19th TREDI Workshop
on Advanced Silicon Radiation Detectors
20 – 22 February 2024
Torino, Italy

Compensated LGADs as a pathway to the extreme fluences

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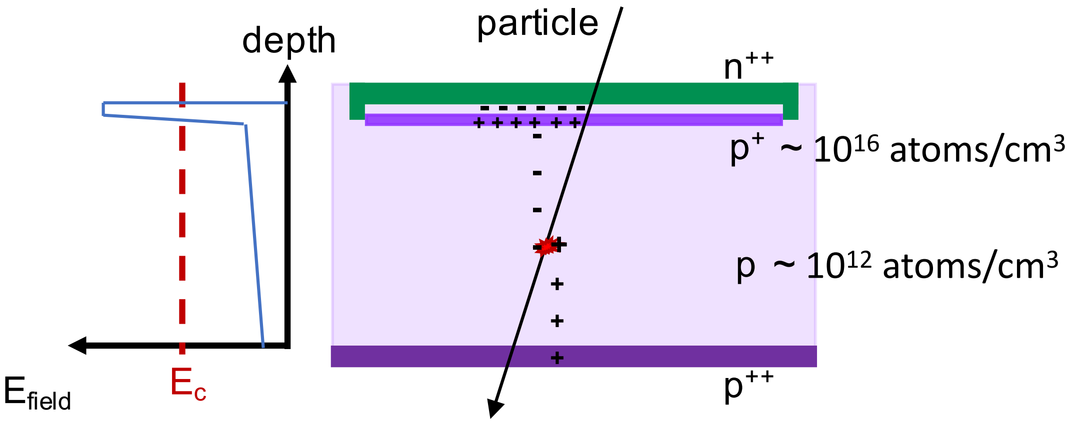
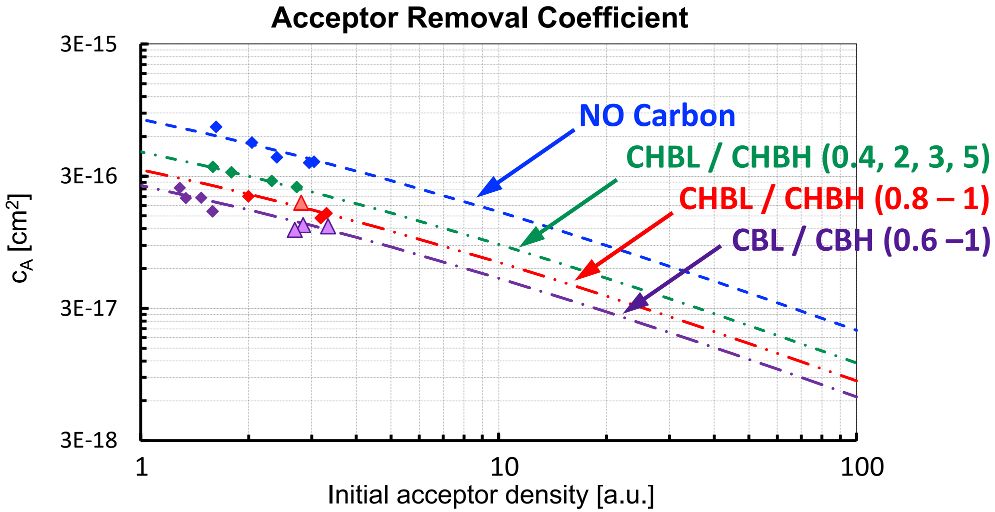
Gain Removal Mechanism in LGADs





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

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

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

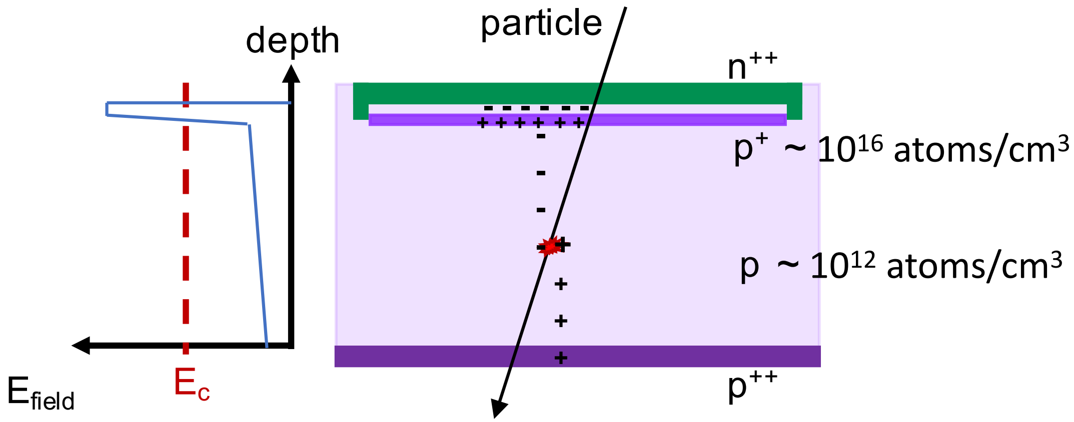
$\Phi_0 = 1/c_A$ ~ the fluence at which multiplication power of the gain implant reaches unity

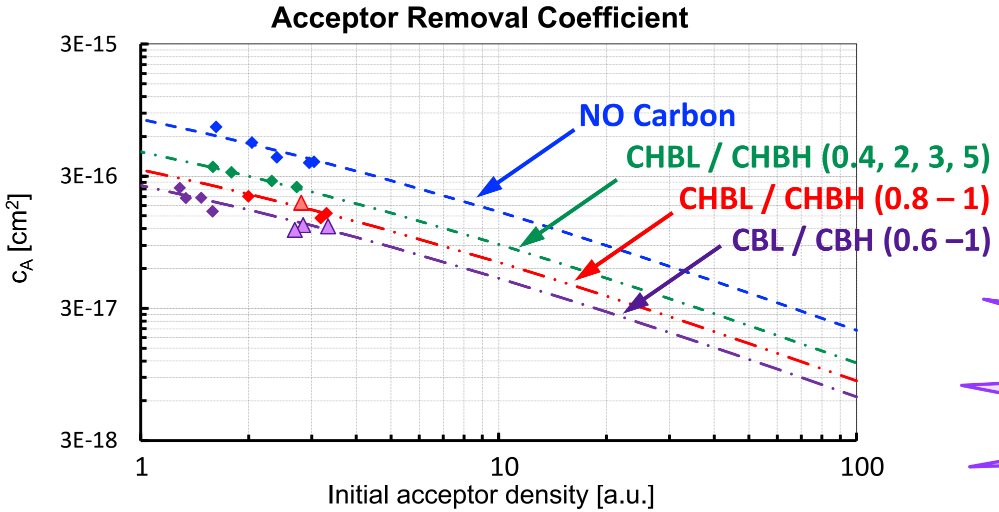
▲ thin sensors from the EXFLU1 batch

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

⇒ Is it possible to reduce c_A further?

Gain Removal Mechanism in LGADs





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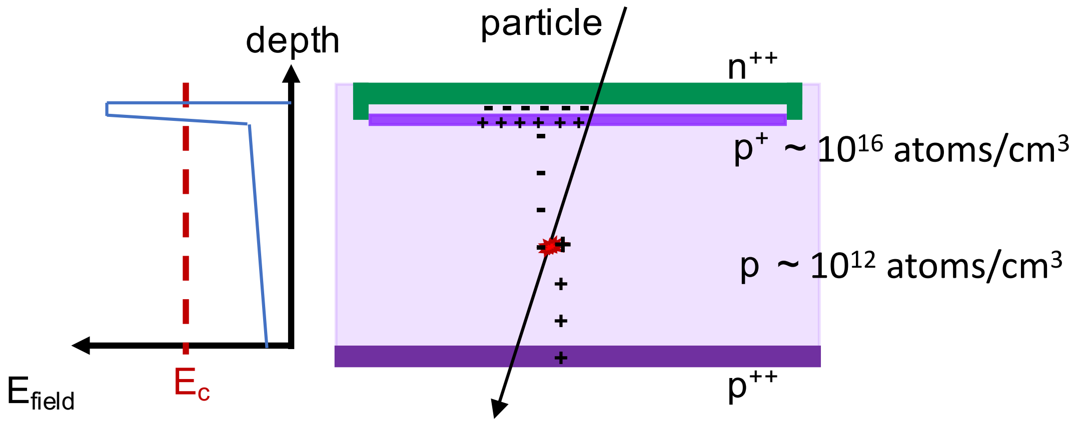
Towards a Radiation Resistant Design



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

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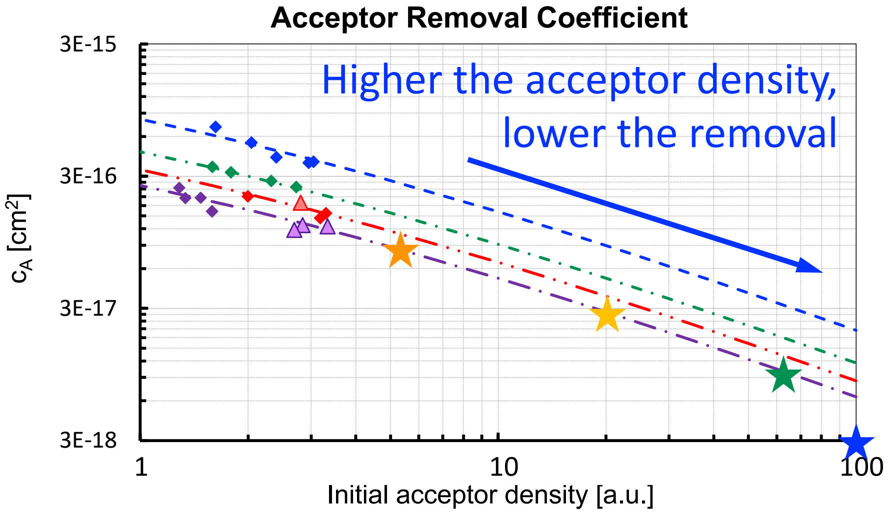
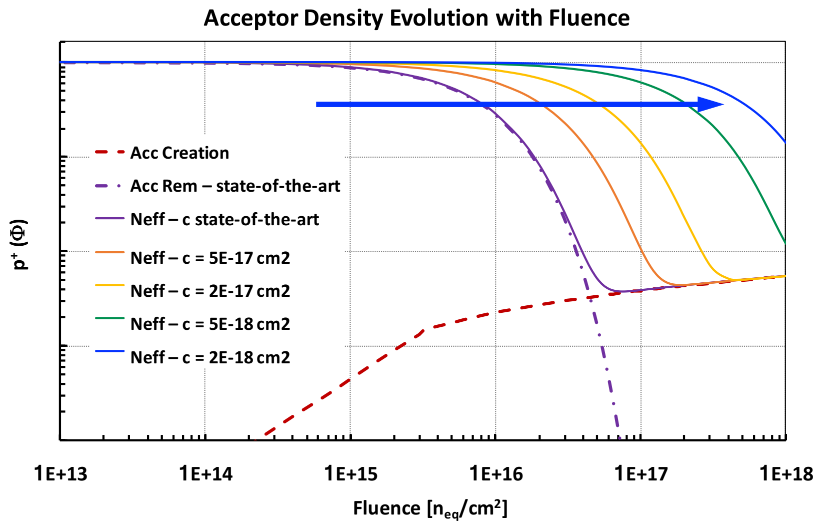
To substantially reduce c_A, it is necessary to increase $p^+(0)$, the initial acceptor density

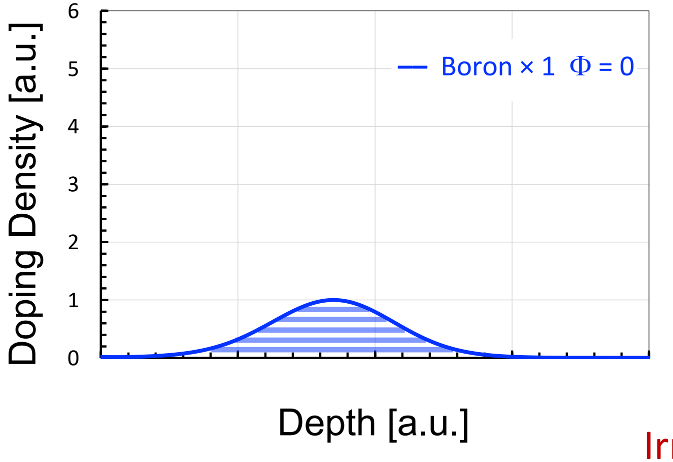




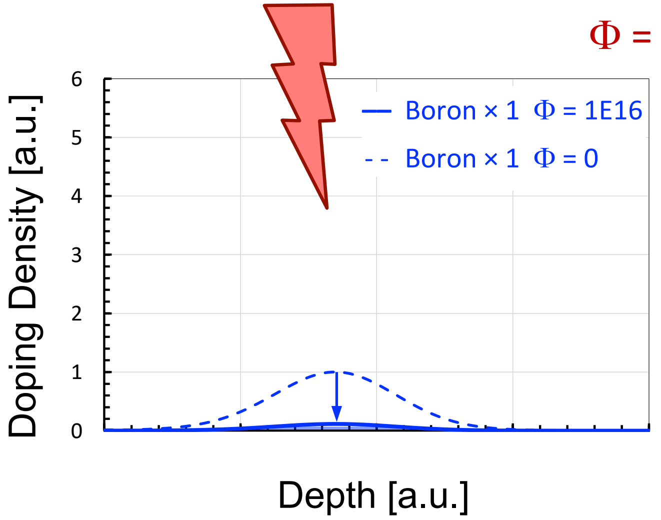
Lowering c_A can extend the gain layer survival up to $\Phi \geq 10^{17}\ n_{eq}/cm^2$

A new Paradigm – Compensation

Doping Profile – Standard LGAD

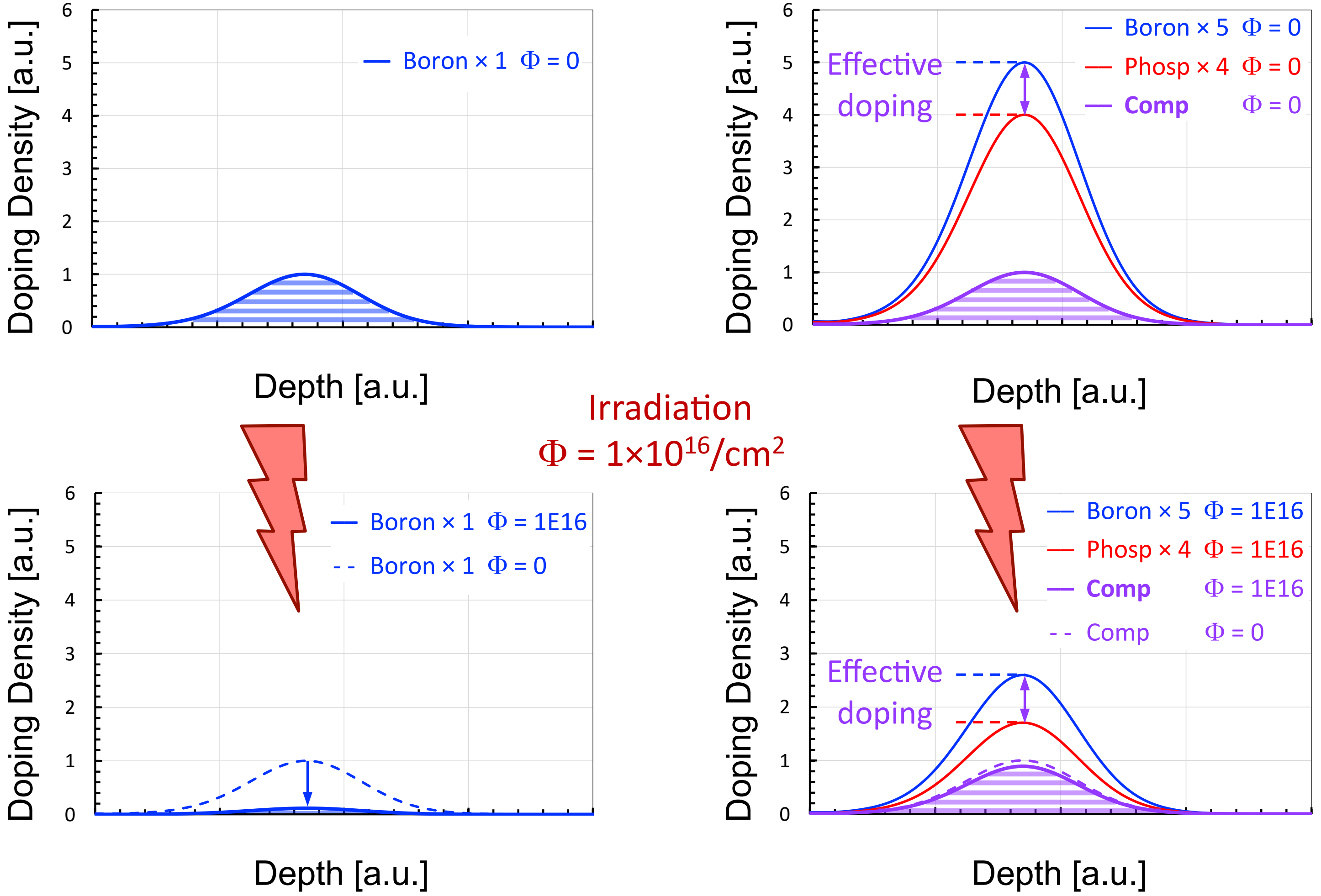


Irradiation
$\Phi = 1\times10^{16}/\text{cm}^2$



A new Paradigm – Compensation

Doping Profile – Standard LGAD **Doping Profile – Compensated LGAD**



A new Paradigm – Compensation

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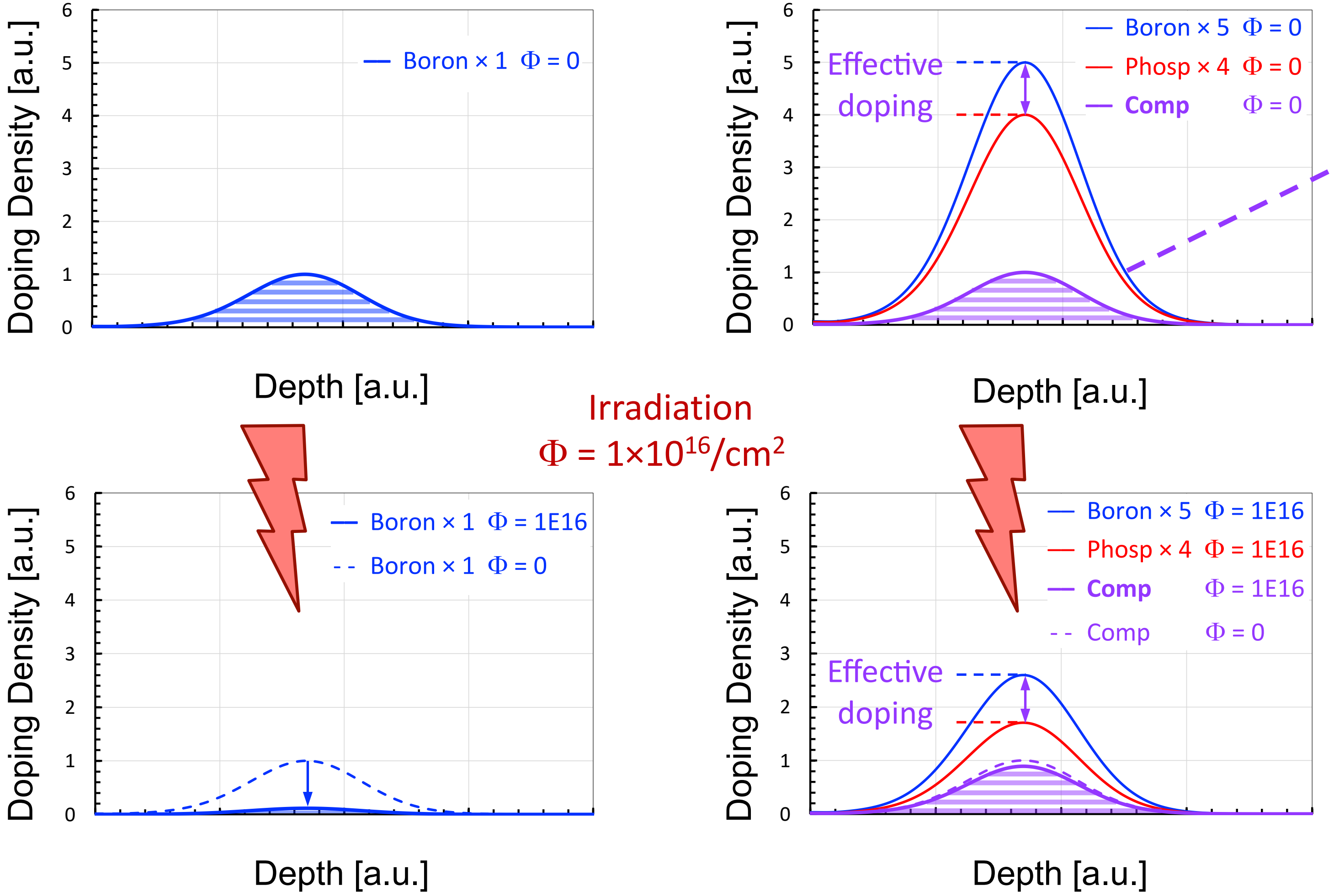
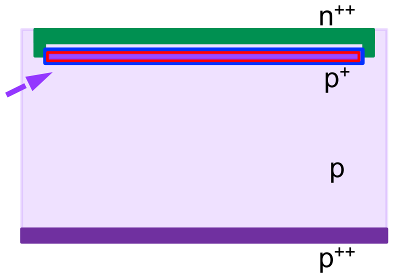




