AIDAinnova 3rd Annual Meeting
18–21 March 2024
Catania, Italy

Thin Silicon Sensors for Extreme Fluences

eXFlu-innova

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A new Sensor Design

Goal: Design planar silicon sensors able to work in the fluence range $10^{16} – 10^{17}$ n_{eq}/cm^2

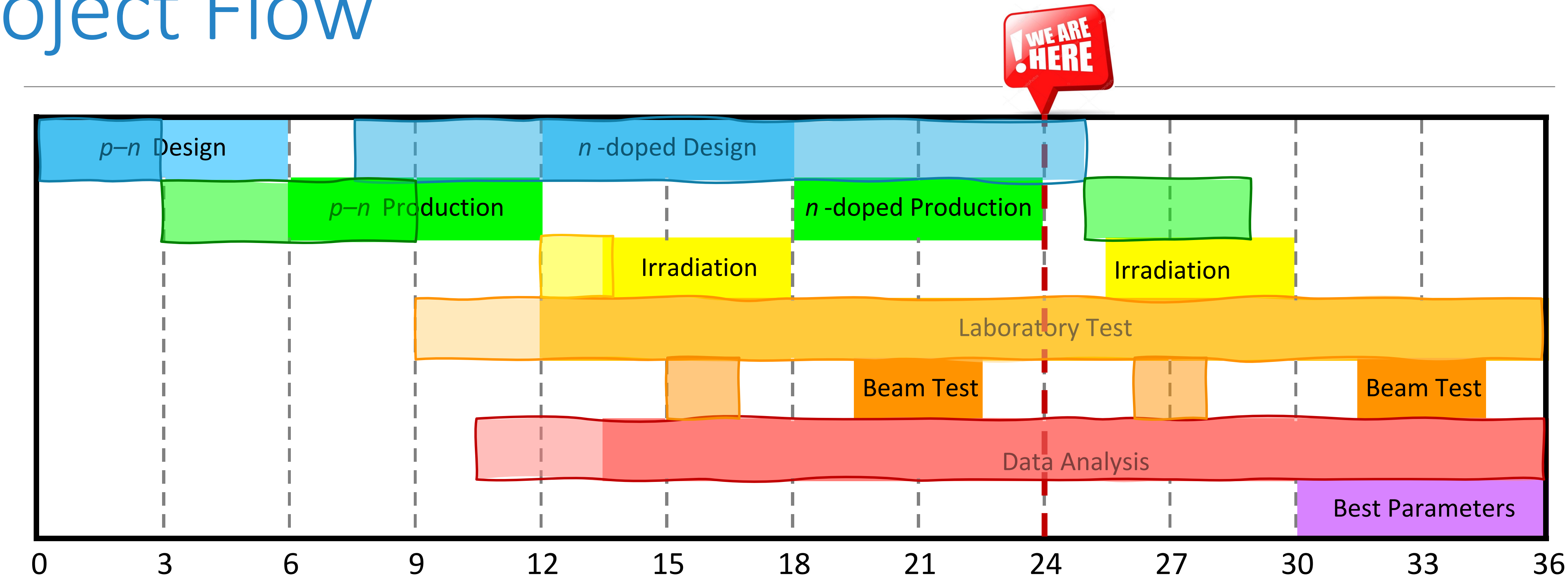
Difficult to operate silicon sensors above 10^{16} n_{eq}/cm^2 due to:

– 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

The ingredients 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 (15 – 45 μm) with **internal gain**
3. **extension** of the charge carrier multiplication up to 10^{17} n_{eq}/cm^2 → **Compensated LGADs**

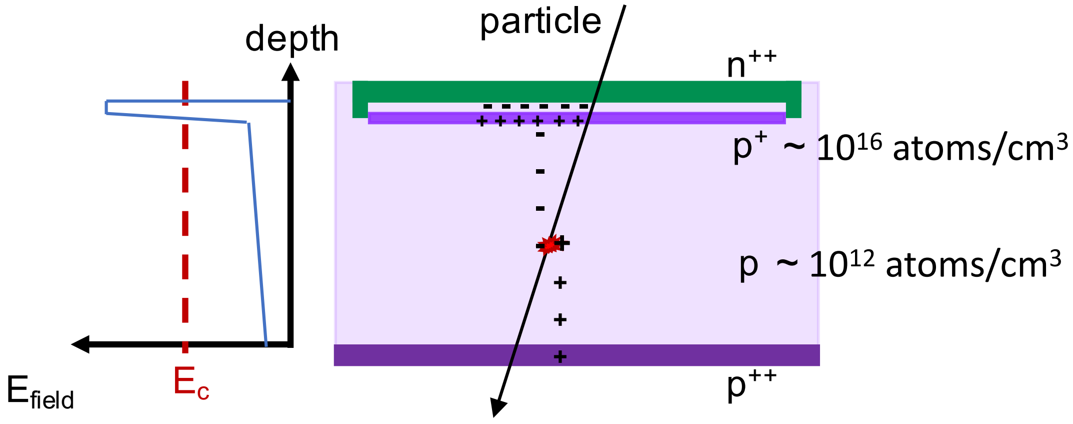
Project Flow

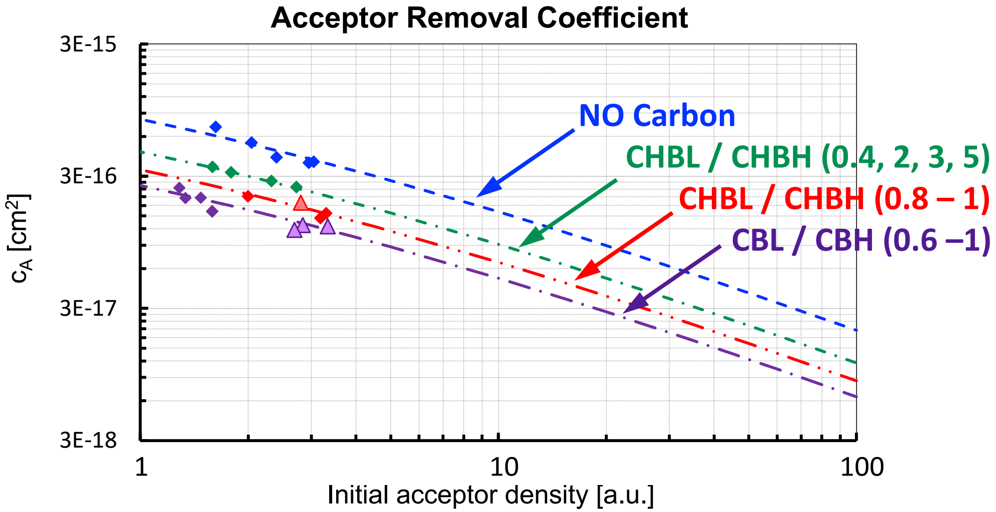


Deliverables:

1. **simulation and design** of the *p–n* compensated gain implant (M6) – DONE
2. **production** of *p–n* compensated sensors (M12) – DONE and *n*-doped sensors (M24) – WORK IN PROGRESS
3. **identifications of the best parameters** to manufacture compensated LGADs (M36) – pending

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

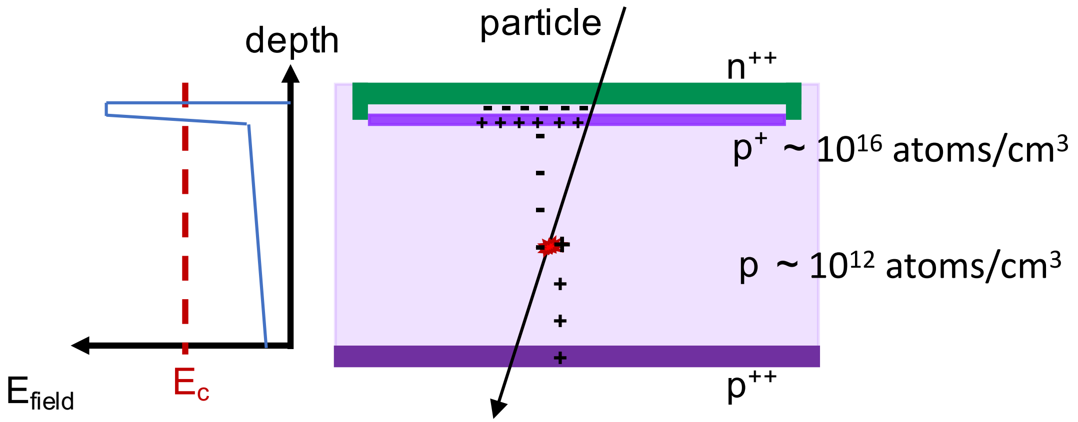
$\Phi_0 = 1/c_A$ ~ the fluence at which multiplication power of the gain implant reaches unity

▲ thin sensors from the EXFLU1 batch

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

⇒ Is it possible to reduce c_A further?

Towards a Radiation Resistant Design

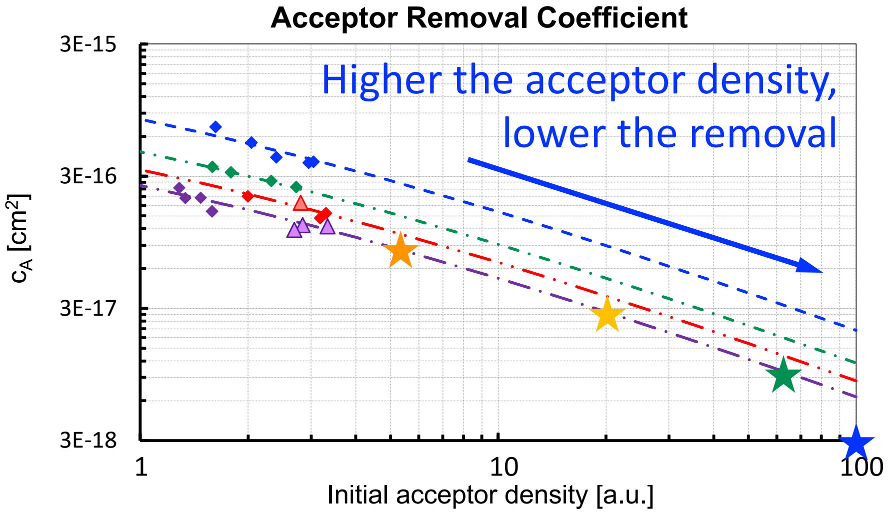


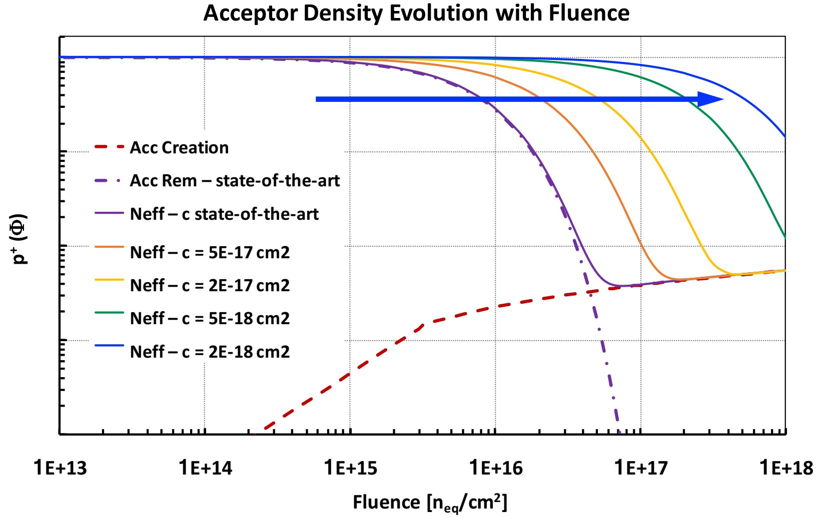
The acceptor removal mechanism deactivates the p^+-doping of the **gain implant** with irradiation as

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

where c_A is the acceptor removal coefficient

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



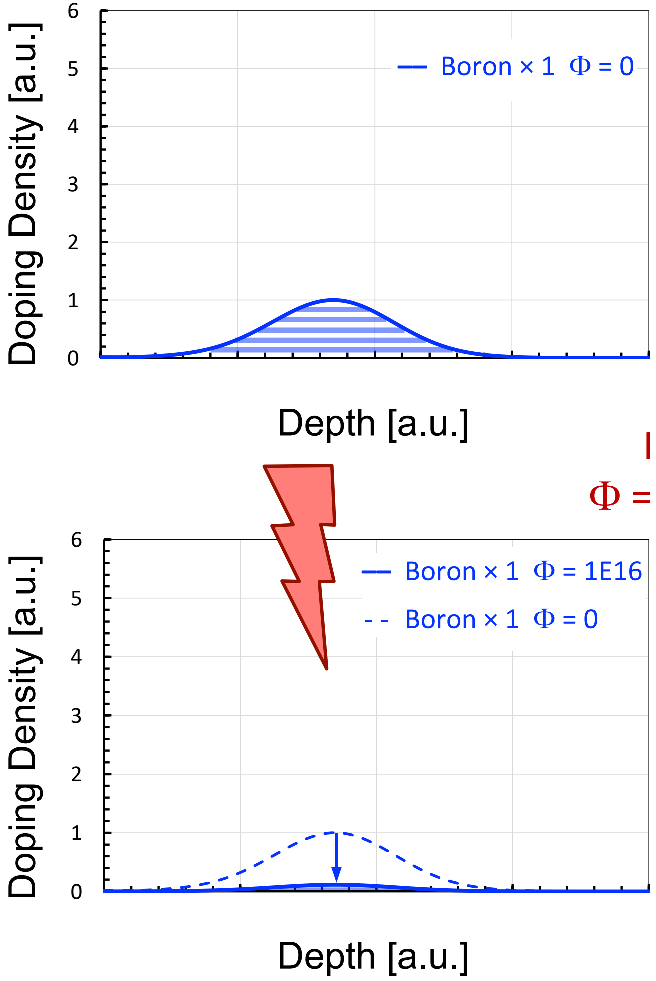


Lowering c_A can extend the gain layer survival up to $\Phi \geq 10^{17}$ n_{eq}/cm^2

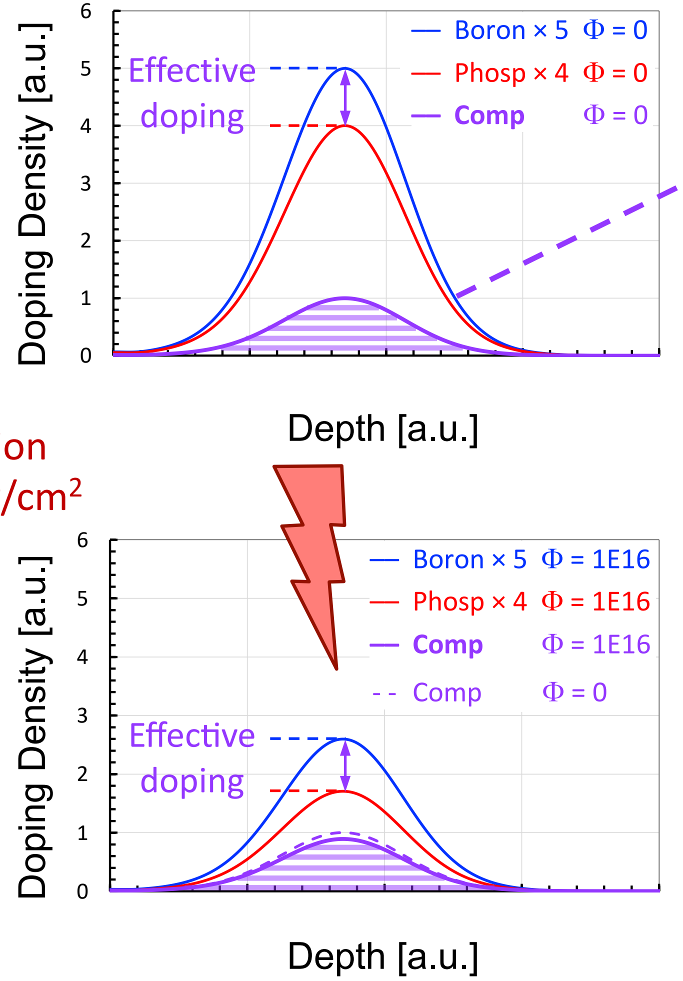
→ compensation

Compensation at a Glance

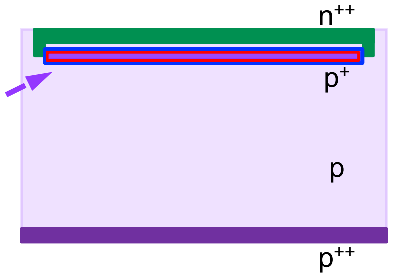
Doping Profile – Standard LGAD



Doping Profile – Compensated LGAD



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



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

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 2024, Torino]

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	

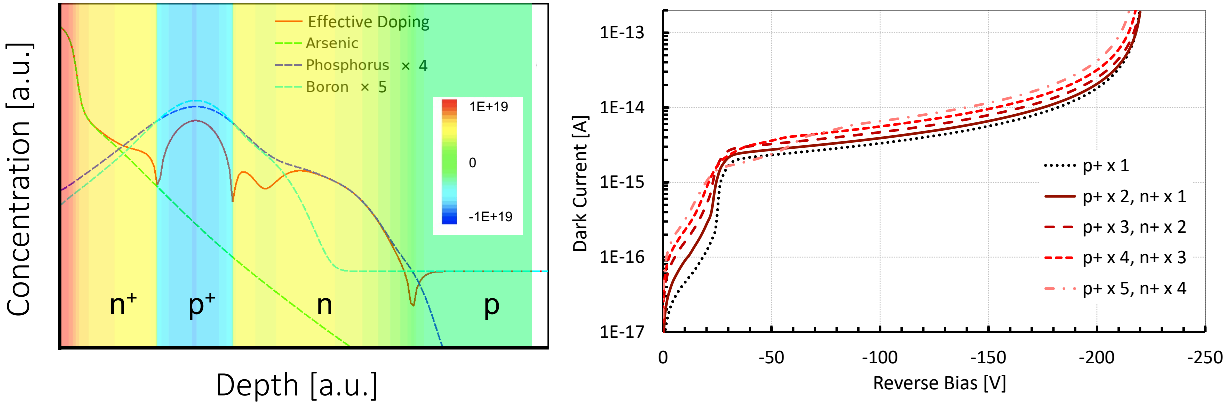
[a < b < c]

