AIDAinnova 2nd Annual Meeting
24–27 April 2023
Valencia, Spain

# Thin Silicon Sensors for Extreme Fluences

## eXFlu-innova


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# The Team

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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:

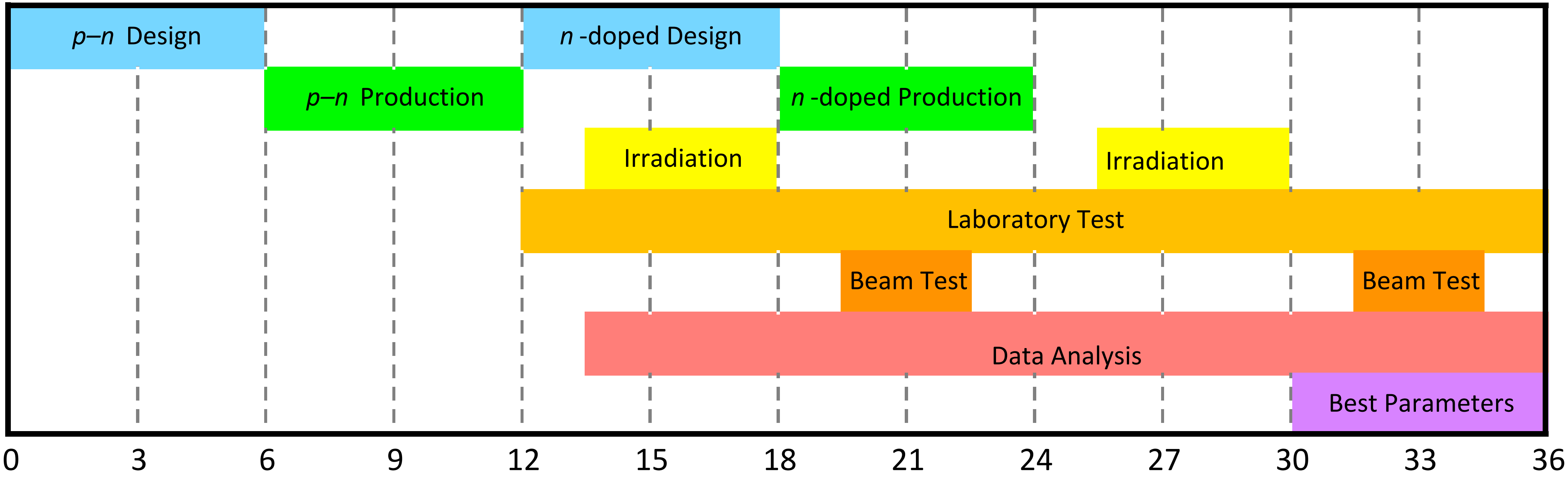
1. **saturation** of the radiation damage effects above $5 \cdot 10^{15}$ $n_{eq}/cm^2$
2. the use of **thin** active substrates (15 – 45 $\mu$m) with **internal gain**
3. **extension** of the charge carrier multiplication up to $10^{17}$ $n_{eq}/cm^2$ → **Compensated LGADs**

# 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)

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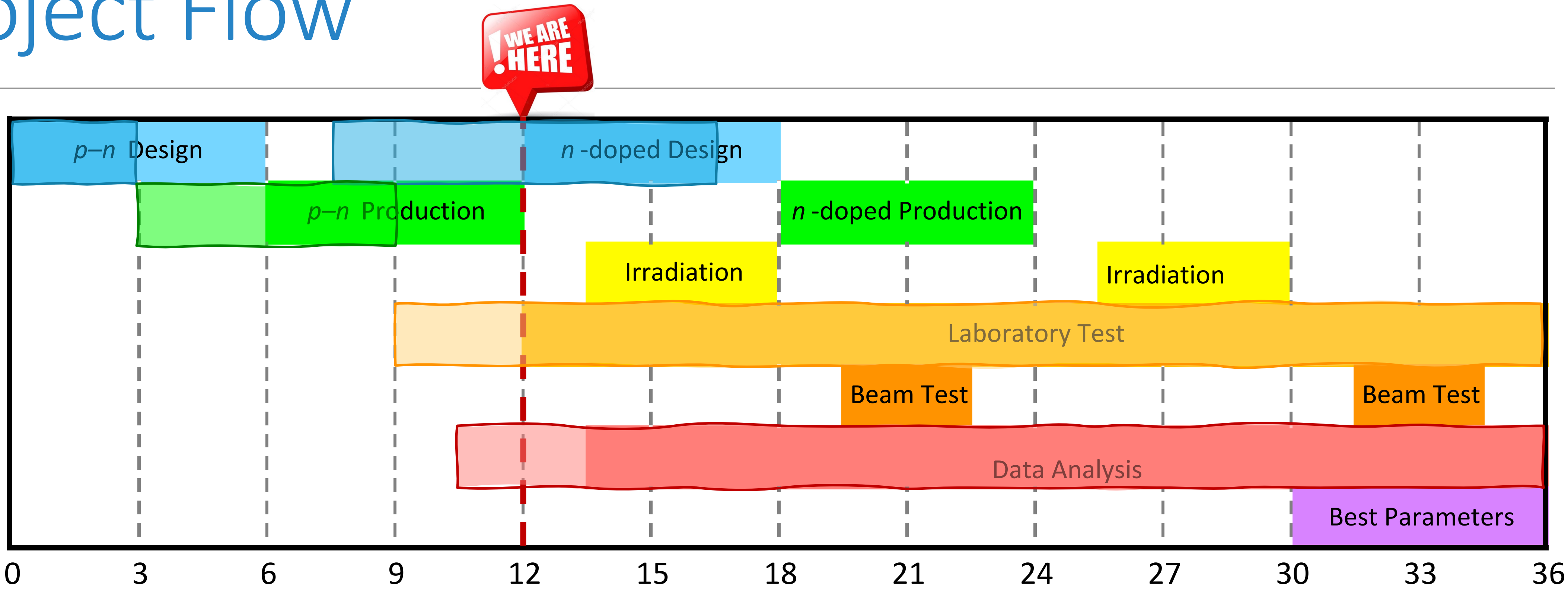
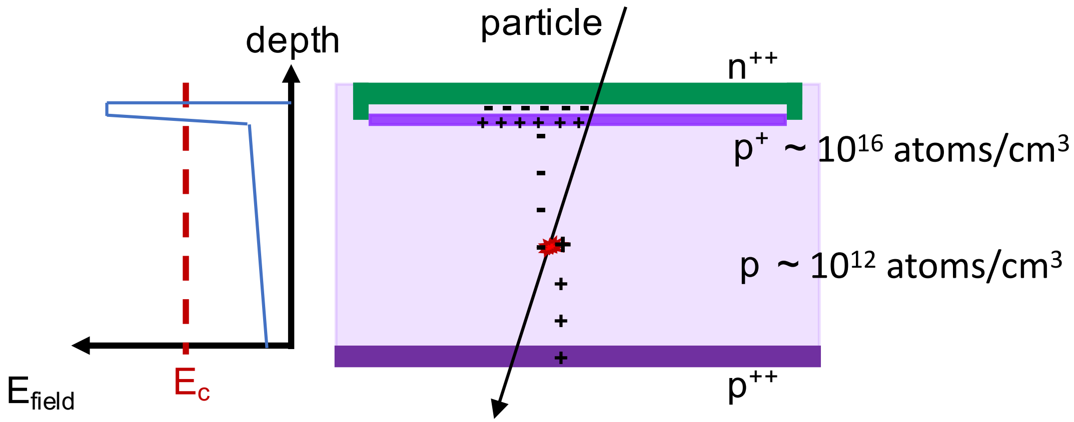



Deliverables:

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) –


3. **identifications of the best parameters** to manufacture compensated LGADs (M36) – pending

# Sensors for Extreme Fluences – Recap

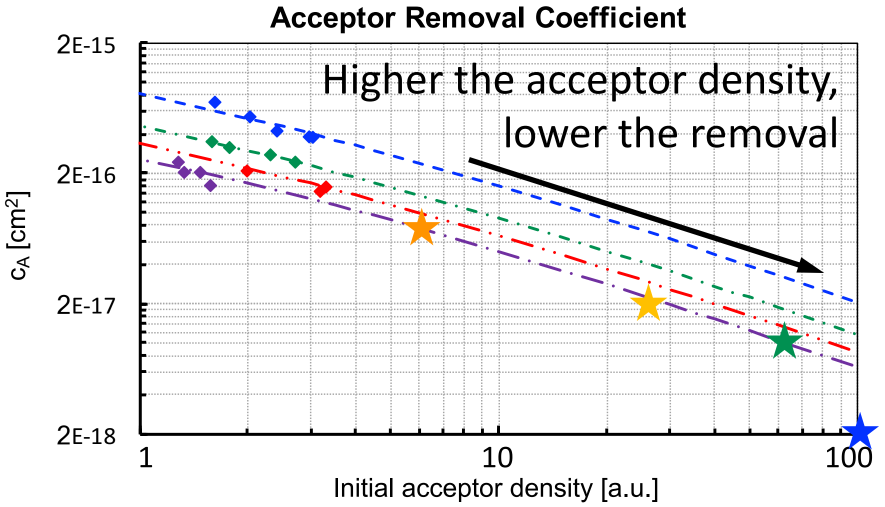


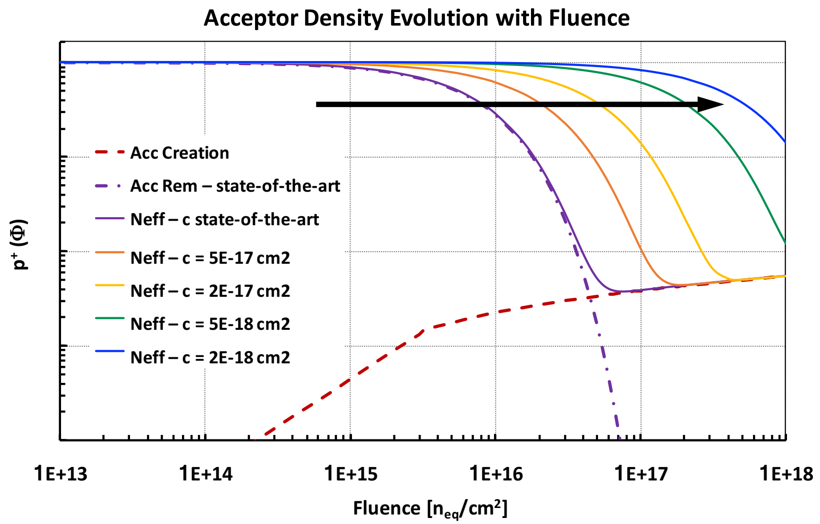

The acceptor removal mechanism deactivates the $p^+$-doping of the **gain layer** with irradiation according to

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

where $\mathbf{c_A}$ is the acceptor removal coefficient

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




Lowering $\mathbf{c_A}$ extends the gain layer survival up to the highest fluences → **compensation**

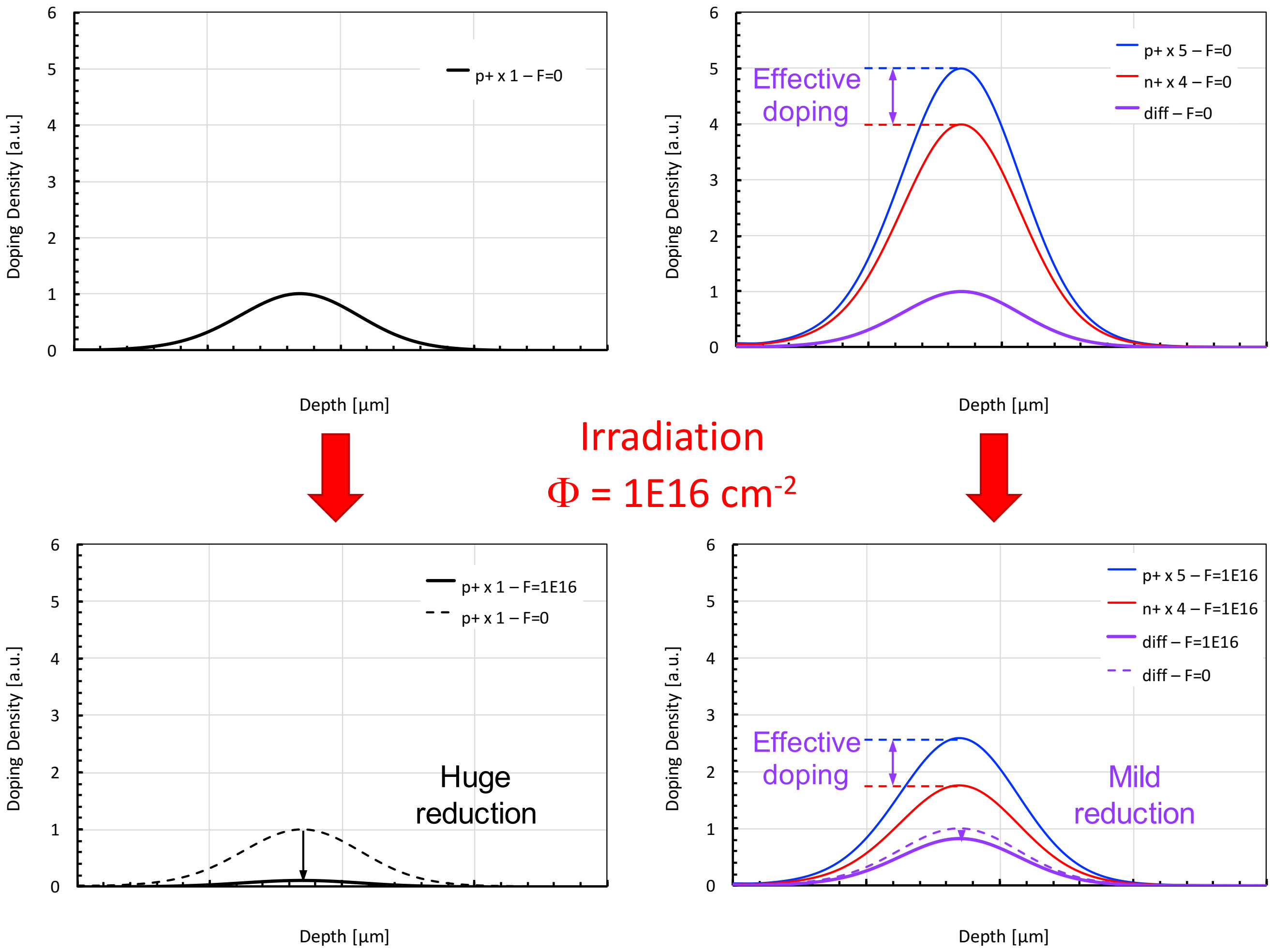
# Compensation at a Glance

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

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

Many unknown:

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




Standard LAGD design | Compensated LAGD design

# The EXFLU1 Production Batch at a Glance

**A batch of thin LGAD for extreme fluences was released by the FBK foundry**
**⇒ EXFLU1**

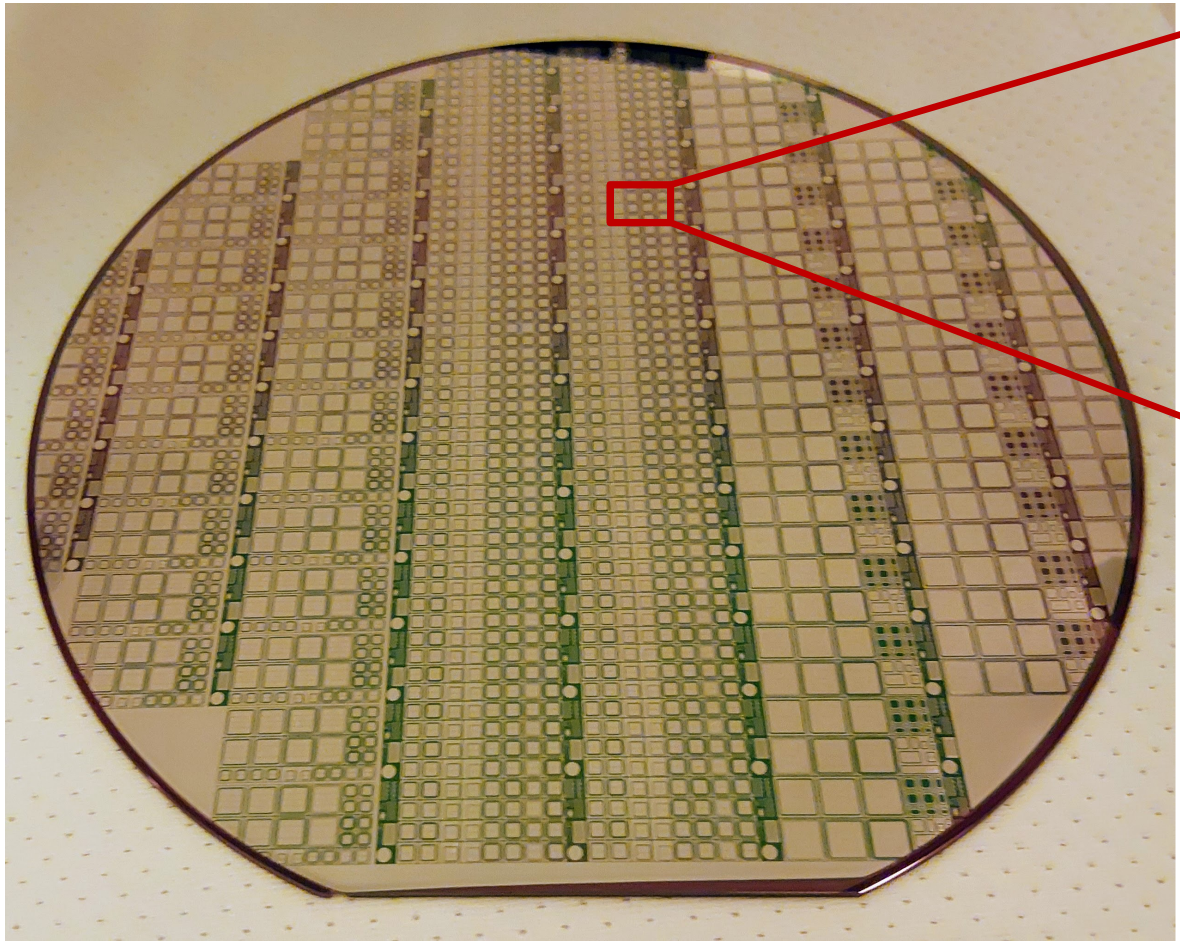
The EXFLU1 batch from FBK explores different innovation strategies to extend the radiation tolerance of silicon sensors up to the extreme fluences:

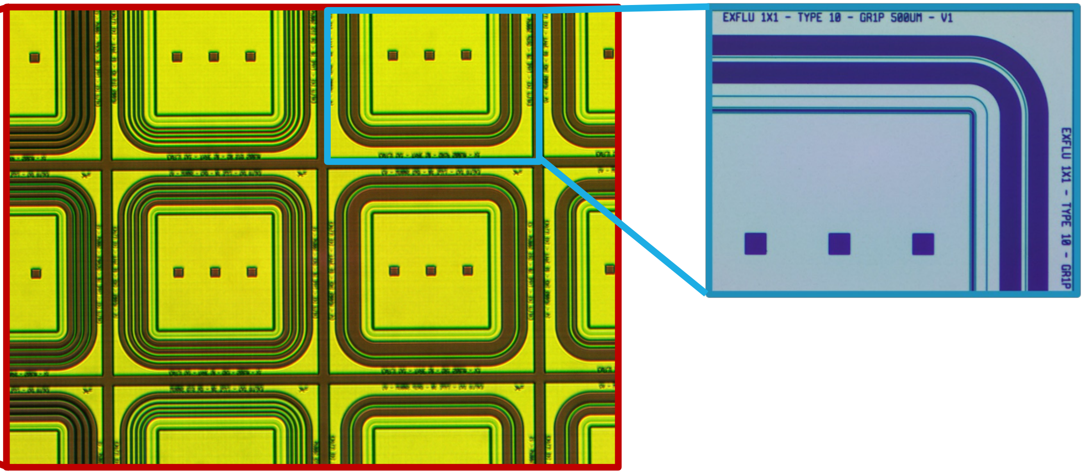
- ▻ carbon shield (in Backup)
- ▻ **compensation**
- ▻ new guard ring design
- ▻ thin substrates (15–45 µm)