Compensated LGAD

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

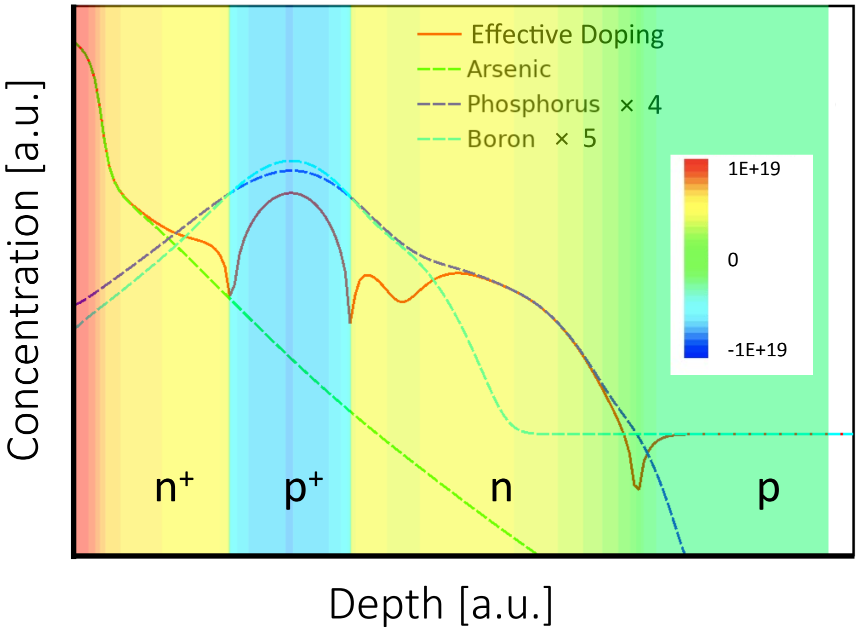
Many unknowns:

- 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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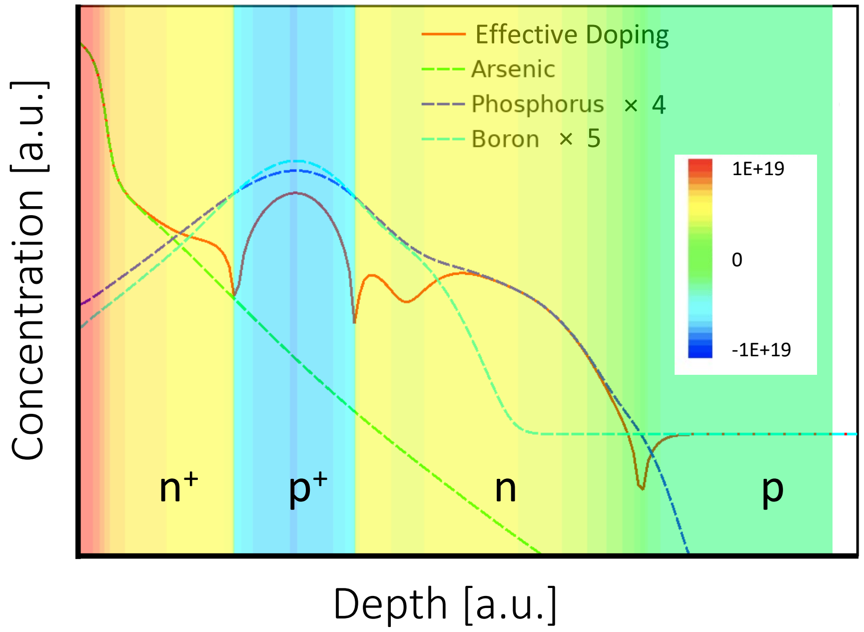
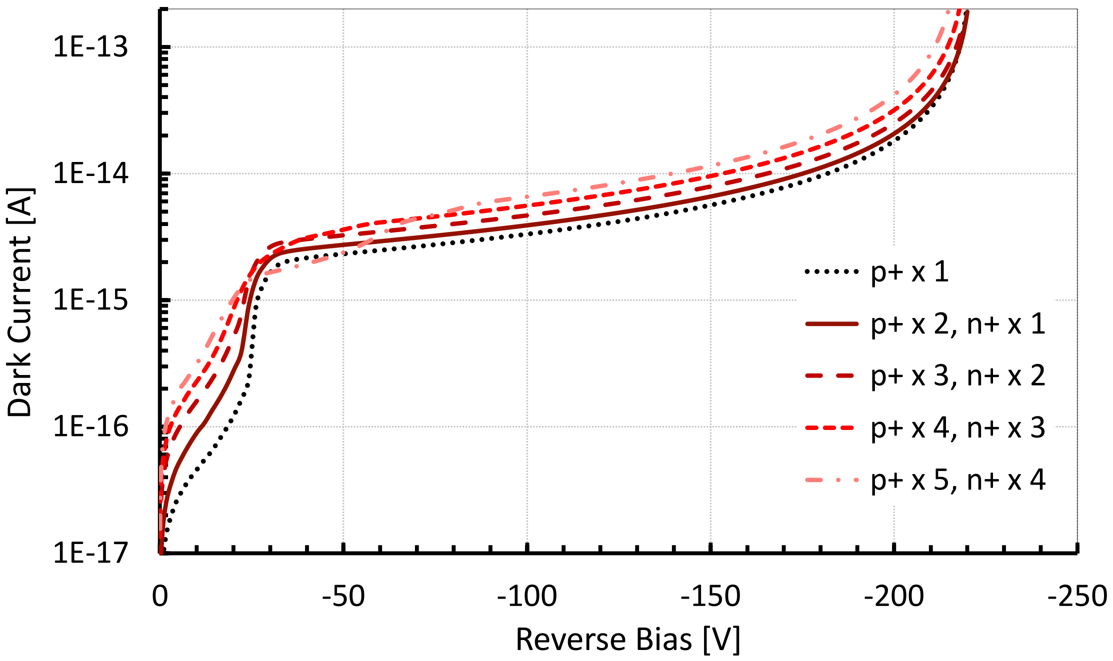


Compensated LGAD – I-V from Simulation



→ 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

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)

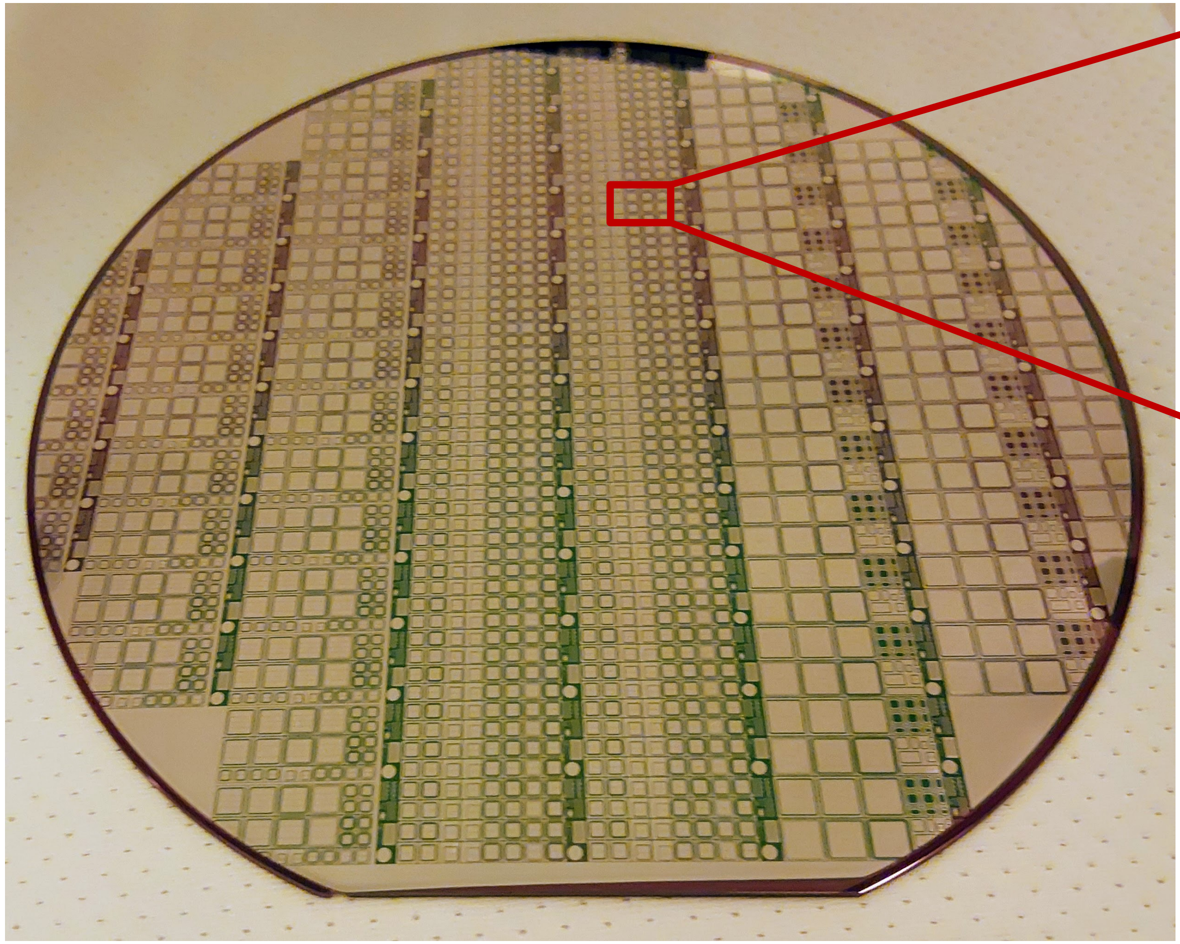
Design and preparatory studies have been performed in collaboration with the **Perugia group**

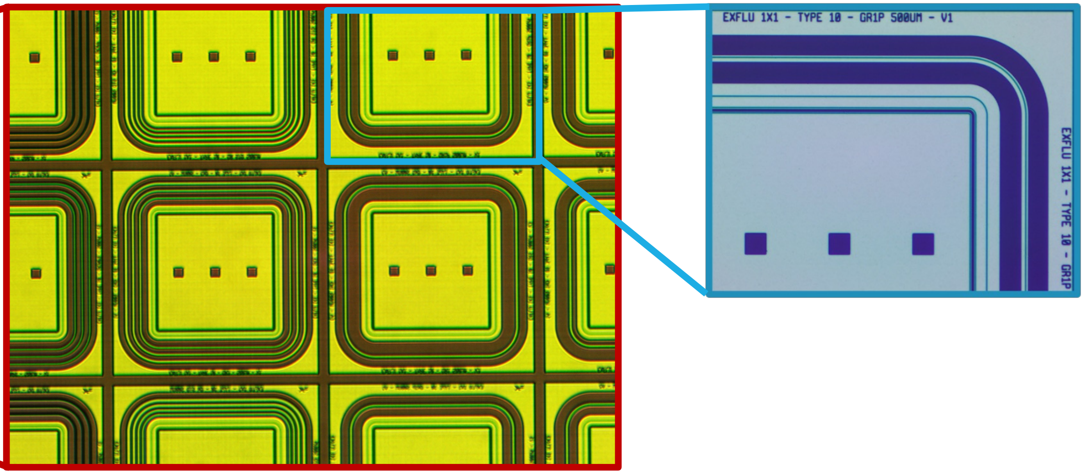
→ The EXFLU1 wafers exited the FBK clean room at the end of 2022

[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

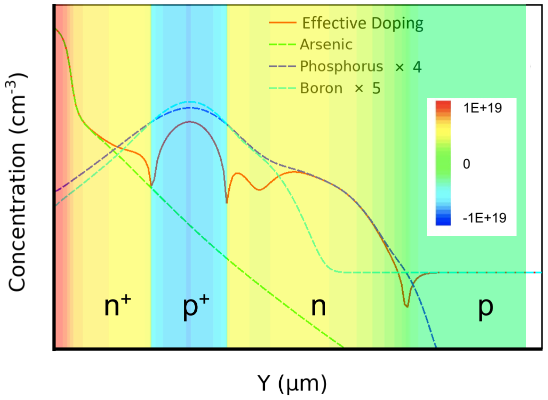
Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
7	30	2 b	1	
8	30	2 b	1	
9	30	2 c	1	
10	30	3 a	2	
11	30	3 b	2	
12	30	3 b	2	
13	30	3 b	2	1.0
14	30	3 c	2	
15	30	5 a	4	

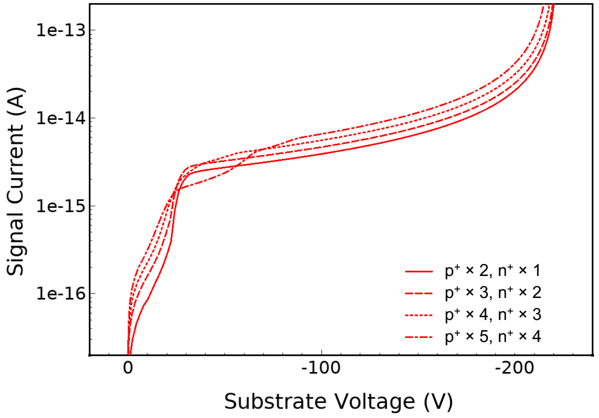
[a < b < c]