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

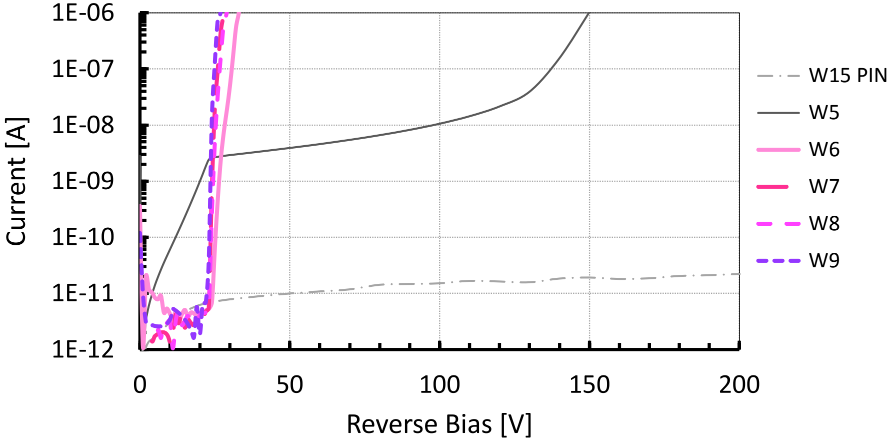
Compensated LGAD – I-V on wafer

Recap from AIDAinnova Meeting 2023

Simulation



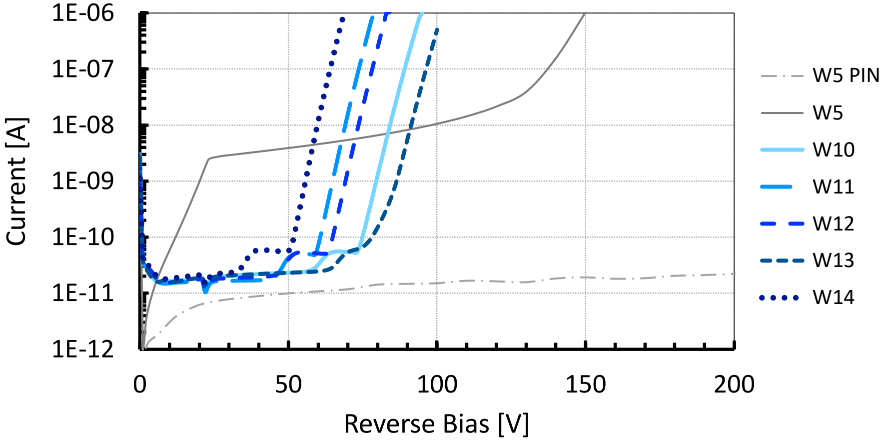
EXFLU1 – Compensated LGAD 2–1 – I-V



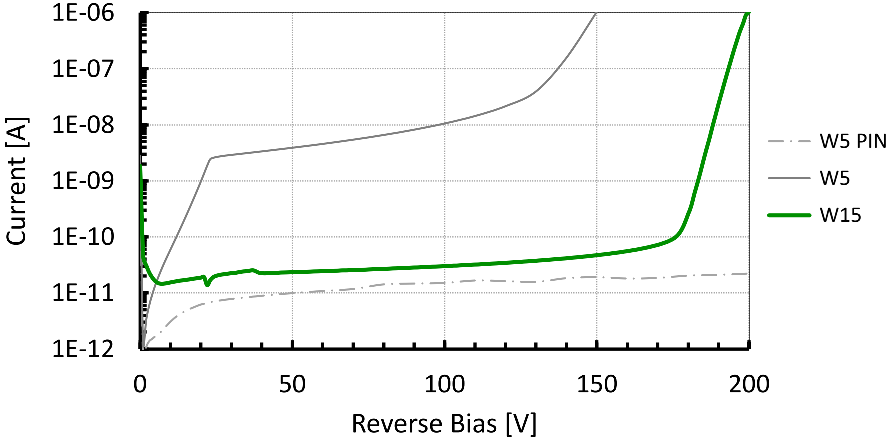
2 – 1

EXFLU1 – Compensated LGAD 3–2 – I-V

3 – 2



EXFLU1 – Compensated LGAD 5–4 – I-V



5 – 4

IR Laser Stimulus on Compensated LGAD

TCT Setup from Particulars

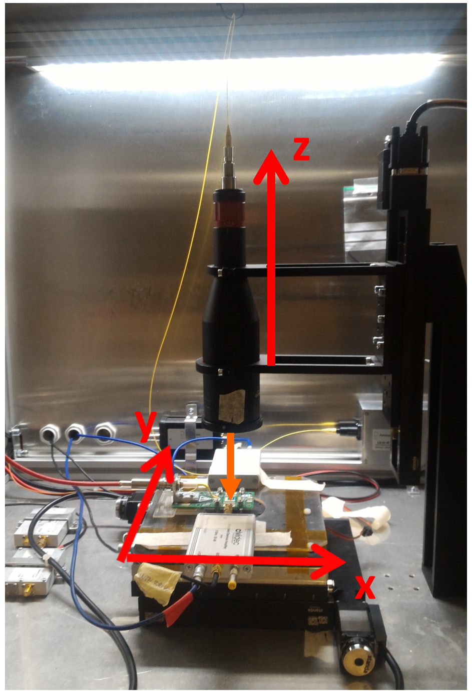
Pico-second IR laser at 1064 nm

Laser spot diameter ~ 10 µm

Cividec Broadband Amplifier (40dB)

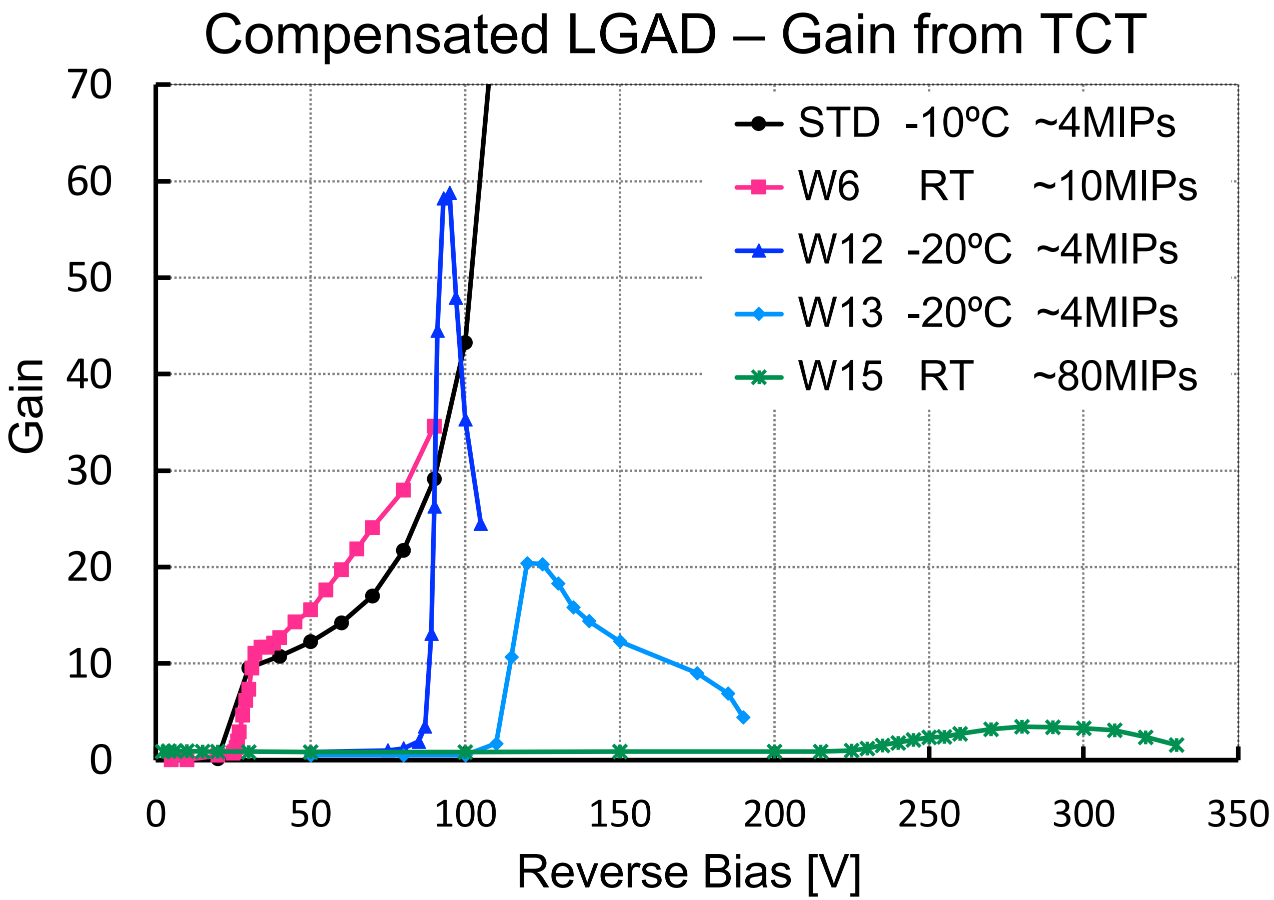
Oscilloscope LeCroy 640Zi

$\Phi = 0$



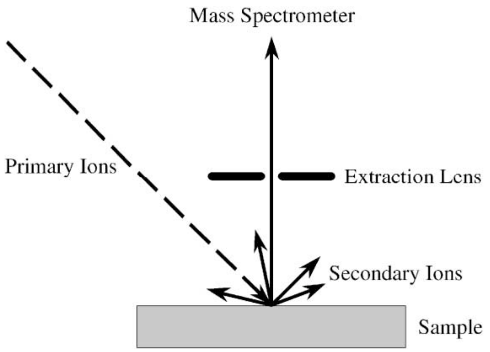
Laser stimulus on LGAD-PiN structures

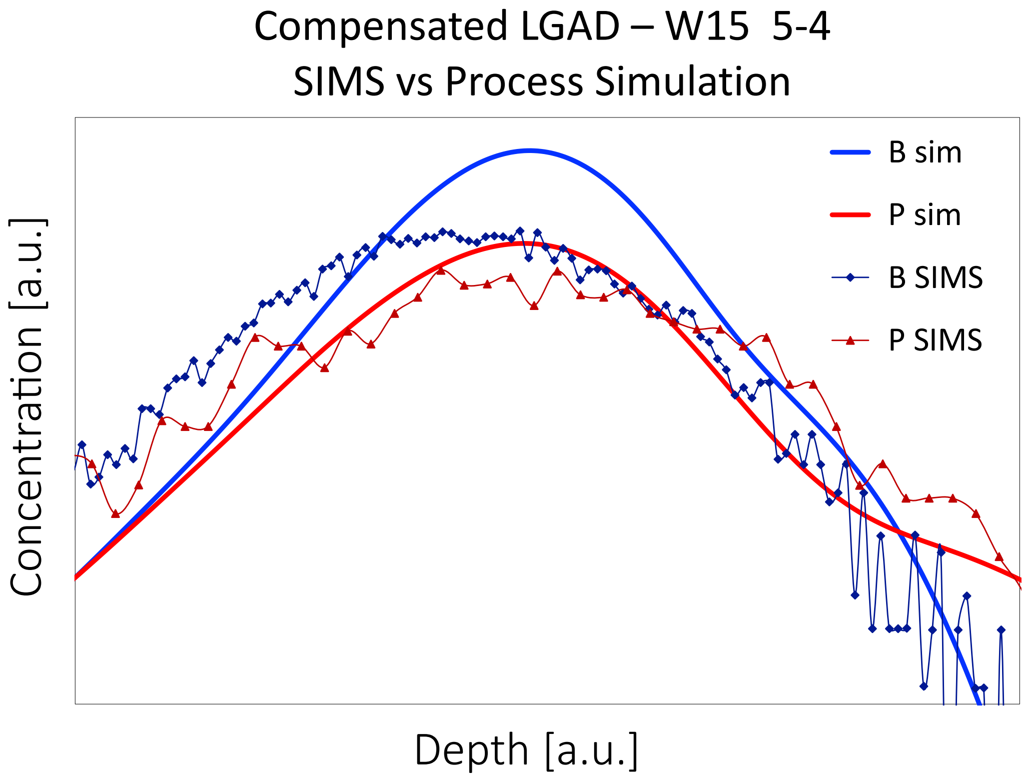
$$\text{Gain} = \frac{Q_{LGAD}}{< Q_{PiN} >}$$



→ **Not trivial to operate compensated LGAD sensors**

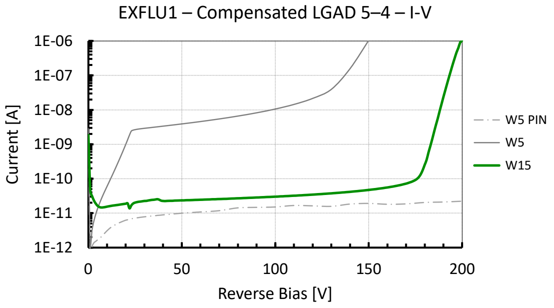
Secondary Ion Mass Spectroscopy – W15



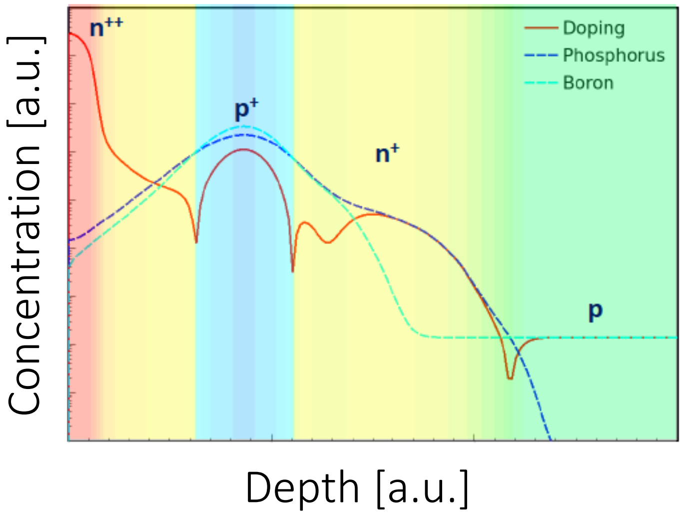


- ▻ Boron peak is shallower than phosphorus
- ▻ Boron peak is lower than predicted from simulation

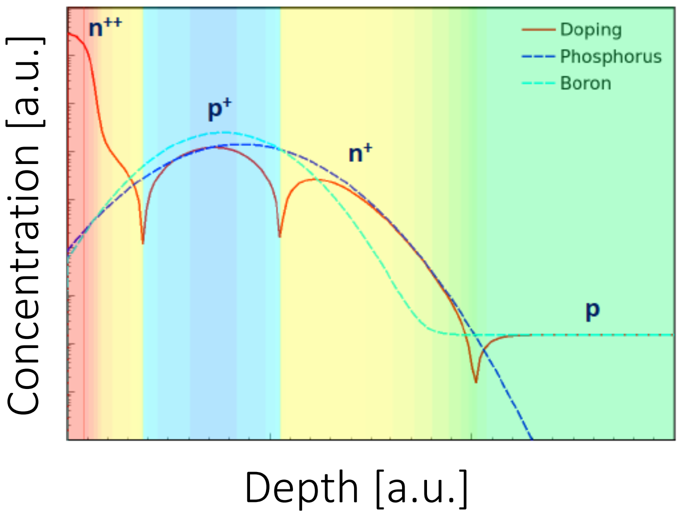
SIMS Profile & I-V – 5–4



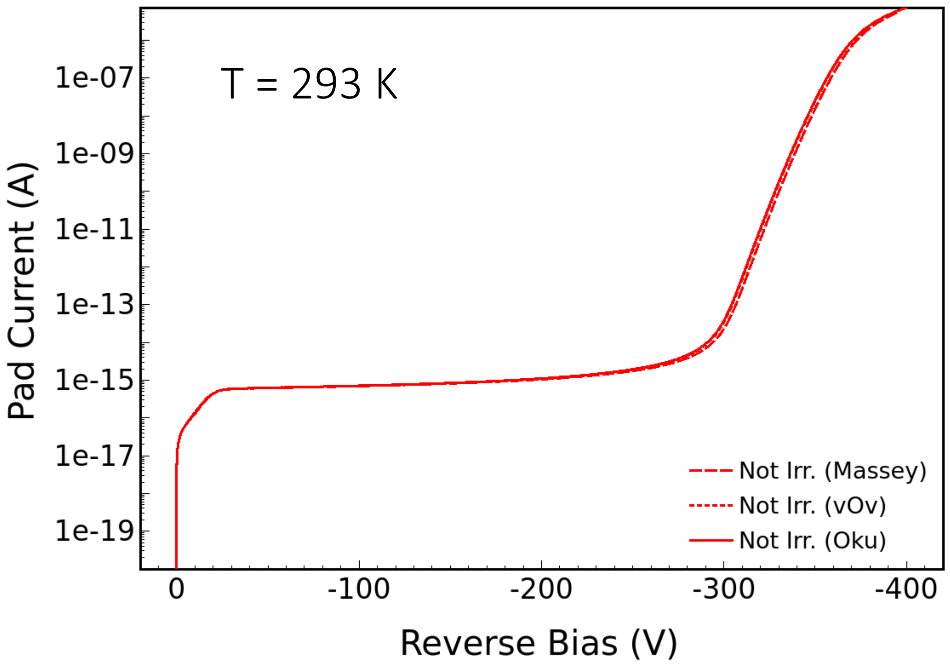
Doping Profiles
from Process Simulation



Doping Profiles
from SIMS

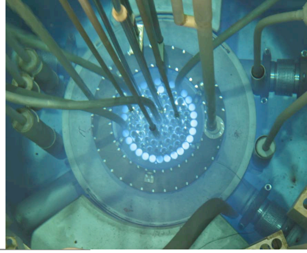


Simulated I-V from SIMS Profiles



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

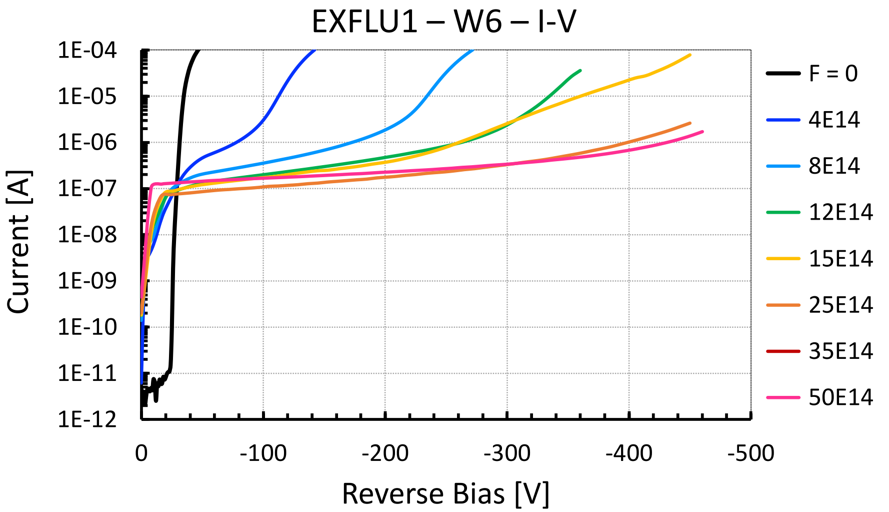
I-V from Compensated LGAD – Irradiated



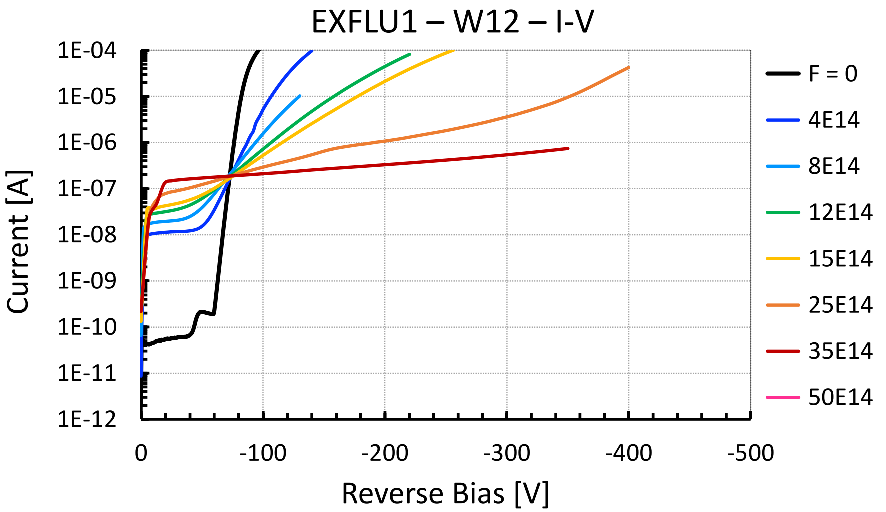
Irradiated
from 1E14 to
5E15 n_{eq}/cm^2

