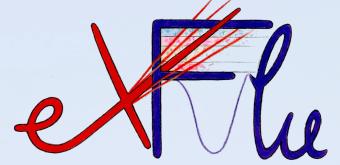




42nd RD50 Workshop on Radiation Hard Semiconductor Devices for Very High Luminosity Colliders

20–23 June 2023

Hotel Regent Porto Montenegro
Tivat, Montenegro



Characterisation of the EXFLU1 batch from FBK

V. Sola, R. Arcidiacono, G. Borghi, M. Boscardin, N. Cartiglia, M. Centis Vignali, M. Costa, T. Croci,
M. Ferrero, F. Ficarella, A. Fondacci, S. Giordanengo, O. Hammad Ali, L. Lanteri, L. Menzio,
A. Morozzi, F. Moscatelli, R. Mulargia, D. Passeri, N. Pastrone, G. Paternoster, F. Siviero



The EXFLU1 Batch at a Glance



Latest batch of thin LGAD by the FBK foundry ⇒ EXFLU1

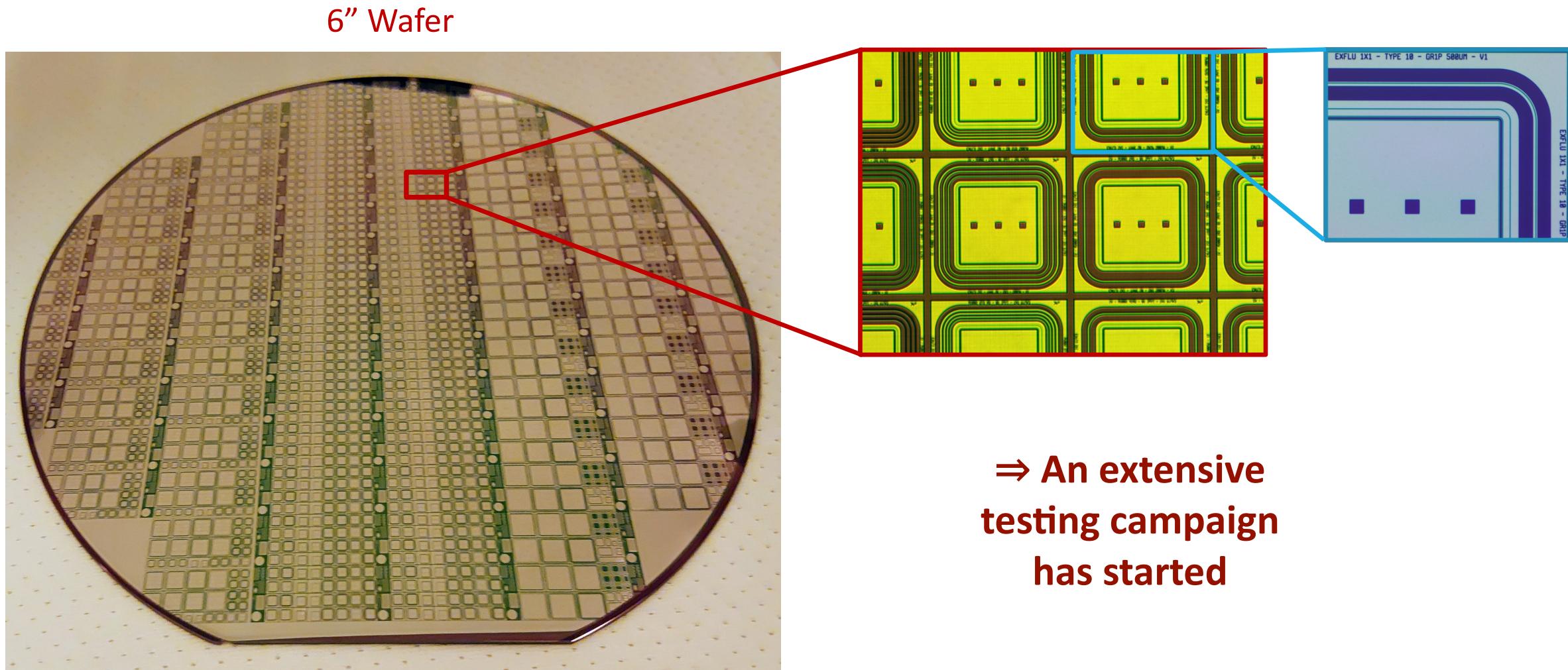
The EXFLU1 batch from FBK explores different innovation strategies to extend the radiation tolerance of silicon sensors up to the extreme fluences:

- ▷ new guard ring design
- ▷ decrease of the acceptor removal – carbon shield
- ▷ thin substrates (15–45 µm)
- ▷ signal multiplication up to the extreme fluences – compensation

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**

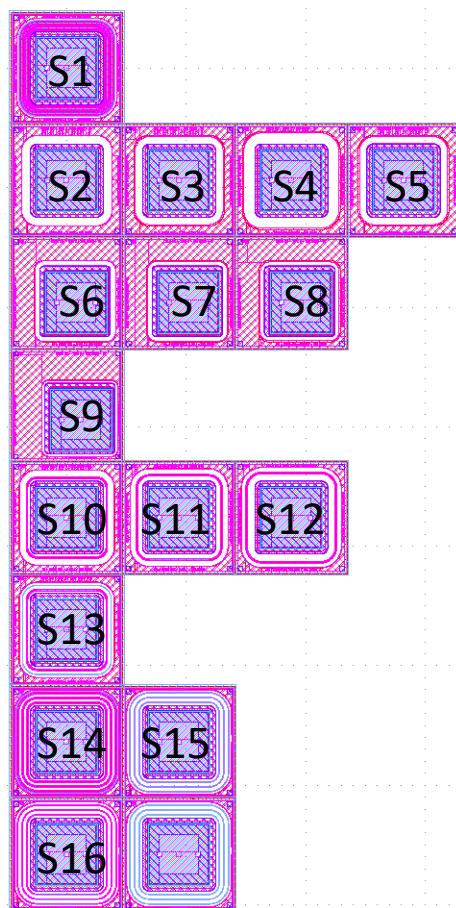
The EXFLU1 Wafers



Guard Ring Design

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

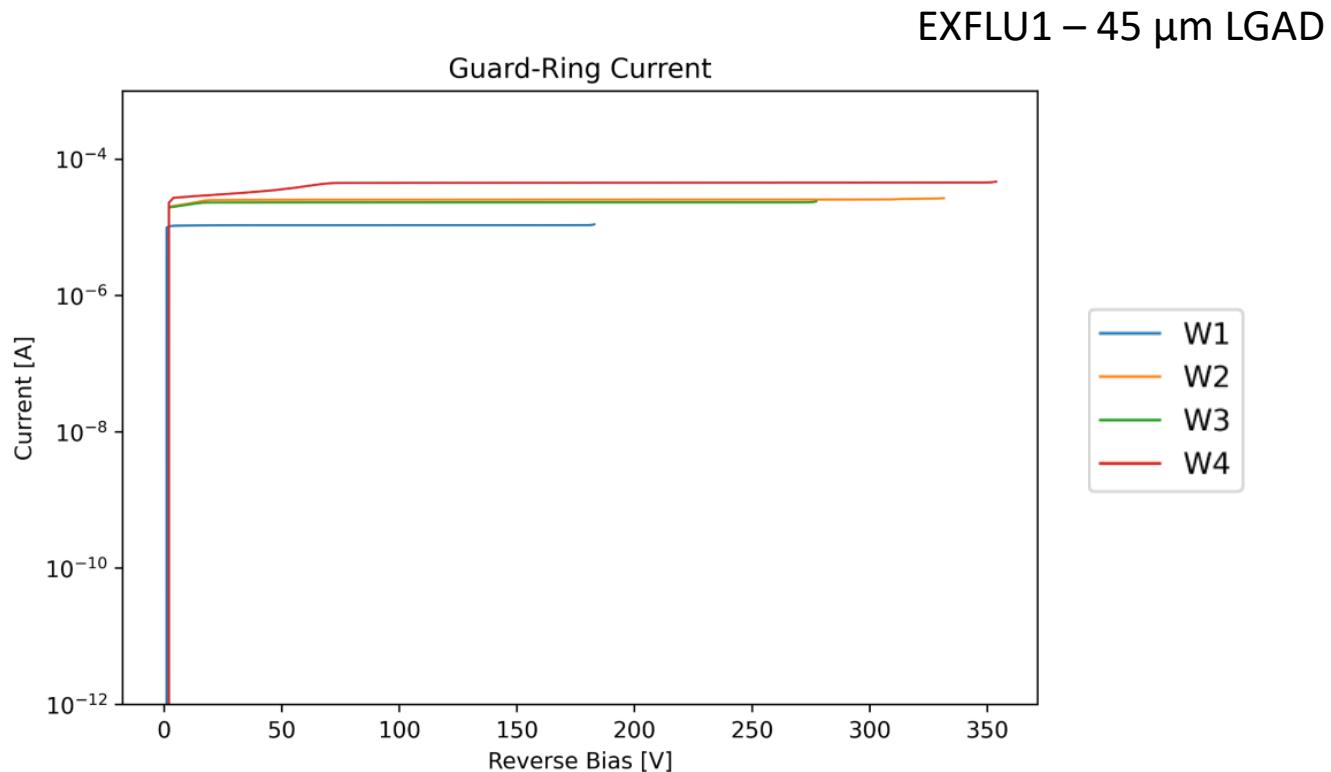
- ▷ 1 GR floating, varying the GR position

- ▷ 3 GR floating with different designs

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

Optimised Guard Ring Design on 45 μm

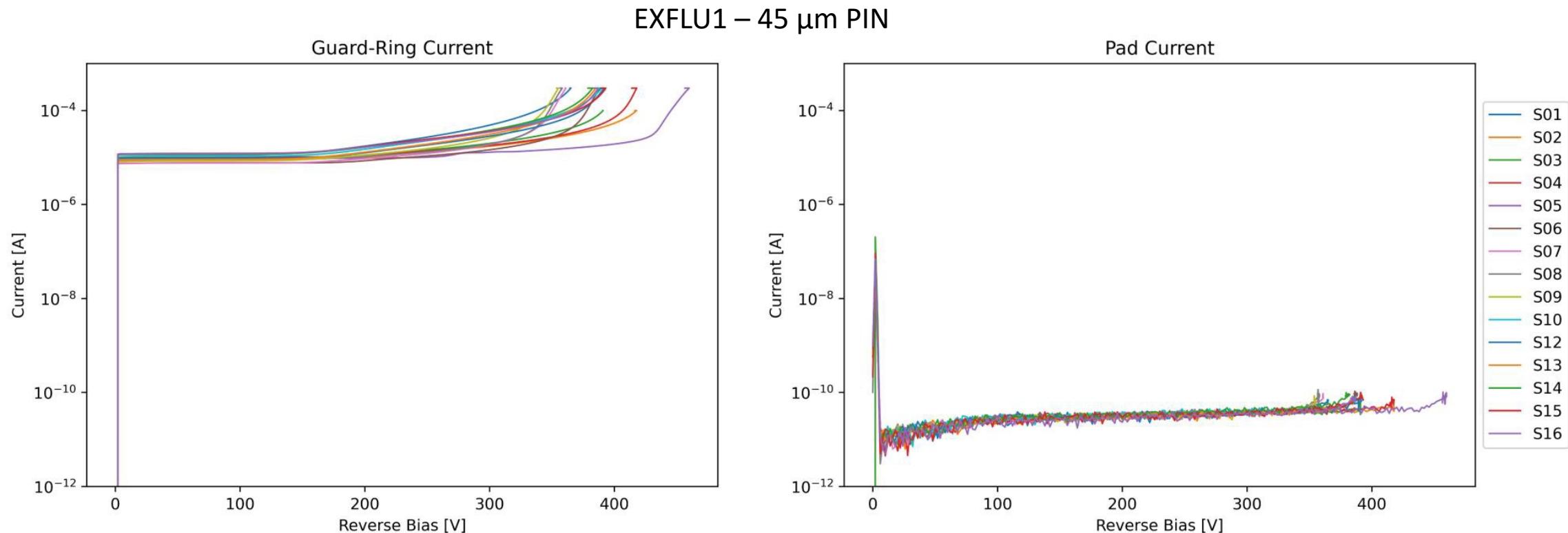
45 μm substrates converted to n-type



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

Optimised Guard Ring Design on 45 µm

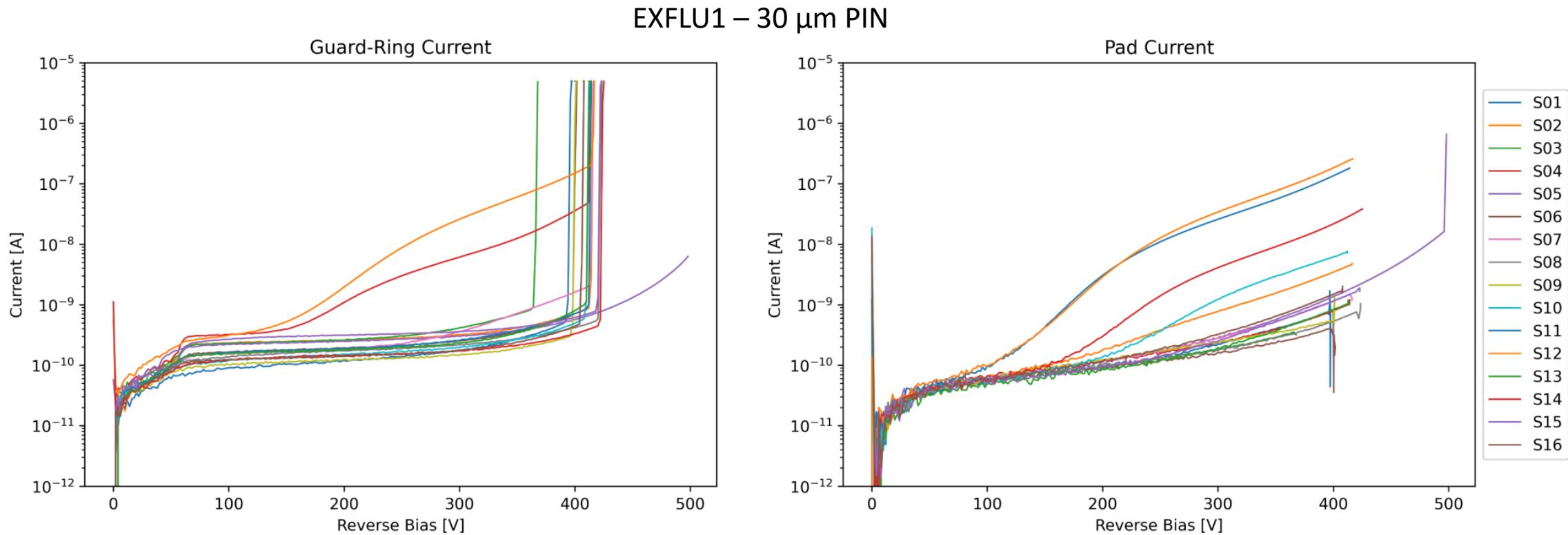
45 µm substrates converted to n-type



- 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

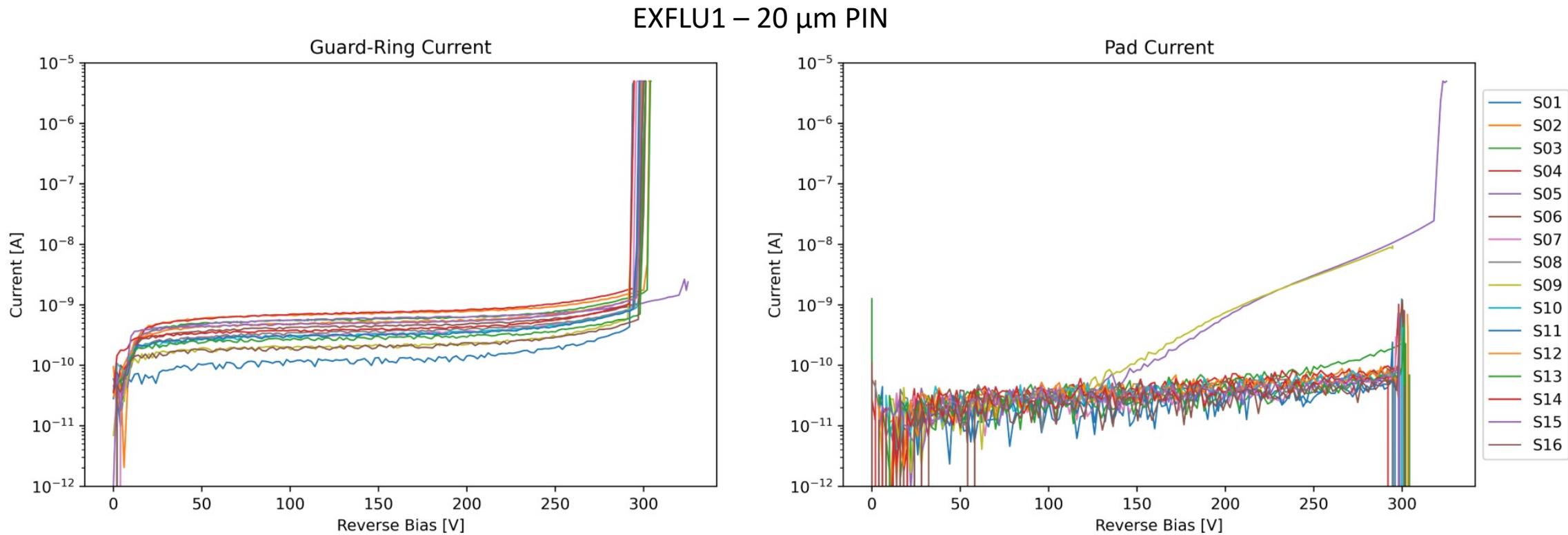
30 μm substrates have a resistivity of $\sim 900 \Omega\cdot\text{cm}$



- Most of the guard rings exhibit a breakdown at $\sim 400 \text{ V}$ ($E_{\text{field}} \sim 14 \text{ V}/\mu\text{m}$), 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