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

Compensated LGAD – I-V on wafer

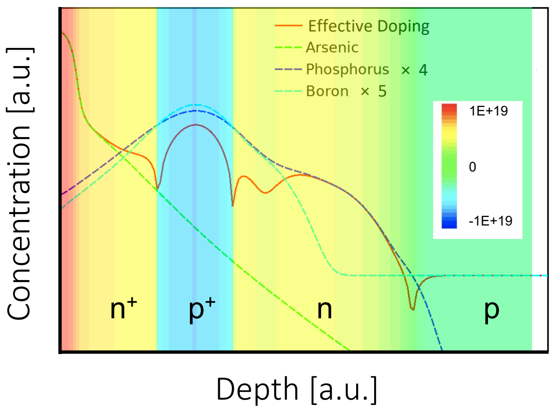
Simulation

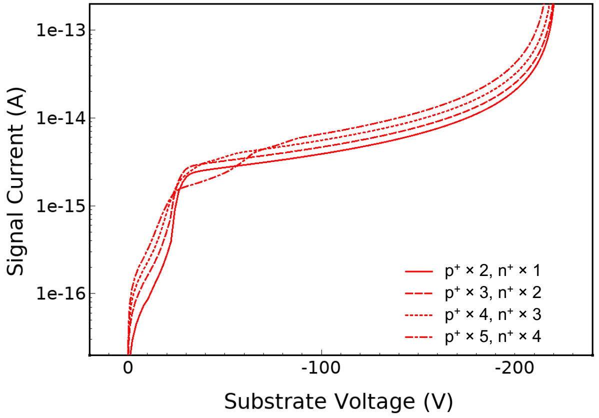




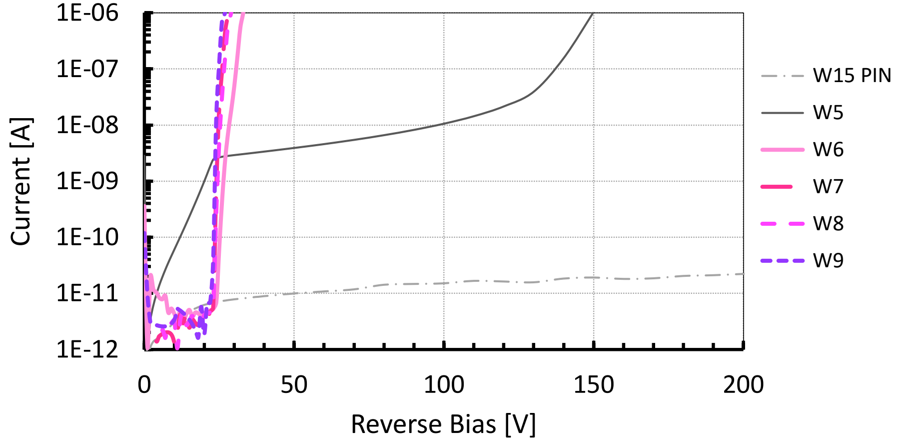
Compensated LGAD – I-V on wafer

Simulation





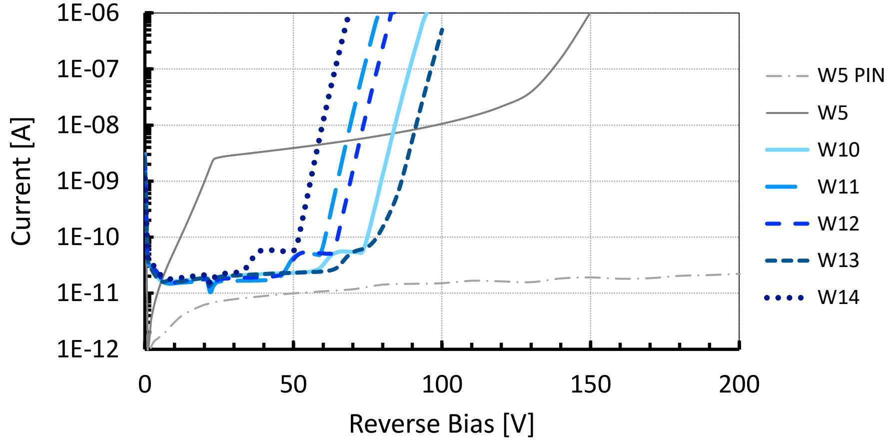
EXFLU1 – Compensated LGAD 2–1 – I-V



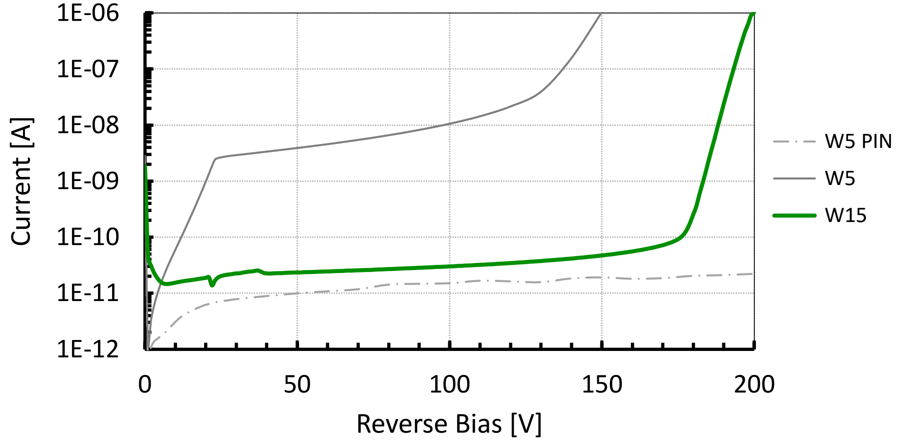
2 – 1

EXFLU1 – Compensated LGAD 3–2 – I-V

3 – 2

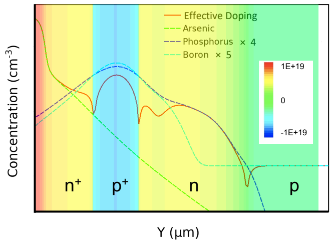


EXFLU1 – Compensated LGAD 5–4 – I-V



5 – 4

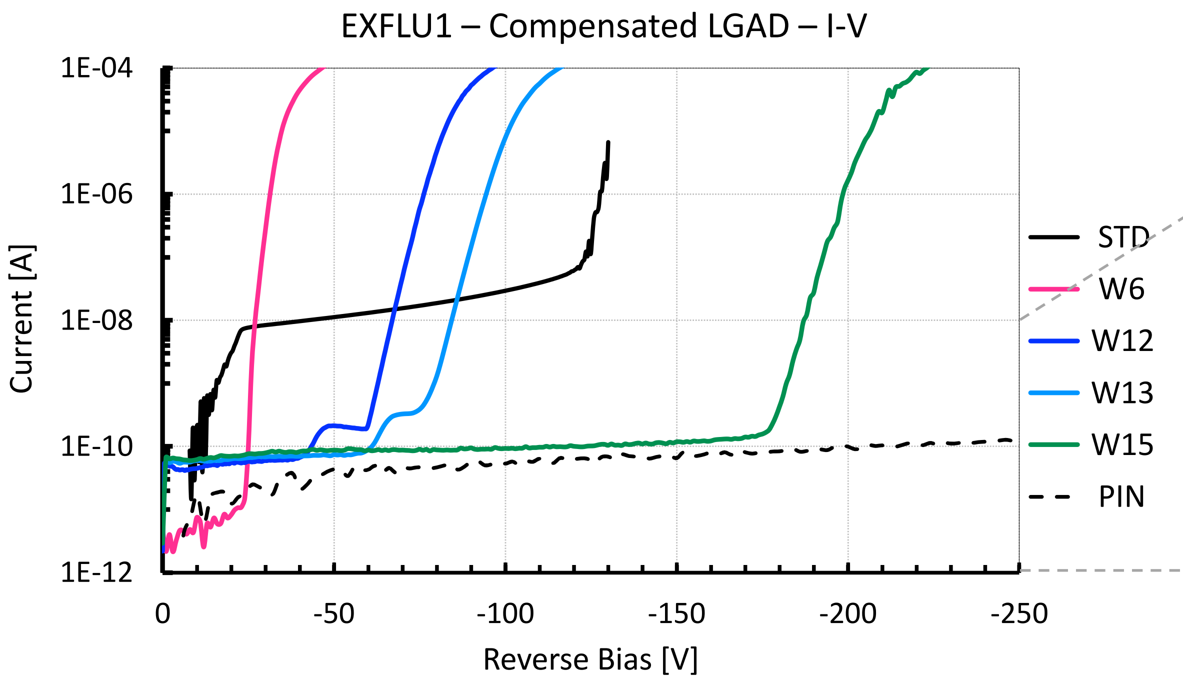
Compensated LGAD – I-V

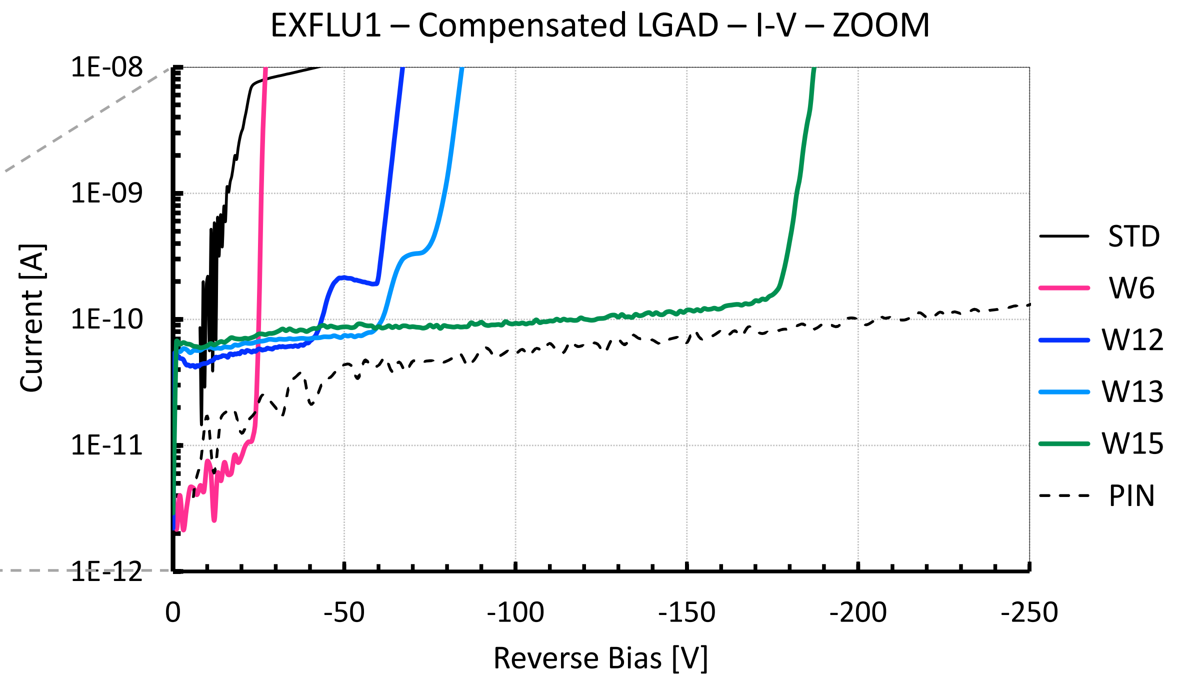


Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
12	30	3 b	2	
13	30	3 b	2	1.0
15	30	5 a	4	

→ **2 – 1 is more doped than standard LGAD**

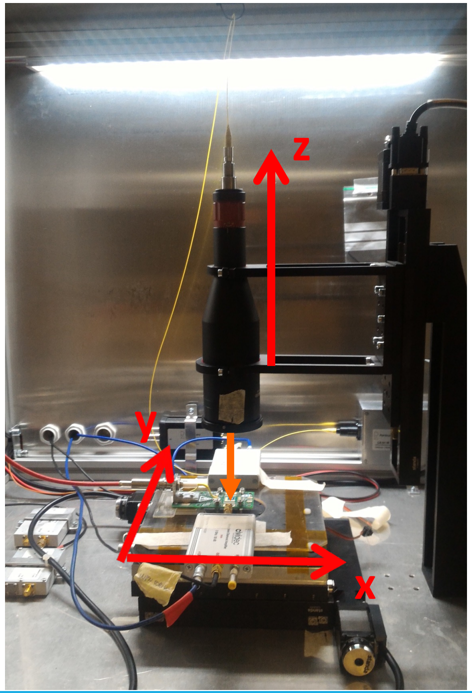
→ **3 – 2 & 5 – 4 exhibit a flat behaviour followed by an abrupt increase of the current**





IR Laser Stimulus on Compensated LGAD 2–1

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

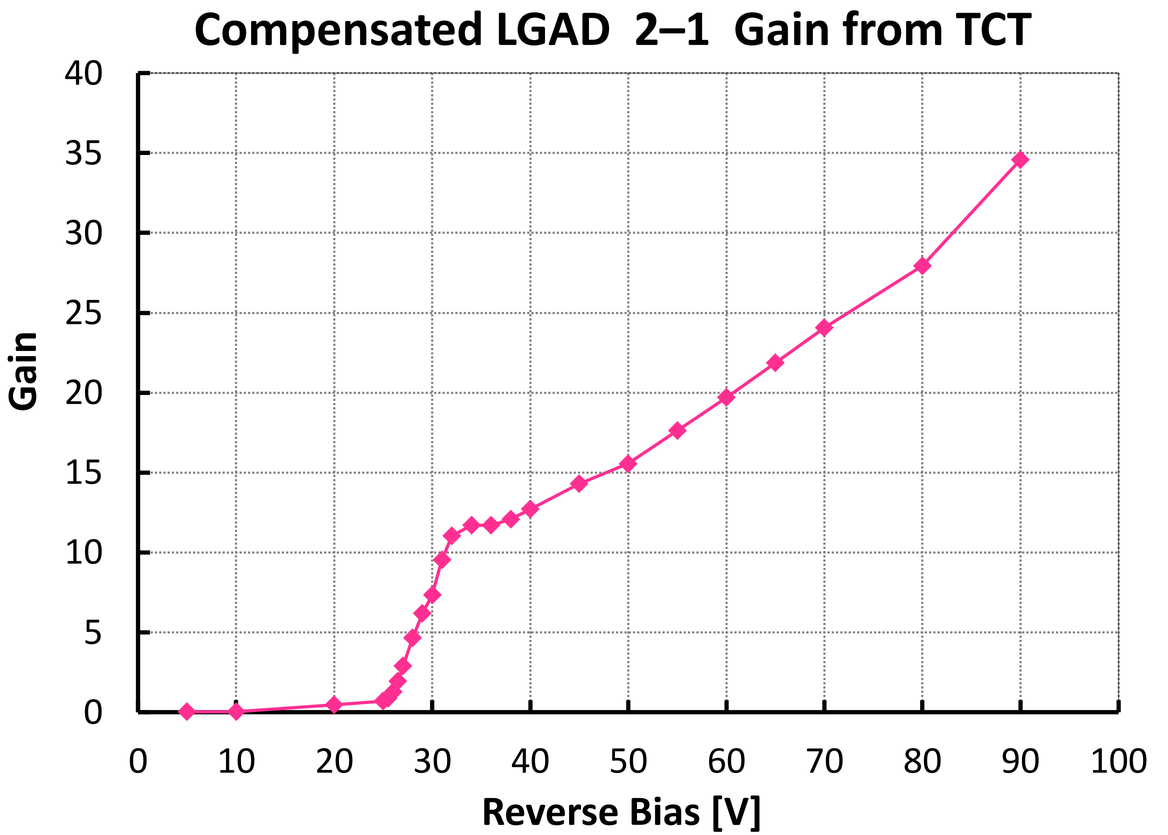


$$\text{Gain} = \frac{Q_{LGAD}}{< Q_{PiN} >}$$

Laser intensity
~ 10 MIPs

T = RT
Φ = 0

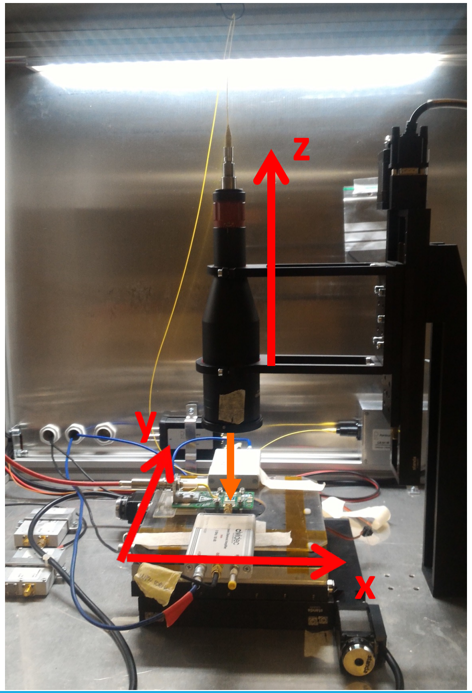
Laser stimulus on a LGAD-PiN structure from W6 (2 – 1)



→ 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 = -20°C

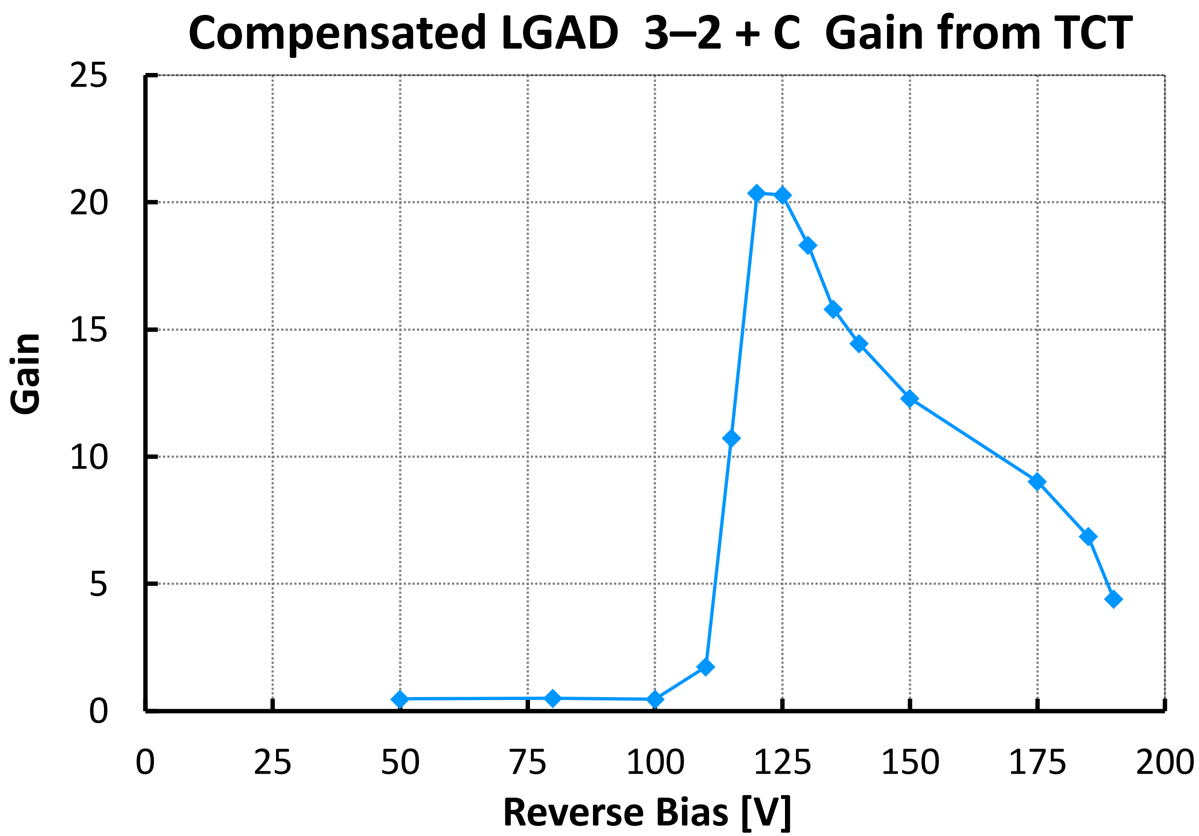


$$\text{Gain} = \frac{Q_{LGAD}}{< Q_{PiN} >}$$

Laser intensity
~ 4 MIPs

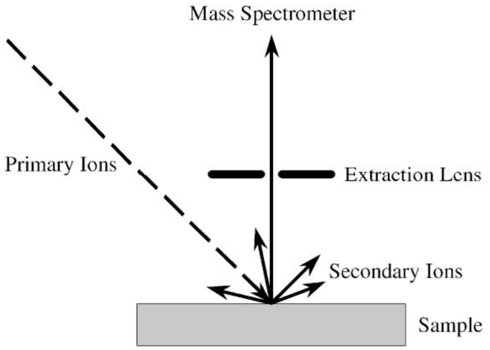
$\Phi = 0$

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

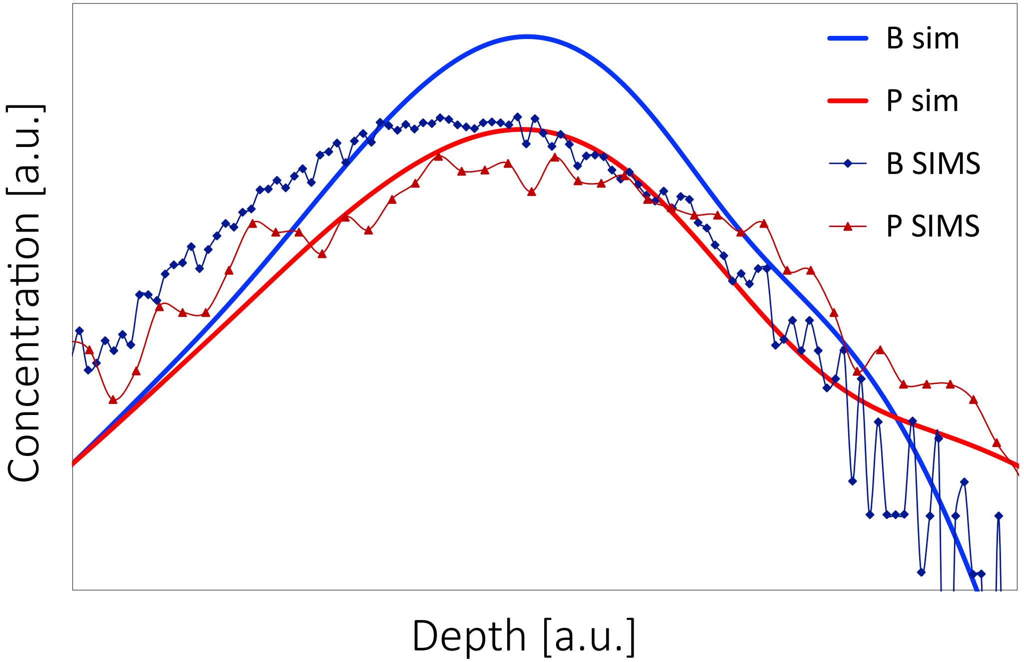


→ Difficult to operate 3 – 2 + C compensated LGAD sensors

Secondary Ion Mass Spectroscopy – W15



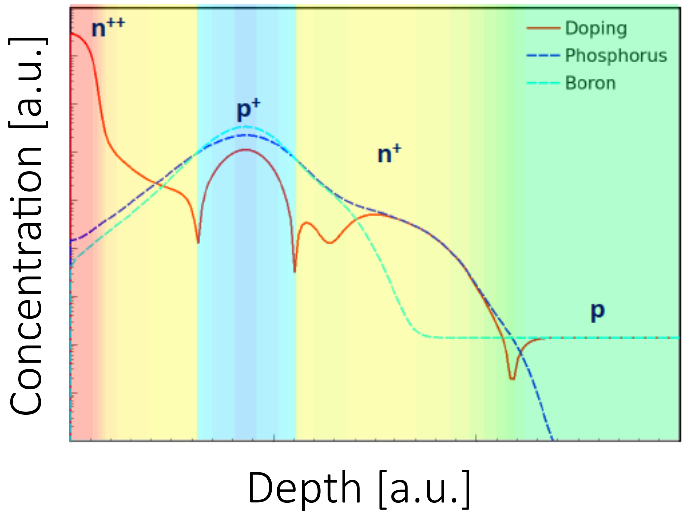
Compensated LGAD – W15 5-4
SIMS vs Process Simulation



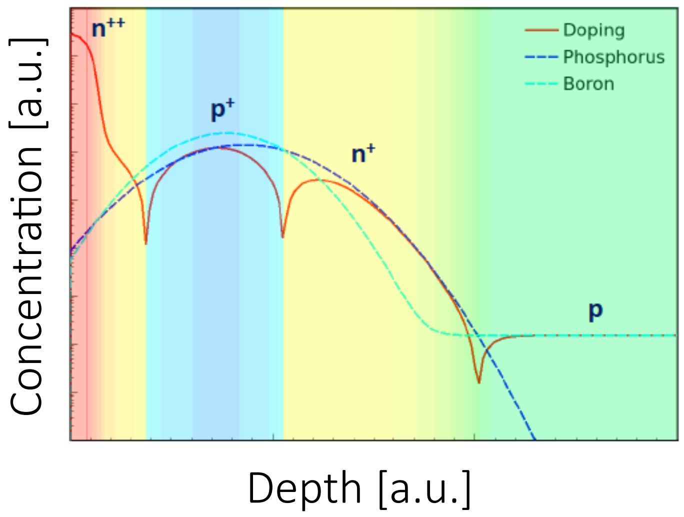
- Boron peak is shallower than phosphorus
- Boron peak is lower than predicted from simulation