W6
2 – 1

EXFLU1 – W6 – I-V



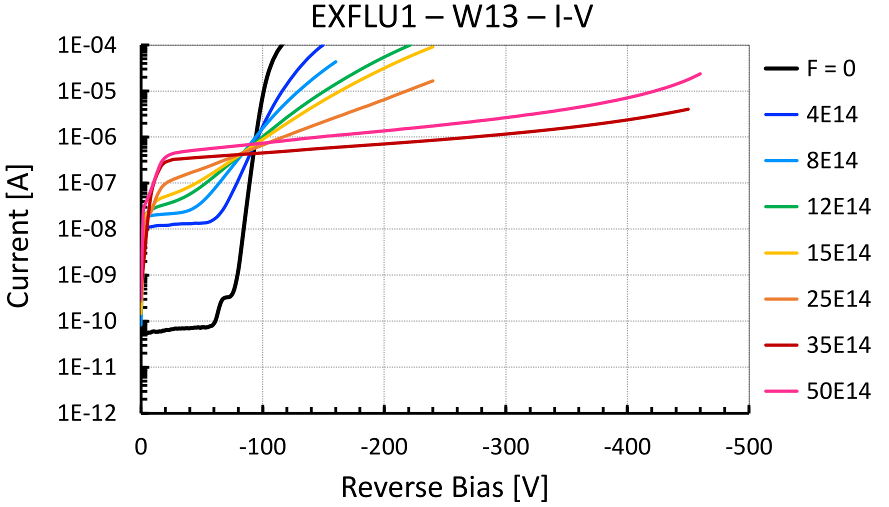
EXFLU1 – W12 – I-V



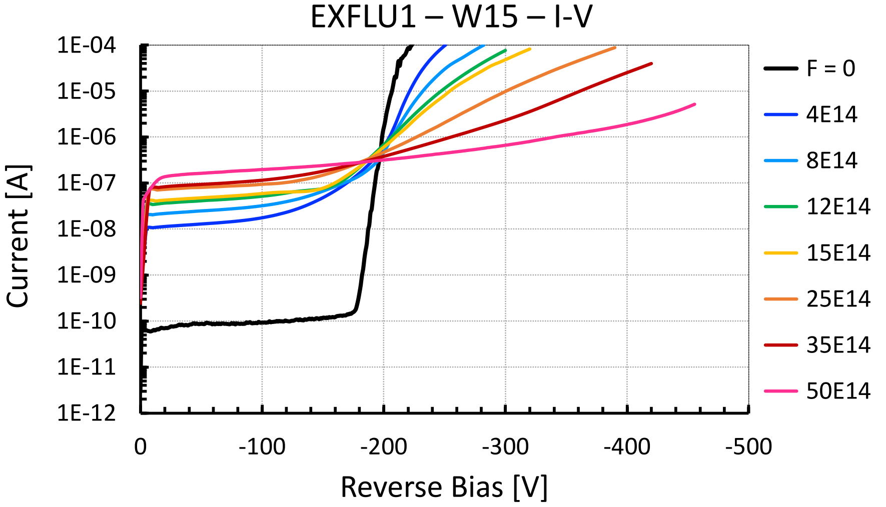
W12
3 – 2

W13
3 – 2 + C

EXFLU1 – W13 – I-V



EXFLU1 – W15 – I-V



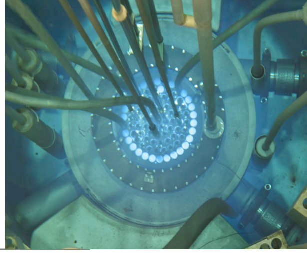
W15
5 – 4

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

$T_{F=0} = +20^{o}C$

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

IR Laser Stimulus on Compensated LGAD



TCT Setup from Particulars

Pico-second IR laser at 1064 nm

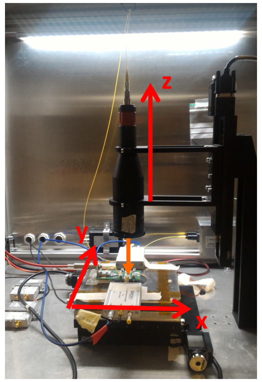
Laser spot diameter ~ 10 µm

Cividec Broadband Amplifier (40dB)

Oscilloscope LeCroy 640Zi

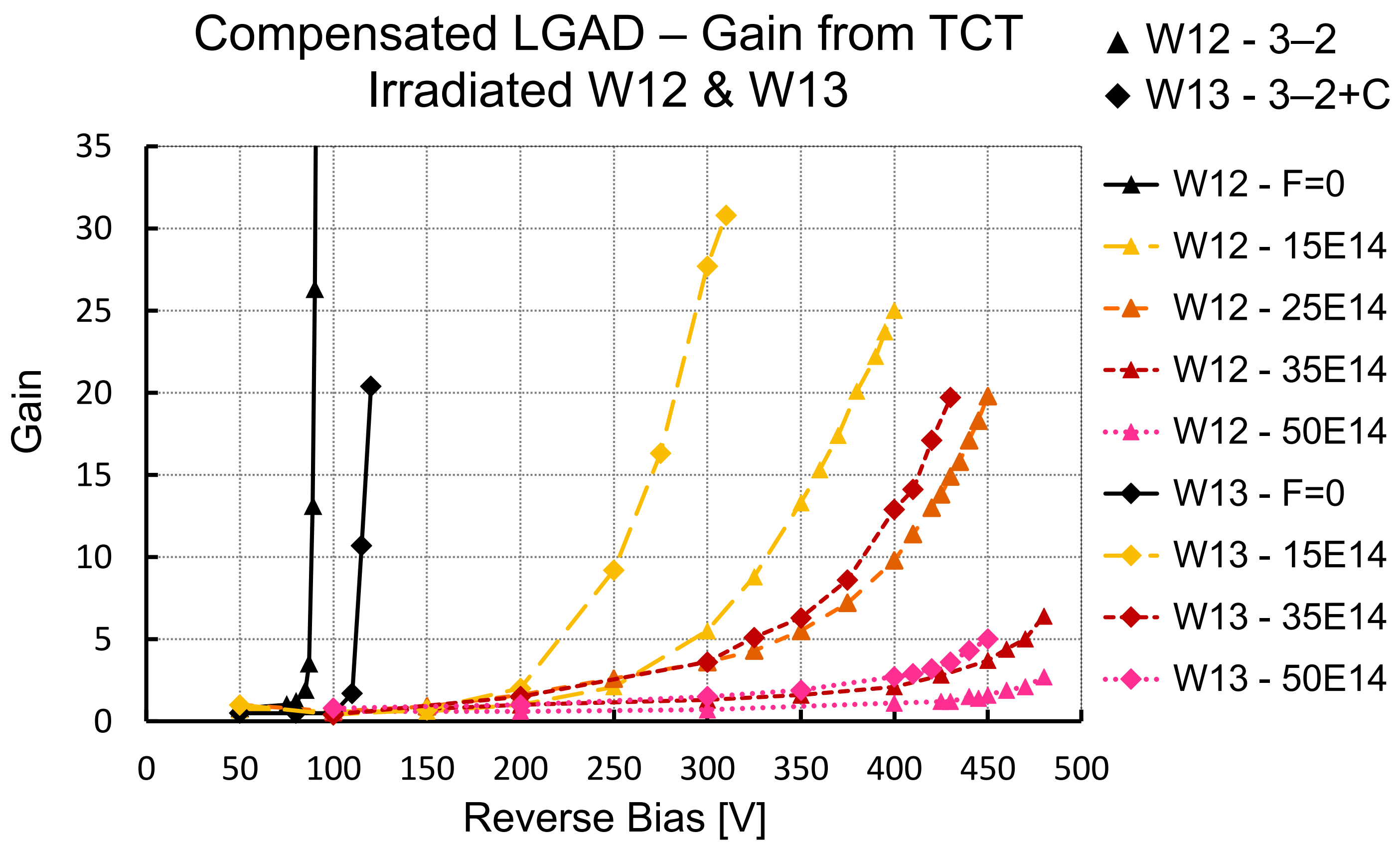
Laser intensity ~ 4 MIPs

T = -20ºC



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

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



→ 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

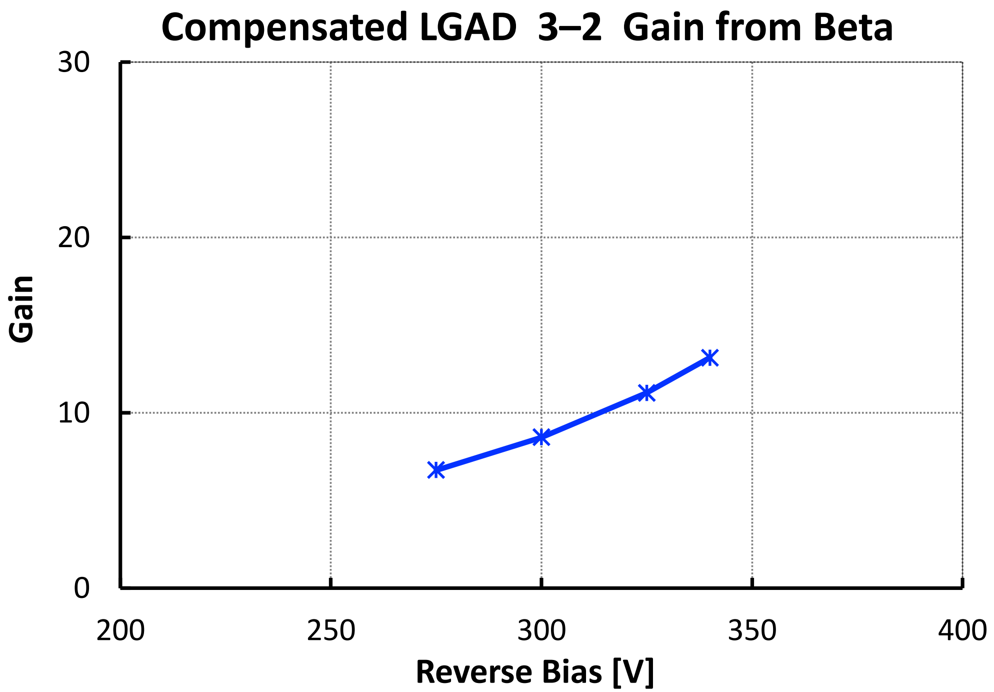
β Setup
Oscilloscope: LeCroy 9254M (2.5GHz - 40Gs/s)
HV Power supply: CAEN DT1471ET
UCSC Board + Cividec Broadband Amplifier (20dB)
Time reference: Photonis MCP-PMT – $\sigma_t \sim 15$ ps
β source: Sr90 – activity ~ 37 kBq
T = -25°C

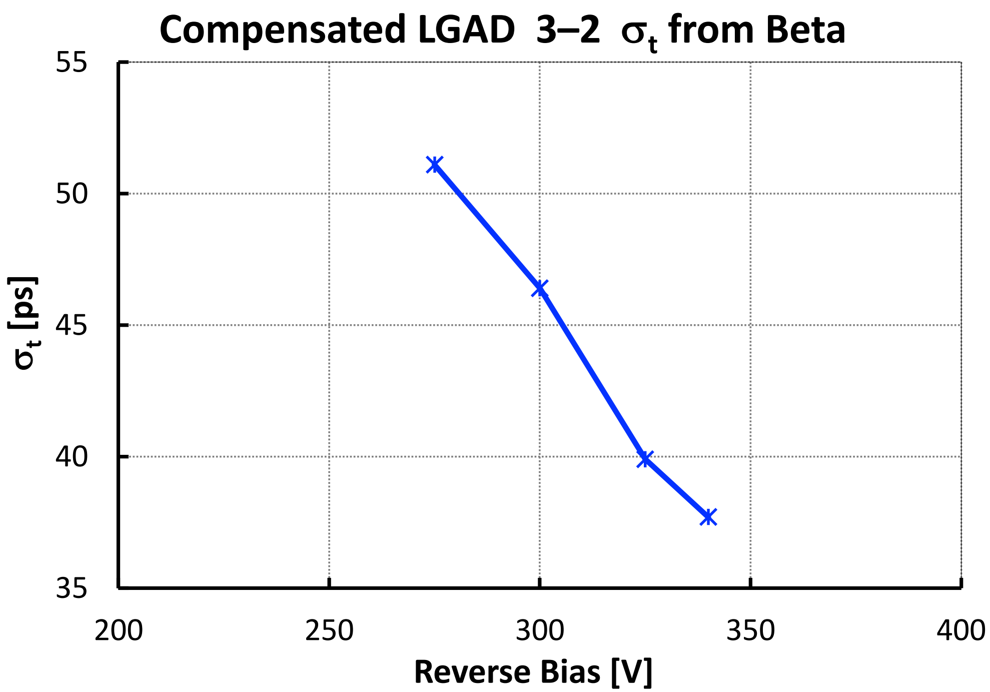
3–2 compensated LGAD from W12 irradiated to 2.5E15 n_{eq}/cm^2 has been tested with beta particles

→ **Good timing performances of compensated LGAD sensors irradiated to 2.5E15 n_{eq}/cm^2**

W12
3–2

Φ = 2.5E15





Compensated LGAD – State-of-the-Art

Lesson from the first batch of compensated LGAD sensors:

- ▻ Difficult to control the shape and the peak concentration of two different elements
  → **Necessary to carefully tune all the process parameters**
- ▻ After irradiation, possible to successfully operate compensated LGAD sensors
  → **Good gain and timing performances after irradiation**
- ▻ Co-implantation of Carbon in the same volume of Boron and Phosphorus
  → **Same effect as in standard LGAD, a reduction of a factor of ~ 3 of the Acceptor removal**
- ▻ Simulation effort in progress to replicate I-V, C-V, and gain behaviour after irradiation
  → **Possible to extract Acceptor and Donor removal by comparing data and simulations**

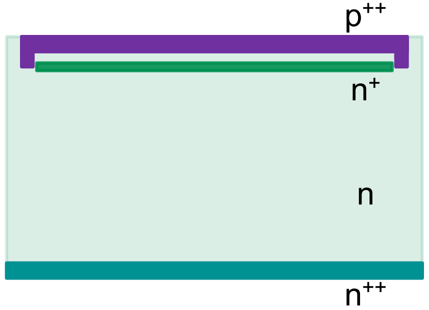
n-doped LGAD Production

A production batch is needed to study the donor removal coefficient, **c_D**

Donor removal has been studied for doping densities of $10^{12} – 10^{14}$ atoms/cm^3

We need to study donor removal in a range $10^{16} – 10^{18}$ atoms/cm^3

NB: Oxygen has for donor removal a very similar effect of Carbon to acceptor removal



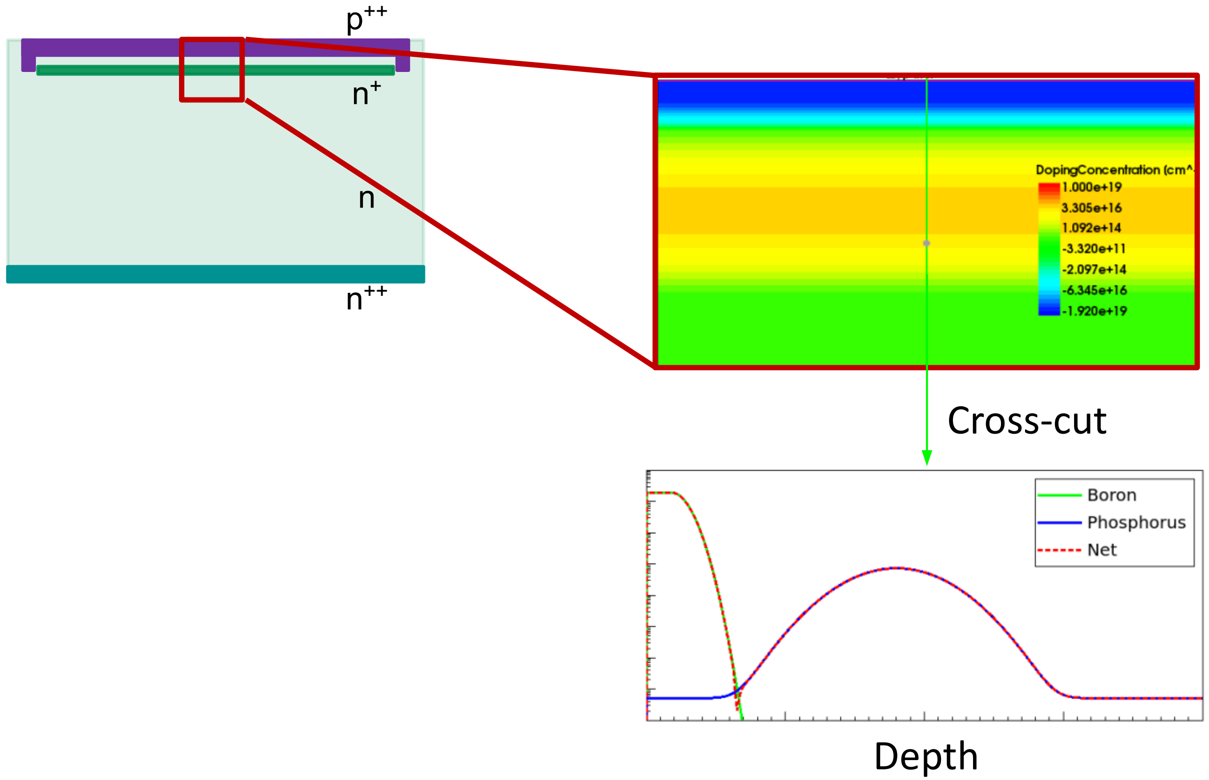
p-in-n LGAD

→ The main goal of the *p-in-n* LGAD production is to study the c_D evolution and its interplay with Oxygen co-implantation

First and second *p-in-n* LGAD (NLGAD) batches produced by CNM [link1,link2]

p-in-n LGAD – Simulation & Design

Process simulation is used to design the p^{++} electrode and the n^{+} gain implant (TCAD Silvaco)



Several short loop runs to investigate

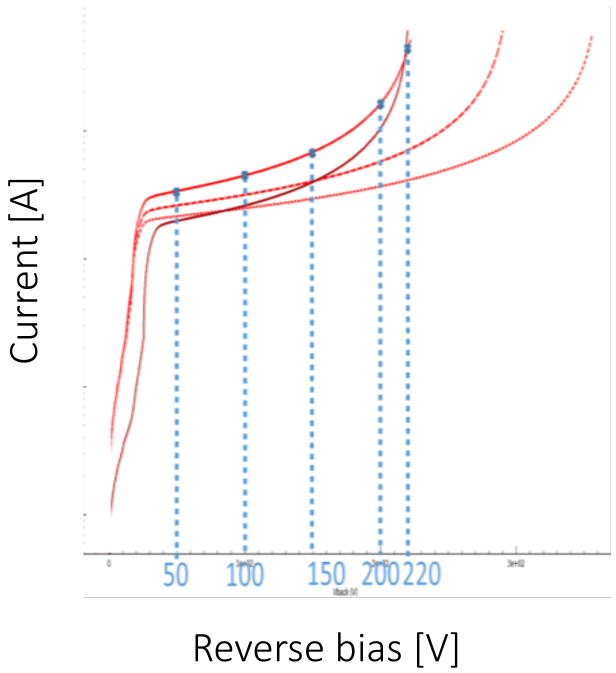
- the Boron diffusion
- the Boron peak dose
- the Phosphorus depth
- the Phosphorus dose