→ **The EXFLU1 wafers exited the FBK clean room in November 2022**

# The EXFLU1 Wafers

6” Wafer






⇒ **The EXFLU1 testing has started**

# Compensated LGAD – Split Table

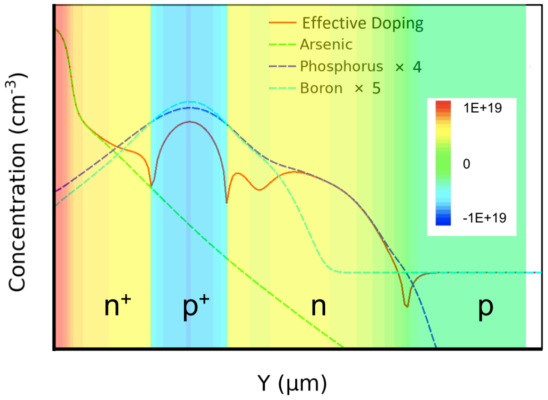
| Wafer # | Thickness | p+ dose | n+ dose | C dose |
|---|---|---|---|---|
| 6 | 30 | 2 a | 1 | |
| 7 | 30 | 2 b | 1 | |
| 8 | 30 | 2 b | 1 | |
| 9 | 30 | 2 c | 1 | |
| 10 | 30 | 3 a | 2 | |
| 11 | 30 | 3 b | 2 | |
| 12 | 30 | 3 b | 2 | |
| 13 | 30 | 3 b | 2 | 1.0 |
| 14 | 30 | 3 c | 2 | |
| 15 | 30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

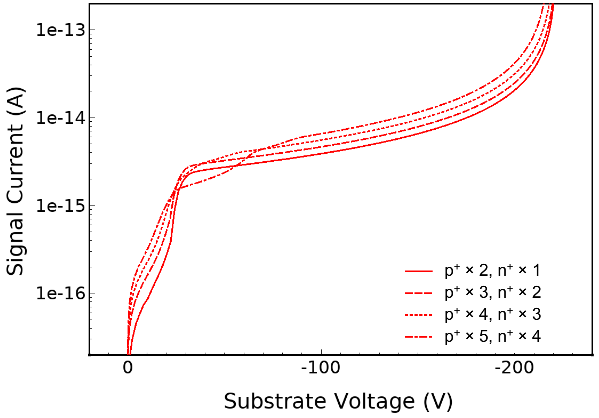
[ a < b < c ]

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

# Compensated LGAD – I-V for different p$^+$ – n$^+$

Simulation



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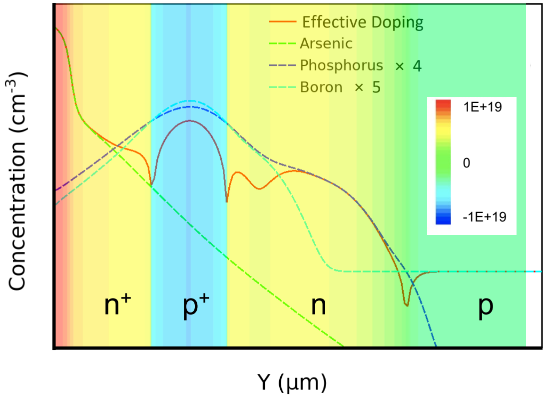
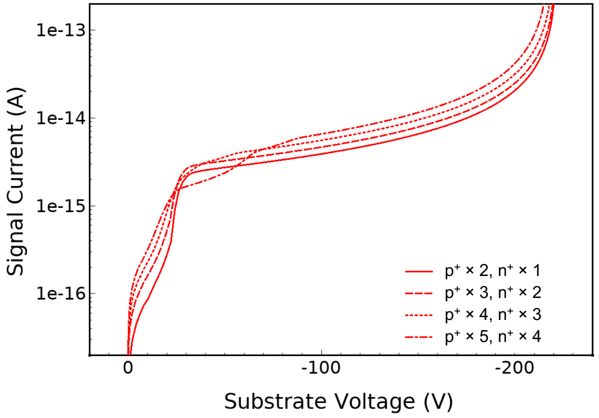
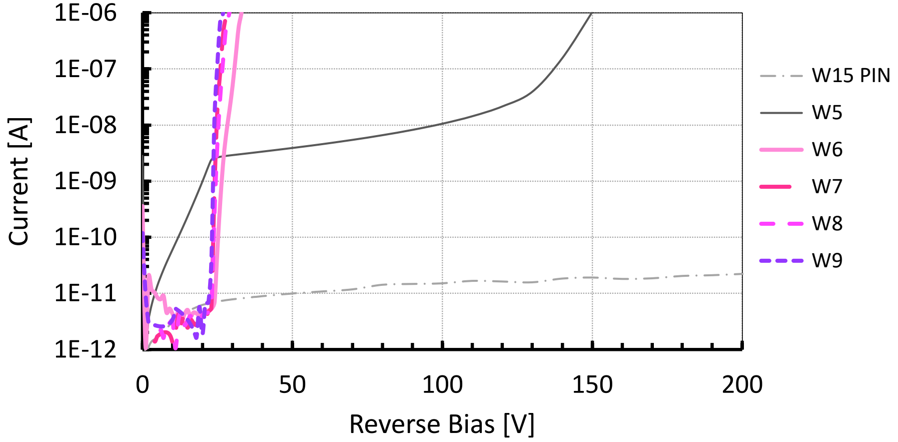


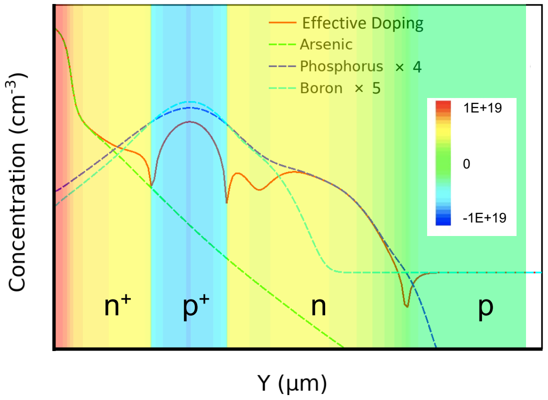

EXFLU1 – Compensated LGAD 2–1 – I-V

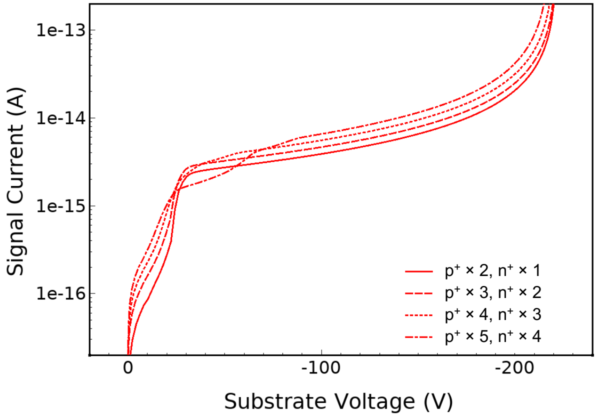



2 – 1

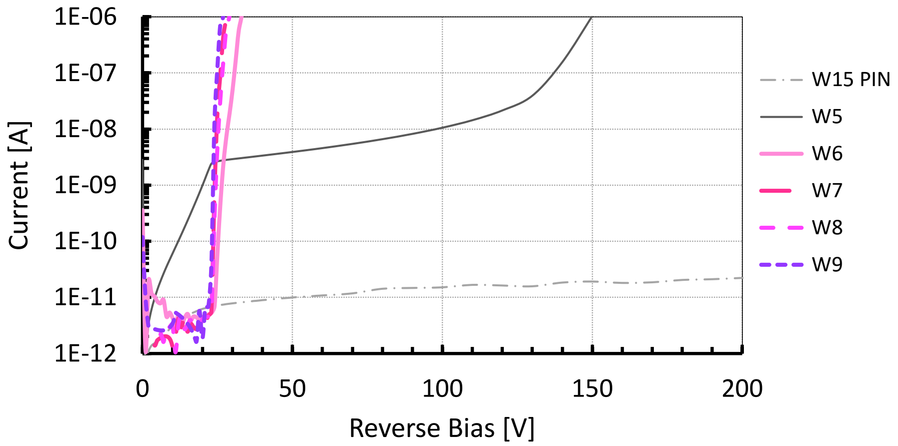
# Compensated LGAD – I-V for different $p^+ - n^+$

## Simulation



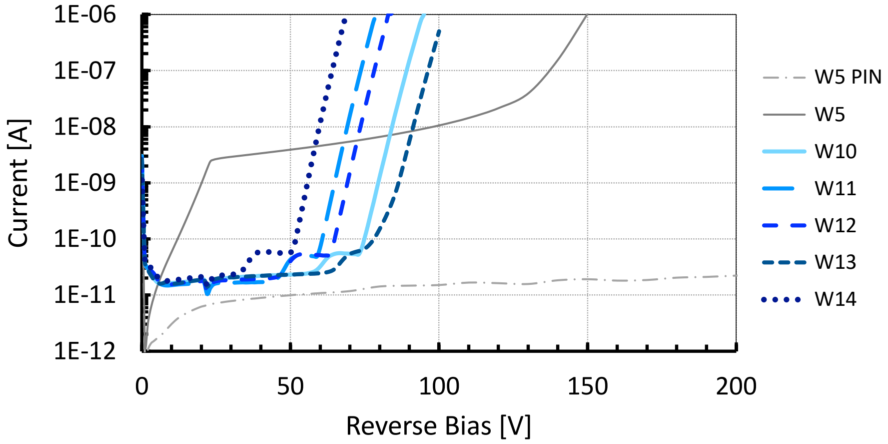

EXFLU1 – Compensated LGAD 2–1 – I-V




2 – 1

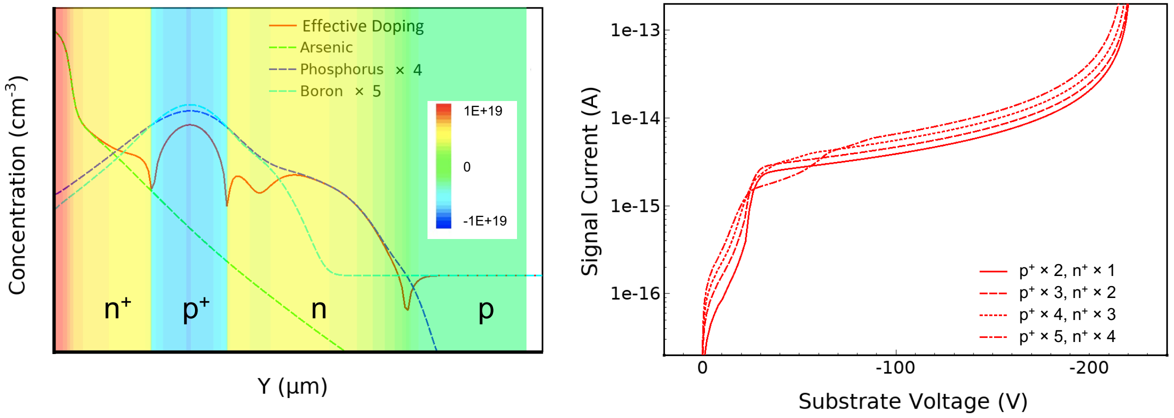
EXFLU1 – Compensated LGAD 3–2 – I-V

3 – 2

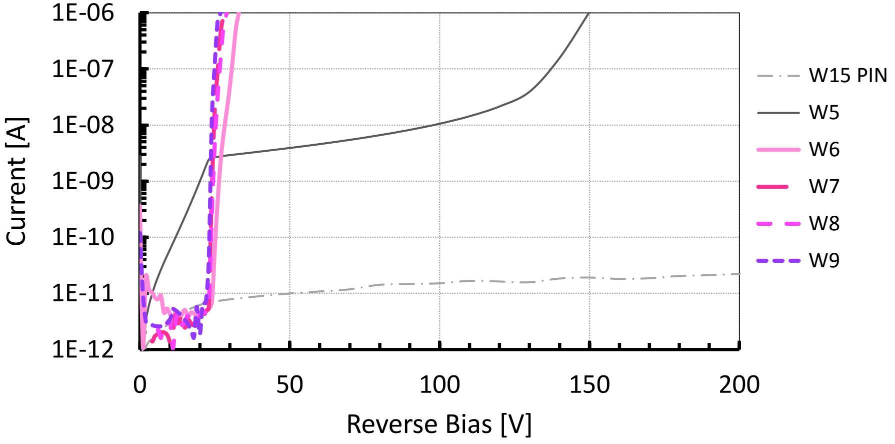


# Compensated LGAD – I-V for different p⁺ – n⁺

## Simulation



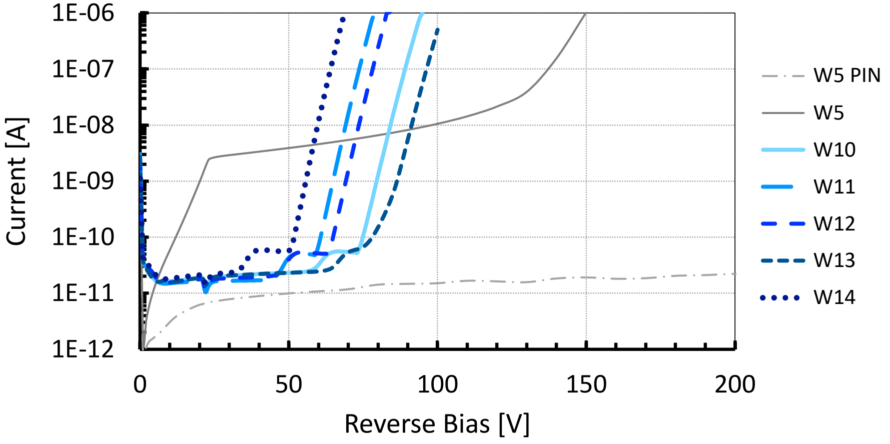

EXFLU1 – Compensated LGAD 2–1 – I-V



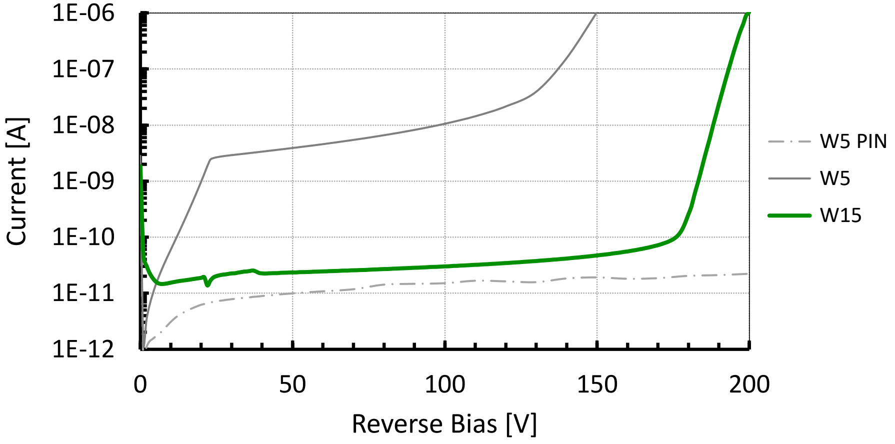

2 – 1

EXFLU1 – Compensated LGAD 3–2 – I-V

3 – 2

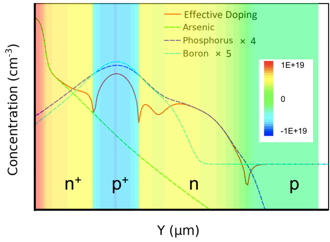



EXFLU1 – Compensated LGAD 5–4 – I-V




5 – 4

# Compensated LGAD – Testing Campaign



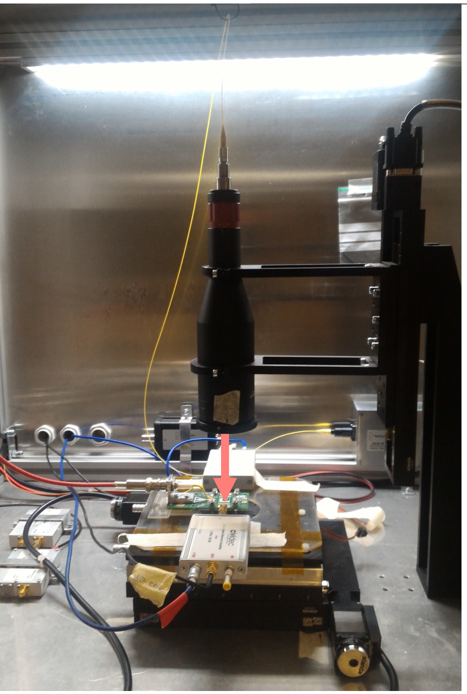

**Observations from compensated LGAD sensors:**

- ▻ the depletion of the gain layer region with bias reflects the depletion of different p-n junctions
- ▻ 2–1 sensors exhibit a too-high gain to be operated
- ▻ 3–2 sensors exhibit sharp gain performance compared to standard LGAD
- ▻ 5–4 sensors exhibit smaller gain with respect to standard LGAD
  → **A correct tuning of the p$^+$–n$^+$ doping densities need to be extrapolated by the EXFLU1 sensors**

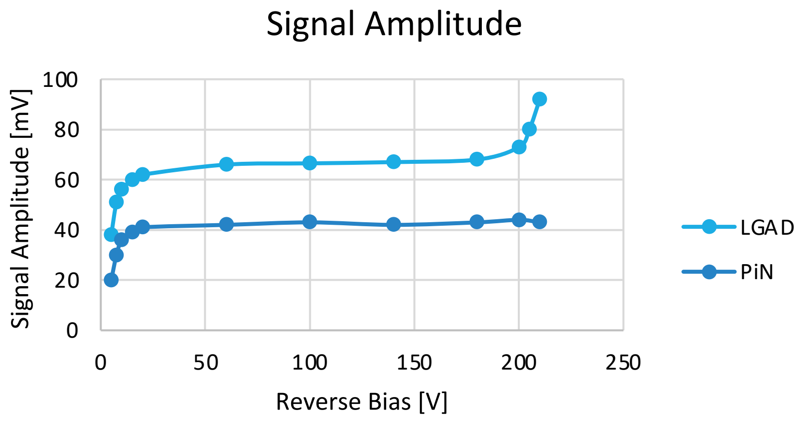
**Investigation of the gain implant doping evolution:**

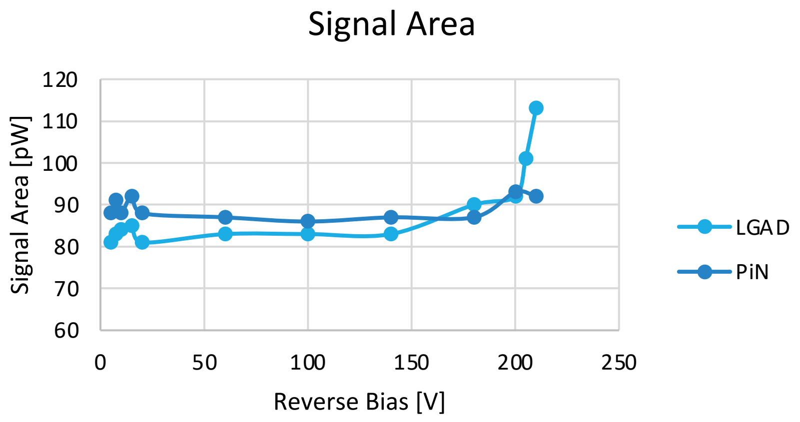
- ▻ SIMS on the compensated LGAD are ongoing to precisely map the p$^+$ and n$^+$ implants
- ▻ The shape and doping density of the gain implant to be investigated before and after irradiation through I-V and C-V measurements
- ▻ The concurrent effect of acceptor and donor removals will be investigated
- ▻ TCT measurements with different laser wavelengths before and after irradiation will be used to study the signal shape evolution at different sensor depths