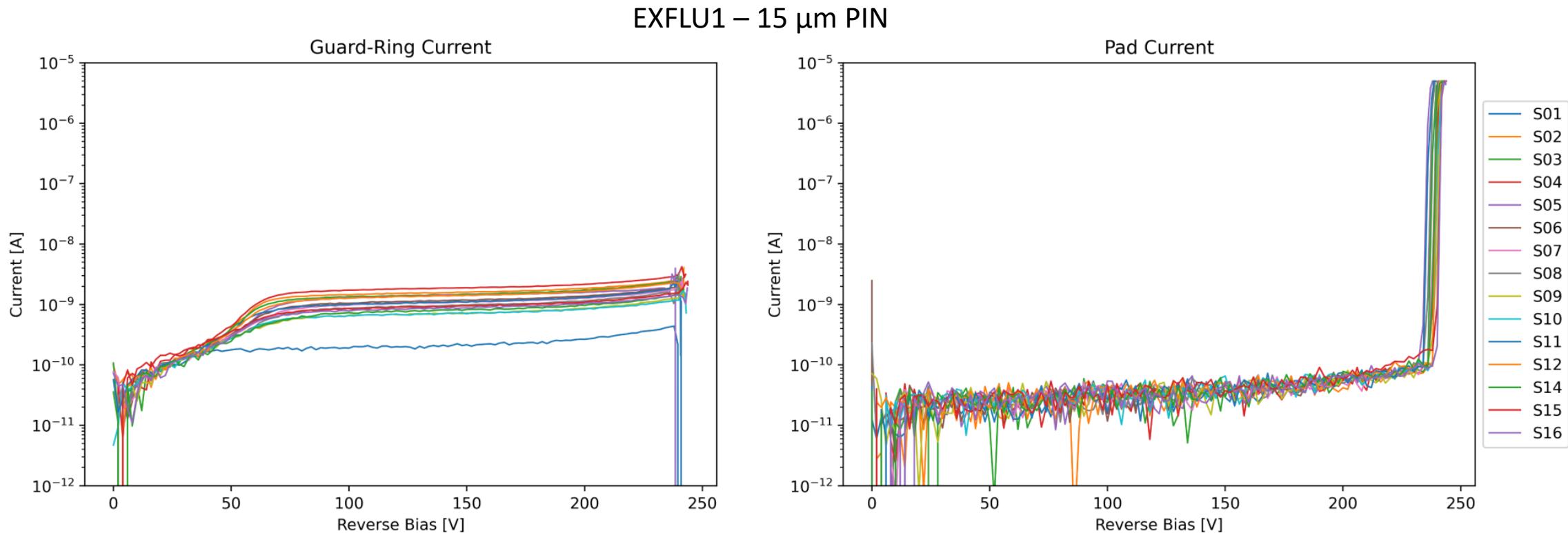
20 μm substrates have a resistivity of $\sim 90 \Omega\cdot\text{cm}$



- Most of the guard rings exhibit a breakdown at $\sim 300 \text{ V}$ ($E_{\text{field}} \sim 15 \text{ V}/\mu\text{m}$), except S5
- S5 design (zero floating guard rings) reaches breakdown in the pad

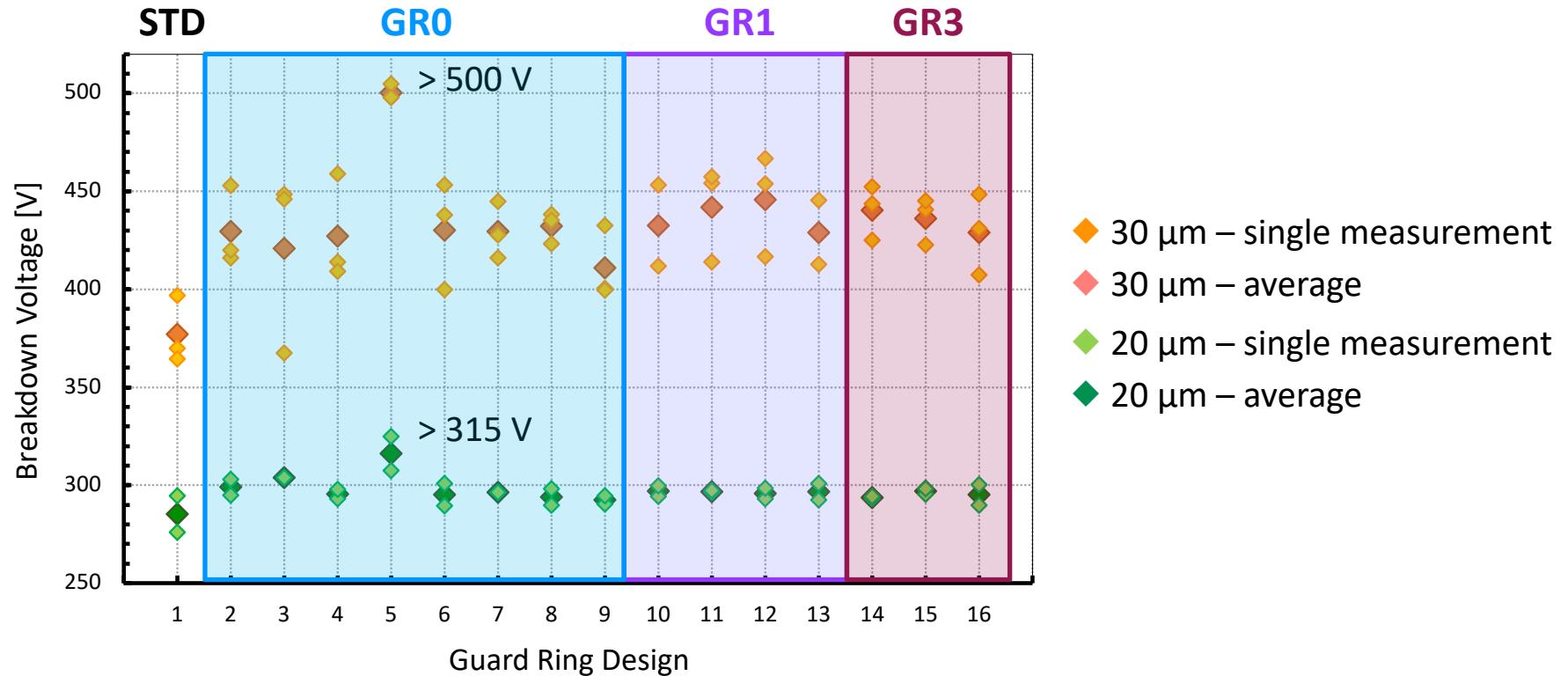
Optimised Guard Ring Design on 15 μm

15 μm substrates have a resistivity of $\sim 90 \Omega\cdot\text{cm}$



- **No breakdown** on guard rings is observed up to 240 V ($E_{\text{field}} \sim 16 \text{ V}/\mu\text{m}$)
- In 15 μm thick sensors, breakdown is reached in the pad

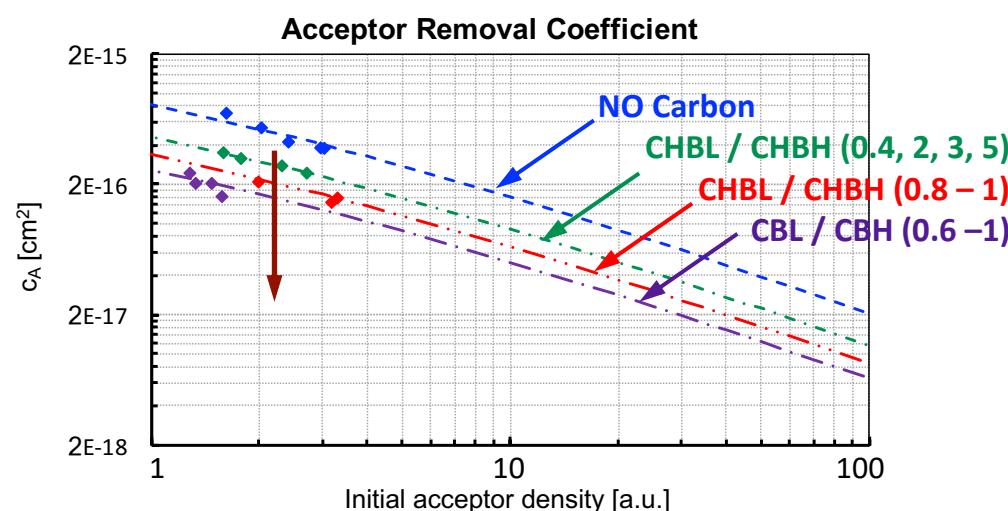
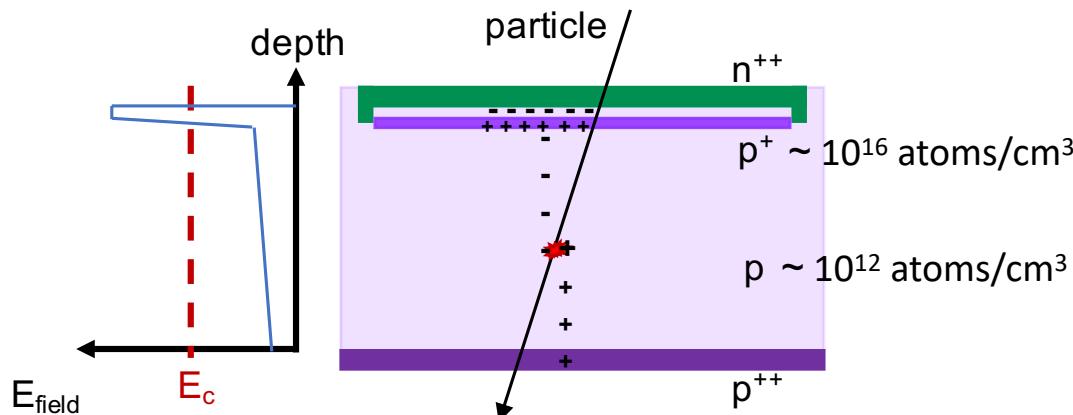
Optimised Guard Ring Design – Summary



- 30 μm thick sensors show a bigger variation in the breakdown voltage wrt 20 μm thick ones
- A study on the appearance of spurious signals depending on the guard ring design still pending
- An extensive irradiation campaign will be performed to study the radiation tolerance of each design

Carbon Shield

Gain Removal Mechanism Mitigation



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 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

[M. Ferrero et al., [doi:10.1201/9781003131946](https://doi.org/10.1201/9781003131946)]

Is it possible to further reduce c_A ?

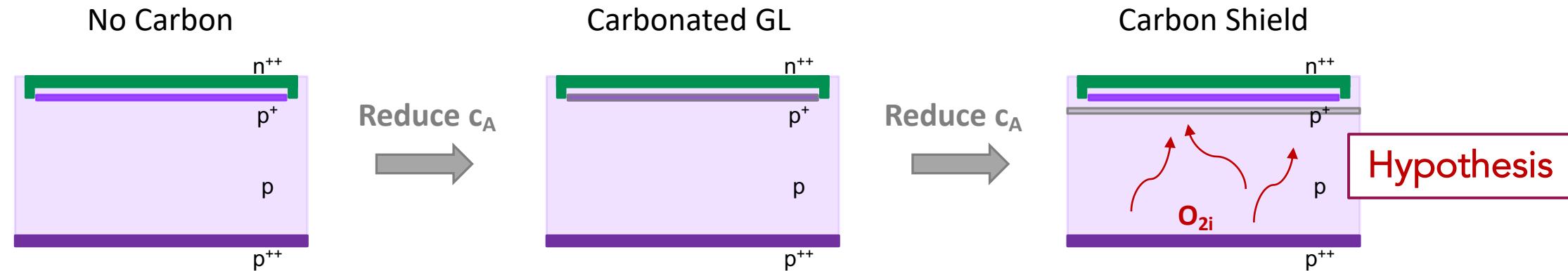
⇒ The goal is to preserve the gain up to
 $\Phi = 5 \cdot 10^{15} n_{\text{eq}}/\text{cm}^2$



A Carbon Shield to further improve c_A

Defect engineering strategy to enhance the gain layer radiation tolerance

→ A **Carbon shield** will be infused below the gain layer volume to protect the gain layer from the diffusion of defect complexes from the bulk region and the support wafer



A spray of Carbon will be introduced below the gain layer region to protect the gain layer atoms from defects moving towards the n⁺⁺ electrode during process thermal loads or exposure to particle radiation

→ Oxygen dimers can be captured by the Carbon atoms, preventing the removal of acceptors

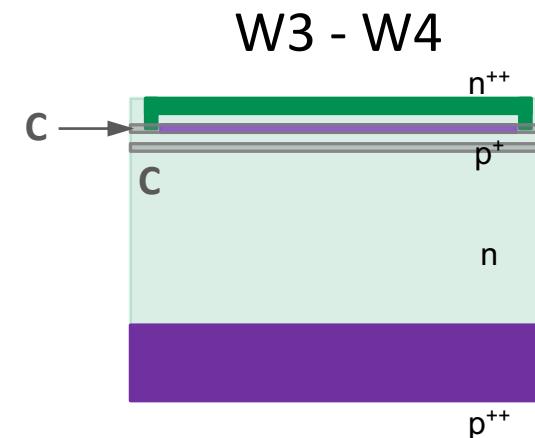
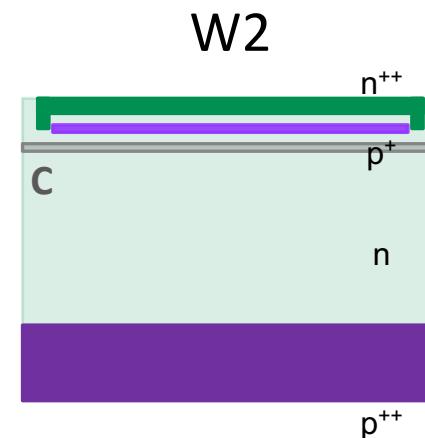
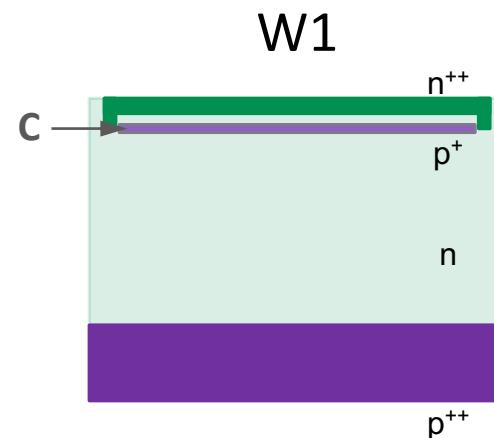


LGAD with Carbon Shield

Wafer #	Thickness	p+ dose	C dose	C shield	Diffusion
1	45	1.14	1.0		CBL
2*	45	1.00		0.6	CBL
3*	45	1.16	1.0	0.6	CBL
4*	45	1.16	1.0	1.0	CBL

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

* C shield



Production costs increase by $\sim 20\%$

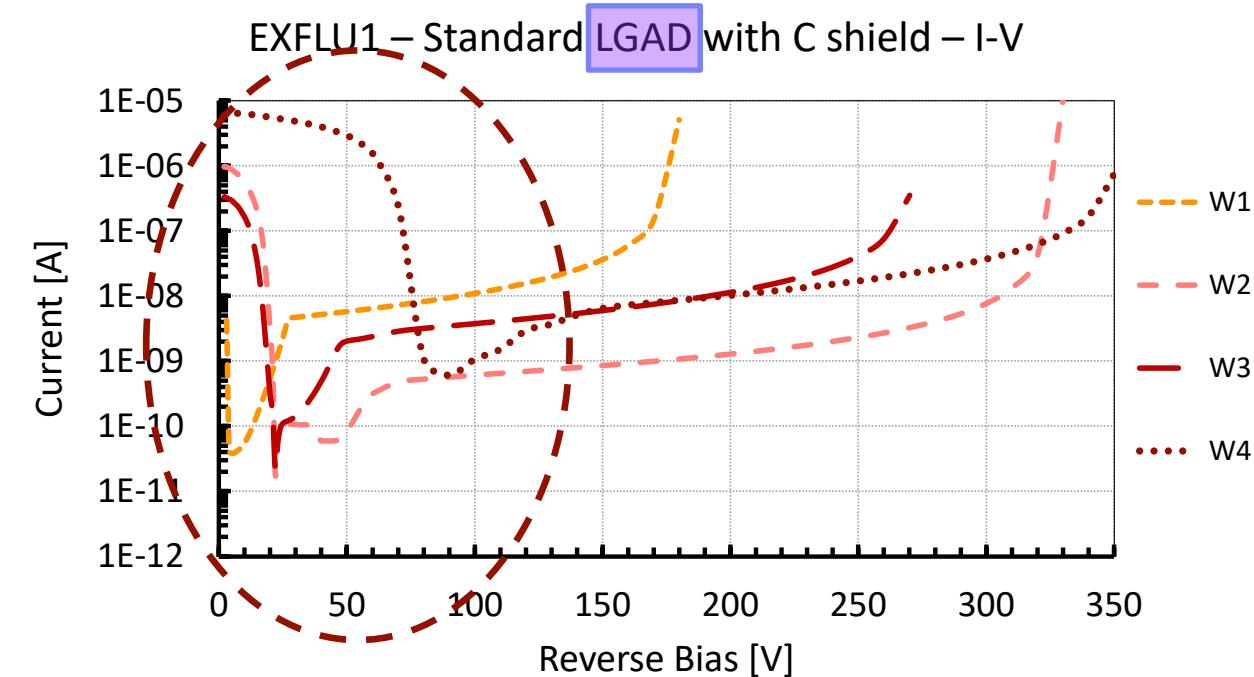
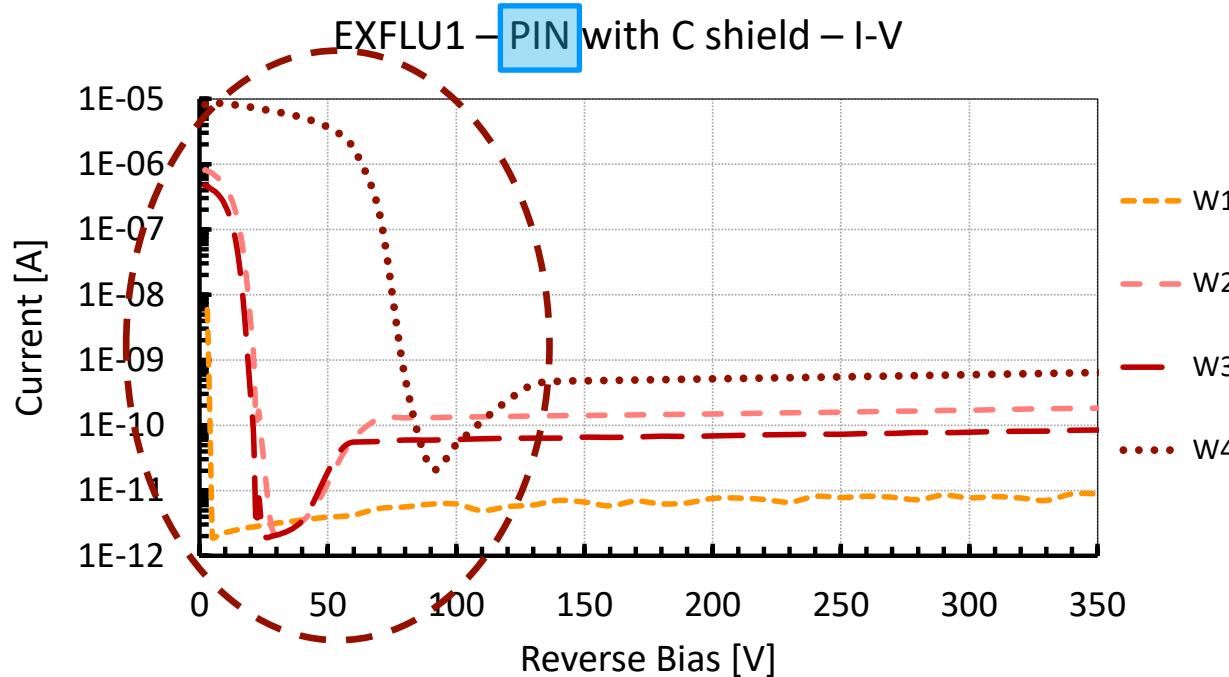
→ Expected improvement in radiation tolerance of 20 – 30%