Two different depth of the n^{+} gain implant will be explored in the batch

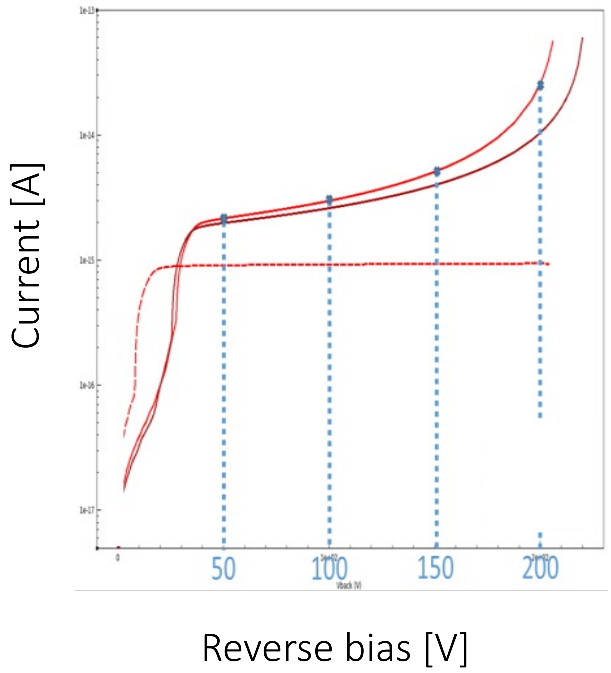
p-in-n LGAD – Simulation & Design

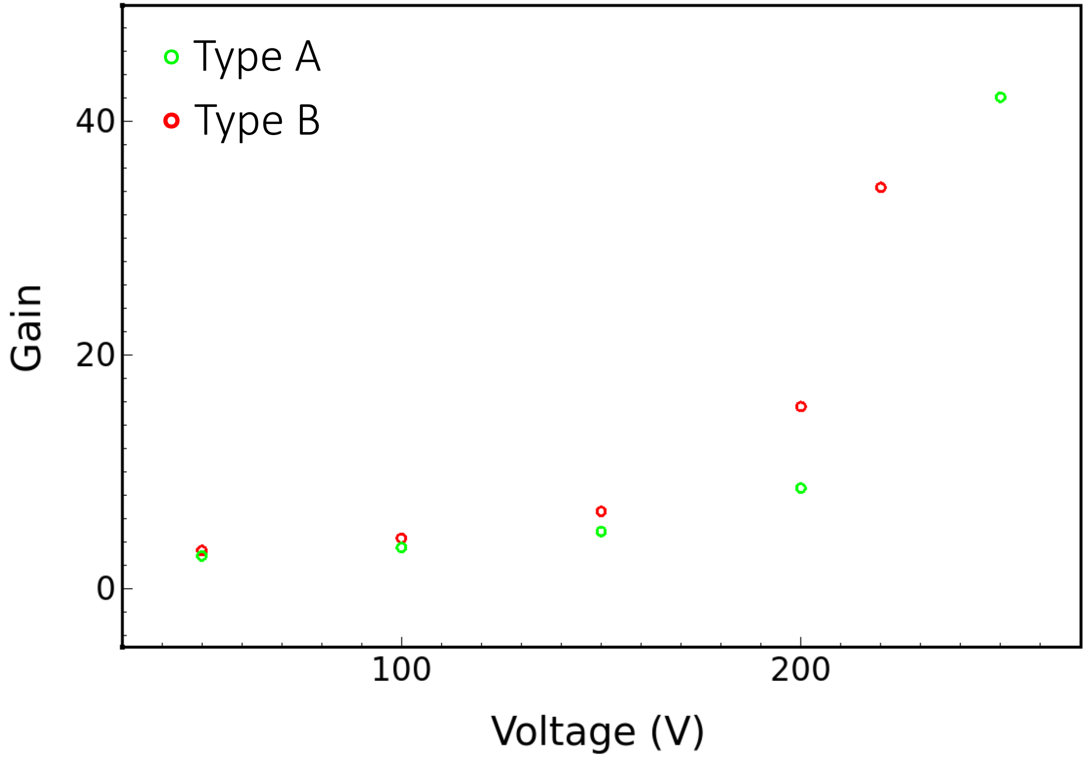
The results from the short loop runs are used as input of the device simulation with Sentaurus

Type A



Type B

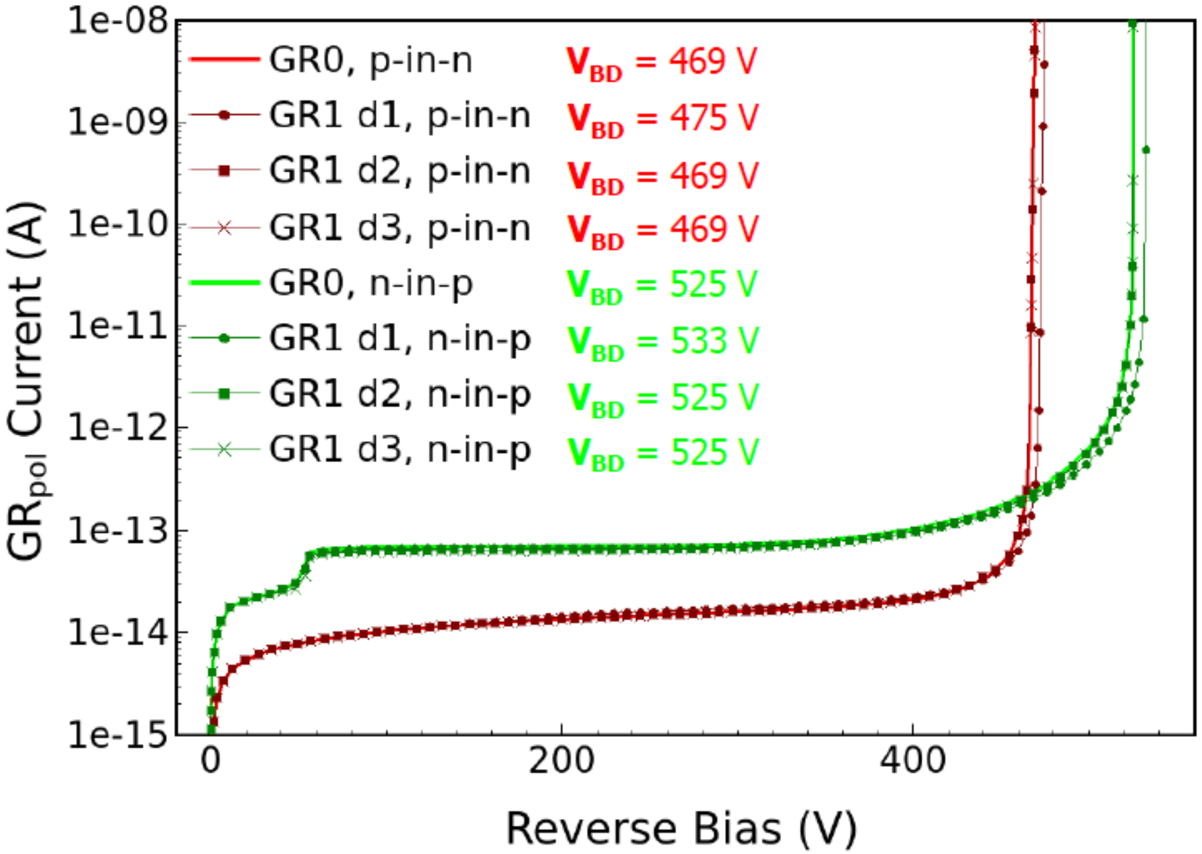


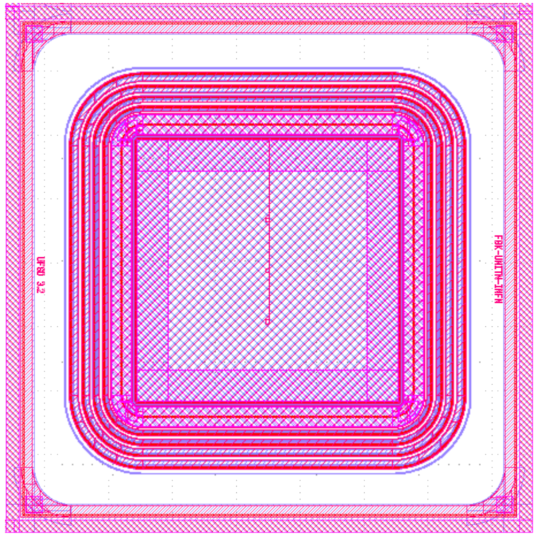


→ **Final simulation of the gain behaviour for different *n*$^+$ designs are in progress**

p-in-n LGAD – Simulation & Design

Different designs of the guard ring structures have been investigated





→ Definition of the sensor and periphery design in progress

Summary on the eXFlu-innova Activities

The eXFlu-innova activities are ongoing

- The p^+–n^+ design has been completed – Deliverable 1 🎯
- The p^+–n^+ production batch has been completed – Part of Deliverable 2 🎯
- The characterisation and testing on the p^+–n^+ sensors is almost complete 🎯
- The *n*-doped LGAD batch is about to start ⏳

→ **Small delay in the eXFlu-innova activities**

An ERC Consolidator Grant awarded to further develop compensated LGAD sensors

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

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

Thank You

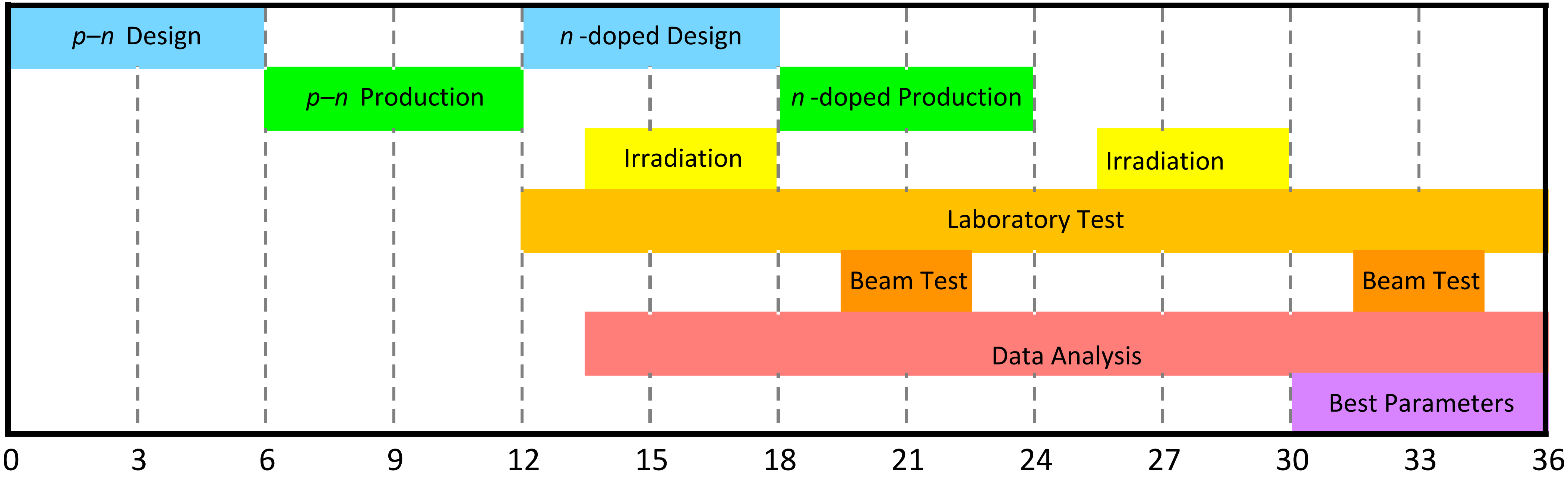
Backup

Project Activities

The activities of the proposal concentrate on the realisation of the most innovative part of our design, **the compensated gain layer**

- ▻ Two sensor productions will be performed, one to manufacture the **first compensated LGADs** and one to study the **donor removal**
- ▻ The production **process flows will be simulated**, to optimise the procedures and sequences of implantation and activation of dopants
- ▻ Both productions will be **tested before and after irradiation** to measure the initial donor removal and the performances of compensated LGADs

Project Flow



Deliverables:

1. **simulation and design** of the *p–n* compensated gain implant (M6)
2. **production** of *p–n* compensated sensors and *n*-doped sensors (M12 & M24)
3. **identifications of the best parameters** to manufacture compensated LGADs (M36)

Project Budget

The project has been funded with 140k EUR + 25%

Matching funds of 140k EUR is being provided by the Participant Institutions

INFN funding

– 60k EUR for personnel, to cover 24 months of experienced Post-Docs
  → 2 Post-Doc hired, 1 Post-Doc selection completed
– 30k EUR of consumables, to cover the cost of dopant implantation at external services
  → in progress

FBK funding

– 50k EUR for the 2 sensor production batches
  → 1 batch completed, 1 batch pending

References – Publications

[1] V. Sola et al., A compensated design of the LGAD gain layer, Nucl. Inst. Meth. A 1040 (2022) 167232, doi:10.1016/j.nima.2022.167232

[2] T. Croci et al., Development and test of innovative Low-Gain Avalanche Diodes for particle tracking in 4 dimensions, Nucl. Inst. Meth. A 1047 (2023) 167815, doi.org:10.1016/j.nima.2022.167815

[3] T. Croci et al., TCAD optimization of LGAD sensors for extremely high fluence applications, J. Instrum. 18 (2023) C01008, doi:10.1088/1748-0221/18/01/C01008

[4] A. Morozzi et al., TCAD simulations for radiation-tolerant silicon sensors, PoS 448 - The 32nd International Workshop on Vertex Detectors (VERTEX2023) - Radiation hardness and simulations doi:10.22323/1.448.0060

References – Presentations

[1] T. Croci et al., Development and test of innovative Low-Gain Avalanche Diodes for particle tracking in 4 dimensions, 15th Pisa Meeting on Advanced Detectors (2022) La Biodola, Italy – poster

[2] T. Croci et al., TCAD optimization of LGAD sensors for extremely high fluence applications, 23rd International Workshop on Radiation Imaging Detectors - IWORID (2022) Riva del Garda, Italy – poster

[3] F. Moscatelli et al., TCAD simulations of innovative Low-Gain Avalanche Diodes for particle detector design and optimization, The 31st International Workshop on Vertex Detectors (2022) Tateyama Resort Hotel, Japan – invited talk

[4] V. Sola et al., Innovations in the design of thin silicon sensors for extreme fluences, IEEE Nuclear Science Symposium (2022) Milano (Italy) – parallel talk

[5] V. Sola et al., Innovations in the design of thin silicon sensors for extreme fluences, 41st RD50 Workshop (2022) Sevilla (Spain) – plenary talk

[6] V. Sola el al., Advances in LGAD Technology for High Radiation Environments, 18th Trento Workshop on Advanced Silicon Radiation Detectors (2023) Trento (Italy) – plenary talk

[7] V. Sola et al., Thin Silicon Sensors for Precise Timing at Very High Fluences, 13th Workshop on Picosecond Timing Detectors – FAST 2023, La Biodola, Isola d'Elba (Italy) – plenary talk

[8] V. Sola et al., Characterisation of the EXFLU1 batch from FBK, 42st RD50 Workshop, Tivat (Montenegro) – plenary talk

[9] F. Moscatelli et al., Design, simulation and characterization of innovative Low-Gain Avalanche Diodes for High Radiation Environments, Workshop on Innovative Detector Technologies and Methods – IDTM, Lisbon (Portugal) – plenary talk

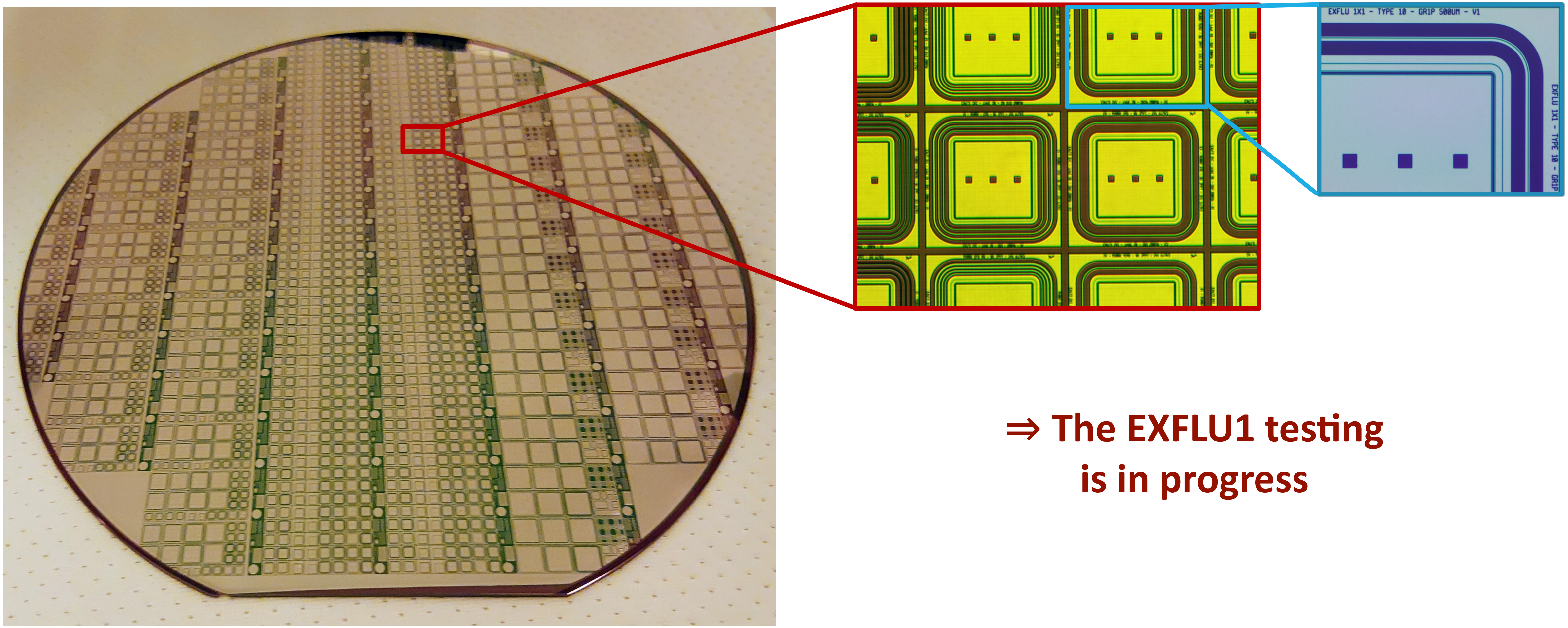
[10] A. Morozzi et al., TCAD simulations for rad-hard sensors, 32nd International Workshop on Vertex Detectors – VERTEX 2023, Sestri Levante (Italy) – plenary talk

[11] V. Sola et al., Characterisation of the first compensated LGADs from FBK before and after irradiation, 13th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors – HSTD13, Vancouver (Canada) – plenary talk

[12] V. Sola et al., Compensated LGADs as a pathway to the extreme fluences, 19th TREDI Workshop on Advanced Silicon Radiation Detectors, Torino (Italy) – plenary talk

