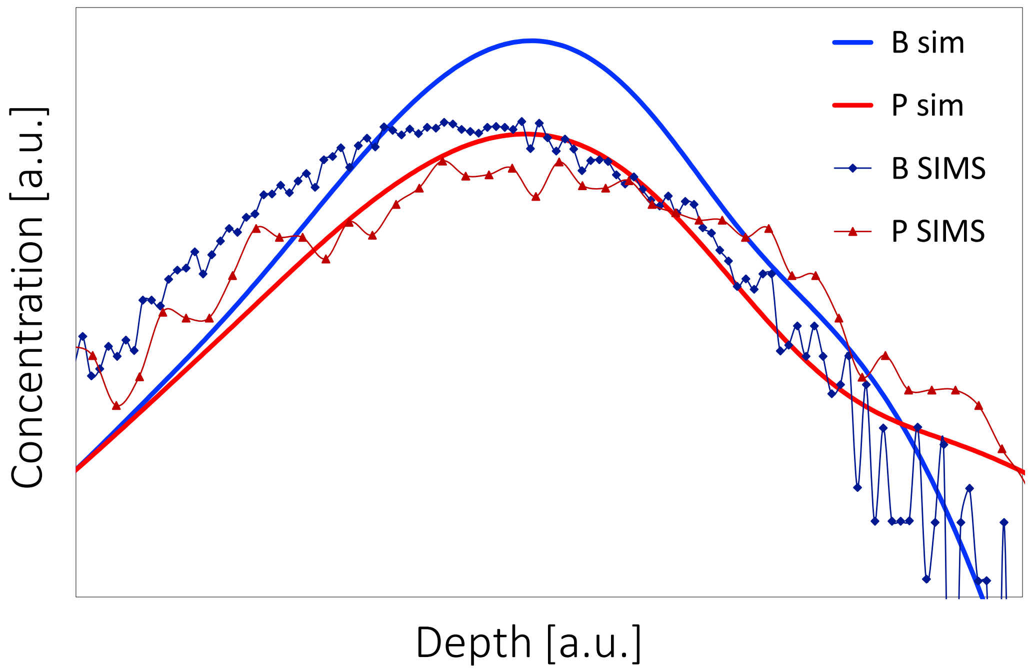
→ **Difficult to operate 3 – 2 + C compensated LGAD sensors**

Secondary Ion Mass Spectroscopy – W15

IFAE_2024, F. Moscatelli



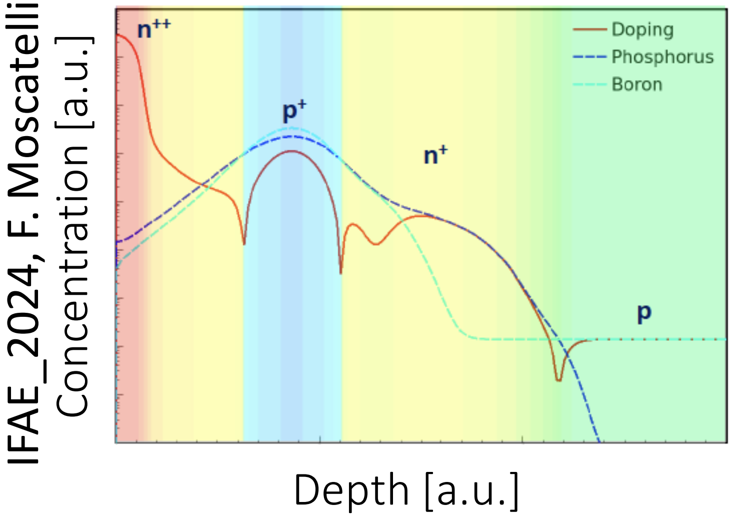
Compensated LGAD – W15 5-4
SIMS vs Process Simulation



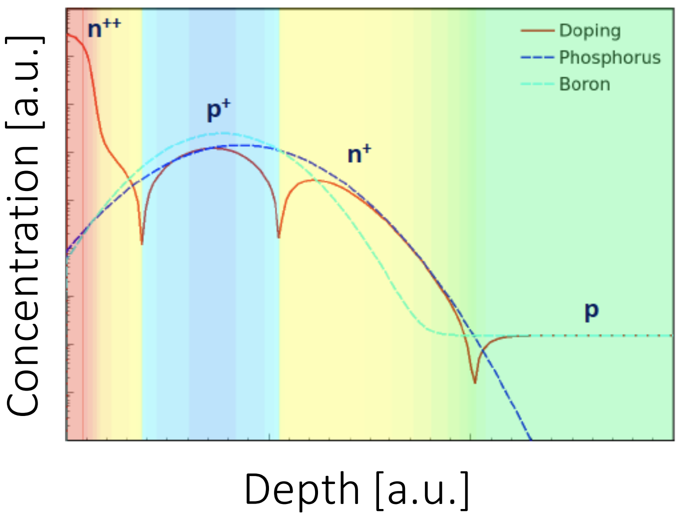
- Boron peak is shallower than phosphorus
- Boron peak is lower than predicted from simulation

SIMS Profile & I-V – 5–4

Doping Profiles
from Process Simulation



Doping Profiles
from SIMS



SIMS Profile & I-V – 5–4

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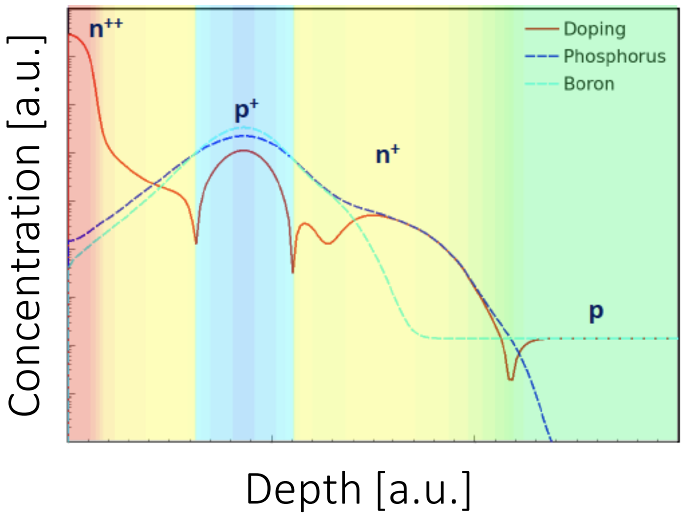
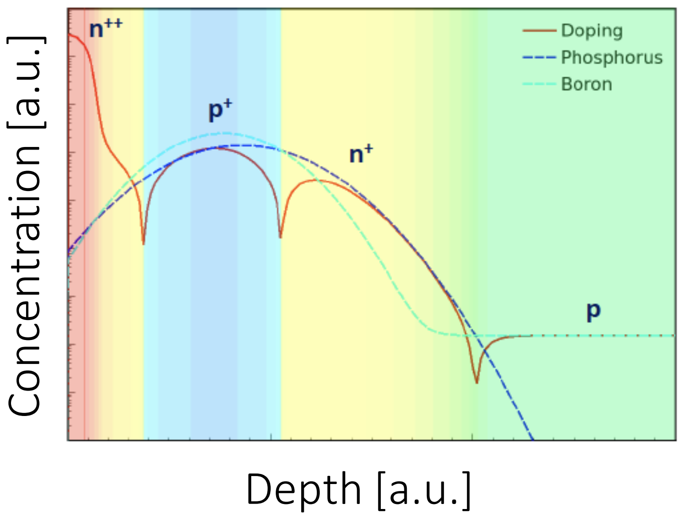
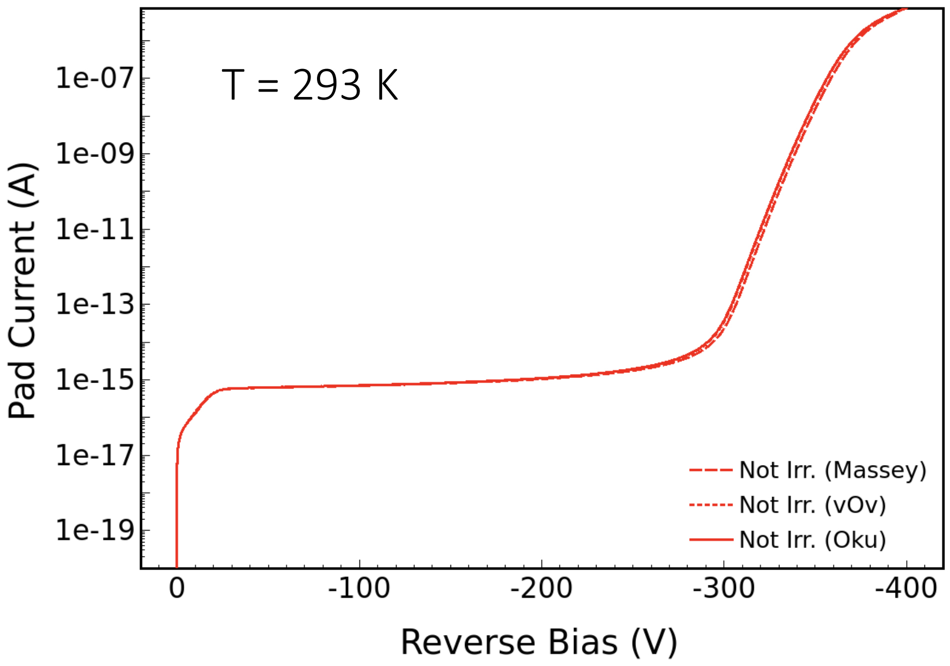
Doping Profiles
from Process Simulation



