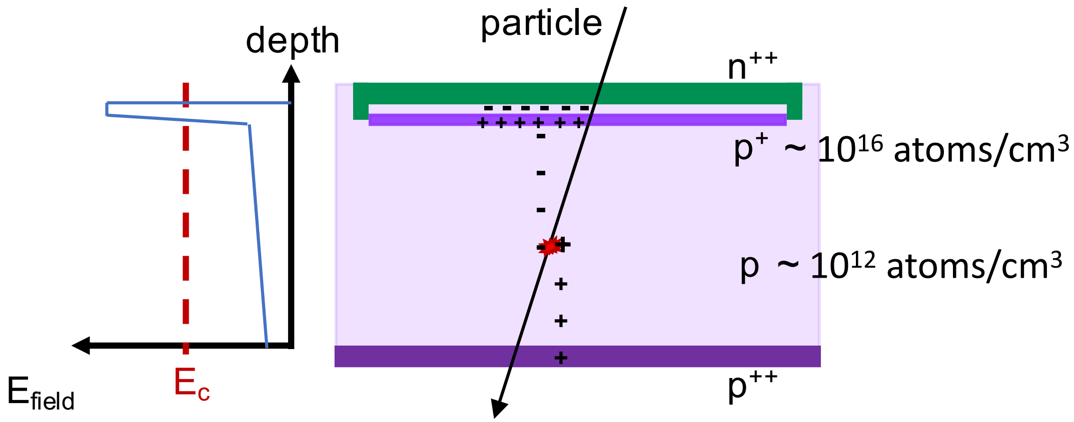
13th International "Hiroshima" Symposium on the
Development and Application of Semiconductor Tracking Detectors (HSTD13)
Simon Fraser University's Wosk Centre for Dialogue
Vancouver, Canada
3 – 8 December 2023

Characterisation of the first Compensated LGADs from FBK before and after irradiation

V. Sola, 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, A. Morozzi, F. Moscatelli, R. Mulargia, D. Passeri, N. Pastrone, G. Paternoster, F. Siviero, R.S. White

Gain Removal Mechanism in LGADs

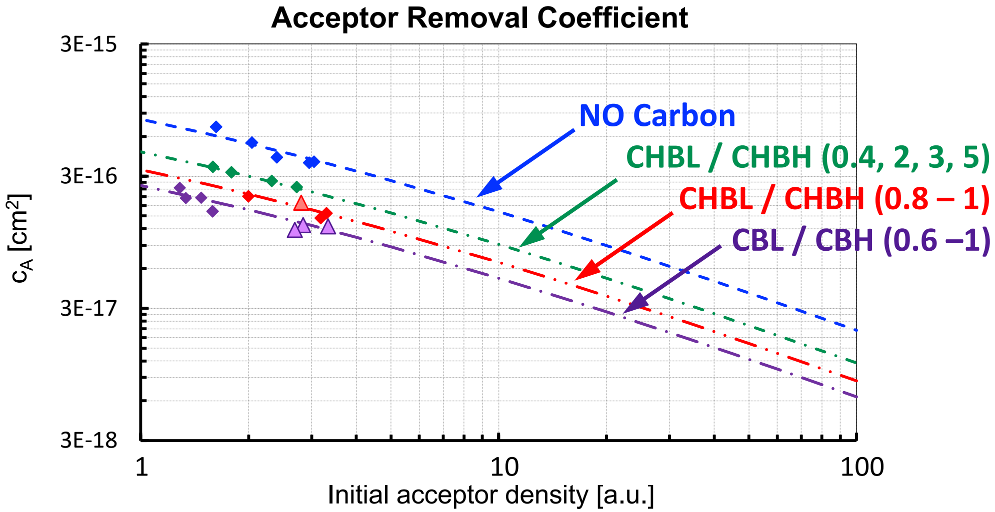


The acceptor removal mechanism deactivates the p^+-doping of the **gain layer** with irradiation according to

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

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

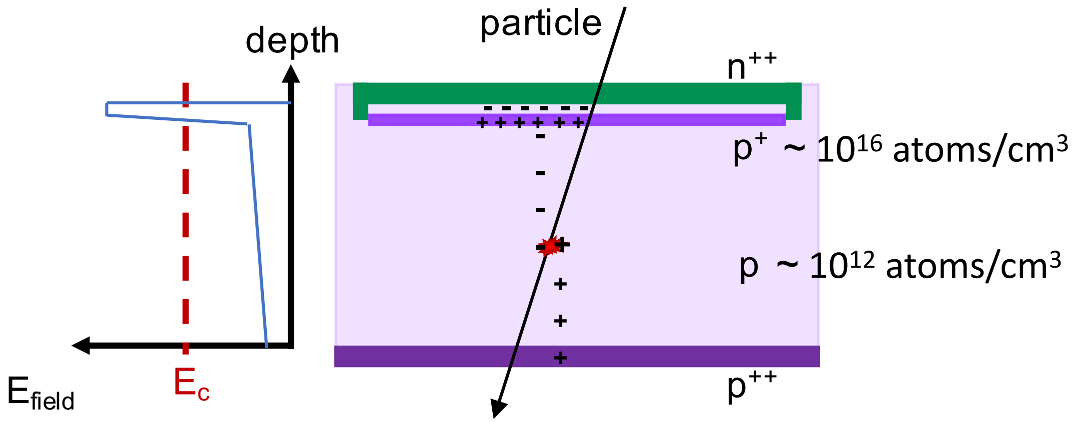


▲ thin sensors from the EXFLU1 batch

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

⇒ Is it possible to improve c_A further?

Towards a Radiation Resistant Design

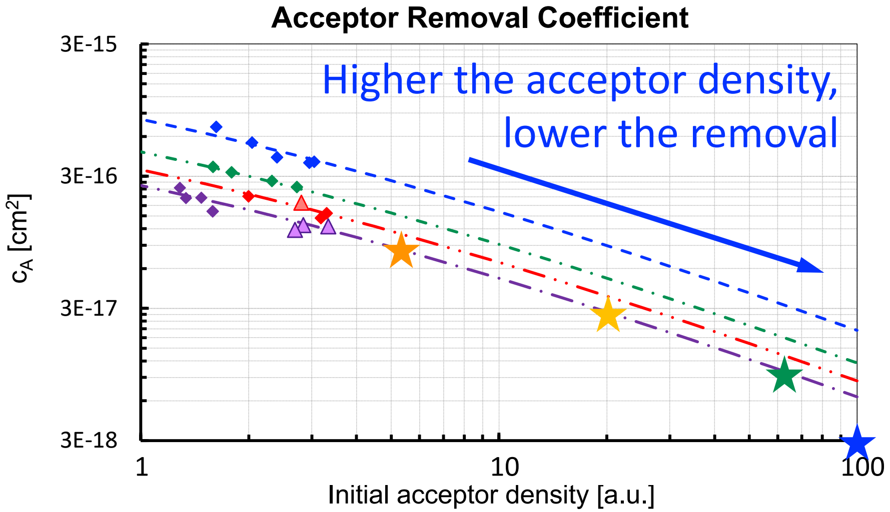


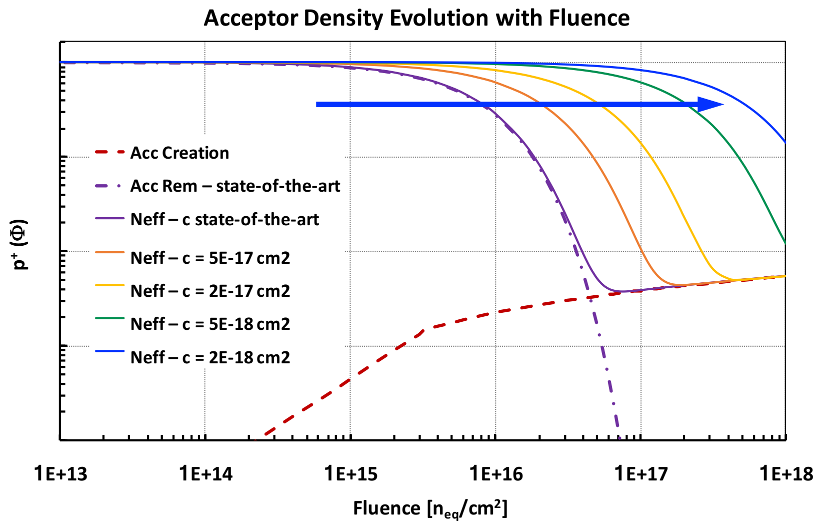
The acceptor removal mechanism deactivates the p^{+}-doping of the **gain layer** with irradiation according to

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

where c_A is the acceptor removal coefficient

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

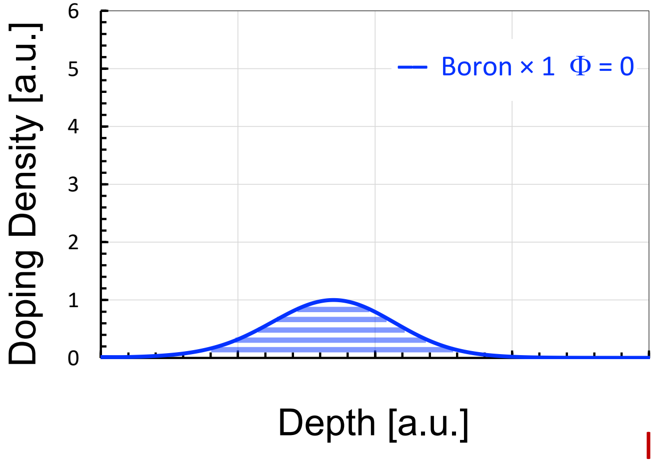




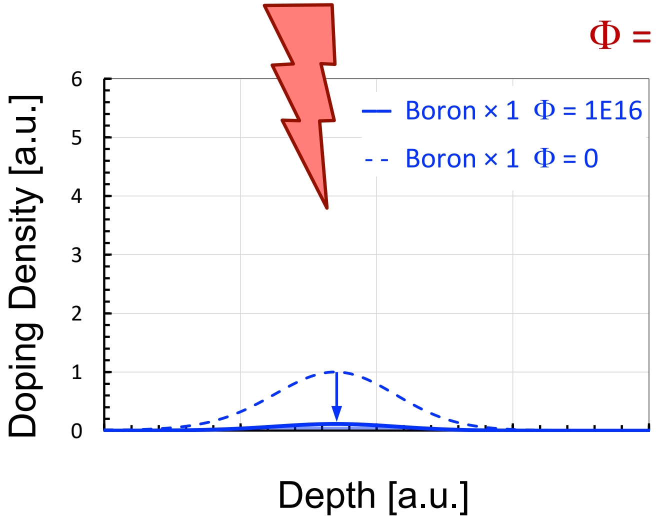
Lowering c_A can extend the gain layer survival up to $\Phi \geq 10^{17}\ n_{eq}/cm^2$