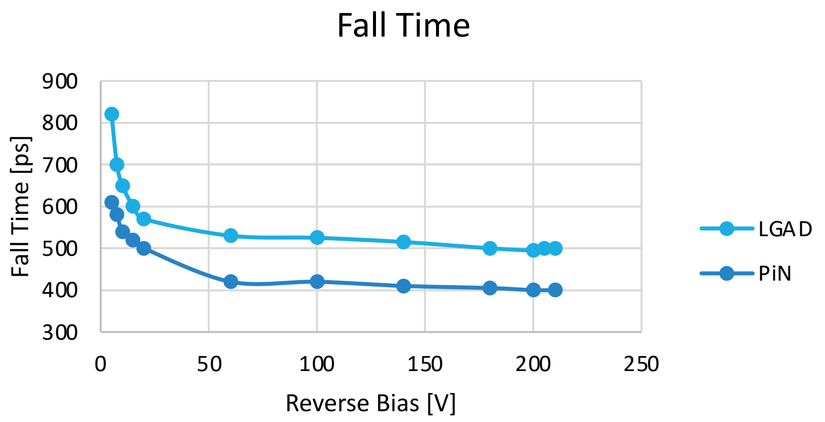
# Compensated LGAD – Signals from TCT

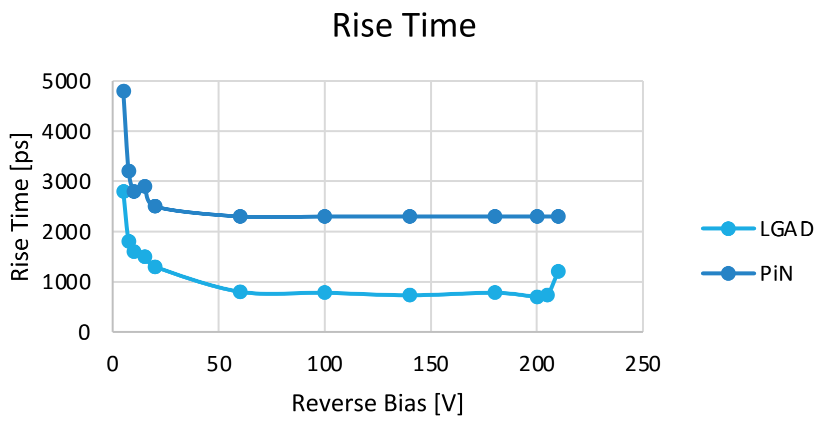


## Signal analysis from an LGAD and a PIN of W15 (5–4)




**TCT Setup from Particulars**

Pico-second IR laser at 1064 nm

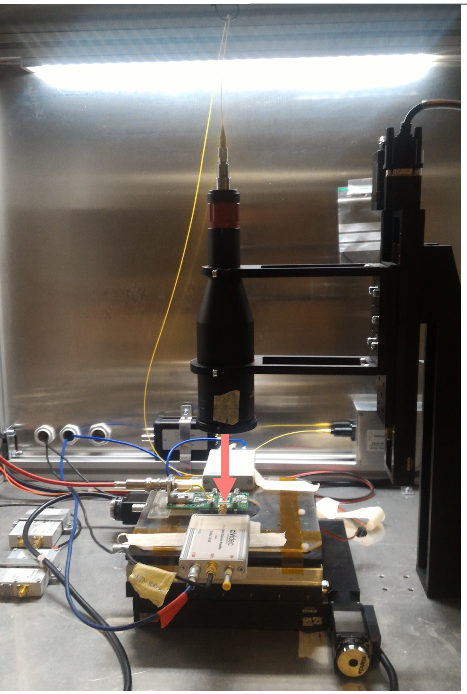
Laser spot diameter ~ 10 µm

Cividec Broadband Amplifier (40dB)

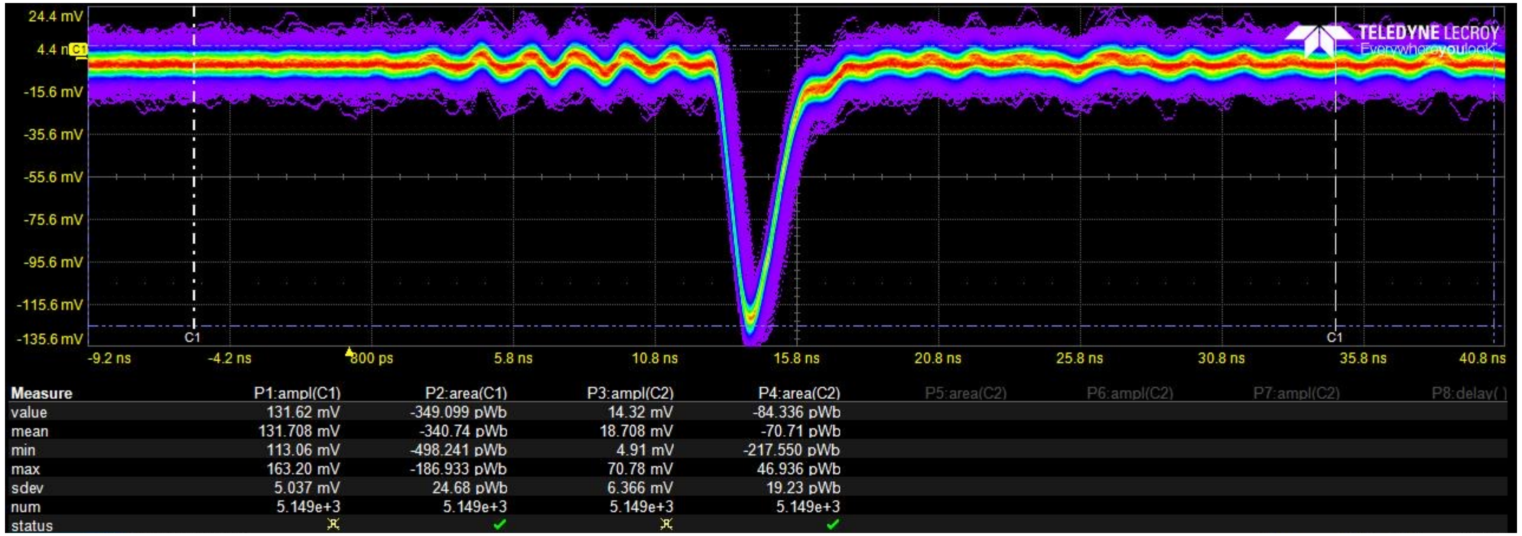
Oscilloscope LeCroy 640Zi

Room temperature

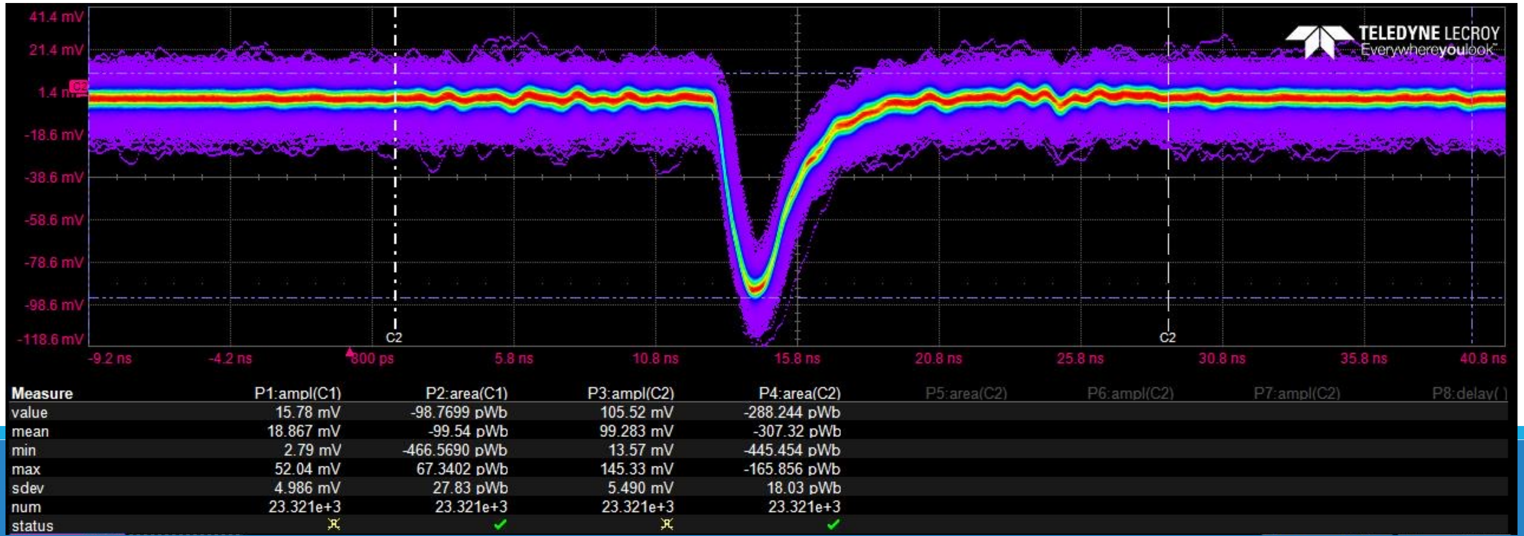
# Compensated LGAD – Waveforms from TCT



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




W15
LGAD
$V_{bias}$ = 150V




W15
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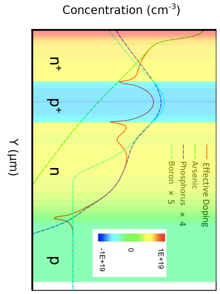
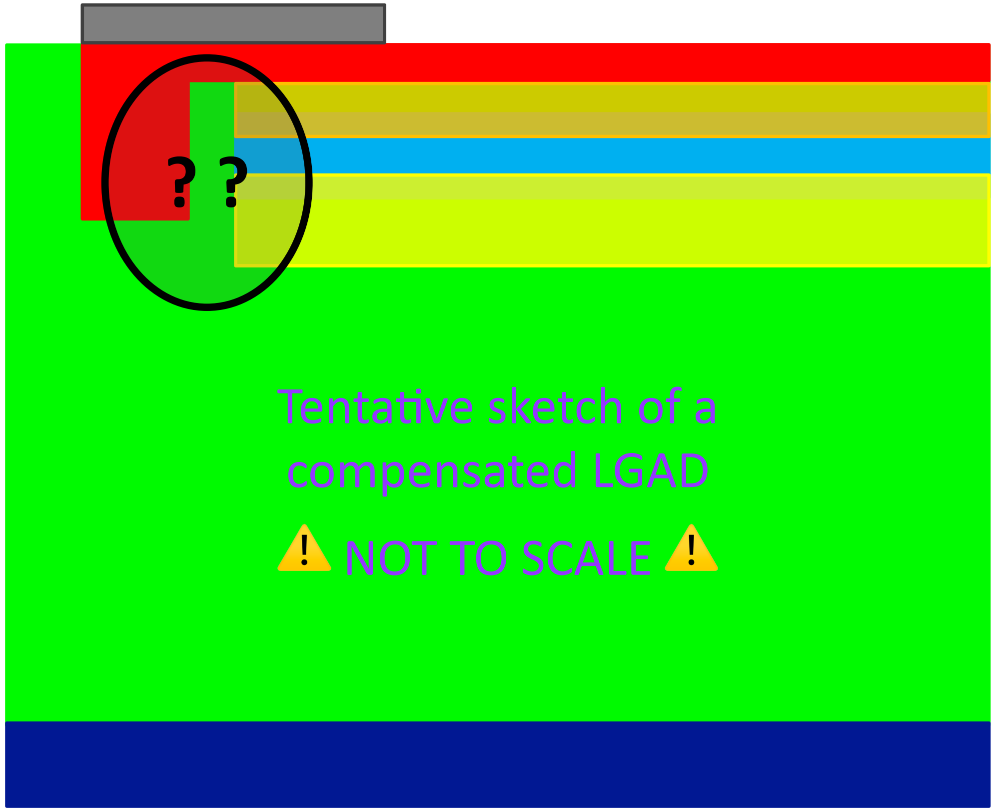
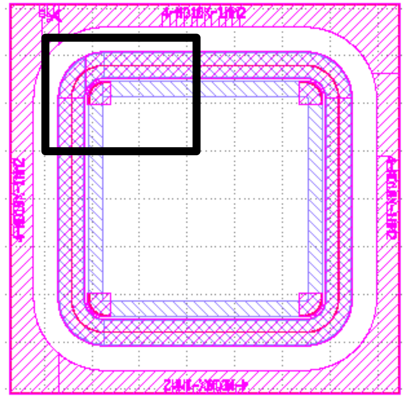
# Compensated LGAD – 2D Scan with IR Laser




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




Scan surface



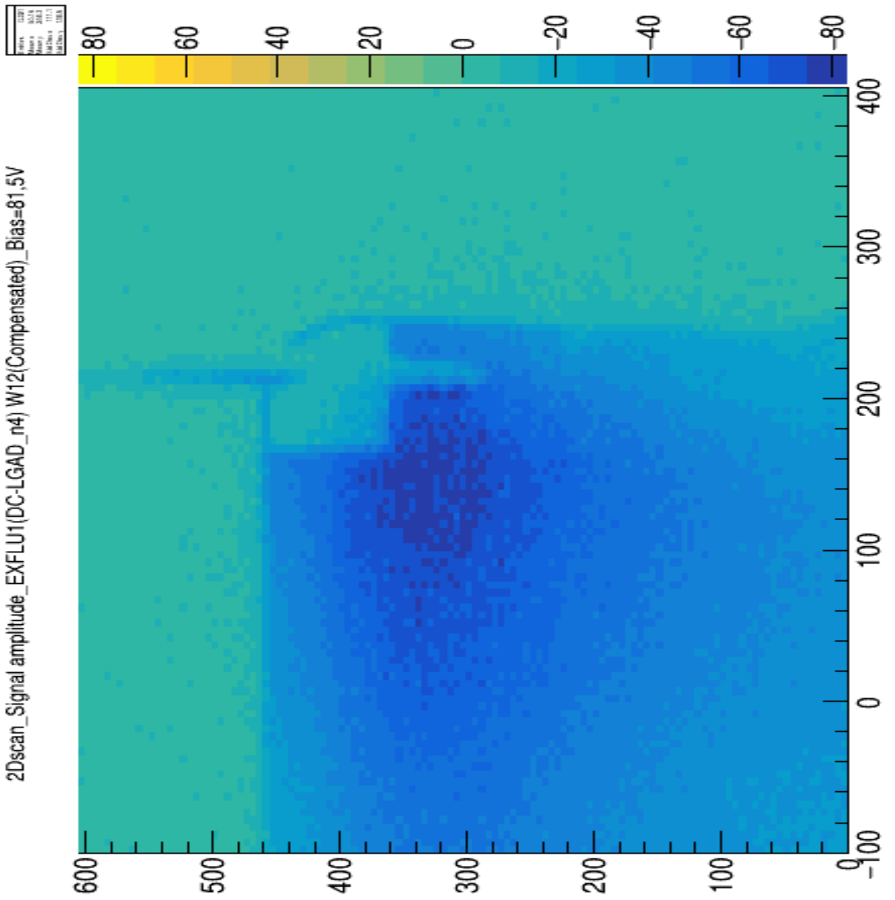
TCT scan with IR laser

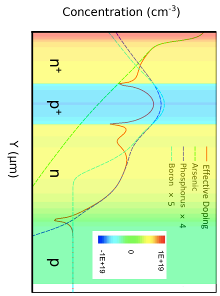
Laser spot ~ 10 µm

Sensor from W12 (3–2)

$V_{bias}$ = 81 V

Very close to BD



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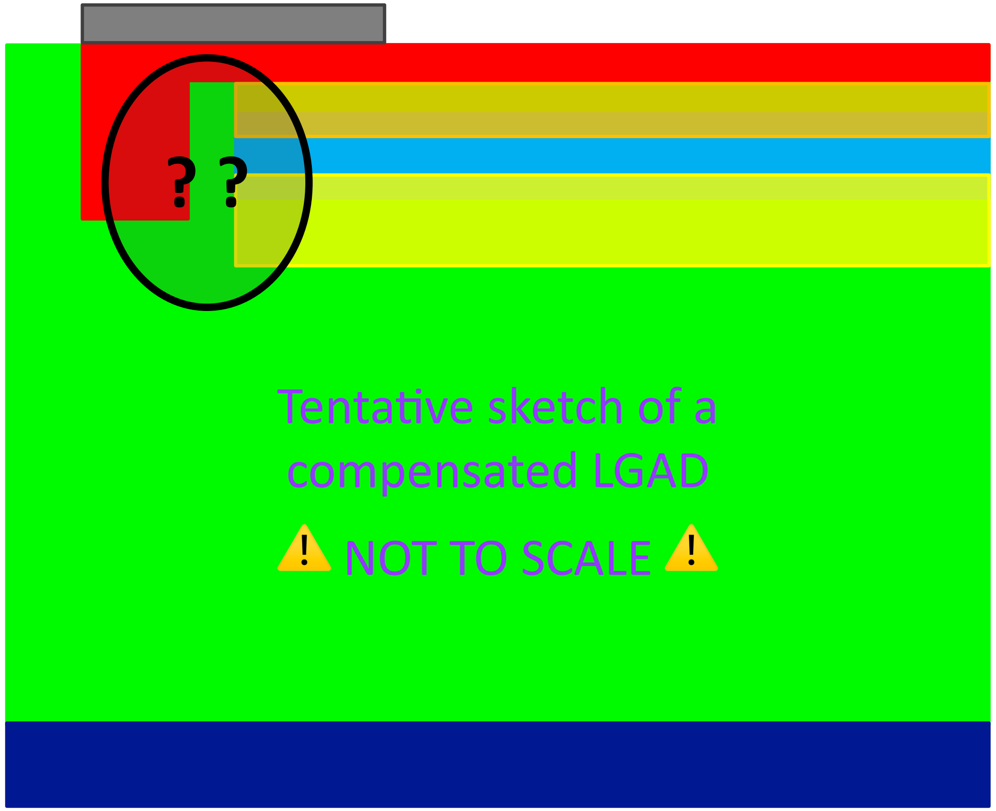


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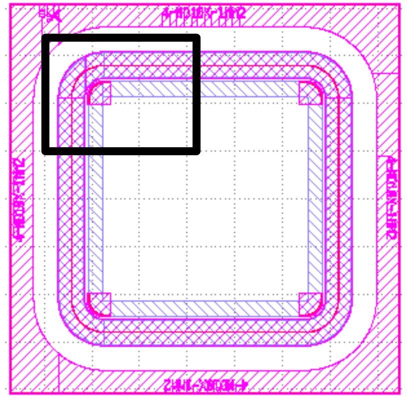

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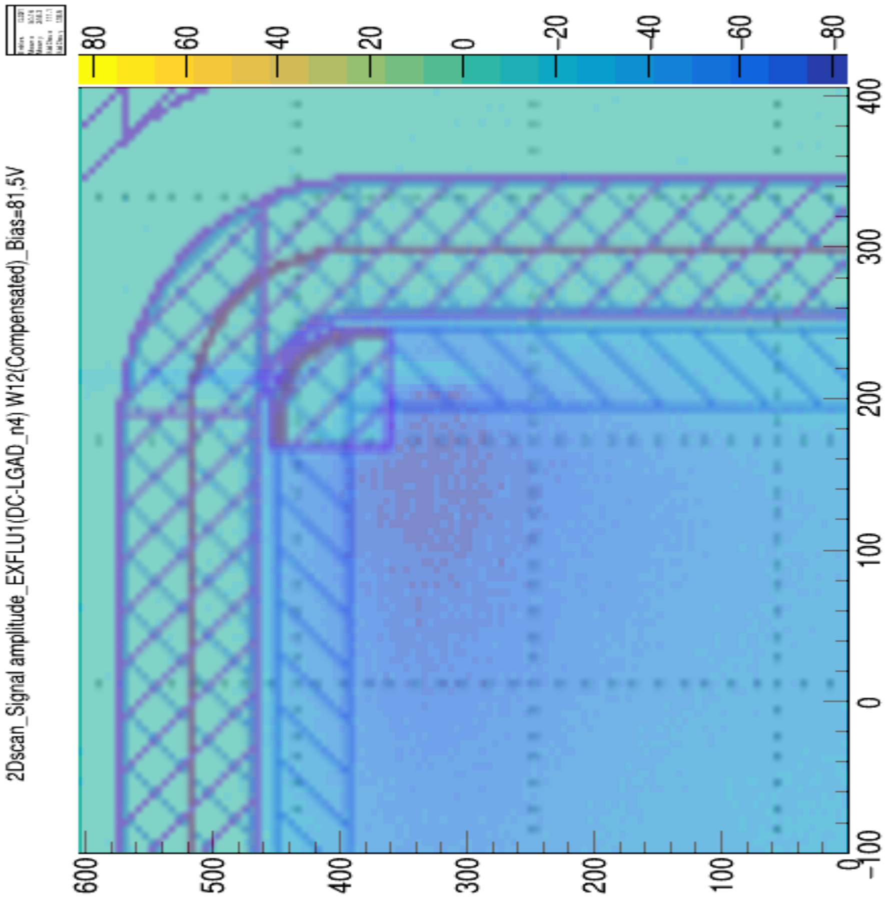



→ No issues observed at the edge of the compensated gain implants

# Compensated LGAD produced by HPK

Presented by K. Hara at TREDI2023 [link]

## Radiation tolerance improvement – trial2

**Compensation**

Result not promising....