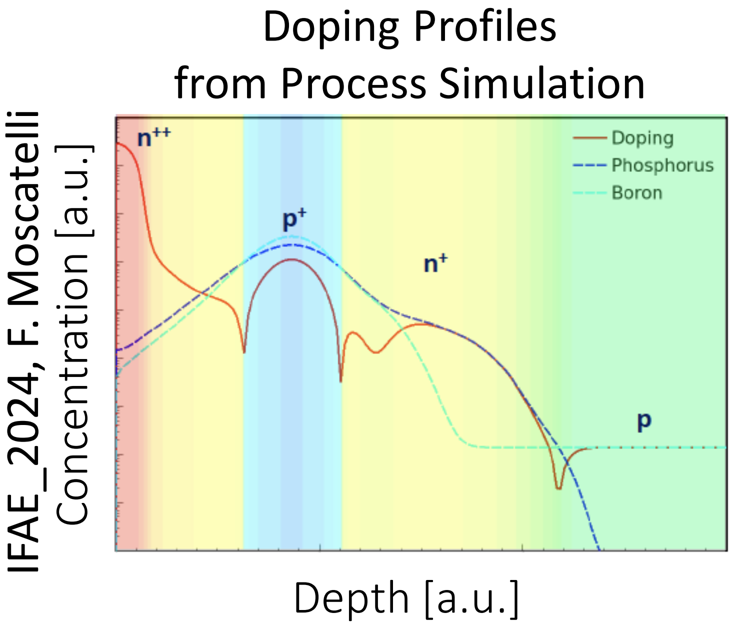
Doping Profiles
from SIMS

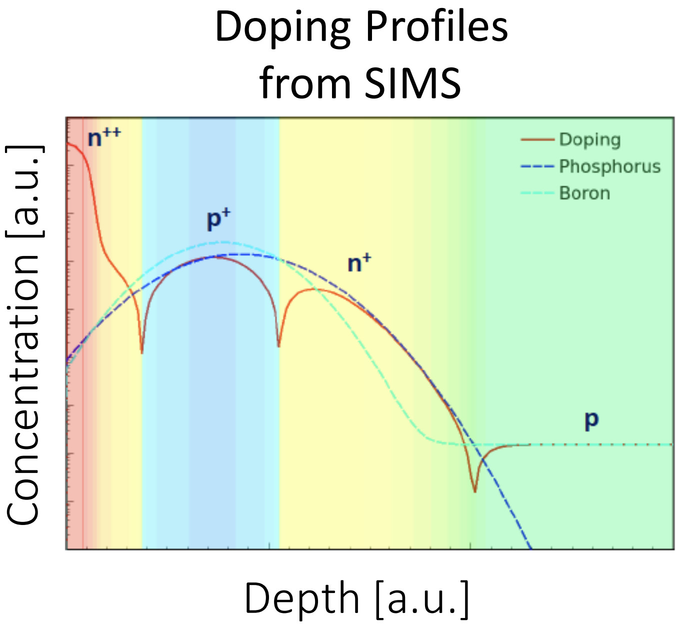


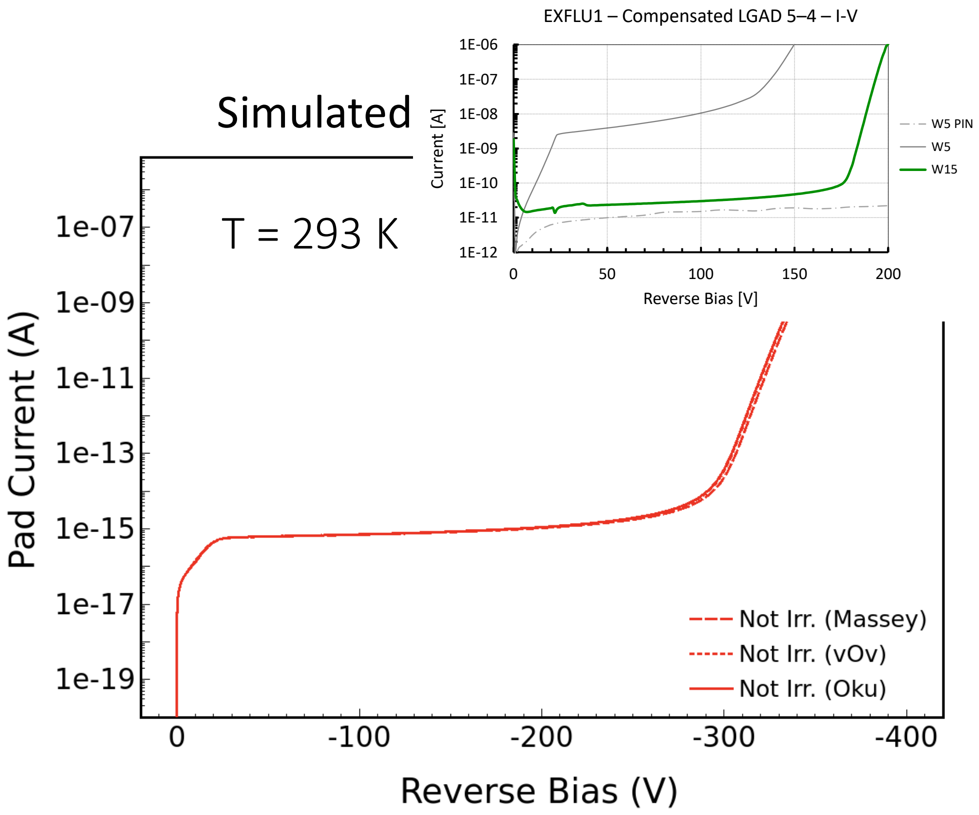
Simulated I-V from SIMS Profiles



SIMS Profile & I-V – 5–4

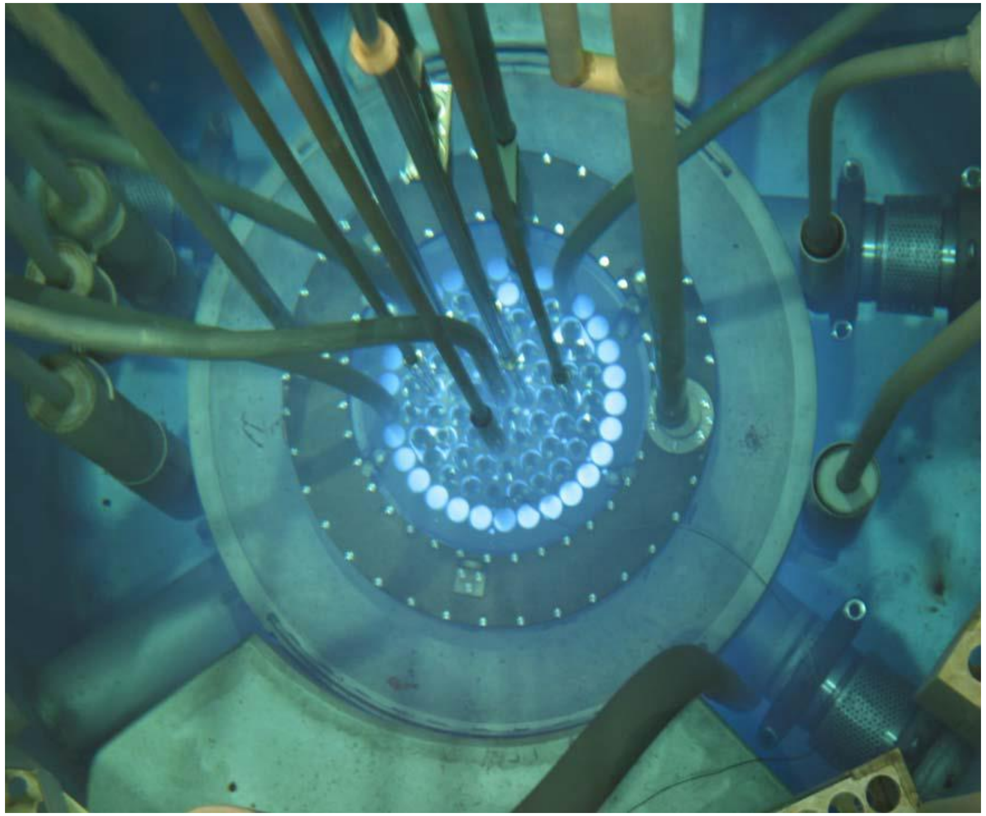






→ **The simulated I-V reproduces the trend of the measured I-V from W15**

Neutron Irradiation of Compensated LGADs



Compensated LGAD sensors have been irradiated with neutrons at the JSI TRIGA Reactor Irradiation Facility (Ljubljana)

Irradiation fluences from 1E14 to 5E15 n_{eq}/cm^2

Fluence uncertainty ± 5%

I-V from Compensated LGAD – Irradiated

$[\Phi] = n_{eq}/cm^2$

$T_{F=0} = +20^oC$

$T_{IRR} = -20^oC$

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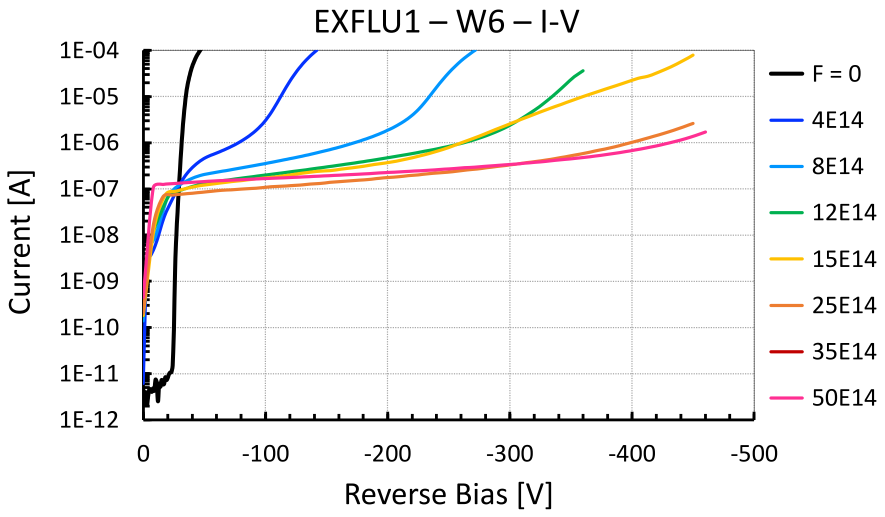
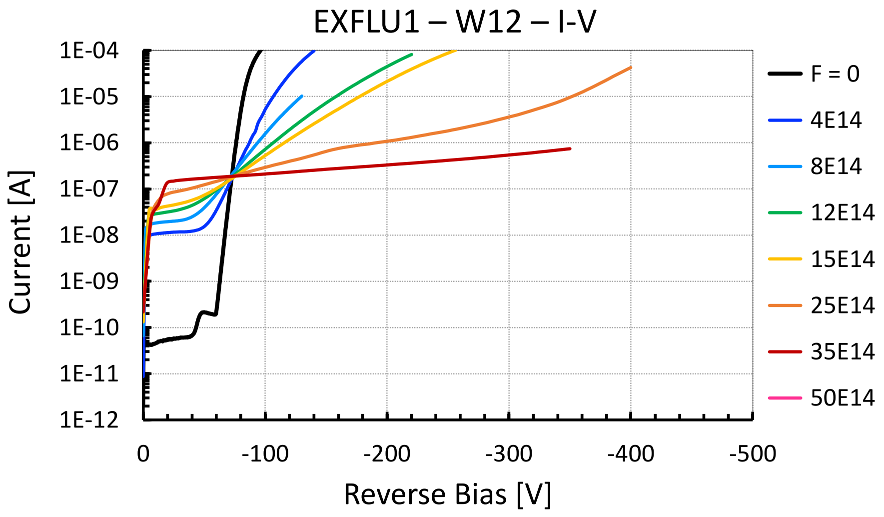
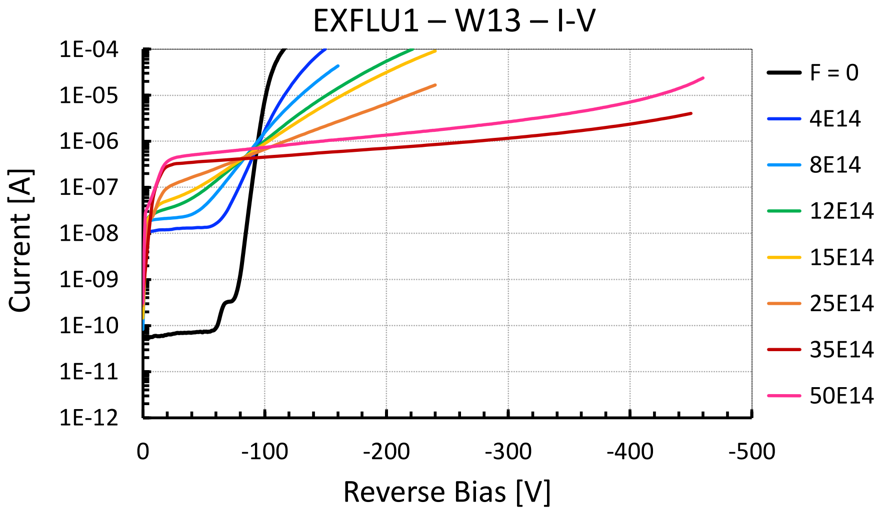
W6
2 – 1