A new Paradigm – Compensation

Doping Profile – Standard LGAD

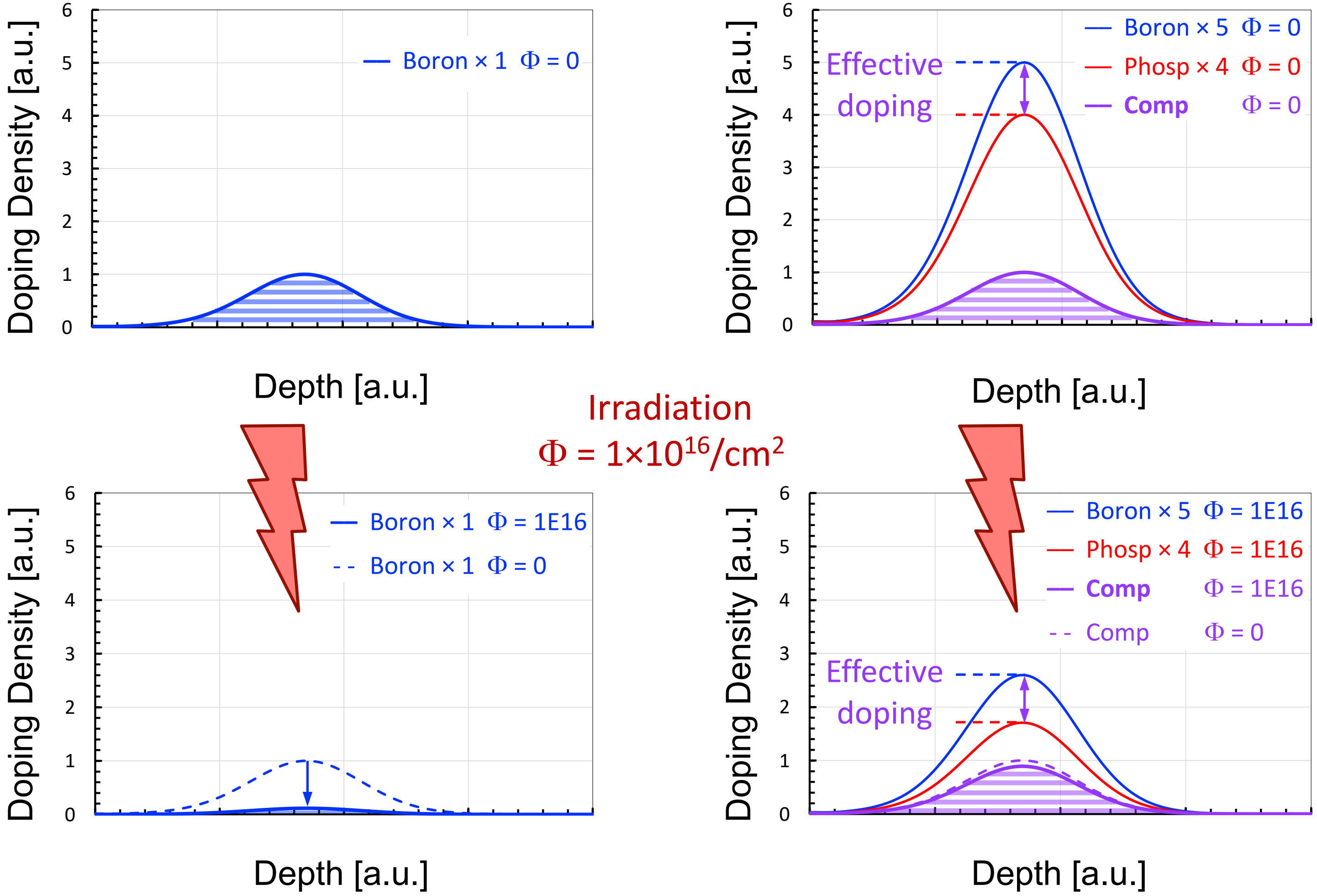


Irradiation
$\Phi = 1\times10^{16}/cm^2$



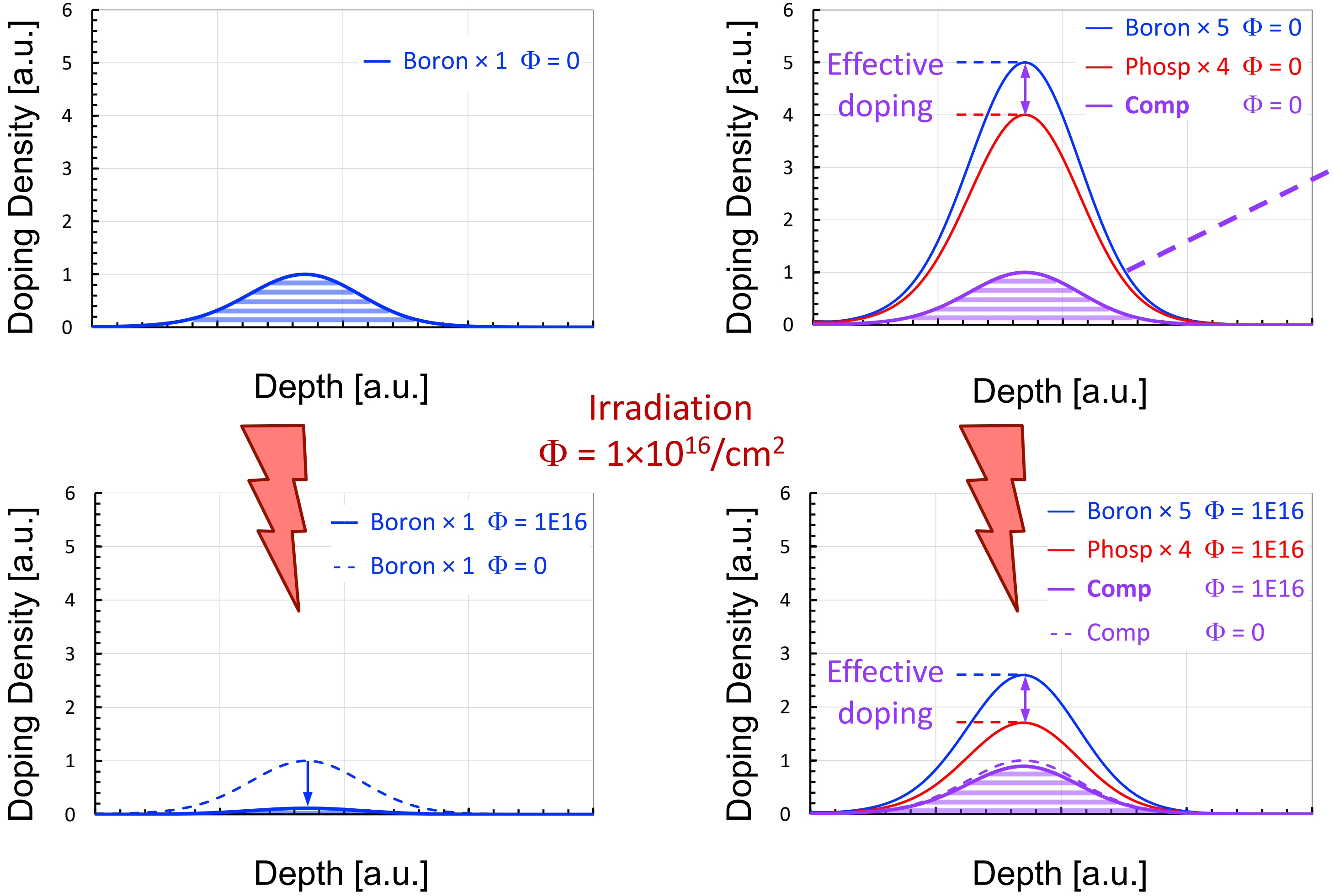
A new Paradigm – Compensation

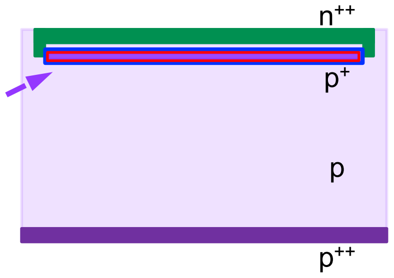
Doping Profile – Standard LGAD **Doping Profile – Compensated LGAD**



A new Paradigm – Compensation

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





Compensated LGAD

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

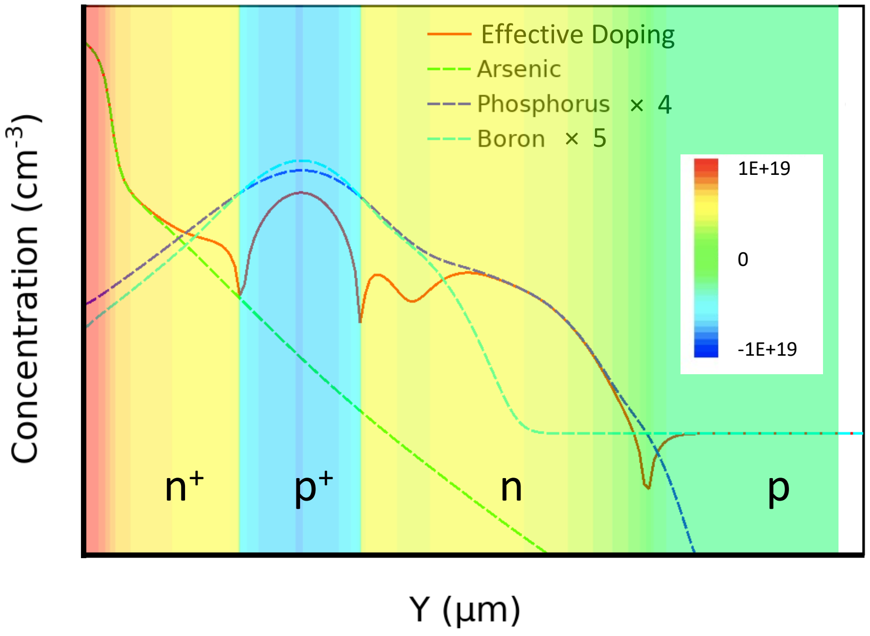
Many unknowns:

- 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



Compensation from Simulation

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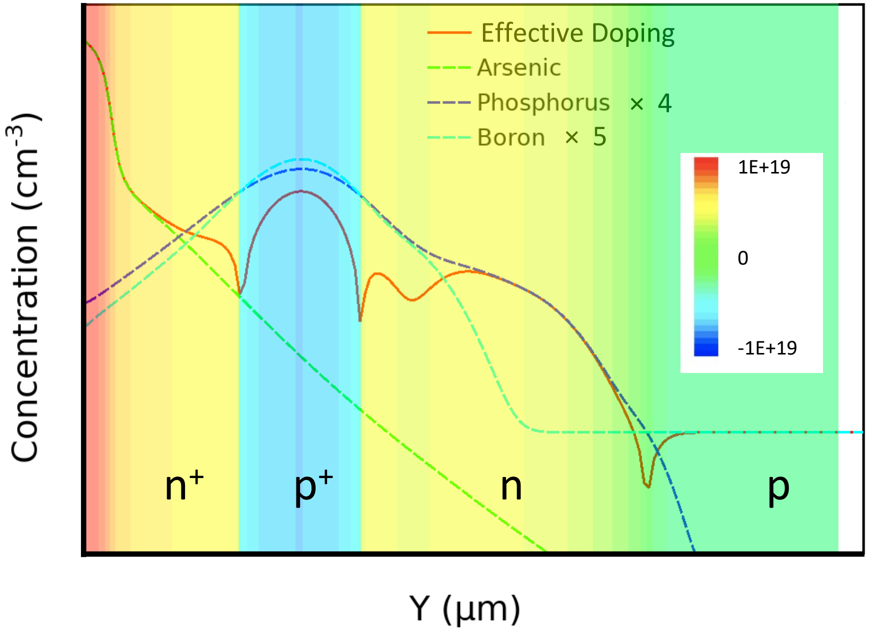
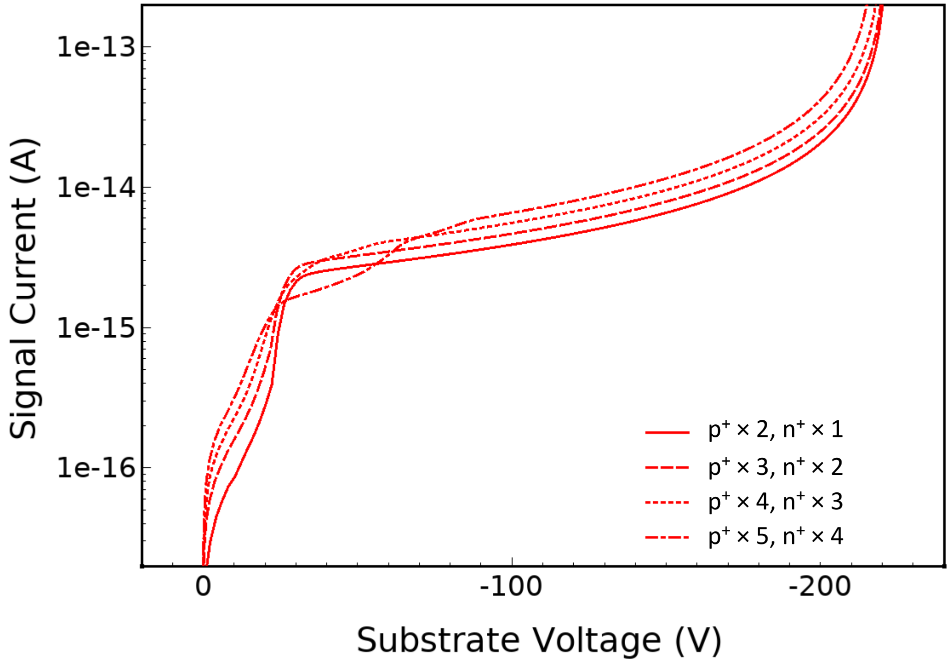
Doping Profiles from Process Simulation



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)

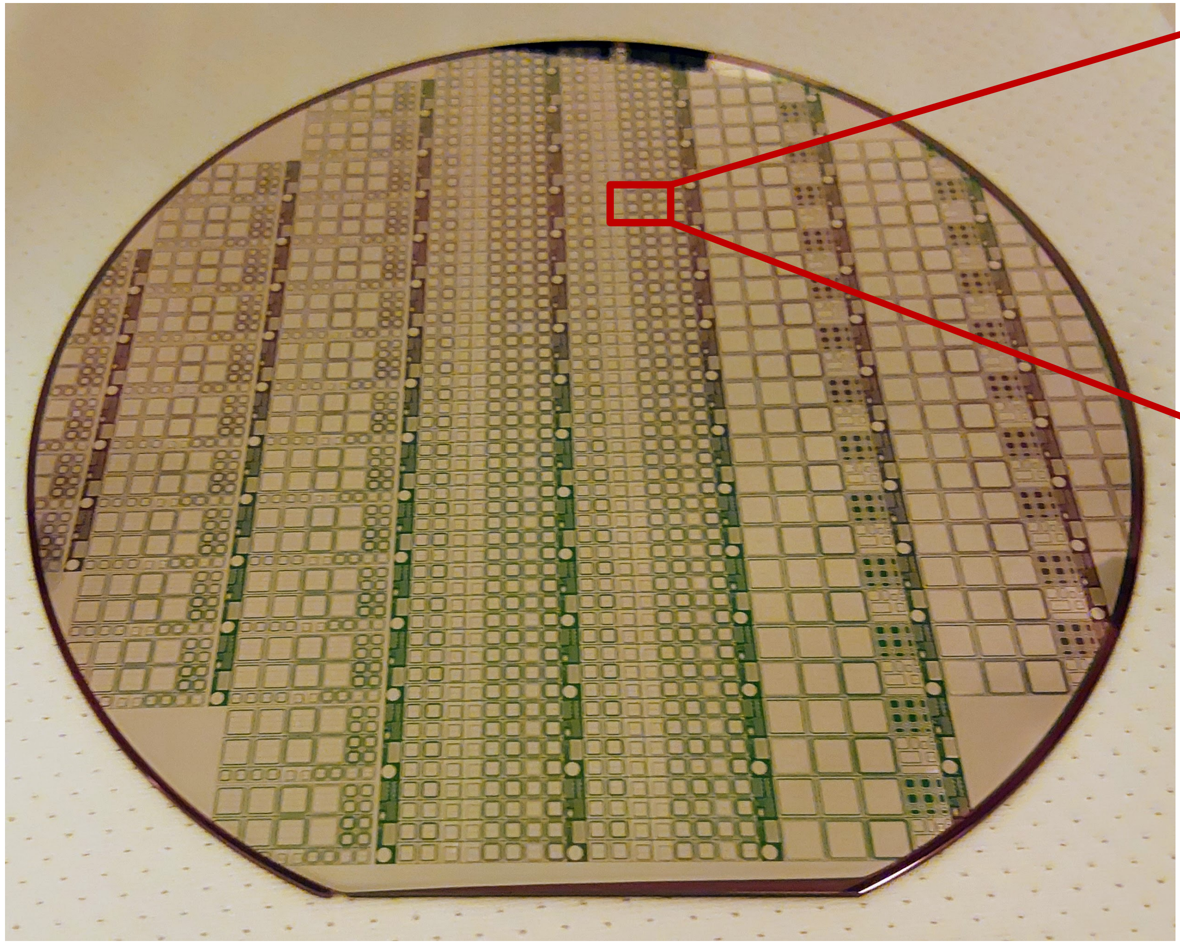
Design and preparatory studies have been performed in collaboration with the **Perugia group**

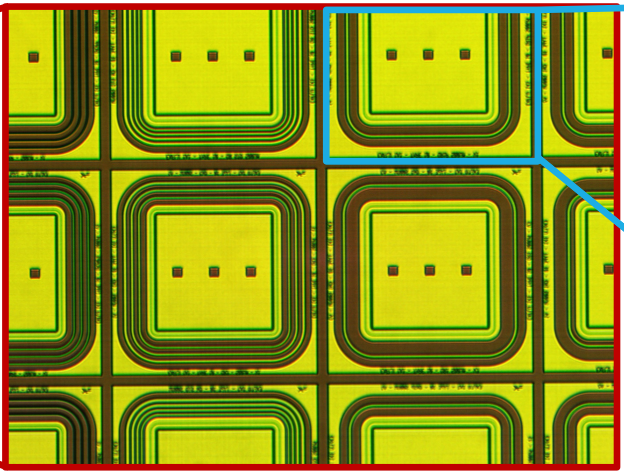
→ The EXFLU1 wafers exited the FBK clean room at the end of 2022

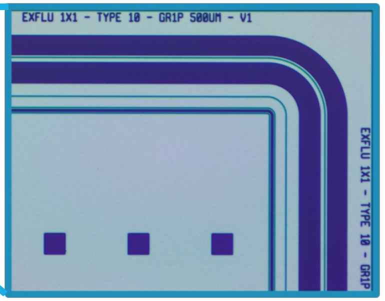
[V. Sola, TREDI 2023, Trento]

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

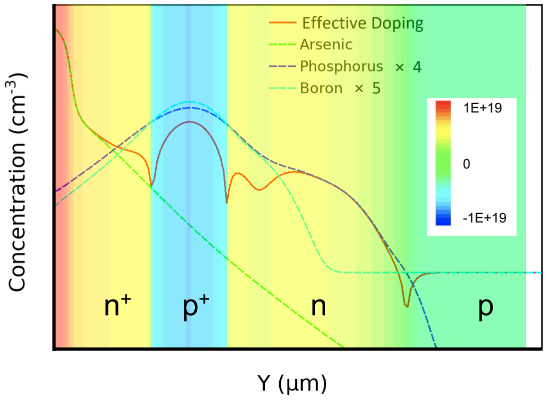
Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
7	30	2 b	1	
8	30	2 b	1	
9	30	2 c	1	
10	30	3 a	2	
11	30	3 b	2	
12	30	3 b	2	
13	30	3 b	2	1.0
14	30	3 c	2	
15	30	5 a	4	

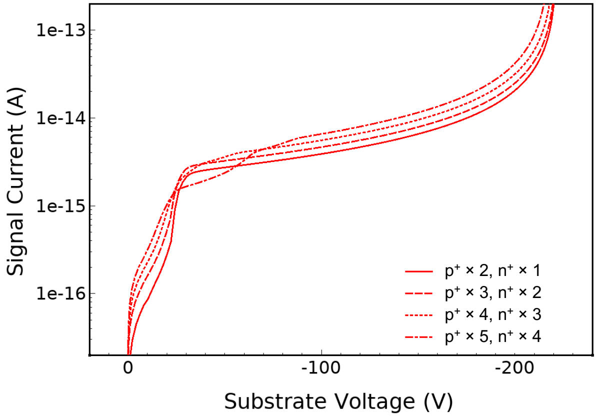
[a < b < c]