The EXFLU1 Wafers

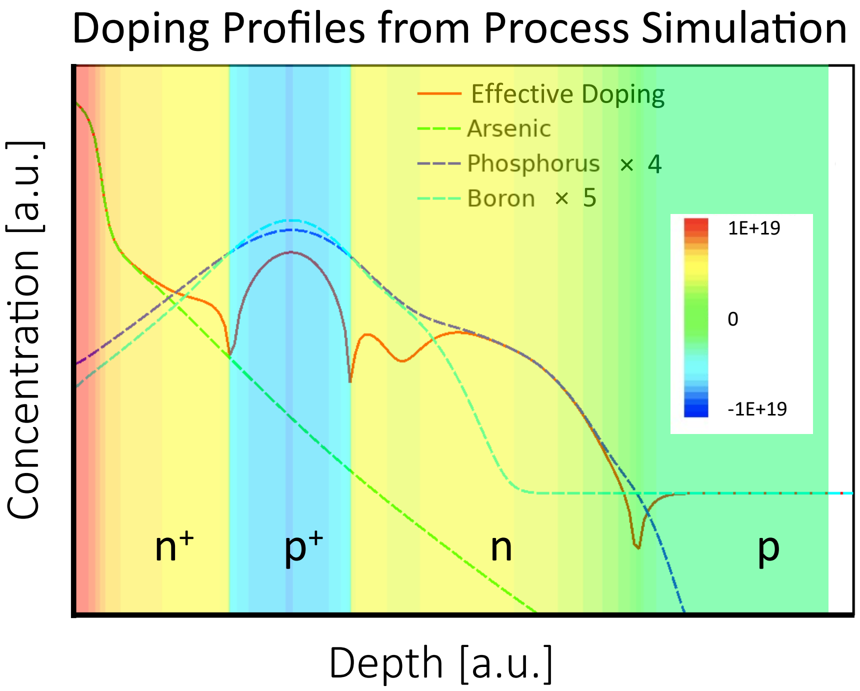
6” Wafer

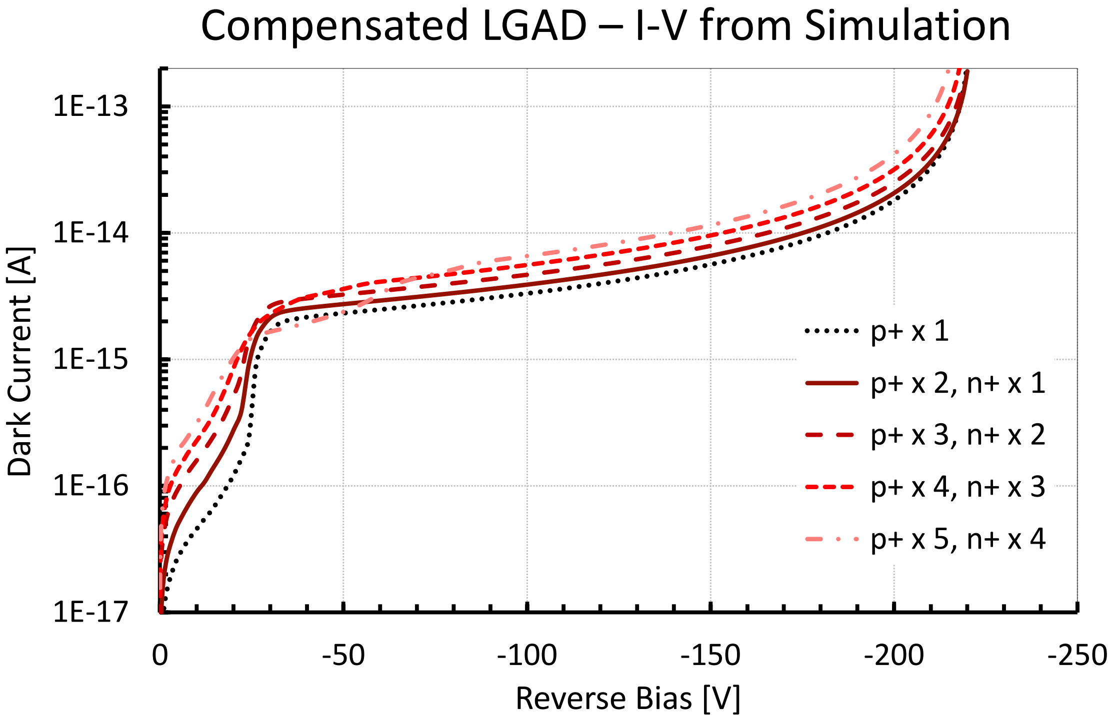


⇒ The EXFLU1 testing is in progress

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

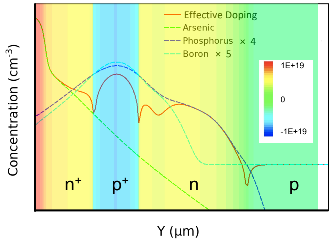
→ The simulation of the electrostatic behaviour shows that it is possible to reach similar multiplication for different initial concentrations of p^+ and n^+ dopants

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 ⇒ unchanged gain with irradiation
   ⟶ **This is the best possible outcome**
2. **$c_A > c_D$**
   effective doping disappearance is slower than in the standard design
   ⟶ **Co-implantation of Carbon** atoms mitigates the removal of p^+-doping
3. **$c_A < c_D$**
   n^+-atoms removal is faster ⇒ increase of the gain with irradiation
   ⟶ **Co-implantation of Oxygen** atoms might mitigate the removal of n^+-doping

Compensated LGAD – I-V

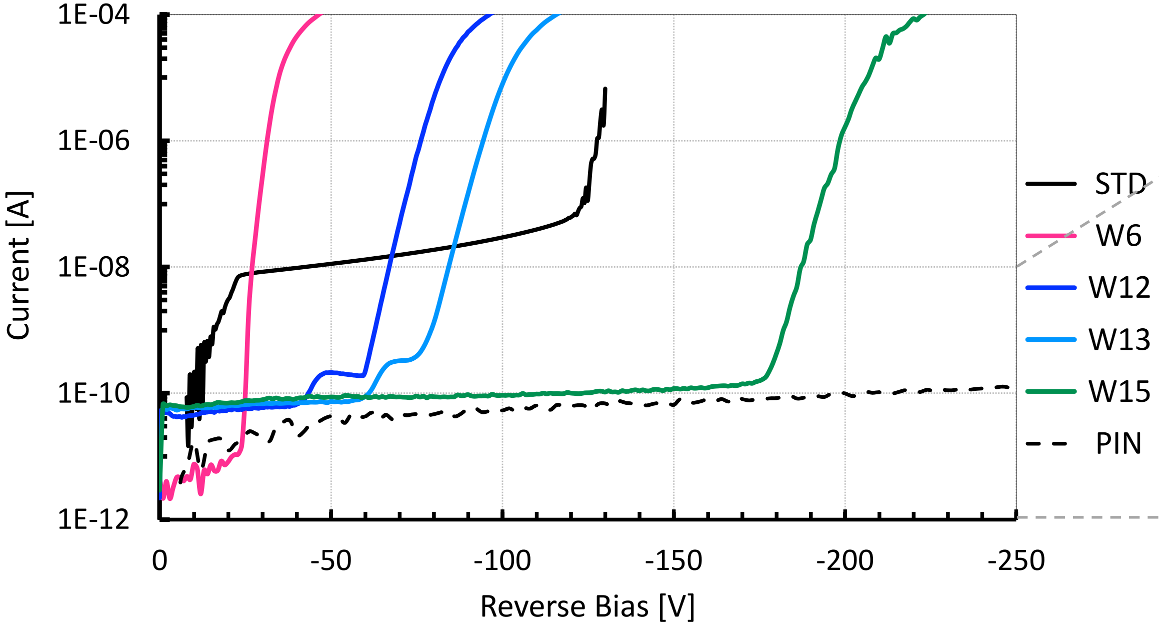


Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
12	30	3 b	2	
13	30	3 b	2	1.0
15	30	5 a	4	

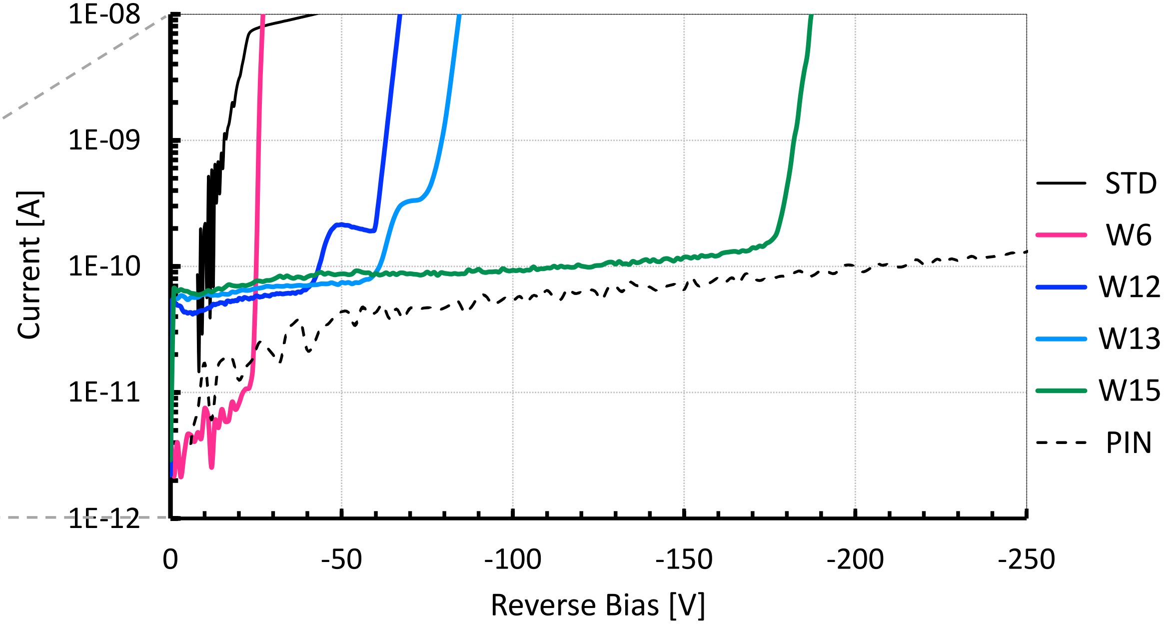
→ **2 – 1 is more doped than standard LGAD**

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

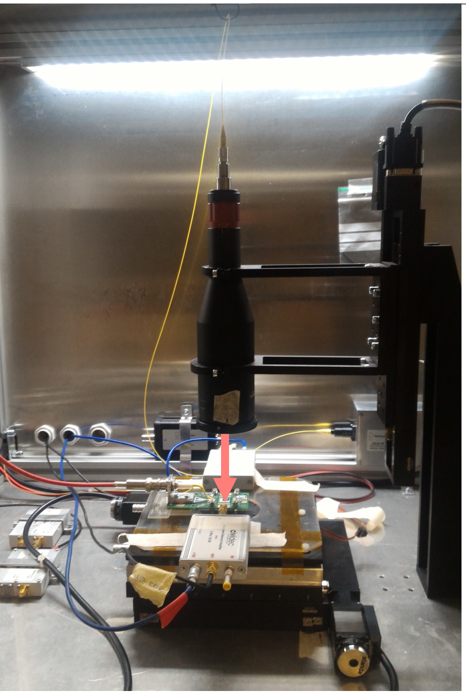
EXFLU1 – Compensated LGAD – I-V



EXFLU1 – Compensated LGAD – I-V – ZOOM



Compensated LGAD – Waveforms from TCT



TCT Setup from Particulars

Pico-second IR laser at 1064 nm

Laser spot diameter ~ 10 µm

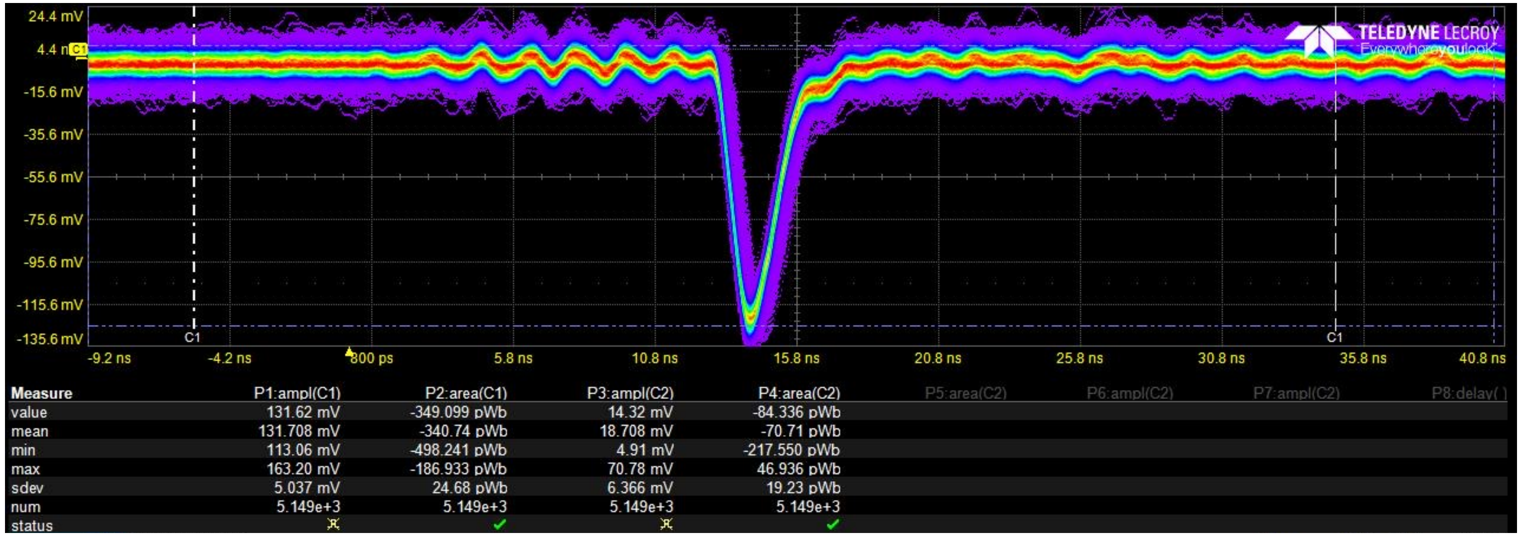
Laser intensity ~ 80 MIPs

Cividec Broadband Amplifier (40dB)

Oscilloscope LeCroy 640Zi

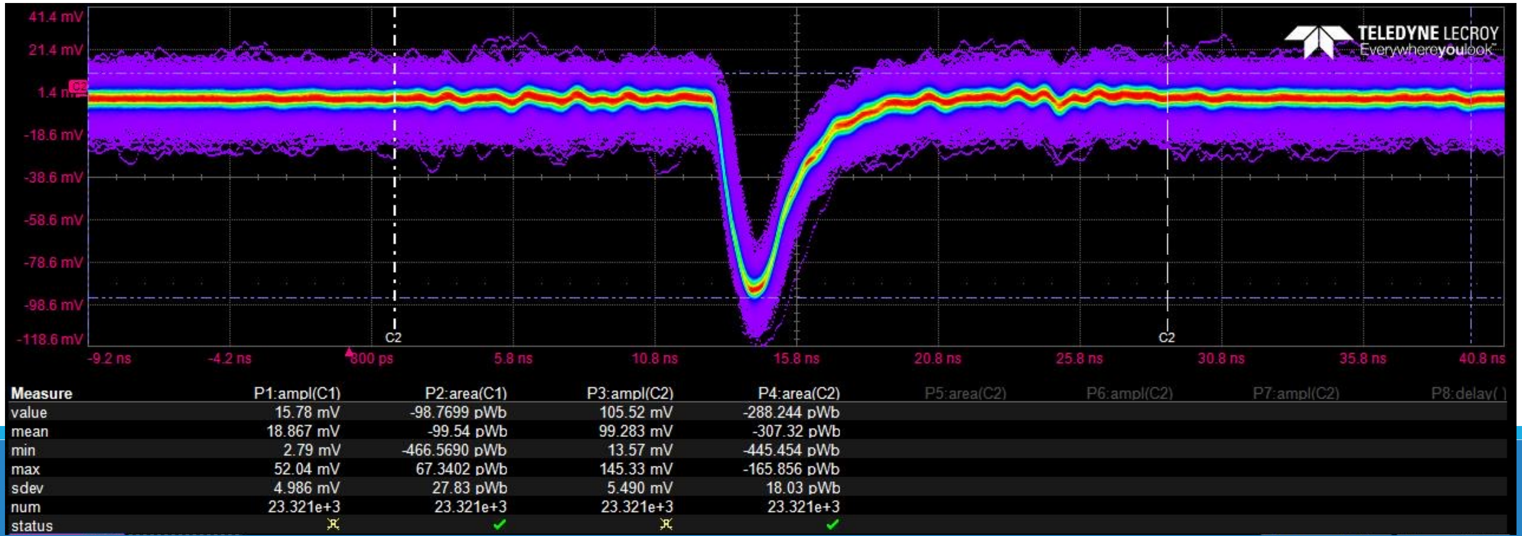
Room temperature

Waveforms from an LGAD and a PIN of W15 (5–4) operated at V_{bias} = 150 V



Measure	P1:ampl(C1)	P2:area(C1)	P3:ampl(C2)	P4:area(C2)	P5:area(C2)	P6:ampl(C2)	P7:ampl(C2)	P8:delay( )
value	131.62 mV	-349.099 pWb	14.32 mV	-84.336 pWb				
mean	131.708 mV	-340.74 pWb	18.708 mV	-70.71 pWb				
min	113.06 mV	-498.241 pWb	4.91 mV	-217.550 pWb				
max	163.20 mV	-186.933 pWb	70.78 mV	46.936 pWb				
sdev	5.037 mV	24.68 pWb	6.366 mV	19.23 pWb				
num	5.149e+3	5.149e+3	5.149e+3	5.149e+3				
status	⚠	✓	⚠	✓				

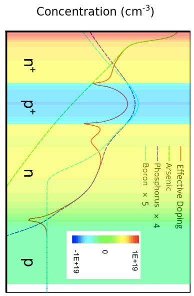
W15
LGAD
V_{bias} = 150V



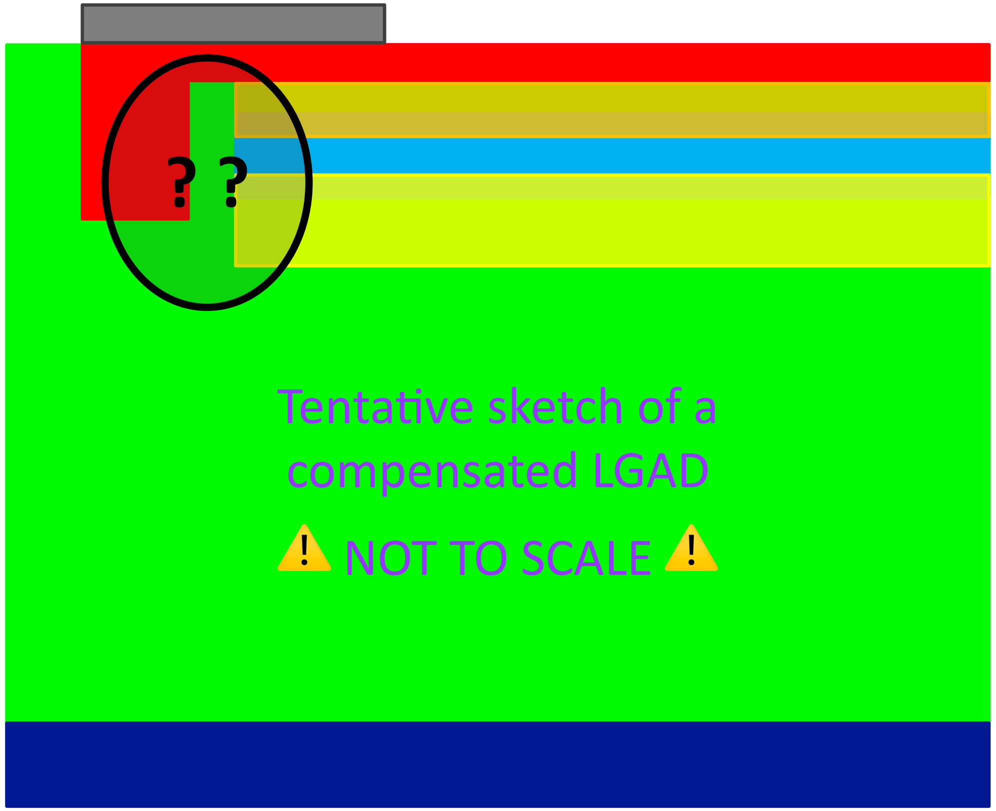
Measure	P1:ampl(C1)	P2:area(C1)	P3:ampl(C2)	P4:area(C2)	P5:area(C2)	P6:ampl(C2)	P7:ampl(C2)	P8:delay( )
value	15.78 mV	-98.7699 pWb	105.52 mV	-288.244 pWb				
mean	18.867 mV	-99.54 pWb	99.283 mV	-307.32 pWb				
min	2.79 mV	-466.5690 pWb	13.57 mV	-445.454 pWb				
max	52.04 mV	67.3402 pWb	145.33 mV	-165.856 pWb				
sdev	4.986 mV	27.83 pWb	5.490 mV	18.03 pWb				
num	23.321e+3	23.321e+3	23.321e+3	23.321e+3				
status	⚠	✓	⚠	✓				