LGAD with Carbon Shield – I-V

Wafer #	Thickness	p+ dose	C dose	C shield	Diffusion
1	45	1.14	1.0		CBL
2 *	45	1.00		0.6	CBL
3 *	45	1.16	1.0	0.6	CBL
4 *	45	1.16	1.0	1.0	CBL

→ Irradiation may cure
the high current
at low bias



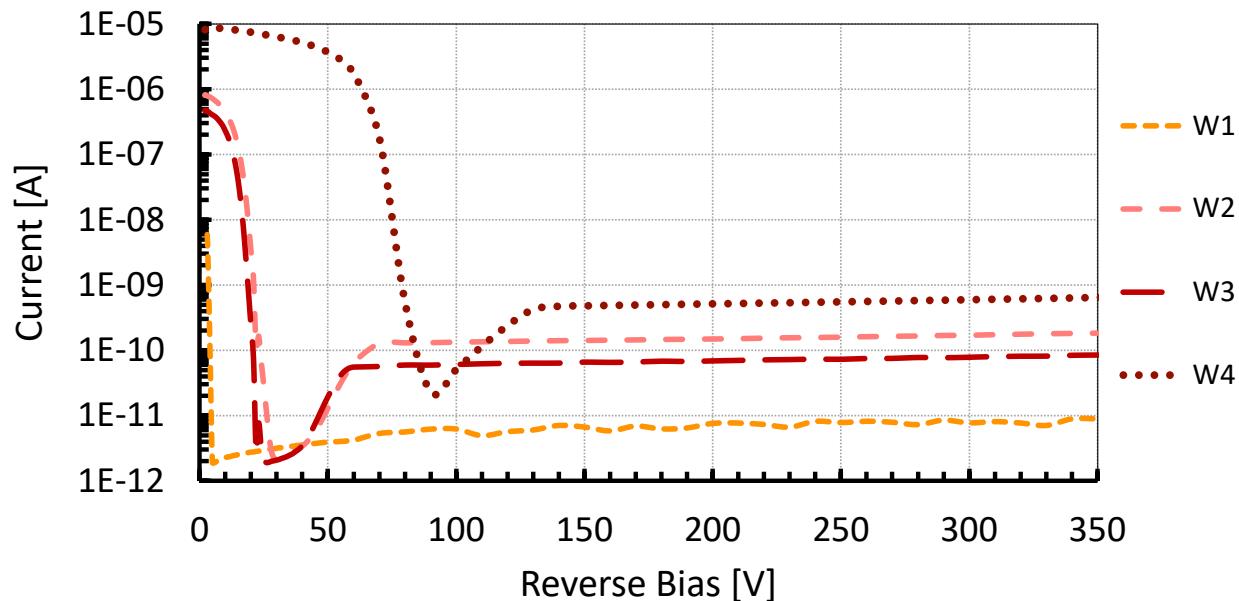


LGAD with Carbon Shield – I-V

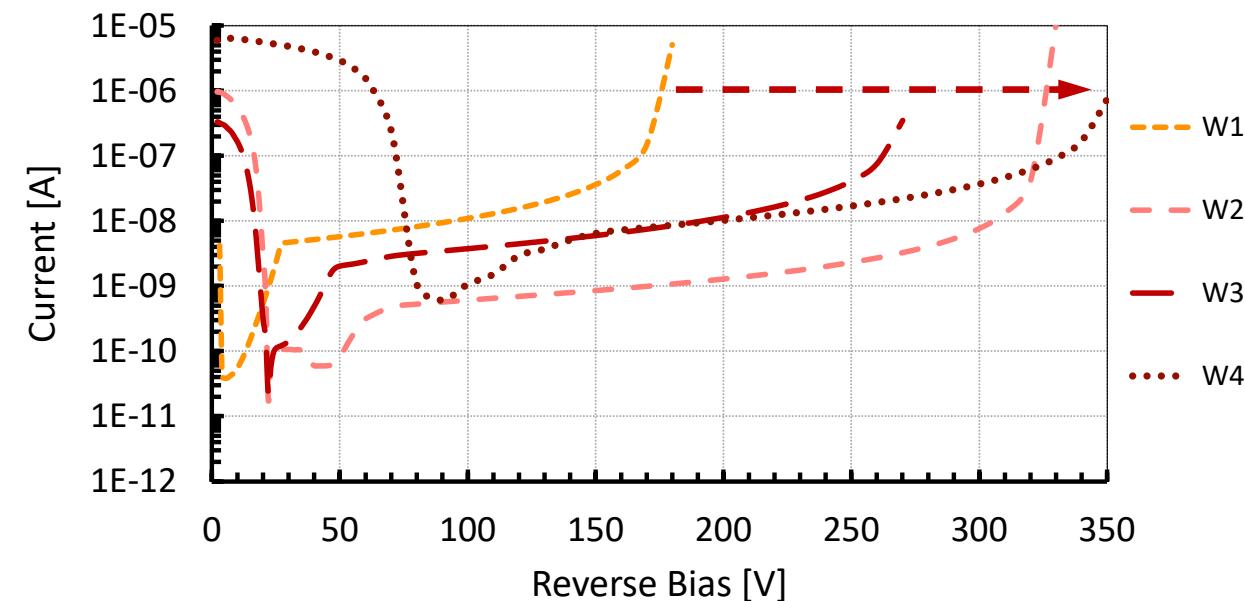
Wafer #	Thickness	p+ dose	C dose	C shield	Diffusion
1	45	1.14	1.0		CBL
2 *	45	1.00		0.6	CBL
3 *	45	1.16	1.0	0.6	CBL
4 *	45	1.16	1.0	1.0	CBL

→ Carbon shield shifts the breakdown voltage to higher values of bias

EXFLU1 – PIN with C shield – I-V

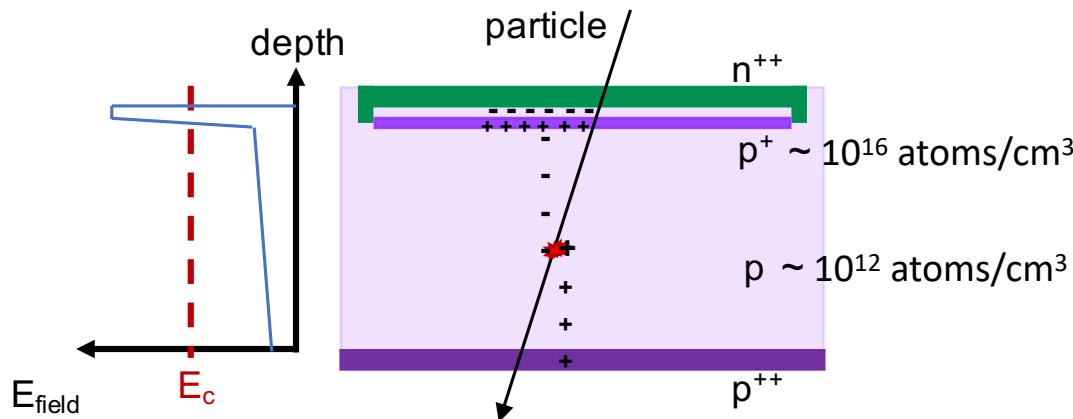


EXFLU1 – Standard LGAD with C shield – I-V



Thin LGAD

Gain Removal Mechanism in LGADs

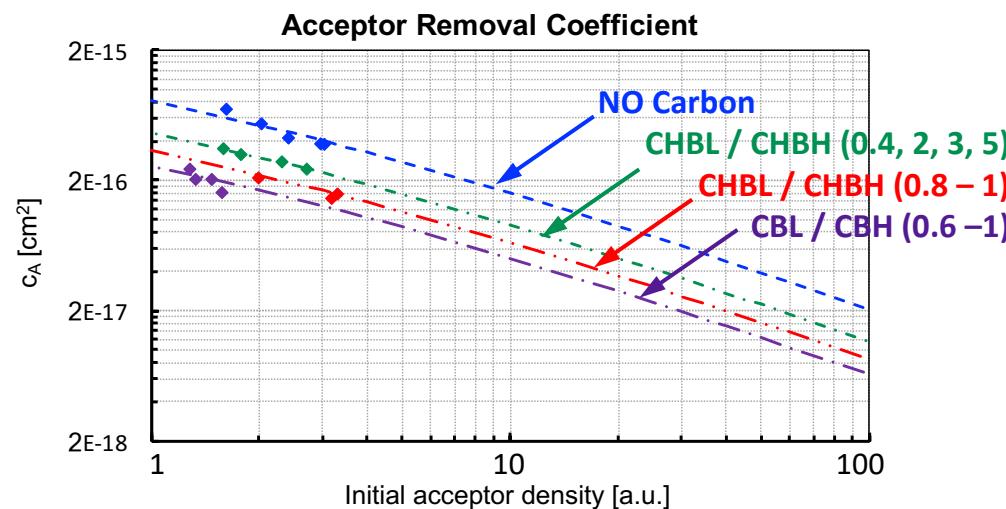


The acceptor removal mechanism deactivates the p⁺-doping of the **gain layer** with irradiation according to

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

where 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



⇒ The goal is to further investigate the CBL design in combination with thin substrates

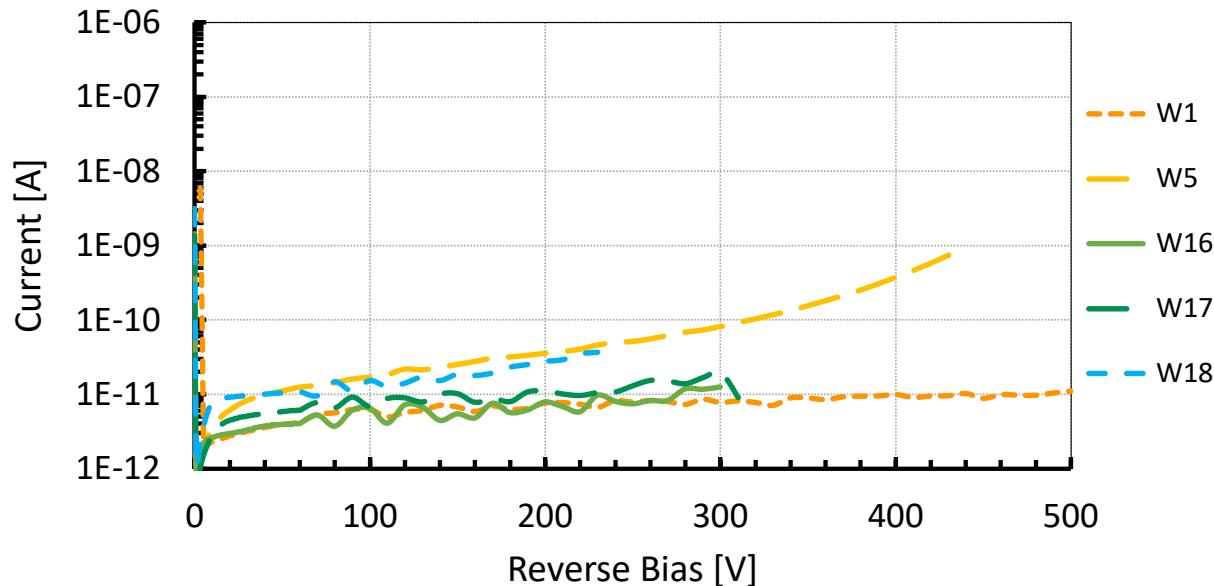
Thin LGAD – I-V at Different Thickness

Wafer #	Thickness	p+ dose	C dose	Diffusion
1	45	1.14	1.0	CBL
5	30	1.12	1.0	CBL
16	20	0.80	1.0	CHBL
17	20	0.96	1.0	CBL
18	15	0.94	1.0	CBL

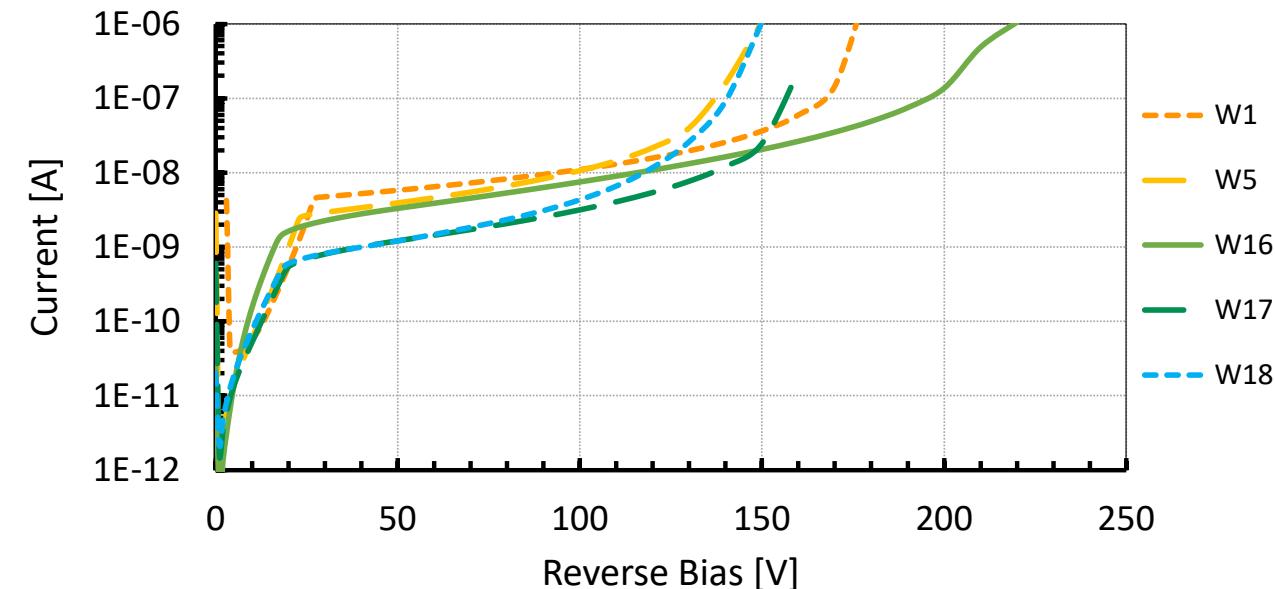
Bulk
n-type
high ρ
low ρ

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

EXFLU1 – PIN vs Thickness – I-V



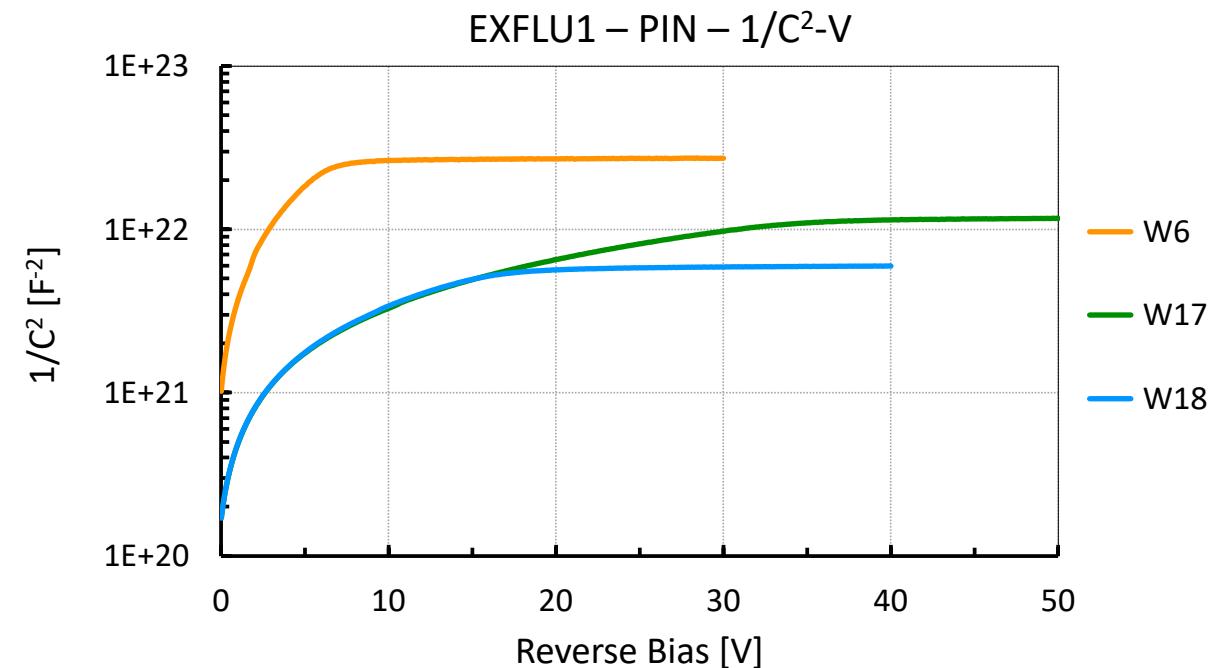
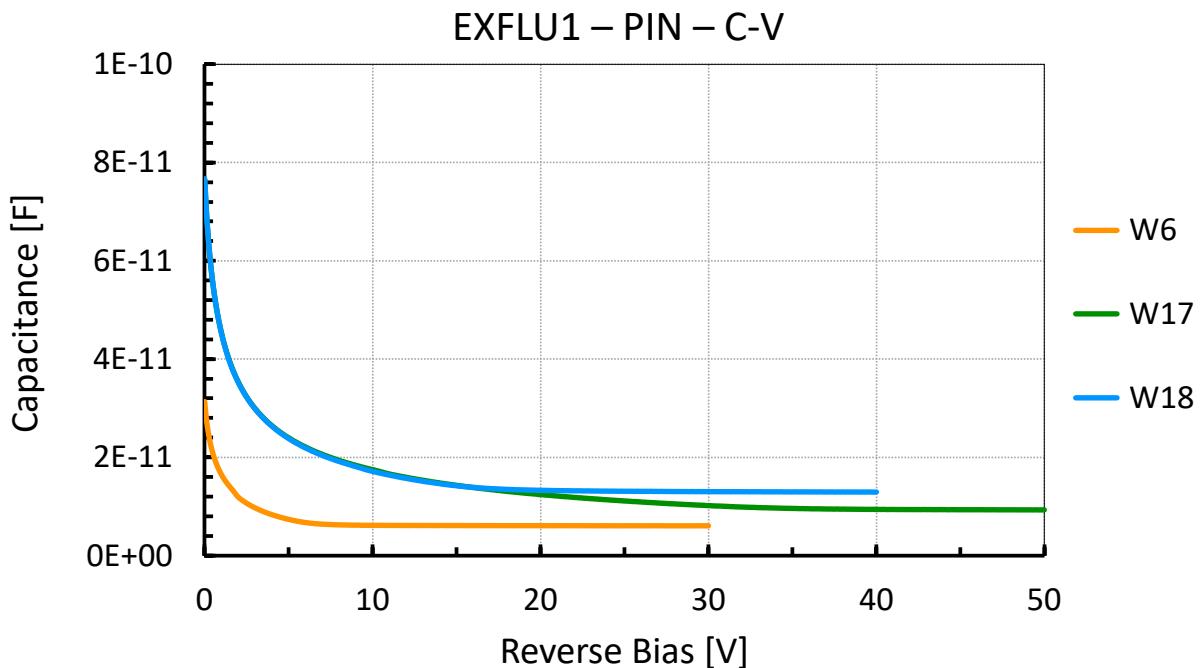
EXFLU1 – Standard LGAD vs Thickness – I-V