Not much change by two different compensation parameters

*2.5B+1.5P*

*1.5B+0.55P*

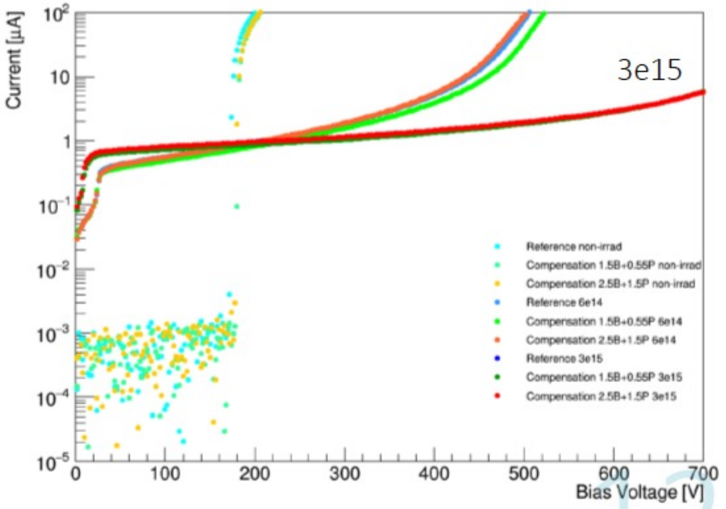
*Initial comensation works perfect*

What does this mean?

Non-irrad

6e14

3e15

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## How should we understand the results?

$$N_A(\emptyset) - N_D(\emptyset) = N_A(0) \cdot e^{-C_A \emptyset} - N_D(0) \cdot e^{-C_D \emptyset}$$

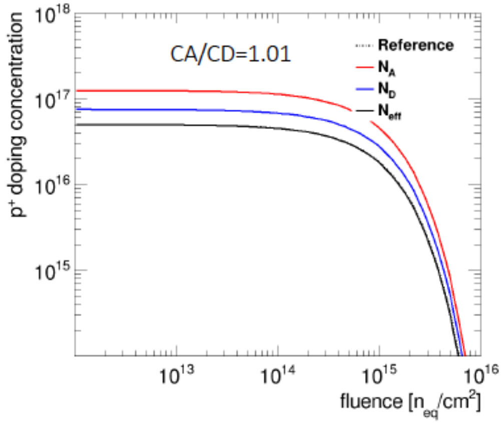
If $C_A = C_D$

$$N_A(\emptyset) - N_D(\emptyset) = (N_A(0) - N_D(0)) \cdot e^{-C_A \emptyset}$$

reference

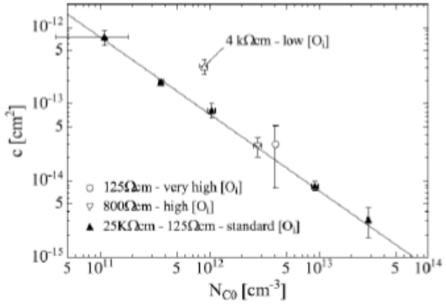
$$N_A(\emptyset) = N_A(0) \cdot e^{-C_A \emptyset}$$

Reduction of effective p+ must be the same as non-compensated case

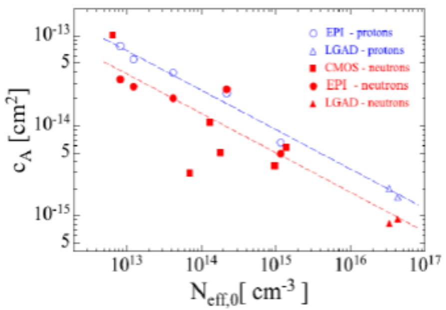



Previous data

Donor removal




Acceptor removal

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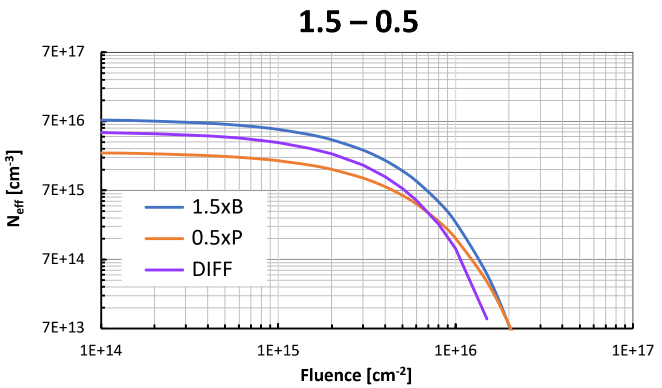
# Compensated LGAD from HPK – $c_A$ vs $c_D$ ?

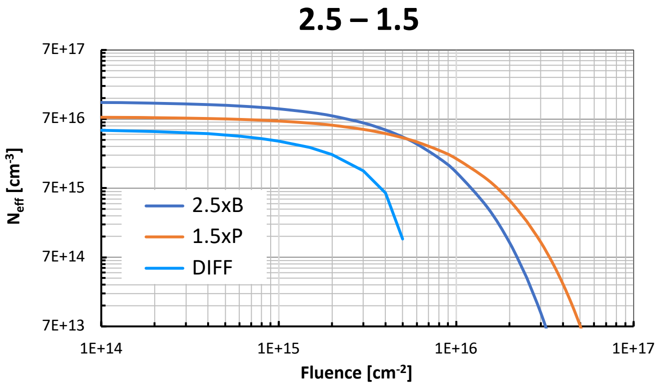
What can we learn from HPK compensated LGAD?

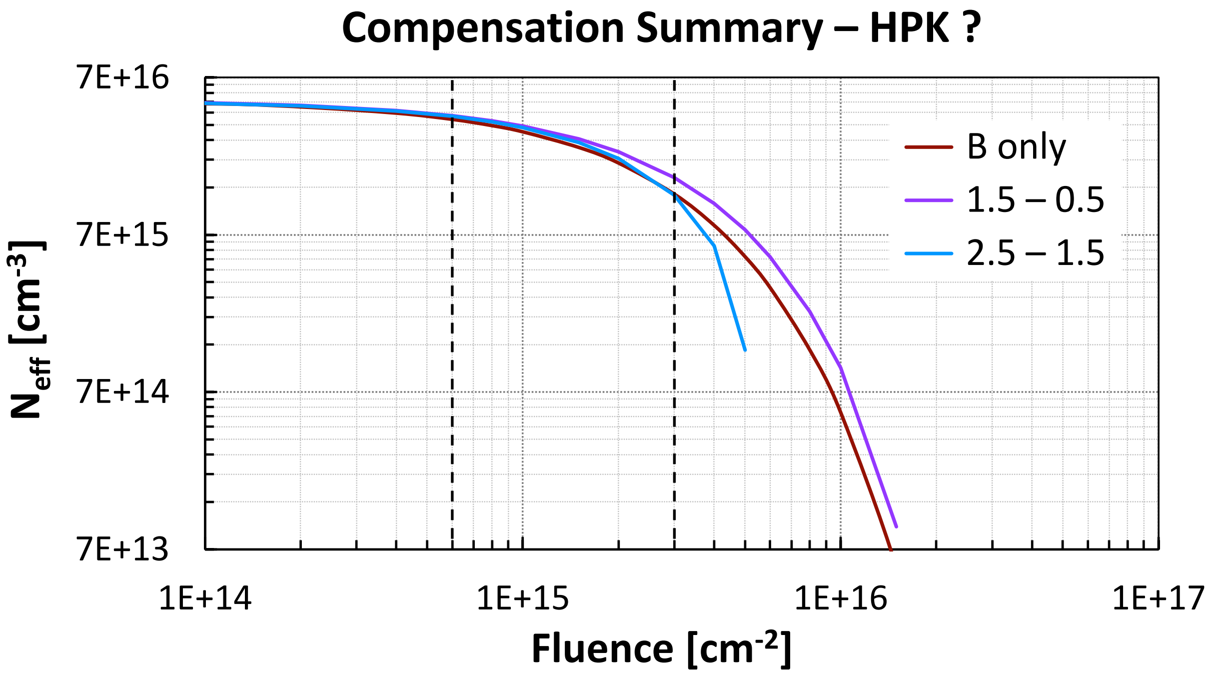
$c_A$ and (presumably) $c_D$ depends on the effective acceptor and donor densities

At fluences of 6E14 & 3E15 $n_{eq}/cm^2 \rightarrow p^+ - n^+$ compensated doping is the same as before irradiation

**⇒ $c_A > c_D$?**



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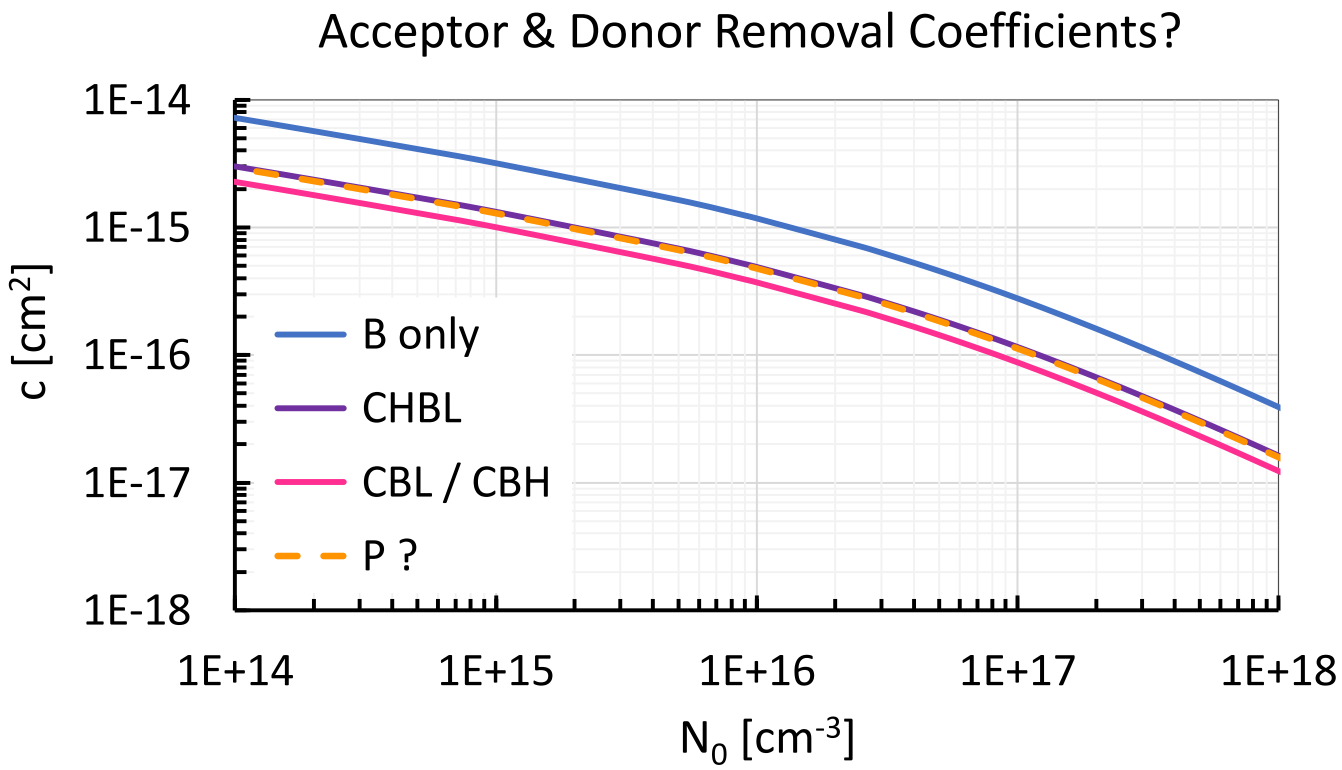



**$c_A / c_D$ = 2.47**
to reproduce
the HPK results

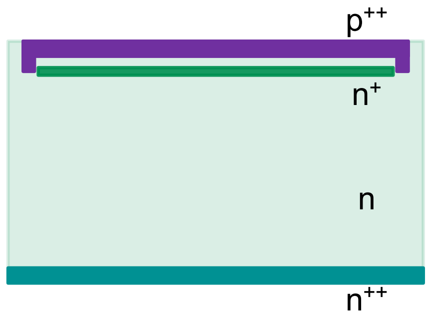
# p-in-n LGAD Production

A production batch is needed to study the donor removal coefficient, $\mathbf{c_D}$

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



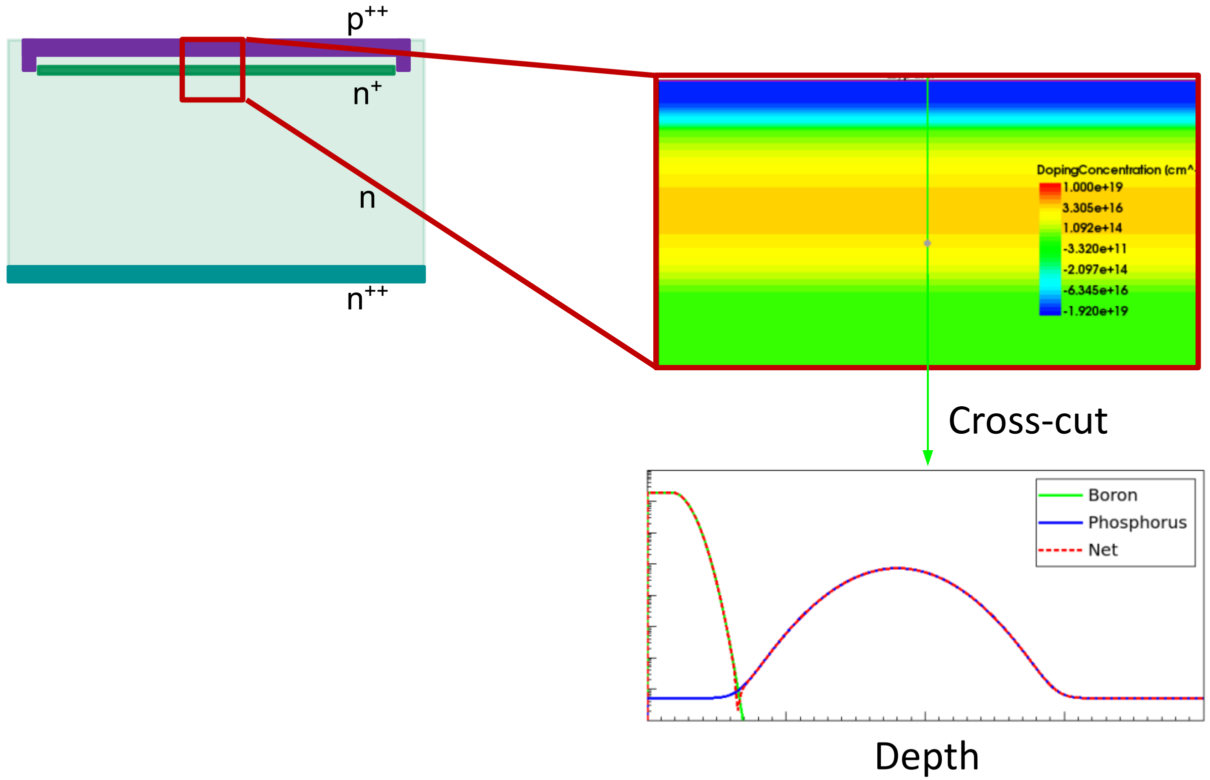

p-in-n LGAD

**→ 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 p-in-n LGAD (NLGAD) batch produced by CNM [link]

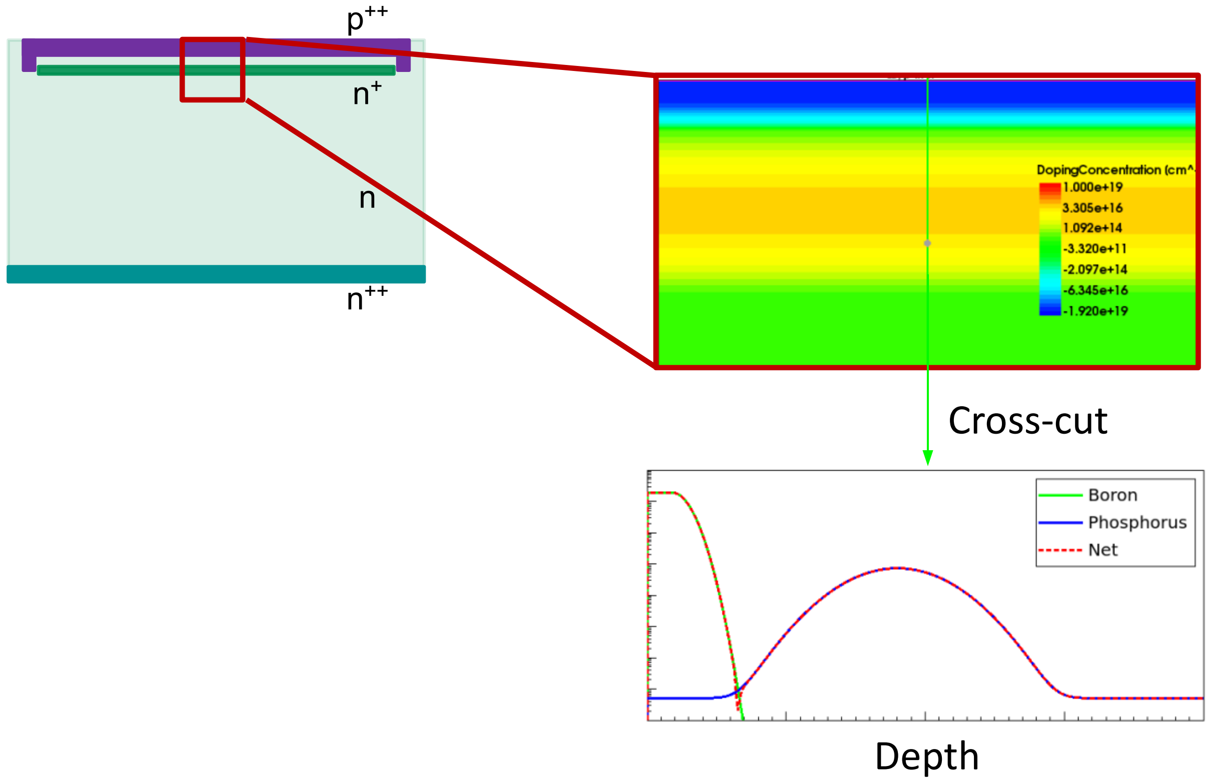
# p-in-n LGAD – Simulation & Design

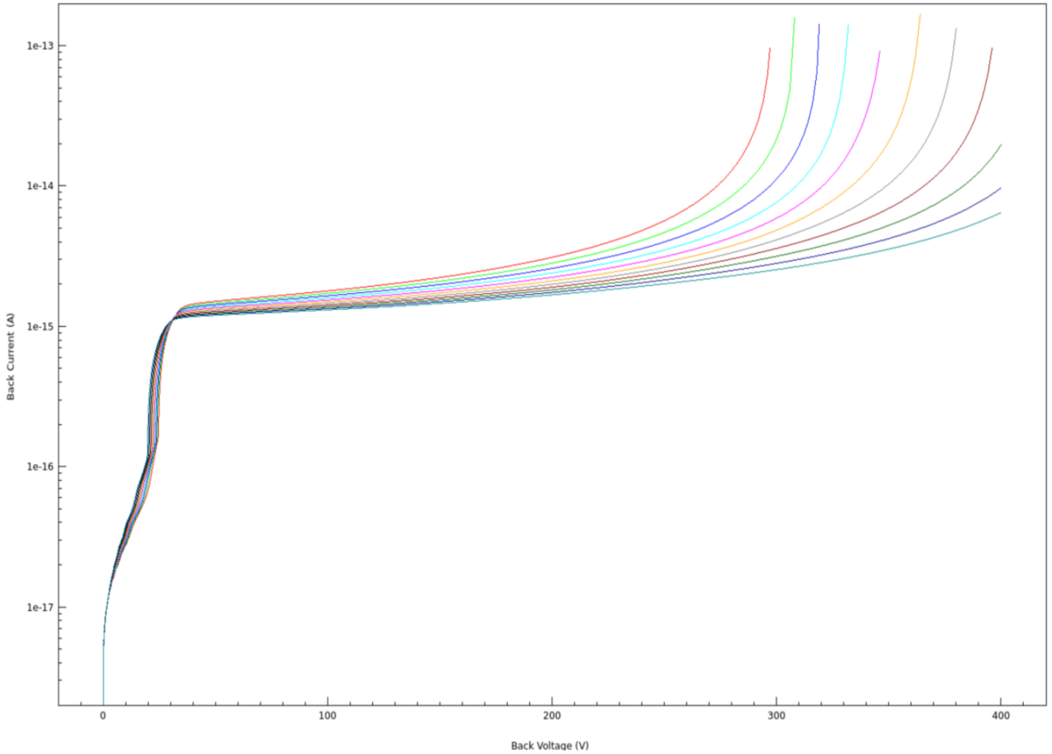
Process simulation is used to design the $p^{++}$ electrode with Boron (TCAD Silvaco)