SIMS Profile & I-V – 5–4

Doping Profiles
from Process Simulation

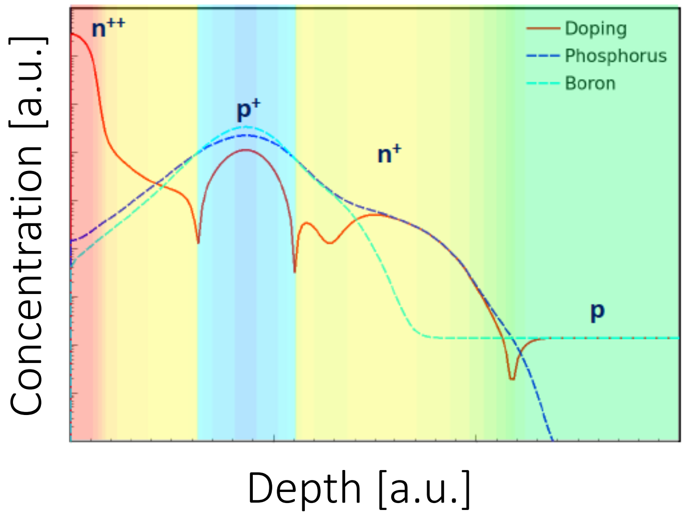


Doping Profiles
from SIMS

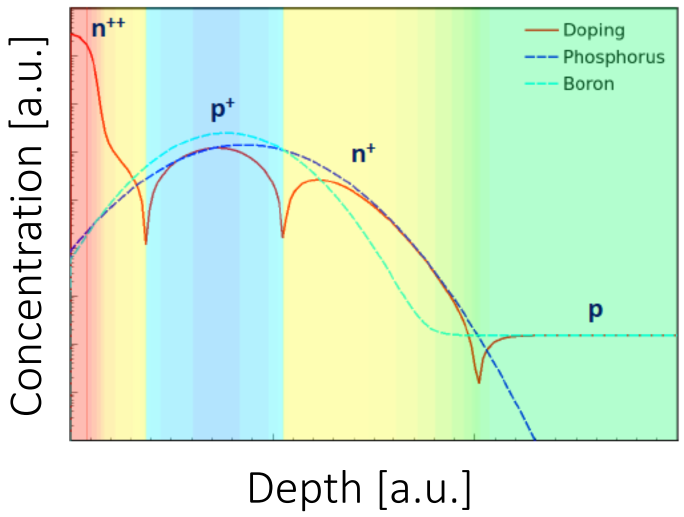


SIMS Profile & I-V – 5–4

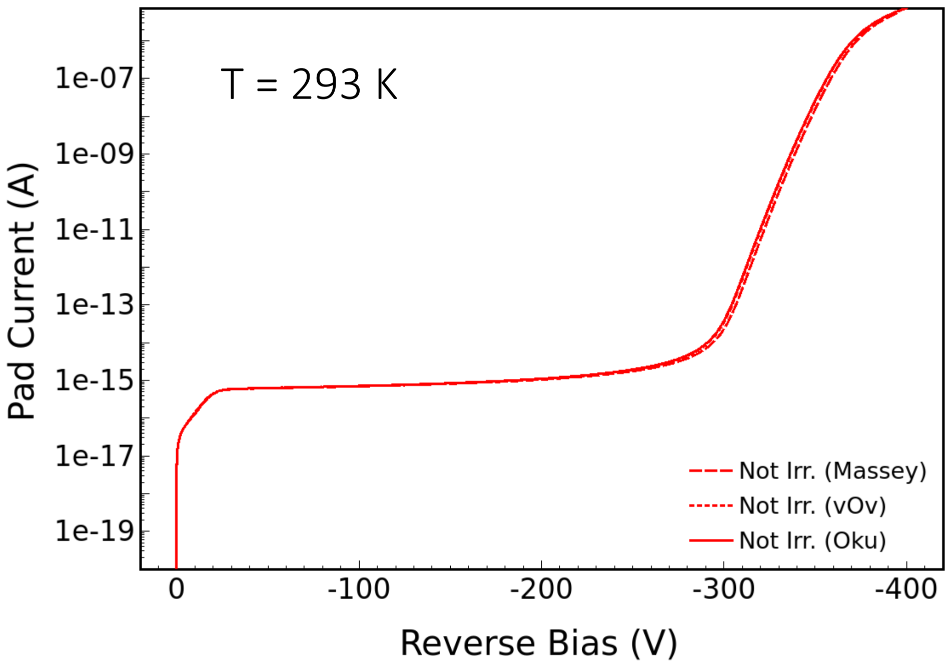
Doping Profiles from Process Simulation



Doping Profiles from SIMS

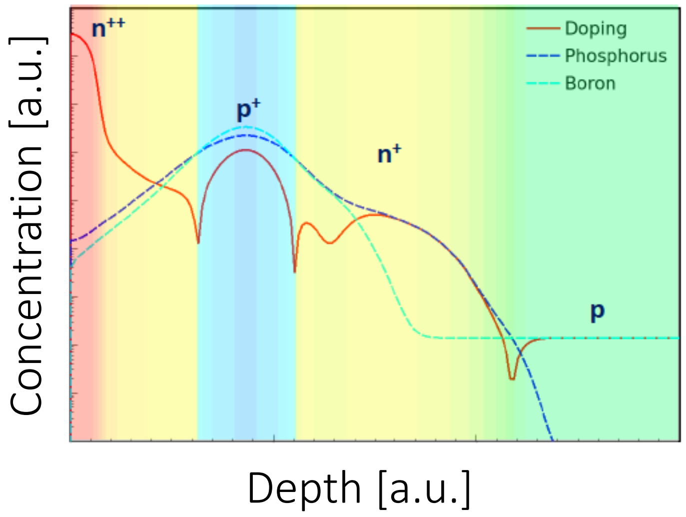


Simulated I-V from SIMS Profiles

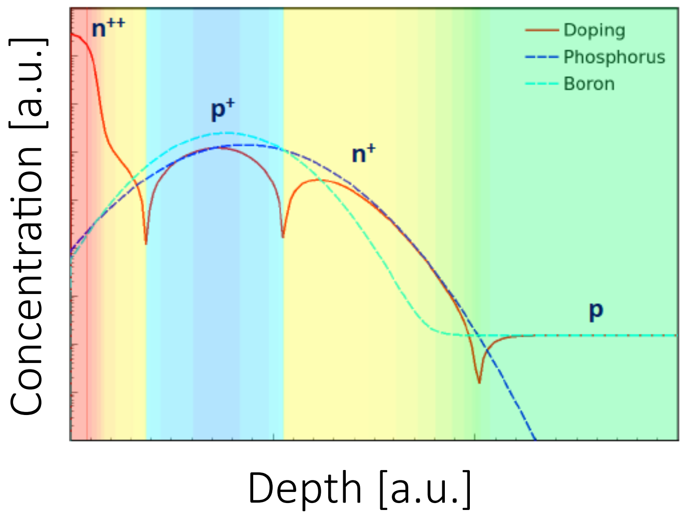


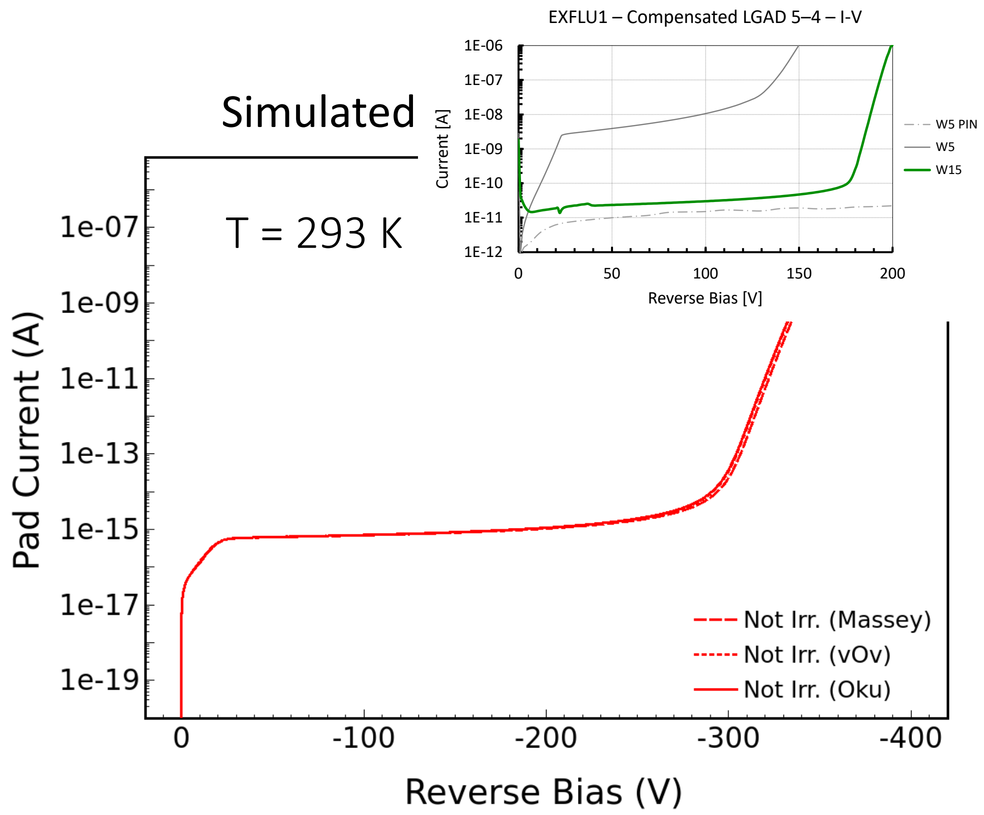
SIMS Profile & I-V – 5–4

Doping Profiles
from Process Simulation



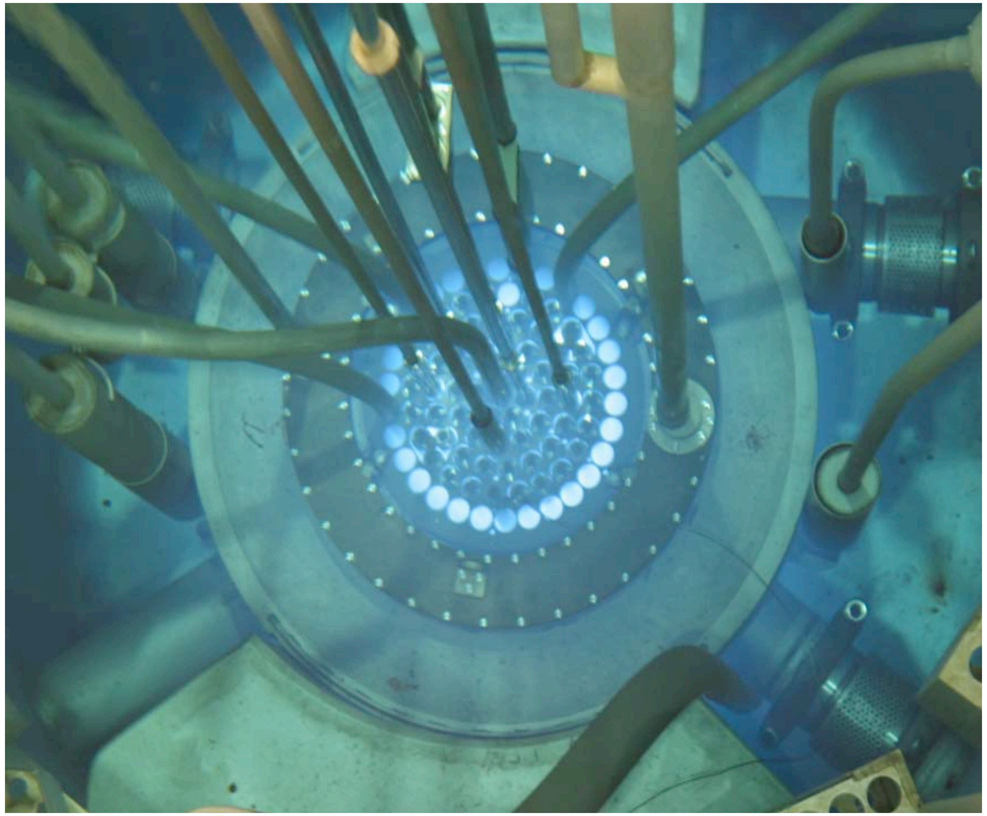
Doping Profiles
from SIMS





→ **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^{o}C

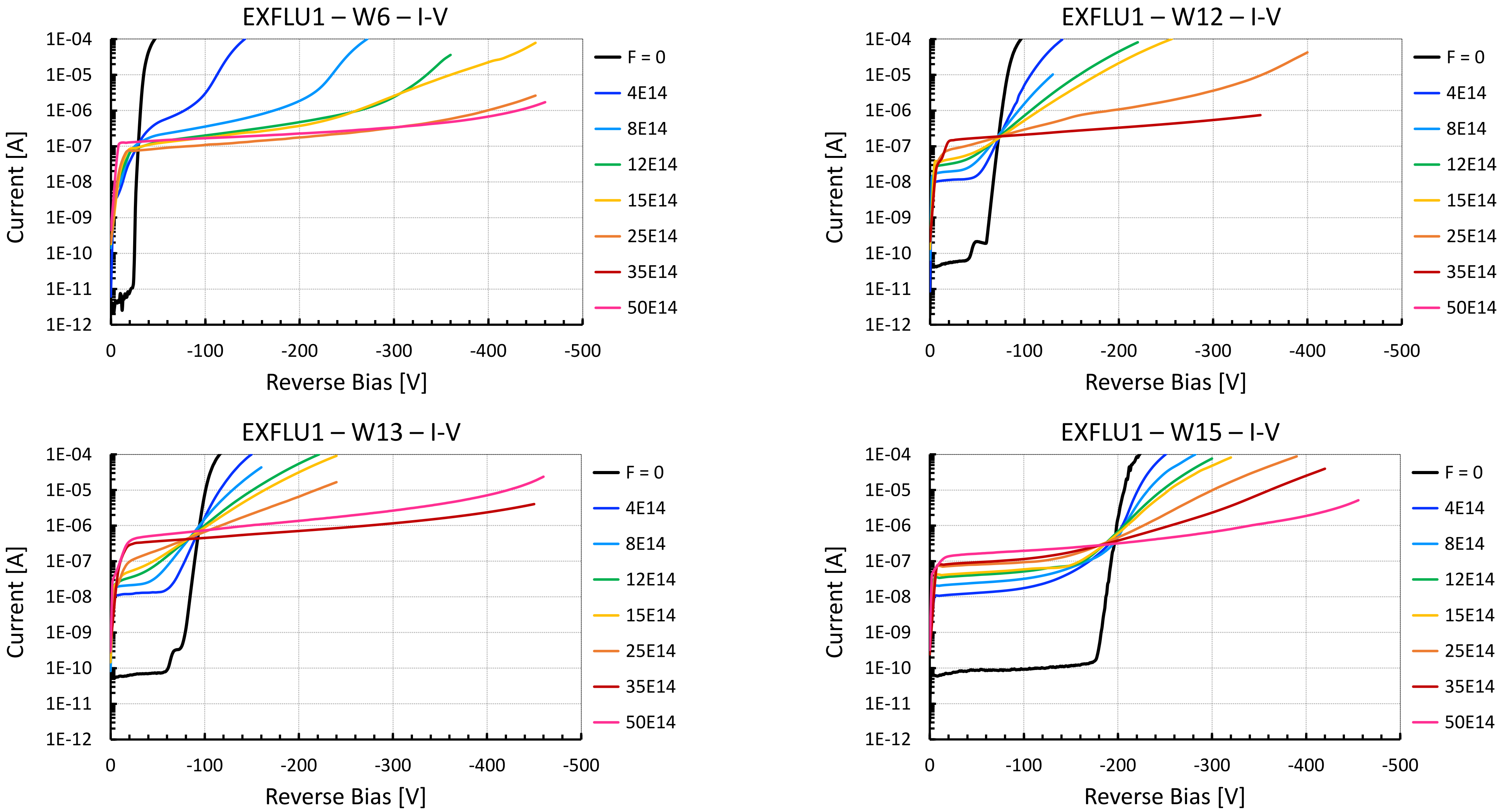
T_{IRR} = - 20^{o}C

W6
2 – 1

W12
3 – 2

W13
3 – 2 + C

W15
5 – 4



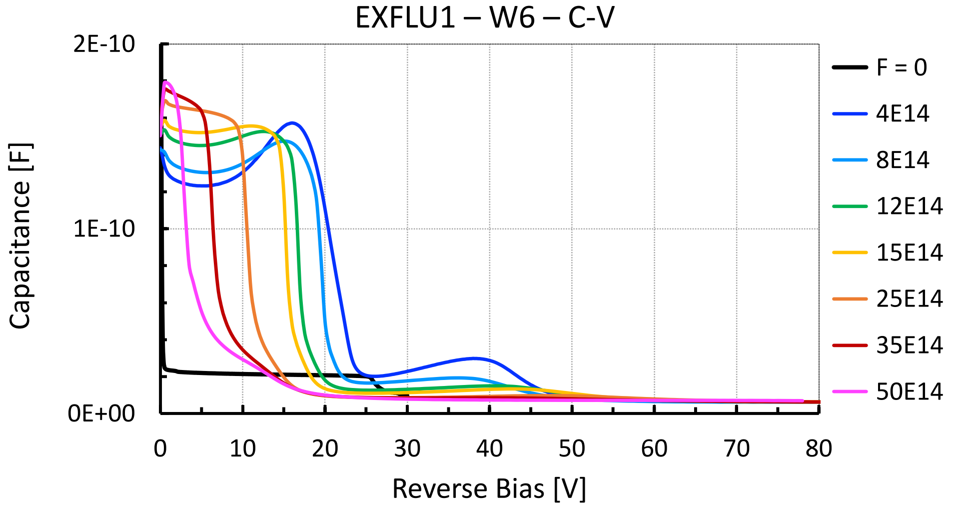
C-V from Compensated LGAD – Irradiated

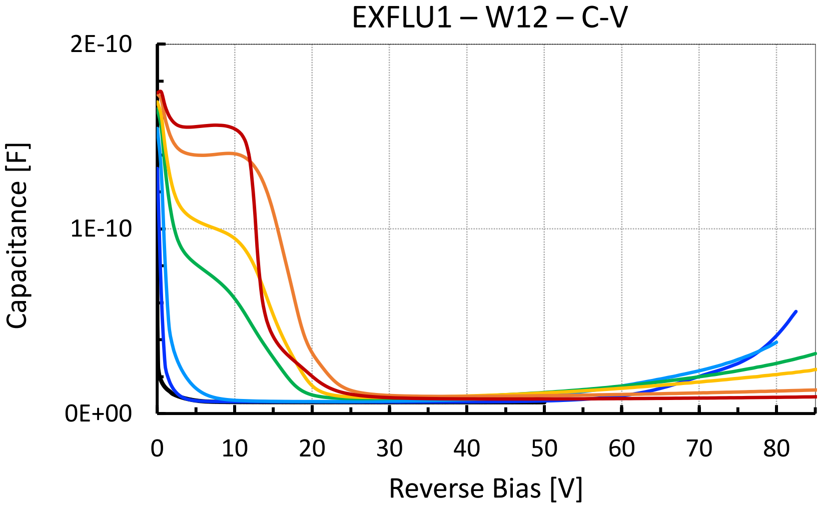
$[\Phi] = n_{eq}/cm^2$

T = + 20°C

f = 2k Hz

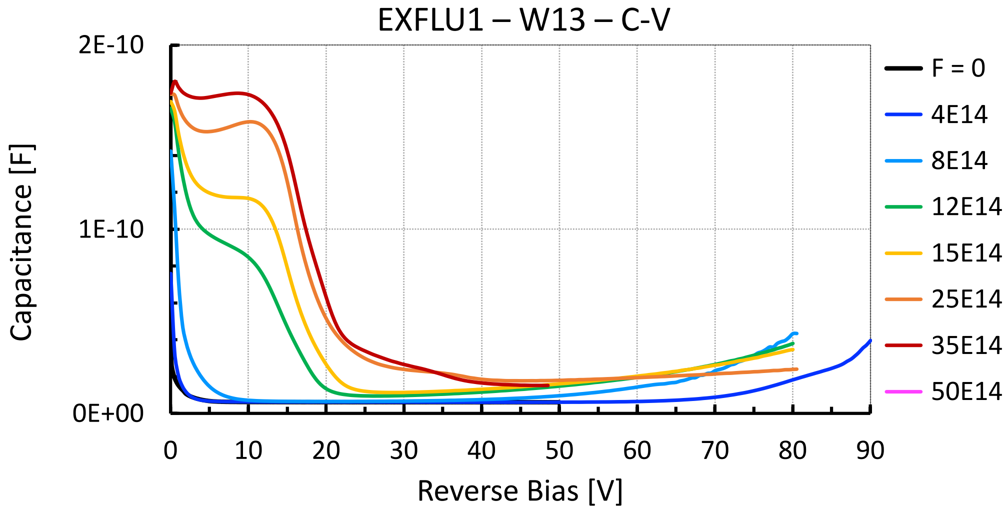
W6
2 – 1

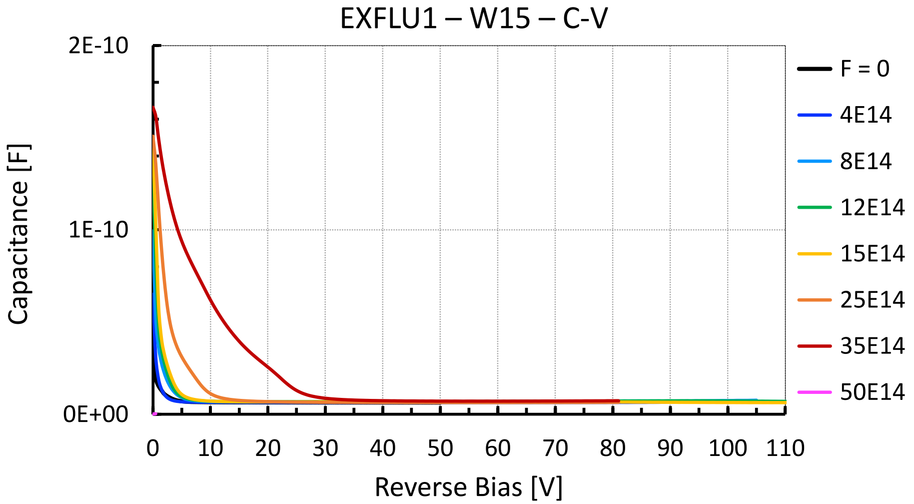




W12
3 – 2

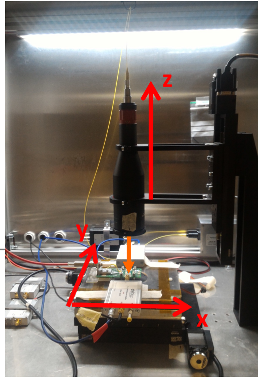
W13
3 – 2 + C





W15
5 – 4

IR Laser Stimulus on Compensated LGAD

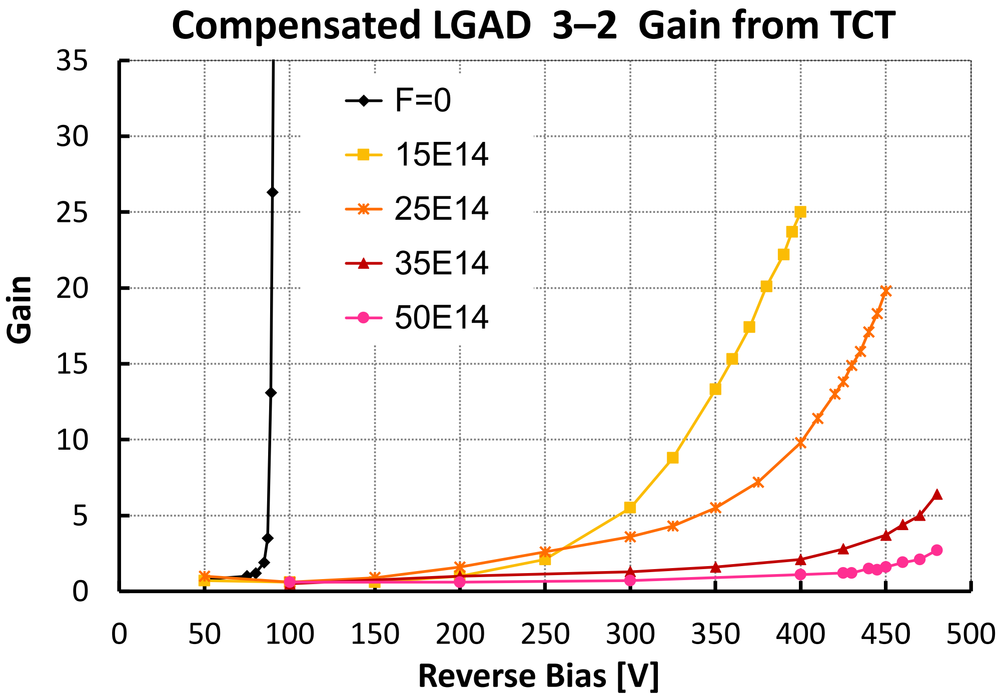


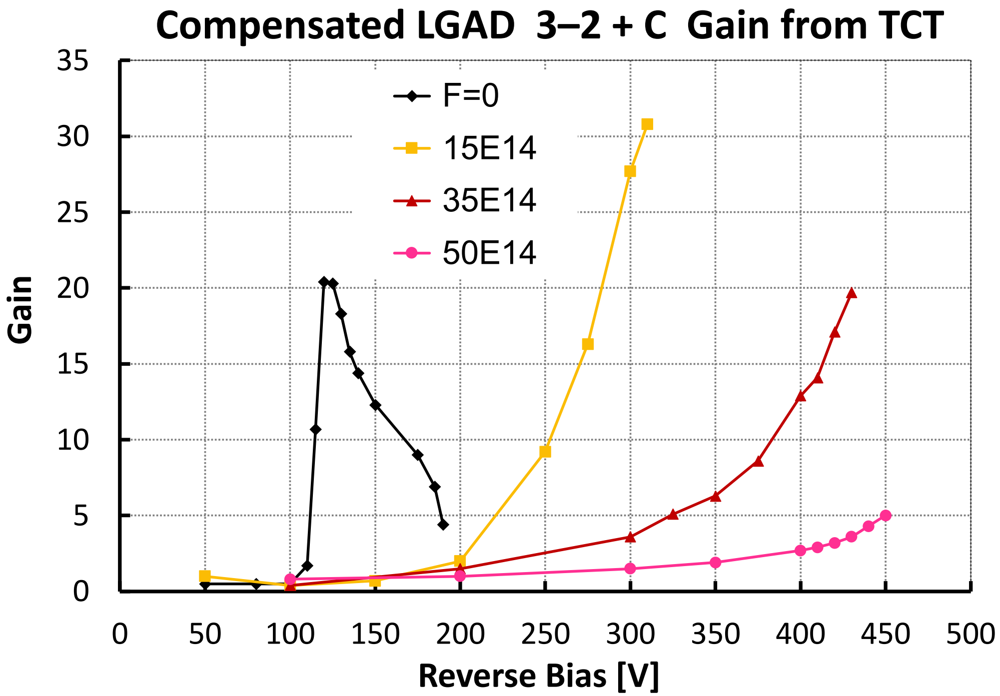
TCT Setup from Particulars
Laser intensity ~ 4 MIPs
T = -20°C

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

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

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**

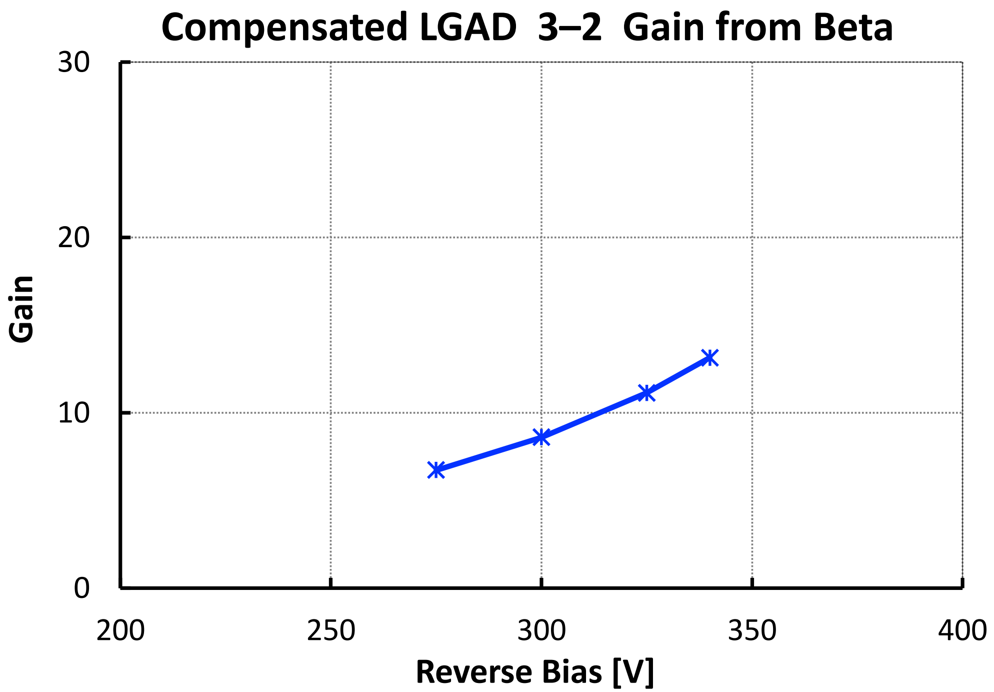
β Particles on Compensated LGAD

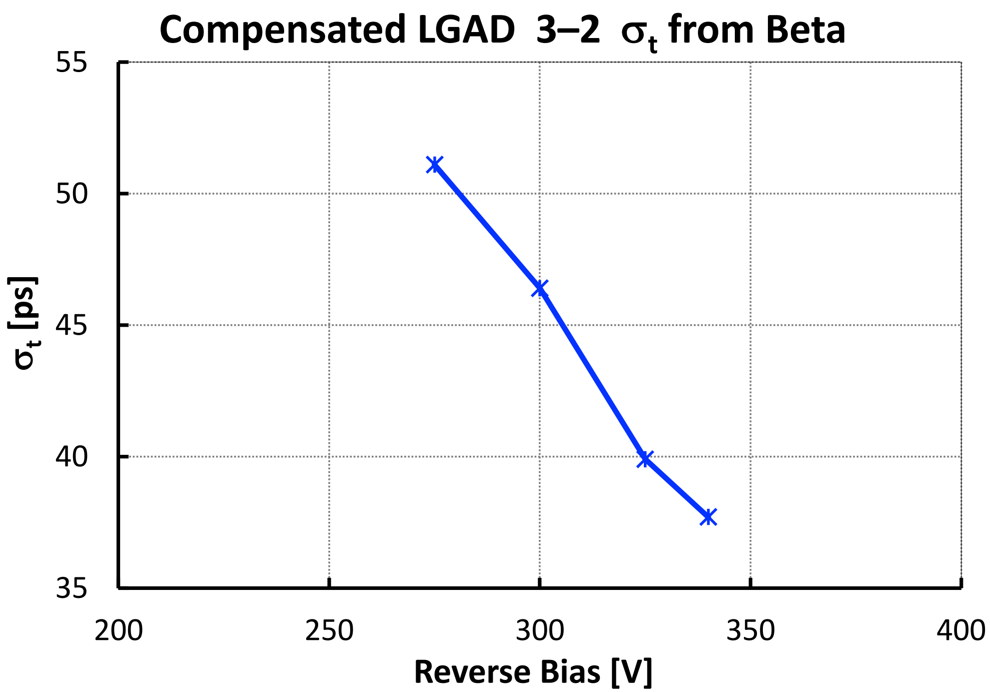
β Setup
Oscilloscope: LeCroy 9254M (2.5GHz - 40Gs/s)