W15
PIN
V_{bias} = 150V

Compensated LGAD – 2D Scan with IR Laser



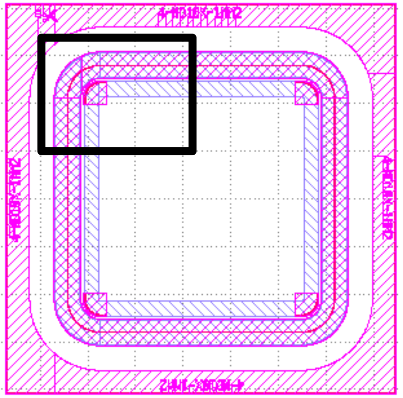
Ongoing characterisation: investigate with IR laser the edge of the compensated gain implants



Tentative sketch of a compensated LGAD

⚠ NOT TO SCALE ⚠

Scan surface



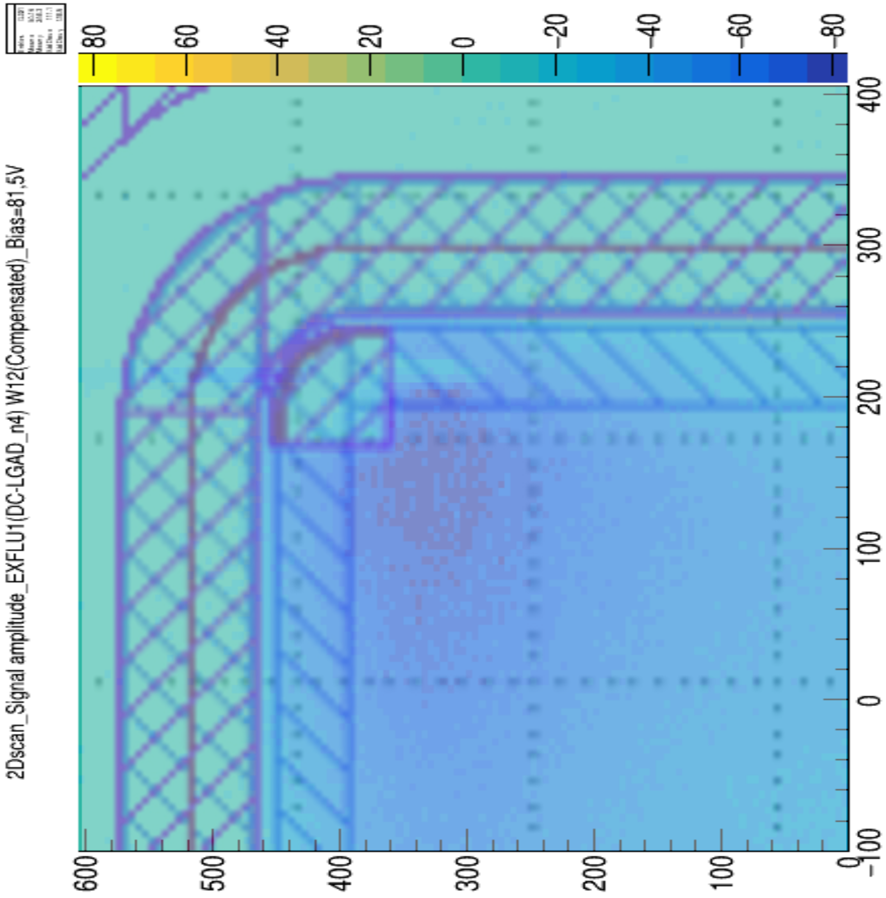
TCT scan with IR laser

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

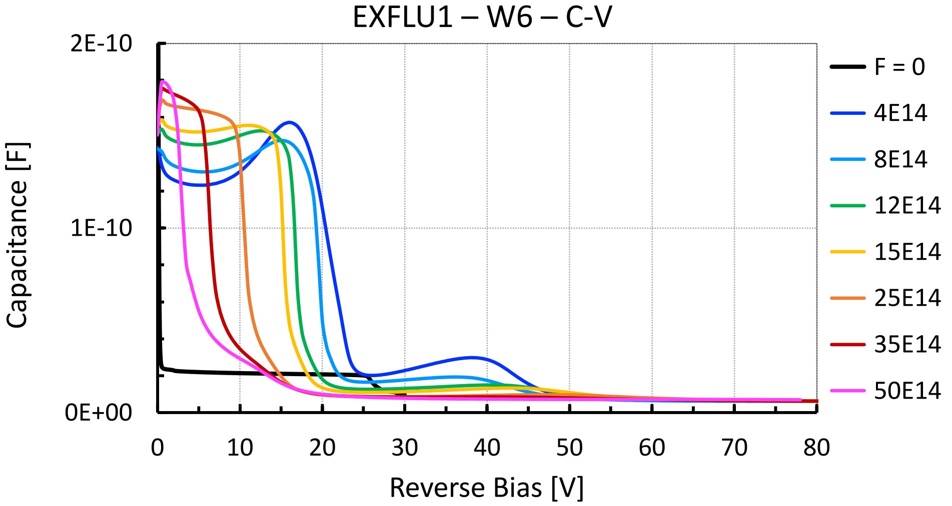
C-V from Compensated LGAD – Irradiated

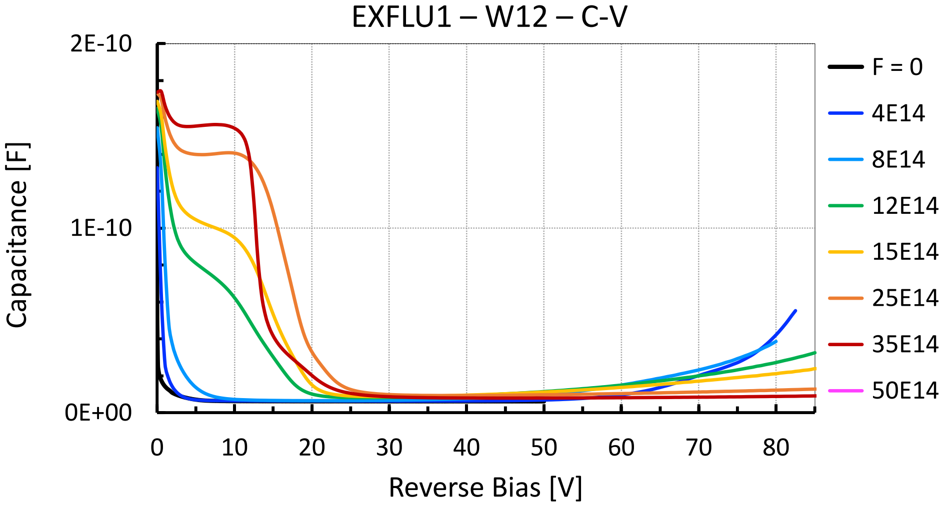
$[\Phi] = n_{eq}/cm^2$

T = + 20°C

f = 2k Hz

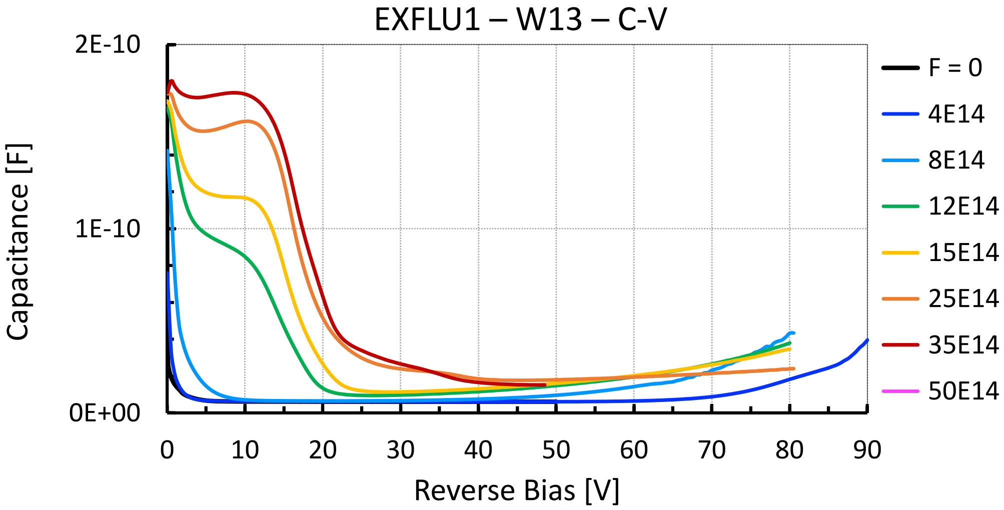
W6
2 – 1

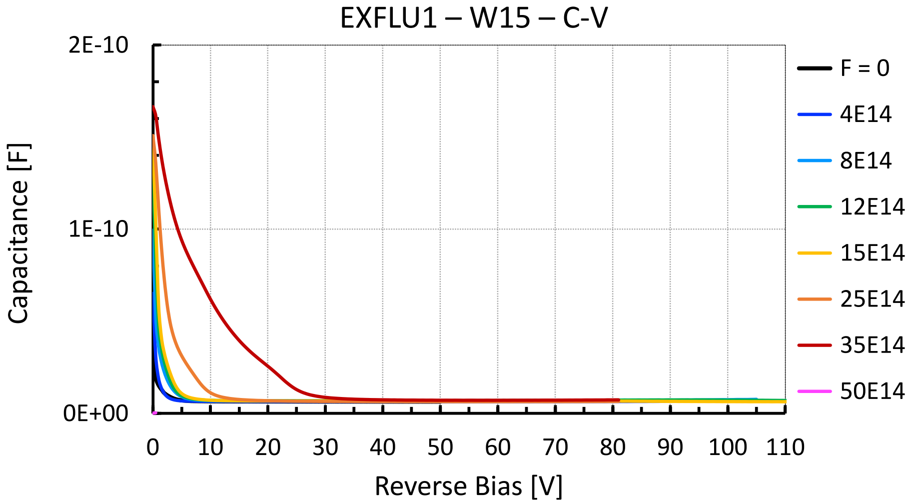




W12
3 – 2

W13
3 – 2 + C





W15
5 – 4

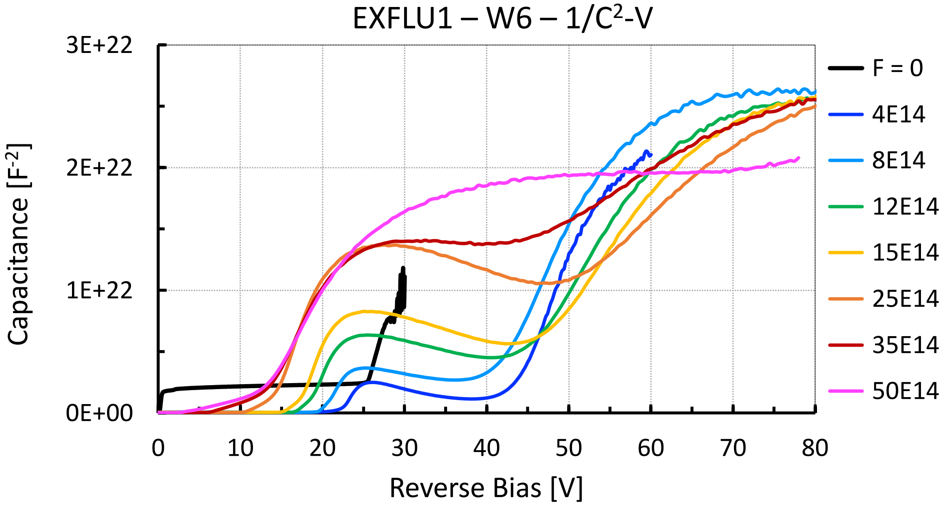
1/C^2-V from Compensated LGAD – Irradiated