# p-in-n LGAD – Simulation & Design

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



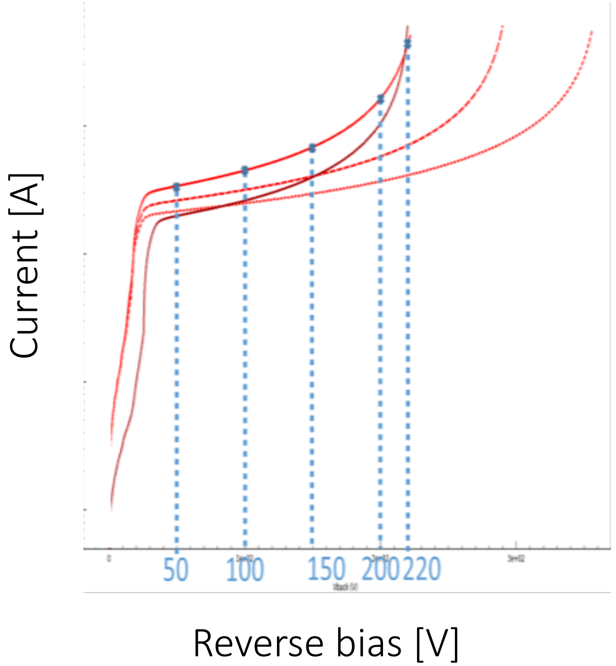




→ The simulation of the electrostatic behaviour shows good performances of the I-V characteristics for different p++ designs (TCAD Synopsys)

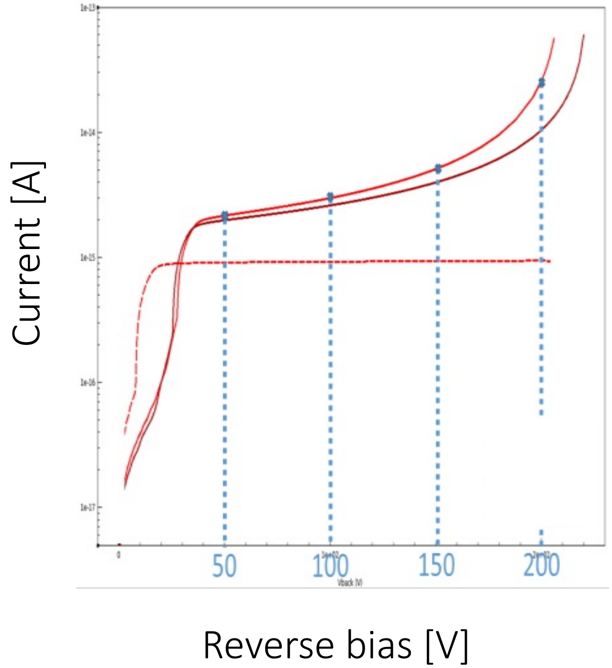
# p-in-n LGAD – Simulation & Design

Different designs of the n⁺ gain layer are investigated

Type A



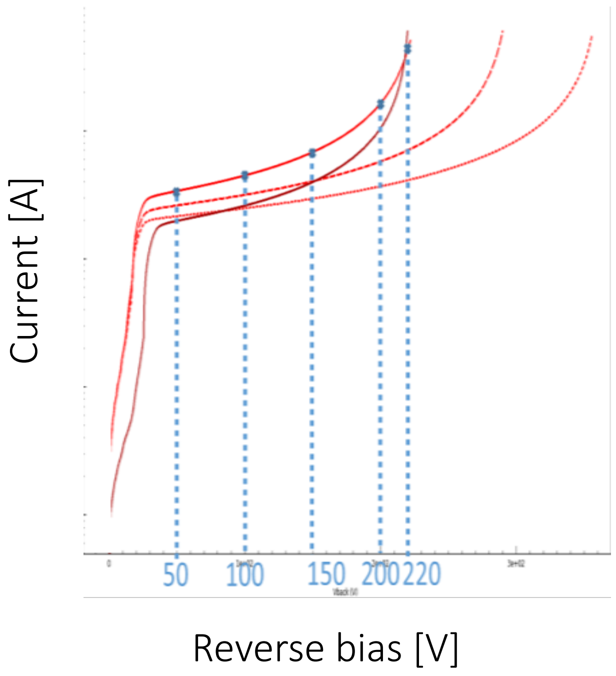

Type B



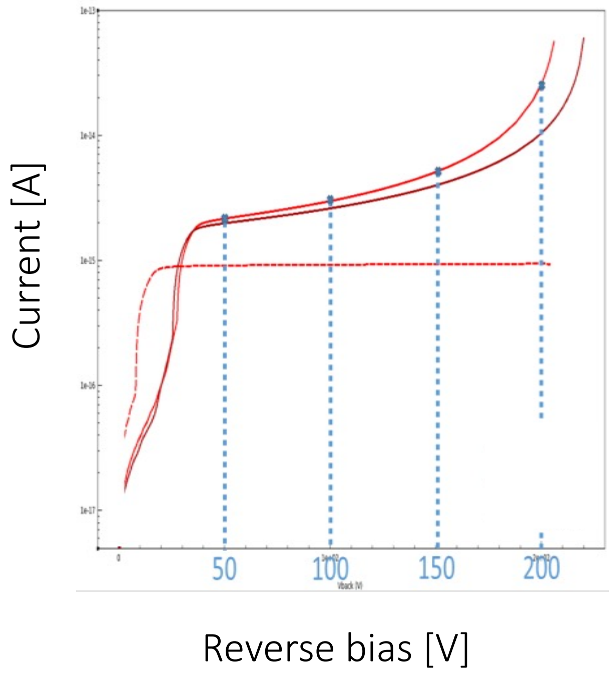
# p-in-n LGAD – Simulation & Design

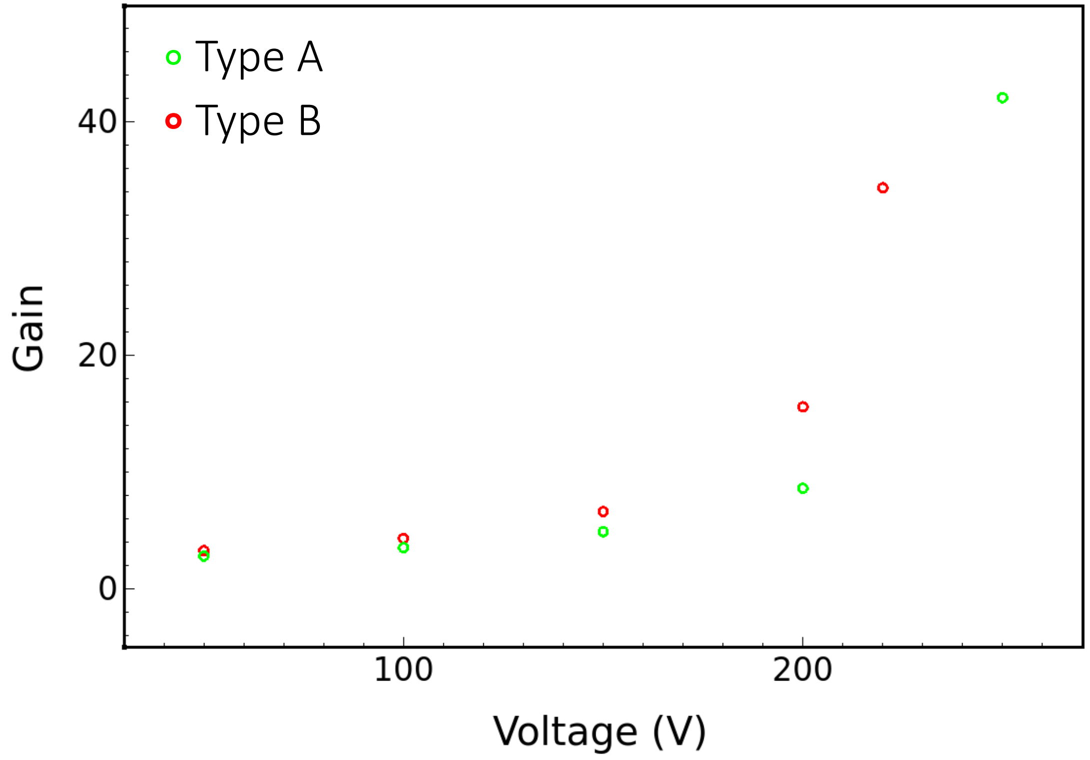
Different designs of the $n^+$ gain layer are investigated

Type A




Type B

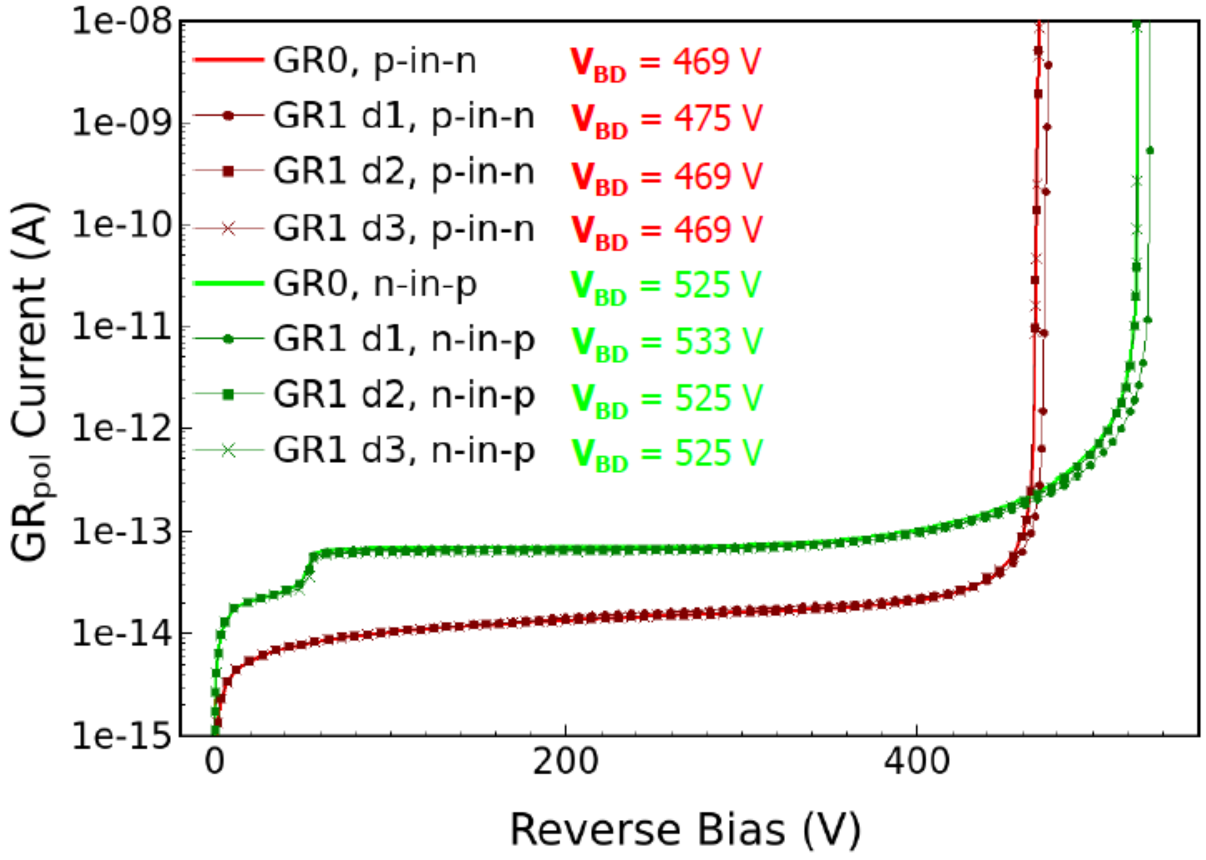



→ Both electrical and transient characteristics exhibit good operation of the sensors

# p-in-n LGAD – Simulation & Design

Different designs of the guard ring structures are investigated



# 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**

# 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
  → 1 Post-Doc hired, 1 Post-Doc selection in progress

– 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

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

# 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 have started
- ▻ The design of the p-in-n LGAD production is ongoing

**⟹ Activities of the eXFlu-innova projects are proceeding timely**

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

*Thank You*

# Backup

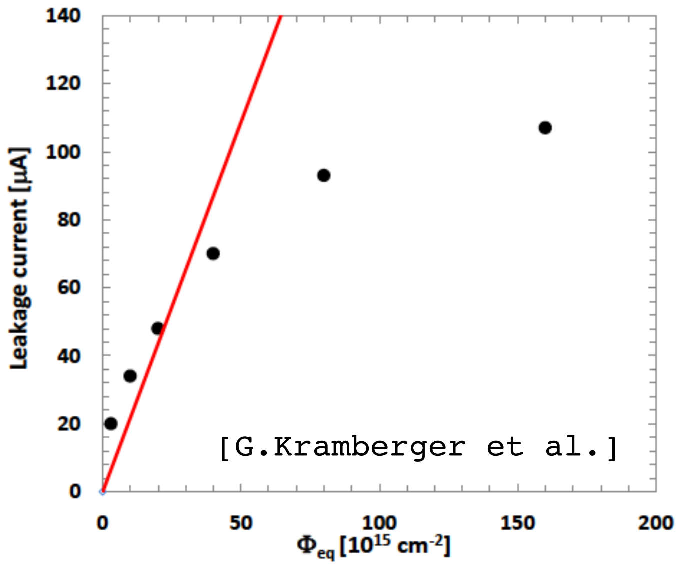
# The Goals

- ➢ Measure the properties of silicon sensors at fluences above $10^{16}$ $cm^{-2}$
- ➢ Design planar silicon sensors able to work in the fluence range $10^{16} – 10^{17}$ $cm^{-2}$
- ➢ Estimate if such sensors generate enough charge to be used in a detector exposed to extreme fluences

⇒ **The R&D activity has started**

# Saturation

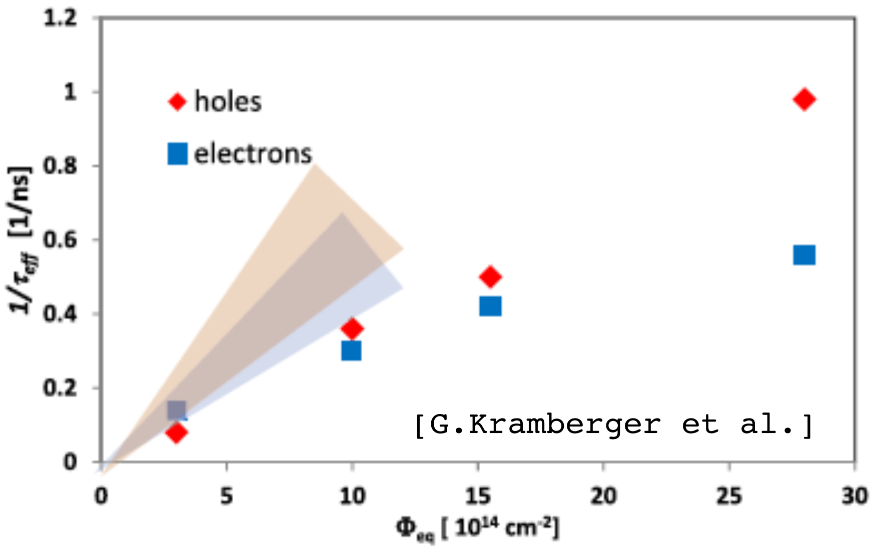
At fluences above $5{\cdot}10^{15}$ cm$^{-2}$ → **Saturation of radiation effects observed**




**Leakage current saturation**

$I = \alpha V \Phi$

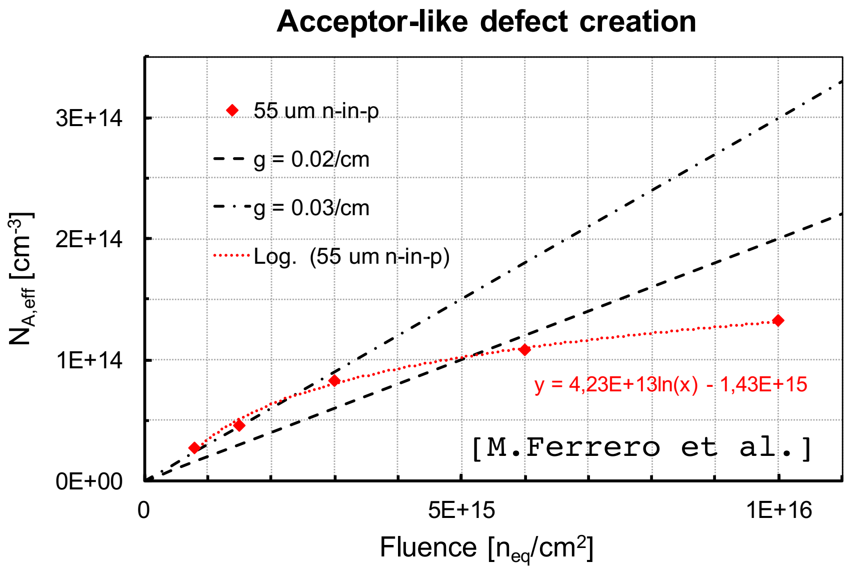
**$\alpha$ from linear to logarithmic**




**Trapping probability saturation**

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

**$\beta$ from linear to logarithmic**




**Acceptor creation saturation**

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

**$g_c$ from linear to logarithmic**

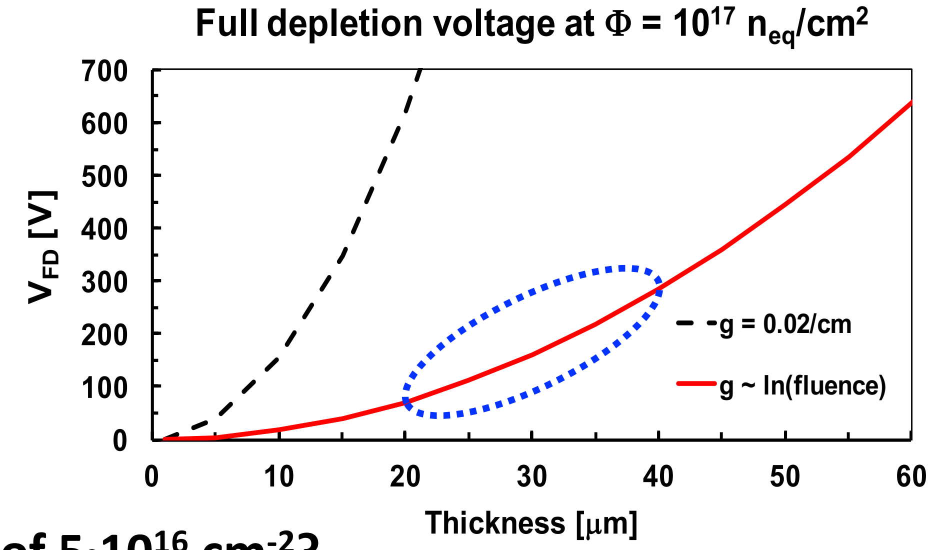
**Silicon detectors irradiated at fluences $10^{16}$ – $10^{17}$ cm$^{-2}$ do not behave as expected → They behave better**