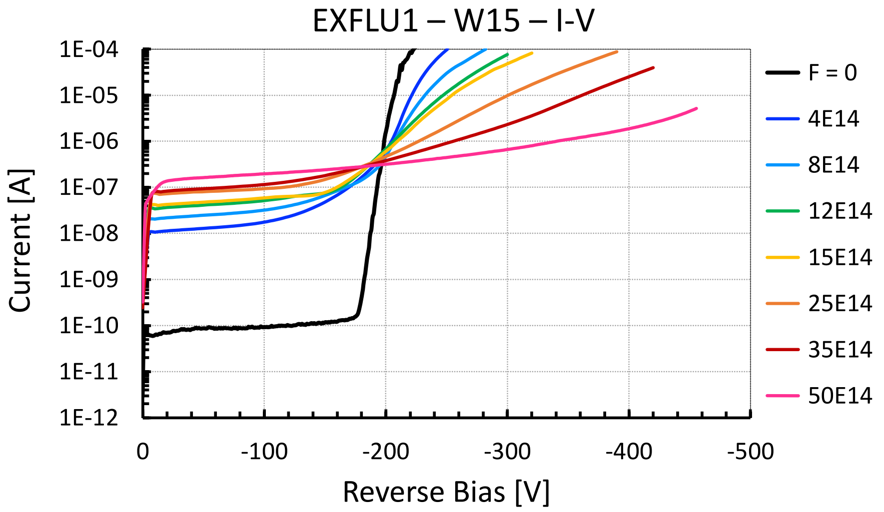




W12
3 – 2

W13
3 – 2 + C





W15
5 – 4

C-V from Compensated LGAD – Irradiated

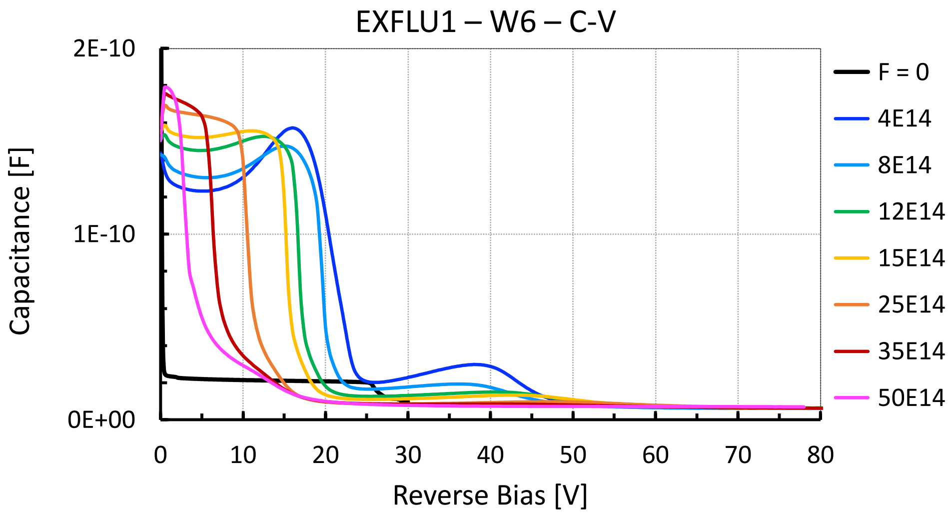
$[\Phi] = n_{eq}/cm^2$

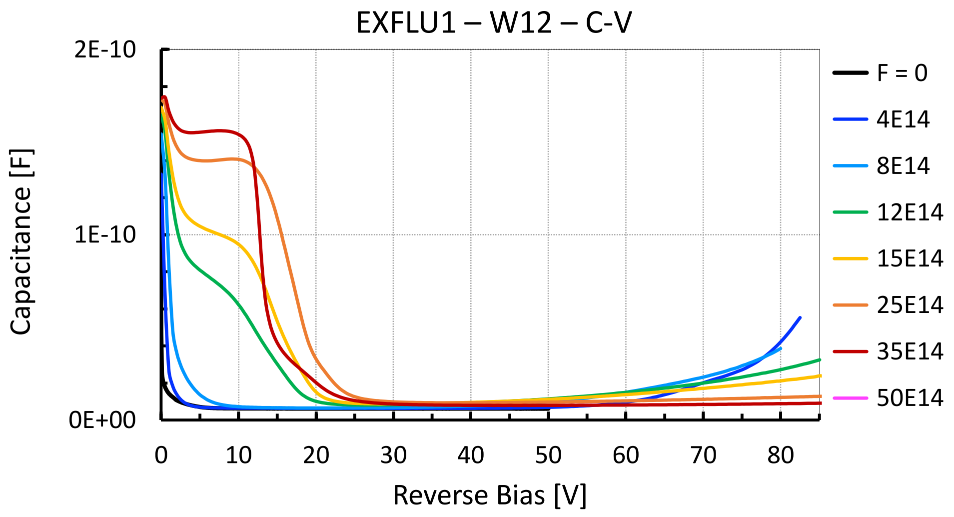
$T = + 20^oC$

f = 2k Hz

IFAE_2024, F. Moscatelli

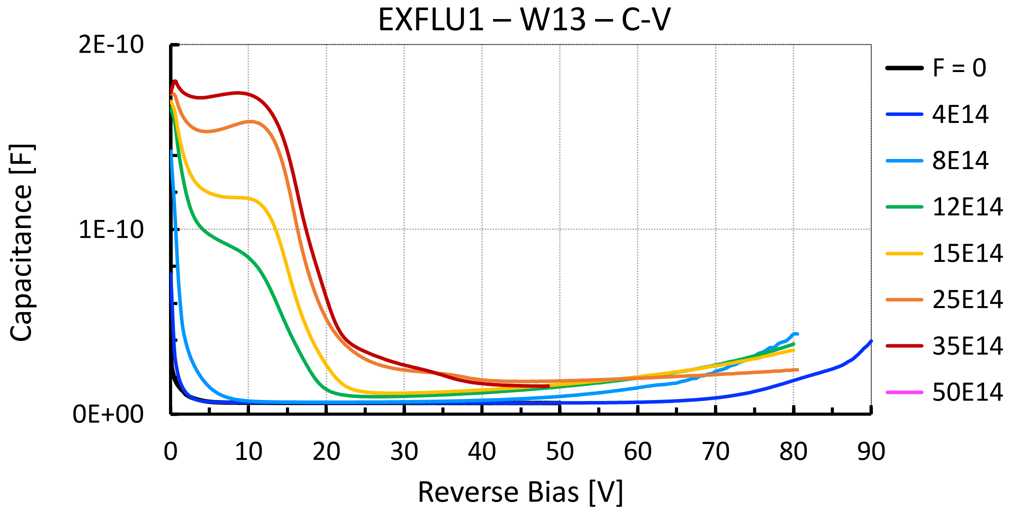
W6
2 – 1

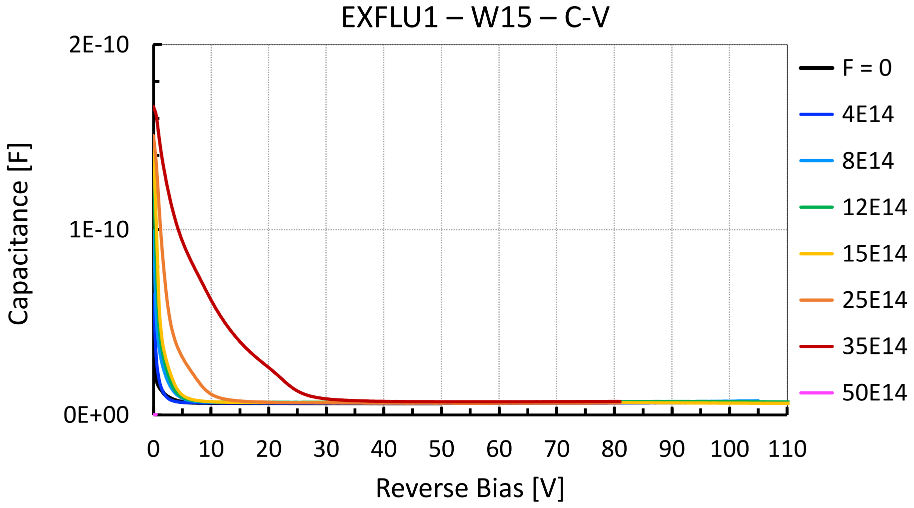




W12
3 – 2

W13
3 – 2 + C



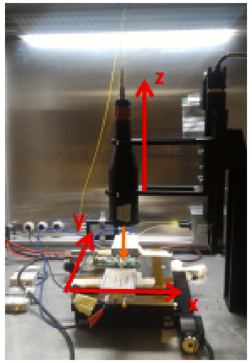


W15
5 – 4

IR Laser Stimulus on Compensated LGAD

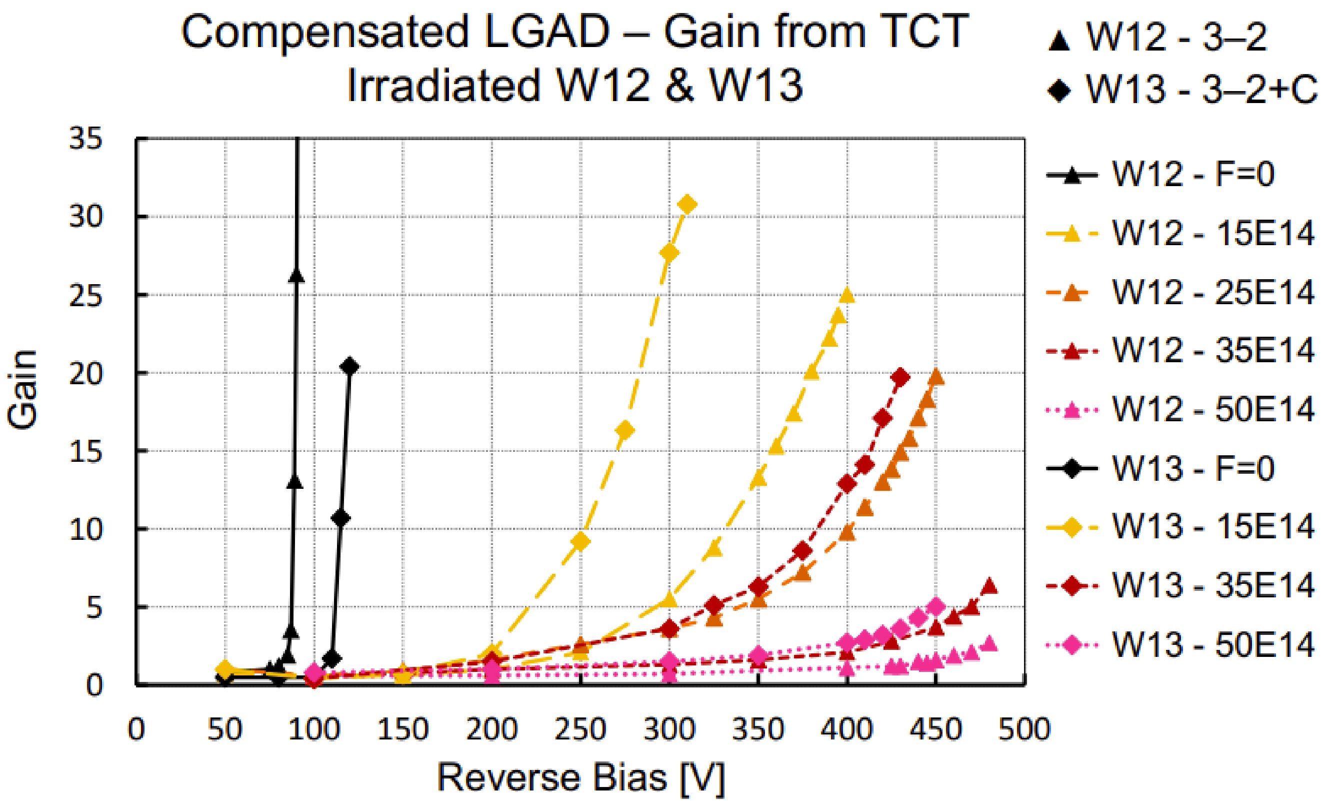
IFAE_2024, F. Moscatelli

TCT Setup from Particulars
Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
Laser intensity ~ 4 MIPs
T = -20°C



Laser stimulus on a LGAD-PiN structures before and after irradiation

$$\text{Gain} = \frac{Q_{LGAD}}{< Q_{PiN}^{No\ Gain} >}$$



→ Good gain behaviour of the compensated LGAD sensors after irradiation

→ Even in compensated LGADs, **the usage of carbon mitigates the acceptor removal**

β Particles on Compensated LGAD

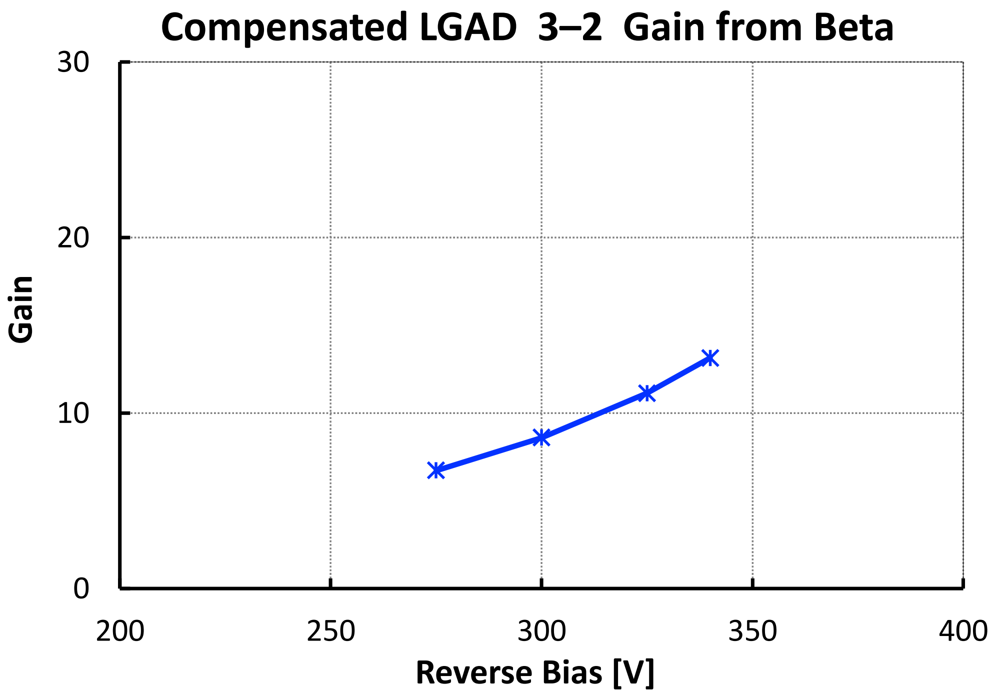
β Setup
Oscilloscope: LeCroy 9254M (2.5GHz - 40Gs/s)
HV Power supply: CAEN DT1471ET
UCSC Board + Cividec Broadband Amplifier (20dB)
Time reference: Photonis MCP-PMT – $\sigma_t \sim 15$ ps
β source: Sr90 – activity ~ 37 kBq
T = -25ºC

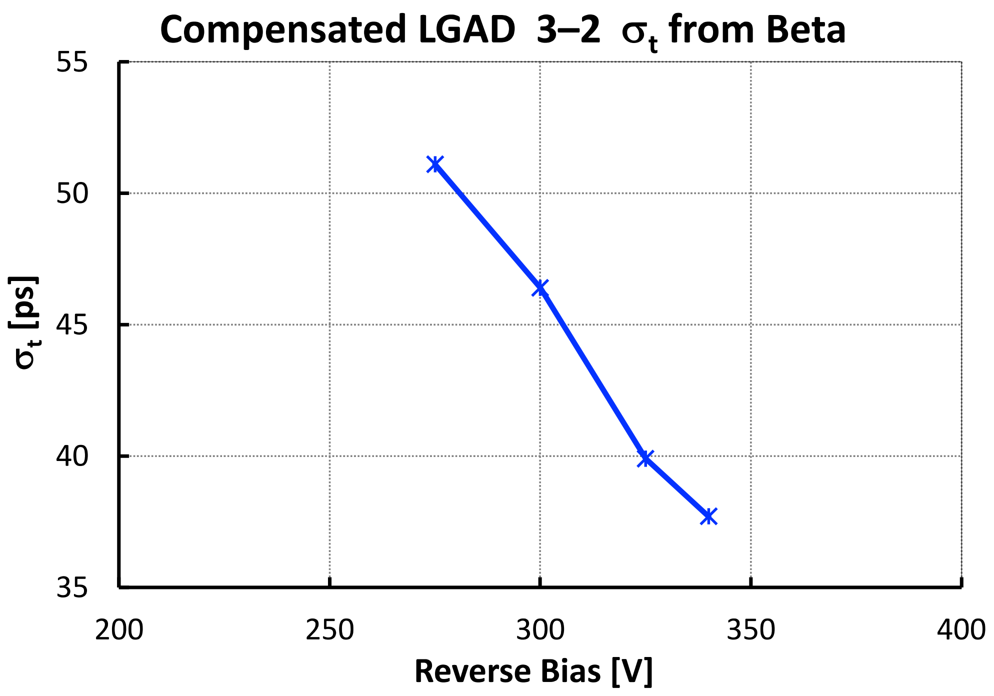
3–2 compensated LGAD from W12 irradiated to $2.5 \cdot 10^{15}$ n_{eq}/cm^2 has been tested with beta particles

→ **Good timing performances of compensated LGAD sensors irradiated to $2.5 \cdot 10^{15}$ n_{eq}/cm^2**

IFAE_2024, F. Moscatelli

W12
3–2
Φ = 2.5E15





Summary & Outlook

- ➢ **Compensated LGADs represent the sensor technology for the extreme fluences**
- ➢ **First compensated LGAD batch has been released 1 year ago**
- ➢ **Good performances of compensated LGAD sensors after irradiation**
- ➢ **An ERC Consolidator Grant is funded to develop compensated LGAD sensors**

Doping Compensation in Thin Silicon Sensors:
the pathway to Extreme Radiation Environments
CompleX

We acknowledge the following funding agencies and collaborations:

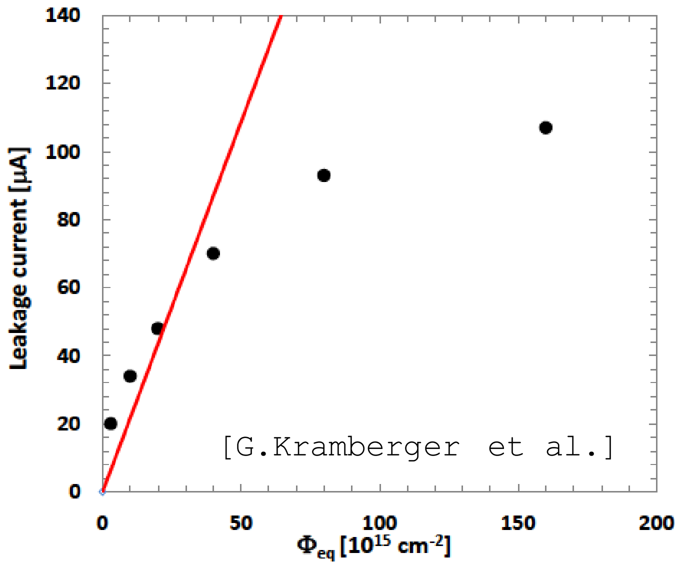
- INFN CSN5
- RD50, CERN
- AIDAinnova, WP13
- Compagnia di San Paolo
- Ministero della Ricerca, Italia, PRIN 2022, progetto 2022RK39RF – ComonSens

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No.101004761 and No 101057511 (EURO-LABS)

Backup

Saturation

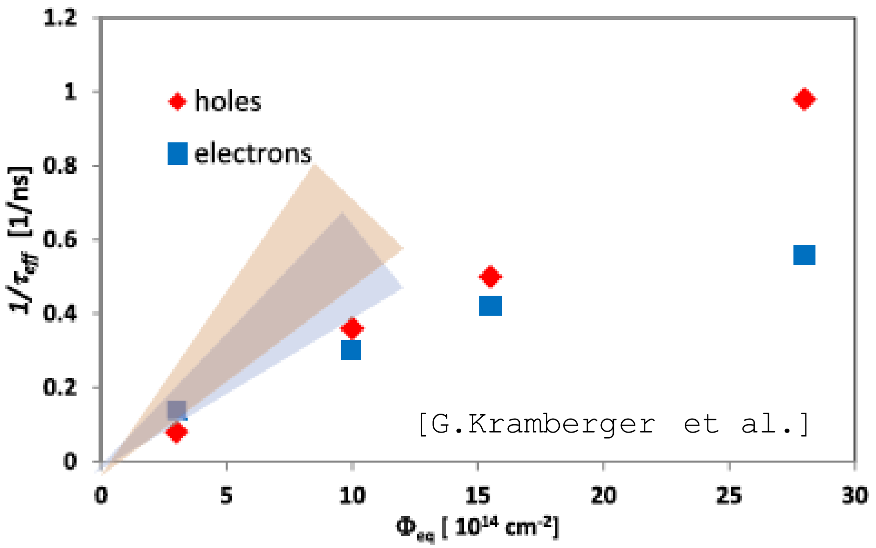
At fluences above $5 \cdot 10^{15}$ cm^{-2} → **Saturation of radiation effects observed**



Leakage current saturation

$I = \alpha V \Phi$

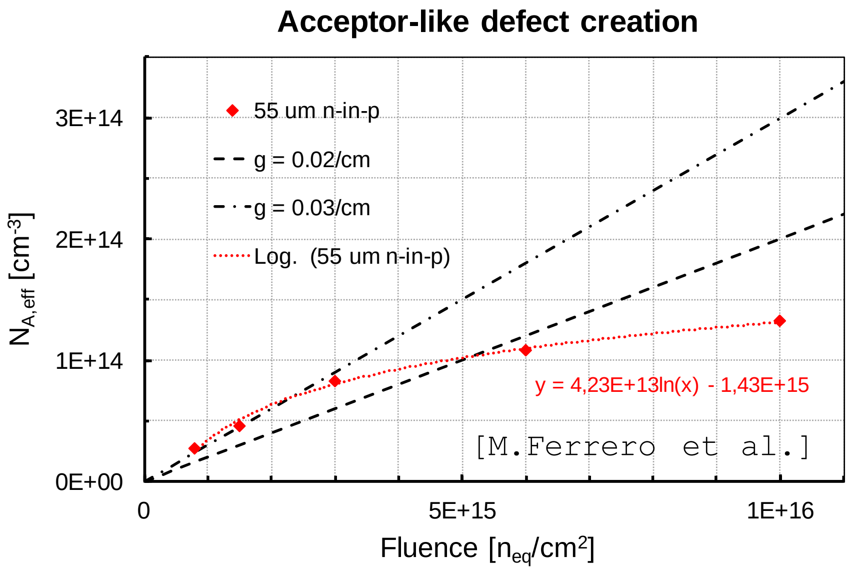
α from linear to logarithmic



Trapping probability saturation

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

β from linear to logarithmic



Acceptor creation saturation

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

g_c from linear to logarithmic

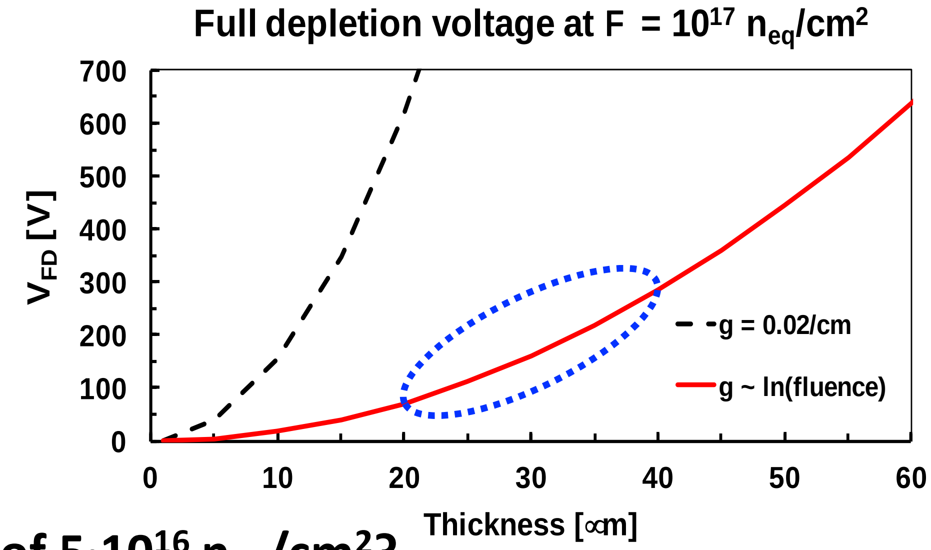
Silicon detectors irradiated at fluences 10^{16} – 10^{17} n_{eq}/cm^2 do not behave as expected → They behave better

Thin Substrates

$$V_{FD} = e|N_{eff}|d^2/2\varepsilon$$

Saturation → N_{eff} **Reduce thickness** → d^2

At high fluences, only thin substrates can be fully depleted



What does it happen to a 25 μm sensor after a fluence of $5{\cdot}10^{16}$ n_{eq}/cm^2?

- ▻ It can still be depleted
- ▻ Trapping is limited (small drift length)
- ▻ Dark current is low (small volume)

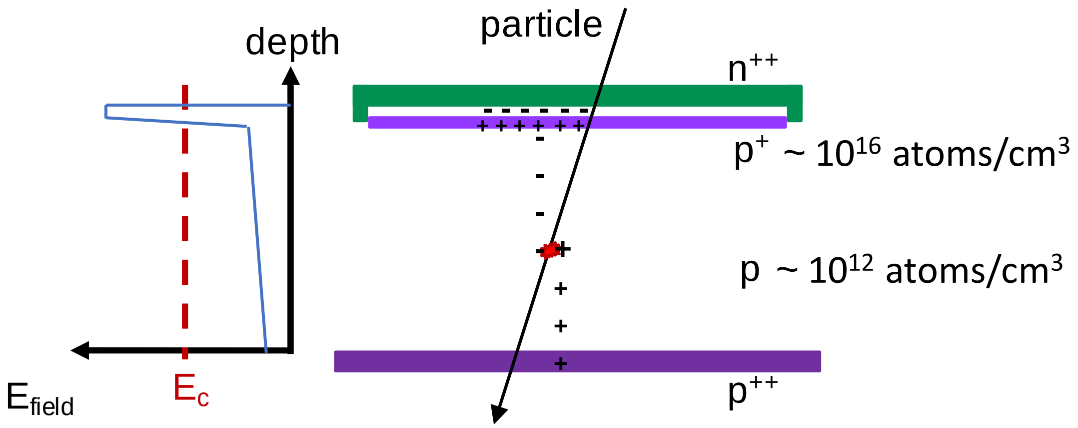
However: charge deposited by a MIP ~ 0.25 fC

→ This charge is lower than the minimum charge requested by the electronics (**~ 1 fC** for tracking, **≳ 5 fC** for timing)

→ **Need a gain of at least ~ 5** in order to efficiently record a hit

Optimal candidate: LGAD sensors

Thin LGAD for the Extreme Fluences



The idea: use thin sensors (15 – 45 μm) with internal gain

→ **Low-Gain Avalanche Diodes** (LGADs) provide a controlled internal multiplication of signal

Minimum charge requested by the electronics

→ **~ 1 fC** for tracking

→ **≳ 5 fC** for timing

Charge from a MIP crossing thin sensors

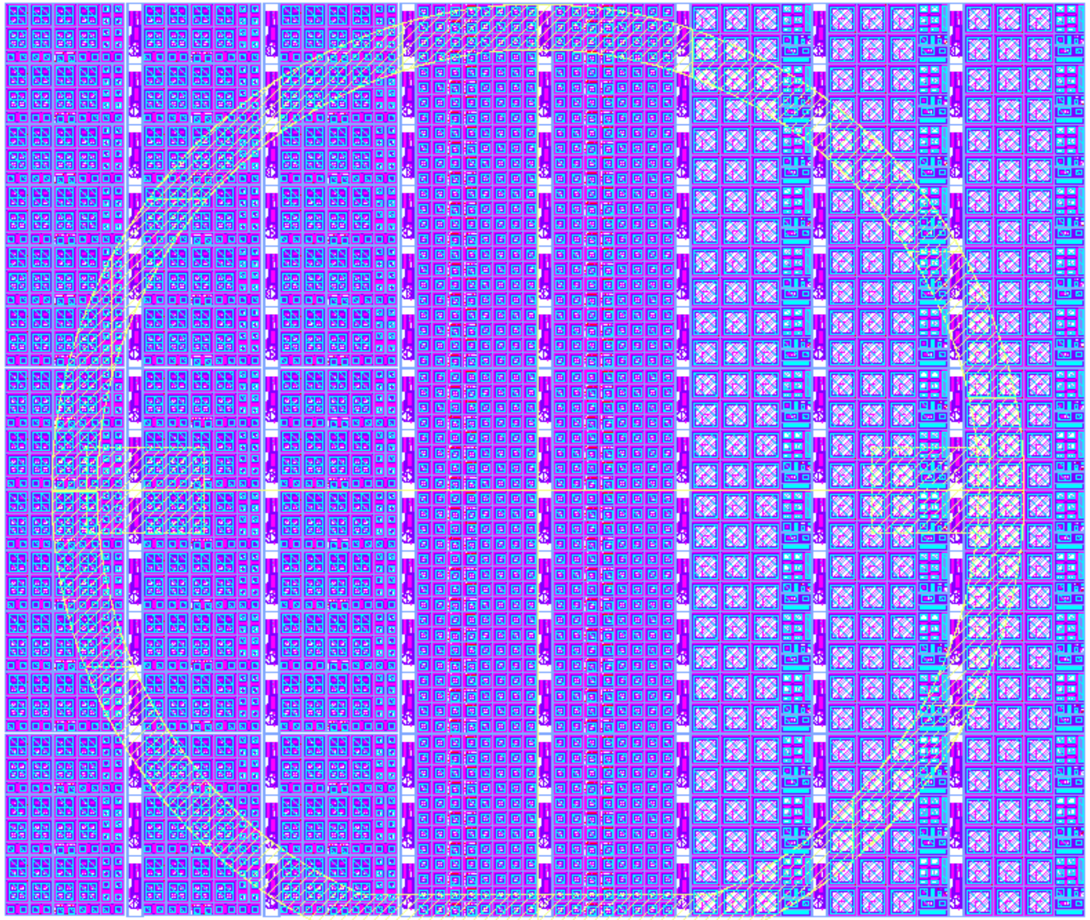
→ **~ 0.1 fC every 10 μm**

[S. Meroli et al., doi:10.1088/1748-0221/6/06/P06013]