HV Power supply: CAEN DT1471ET
UCSC Board + Cividec Broadband Amplifier (20dB)
Time reference: Photonis MCP-PMT – $\sigma_t \sim 15$ ps
β source: Sr90 – activity ~ 37 kBq
T = -25°C

3–2 compensated LGAD from W12 irradiated to $2.5\cdot10^{15}$ n_{eq}/cm^2 has been tested with beta particles

→ **Good timing performances of compensated LGAD sensors irradiated to $2.5\cdot10^{15}$ n_{eq}/cm^2**

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:

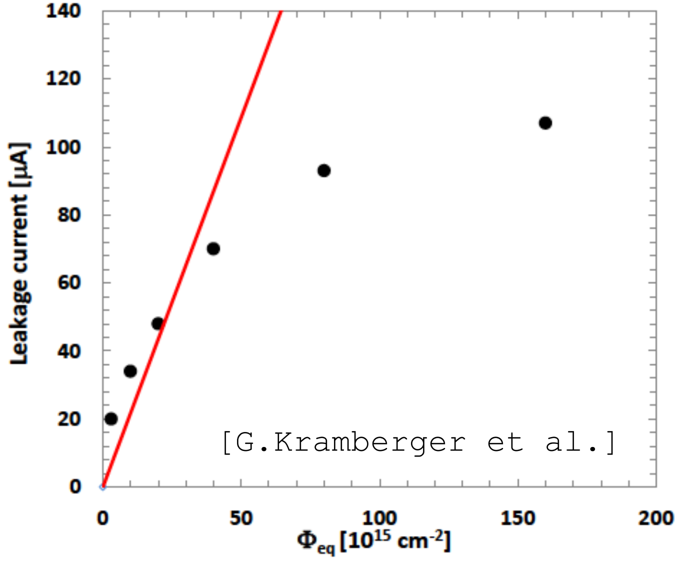
- INFN CSN5
- RD50, CERN
- AIDAinnova, WP13
- Compagnia di San Paolo
- Ministero della Ricerca, Italia, PRIN 2022, progetto 2022RK39RF – ComonSens

This project has received funding from the European Union’s Horizon 2020 Research and Innovation programme under Grant Agreement No.101004761

Backup

Saturation

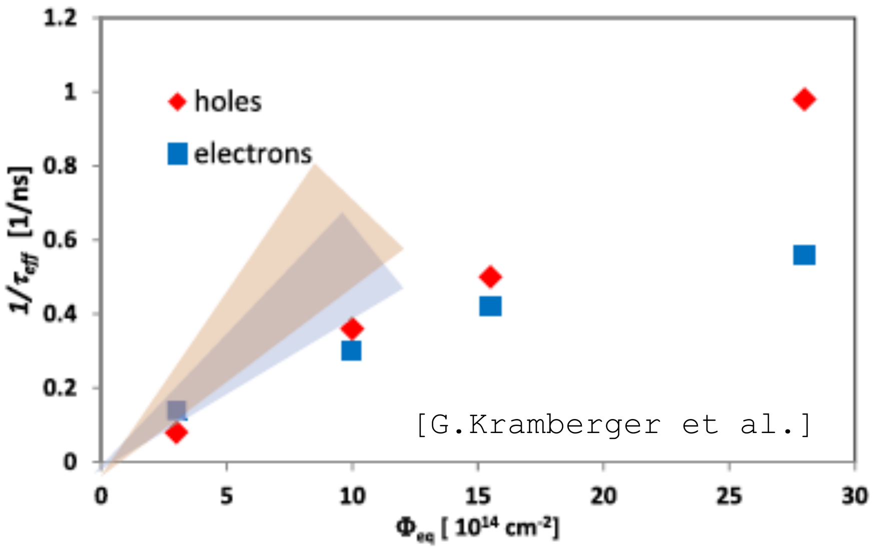
At fluences above $5 \cdot 10^{15}$ cm^{-2} → **Saturation of radiation effects observed**



Leakage current saturation

$I = \alpha V \Phi$

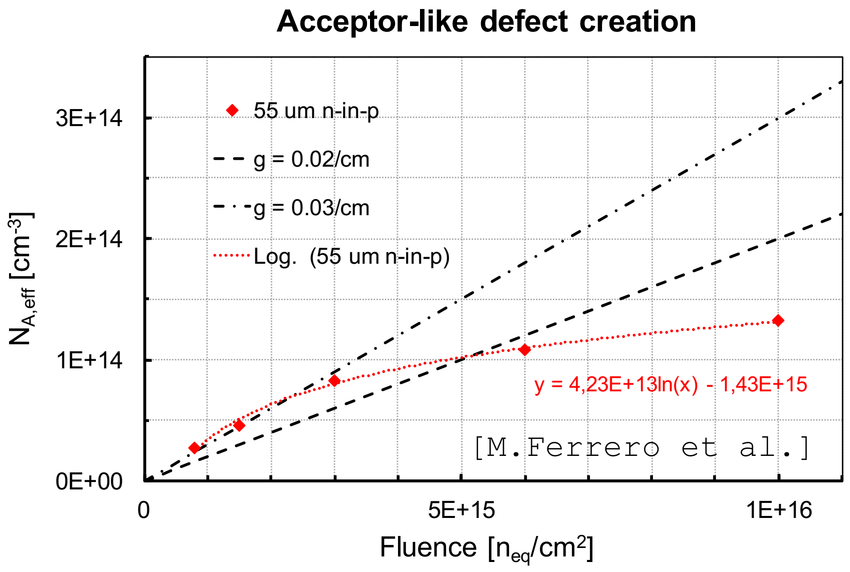
α from linear to logarithmic



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

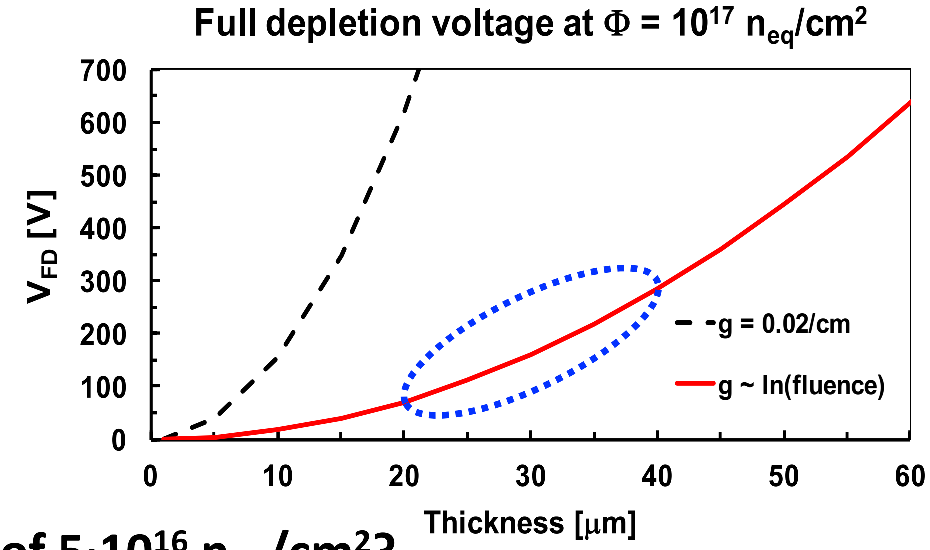
Silicon detectors irradiated at fluences 10^{16} – 10^{17} n_{eq}/cm^2 do not behave as expected → They behave better

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)

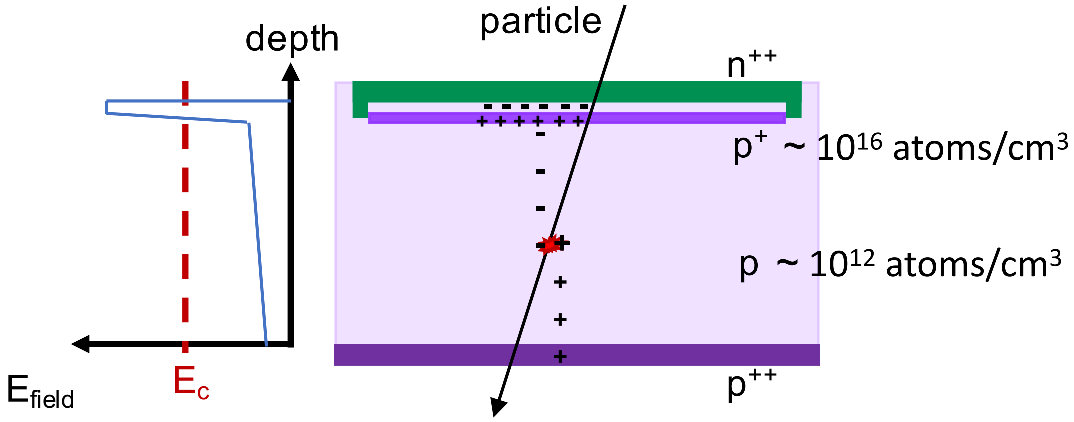
However: charge deposited by a MIP ~ 0.25 fC

→ 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

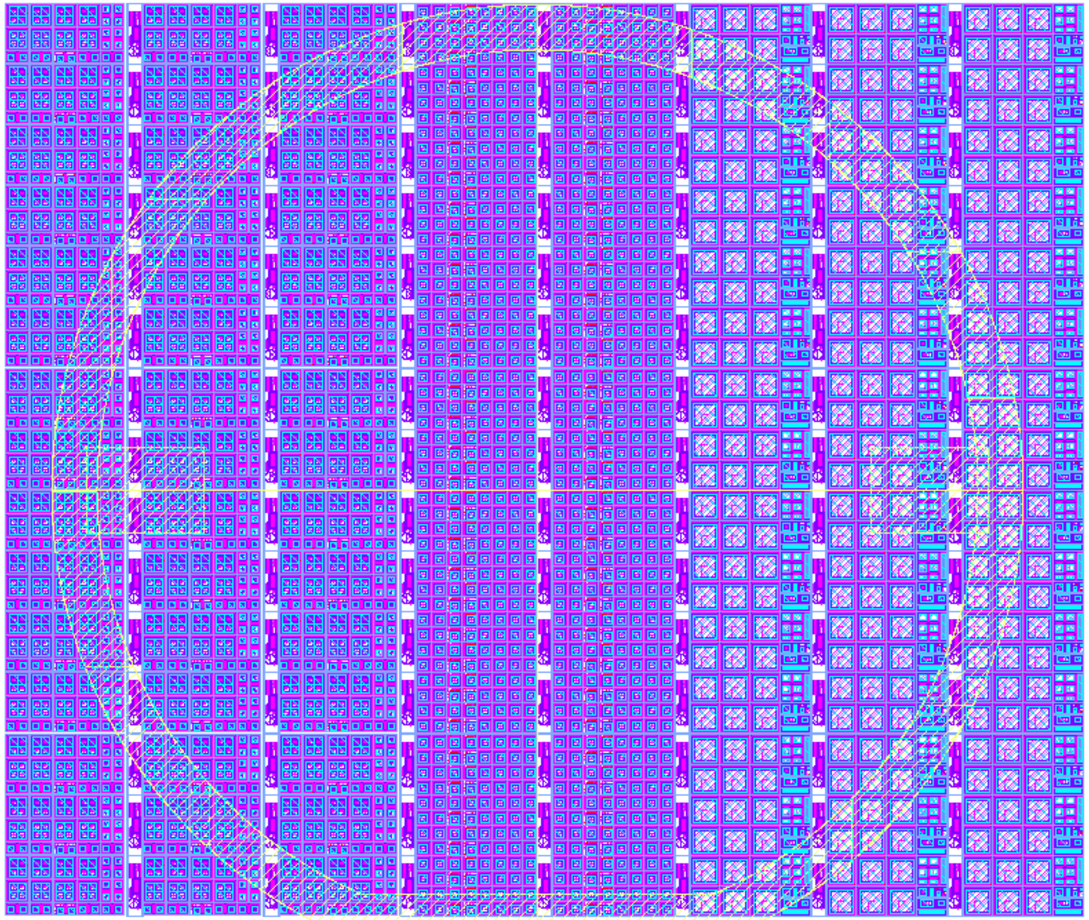
Minimum charge requested by the electronics
→ **~ 1 fC** for tracking
→ **≳ 5 fC** for timing

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]