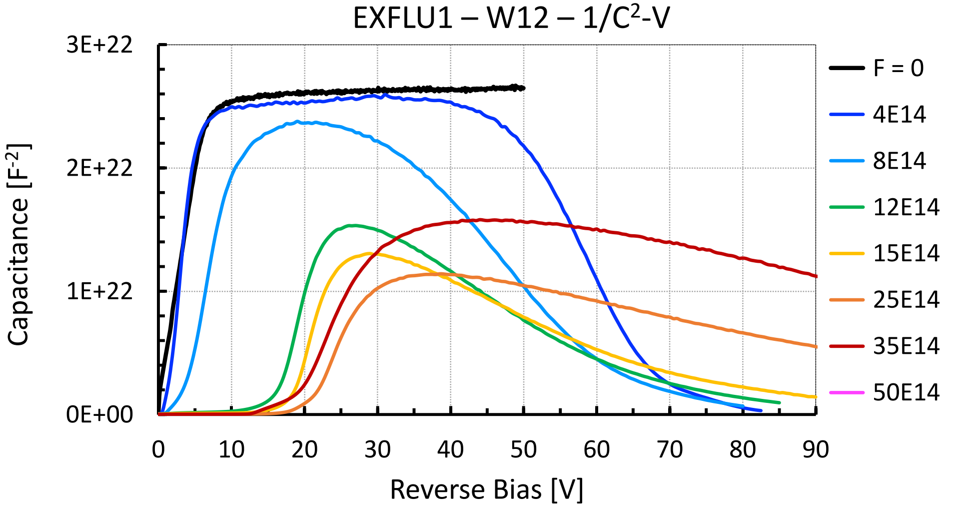
$[\Phi] = n_{eq}/cm^2$

T = + 20°C

f = 2k Hz

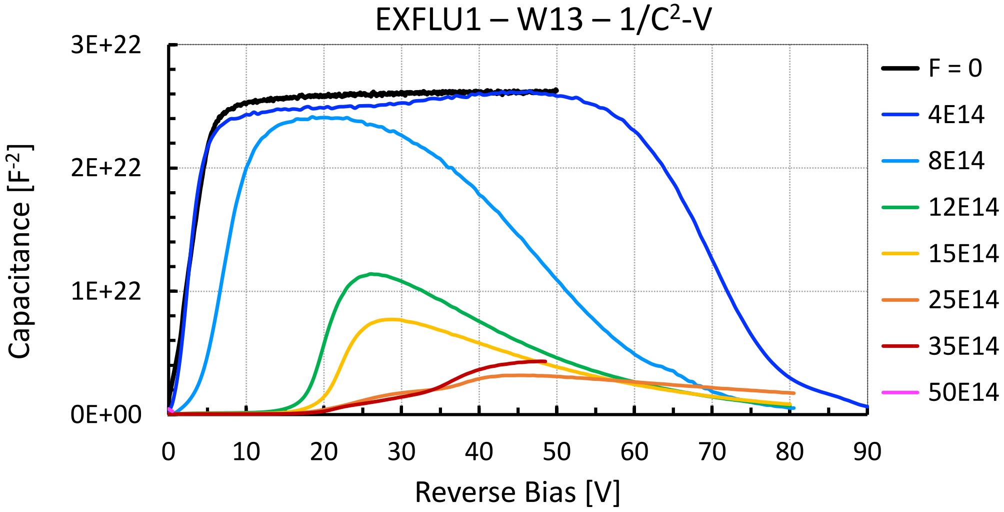
W6
2 – 1

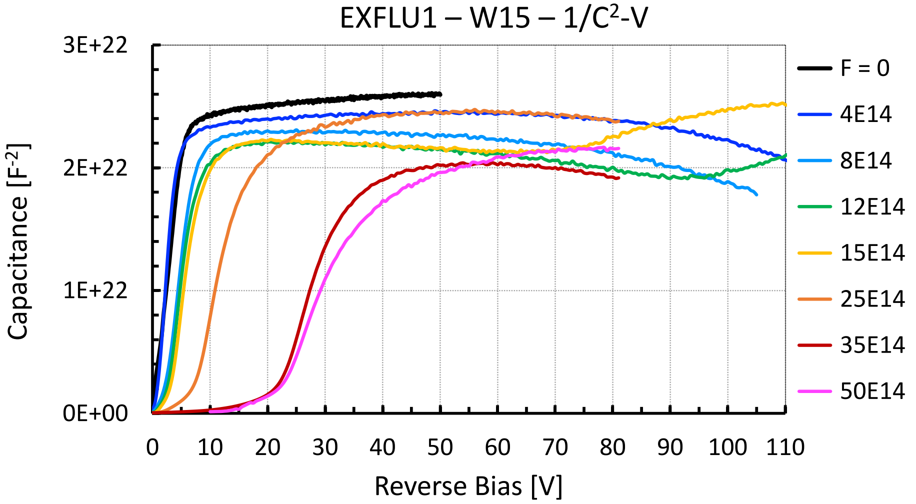

EXFLU1 – W6 – 1/C^2-V


EXFLU1 – W12 – 1/C^2-V

W12
3 – 2

W13
3 – 2 + C


EXFLU1 – W13 – 1/C^2-V


EXFLU1 – W15 – 1/C^2-V

W15
5 – 4

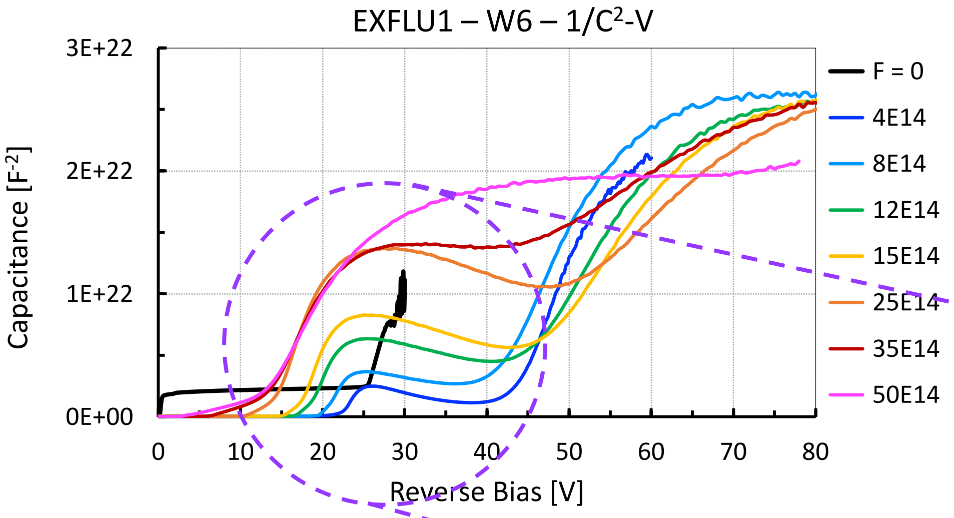
Doping Profile of W6

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

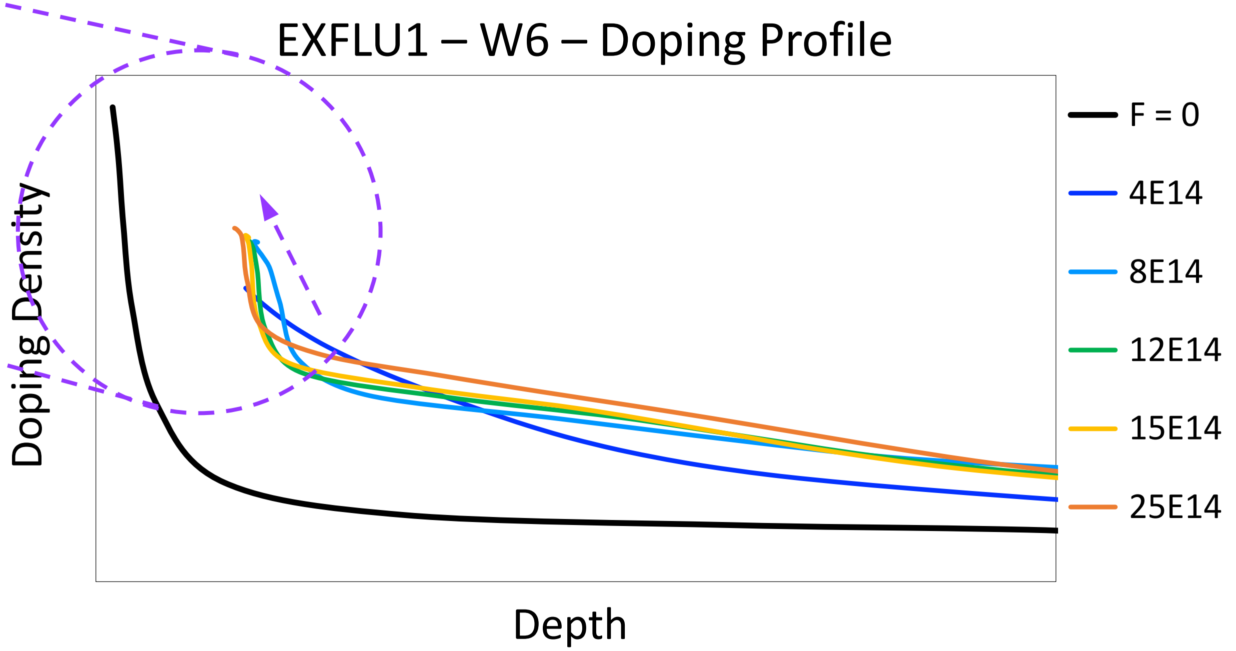
T = + 20°C

f = 2k Hz

W6
2 – 1



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

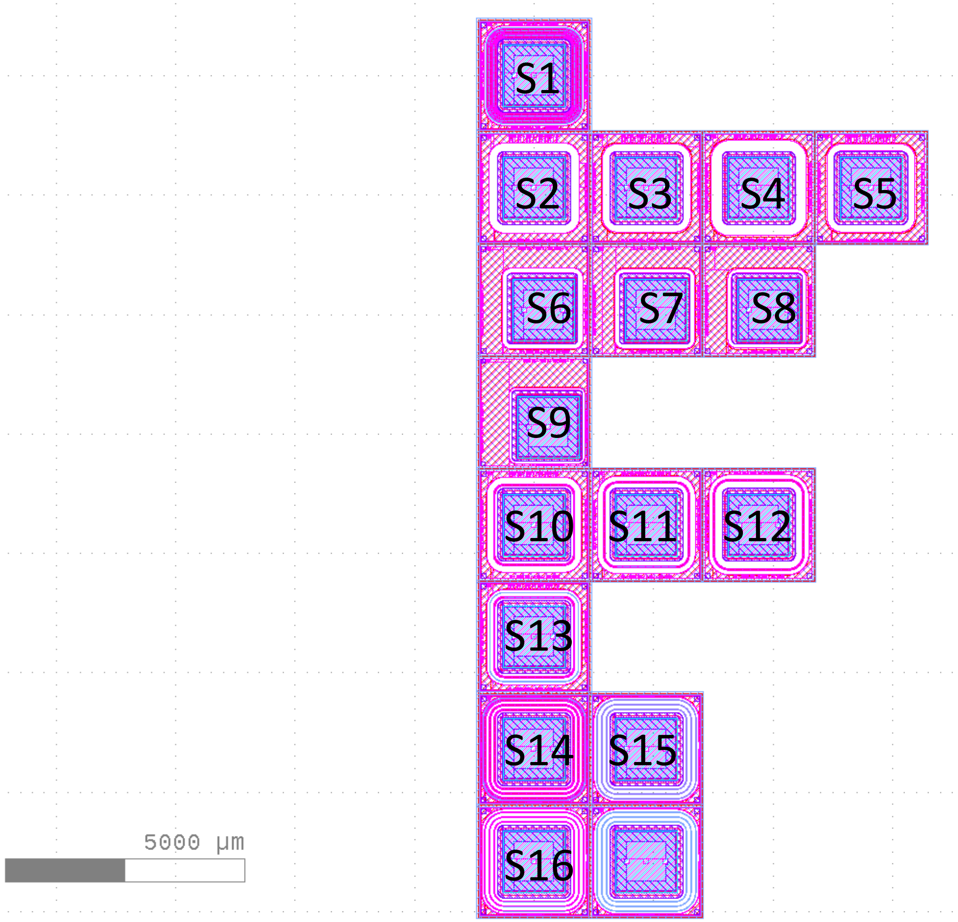


Gain implant profile appears
more and more evident
as the fluence increases

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

Guard Ring Design Optimised for Thin Sensors

16 different guard rings have been designed, optimised for thin substrates and extreme fluences

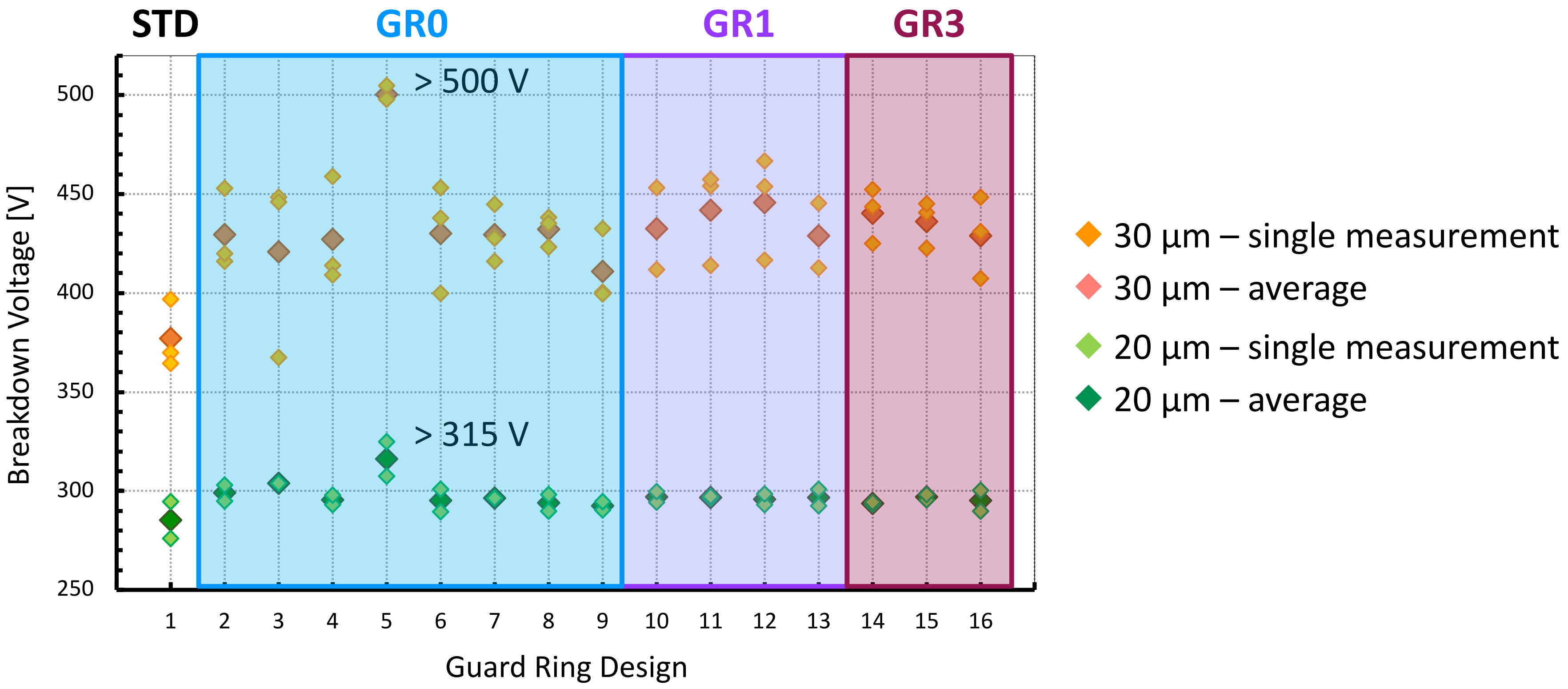


3 different guard ring strategies:

- ▻ 0 GR floating, varying the edge size
  - – different size of the ‘empty’ region
  - – different size of the edge region: 500, 300 & 200 µm
- ▻ 1 GR floating, varying the GR position
- ▻ 3 GR floating with different designs

[S1 is the standard design used in previous UFSD batches]

Optimised Guard Ring Design – Summary



→ 30 µm thick sensors show a bigger variation in the breakdown voltage wrt 20 µm thick ones

→ All guard ring designs are working properly and ensure good operation of the sensors

→ An extensive irradiation campaign will be performed to study the radiation tolerance of each design

Evolution of the Donor Removal

A further production batch is needed to study the donor removal

Evolution of donor density: $\mathbf{N_{eff}(\Phi) = N_D(0)e^{-c_D \cdot \Phi} - g_c \cdot \Phi}$

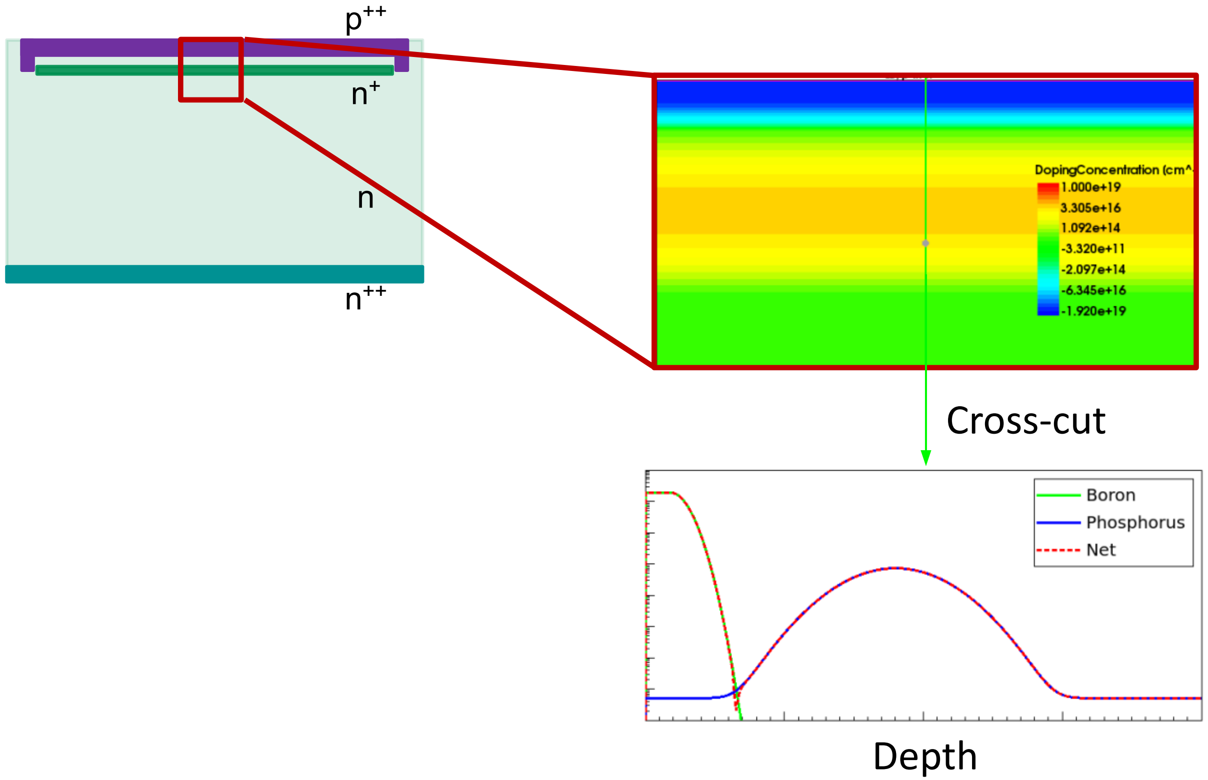
State-of-the-art [`M.Moll et al., doi:10.1016/S0168-9002(99)00842-6`]

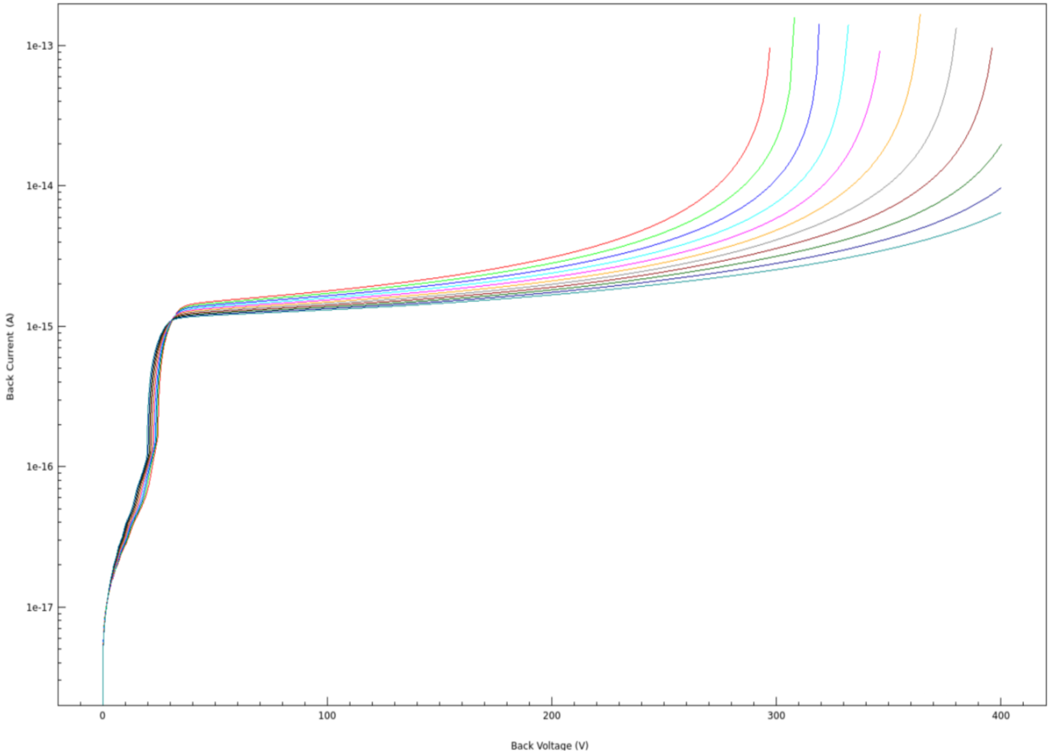
We need to study donor removal in a range $10^{16} – 10^{18}$ atoms/cm^3

NB: Oxygen has for donor removal a very similar effect of Carbon to acceptor removal

p-in-n LGAD – Simulation & Design

Process simulation is used to design the p^{++} electrode with Boron (TCAD Silvaco)





→ The simulation of the electrostatic behaviour shows good performances of the I-V characteristics for different p^{++} designs (TCAD Synopsys)

Involved Partners – INFN TO

▻ The Torino Unit of the Istituto Nazionale di Fisica Nucleare (INFN) will
  - ⟶ coordinate the project and organise the activities
  - ⟶ follow the sensor design and production processes
  - ⟶ characterisation and test of the sensors
  - ⟶ organise of the irradiation campaign
  - ⟶ provide the input to the simulation and modelling process

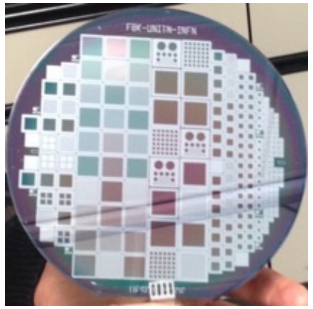
Laboratory of Innovative Silicon Sensors

⇒ Well-established tradition in the development of Low-Gain Avalanche Diodes since the early stage

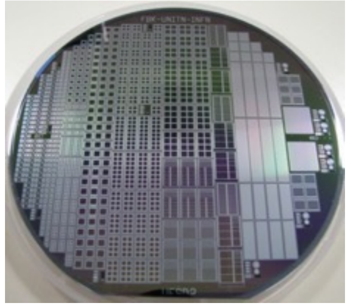
Involved Partners – FBK

- Fondazione Bruno Kessler (FBK) will
  - → define the optimal process flow for the two sensor production
  - → take care of the **sensors fabrication process**
  - → provide the first sensor characterisation at the foundry

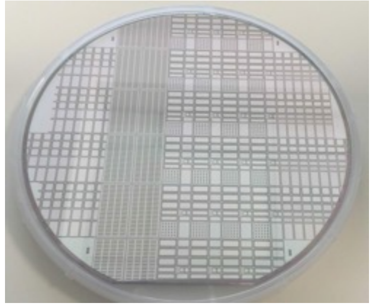
Previous LGAD productions at FBK (not-exhaustive list)



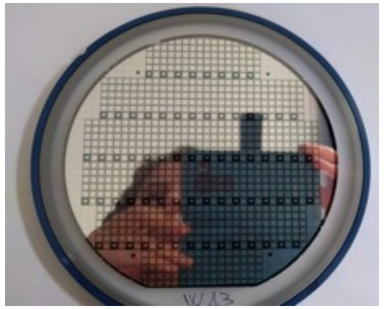
UFSD1
2016



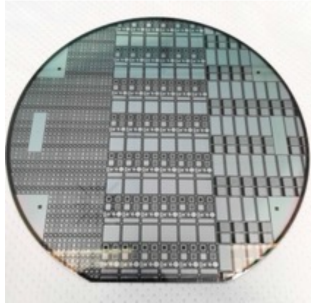
UFSD2
2017



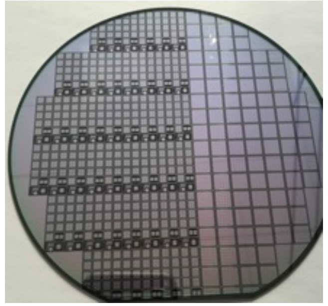
UFSD3
2018



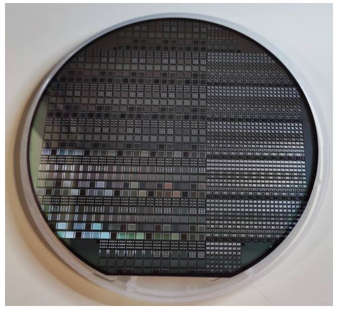
UFSD3.1
2019



RSD1
2019



UFSD3.2 + EXFLU0
2020



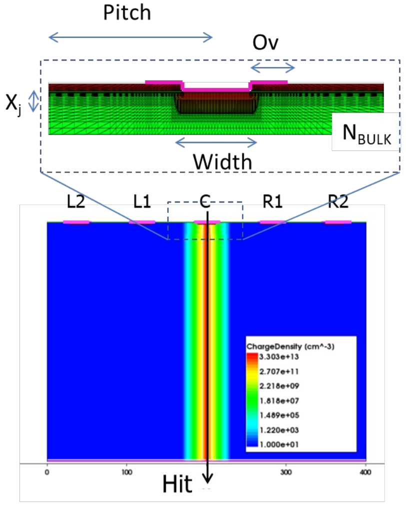
TI–LGAD
2021

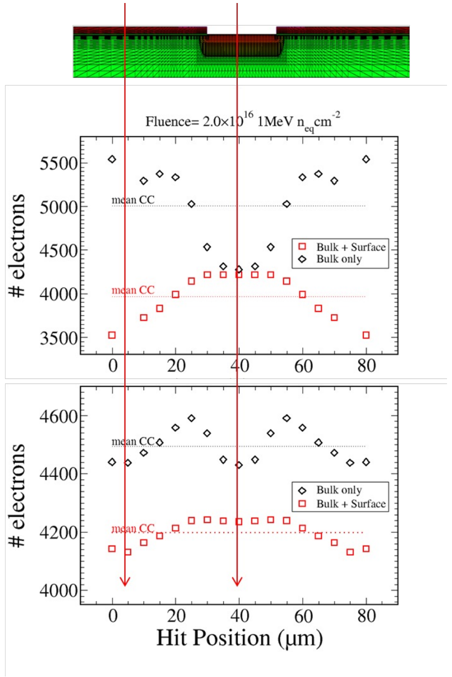
⇒ FBK will bring its strong expertise in the design and production of silicon sensors with internal gain, now considered at the state-of-the-art by the scientific community.