Thin PIN – C-V at Different Thickness

Wafer #	Thickness	p+ dose	C dose	Diffusion
1	45	1.14	1.0	CBL
5	30	1.12	1.0	CBL
16	20	0.80	1.0	CHBL
17	20	0.96	1.0	CBL
18	15	0.94	1.0	CBL

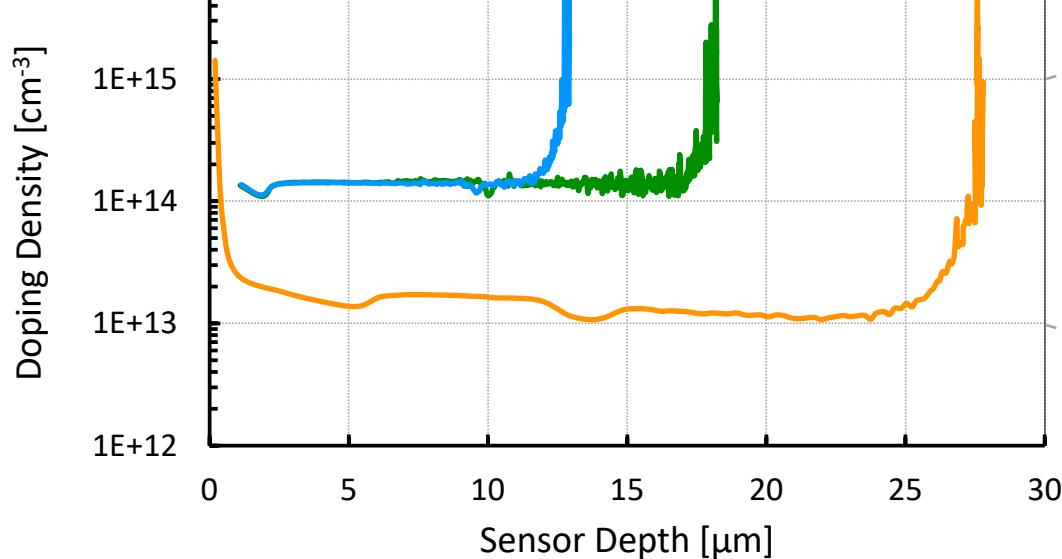
Bulk
n-type
high ρ
low ρ



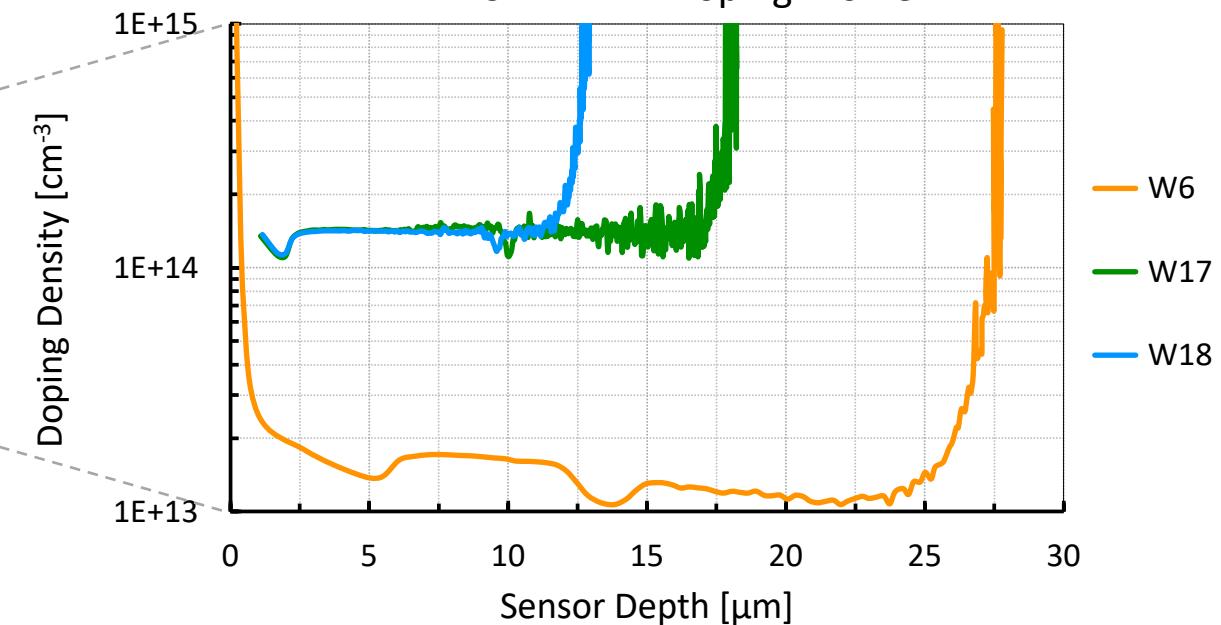
Thin PIN – Doping Profile

Wafer #	Thickness	p+ dose	C dose	Diffusion	Bulk
1	45	1.14	1.0	CBL	n-type
5	30	1.12	1.0	CBL	1.5E13/cm ³
16	20	0.80	1.0	CHBL	1.5E14/cm ³
17	20	0.96	1.0		
18	15	0.94	1.0	CBL	

EXFLU1 – PIN – Doping Profile

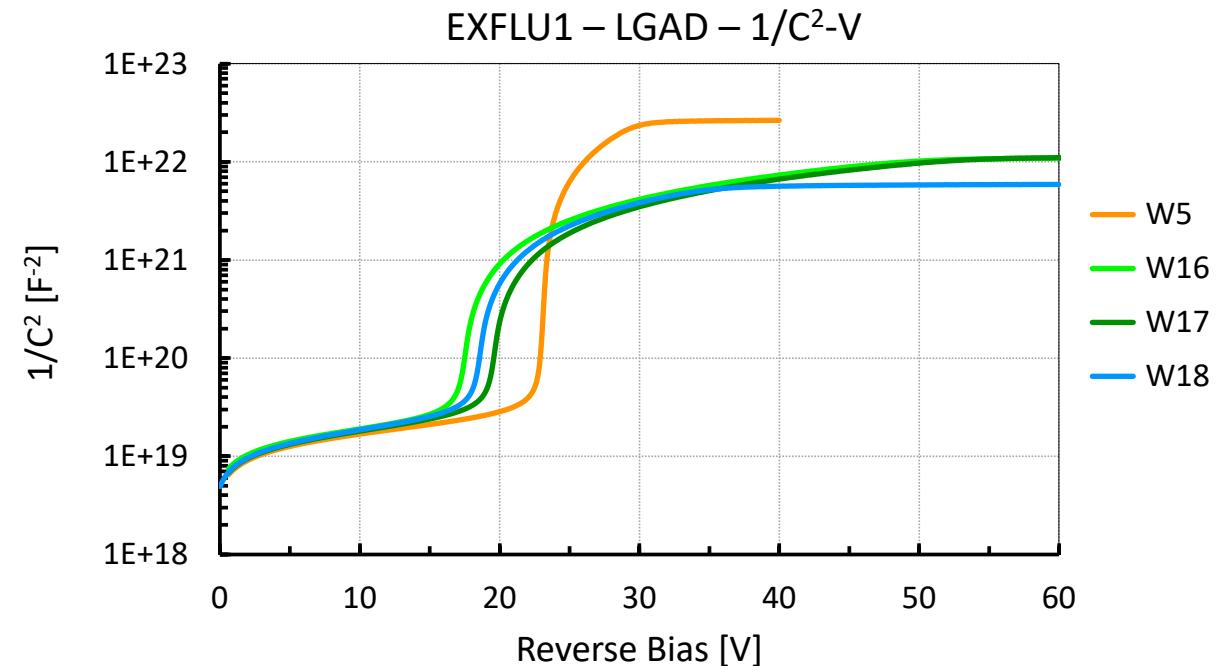
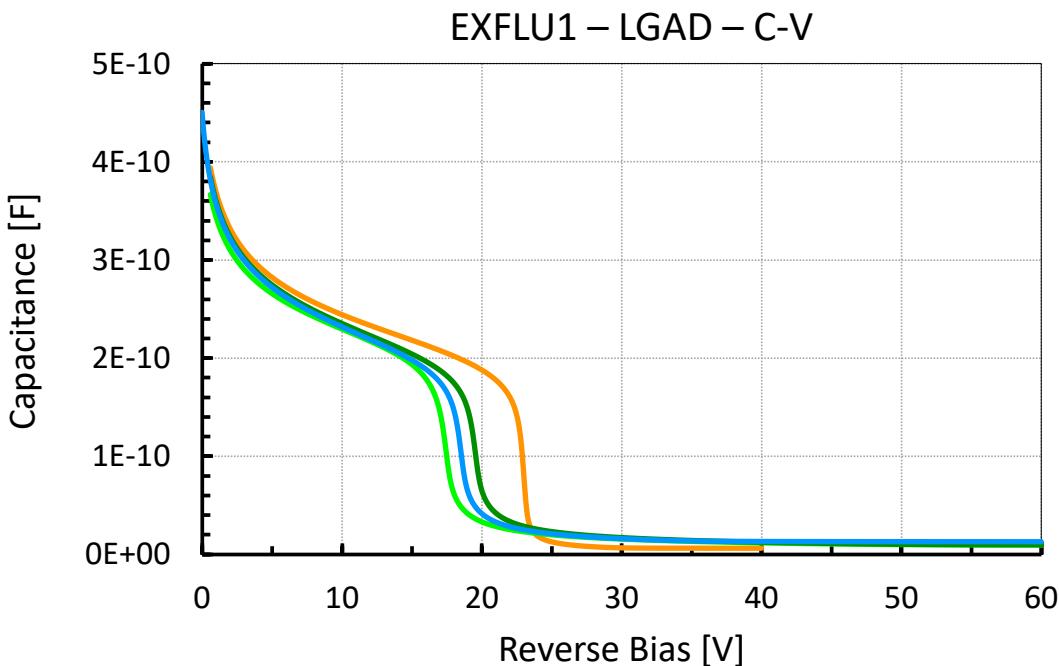


EXFLU1 – PIN – Doping Profile



Thin LGAD – C-V at Different Thickness

Wafer #	Thickness	p+ dose	C dose	Diffusion	Bulk
1	45	1.14	1.0	CBL	n-type
5	30	1.12	1.0	CBL	1.5E13/cm ³
16	20	0.80	1.0	CHBL	
17	20	0.96	1.0	CBL	1.5E14/cm ³
18	15	0.94	1.0	CBL	



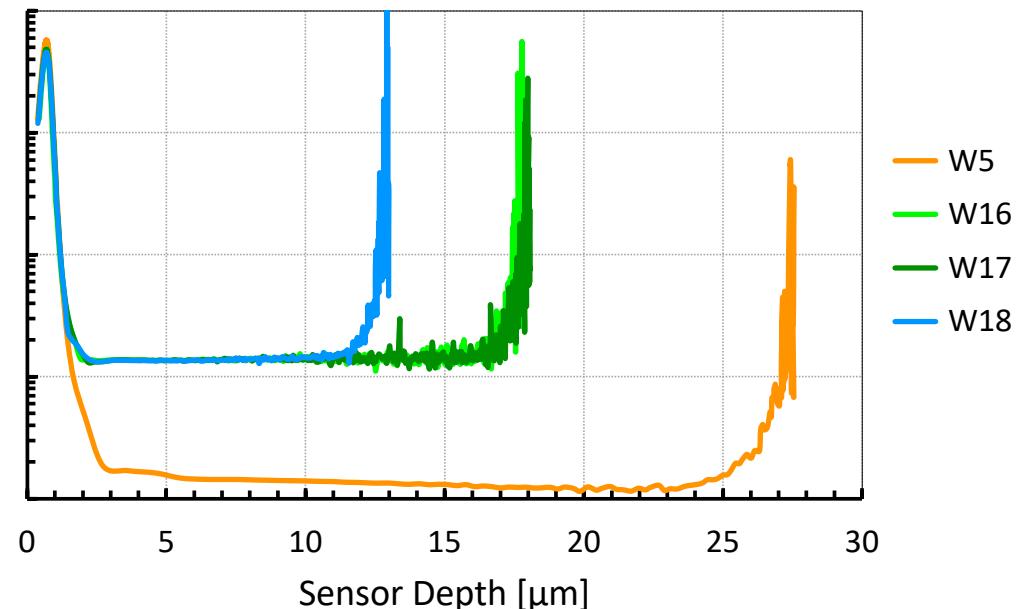
Thin LGAD – Doping Profile

Wafer #	Thickness	p+ dose	C dose	Diffusion	Bulk
1	45	1.14	1.0	CBL	n-type
5	30	1.12	1.0	CBL	1.5E13/cm ³
16	20	0.80	1.0	CHBL	
17	20	0.96	1.0	CBL	1.5E14/cm ³
18	15	0.94	1.0	CBL	