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

Compensated LGAD – I-V on wafer

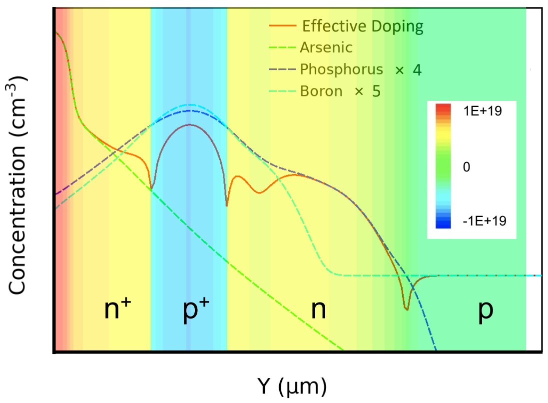
Simulation

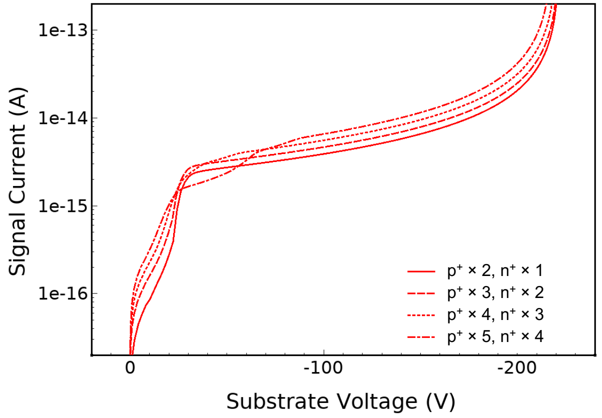




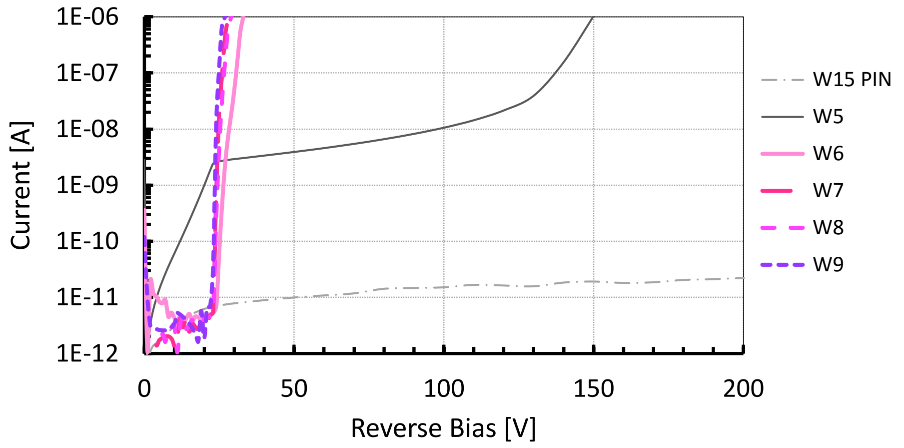
Compensated LGAD – I-V on wafer

Simulation





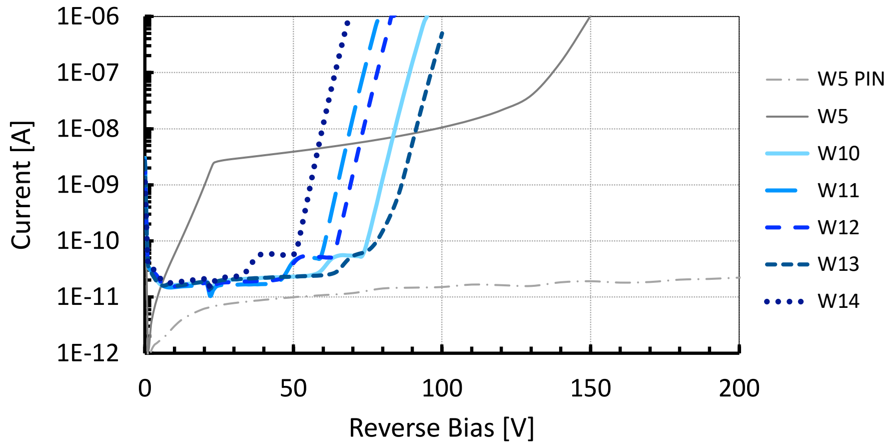
EXFLU1 – Compensated LGAD 2–1 – I-V



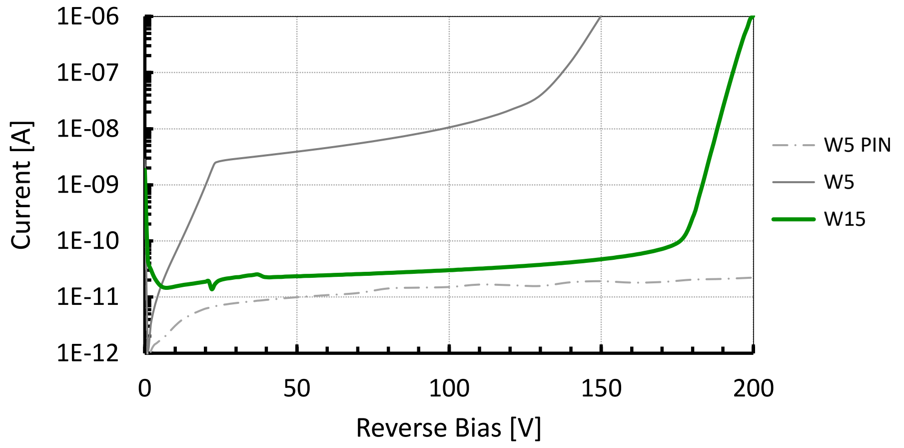
2 – 1

EXFLU1 – Compensated LGAD 3–2 – I-V

3 – 2

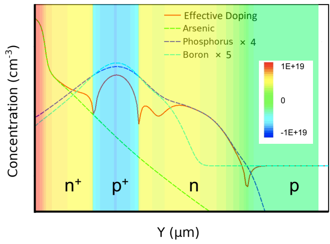


EXFLU1 – Compensated LGAD 5–4 – I-V



5 – 4

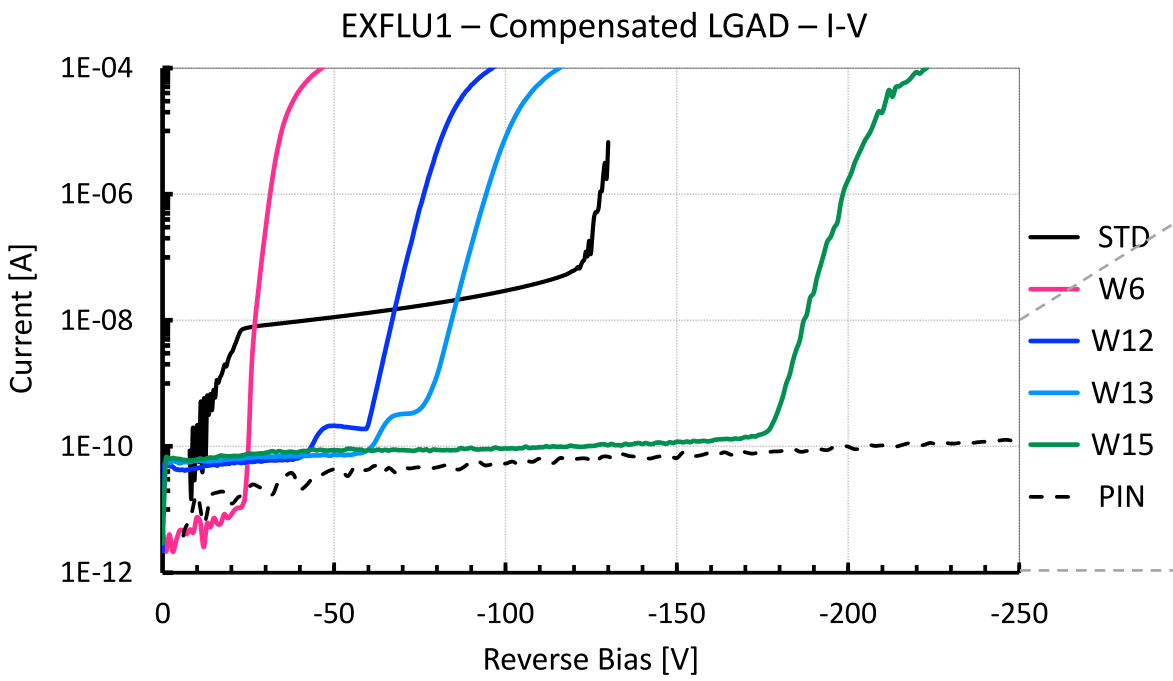
Compensated LGAD – I-V

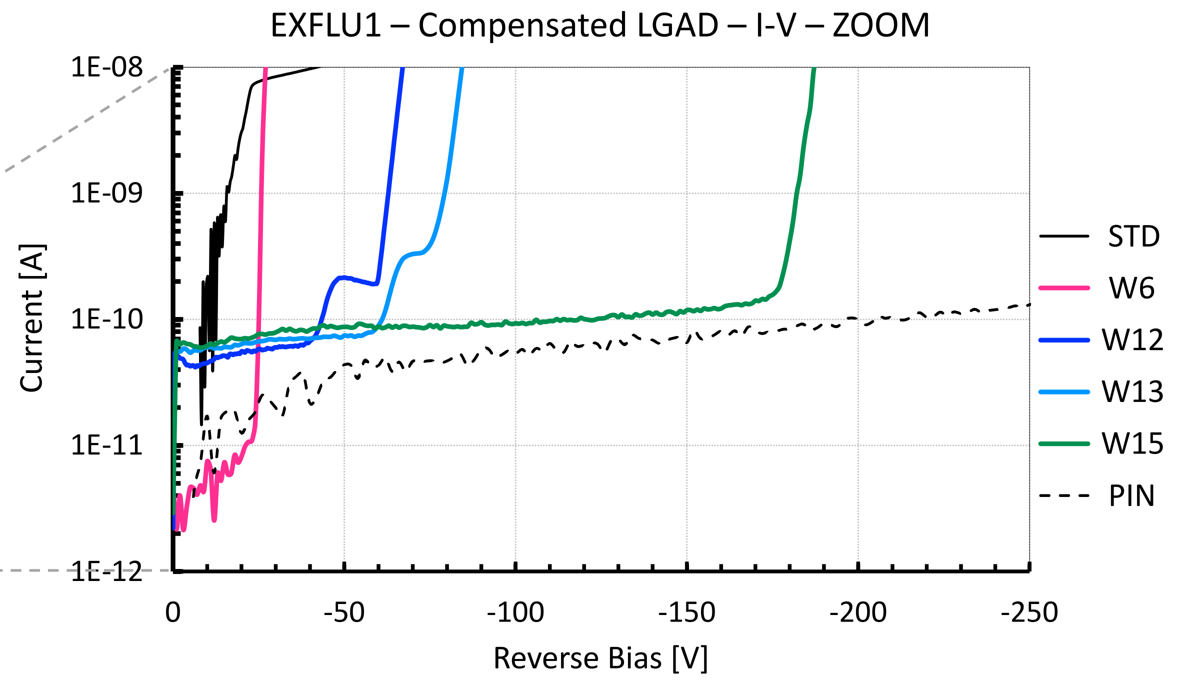


Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
12	30	3 b	2	
13	30	3 b	2	1.0
15	30	5 a	4	

→ 2 – 1 is more doped than standard LGAD

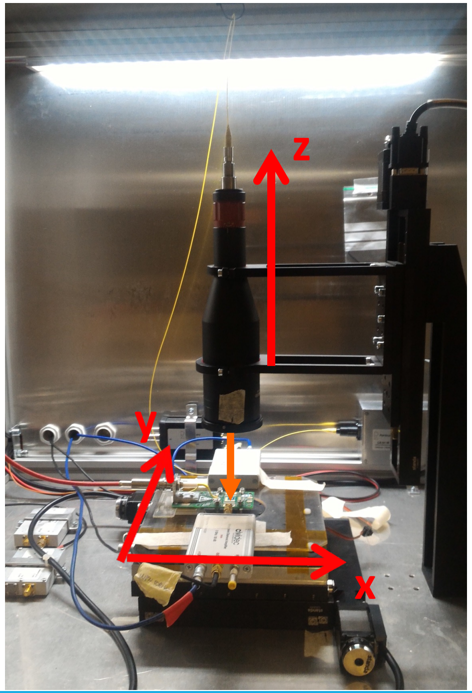
→ 3 – 2 & 5 – 4 exhibit a flat behaviour followed by an abrupt increase of the current





IR Laser Stimulus on Compensated LGAD 2–1

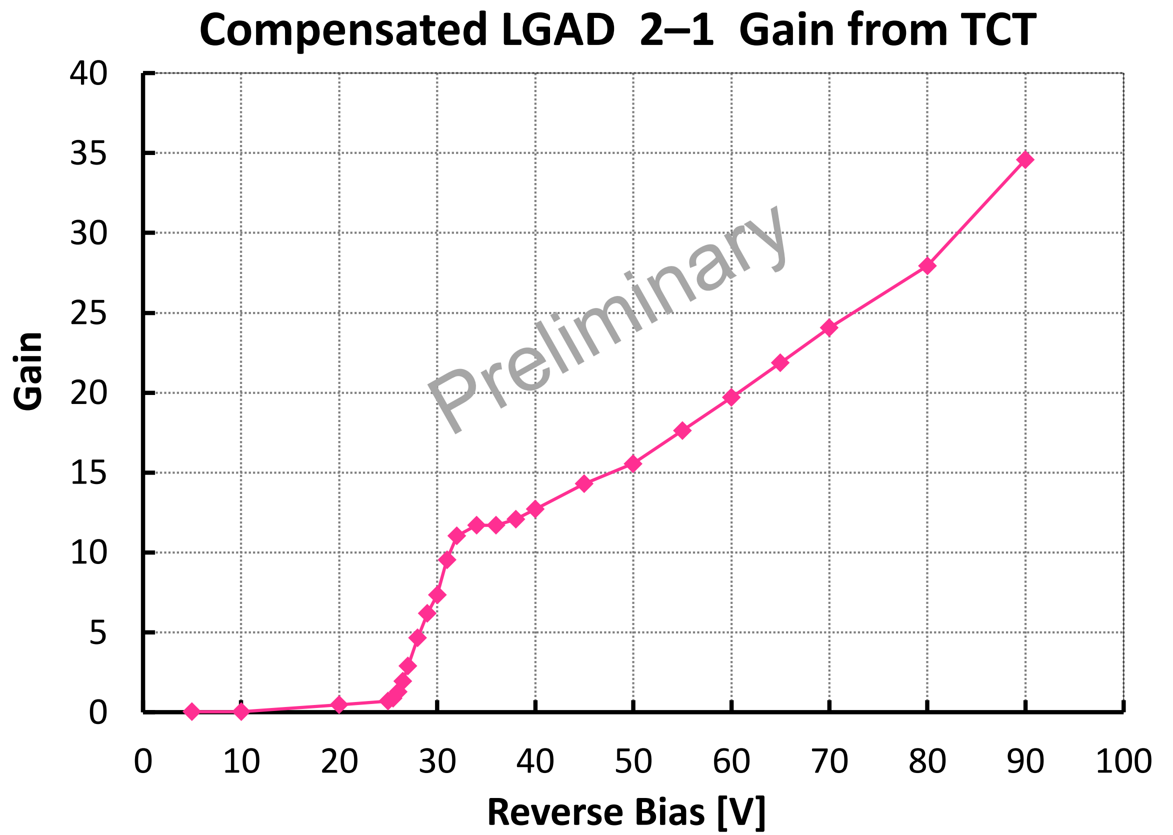
TCT Setup from Particulars
Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
Room temperature



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

Laser intensity
~ 10 MIPs

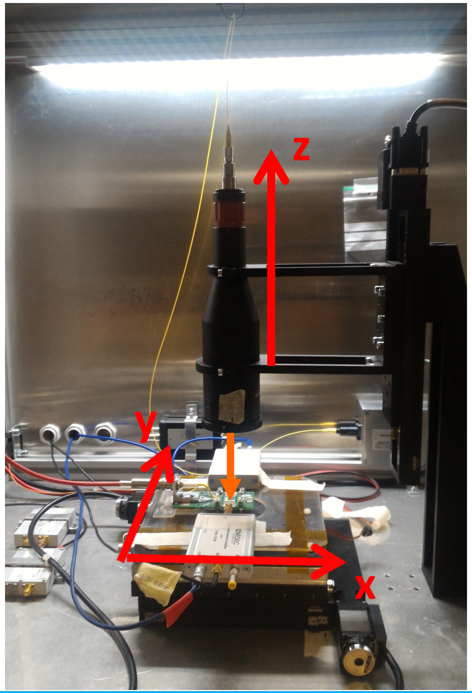
Laser stimulus on a LGAD-PiN structure from W6 (2 – 1)