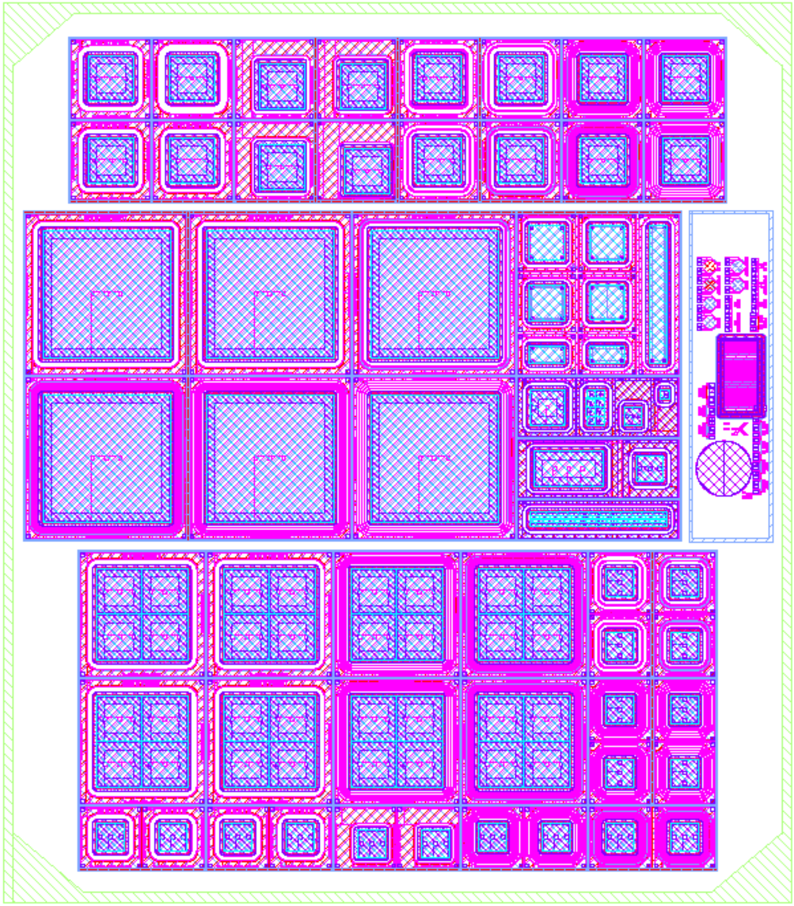
⇒ **Need a gain of at least 5 – 10**
up to $\Phi = 10^{17}\ n_{eq}/cm^2$ to efficiently record a hit

The EXFLU1 Layout

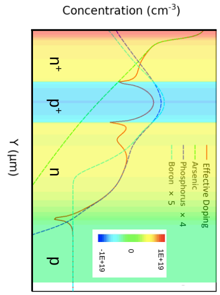
6” Wafer Layout

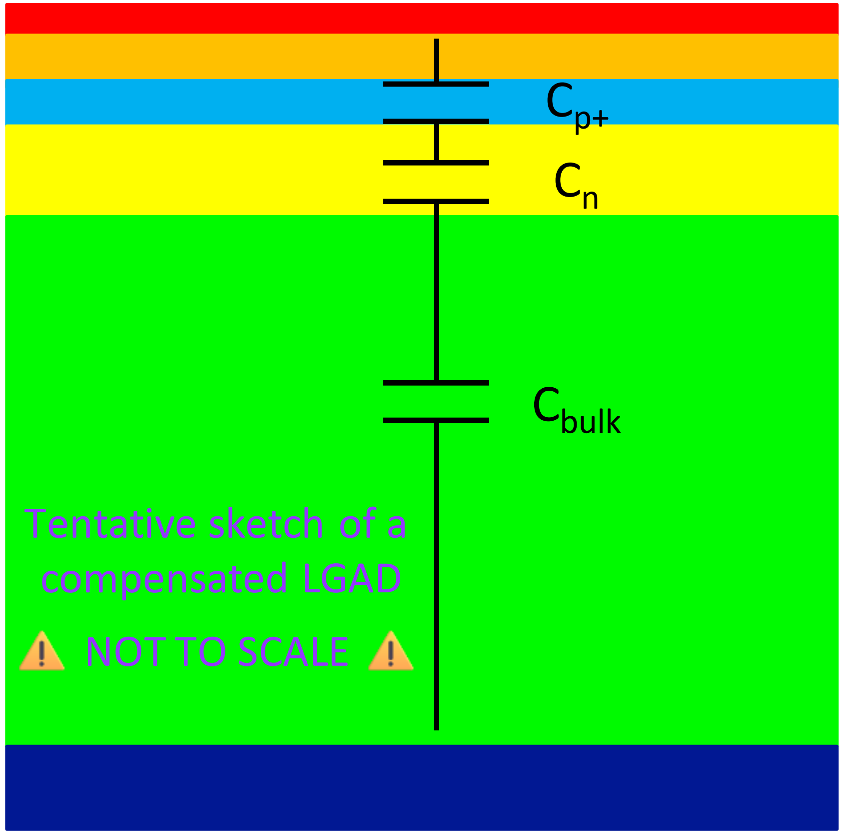


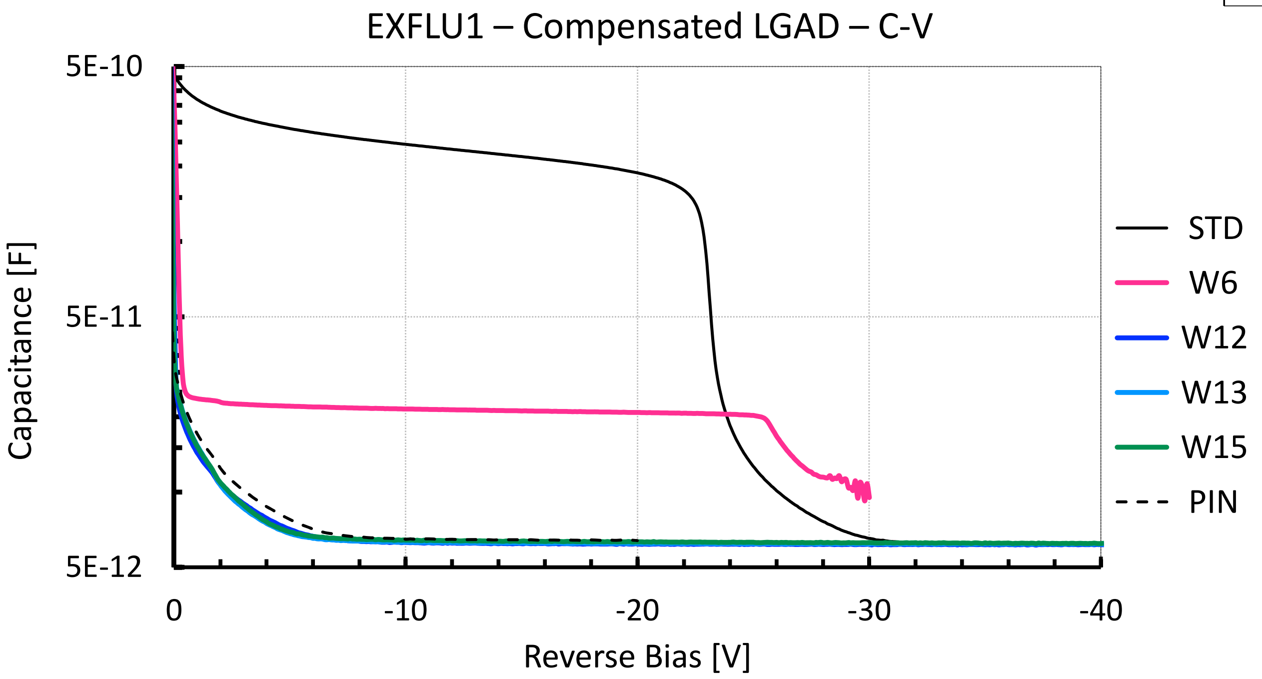
Reticle Layout



Compensated LGAD – C-V

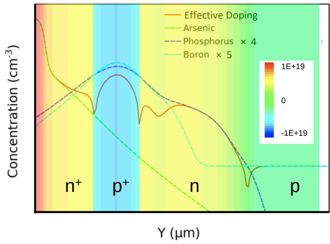






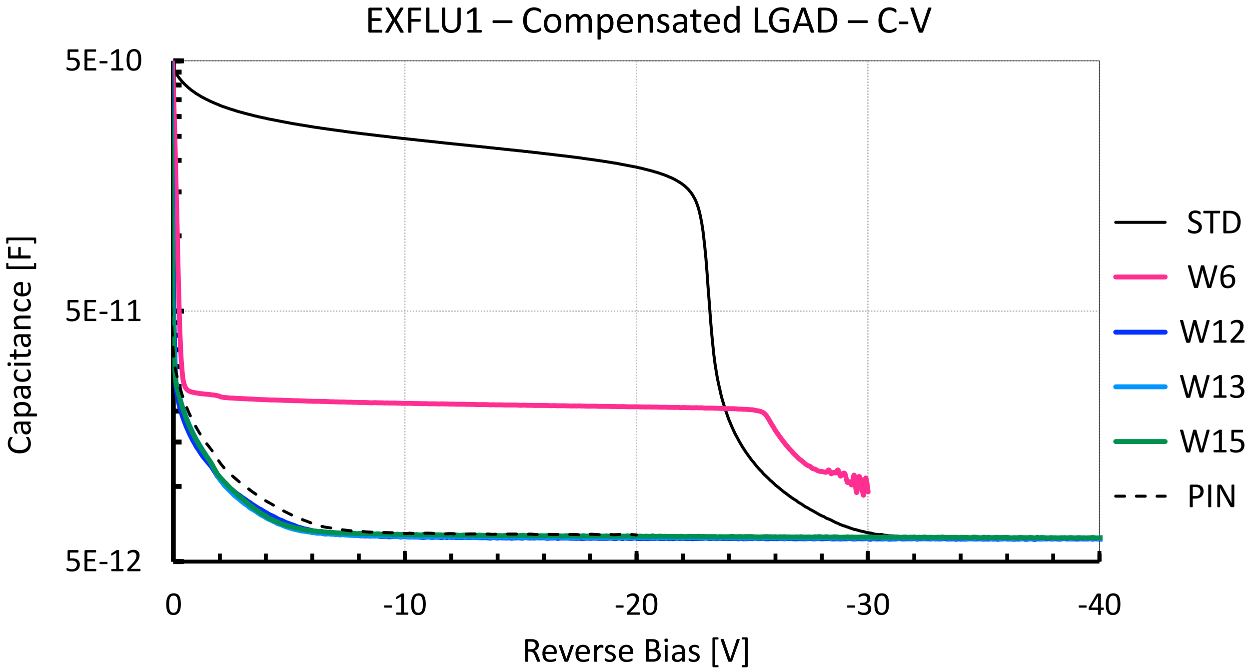
→ 3–2 & 5–4 C-V measurements have shapes similar to the one from the PIN diode, measuring a slightly bigger thickness at bias values between 0 and -10 V

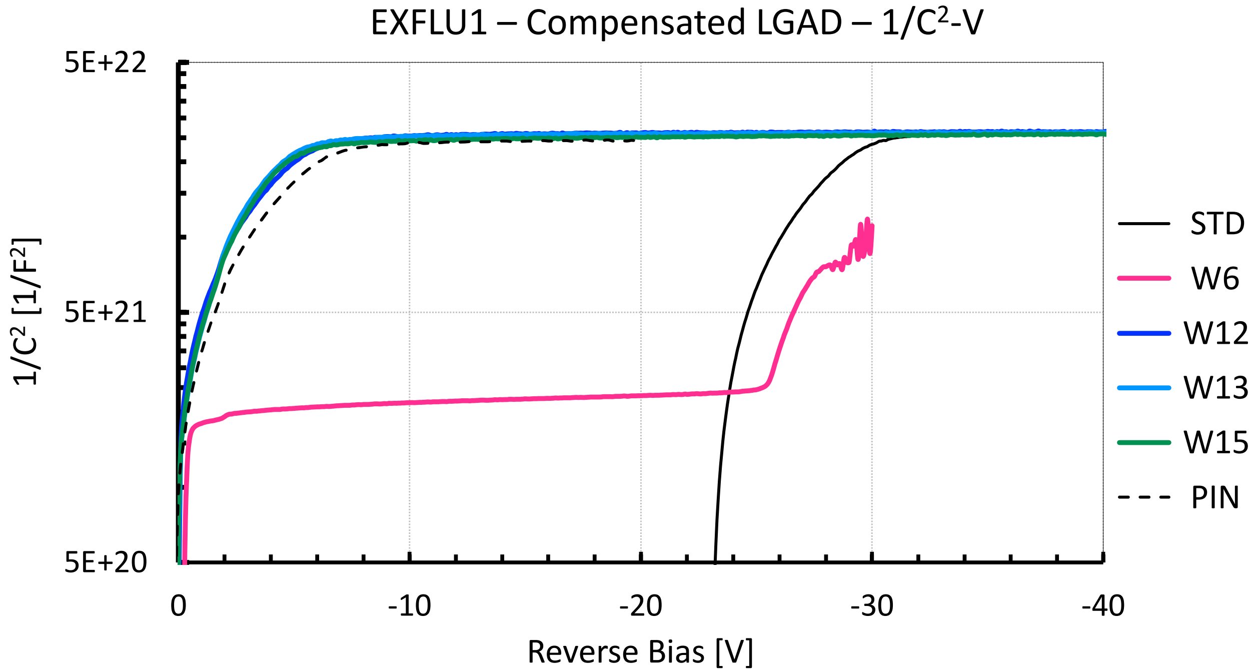
Compensated LGAD – C-V



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 lower capacitance than PIN





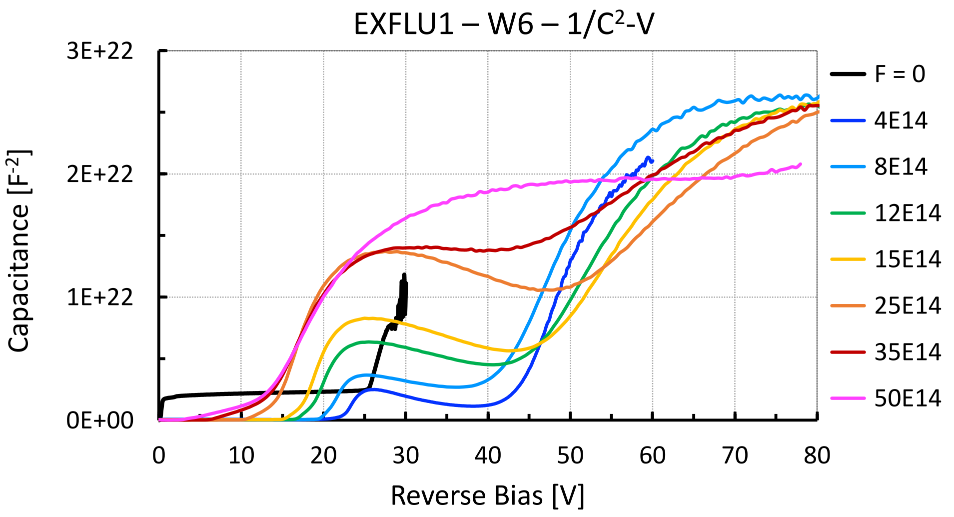
1/C²-V from Compensated LGAD – Irradiated