# Thin Substrates

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

**Saturation** **Reduce thickness**

**At high fluences, only thin substrates can be fully depleted**




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

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

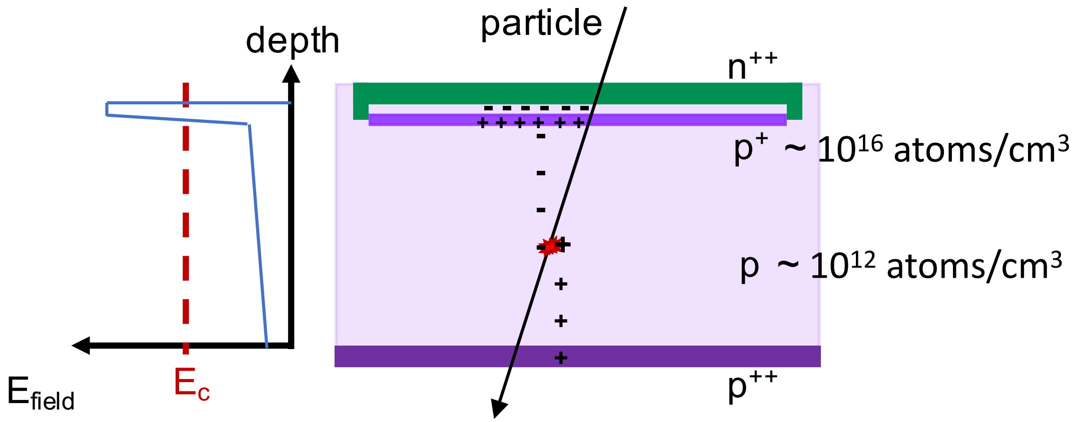
**However: charge deposited by a MIP ~ 0.25 fC**

→ 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



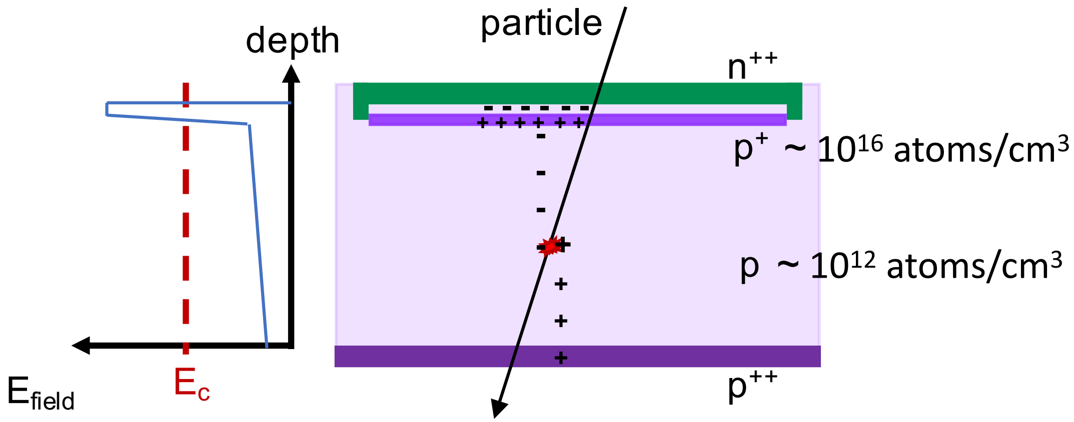

Minimum charge requested by the electronics
→ **~ 1 fC** for tracking
→ **≳ 5 fC** for timing

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

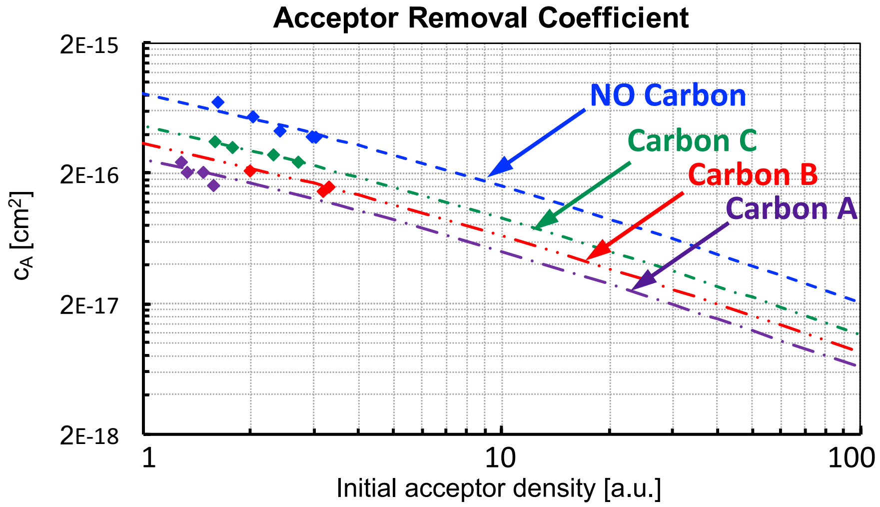
# Low-Gain Avalanche Diodes & Irradiation




LGADs are n-in-p silicon sensors

Operated in low-gain regime (20−30) controlled by the external bias

Critical electric field ~ 20−30 V/μm




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

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

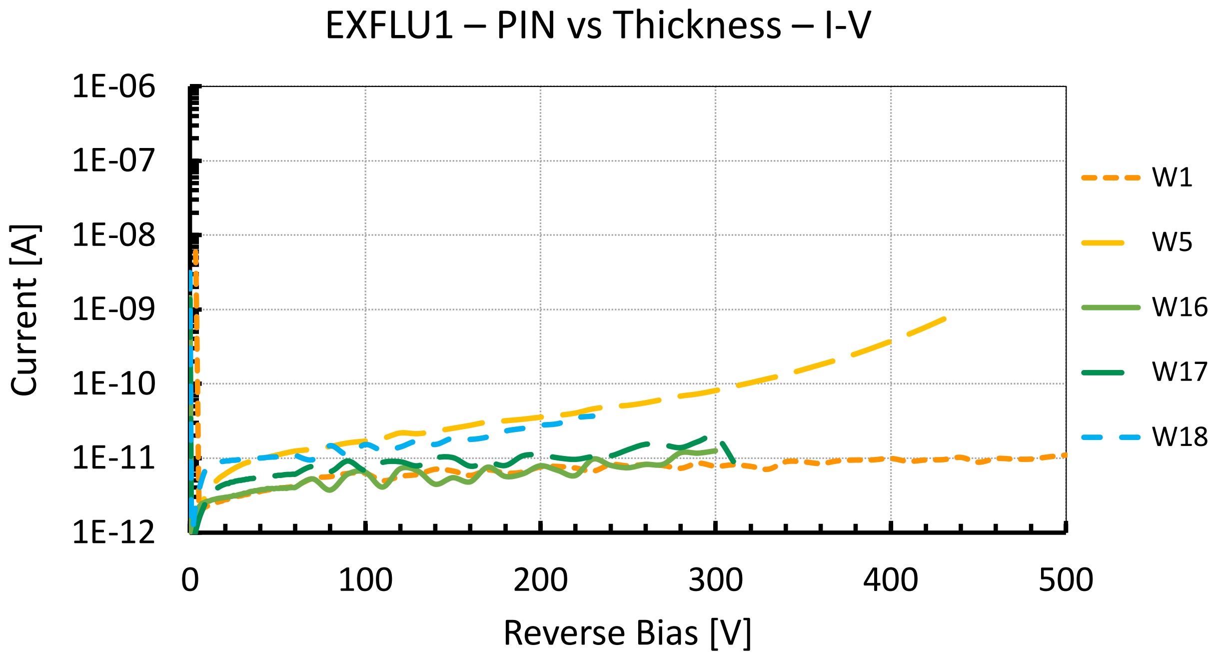
where $\mathbf{c_A}$ is the acceptor removal coefficient

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

[M. Ferrero et al., doi:10.1016/j.nima.2018.11.121]

# Standard LGAD – I-V at Different Thickness

| Wafer # | Thickness | p+ dose | C dose | Diffusion |
|---|---|---|---|---|
| 1 | 45 | 1.04 | 1.0 | CBL |
| 5 | 30 | 1.02 | 1.0 | CBL |
| 16 | 20 | 0.80 | 1.0 | CHBL |
| 17 | 20 | 0.86 | 1.0 | CBL |
| 18 | 15 | 0.84 | 1.0 | CBL |



# Standard LGAD – I-V at Different Thickness

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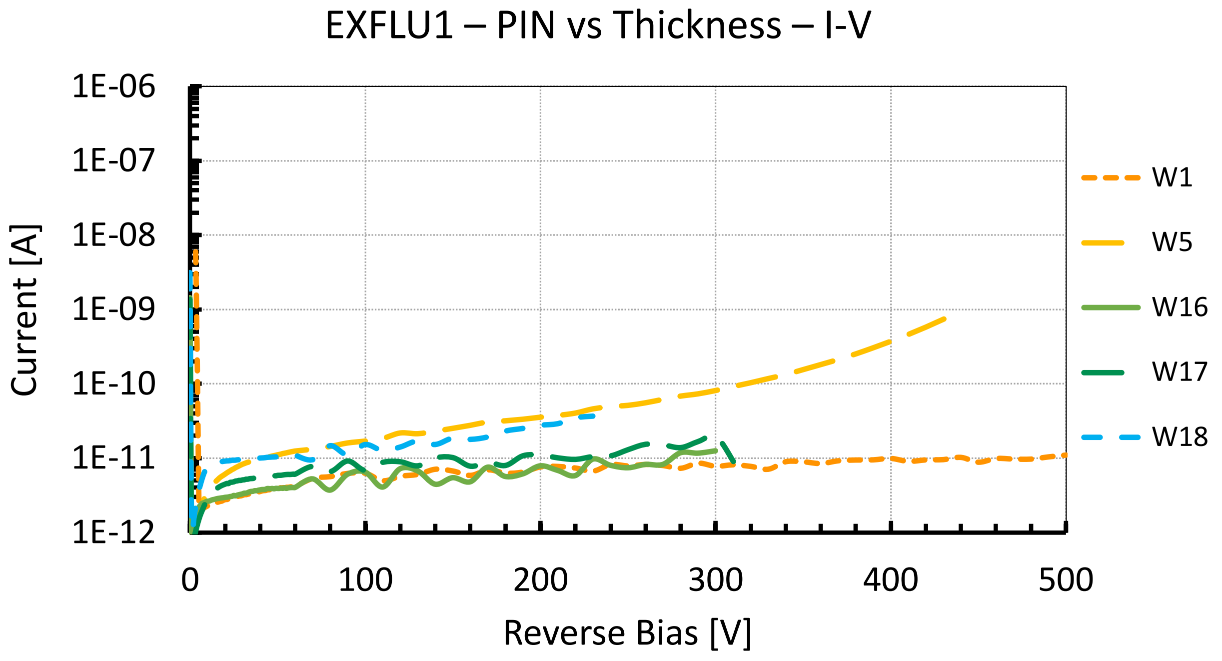
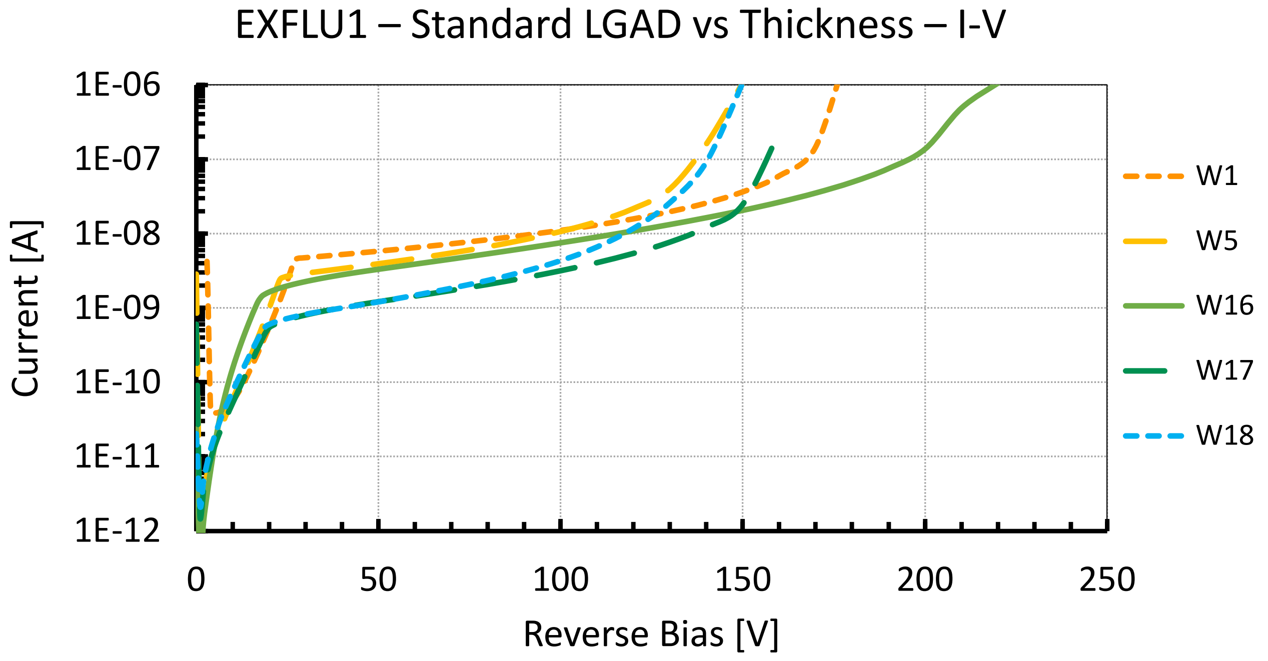
| 16 | 20 | 0.80 | 1.0 | CHBL |
| 17 | 20 | 0.86 | 1.0 | CBL |
| 18 | 15 | 0.84 | 1.0 | CBL |