→ Good transient behaviour of 2 – 1 compensated LGAD sensors

IR Laser Stimulus on Compensated LGAD 3–2+C

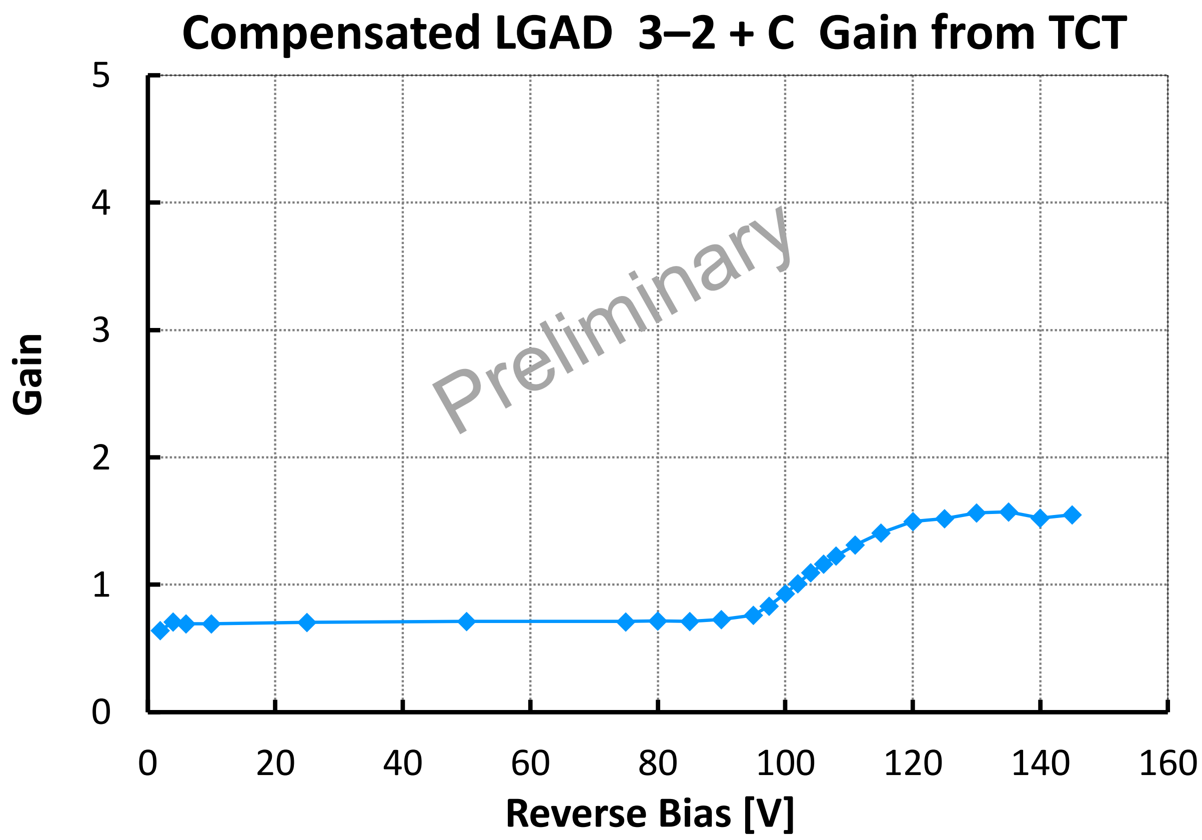
TCT Setup from Particulars
Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
Room temperature



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

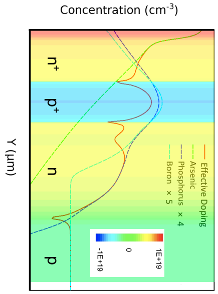
Laser intensity
~ 80 MIPs

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

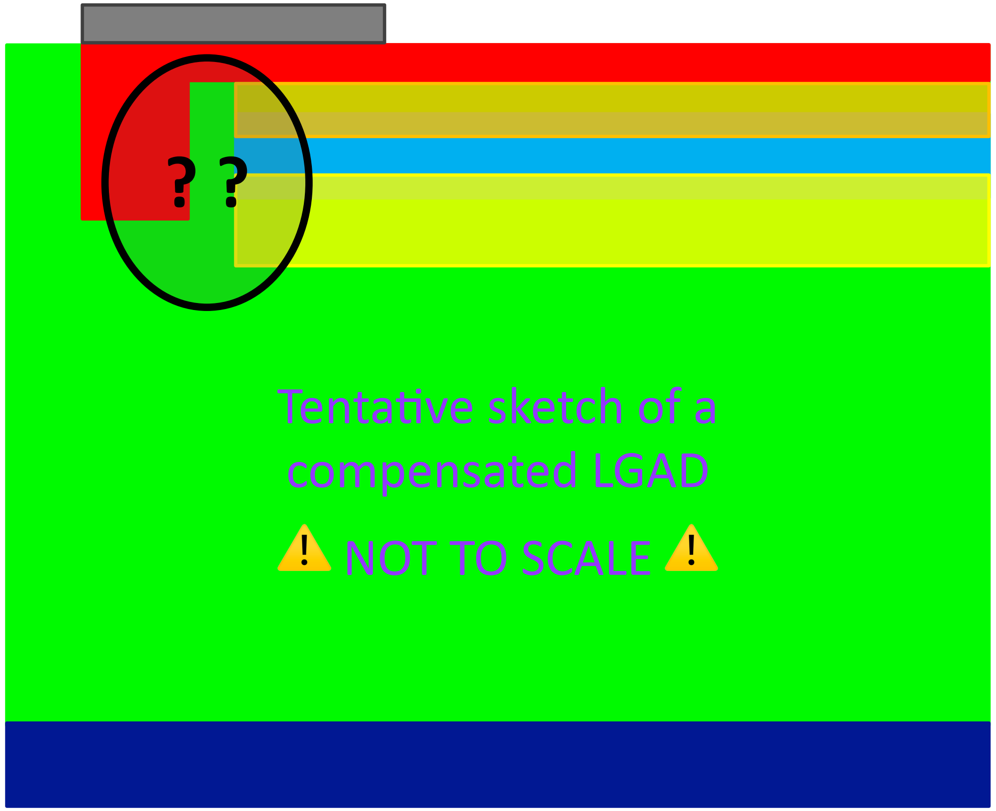


→ Very low gain from 3 – 2 compensated LGAD sensors

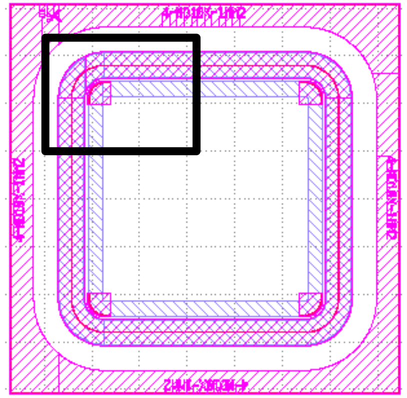
Compensated LGAD – 2D Scan with IR Laser



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



Scan surface



TCT scan with IR laser

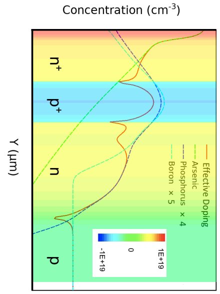
Laser spot ~ 10 μm

Sensor from W12 (3–2)

V_{bias} = 81 V

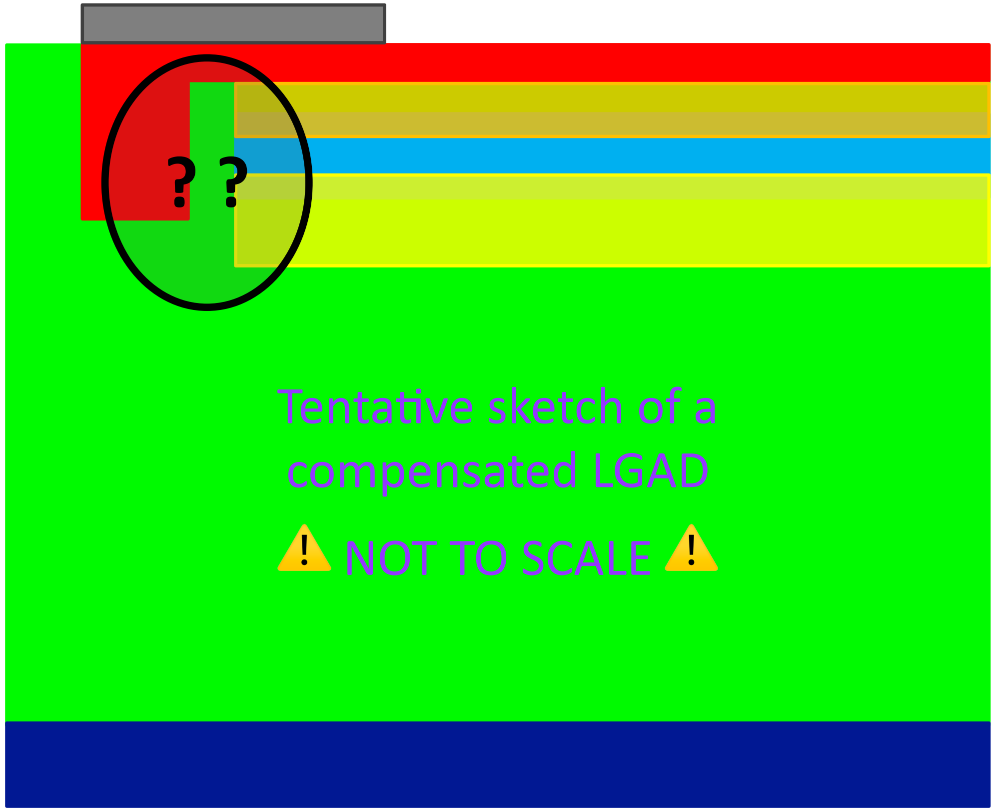
Very close to BD

→ Investigate the edges of the compensated gain implant using TCT

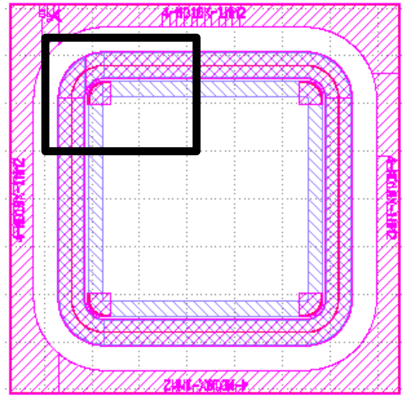


Compensated LGAD – 2D Scan with IR Laser

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



Scan surface



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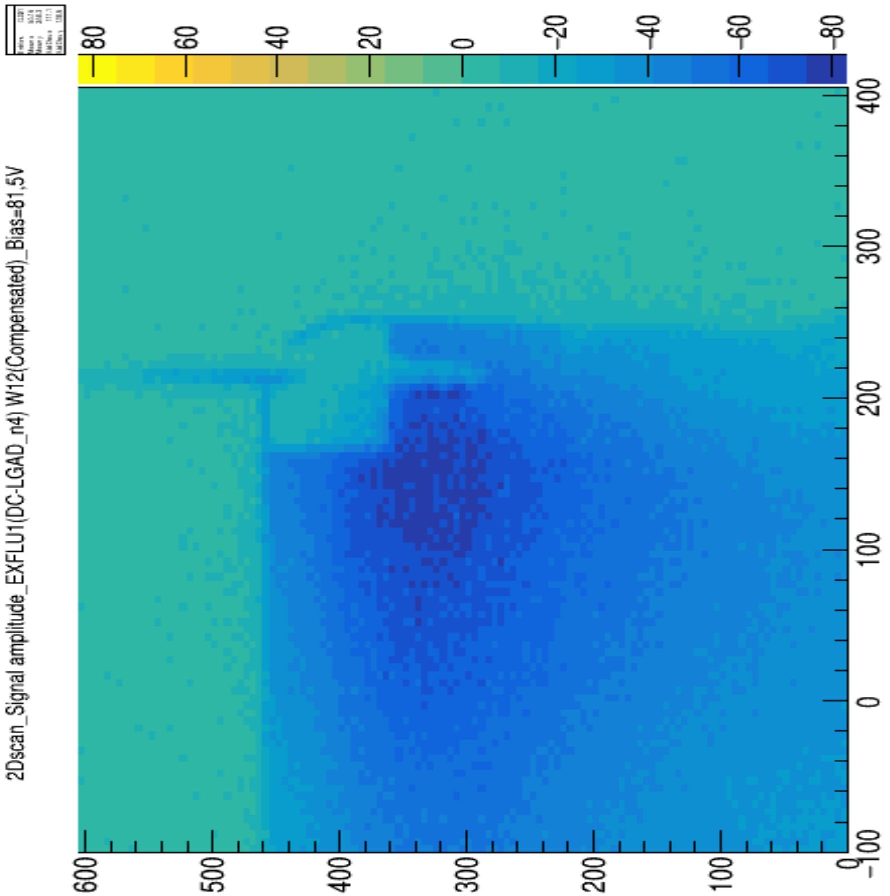
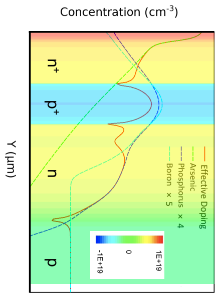


→ Investigate the edges of the compensated gain implant using TCT

Compensated LGAD – 2D Scan with IR Laser



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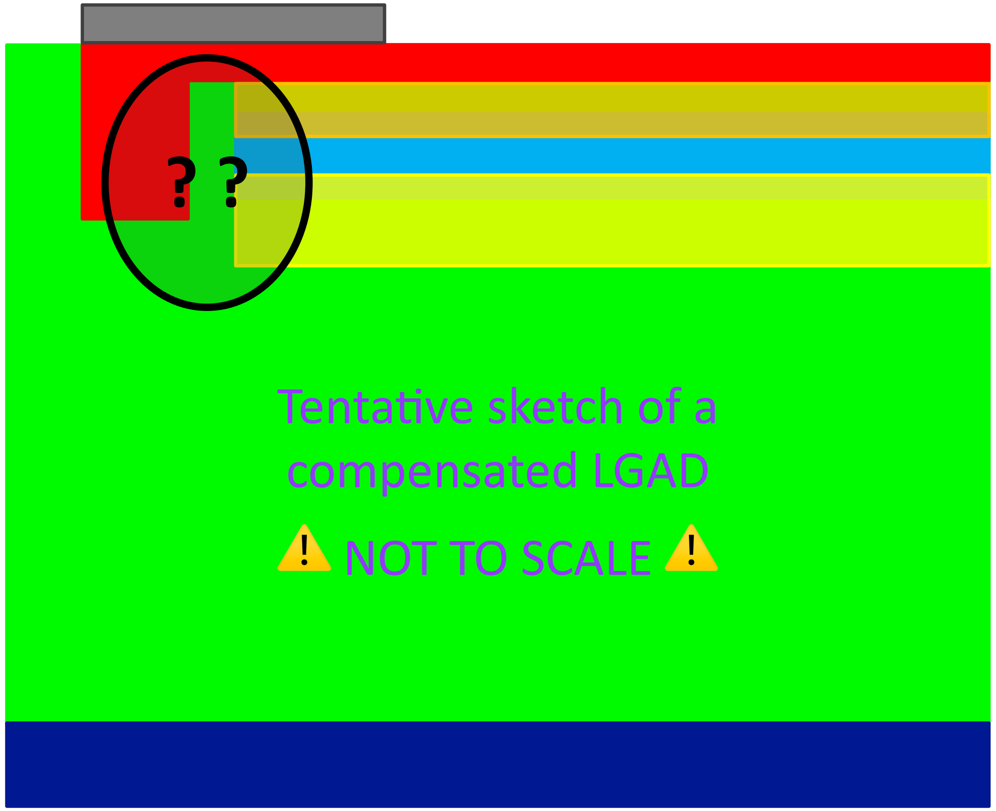
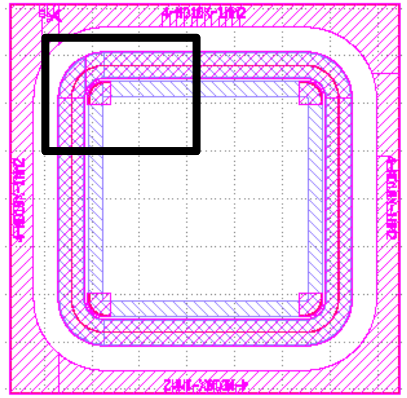