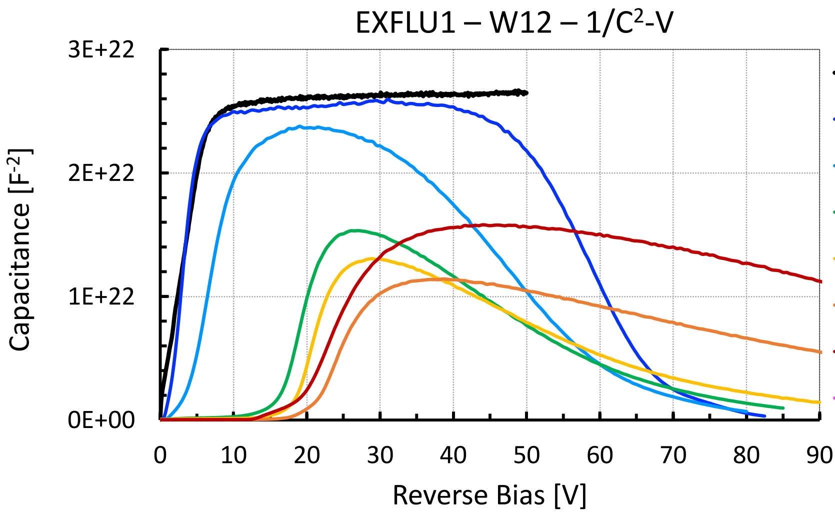
[Φ] = n_{eq}/cm^2

T = + 20ºC

f = 2k Hz

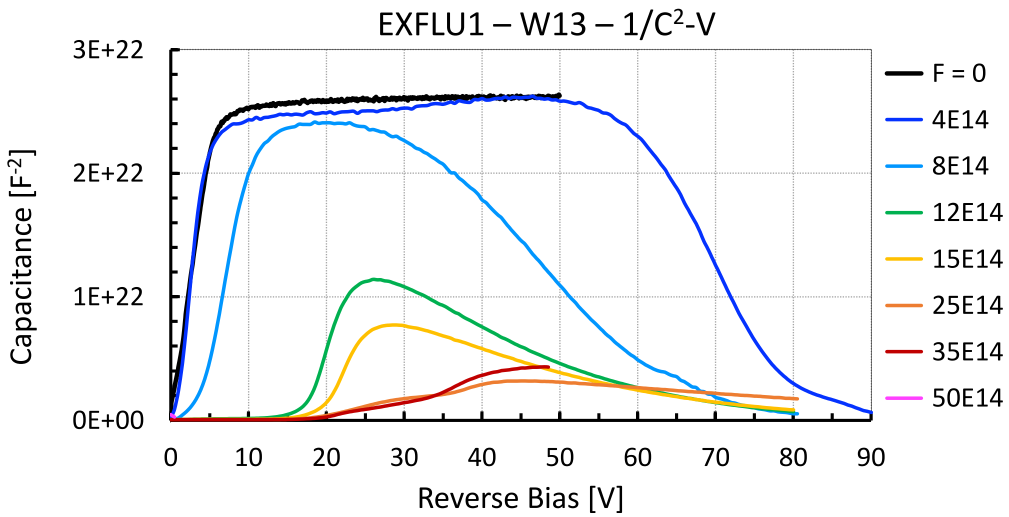
W6
2 – 1

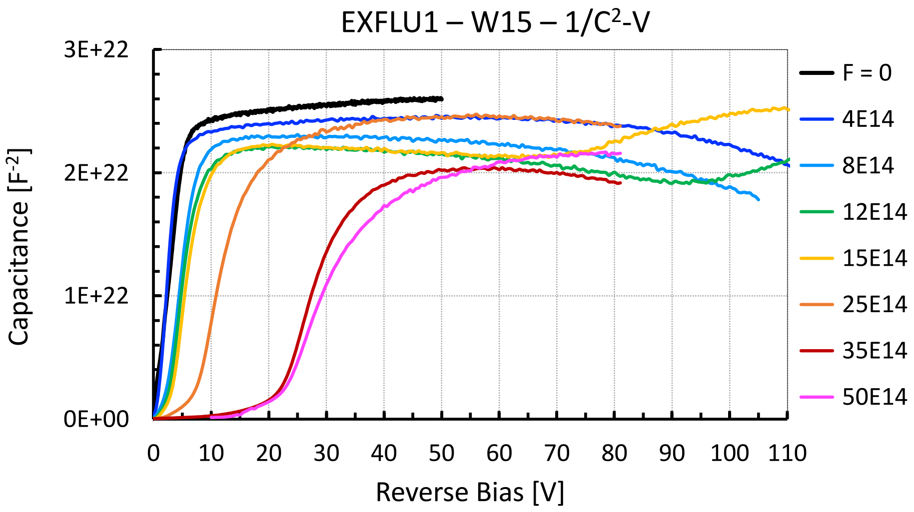




W12
3 – 2

W13
3 – 2 + C





W15
5 – 4

$1/C^2$-V from Compensated LGAD – Irradiated

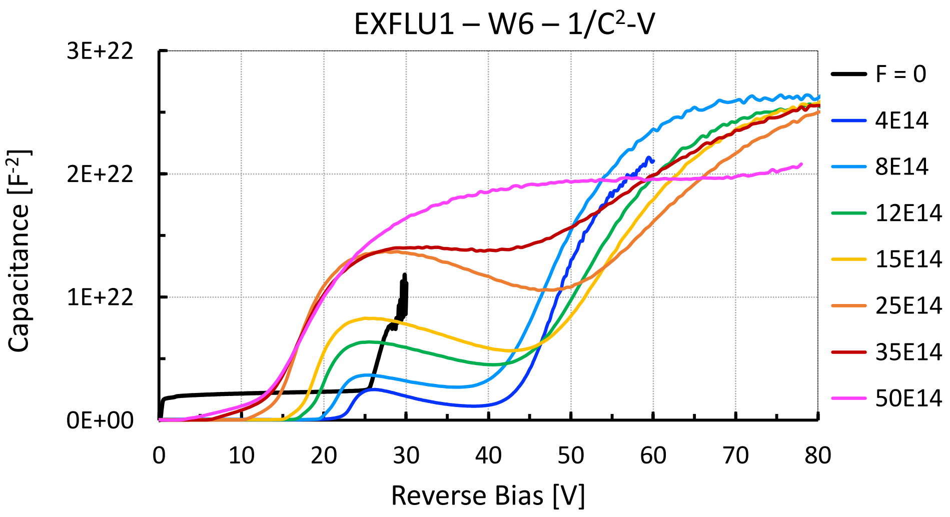
$[\Phi] = n_{eq}/cm^2$

T = + 20ºC

f = 2k Hz

W6

2 – 1



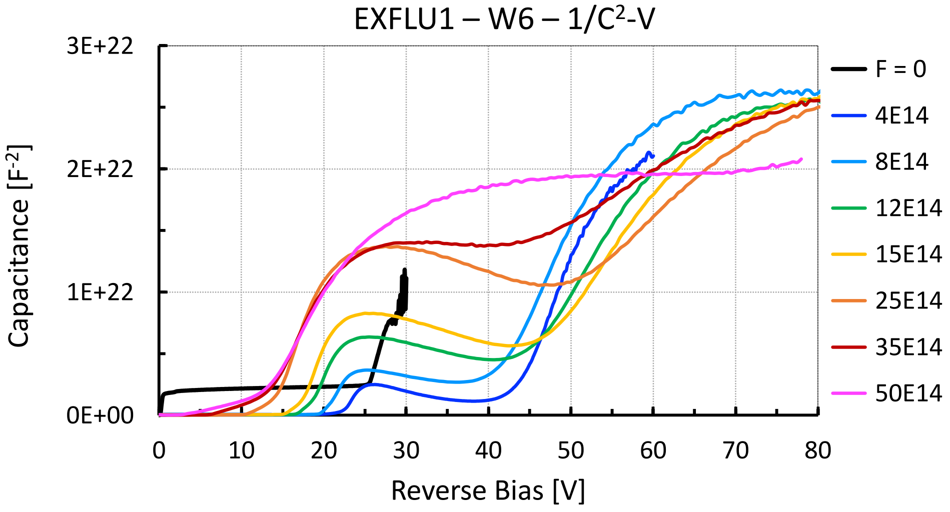
Doping Profile of Compensated LGAD 2 – 1

$[\Phi] = n_{eq}/cm^2$

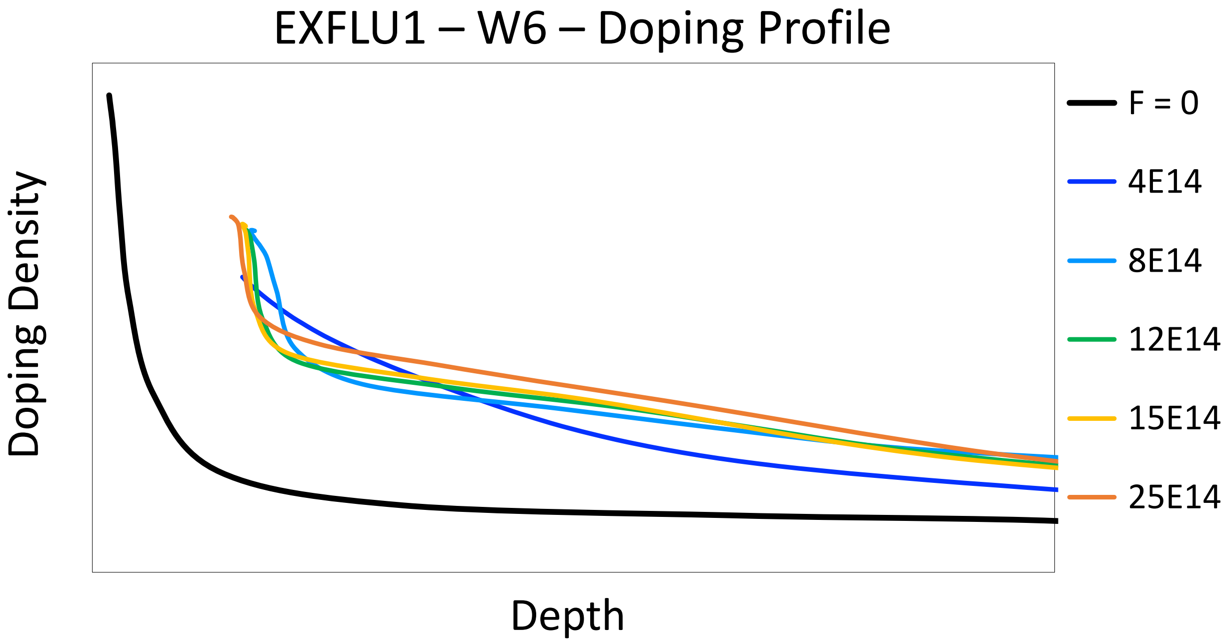
$T = +\ 20^oC$

f = 2k Hz

W6
2 – 1



Doping density profiling as a function of depth is extracted from the $1/C^2$-V information