In LGAD sensors, the breakdown due to gain occurs between 150 and 220 V

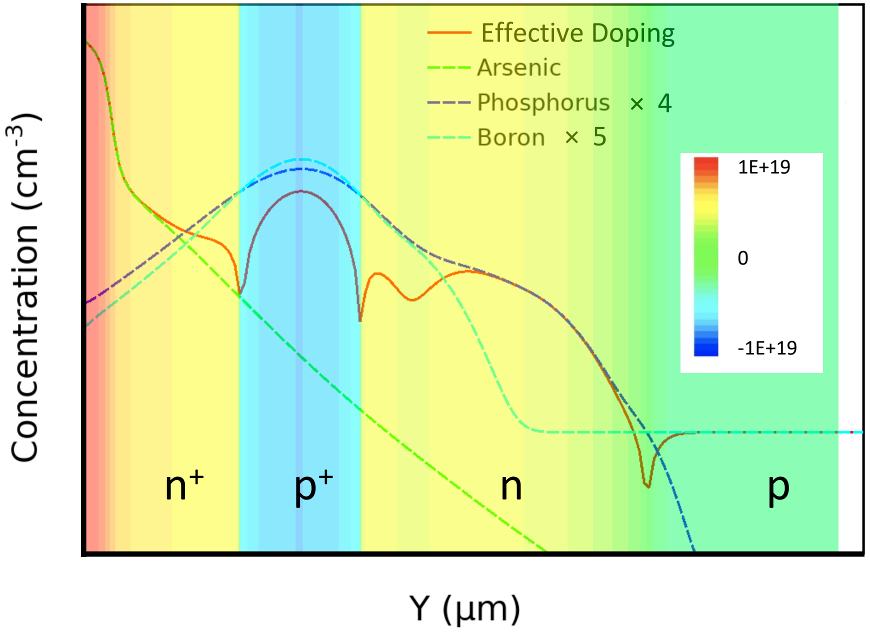


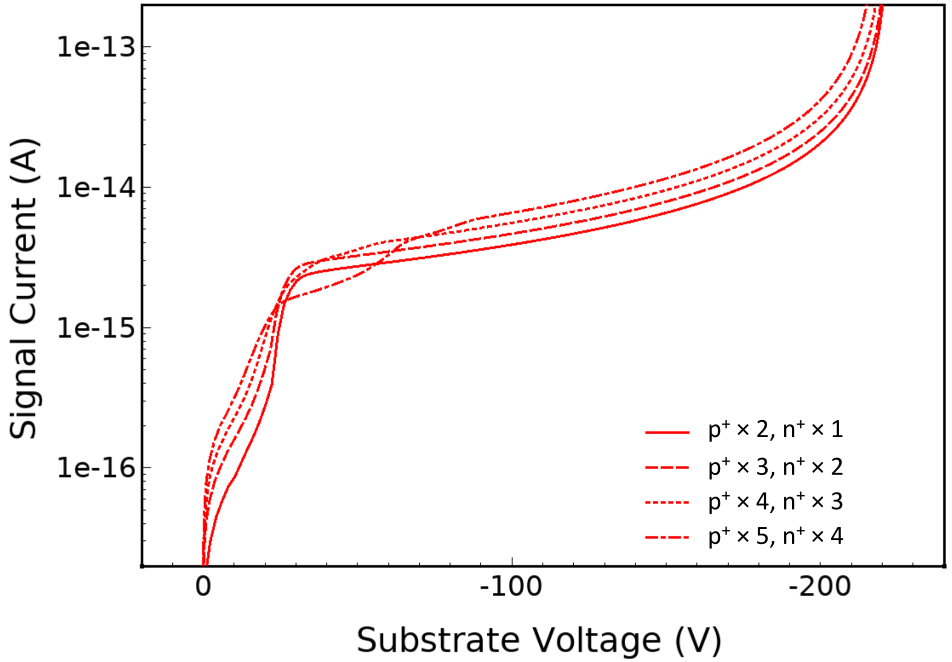
# Compensation – Simulation & Design

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

Doping Profiles from Process Simulation




I-V from Simulation




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

# 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

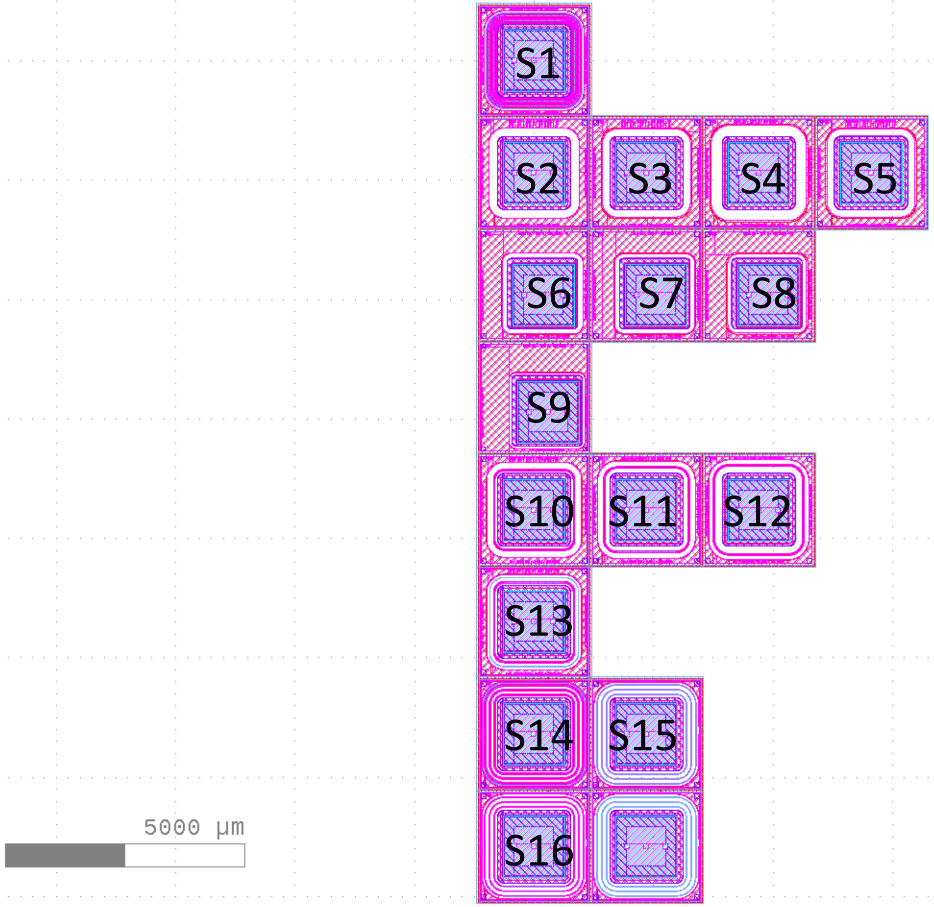
3. **$c_A < c_D$**

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

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

# 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

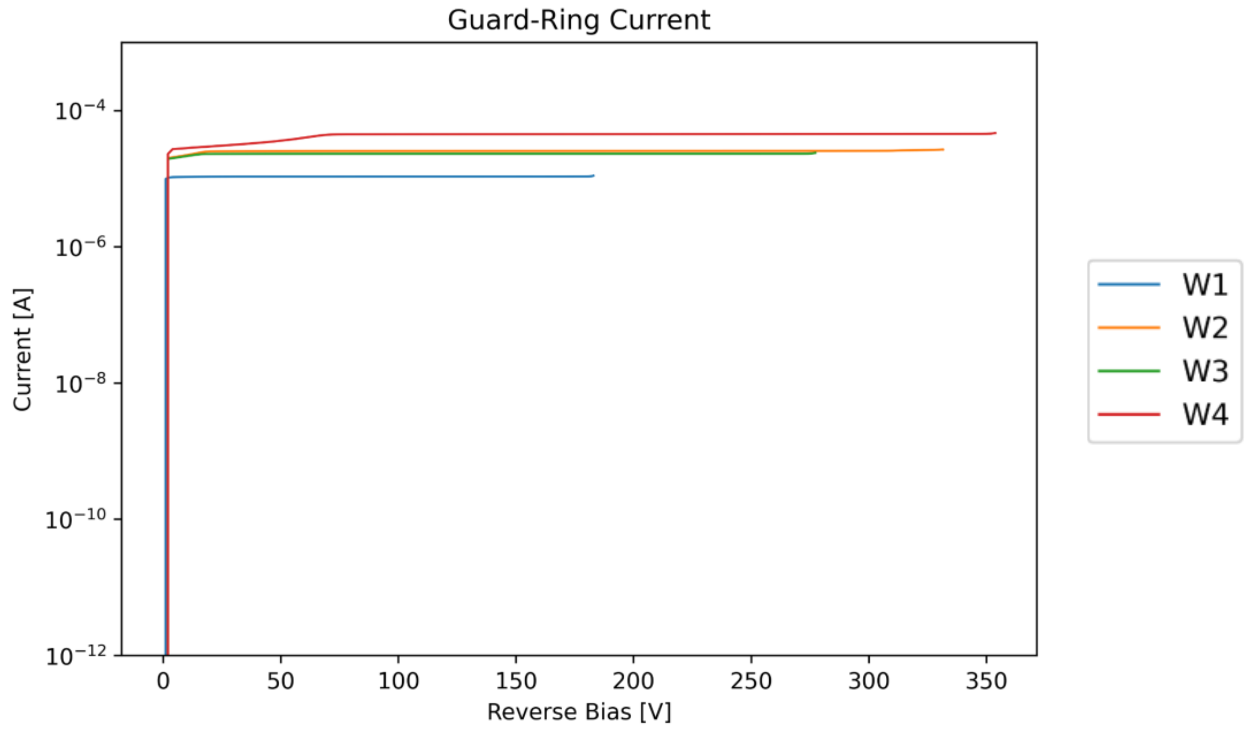
▻ 3 GR floating with different designs

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

# Optimised Guard Ring Design on 45 µm

45 µm substrates converted to n-type

EXFLU1 – 45 µm LGAD

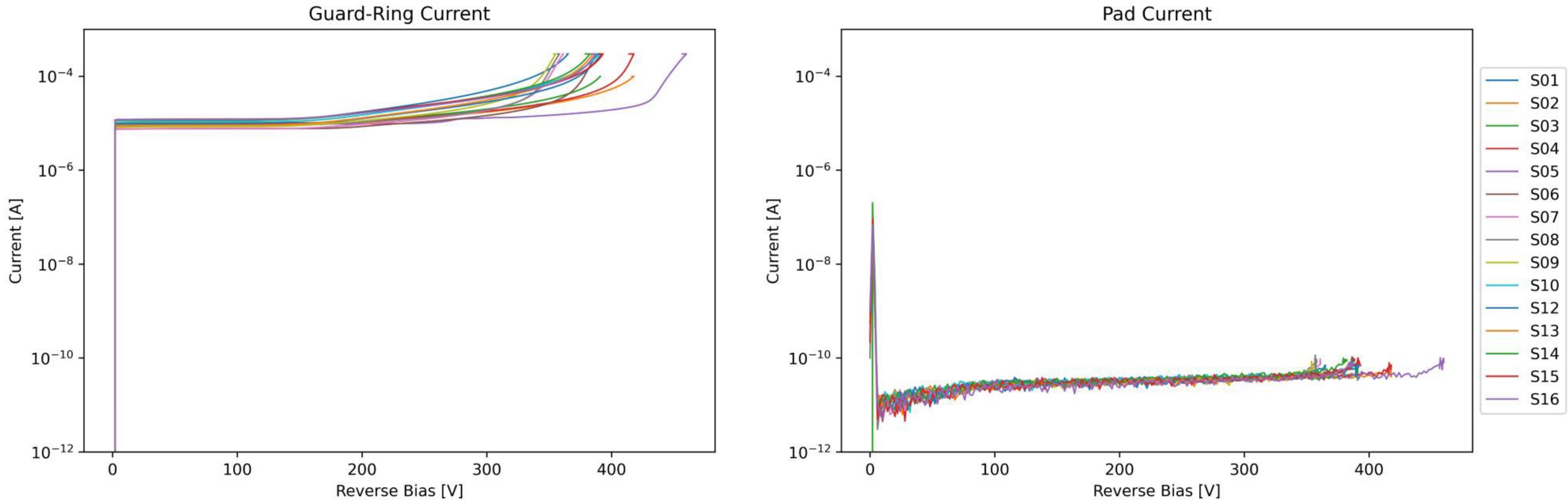



→ Due to the substrate doping, the guard ring current is high and almost constant

# Optimised Guard Ring Design on 45 µm

45 µm substrates converted to n-type

EXFLU1 – 45 µm PIN



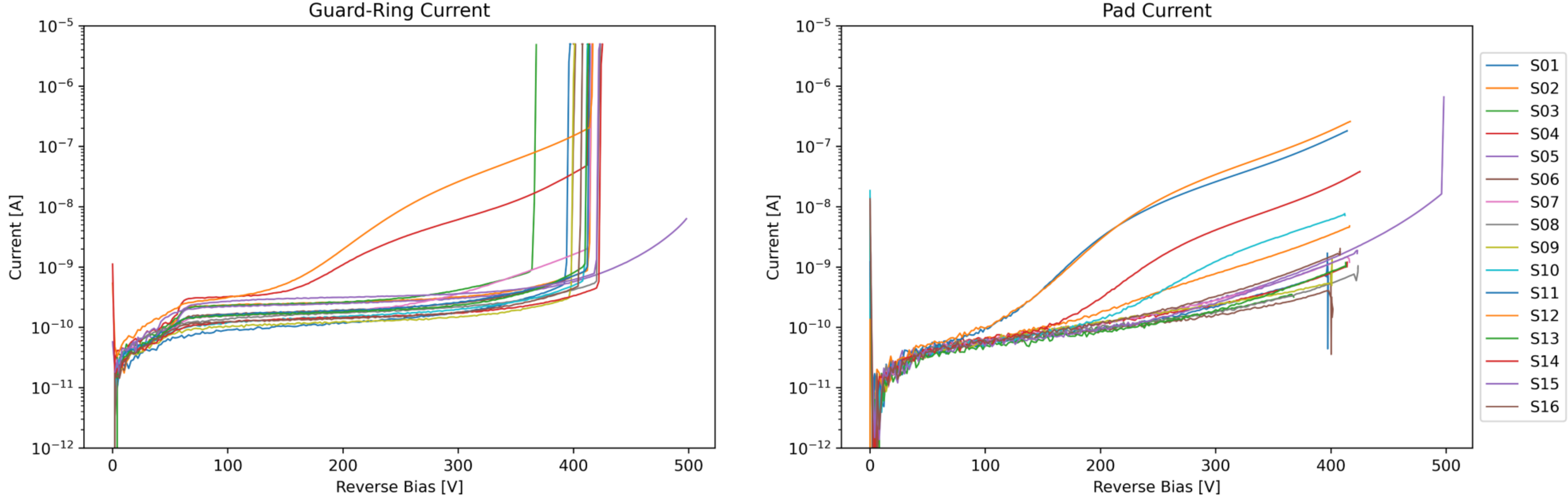

→ Due to the substrate doping, the guard ring current increases above 350 V

→ Current on the pad is small

# Optimised Guard Ring Design on 30 µm

30 µm substrates have a resistivity of ~ 900 Ω·cm

EXFLU1 – 30 µm PIN



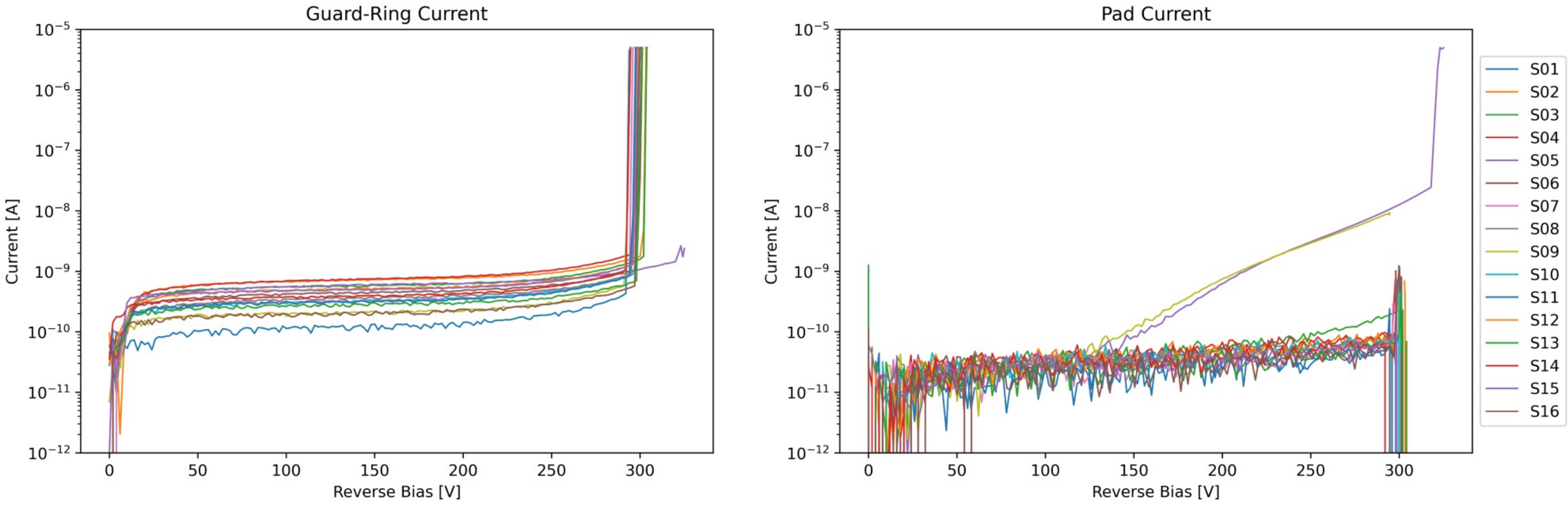

→ Most of the guard rings exhibit a breakdown at ~ 400 V ($E_{field}$ ~ 14 V/µm), except S5

→ High current observed on guard rings and pads may be due to defects in the substrate

# Optimised Guard Ring Design on 20 µm

20 µm substrates have a resistivity of ~ 90 Ω·cm

EXFLU1 – 20 µm PIN



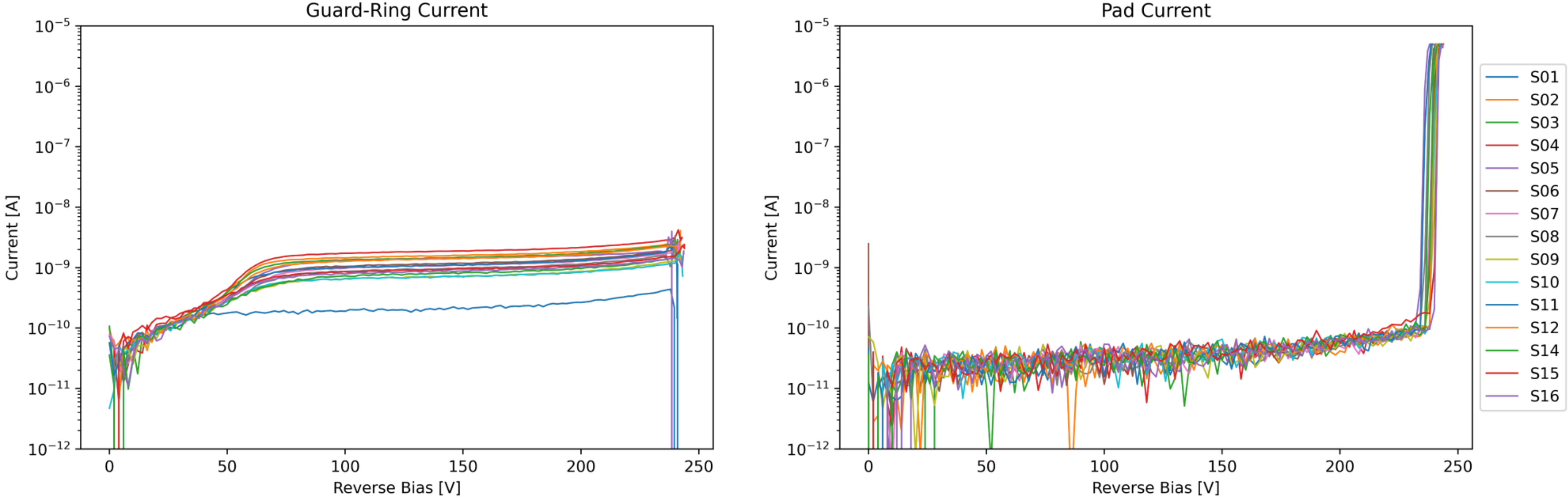

→ Most of the guard rings exhibit a breakdown at ~ 300 V ($E_{field}$ ~ 15 V/µm), except S5

→ S5 design (zero floating guard rings) reaches breakdown in the pad

# Optimised Guard Ring Design on 15 μm

15 μm substrates have a resistivity of ~ 90 Ω·cm

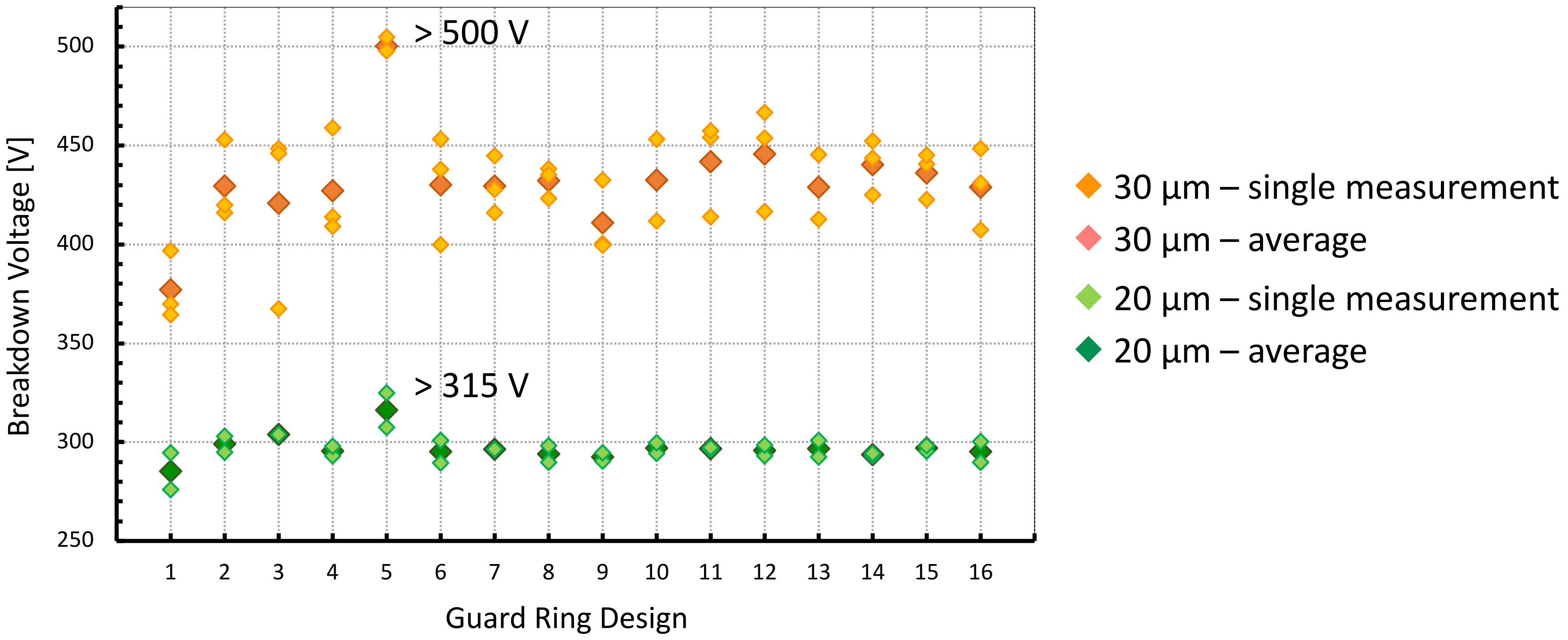
EXFLU1 – 15 μm PIN



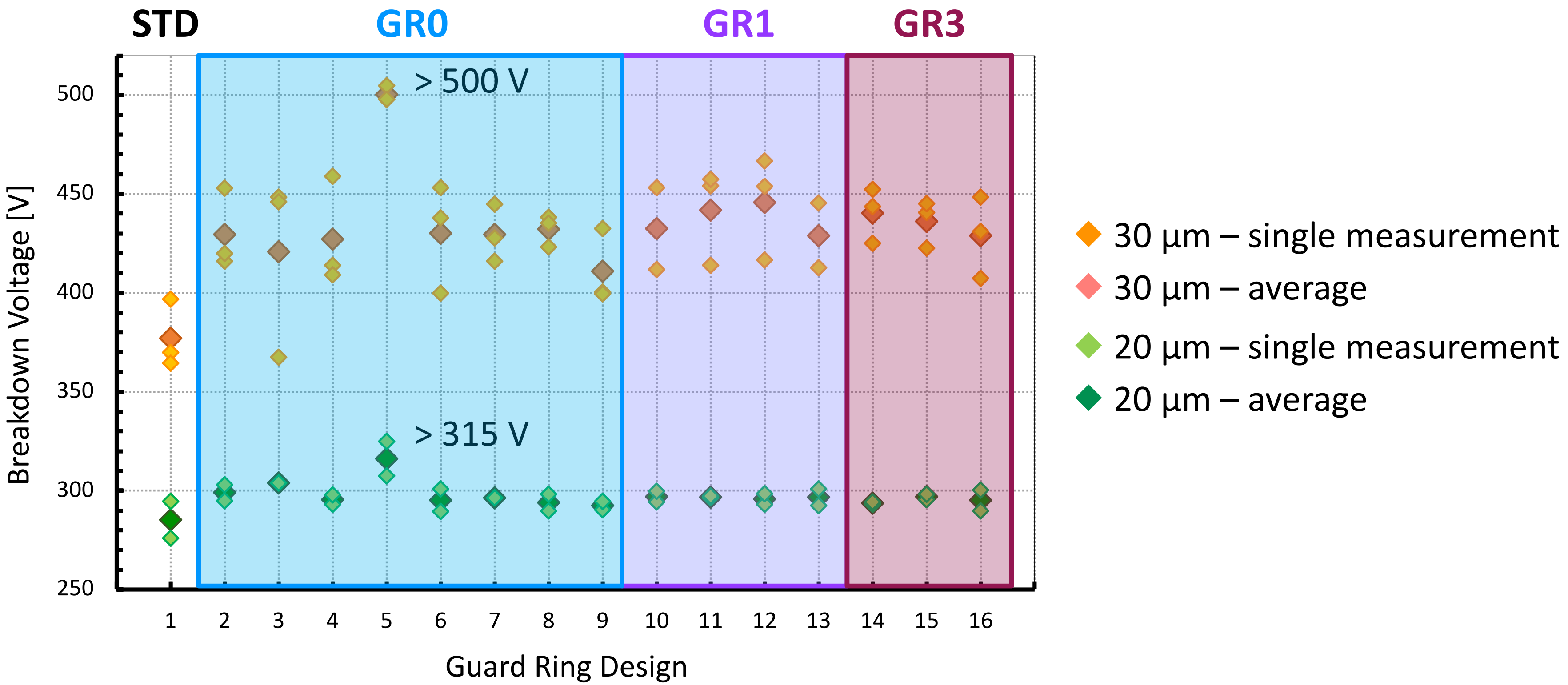

→ No breakdown on guard rings is observed up to 240 V ($E_{field}$ ~ 16 V/μm)