Scan surface



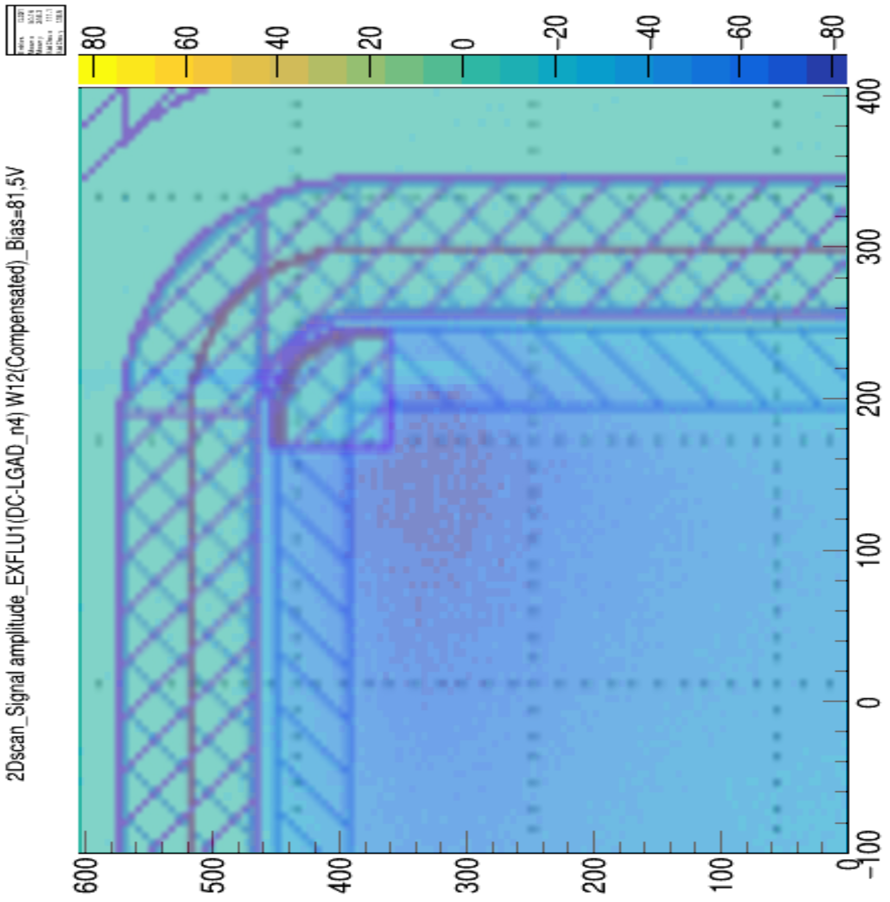
TCT scan with IR laser

Laser spot ~ 10 μm

Sensor from W12 (3–2)

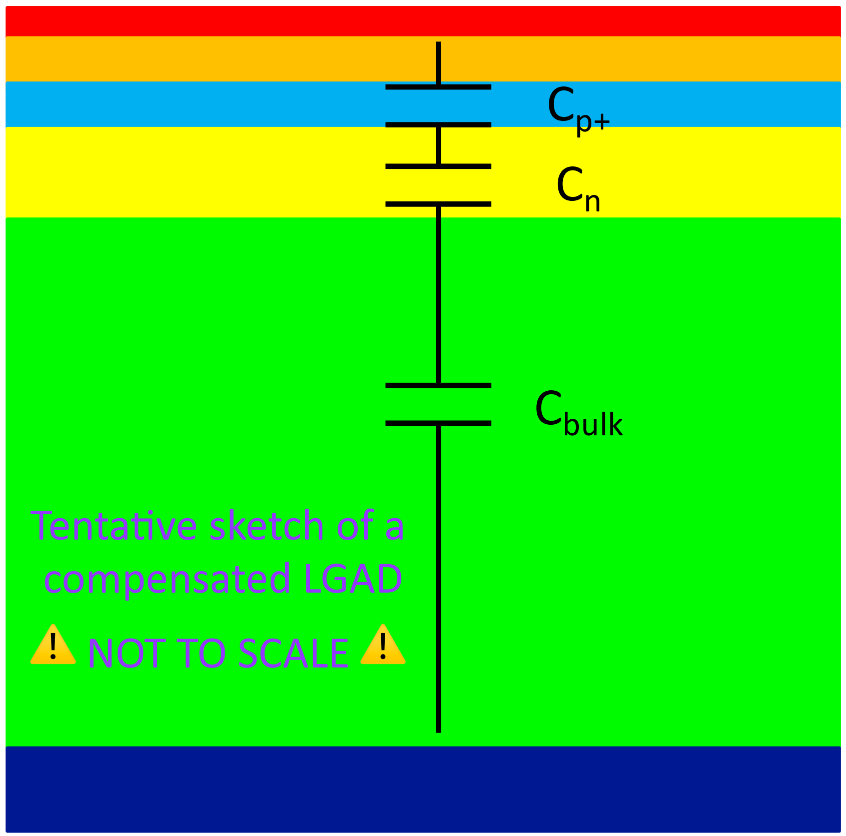
V_{bias} = 81 V

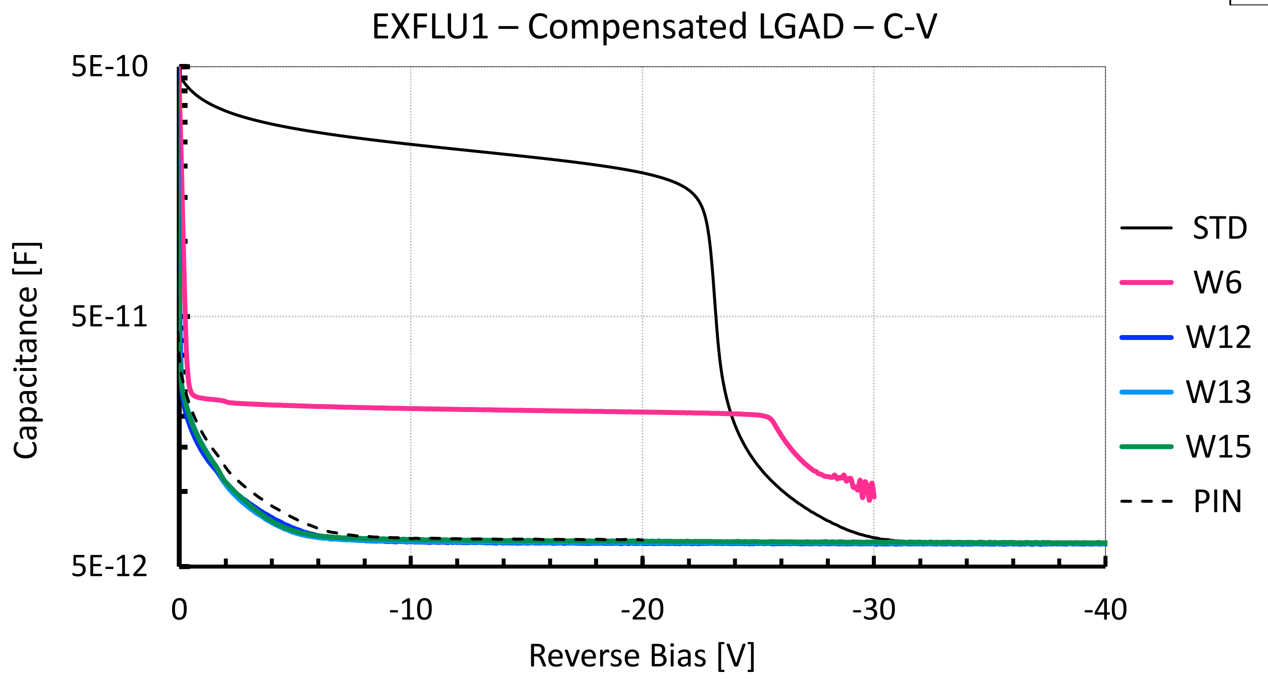
Very close to BD

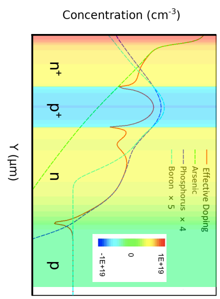


→ **No issues observed at the edge of the compensated gain implants**

Compensated LGAD – C-V

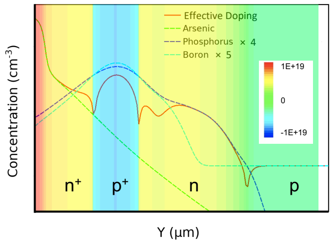


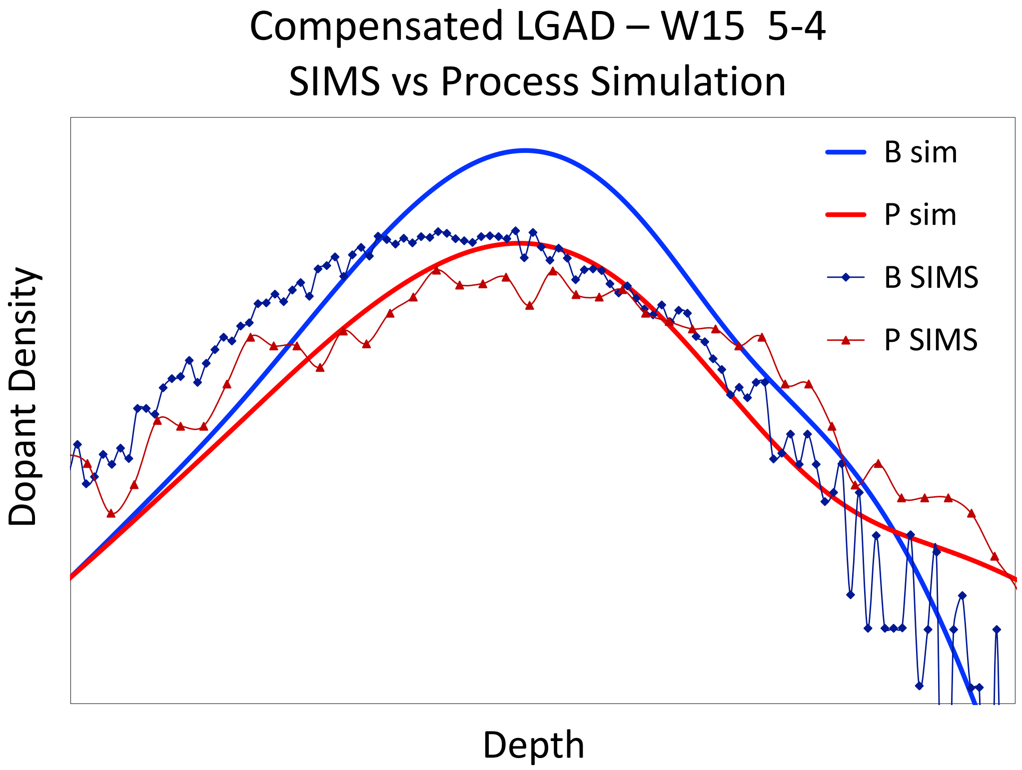




→ 3–2 & 5–4 C-V measurements have shapes similar to the one from the PIN diode, measuring a slightly bigger thickness at bias values between 0 and -10 V