Doping Profile of W6

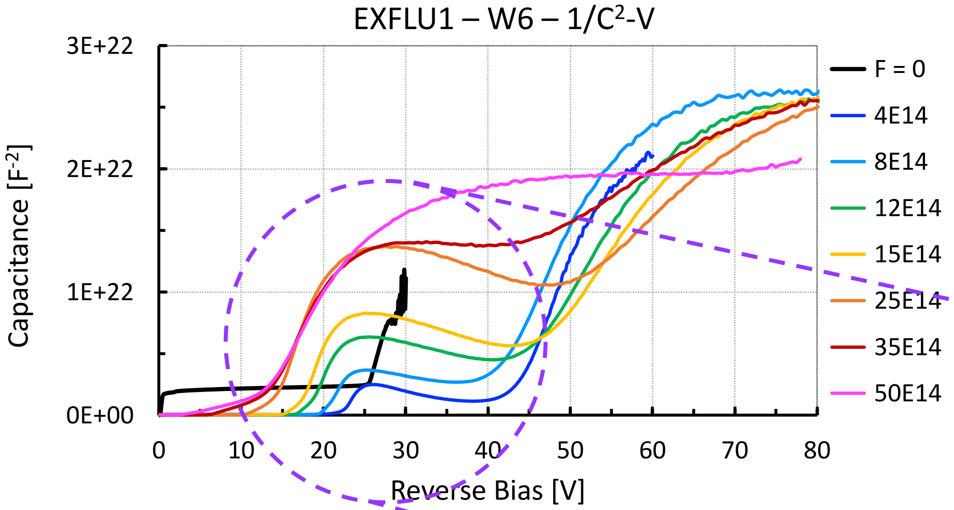
[Φ] = n_{eq}/cm^2

T = + 20ºC

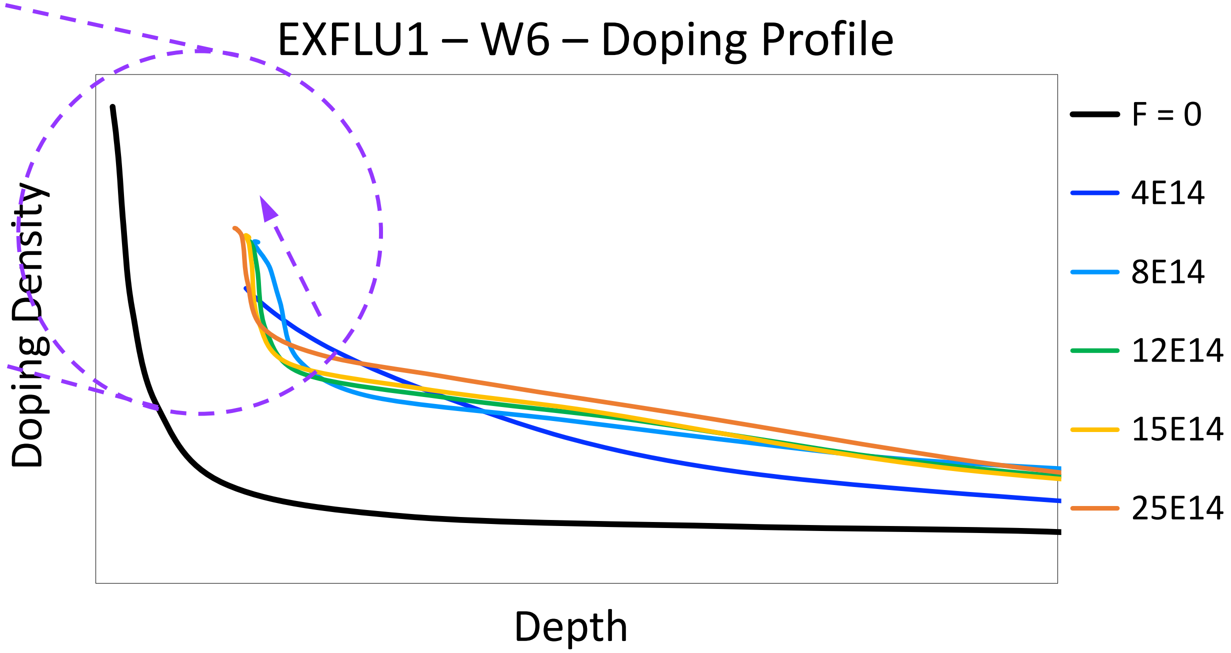
f = 2k Hz

W6

2 – 1



Doping density profiling as a function of depth is extracted from the 1/C²-V information

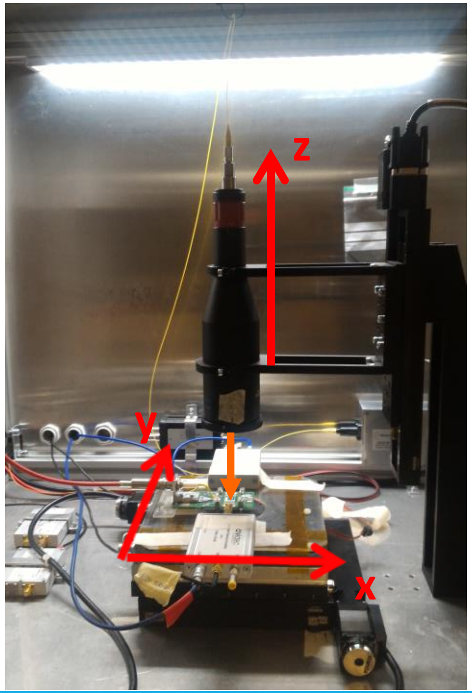


Gain implant profile appears more and more evident as the fluence increases

→ **Is donor removal faster than acceptor removal?**

IR Laser Stimulus on Compensated LGAD 3–2

TCT Setup from Particulars
Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
T = -20°C

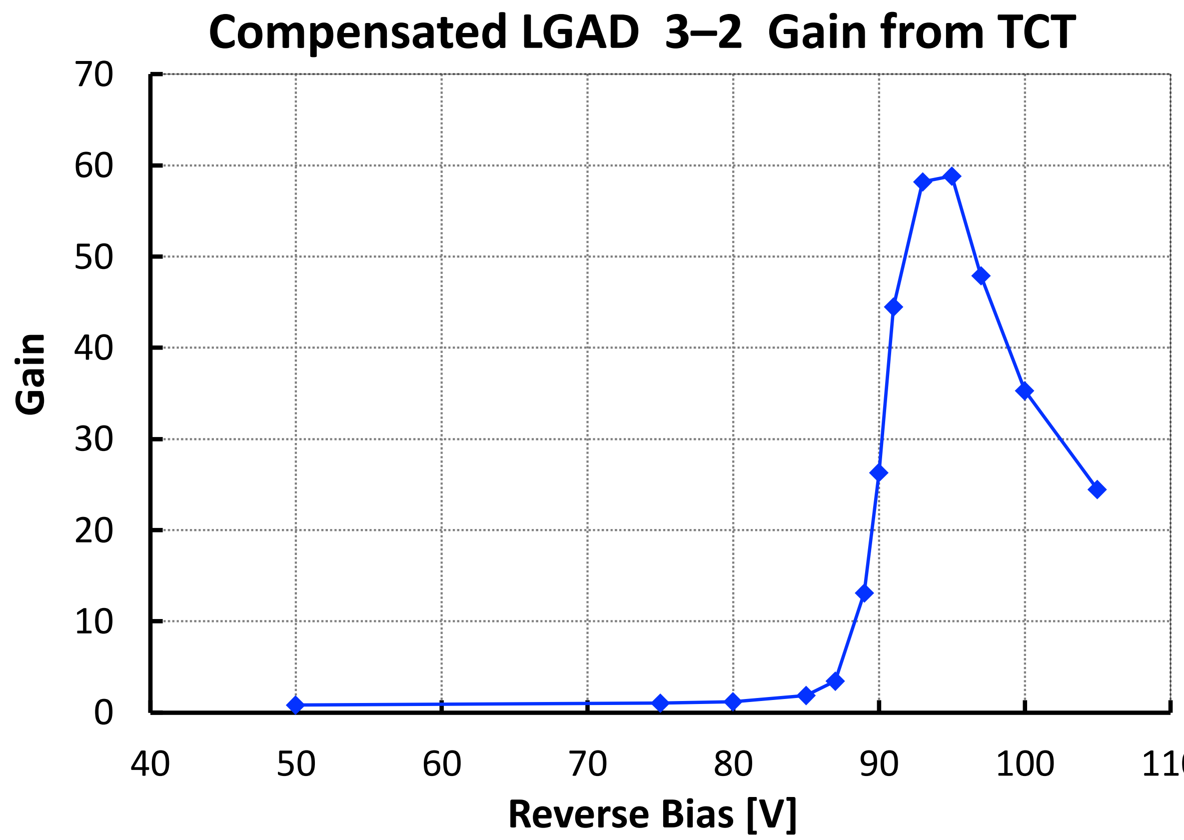


$$\textbf{Gain} = \frac{Q_{LGAD}}{< Q_{PiN} >}$$

Laser intensity
~ 4 MIPs

$\Phi = 0$

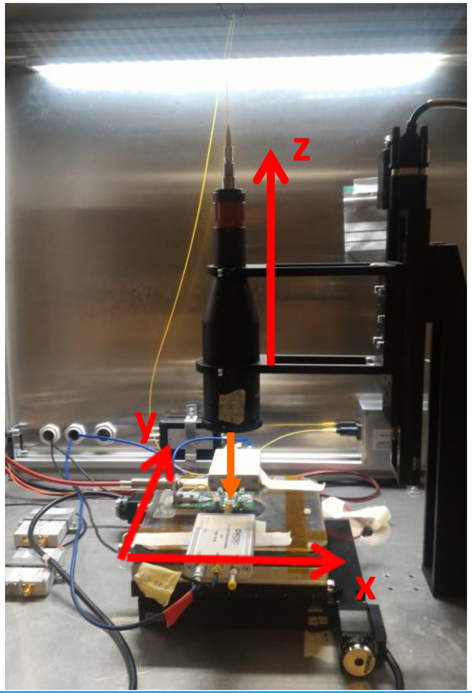
Laser stimulus on a LGAD-PiN structure from W12 (3 – 2)



→ Not easy to operate 3 – 2 compensated LGAD sensors

IR Laser Stimulus on Compensated LGAD 3–2+C

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

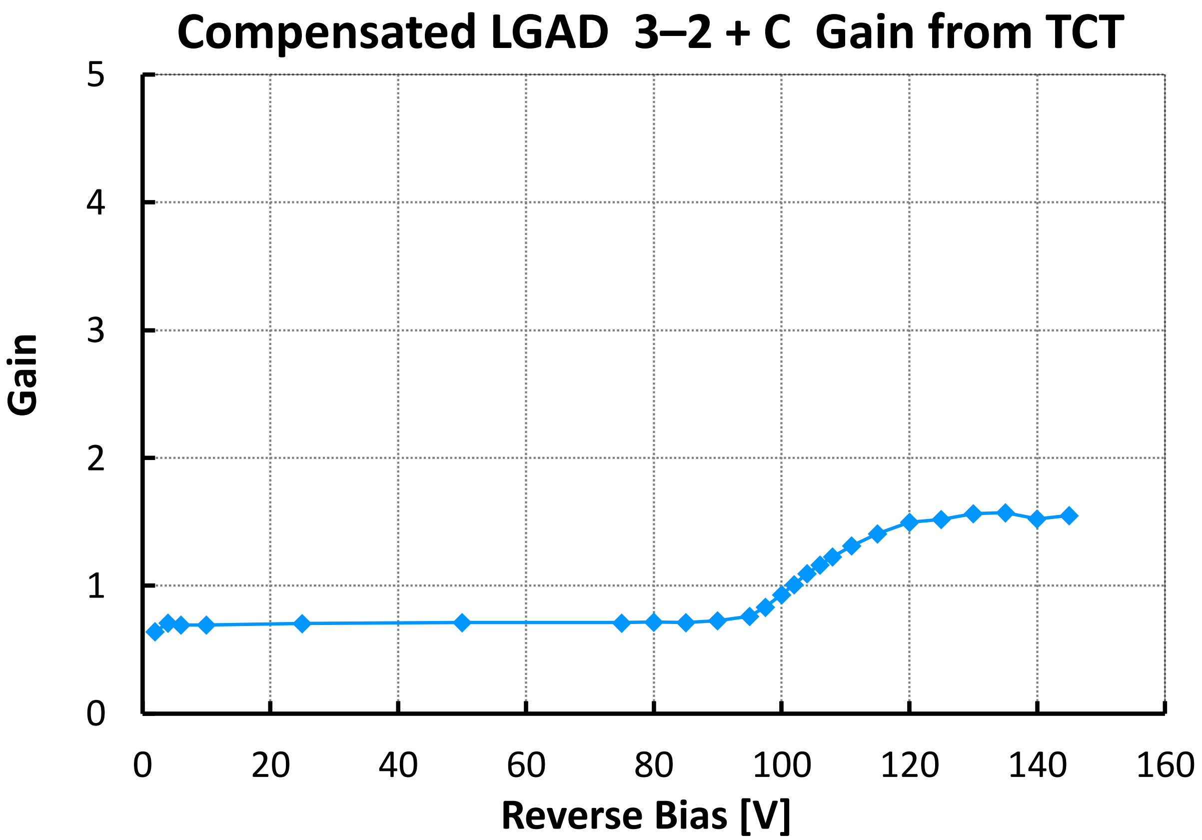


$$\text{Gain} = \frac{Q_{LGAD}}{\langle Q_{PiN} \rangle}$$

Laser intensity
~ 80 MIPs

$\Phi = 0$

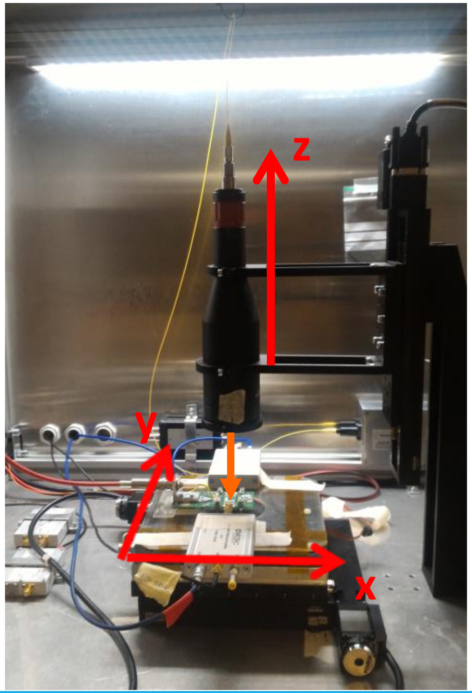
Laser stimulus on a LGAD-PiN structure from W13 (3 – 2 + C)