CBL profile is broader than CHBL one

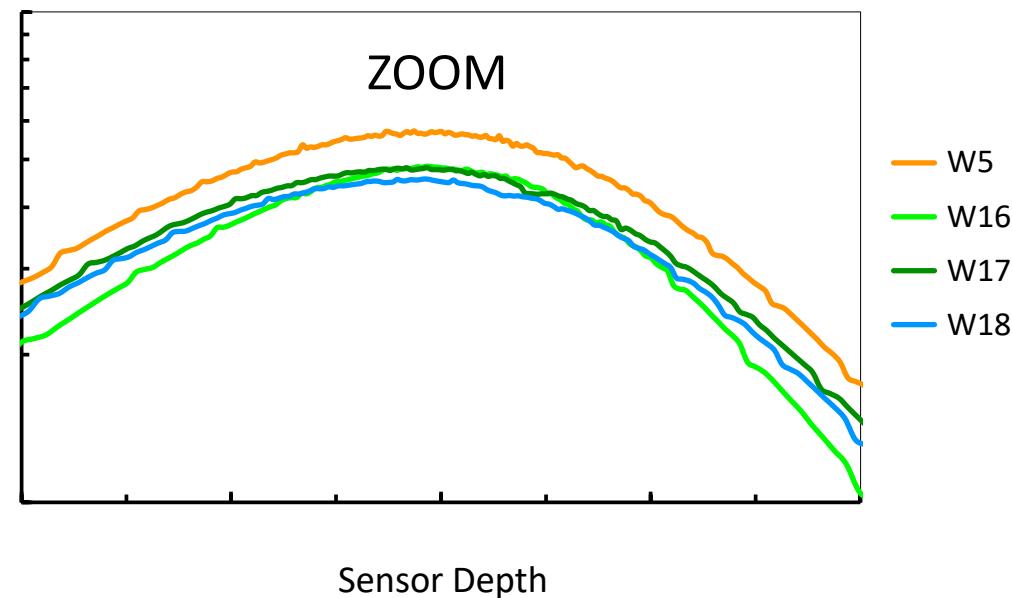
EXFLU1 – LGAD – Doping Profile

Doping Density



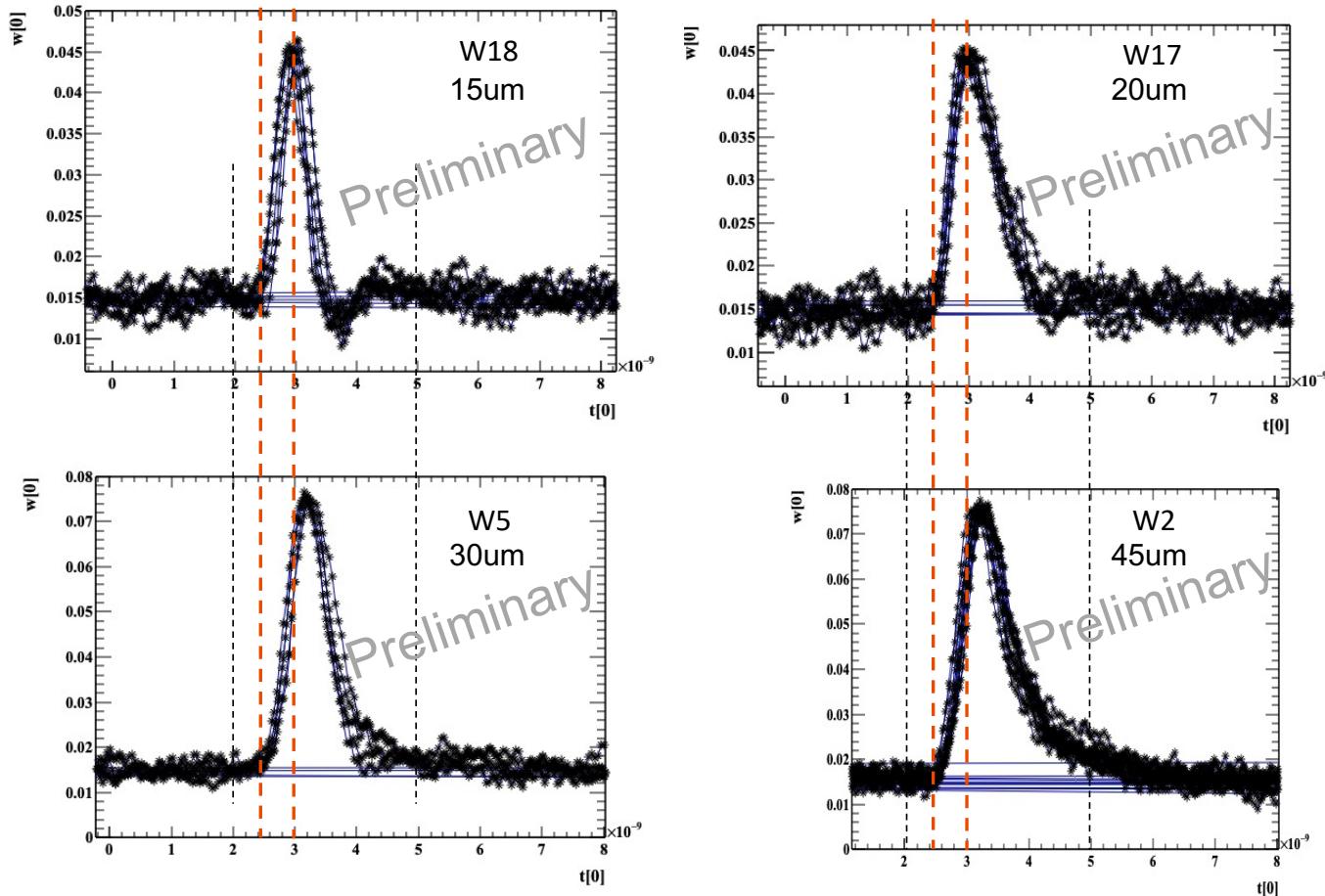
EXFLU1 – LGAD – Doping Profile

Doping Density



EXFLU1 – Signal Waveforms from β source

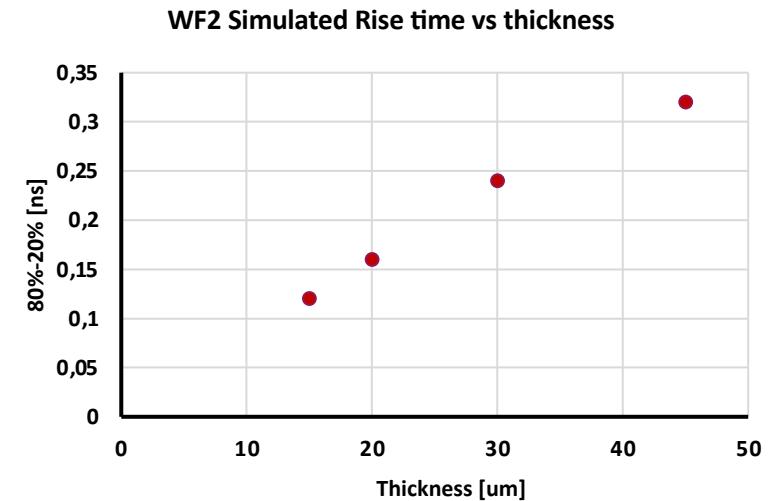
The timing performances of the four different sensor thicknesses have been investigated using a β source



Signal waveforms

- - - Black dotted: 2 – 5 ns range
- Red dotted: 0 – 100% of 15 μm rise time
- The rise time becomes only marginally shorter with the sensor thickness

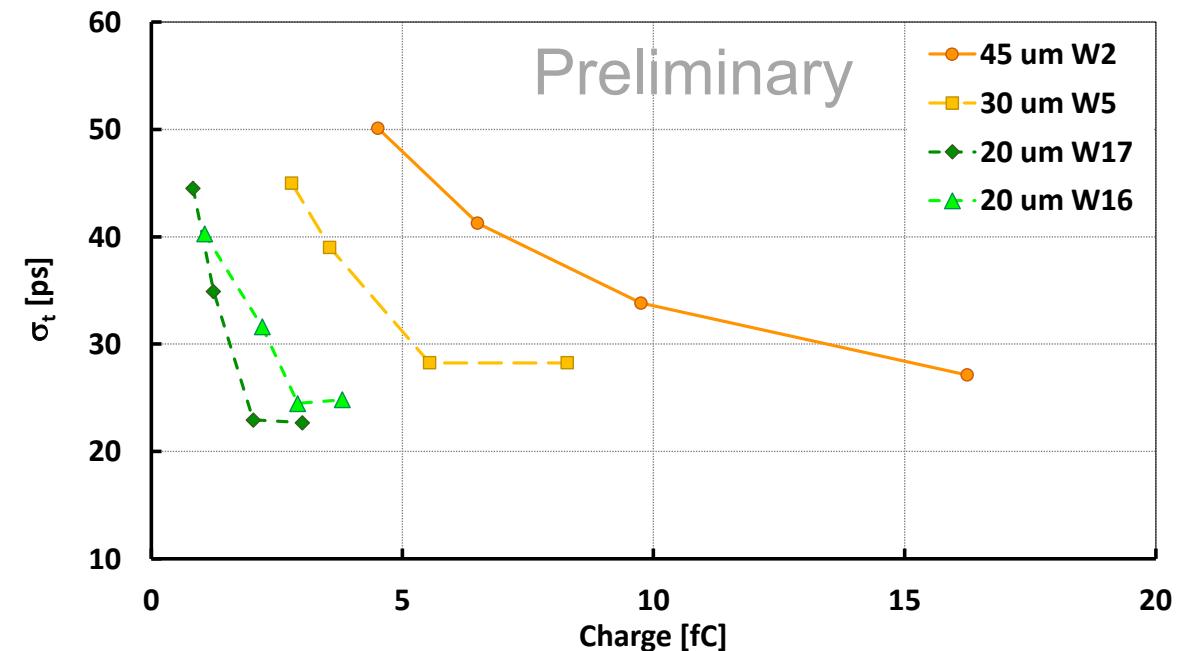
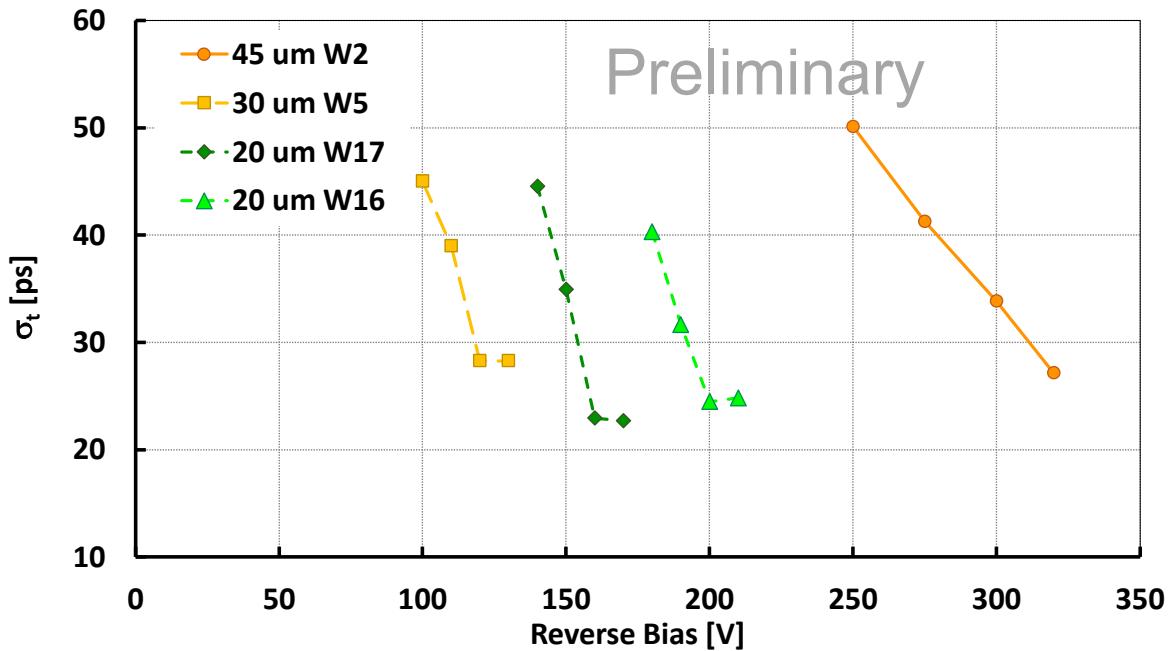
Rise time as simulated by [Weightfield2](#)





EXFLU1 – Timing Performances

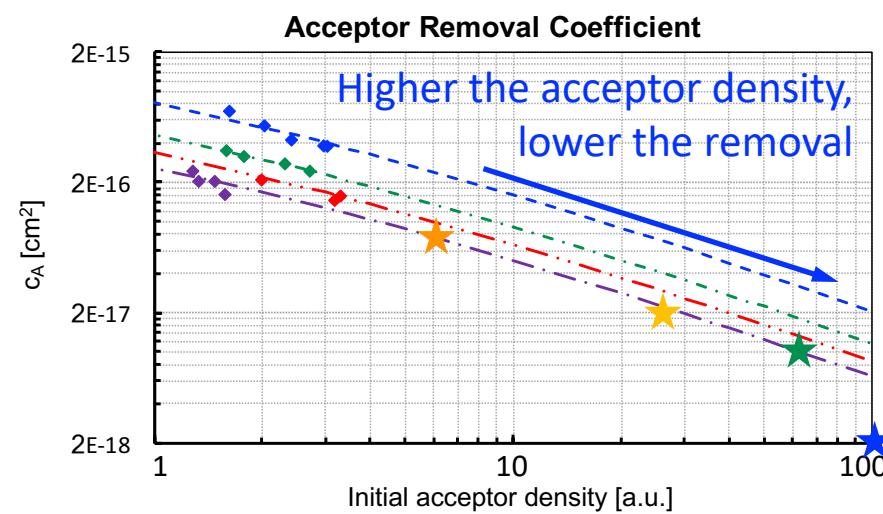
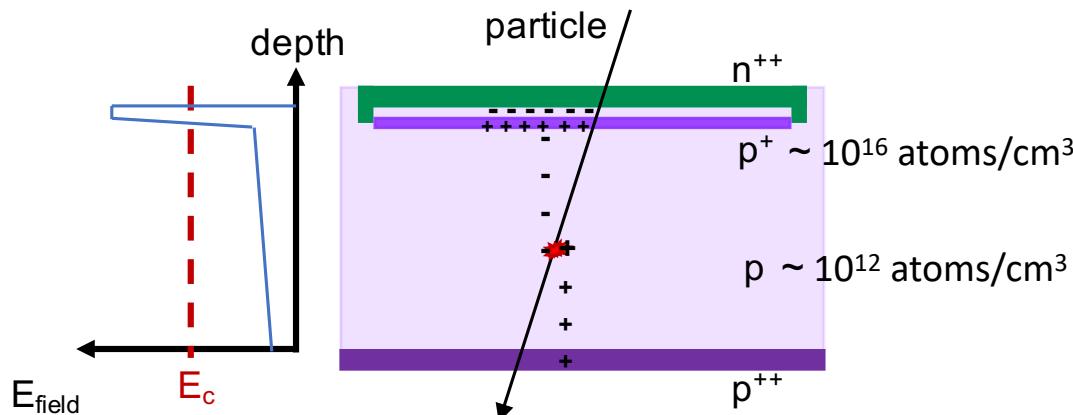
EXFLU1 single pads $1.3 \times 1.3 \text{ mm}^2$ read out by SC board + 20 dB BB Cividec amplifier



→ Challenging to reach a time resolution below 20 ps with the present experimental setup

Compensated LGAD

Towards a Radiation Resistant Design

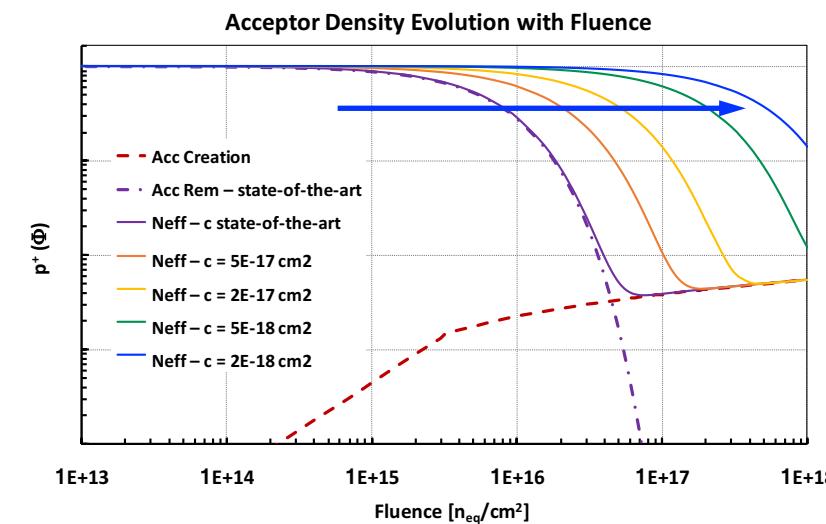


The acceptor removal mechanism deactivates the p⁺-doping of the **gain layer** with irradiation according to

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

where c_A is the acceptor removal coefficient

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



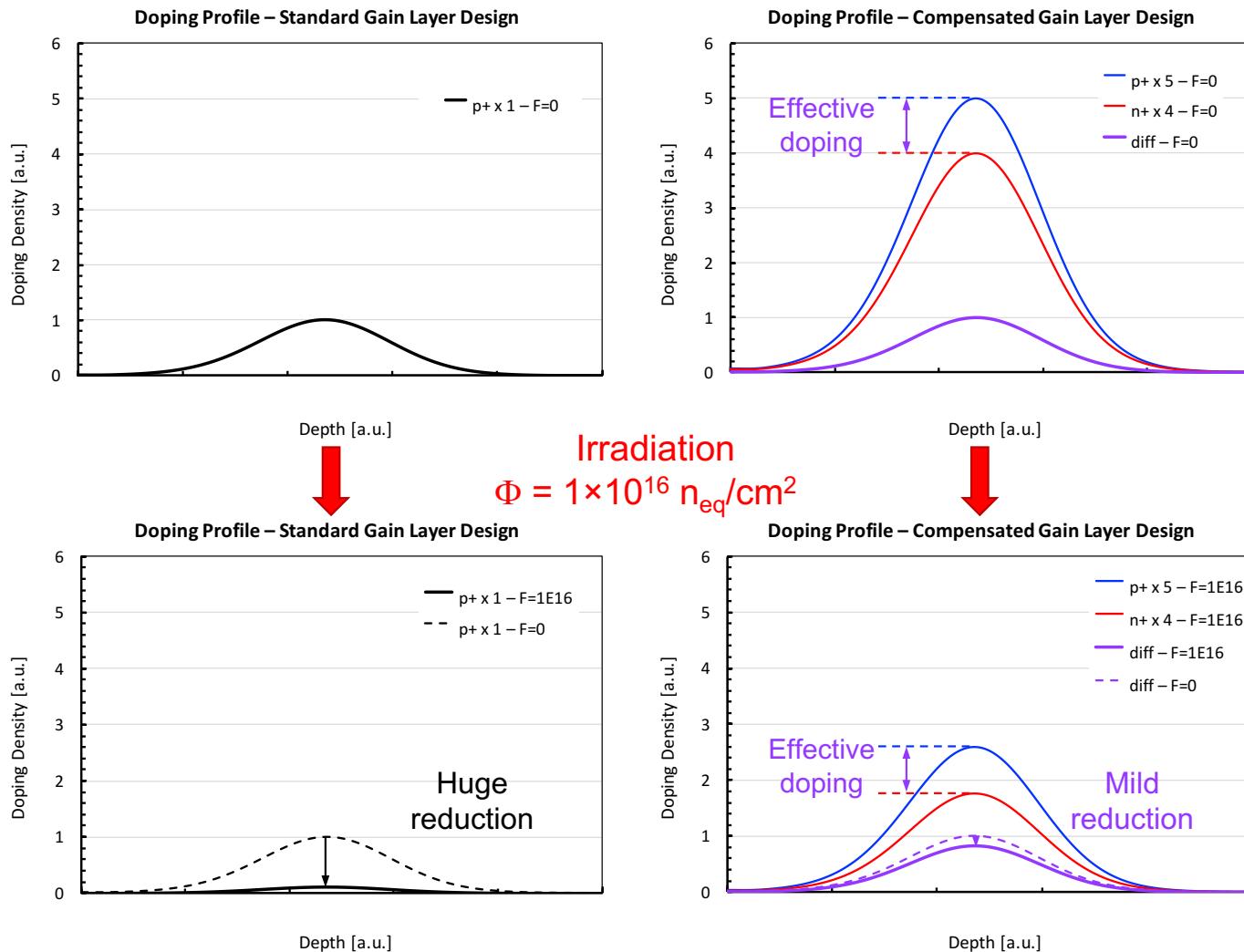
A new Paradigm – Compensation

Impossible to reach the desired target with the present design of the gain implant