Involved Partners – INFN Pg

▻ The Perugia Unit of the Istituto Nazionale di Fisica Nucleare (INFN) will
- ⟶ provide simulation of the sensor behaviour to drive the production processes
- ⟶ participate to the sensor characterisation and testing
- ⟶ implement the observations into the model
- ⟶ extend the sensor modelling to unexplored regions of fluence

MPI TS2000 SE
Semi-automatic probe station
Triaxial thermal chuck -60°C ÷ +200°C





⇒ INFN Pg contribute to the project bringing its experience in the interpretation and modelling of silicon damage through the development and application of Technology CAD tools

Possible Fields of Interest

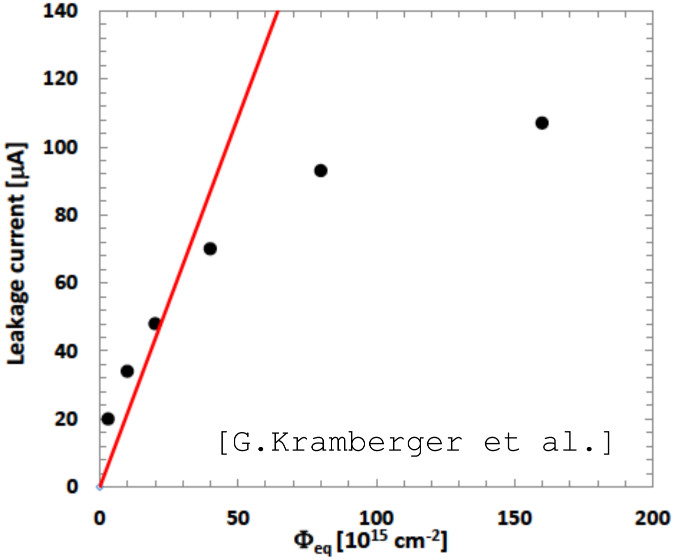
▻ **Silicon-based tracker detectors at future high-energy and high-intensity hadron colliders**, where the expected radiation budget at those machines is above 1E16 cm^{-2} in the outermost part of the tracking region and up to 1E18 cm^{-2} close to the interaction point.

▻ **Beam monitor for particle therapy facility**, as cancer treatment effectiveness strongly relates to the accuracy of real-time monitoring of the beam intensity and profile to optimise the dose delivery to the cancer tissue, the patient safety, and the operation of the accelerating machine. Particle therapy will significantly benefit from silicon-based monitors that can operate for about one year of patient's treatments (~ 1E17 cm^{-2}) without being replaced.

▻ **Monitors at the thermonuclear fusion reactors under development**. In such an environment, with high neutron and g fluxes, X-ray monitors are crucial to ensure safe operations, control of the nuclear plasma, and precise evaluation of physics phenomena.

Saturation of Radiation Damage Effects

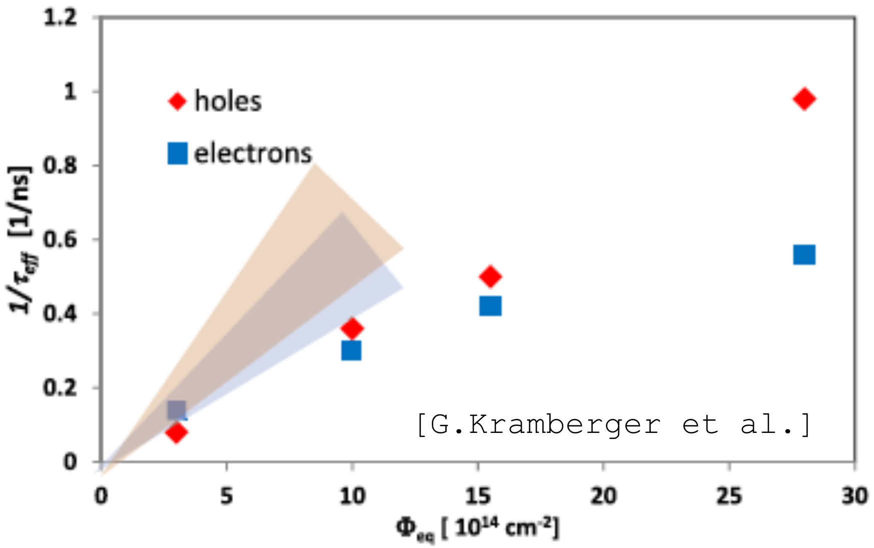
At fluences above $5 \cdot 10^{15}$ cm^{-2} → **Saturation of radiation effects observed**



Leakage current saturation

$I = \alpha V \Phi$

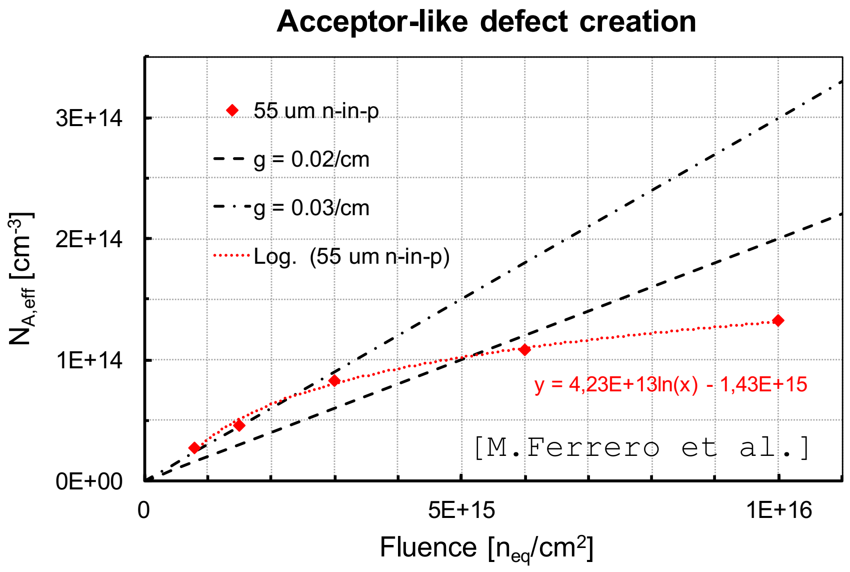
α from linear to logarithmic



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

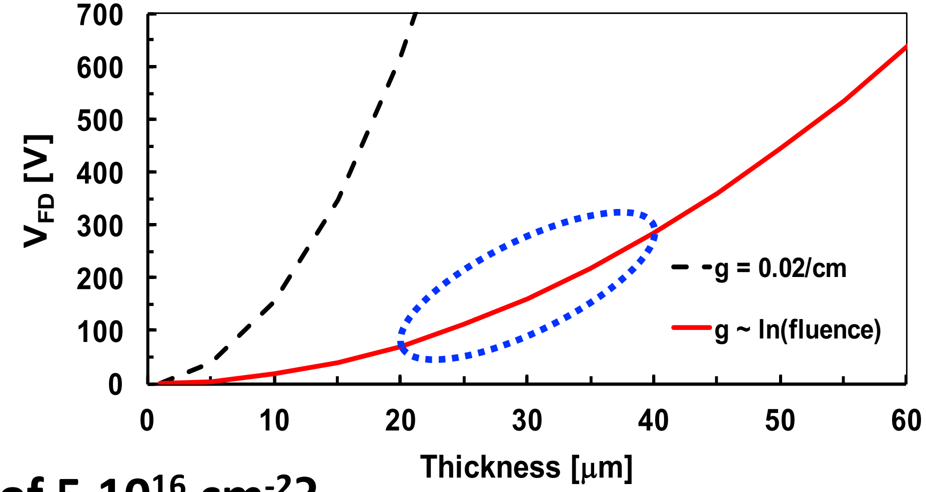
Silicon detectors irradiated at fluences $10^{16} - 10^{17}$ cm^{-2} do not behave as expected → They behave better

Thin Substrates

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

Saturation **Reduce thickness**

At high fluences, only thin substrates can be fully depleted



Full depletion voltage at $\Phi = 10^{17}\ n_{eq}/cm^2$

What does it happen to a 25 μm sensor after a fluence of $5\cdot10^{16}$ cm^{-2}?

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

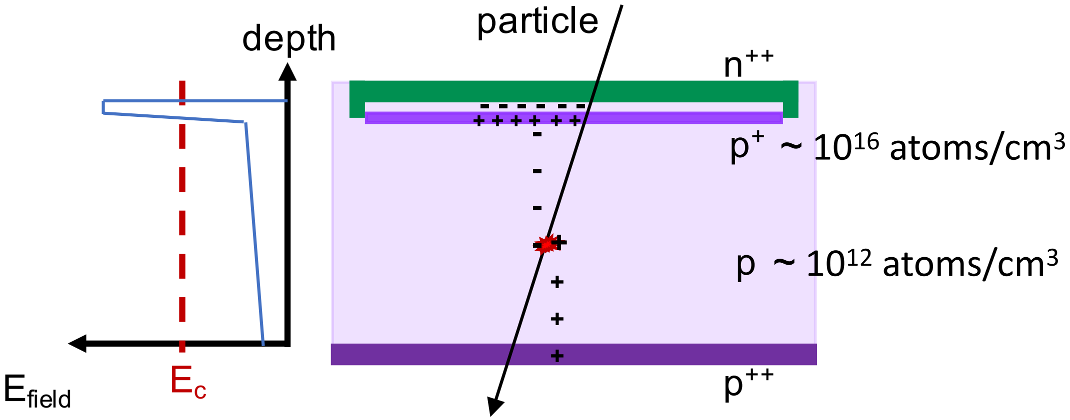
However: **charge deposited by a MIP ~ 0.25 fC**

→ 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

Low-Gain Avalanche Diodes – LGADs



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]`

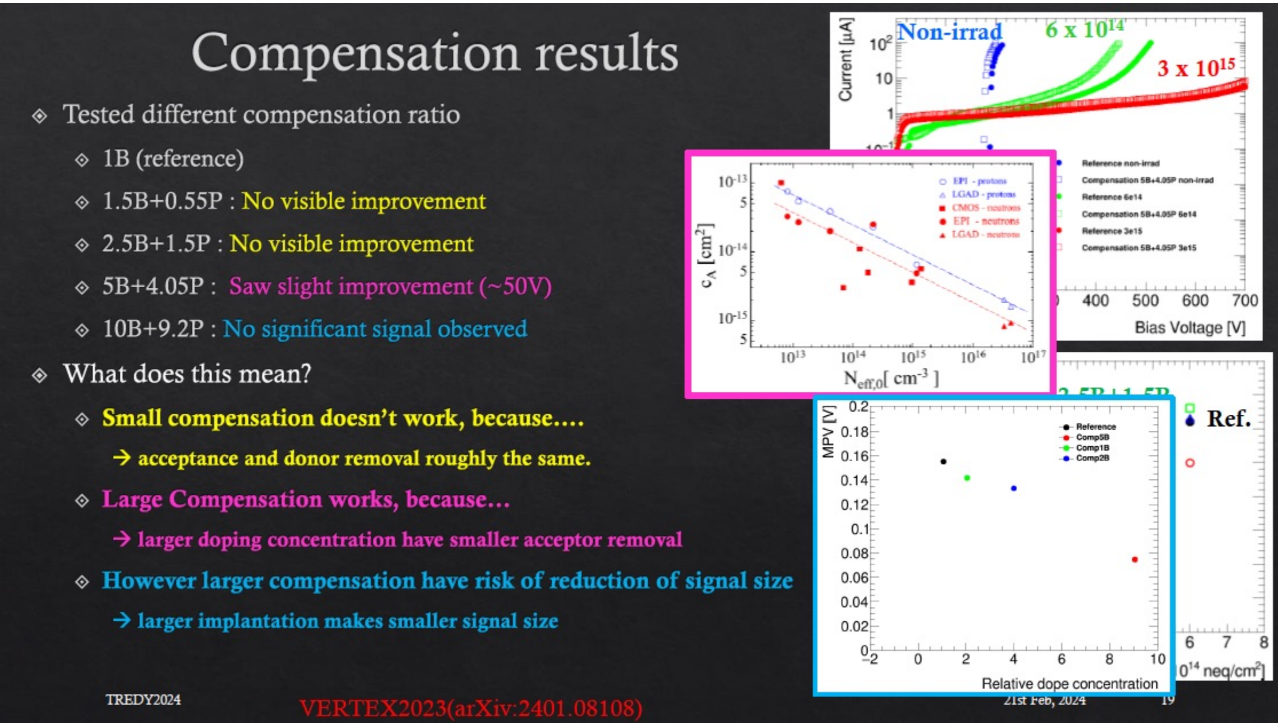
Low-Gain Avalanche Diodes (LGADs) provide a controlled internal multiplication of signal

→ E_{field} above E_c for short distance well controlled by V_{bias}

⇒ **Need a gain of at least 5 – 10**
to efficiently record a hit

Compensated LGAD produced by HPK

Presented by K. Nakamura at TREDI2024 [link]



Compensation results

- Tested different compensation ratio
  - 1B (reference)
  - 1.5B+0.55P : No visible improvement
  - 2.5B+1.5P : No visible improvement
  - 5B+4.05P : Saw slight improvement (~50V)
  - 10B+9.2P : No significant signal observed
- What does this mean?
  - **Small compensation doesn't work, because….**
    - **→ acceptance and donor removal roughly the same.**
  - **Large Compensation works, because…**
    - **→ larger doping concentration have smaller acceptor removal**
  - **However larger compensation have risk of reduction of signal size**
    - **→ larger implantation makes smaller signal size**

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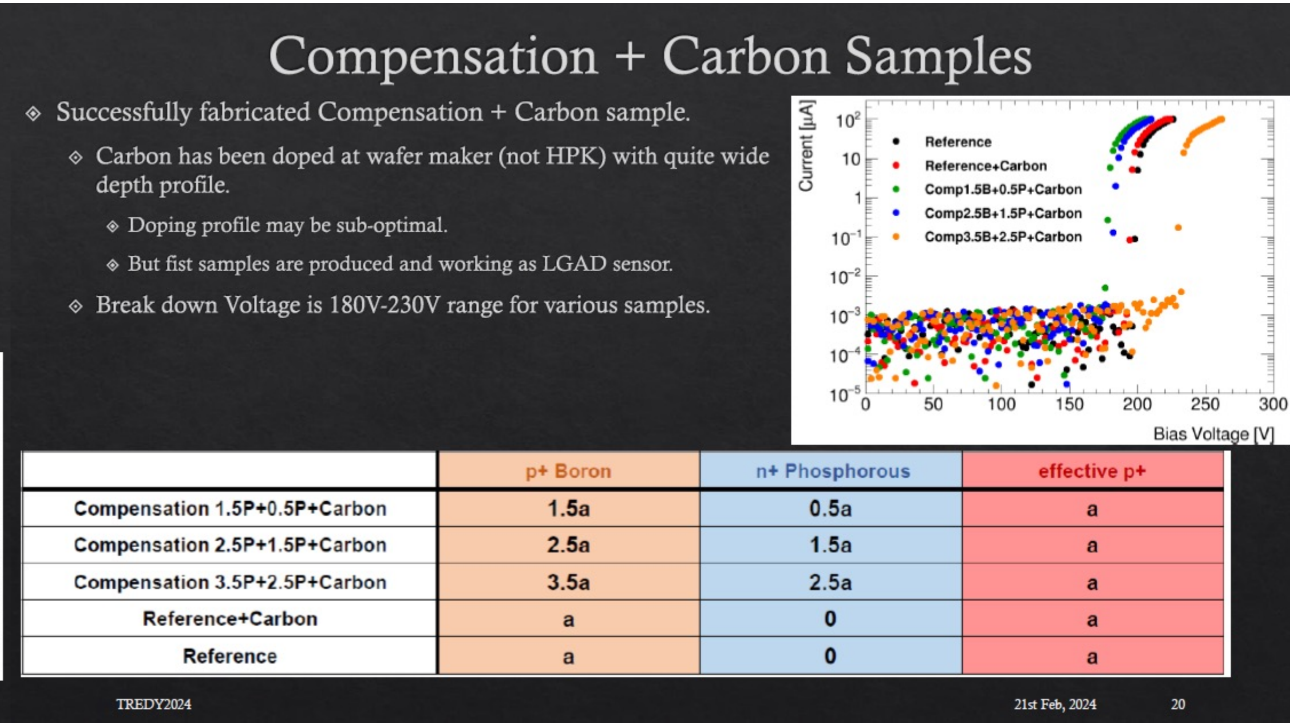
VERTEX2023(arXiv:2401.08108)

21st Feb, 2024 19



Compensation + Carbon Samples

- Successfully fabricated Compensation + Carbon sample.
  - Carbon has been doped at wafer maker (not HPK) with quite wide depth profile.
    - Doping profile may be sub-optimal.
    - But fist samples are produced and working as LGAD sensor.
- Break down Voltage is 180V-230V range for various samples.

	p+ Boron	n+ Phosphorous	effective p+
Compensation 1.5P+0.5P+Carbon	1.5a	0.5a	a
Compensation 2.5P+1.5P+Carbon	2.5a	1.5a	a
Compensation 3.5P+2.5P+Carbon	3.5a	2.5a	a
Reference+Carbon	a	0	a
Reference	a	0	a

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21st Feb, 2024 20

Participation to an RD50 Project

Defect engineering in PAD diodes mimicking the gain layer in LGADs

PI: Ioana Pintilie (Bucharest, Nat. Inst. Mat. Sci.)
Paticipants: Michael Moll (CERN), Kevin Lauer (CiS), Gregor Kramberger (JSI),
Eckhart Fretwurst (Hamburg University), Valentina Sola (INFN-Torino),
and Tomas Ceponis (Vilnius University)

‘The proposed project is focusing on the acceptor removal process (ARP) in the irradiated gain layer of LGAD sensors, aiming to understand it and parametrize it for various content of B, C and O impurities and irradiation fluences, in order to find proper defect engineering solutions to maximize the radiation hardness of the gain layers.’

⇒ To study and characterise acceptor and donor removal mechanisms