→ Very low gain from 3 – 2 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

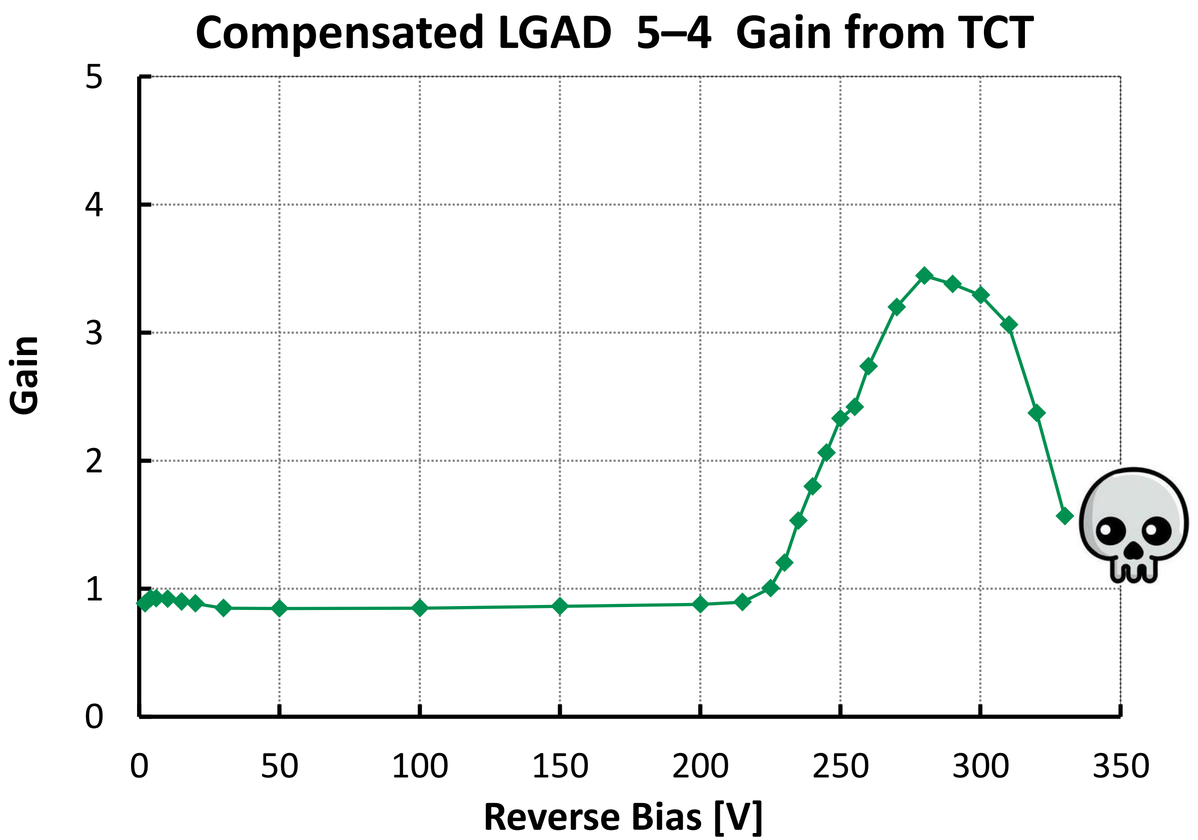


$$\text{Gain} = \frac{Q_{LGAD}}{\langle Q_{PiN} \rangle}$$

Laser intensity
~ 60 MIPs

$\Phi = 0$

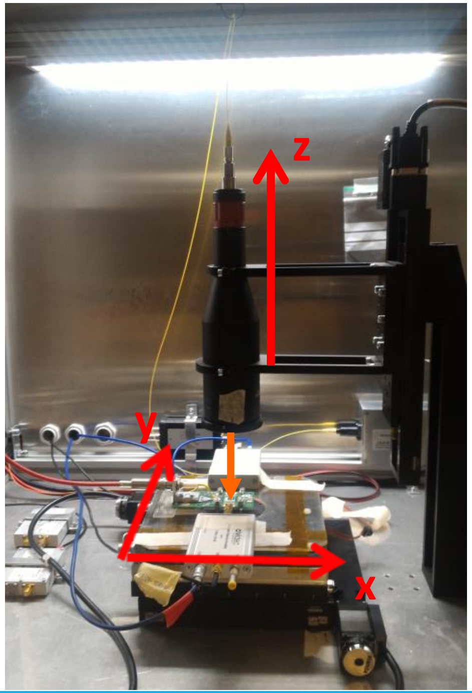
Laser stimulus on a LGAD-PiN structure from W15 (5 – 4)



→ **Not easy to operate 5 – 4 compensated LGAD sensors**

IR Laser Stimulus on Standard LGAD W5 EXFLU1

TCT Setup from Particulars
Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
T = -20ºC

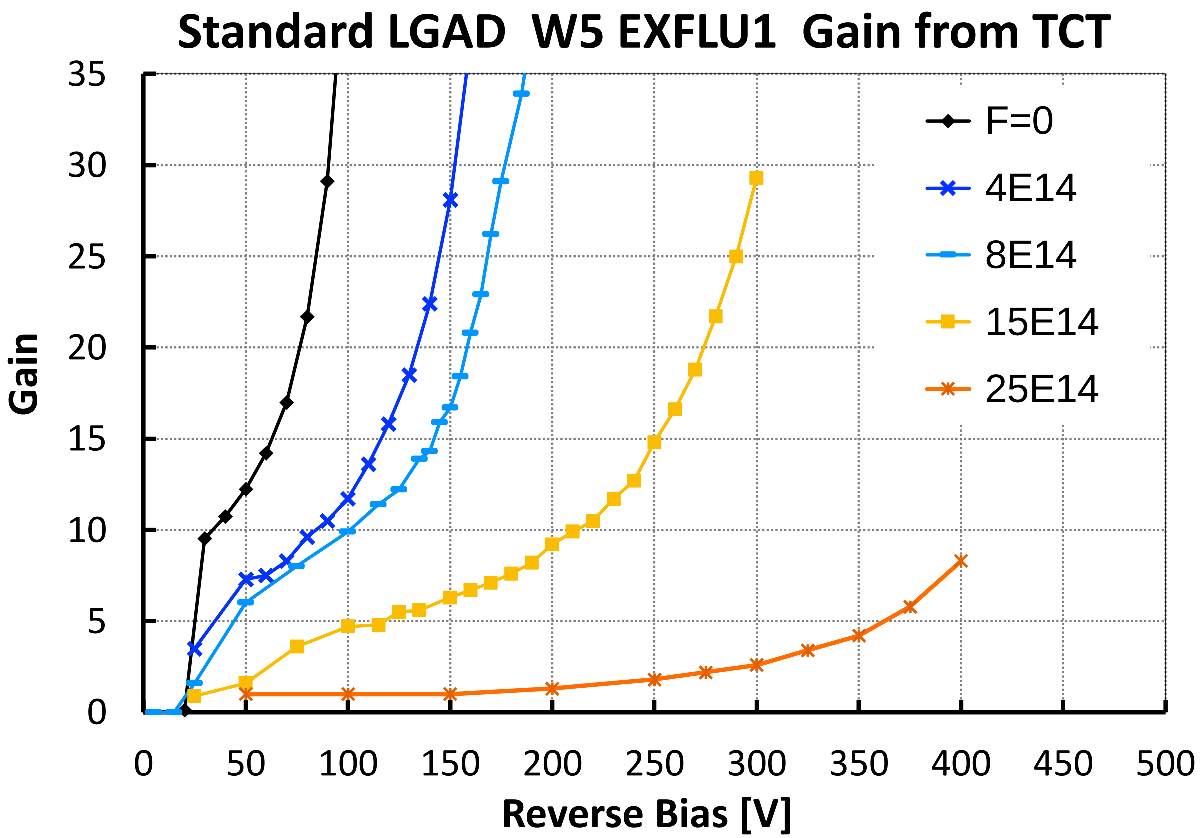


$$\mathbf{Gain} = \frac{\mathbf{Q_{LGAD}}}{<\mathbf{Q_{PiN}^{No\ Gain}}>}$$

Laser intensity
~ 4 MIPs

$\Phi = 0$

Laser stimulus on a LGAD-PiN structure from W5 EXFLU1



[R.S. White, 43rd RD50 Workshop (2023) CERN]

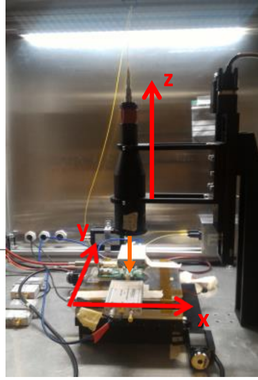
I-V Simulation Setup

Physical models

- ✓ **Standard drift-diffusion model**
  - => Fermi-Dirac statistics
- ✓ **Generation/Recombination rate**
  - => Shockley-Read-Hall (SRH)
  - => Band-To-Band Tunneling (BTBT)
  - => Auger
  - => Massey impact ionization model
- ✓ **Carriers mobility variation**
  - => doping and field dependent
- ✓ **Bandgap narrowing model**
  - => OldSlotboom
- ✓ **Physical parameters**
  - => s_0 = 0 cm/s (surface recomb. velocity)
  - => $\tau_n = \tau_p$ = 1E-3 s (e-/h+ recomb. lifetime)

Pre-irradiation values
$Q_{OX}(0) = 8.0 \times 10^{+10}$
$N_{IT_{acc}}(0) = 7.0 \times 10^{+09}$
$N_{IT_{don}}(0) = 9.0 \times 10^{+09}$

IR Laser Stimulus on Compensated LGAD



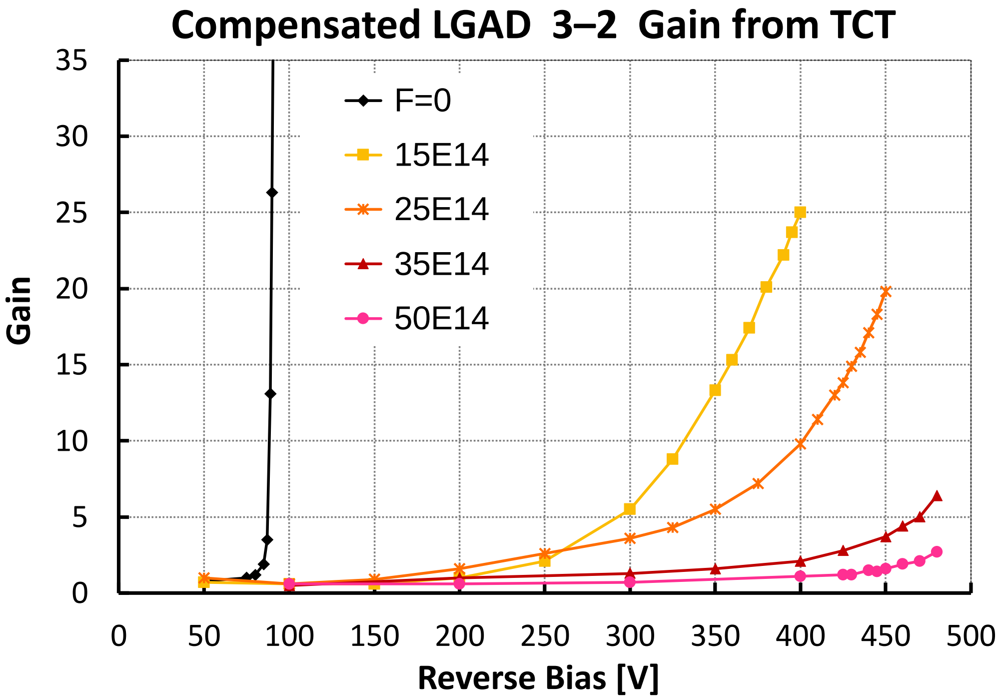
TCT Setup from Particulars
Laser intensity ~ 4 MIPs
T = -20ºC

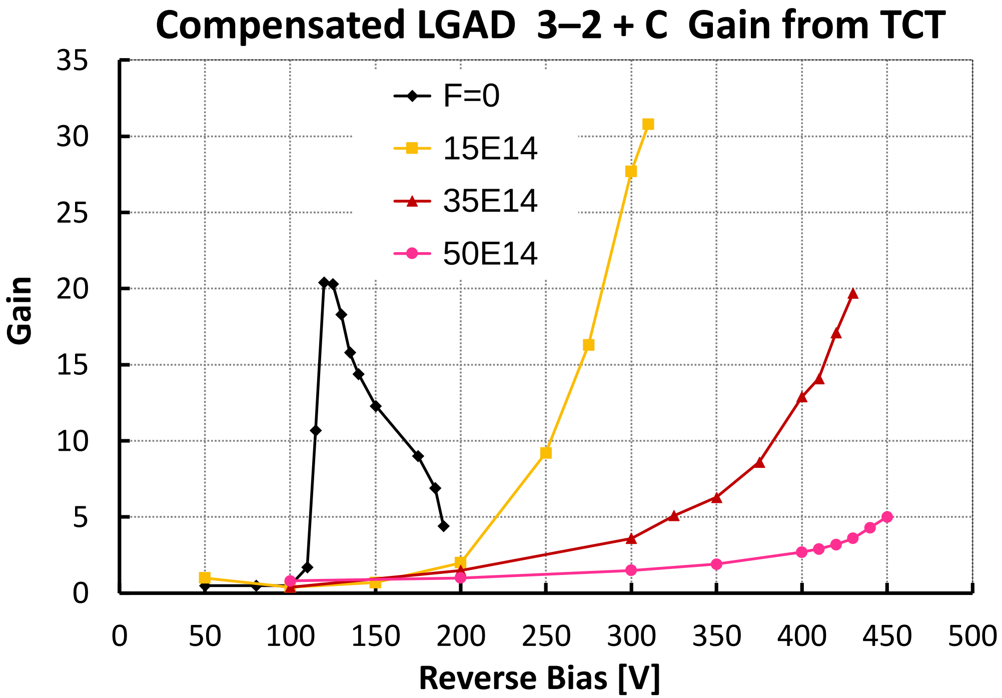
Laser stimulus on a LGAD-PiN structures before and after irradiation

$$\mathbf{Gain} = \frac{\mathbf{Q_{LGAD}}}{<\mathbf{Q_{PiN}^{No\ Gain}}>}$$

IFAE_2024, F. Moscatelli

W12 3–2





W13 3–2 + C

→ Good gain behaviour of the compensated LGAD sensors after irradiation

→ Even in compensated LGADs, **the usage of carbon mitigates the acceptor removal**