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

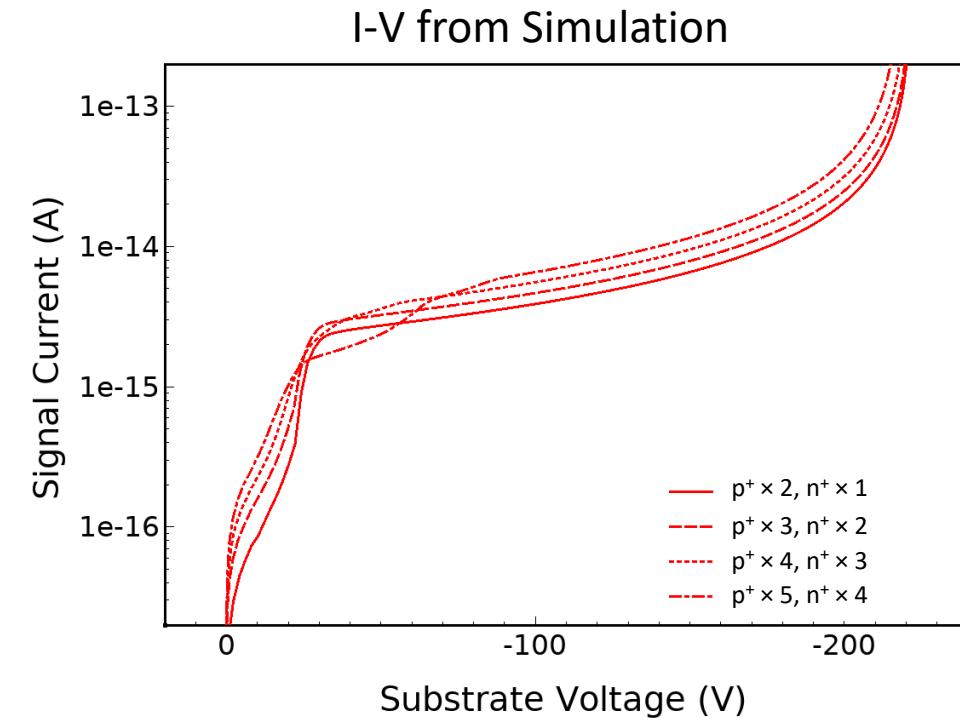
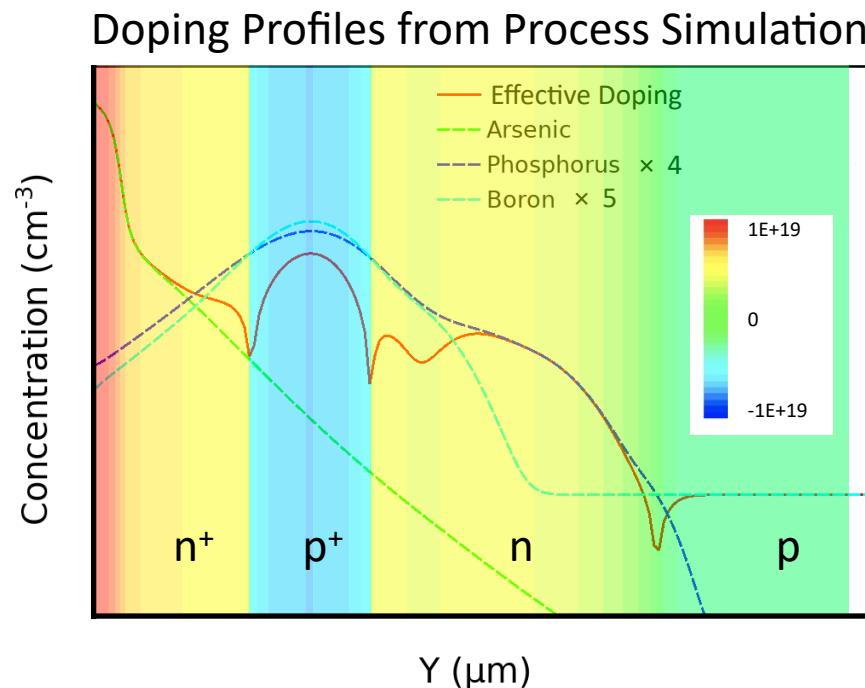
Many unknowns:

- ▷ 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



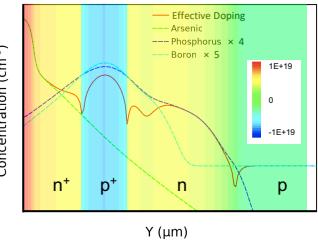
→ The simulation of the electrostatic behaviour show that it is possible to reach similar multiplication for different initial concentrations of p^+ and n^+ dopants

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]

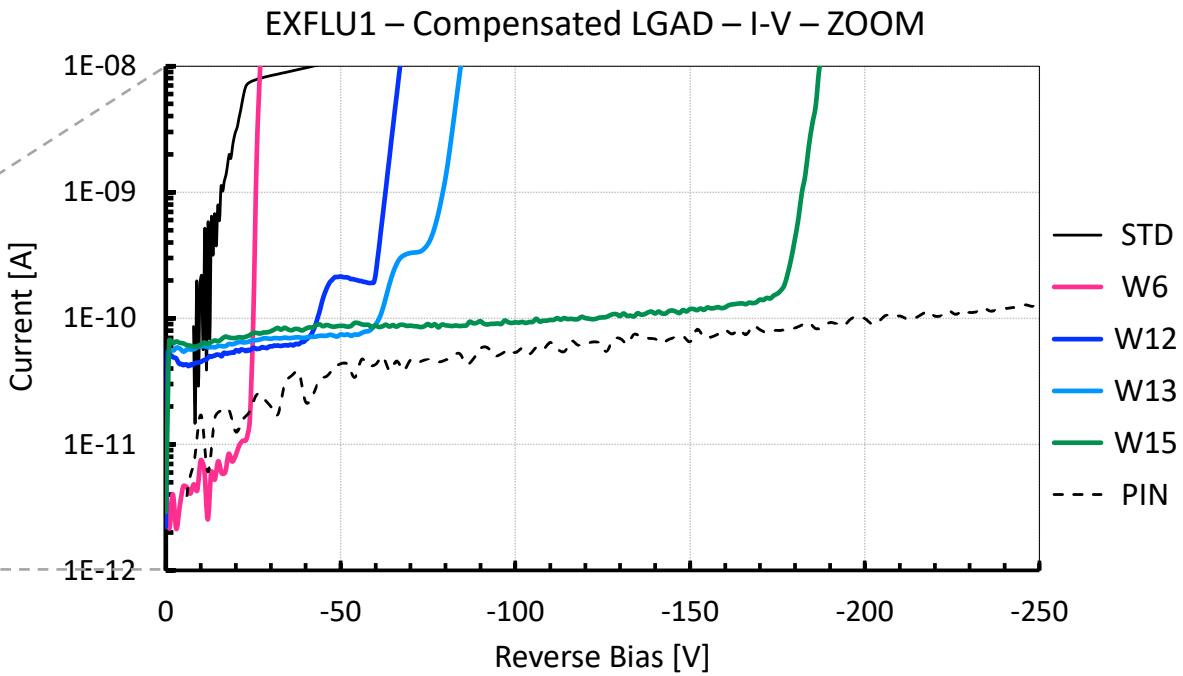
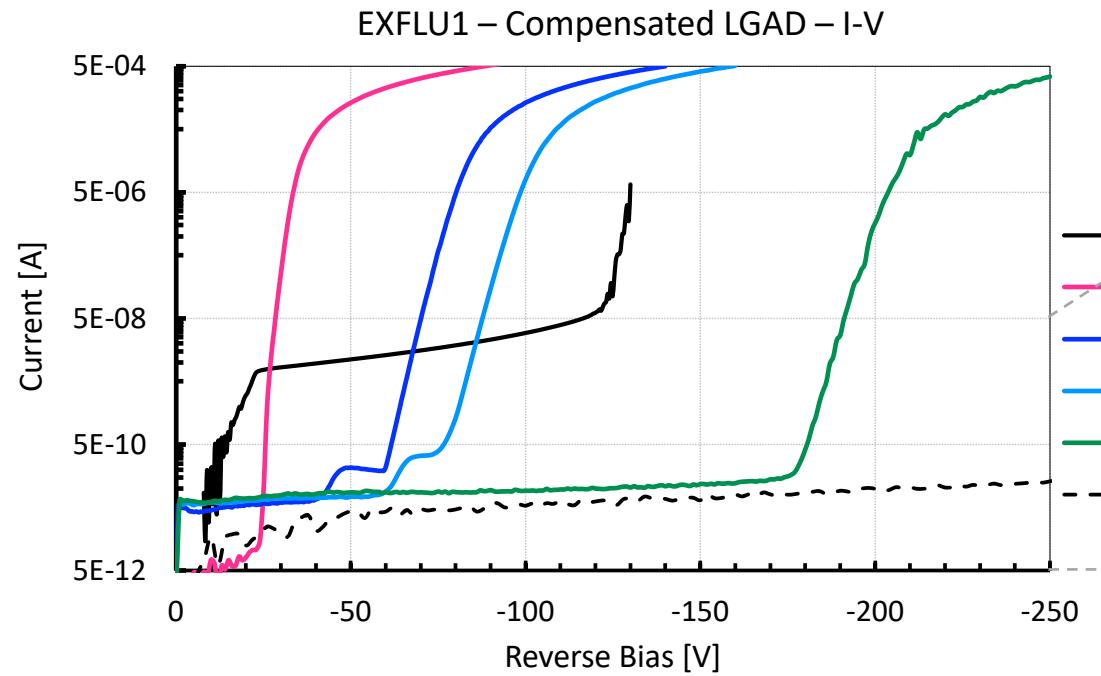
3 different combinations of p⁺ – n⁺ doping: 2 – 1, 3 – 2, 5 – 4



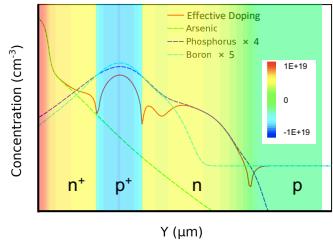
Compensated LGAD – I-V

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

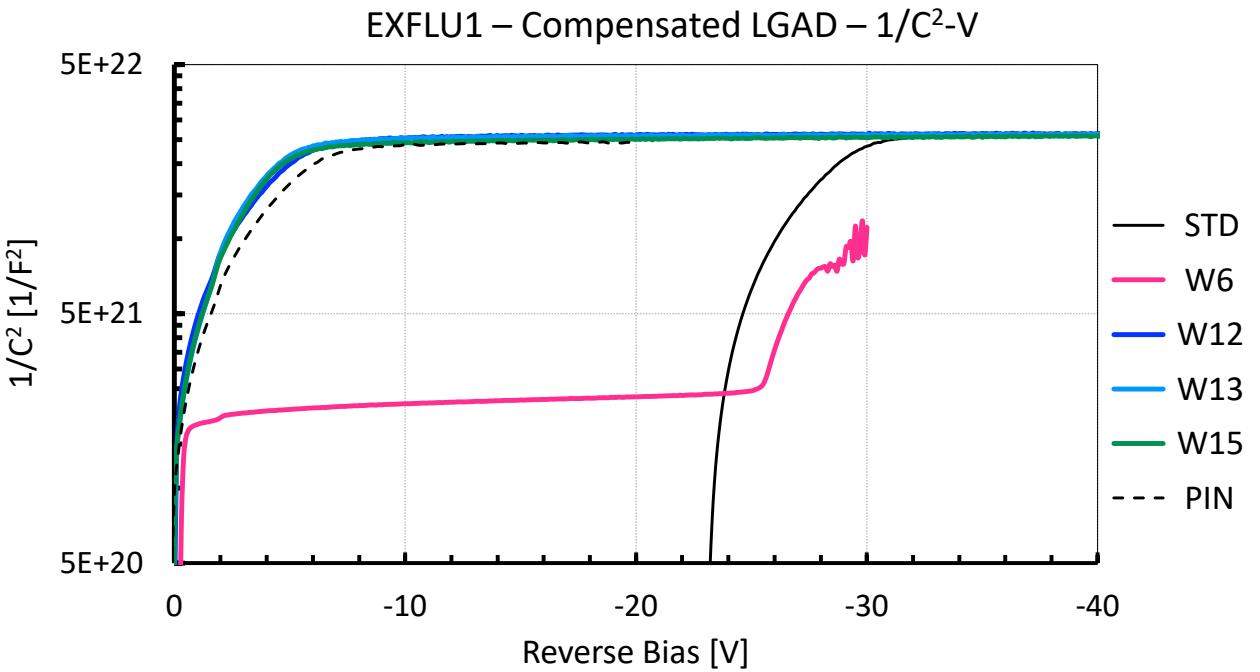
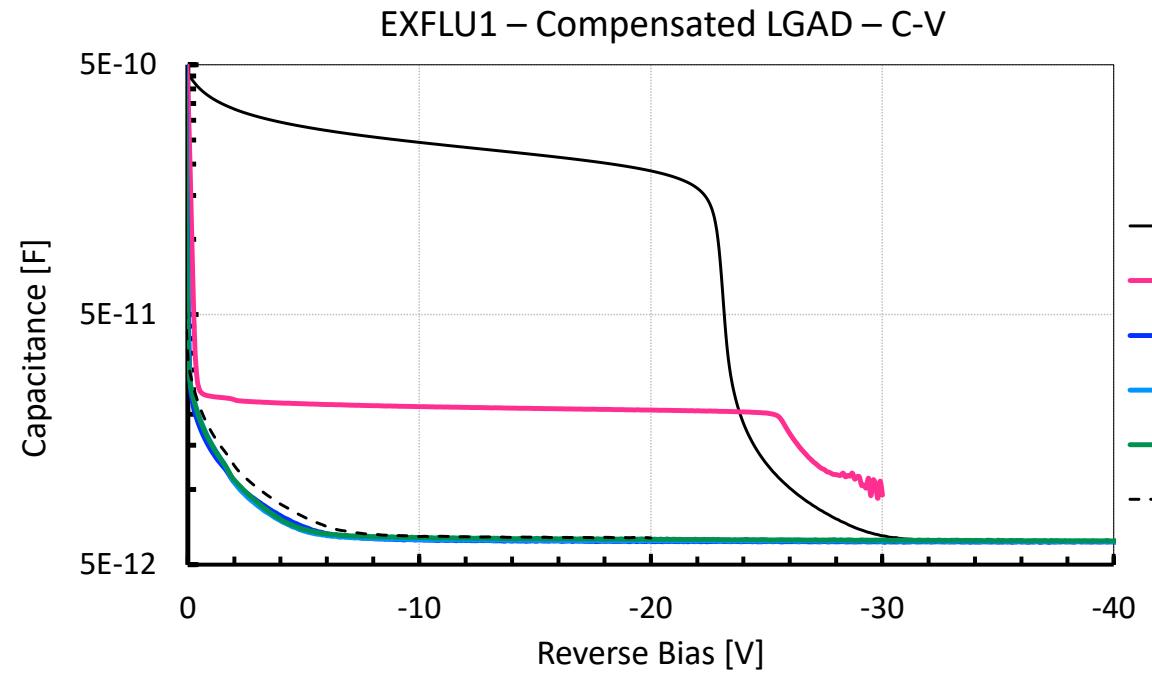


Compensated LGAD – C-V

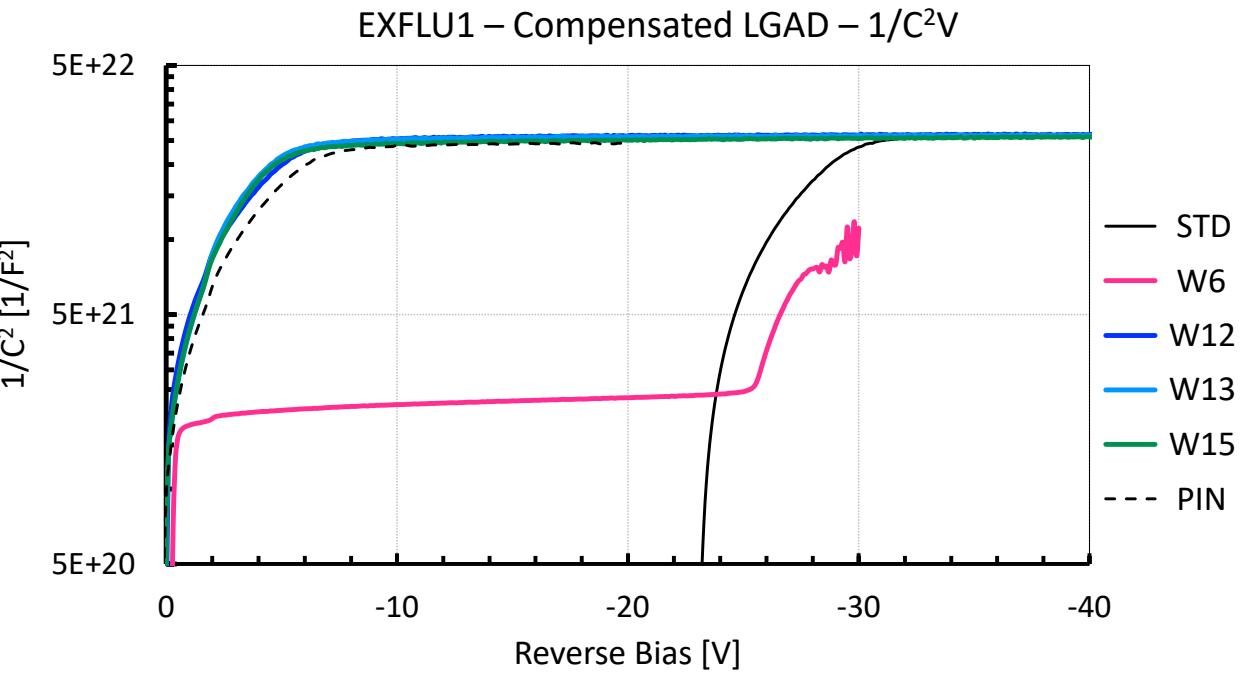
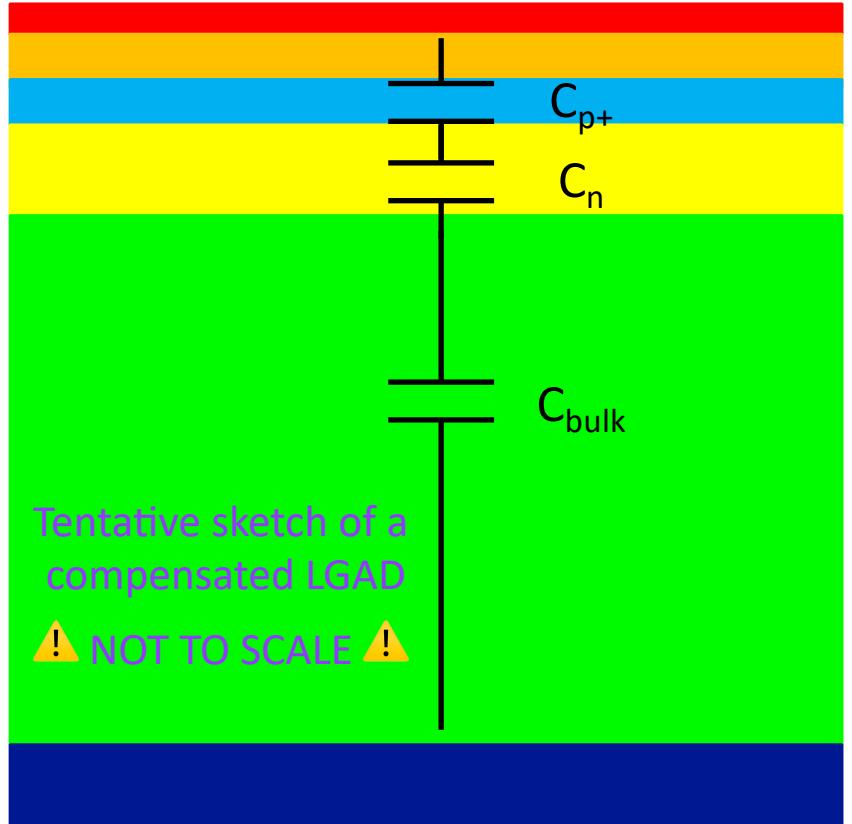
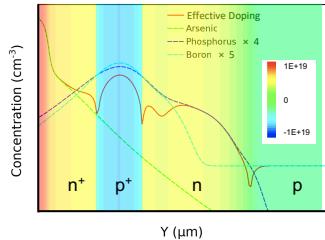