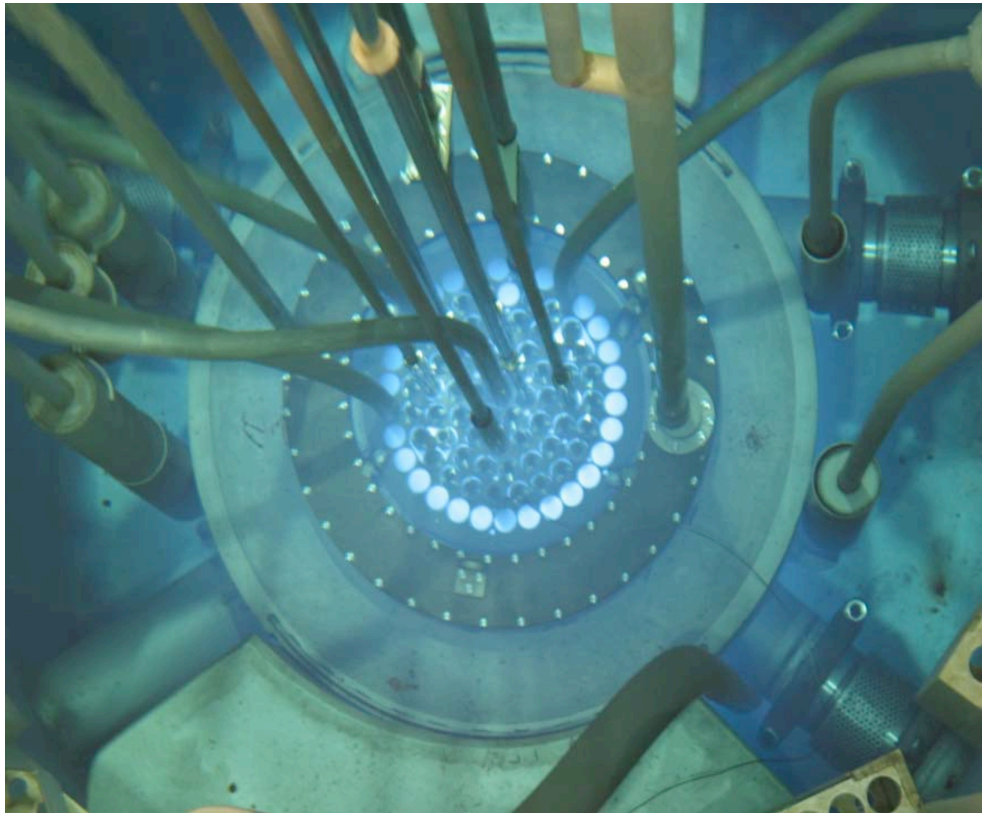
Secondary Ion Mass Spectroscopy – W15





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

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%

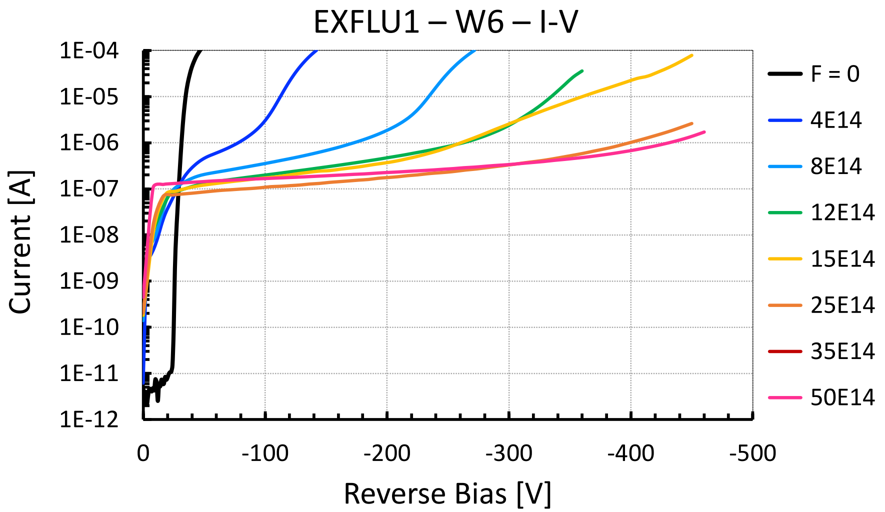
I-V from Compensated LGAD – Irradiated

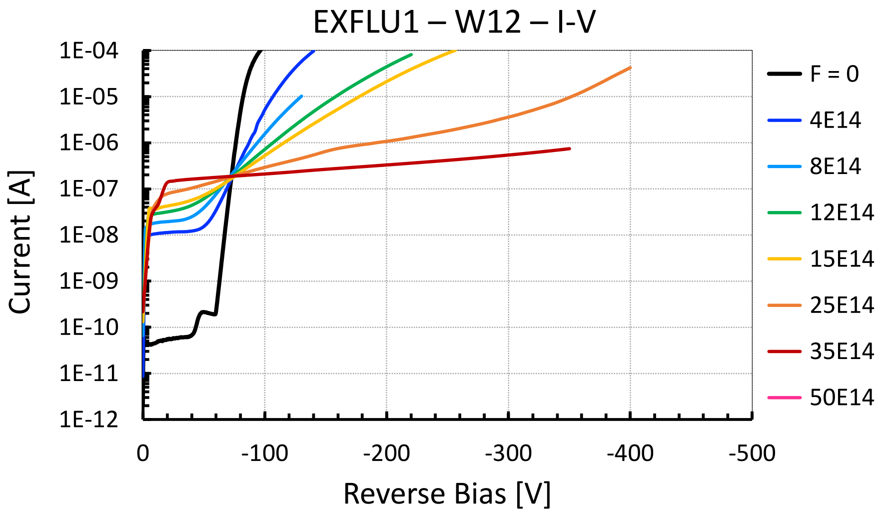
[Φ] = n_{eq}/cm^2

$T_{F=0}$ = + 20°C

T_{IRR} = - 20°C

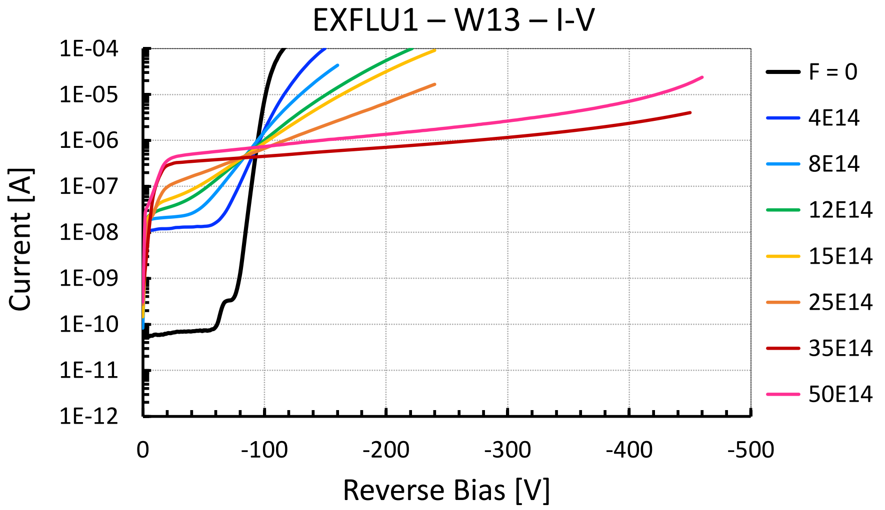
W6
2 – 1

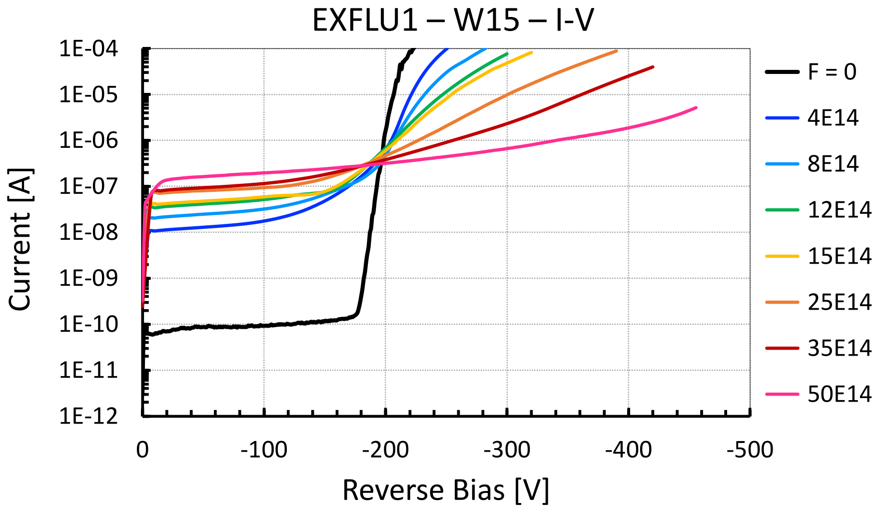




W12
3 – 2

W13
3 – 2 + C





W15
5 – 4

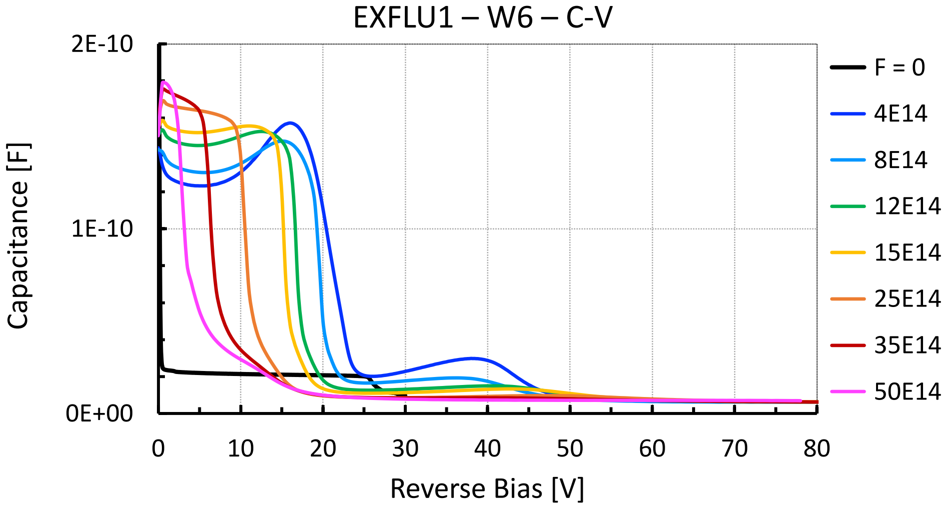
C-V from Compensated LGAD – Irradiated

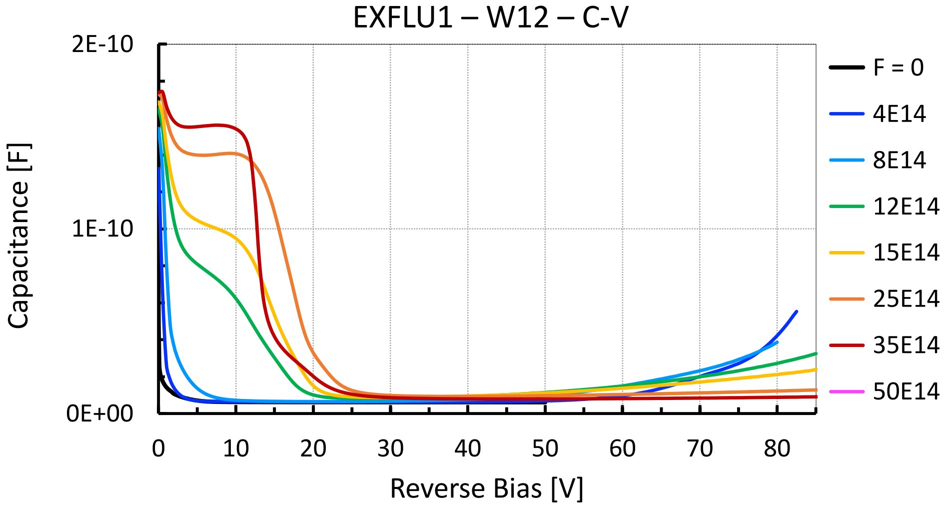
$[\Phi] = n_{eq}/cm^2$

$T = +20^{o}C$

$f = 2k\ Hz$

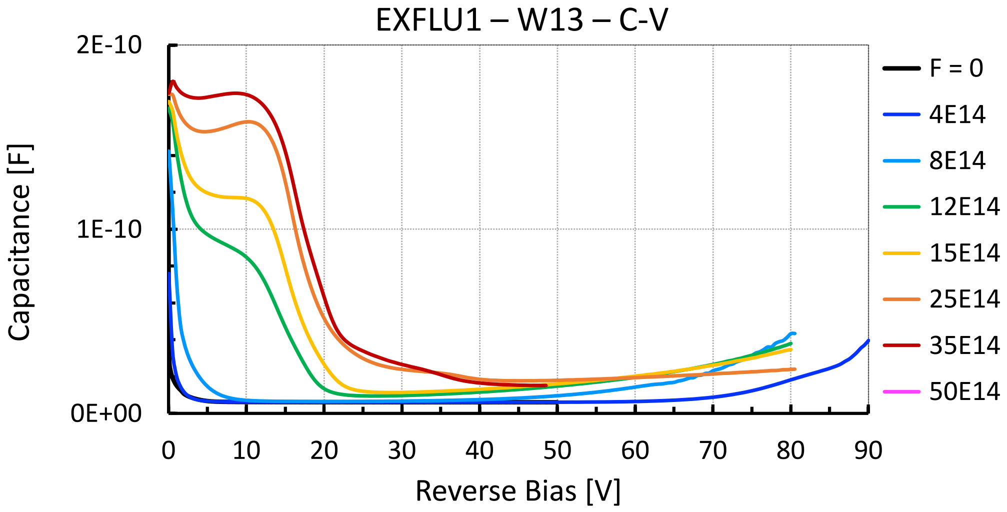
W6
2 – 1

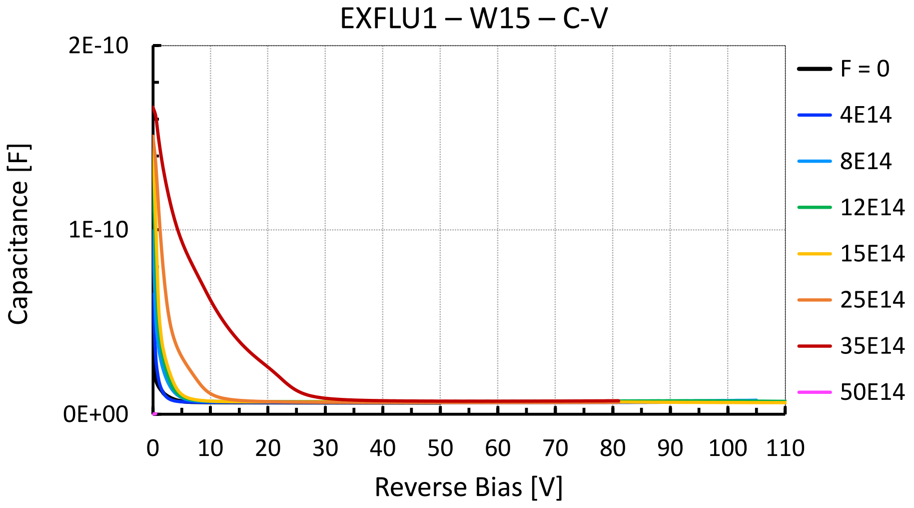




W12
3 – 2

W13
3 – 2 + C





W15
5 – 4

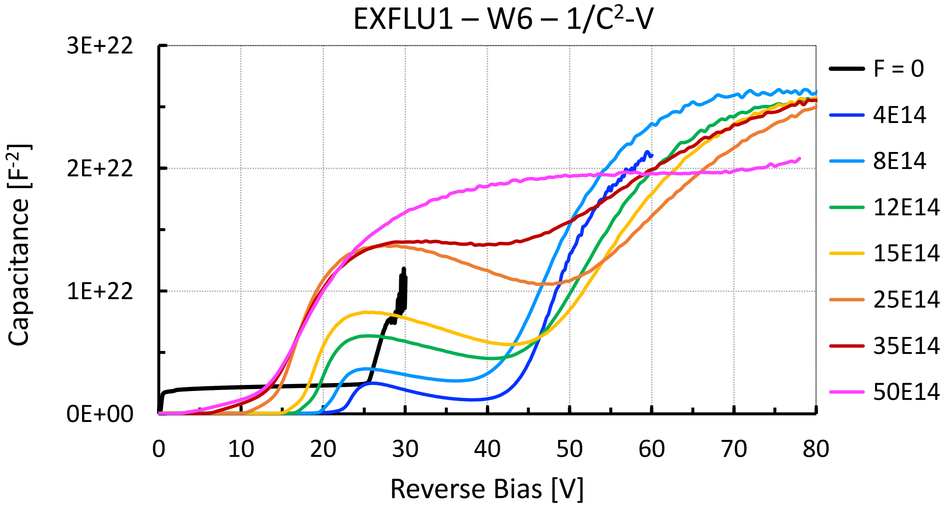
1/C²-V from Compensated LGAD – Irradiated

[Φ] = n_{eq}/cm^2

T = + 20ºC

f = 2k Hz

W6
2 – 1



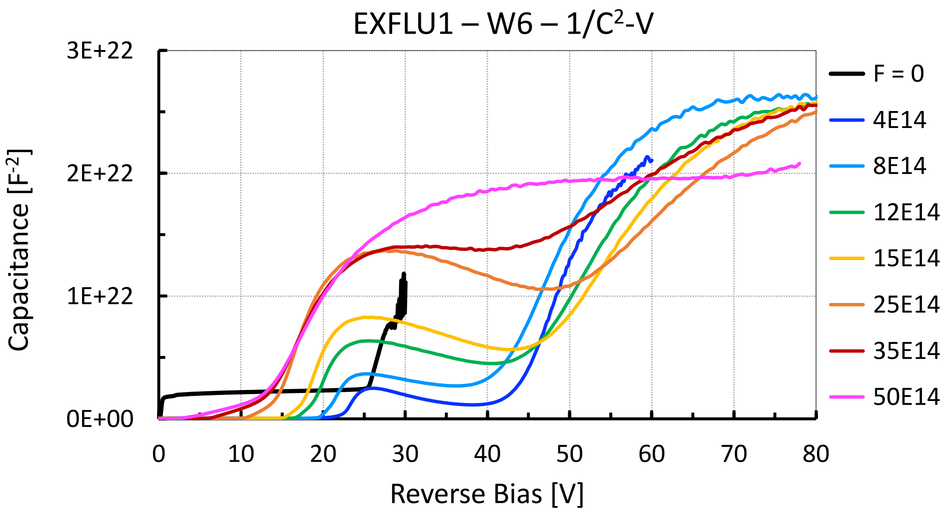
Doping Profile of Compensated LGAD 2 – 1