→ In 15 μm thick sensors, breakdown is reached in the pad

# Optimised Guard Ring Design – Summary



# 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

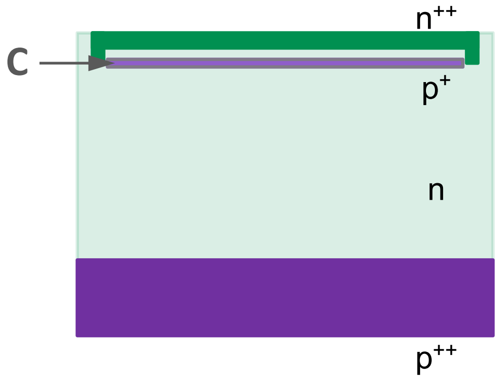
→ An extensive irradiation campaign will be performed to study the radiation tolerance of each design

# Standard LGAD with Carbon Shield

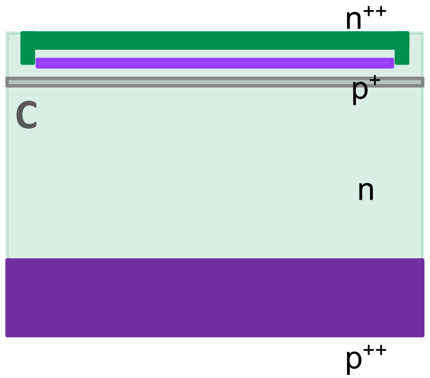
| Wafer # | Thickness | p+ dose | C dose | C shield | Diffusion |
|---|---|---|---|---|---|
| 1 | 45 | 1.04 | 1.0 | | CBL |
| 2 | 45 | 1.00 | | 0.6 | CBL |
| 3 | 45 | 1.06 | 1.0 | 0.6 | CBL |
| 4 | 45 | 1.06 | 1.0 | 1.0 | CBL |

NB: the bulk of the 45 μm substrates swapped into n-type

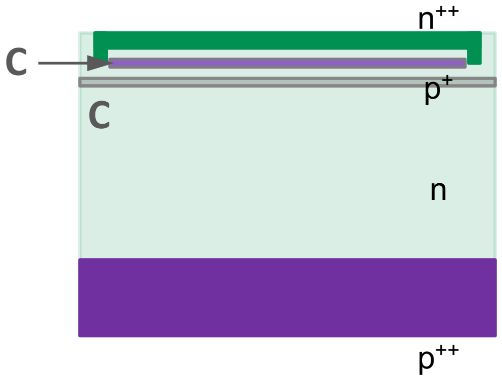
W1




W2




W3 - W4




Production costs increase by ~ 20%

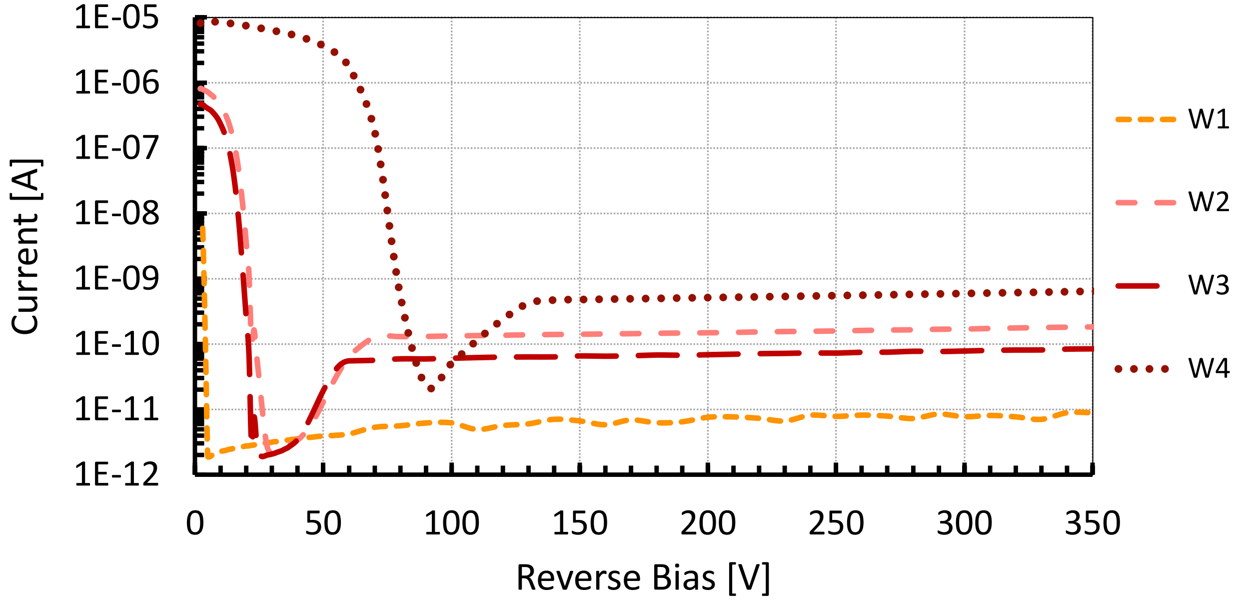
→ Expected improvement in radiation tolerance of 20 – 30%

# Standard LGAD – I-V with Carbon Shield

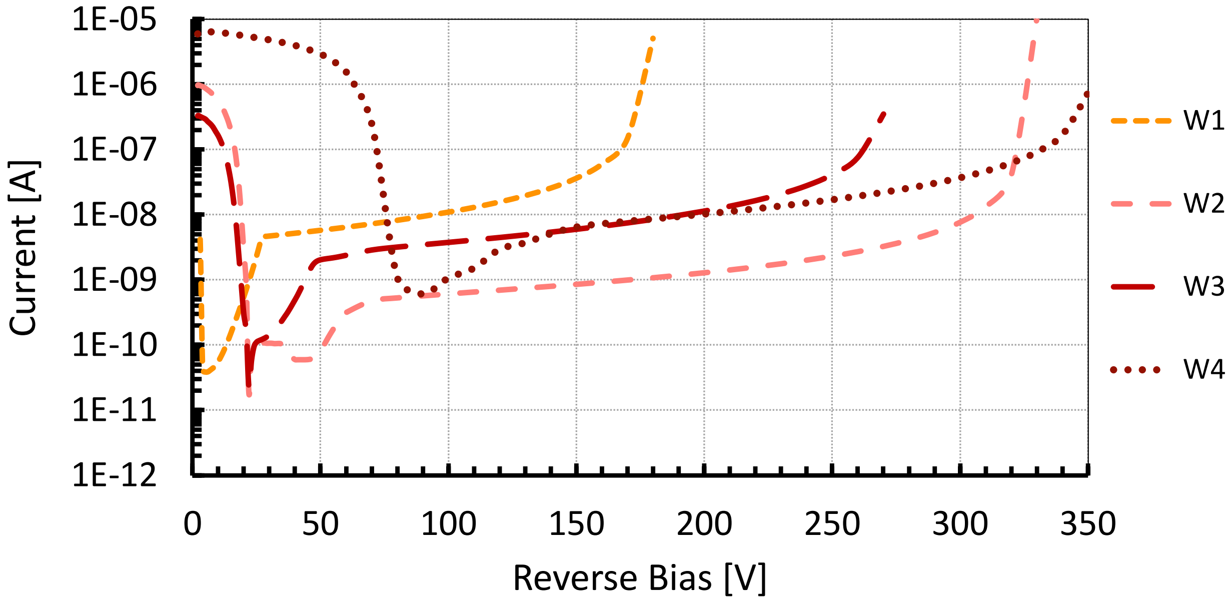
| Wafer # | Thickness | p+ dose | C dose | C shield | Diffusion |
|---|---|---|---|---|---|
| 1 | 45 | 1.04 | 1.0 | | CBL |
| 2 | 45 | 1.00 | | 0.6 | CBL |
| 3 | 45 | 1.06 | 1.0 | 0.6 | CBL |
| 4 | 45 | 1.06 | 1.0 | 1.0 | CBL |

Carbon shield shifts
the breakdown voltage
to higher values of bias

EXFLU1 – PIN with C shield – I-V




EXFLU1 – Standard LGAD with C shield – I-V



# 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

# The State-of-the-Art

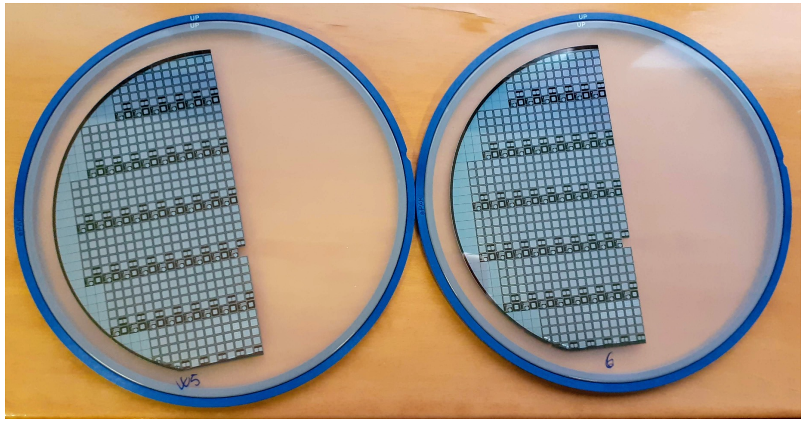
***Silicon Sensor for Extreme Fluences (eXFlu)*** **project – V. Sola as PI**

In 2020, INFN awarded for funding a 2 years grant for young researchers to **develop, produce, irradiate and study thin silicon sensors**

Thin LGAD wafers have been produced at FBK
→ **EXFLU0 production**

- 2 different wafer thicknesses: **25 & 35 μm**
- epitaxial substrates
- **single pads** and 2×2 arrays

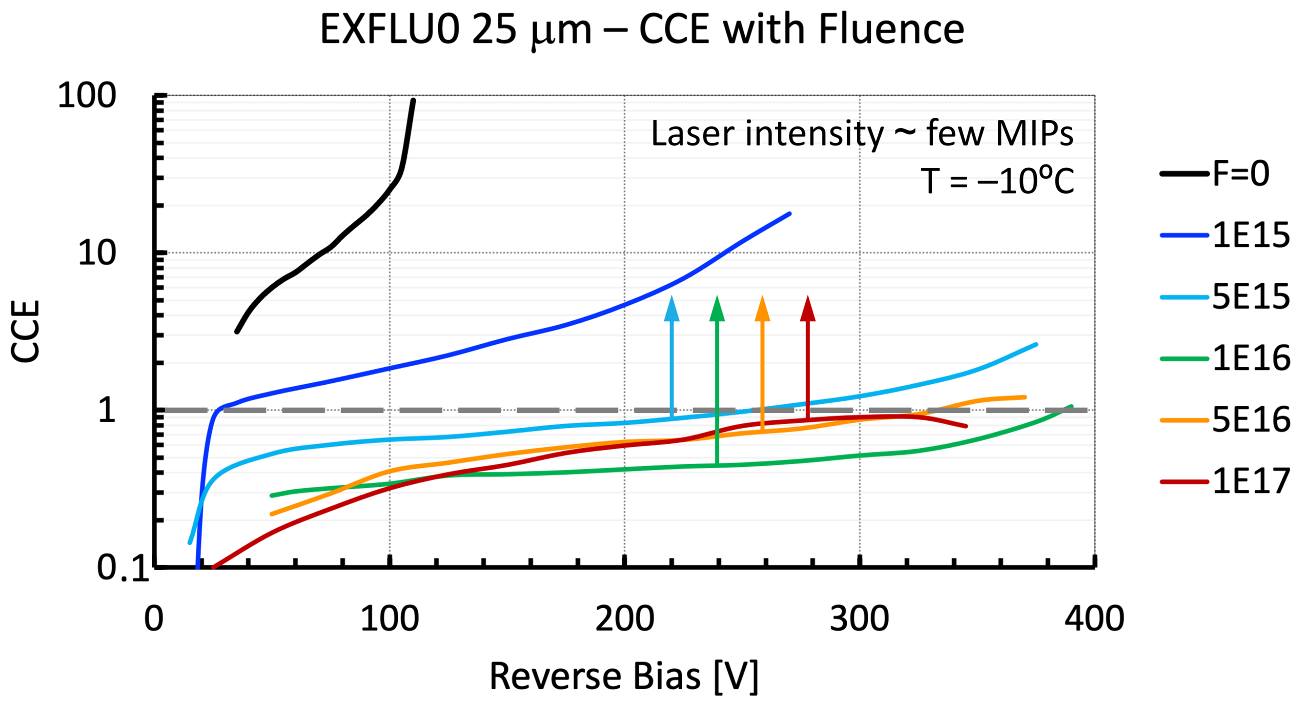
Arrived in Torino at the end of 2020



**EXFLU0 sensors have been irradiated at JSI, Ljubljana, to 5 different fluences 1E15, 5E15, 1E16, 5E16, 1E17 $n_{eq}/cm^2$**

# 25 μm LGAD Signal at Different Fluences

Measurements of charge collection efficiency (CCE) with an infra-red laser stimulus show that sensors can be operated up to the highest fluences




- The LGAD multiplication mechanism ceases existing at ~ $5 \cdot 10^{15}$ $cm^{-2}$
- From $10^{16}$ to $10^{17}$ $cm^{-2}$ the collected signal is roughly constant
- At high bias the signal increases due to internal gain, but does not reach the minimum charge required by the electronics

**→ Necessary to increase the radiation tolerance of the gain mechanism above $10^{15}$ $cm^{-2}$**

# Involved Partners – INFN TO

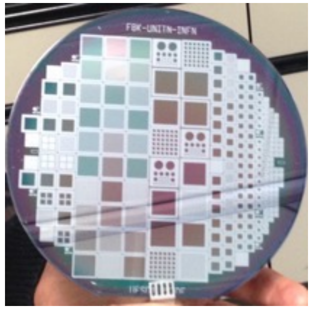
- ▻ The Torino Unit of the Istituto Nazionale di Fisica Nucleare (INFN) will
  - ⟶ coordinate the project and organise the activities
  - ⟶ follow the sensor design and production processes
  - ⟶ characterisation and test of the sensors
  - ⟶ organise of the irradiation campaign
  - ⟶ provide the input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


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

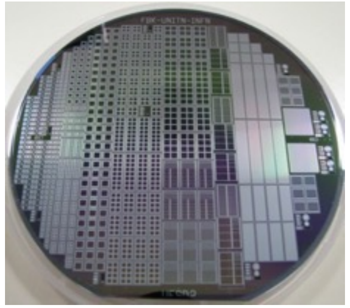
# Involved Partners – FBK

- 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

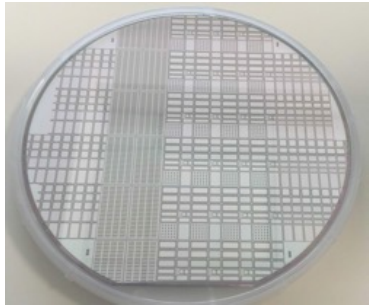
Previous LGAD productions at FBK (not-exhaustive list)



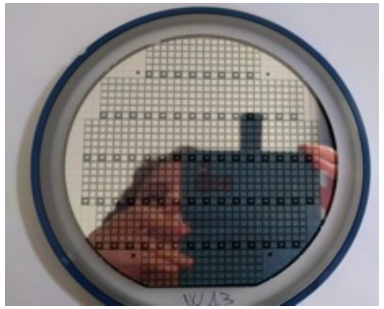
UFSD1
2016



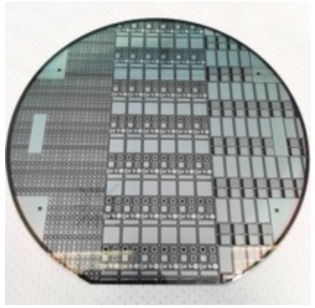
UFSD2
2017



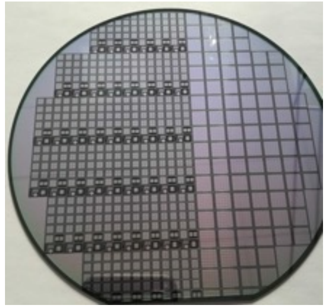
UFSD3
2018



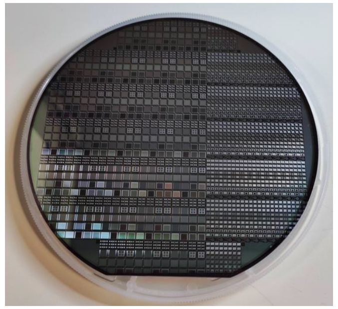
UFSD3.1
2019



RSD1
2019



UFSD3.2 + EXFLU0
2020



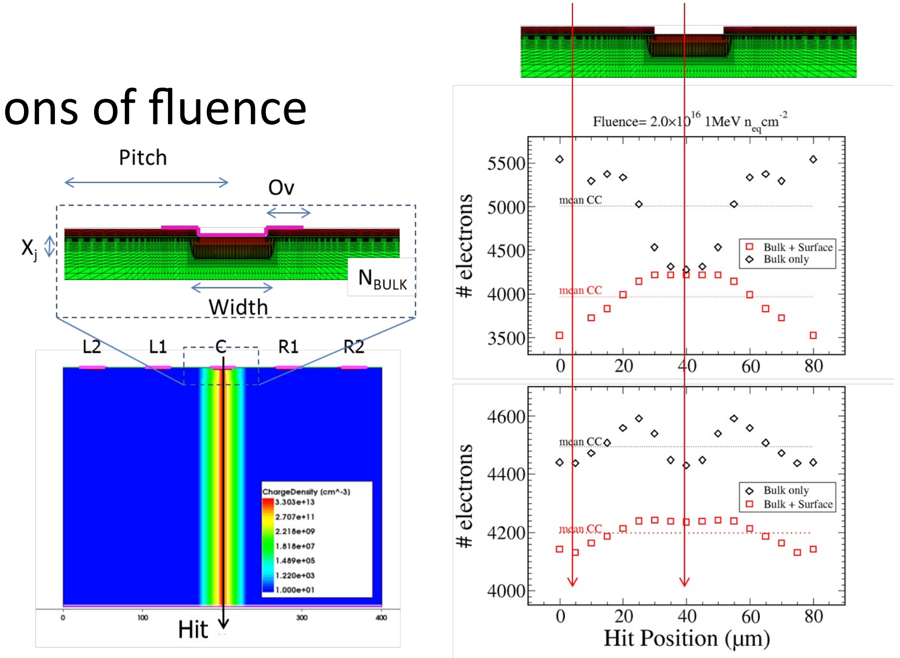
TI–LGAD
2021

⇒ 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.