Wafer #	Thickness	p^+ dose	n^+ dose	C dose
6	30	2 a	1	
12	30	3 b	2	
13	30	3 b	2	1.0
15	30	5 a	4	

→ 2–1 is more doped than standard LGAD
→ 3–2 & 5–4 exhibit a capacitance lower than PIN



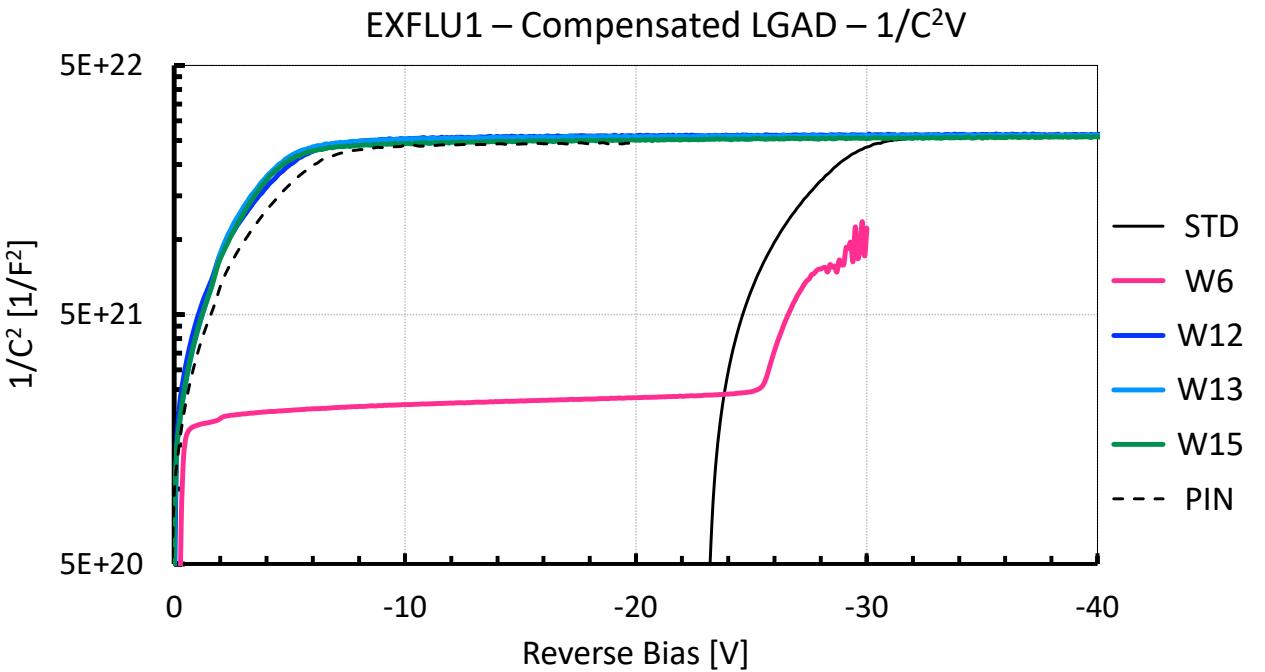
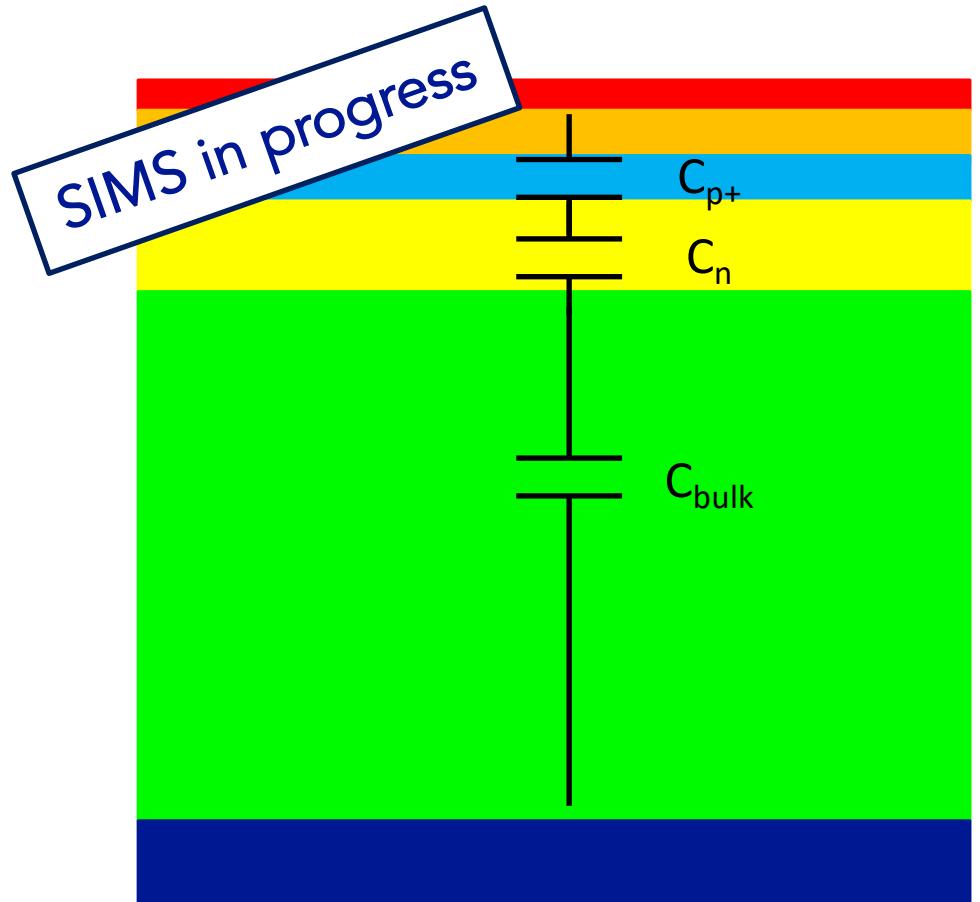
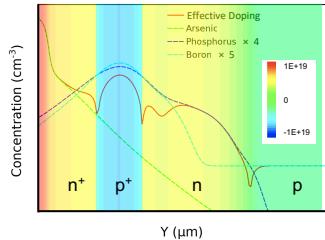
Compensated LGAD – C-V



3–2 & 5–4 C-V measurements appear as the series of two different p-n junctions, and the sensor depletion starts from the n-bulk junction

Hypothesis: the concurrent activation of Boron and Phosphorus may reduce the lateral diffusion of Boron

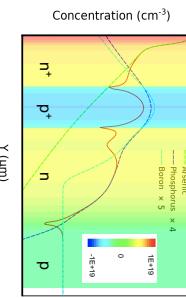
Compensated LGAD – C-V



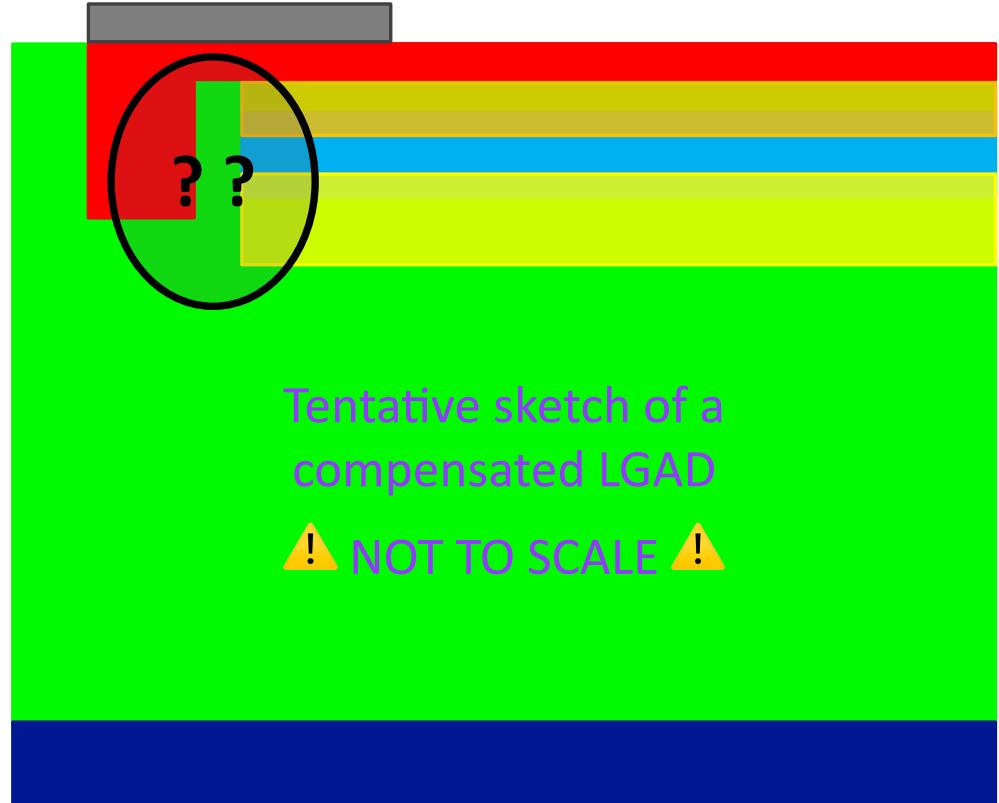
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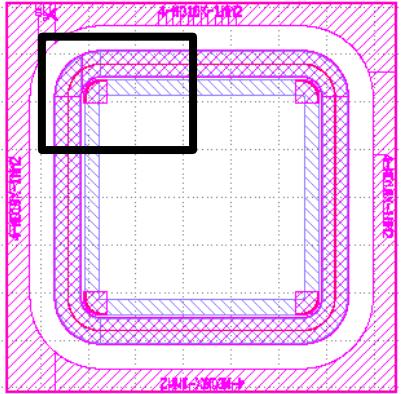
Compensated LGAD – 2D Scan with IR Laser



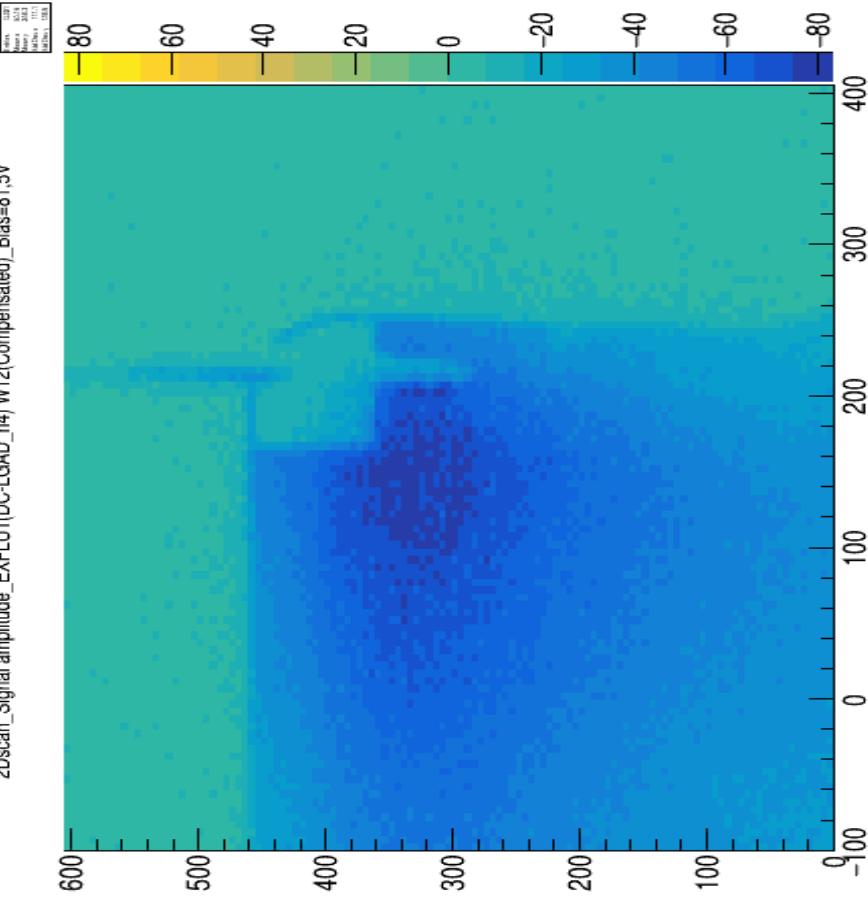
Ongoing characterisation: investigate with IR laser the edge of the compensated gain implants



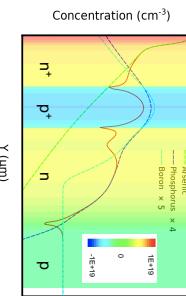
Scan surface



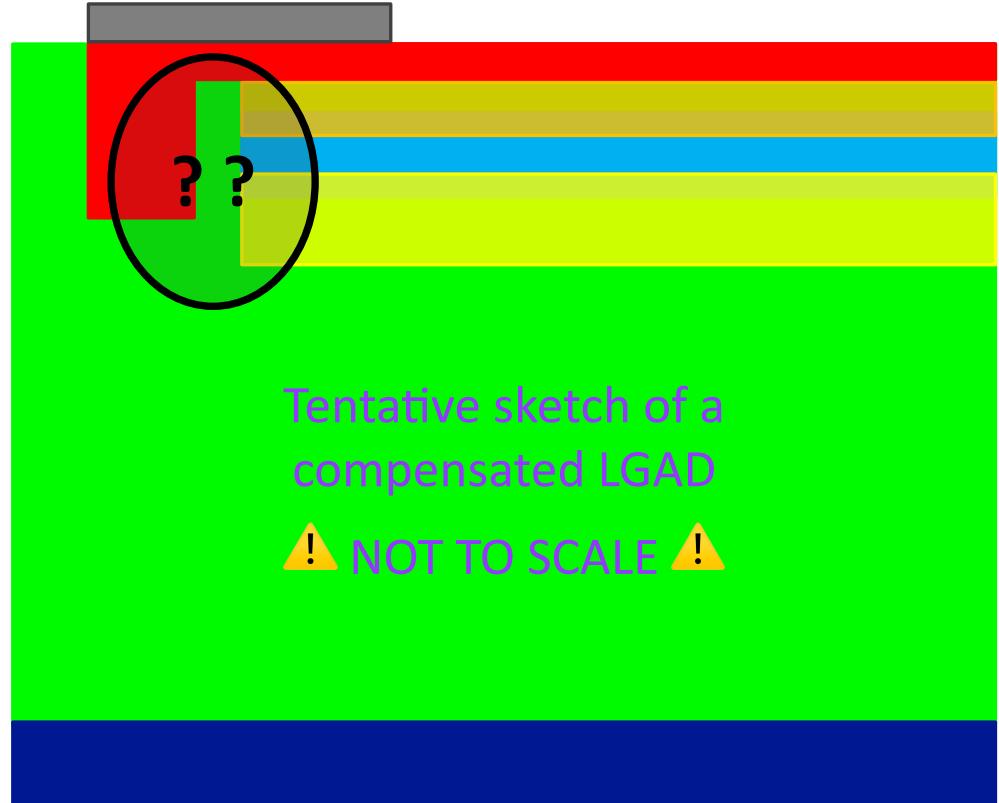
TCT scan with IR laser
Laser spot ~ 10 μm
Sensor from W12 (3–2)
 $V_{bias} = 81$ V
Very close to BD



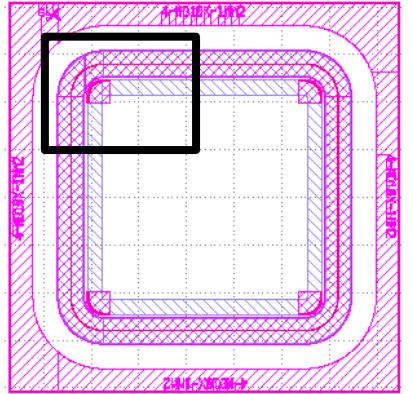
Compensated LGAD – 2D Scan with IR Laser



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



Scan surface



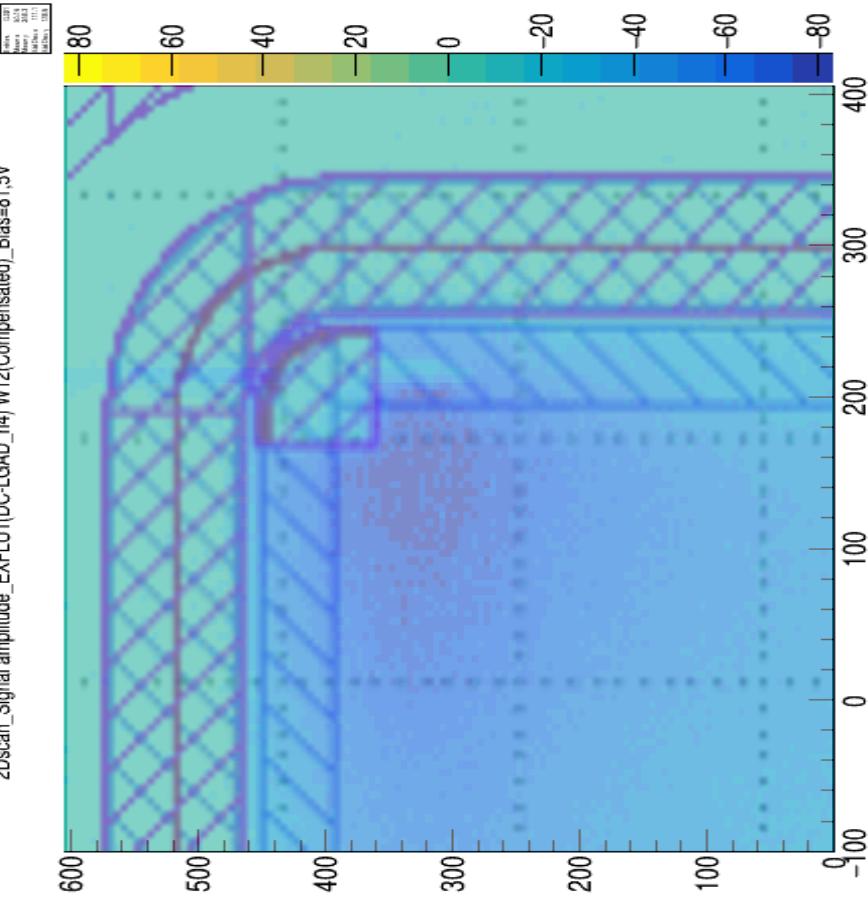
TCT scan with IR laser

Laser spot ~ 10 μm

Sensor from W12 (3-2)