[Φ] = n_{eq}/cm^2

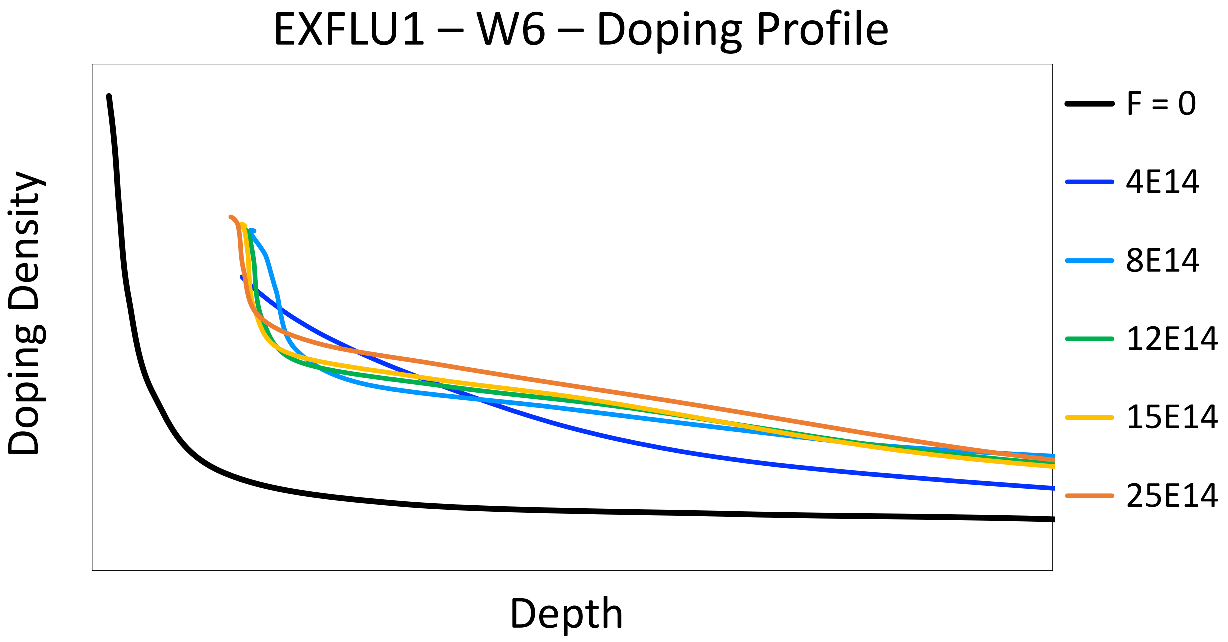
T = + 20°C

f = 2k Hz

W6
2 – 1



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



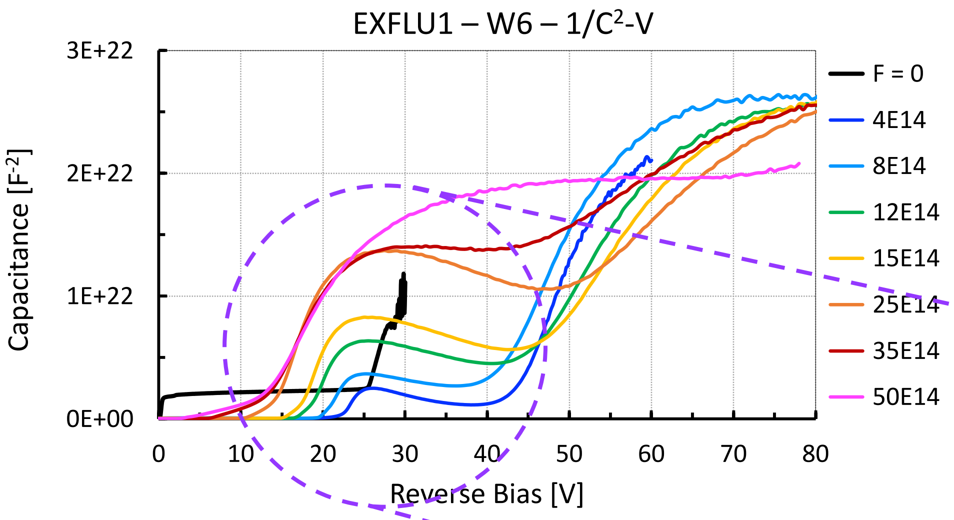
Doping Profile of W6

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

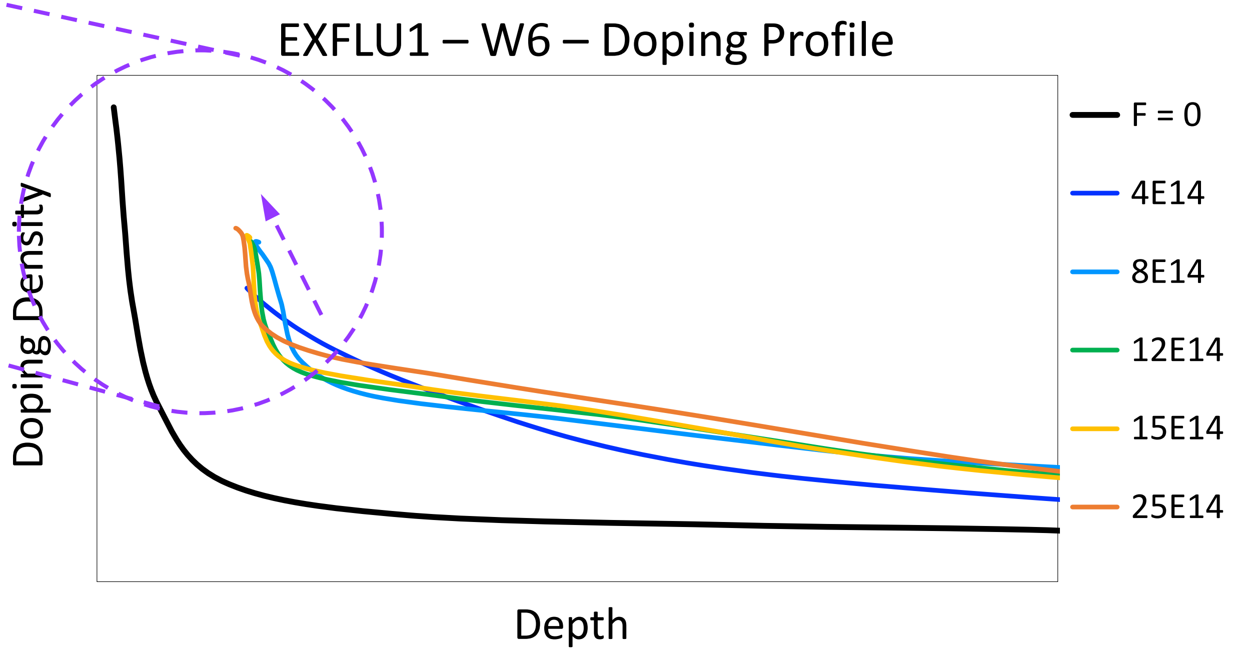
T = + 20°C

f = 2k Hz

W6
2 – 1



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

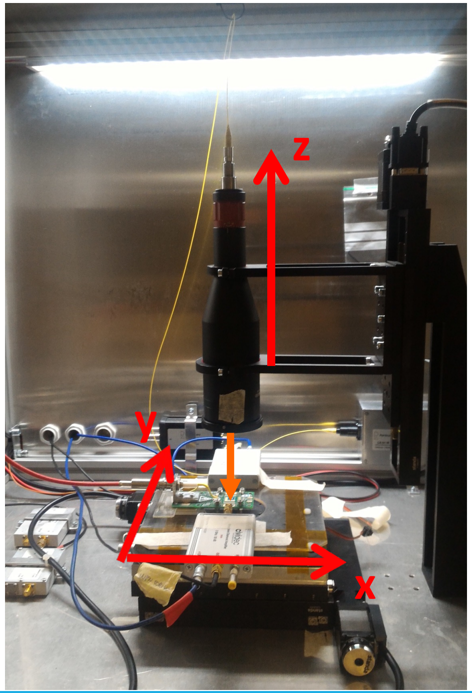


Gain implant profile appears more and more evident as the fluence increases

→ **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 = -10°C

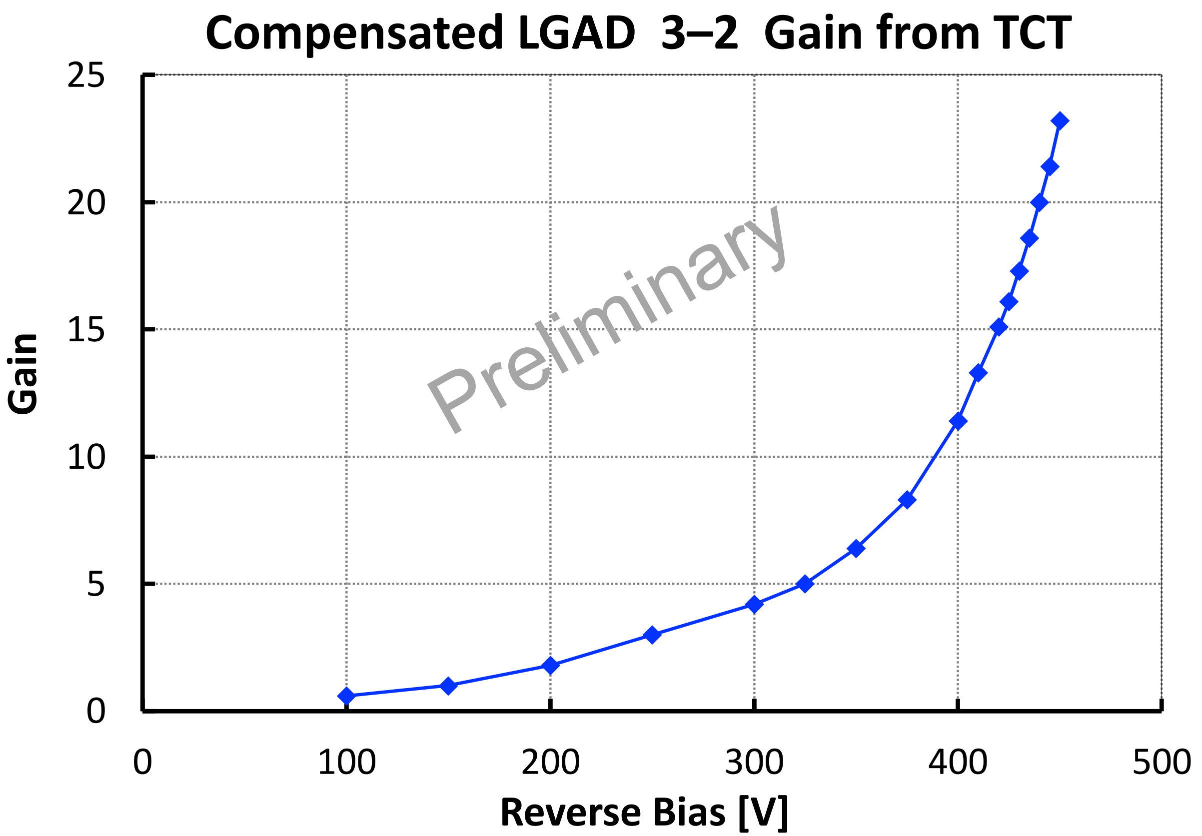


$$\mathbf{Gain} = \frac{Q_{LGAD}}{< Q_{PiN} >}$$

Laser intensity
~ 4 MIPs

Φ = 2.5E15 n_{eq}/cm^2

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



→ Exceptional gain behaviour at a fluence of 2.5E15 n_{eq}/cm^2

Summary & Outlook

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

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

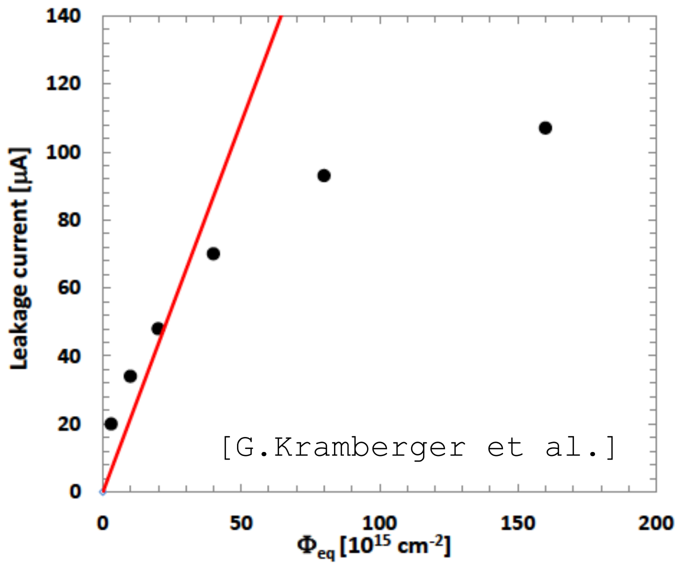
We acknowledge the following funding agencies and collaborations:

- INFN CSN5
- RD50, CERN
- AIDAinnova, WP13
- Compagnia di San Paolo
- Ministero della Ricerca, Italia, PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
- Ministero della Ricerca, Italia, PRIN 2022, progetto 2022RK39RF – ComonSens
- European Union’s Horizon 2020 Research and Innovation programme, Grant Agreements Nos 101004761 (AIDAinnova) and 101057511 (EURO-LABS)

Backup

Saturation

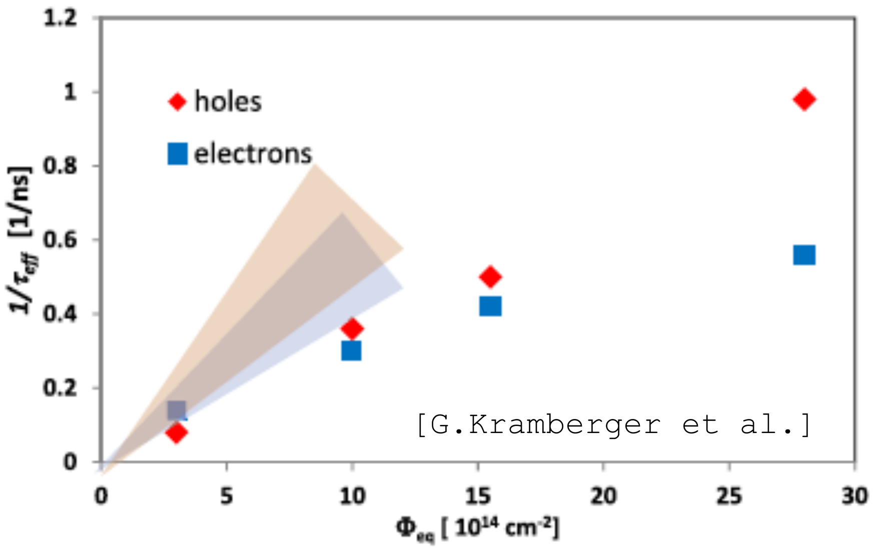
At fluences above $5{\cdot}10^{15}$ cm^{-2} → **Saturation of radiation effects observed**



Leakage current saturation

$I = \alpha V \Phi$

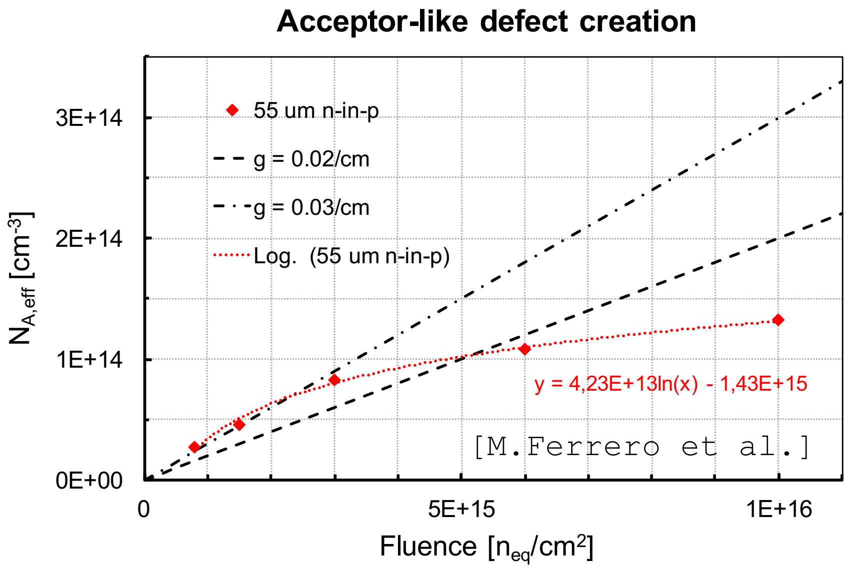
α from linear to logarithmic



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

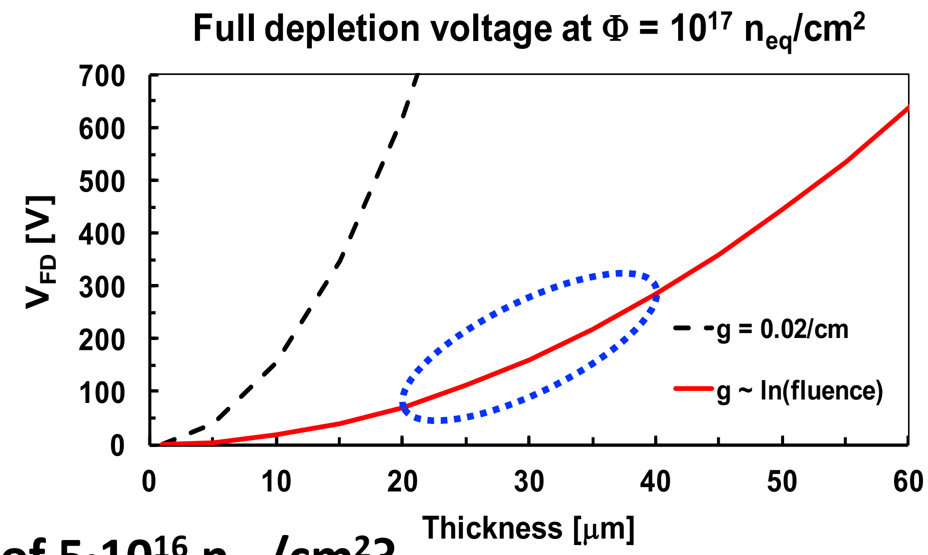
Silicon detectors irradiated at fluences 10^{16} – 10^{17} n_{eq}/cm^2 do not behave as expected → They behave better

Thin Substrates

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

Saturation **Reduce thickness**

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)

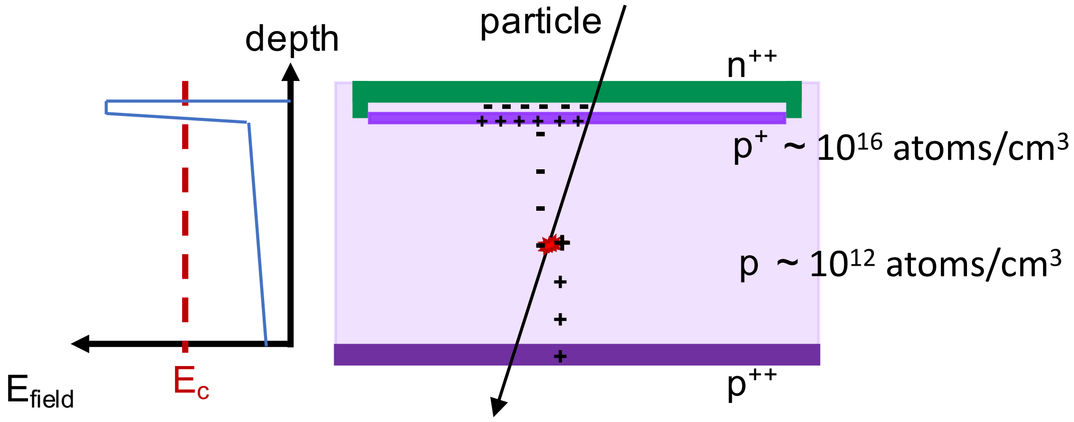
However: charge deposited by a MIP ~ 0.25 fC