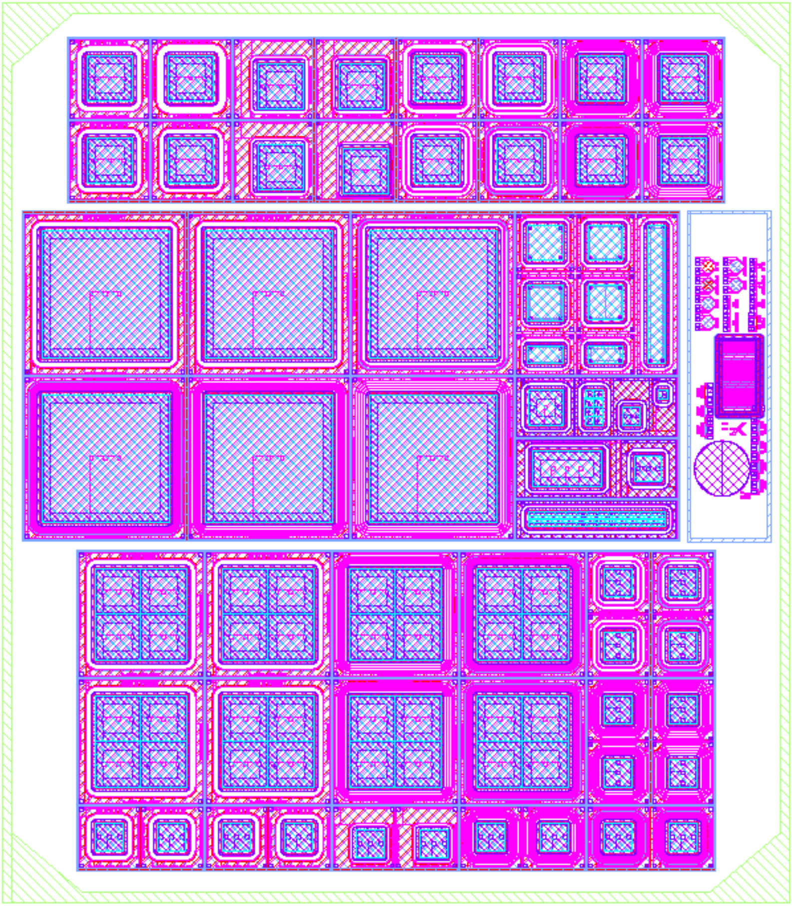
⇒ **Need a gain of at least 5 – 10**
up to $\Phi = 10^{17}\ n_{eq}/cm^2$ to efficiently record a hit

The EXFLU1 Layout

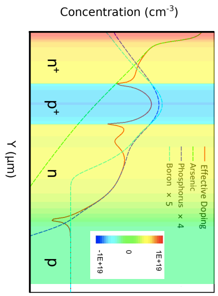
6” Wafer Layout



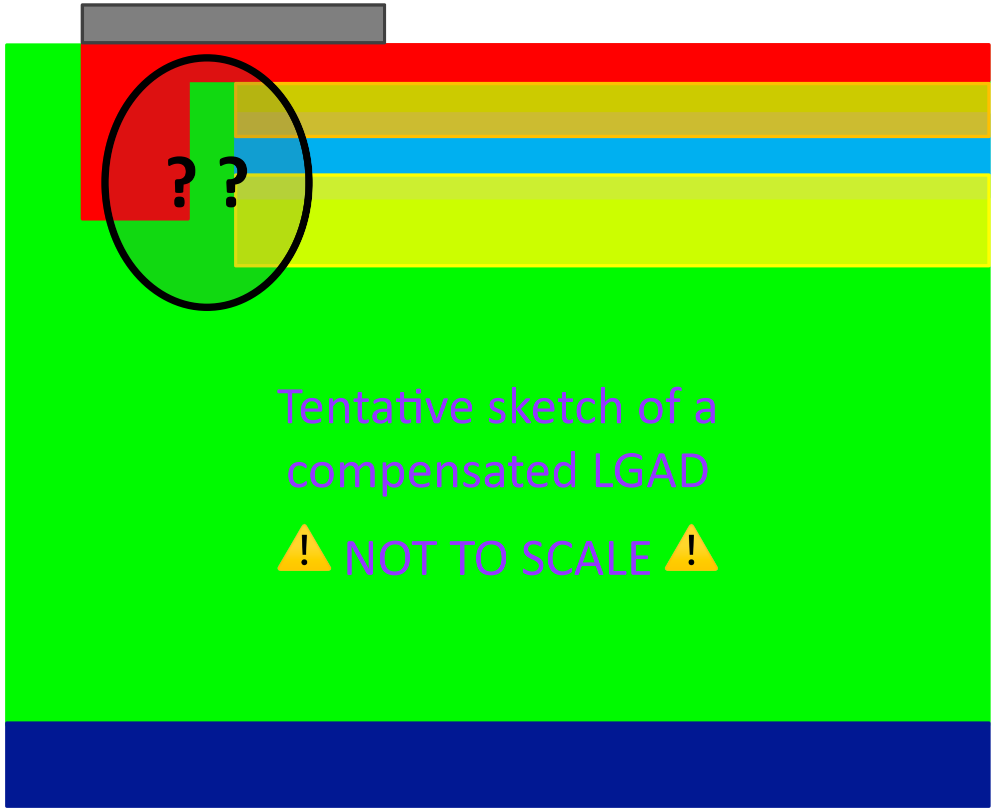
Reticle Layout



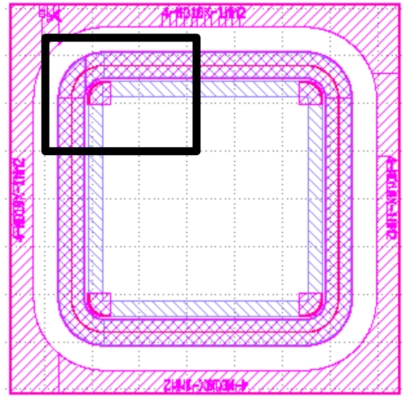
Compensated LGAD – 2D Scan with IR Laser



What is the origin of the abrupt rise of the dark current?



Scan surface



TCT scan with IR laser

Laser spot ~ 10 μm

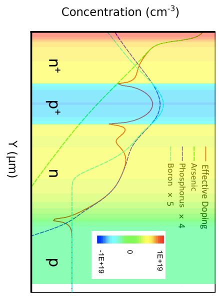
Sensor from W12 (3–2)

V_{bias} = 81 V

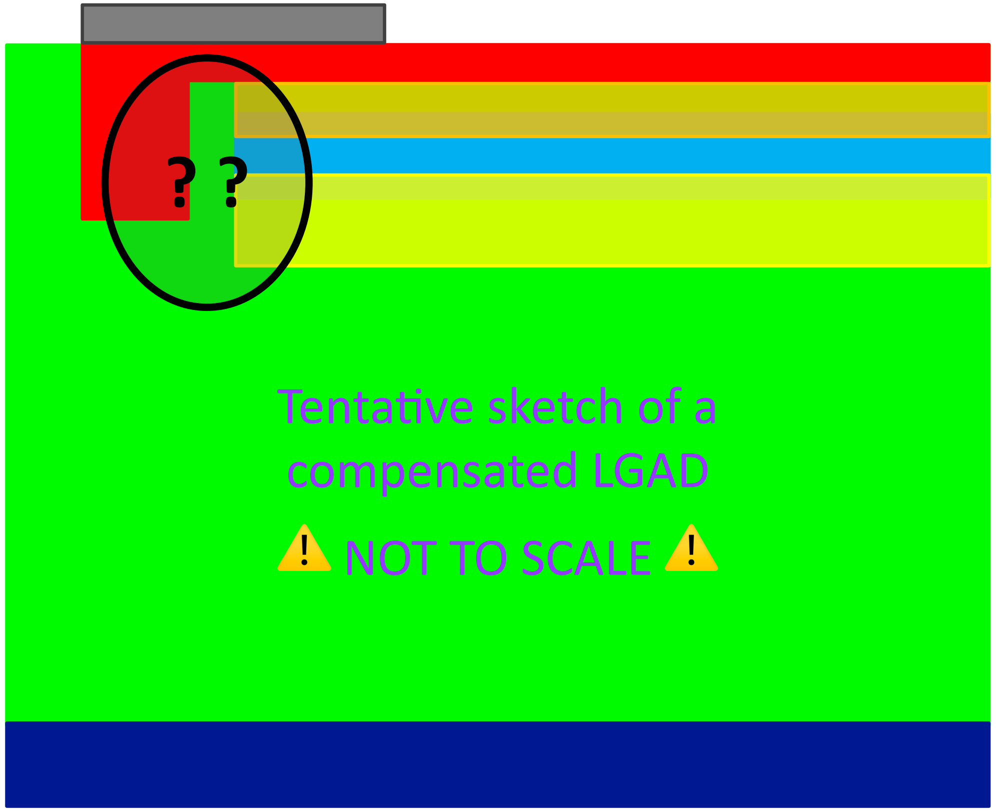
Very close to BD

→ Investigate the edges of the compensated gain implant using TCT

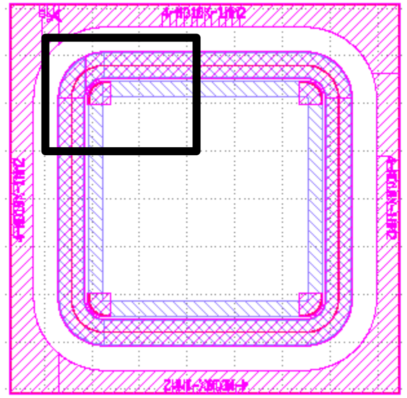
Compensated LGAD – 2D Scan with IR Laser



What is the origin of the abrupt rise of the dark current?



Scan surface



TCT scan with IR laser

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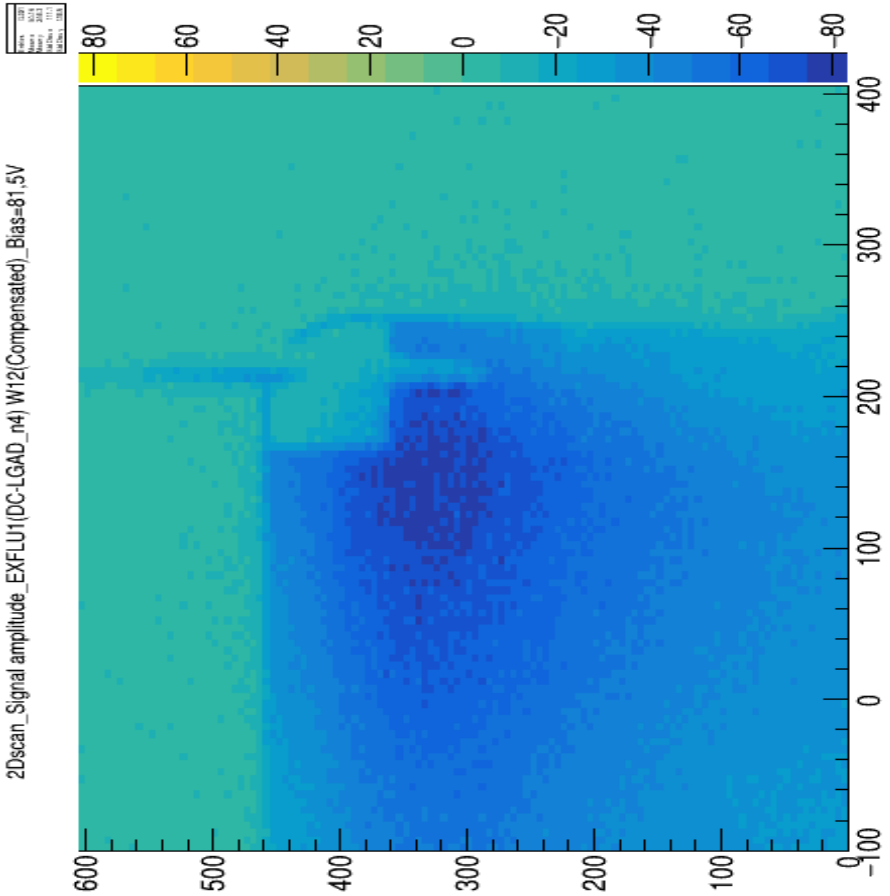
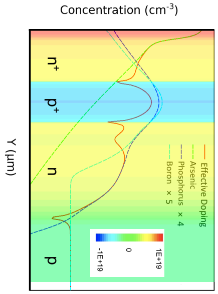
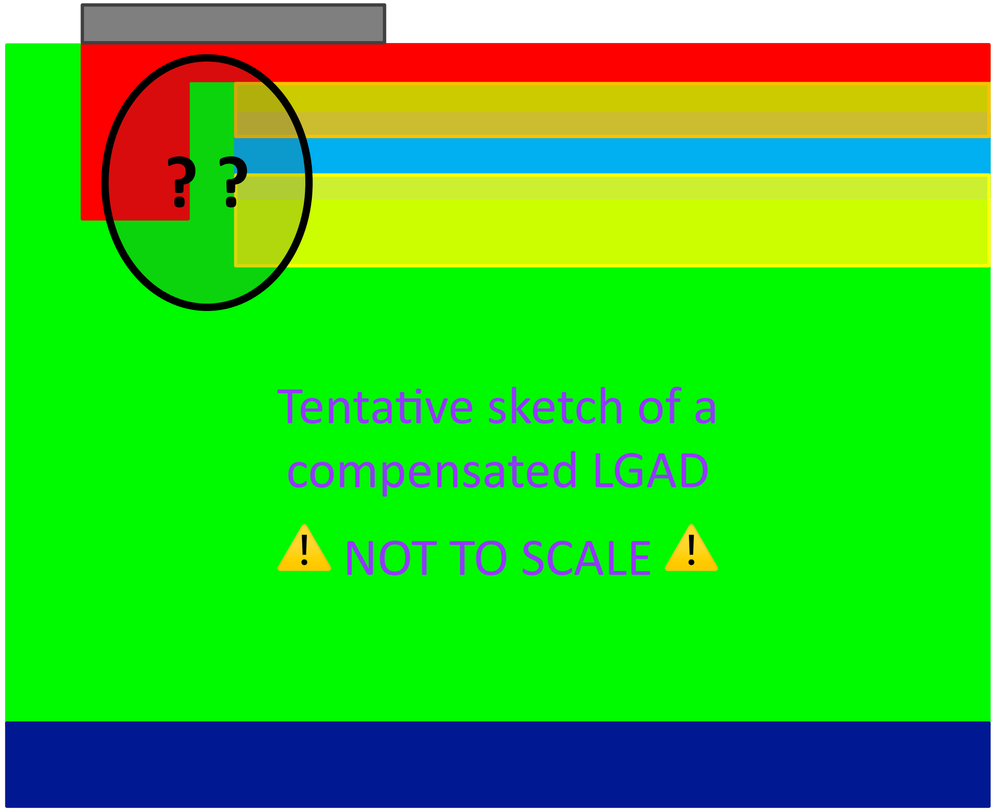


→ Investigate the edges of the compensated gain implant using TCT

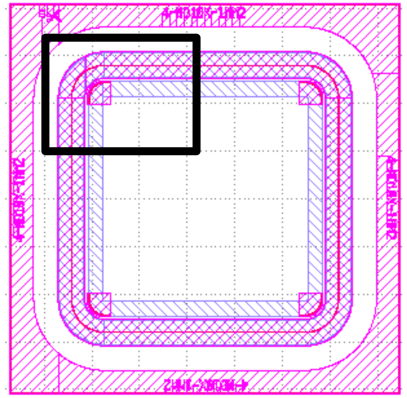
Compensated LGAD – 2D Scan with IR Laser



What is the origin of the abrupt rise of the dark current?



Scan surface



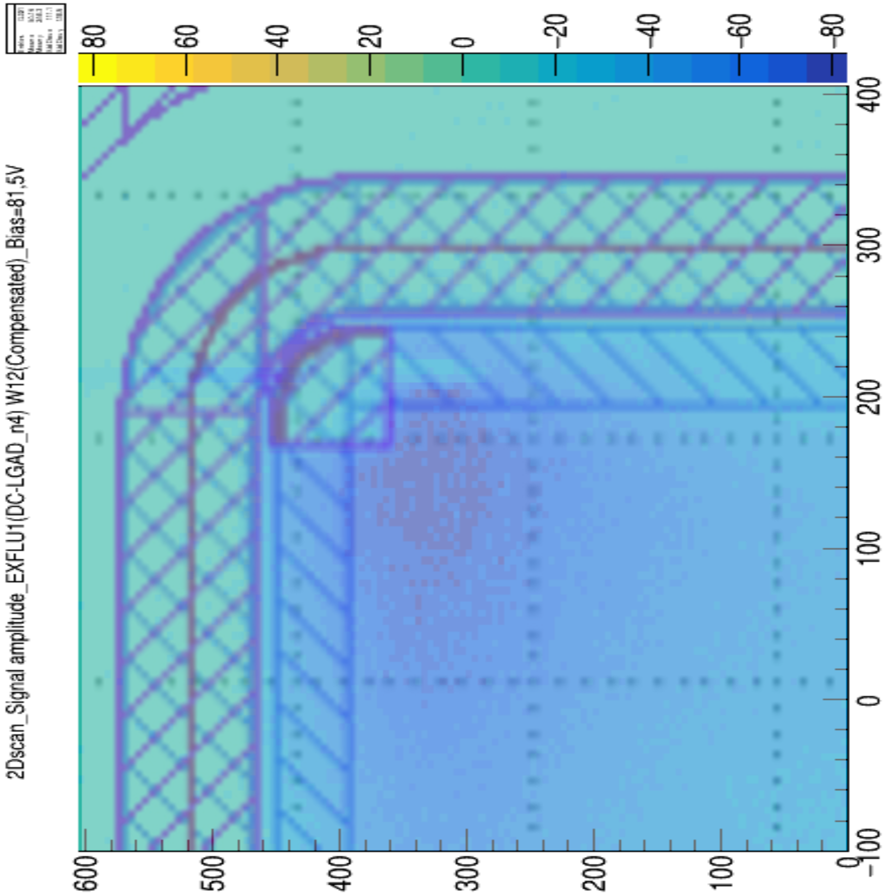
TCT scan with IR laser

Laser spot ~ 10 μm

Sensor from W12 (3–2)

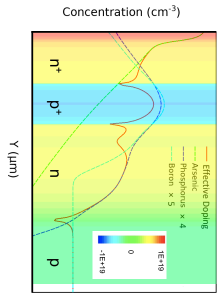
V_{bias} = 81 V

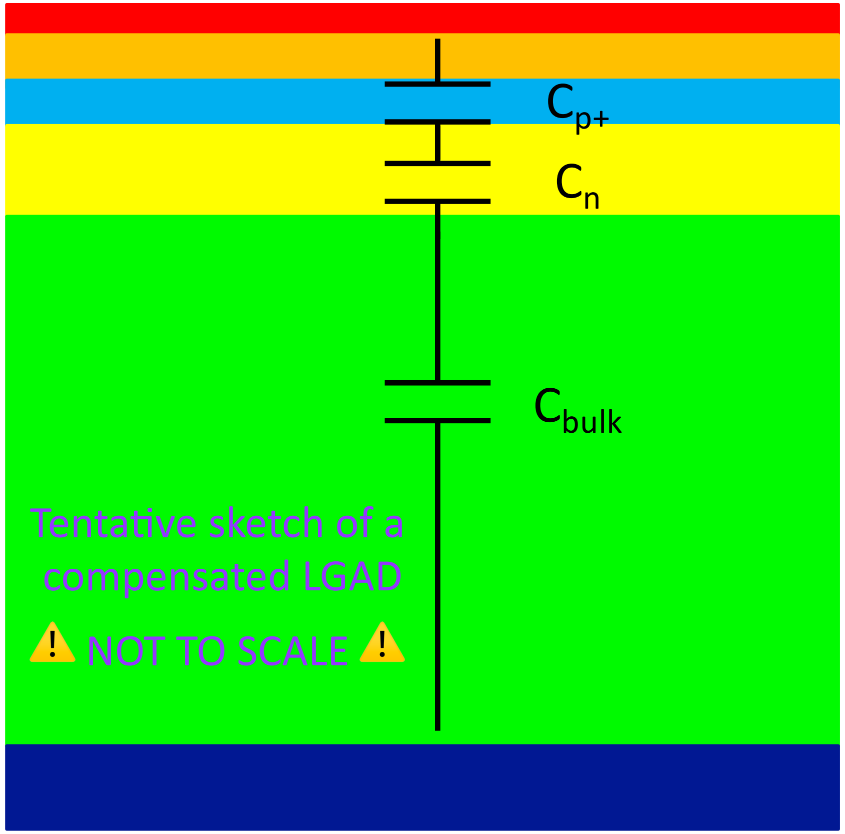
Very close to BD

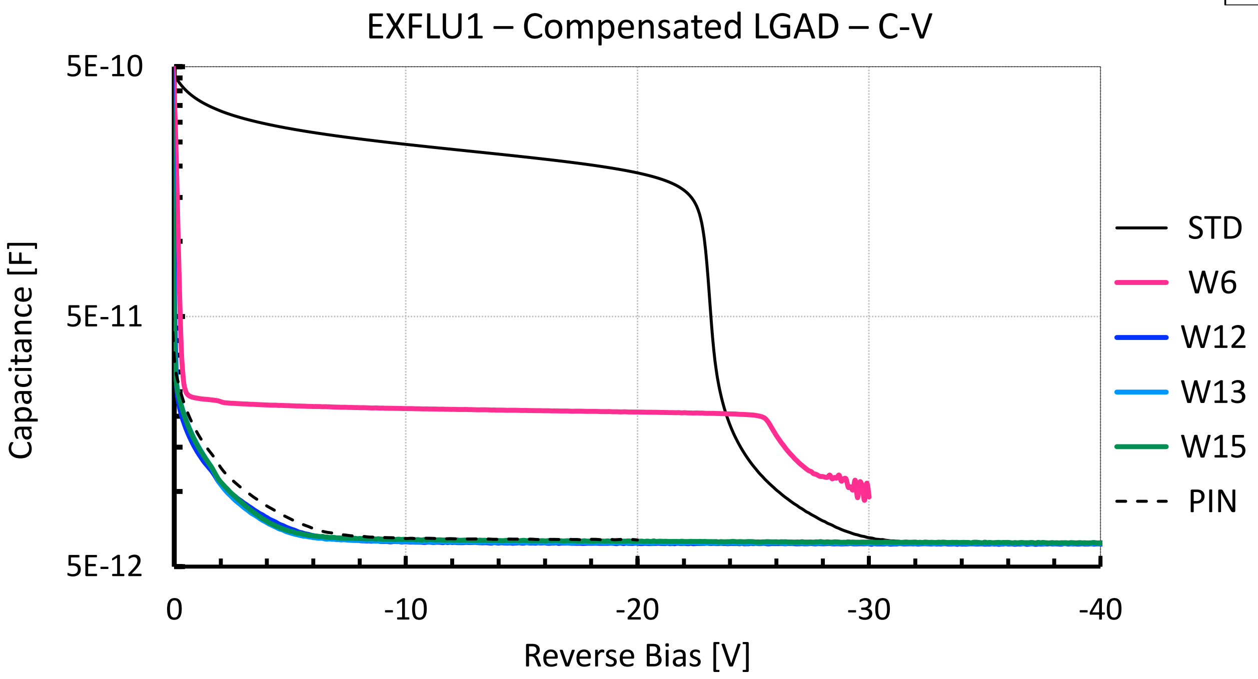


→ **No issues observed at the edge of the compensated gain implants**

Compensated LGAD – C-V

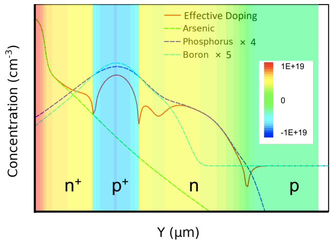






→ 3–2 & 5–4 C-V measurements have shapes similar to the one from the PIN diode, measuring a slightly bigger thickness at bias values between 0 and -10 V