→ 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**

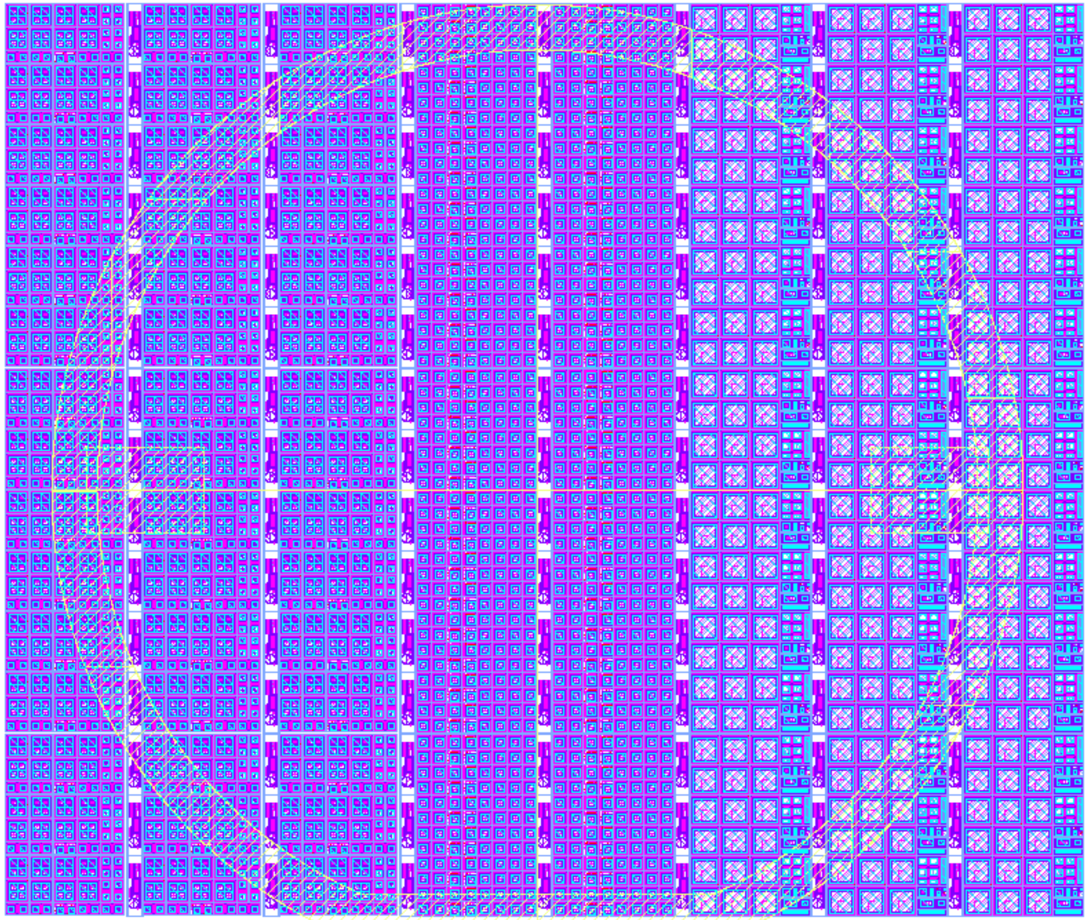
[S. Meroli et al., doi:10.1088/1748-0221/6/06/P06013]

⇒ **Need a gain of at least 5 – 10**

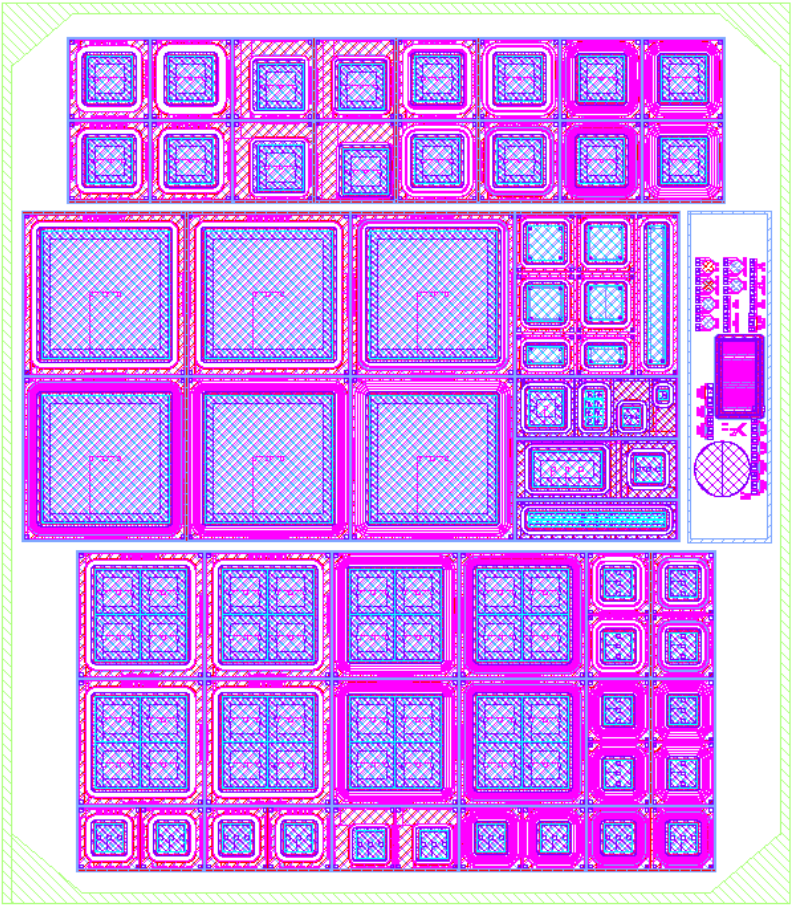
up to $\Phi = 10^{17}\ n_{eq}/cm^2$ to efficiently record a hit

The EXFLU1 Layout

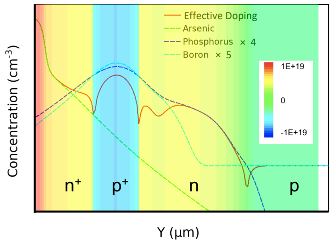
6” Wafer Layout



Reticle Layout



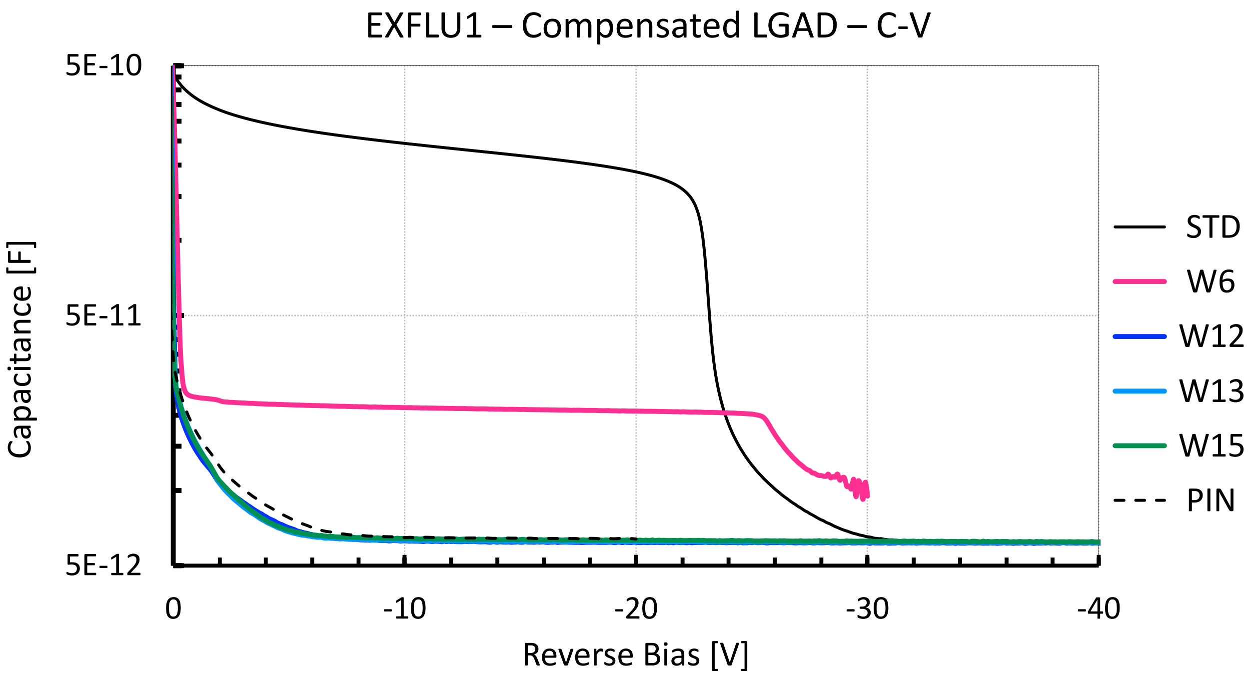
Compensated LGAD – C-V

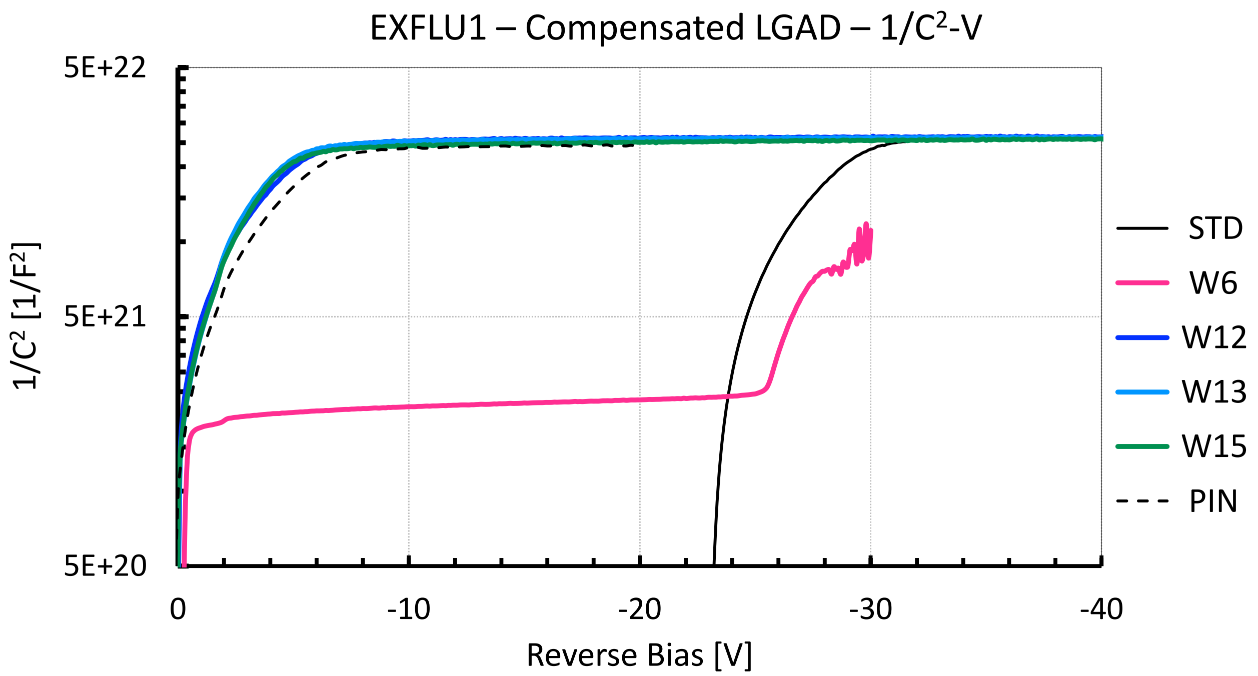


Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
12	30	3 b	2	
13	30	3 b	2	1.0
15	30	5 a	4	

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

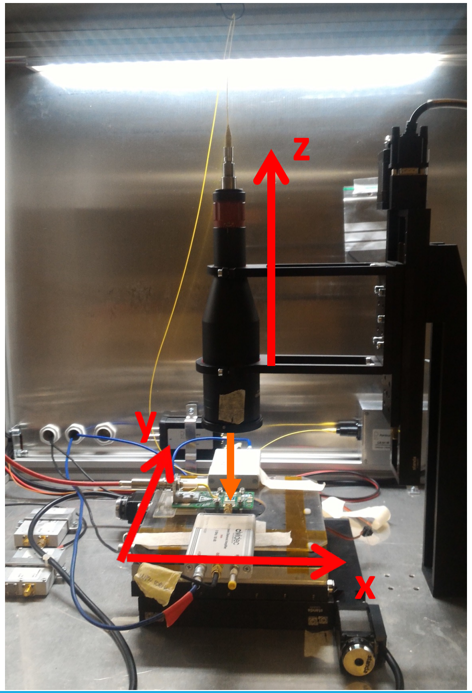
→ **3–2 & 5–4 exhibit a lower capacitance than PIN**





IR Laser Stimulus on Compensated LGAD 5–4

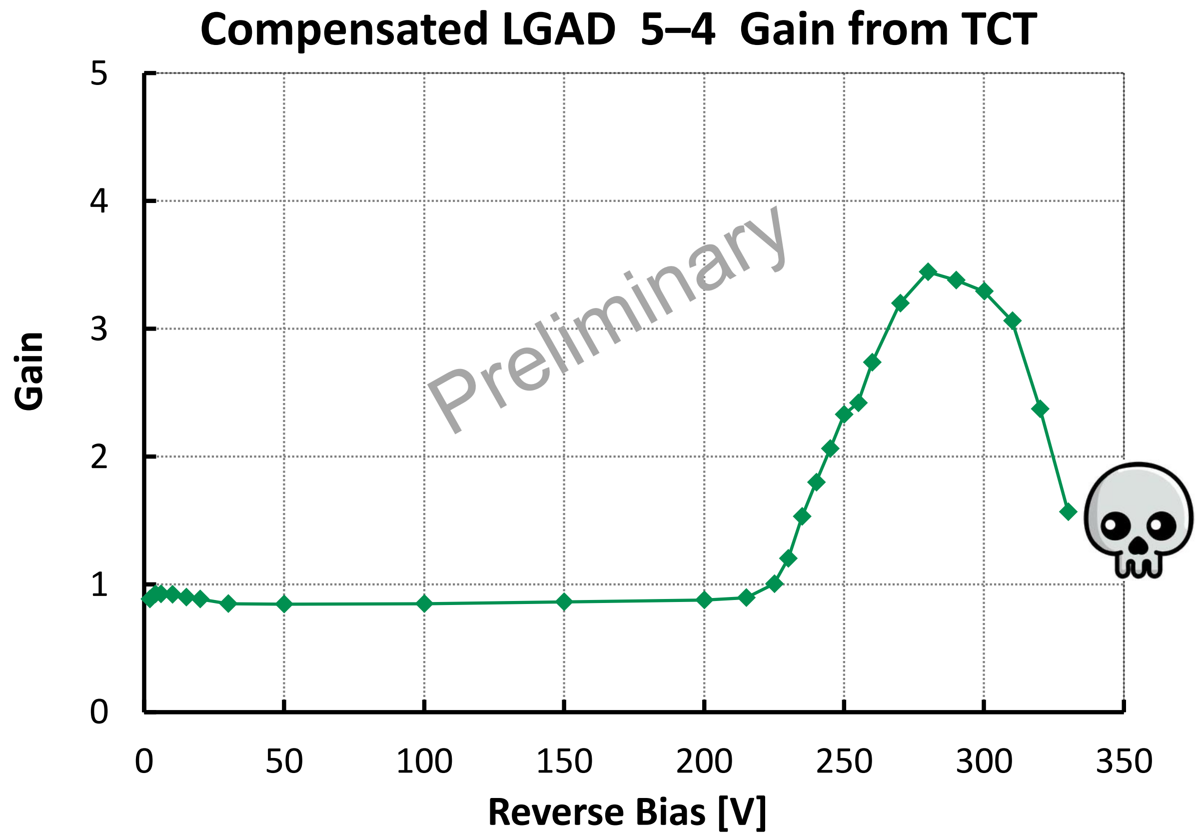
TCT Setup from Particulars
Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 μm
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
Room temperature



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

Laser intensity
~ 60 MIPs

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



→ Not easy to operate 5 – 4 compensated LGAD sensors

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