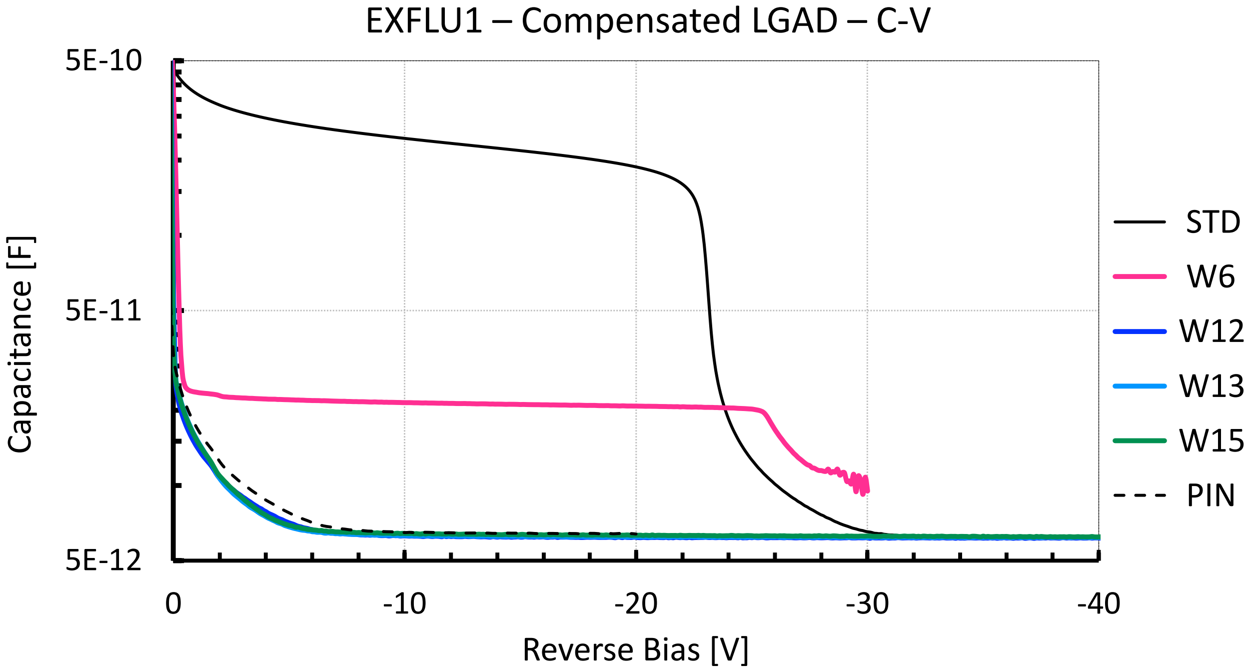
Compensated LGAD – C-V

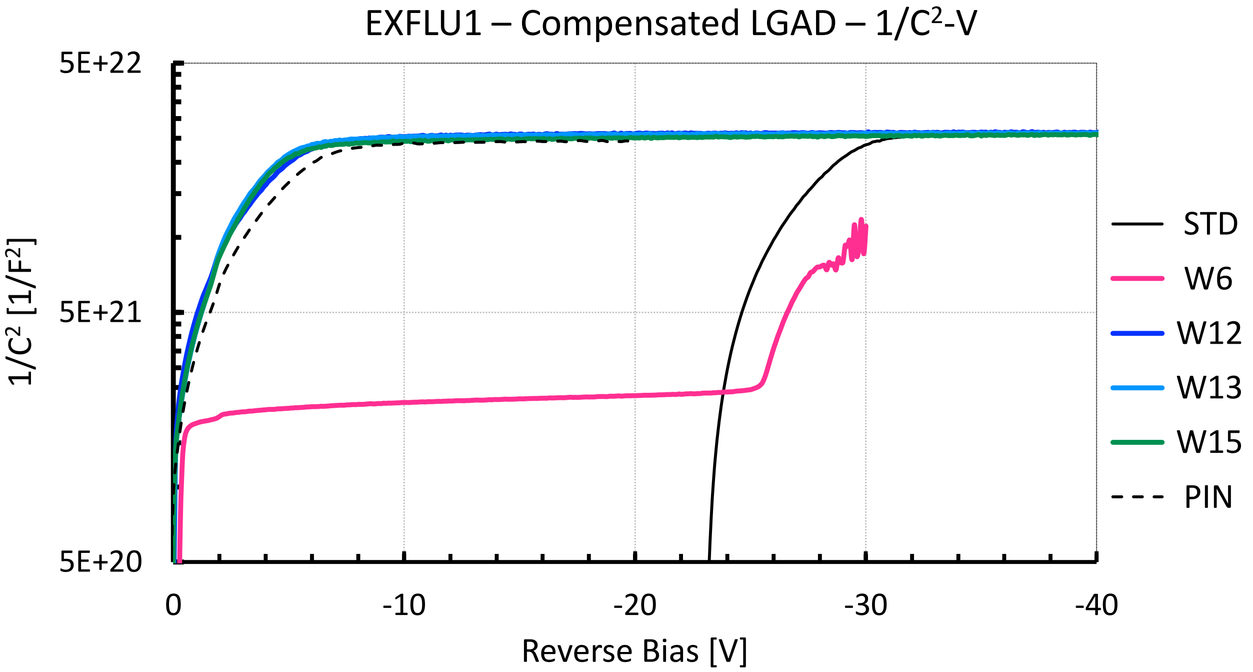


Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
12	30	3 b	2	
13	30	3 b	2	1.0
15	30	5 a	4	

→ 2 – 1 is more doped than standard LGAD

→ 3–2 & 5–4 exhibit a lower capacitance than PIN





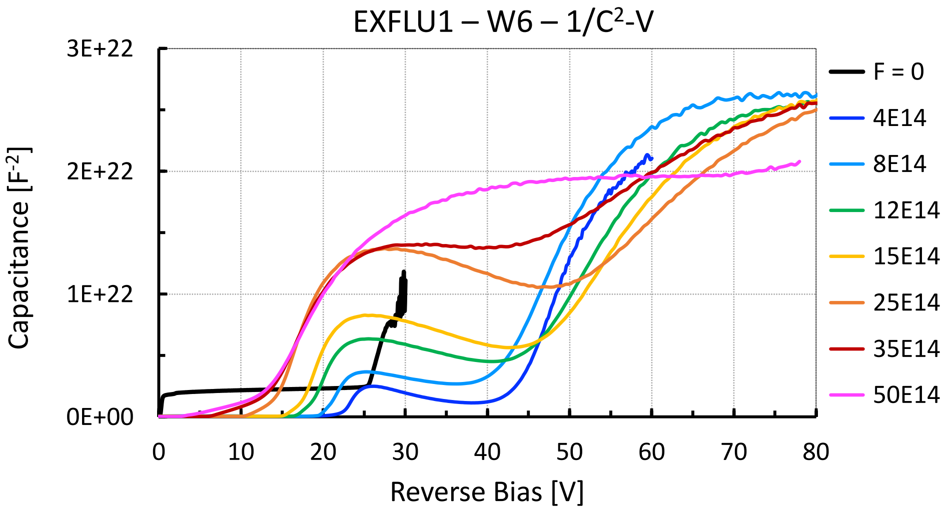
1/C²-V from Compensated LGAD – Irradiated

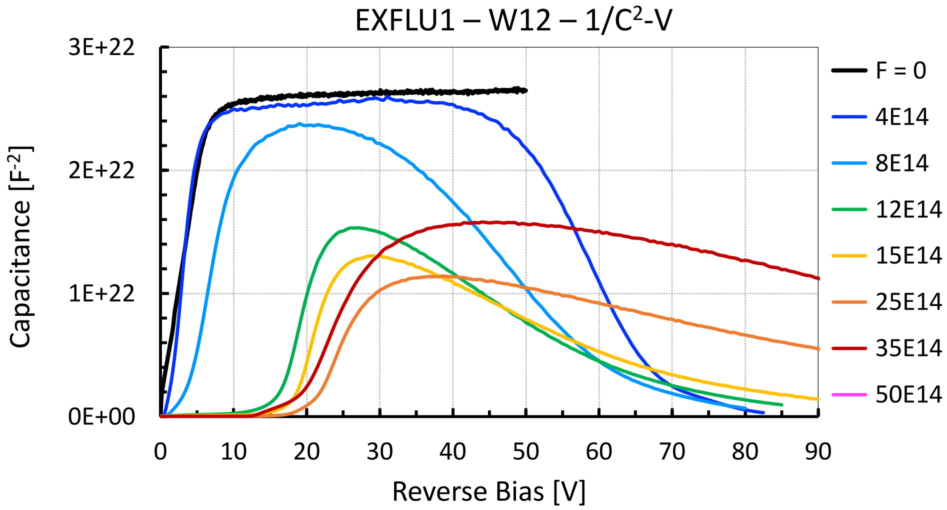
[Φ] = n_{eq}/cm^2

T = + 20°C

f = 2k Hz

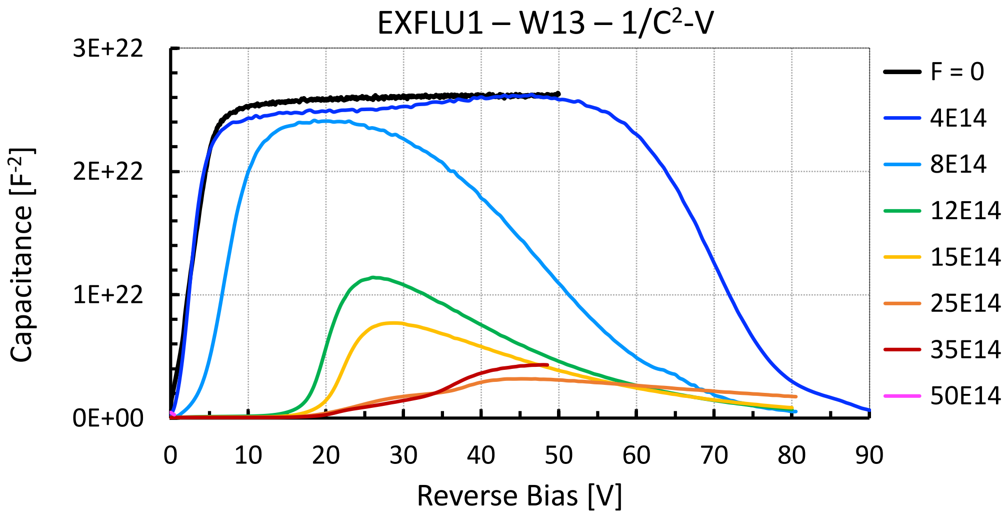
W6
2 – 1

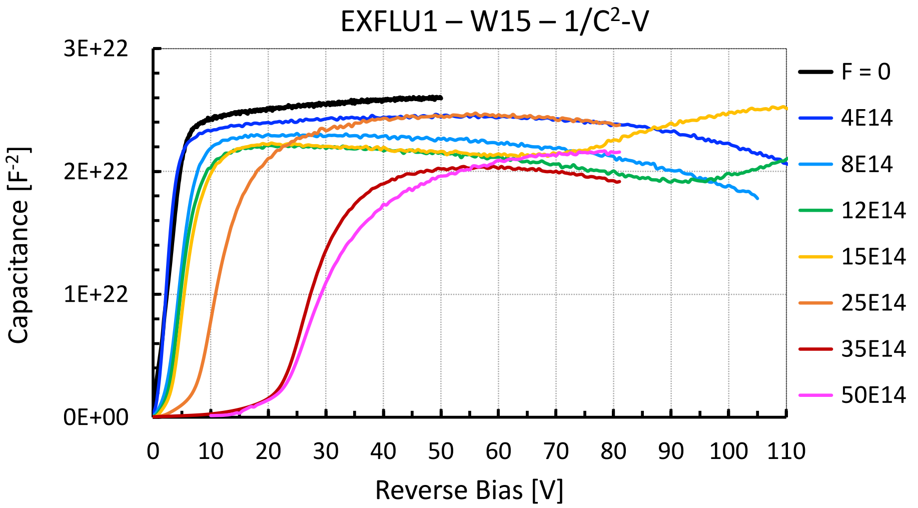




W12
3 – 2

W13
3 – 2 + C





W15
5 – 4

1/C²-V from Compensated LGAD – Irradiated

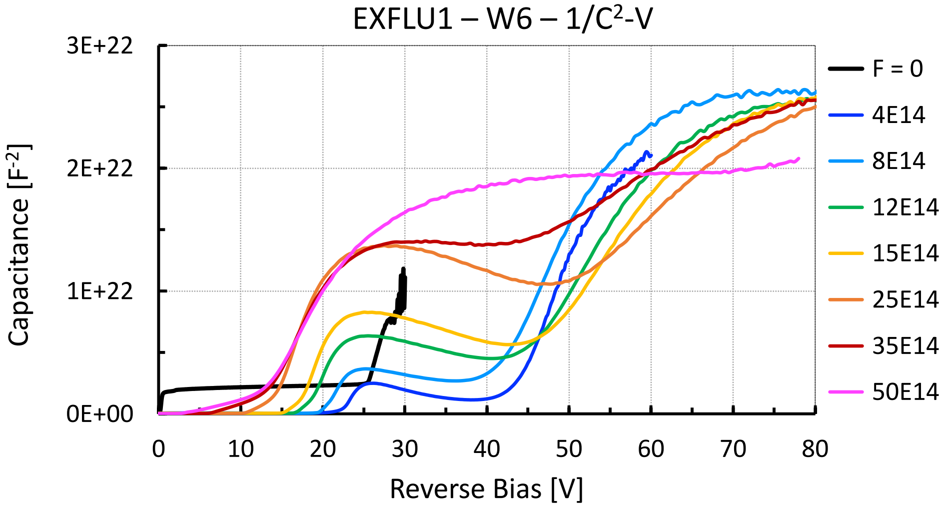
[Φ] = n_{eq}/cm^2

T = + 20ºC

f = 2k Hz

W6

2 – 1



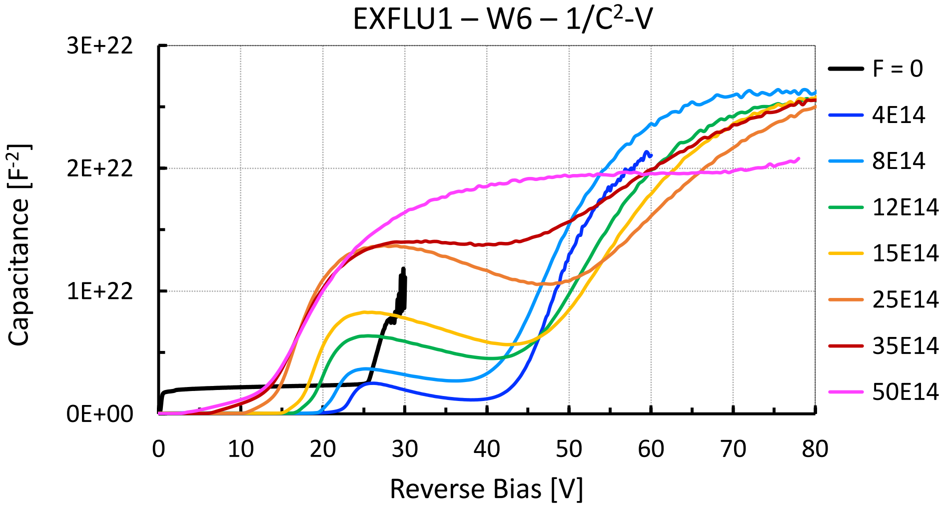
Doping Profile of Compensated LGAD 2 – 1

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

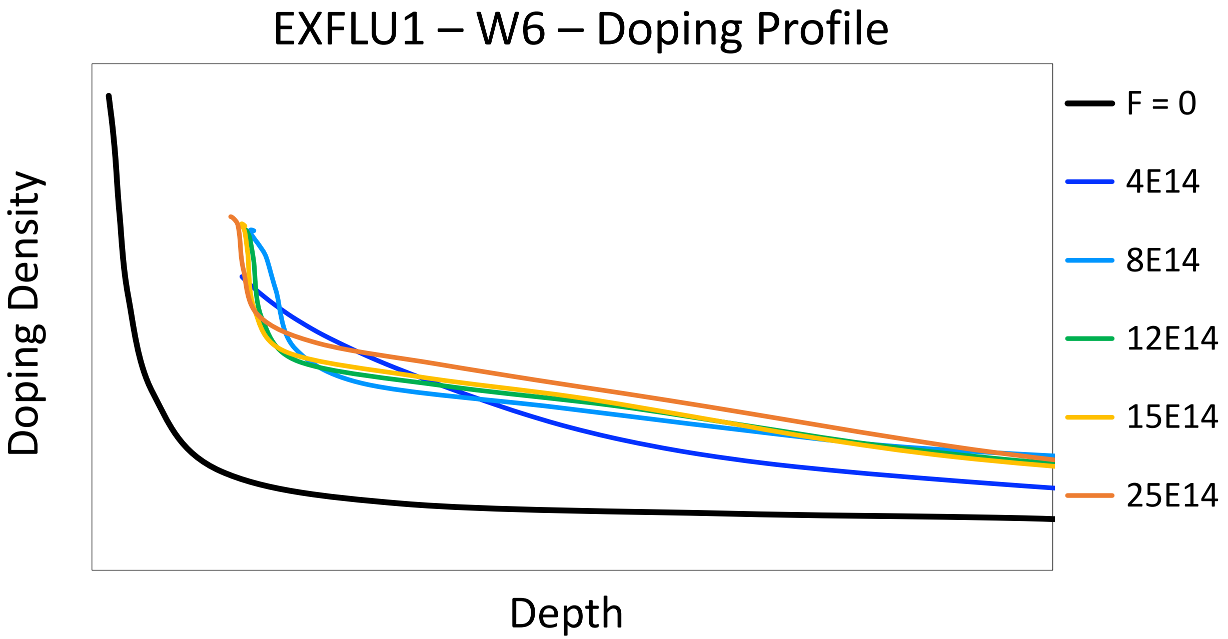
T = + 20°C

f = 2k Hz

W6
2 – 1



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



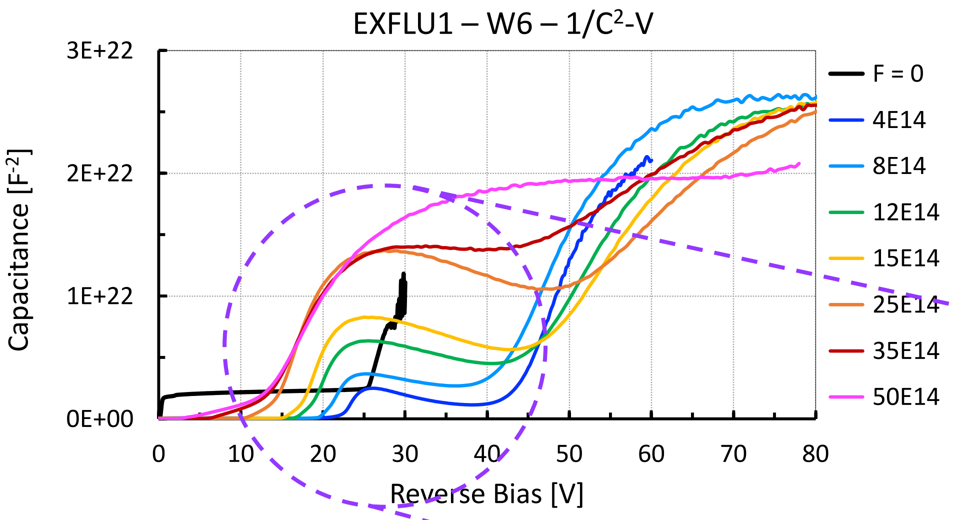
Doping Profile of W6

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

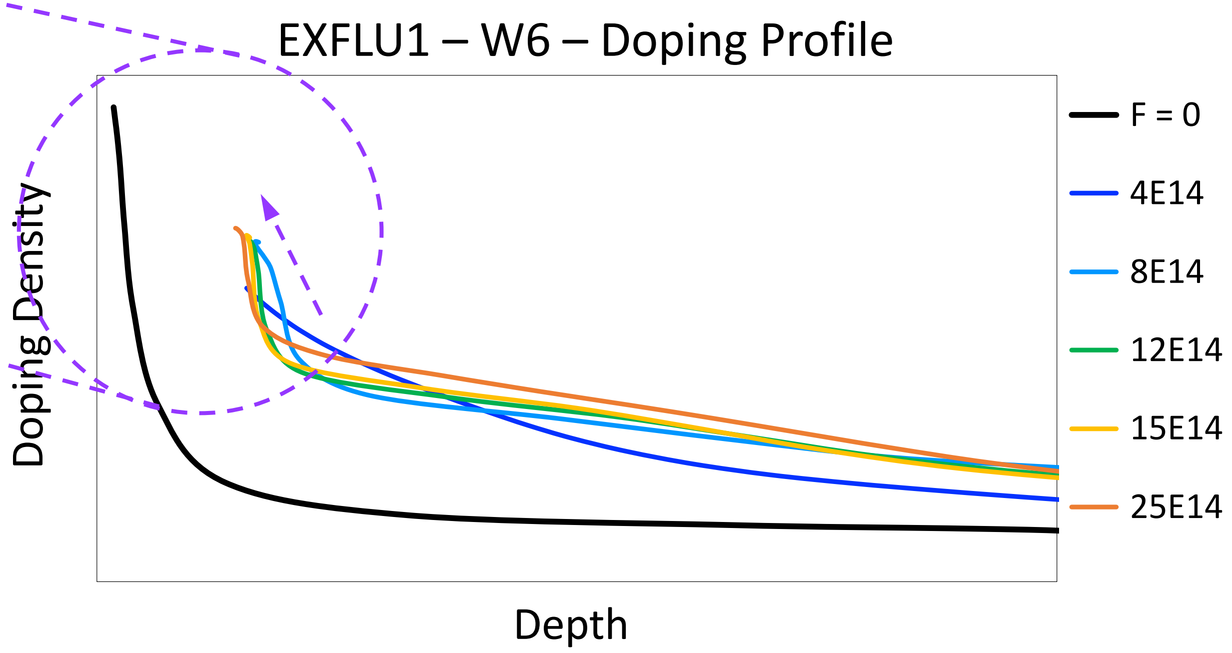
T = + 20°C

f = 2k Hz

W6
2 – 1



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

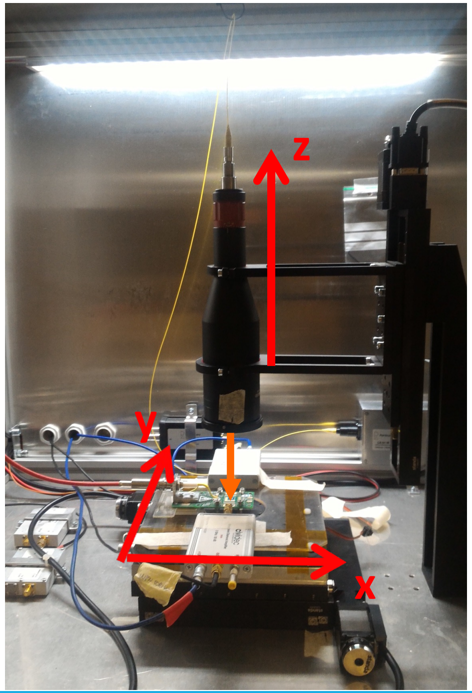


Gain implant profile appears more and more evident as the fluence increases

→ **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

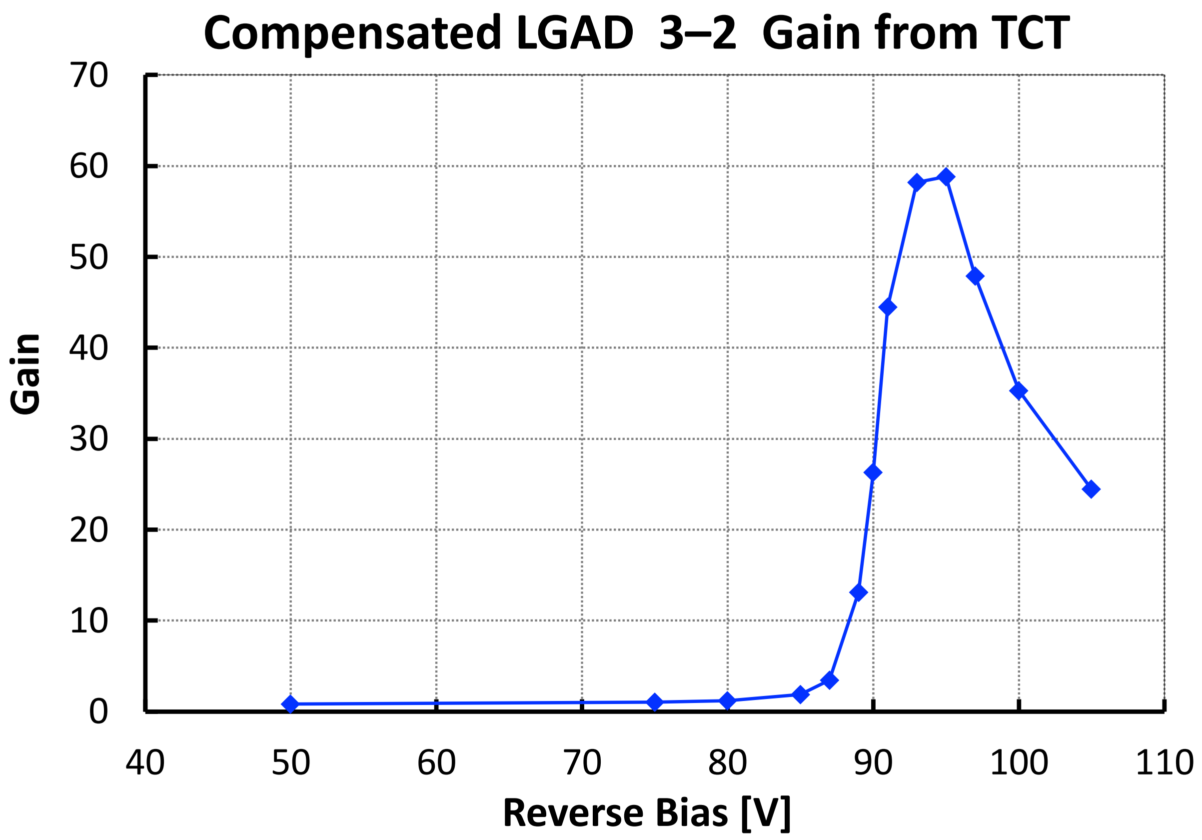


$$\text{Gain} = \frac{Q_{LGAD}}{< Q_{PiN} >}$$

Laser intensity
~ 4 MIPs

$\Phi = 0$

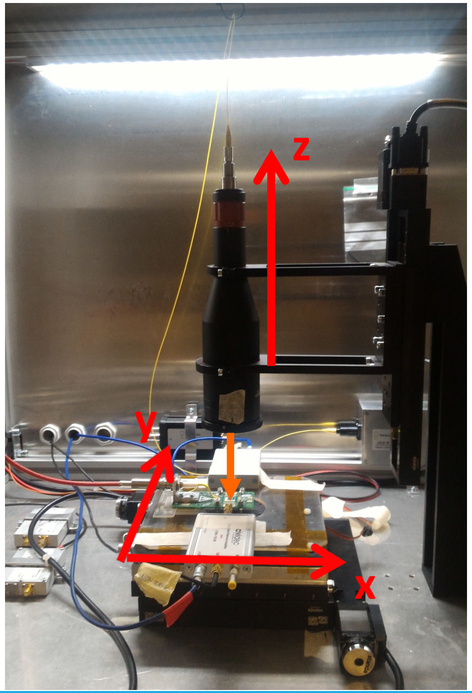
Laser stimulus on a LGAD-PiN structure from W12 (3 – 2)



→ 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

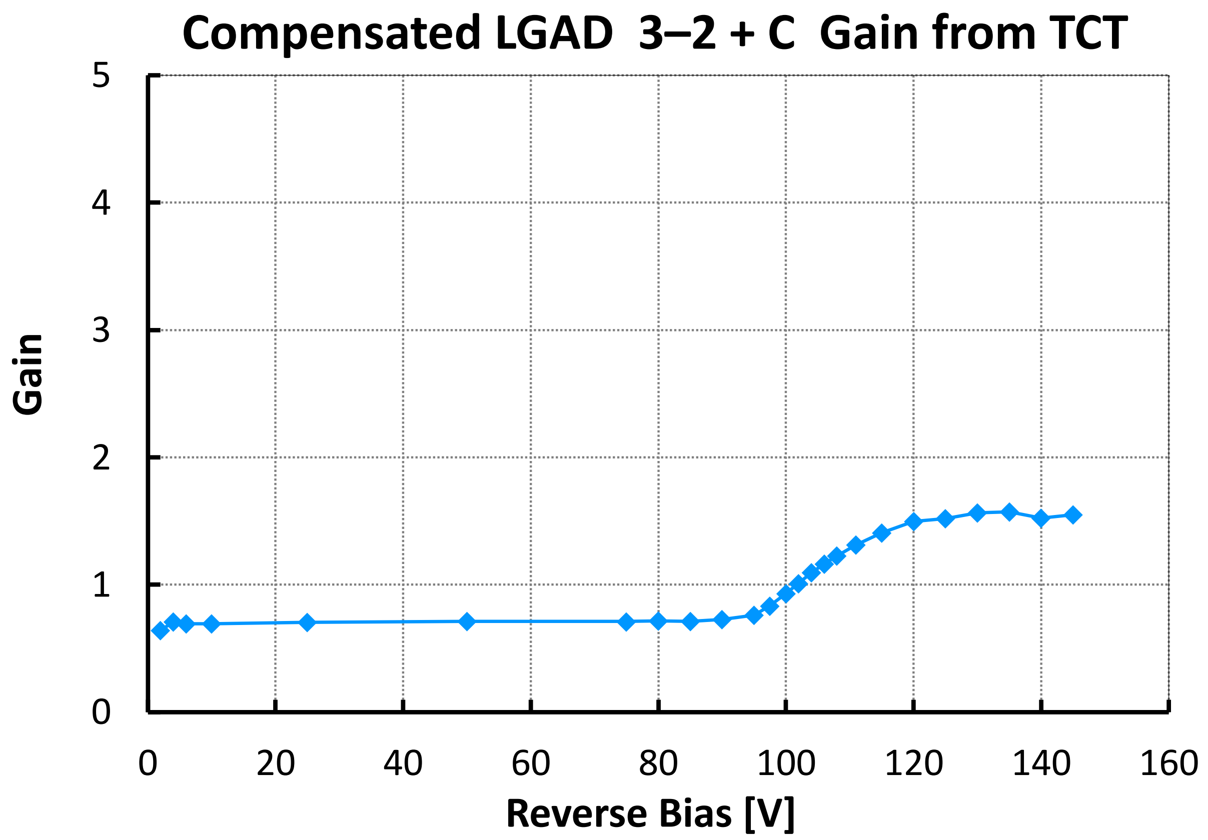


$$\mathbf{Gain} = \frac{\mathbf{Q_{LGAD}}}{< \mathbf{Q_{PiN}} >}$$

Laser intensity
~ 80 MIPs

$\Phi = 0$

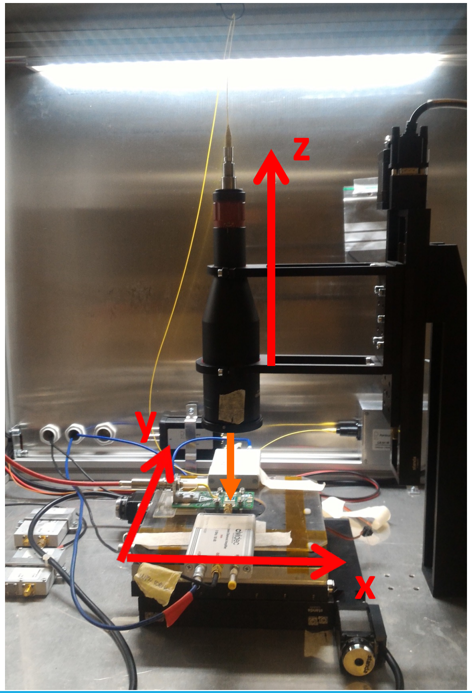
Laser stimulus on a LGAD-PiN structure from W13 (3 – 2 + C)



→ **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

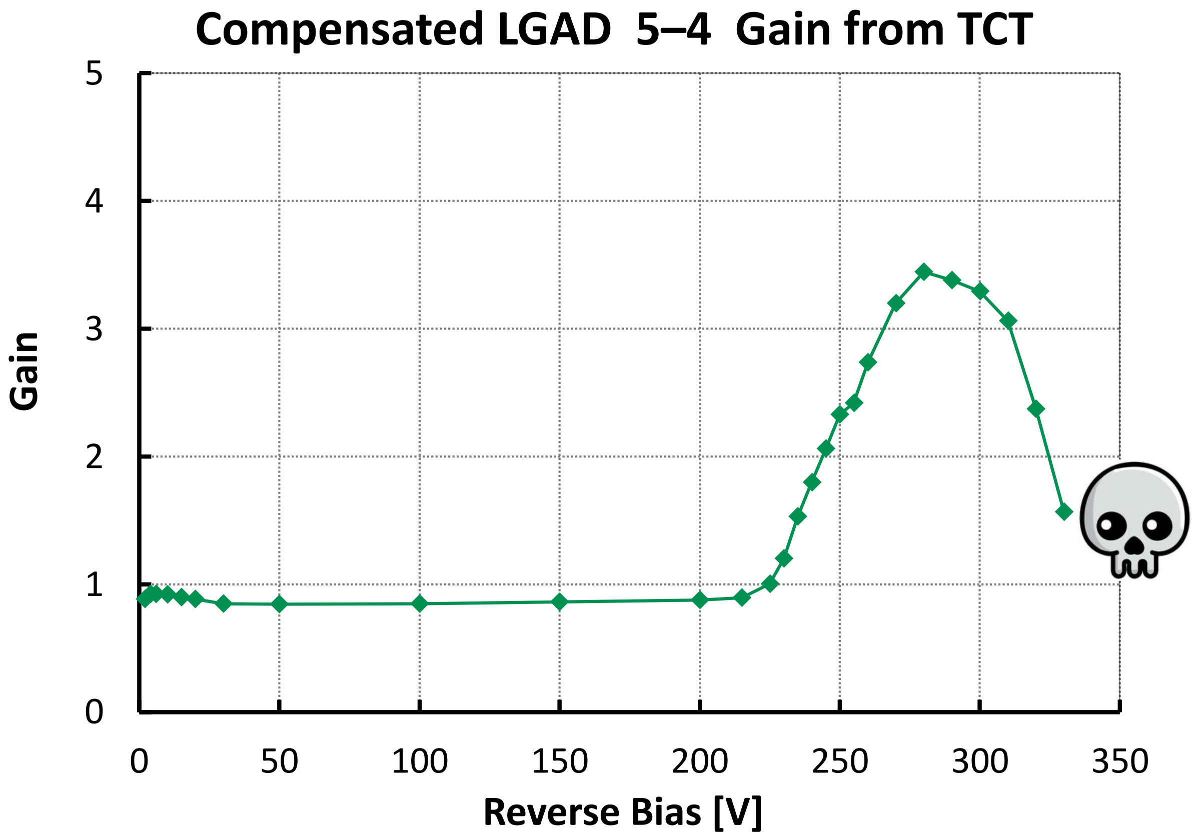


$$\textbf{Gain} = \frac{Q_{LGAD}}{< Q_{PiN} >}$$

Laser intensity
~ 60 MIPs

Φ = 0

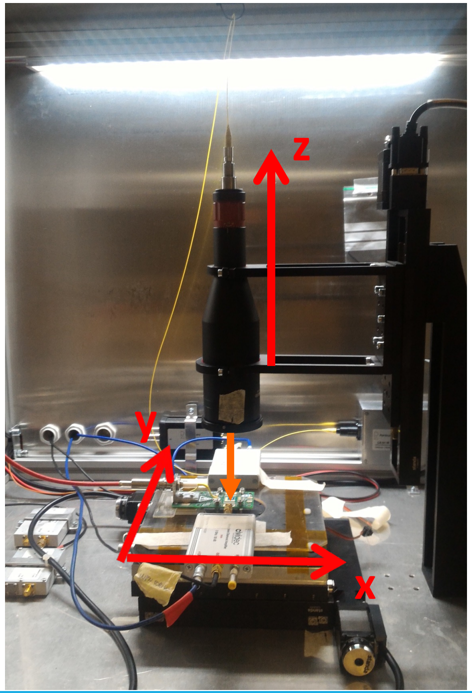
Laser stimulus on a LGAD-PiN structure from W15 (5 – 4)



→ 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

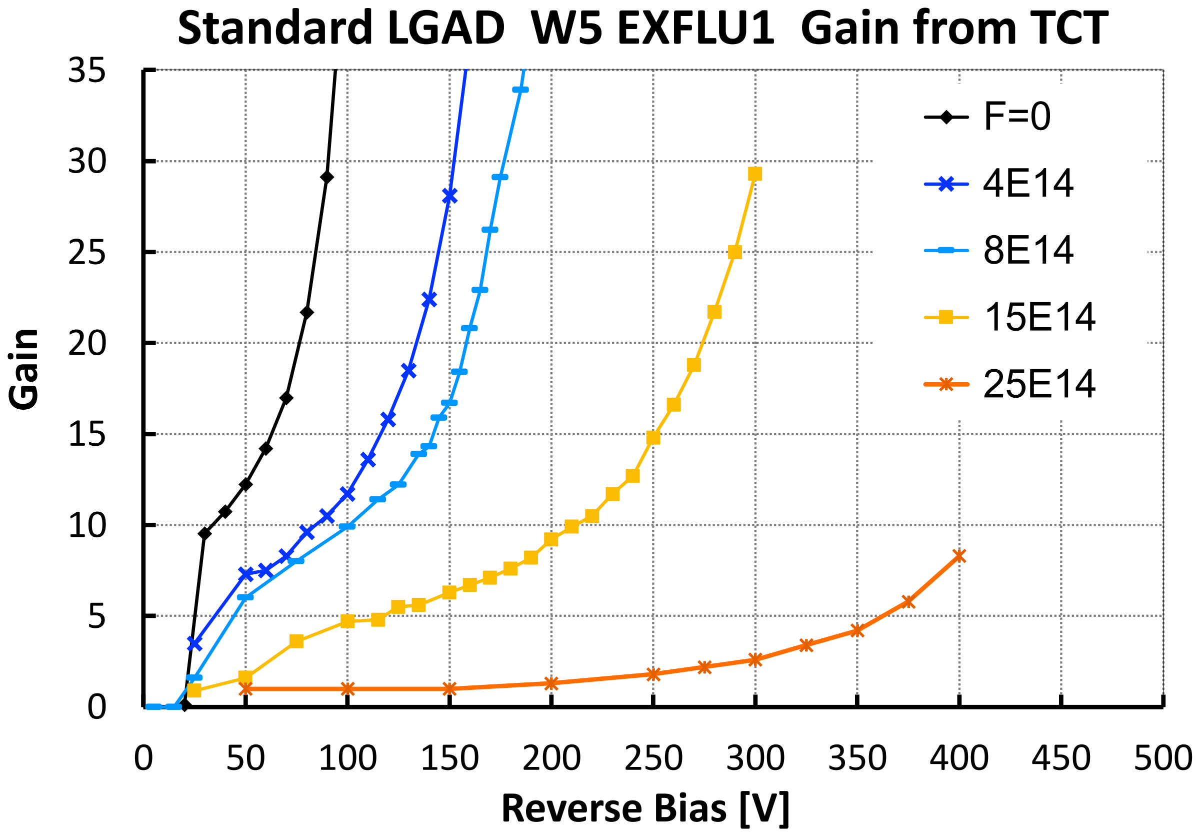


$$\text{Gain} = \frac{Q_{LGAD}}{< Q_{PiN}^{\text{No Gain}} >}$$

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