$V_{bias} = 81 V$

Very close to BD



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

IR Laser Stimulus on Compensated LGAD 2–1

TCT Setup from Particulars

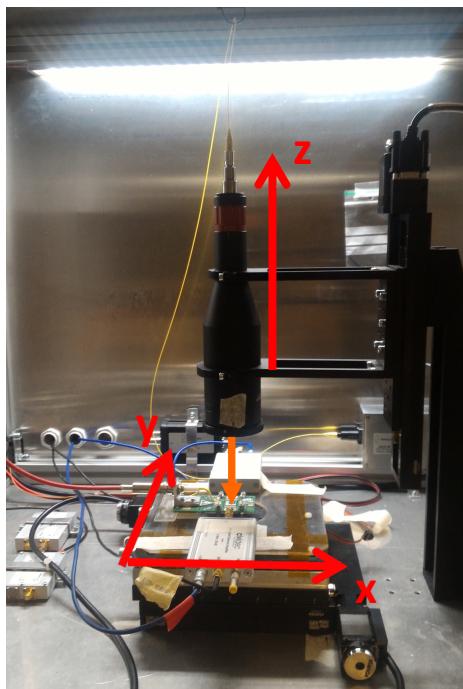
Pico-second IR laser at 1064 nm

Laser spot diameter $\sim 10 \mu\text{m}$

Cividec Broadband Amplifier (40dB)

Oscilloscope LeCroy 640Zi

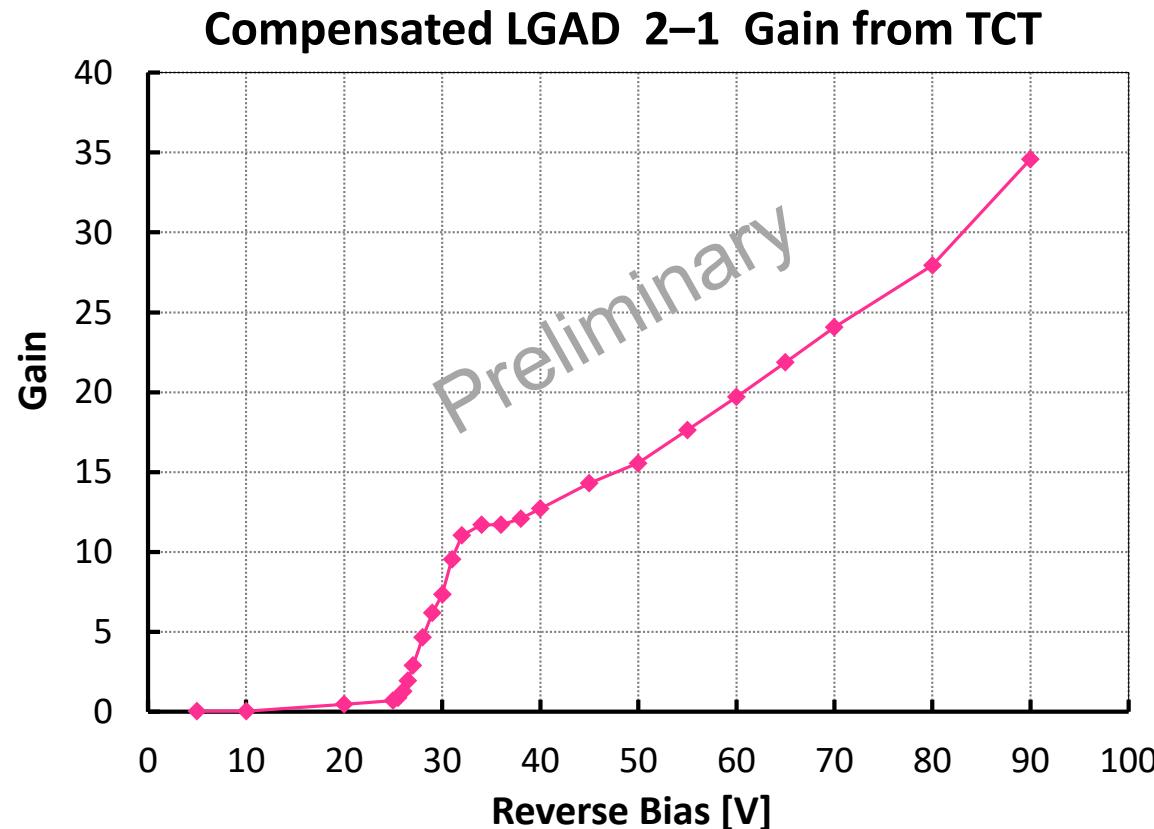
Room temperature



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

Laser intensity
 $\sim 10 \text{ MIPs}$

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 5–4

TCT Setup from Particulars

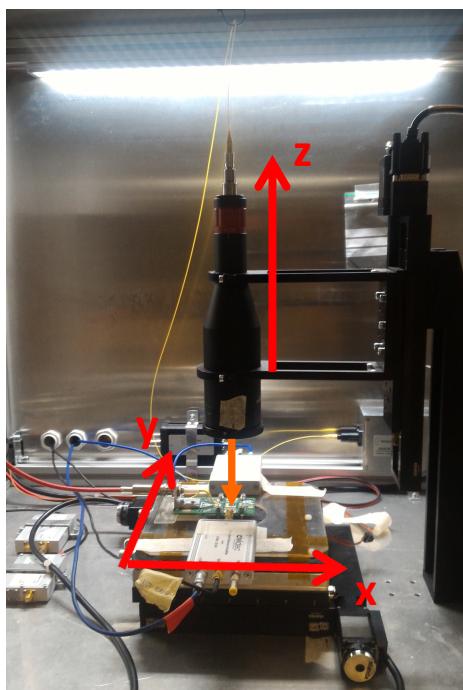
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Cividec Broadband Amplifier (40dB)

Oscilloscope LeCroy 640Zi

Room temperature

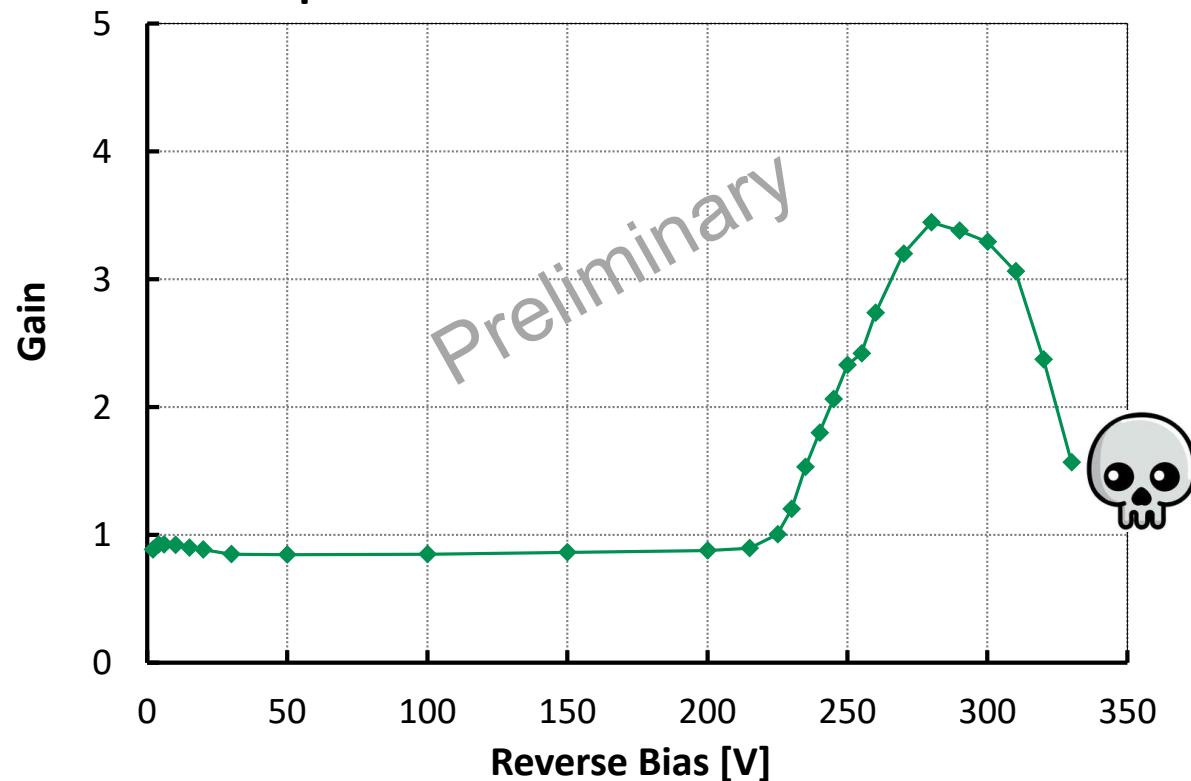


$$\text{Gain} = \frac{Q_{\text{LGAD}}}{Q_{\text{PiN}}}$$

Laser intensity
 $\sim 90 \text{ MIPs}$

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

Compensated LGAD 5–4 Gain from TCT



→ Not optimal behaviour of 5 – 4 compensated LGAD sensors

Summary & Outlook

The EXFLU1 production batch has been extensively tested before irradiation

- R&D on guard ring structures show good performances for different design strategies
 - Carbon shield to protect the gain implant from acceptor removal to be investigated
 - Thin substrate are working nicely – but difficult to reach ultimate timing resolution
 - First LGAD with compensated gain implant are carefully investigation
- ⇒ An extensive irradiation campaign is about to start





Acknowledgements

We kindly acknowledge the following funding agencies and collaborations:

- ▷ INFN CSN5
- ▷ AIDAinnova, WP13
- ▷ Compagnia di San Paolo
- ▷ Ministero della Ricerca, Italia, FARE, R165xr8frt_fare
- ▷ Ministero della Ricerca, Italia, PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
- ▷ MIUR, Dipartimenti di Eccellenza (ex L. 232/2016, art. 1, cc. 314, 337)
- ▷ European Union's Horizon 2020 Research and Innovation programme,
Grant Agreement No. 101004761
- ▷ RD50, CERN

Backup

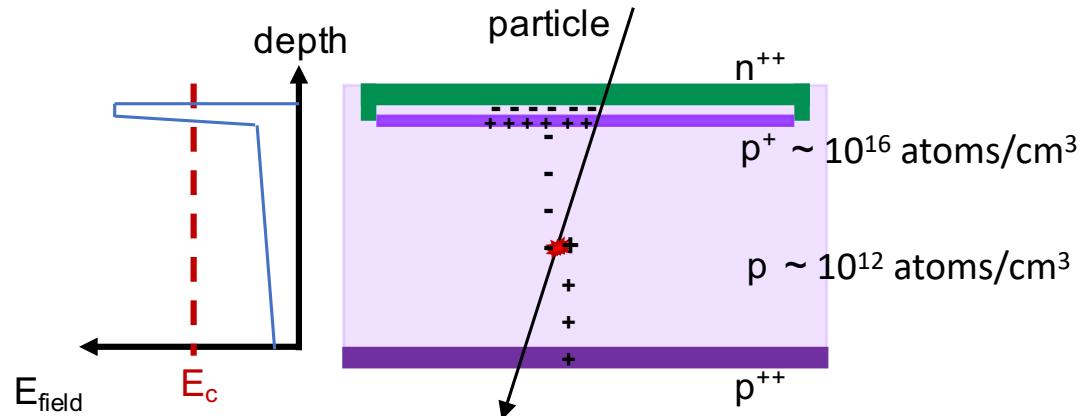
Projects towards the Extreme Fluences

- Silicon Sensor for Extreme Fluences (eXFlu), INFN grant for young researchers to develop, produce, irradiate and study thin silicon sensors (2020 – 2022)
- Thin Silicon Sensors for Extreme Fluences (eXFlu-innova), AIDAinnova Blue-Sky Technology, to investigate and develop the compensated LGAD design (2022 – 2025)
- Sensori al silicio per fluenze esterne (FLEX), Grant for Internationalization – UniTO, to share the experience on silicon sensors for extreme fluences between different participating institutes (2022 – 2023)

Participation to

- Defect engineering in PAD diodes mimicking the gain layer in LGADs, RD50 Project
PI: I. Pintilie

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

→ $\sim 1 \text{ fC}$ for tracking

→ $\gtrsim 5 \text{ fC}$ for timing

Charge from a MIP crossing thin sensors

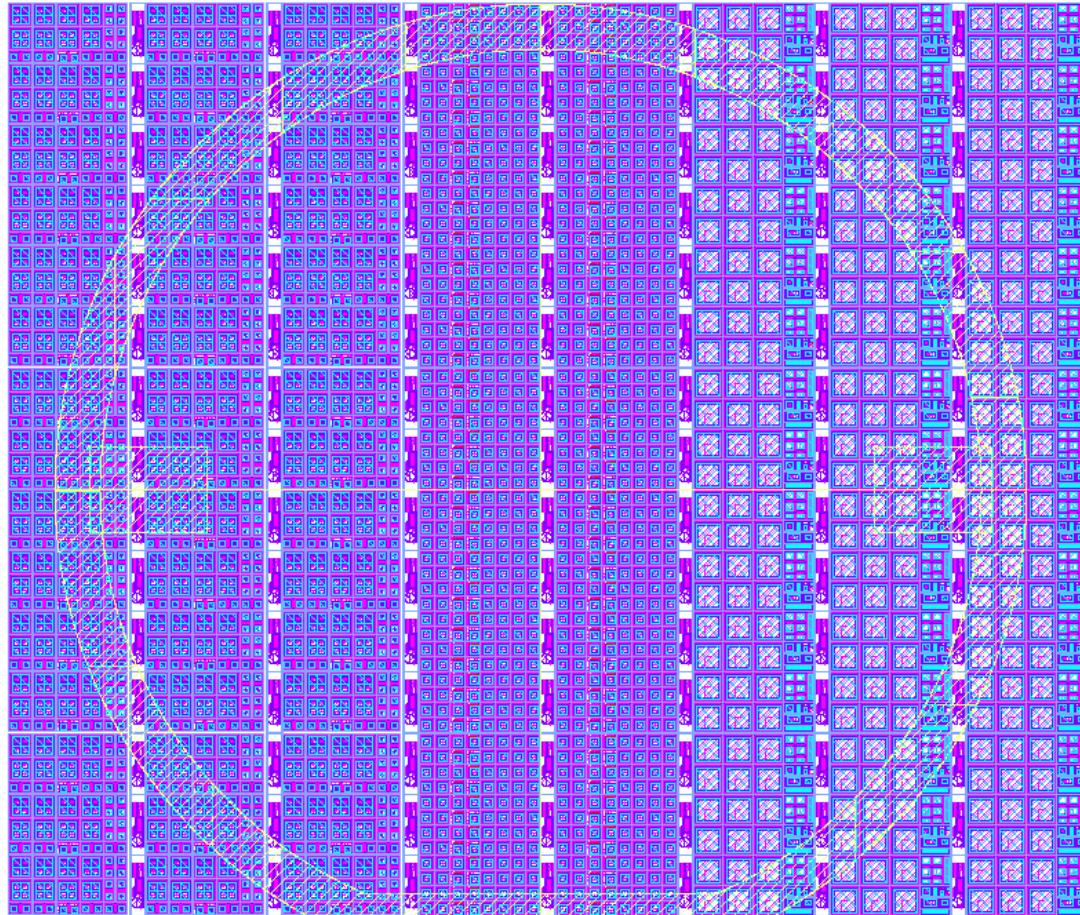
→ $\sim 0.1 \text{ fC}$ every 10 μm

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

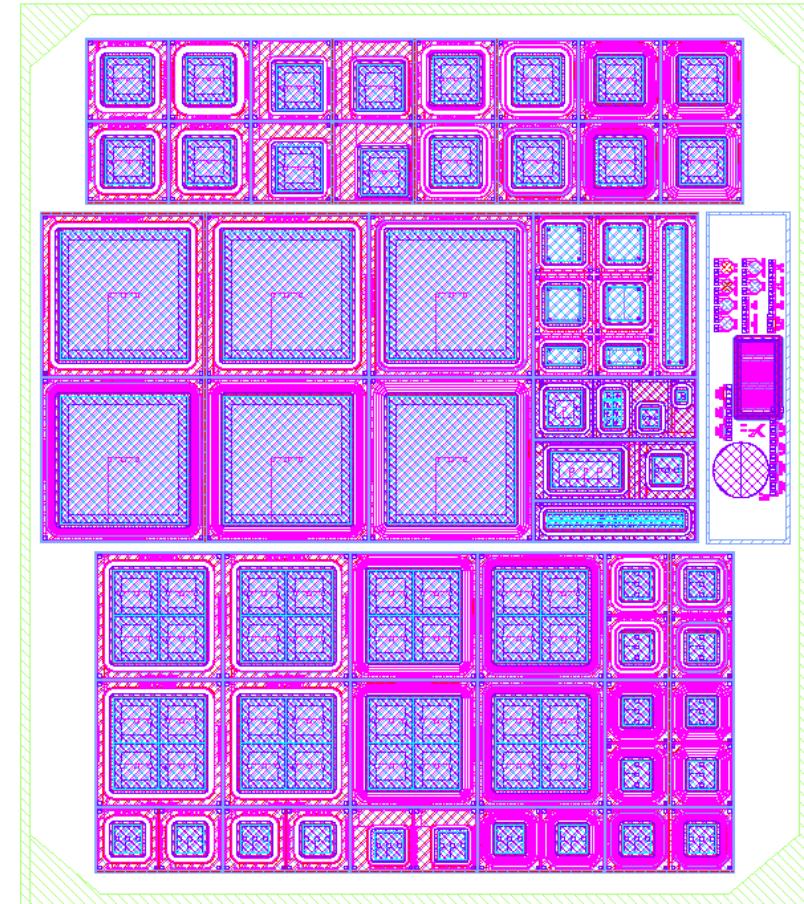
⇒ **Need a gain of at least 5 – 10 up to $\Phi = 10^{17} \text{ n}_{\text{eq}}/\text{cm}^2$ to efficiently record a hit**

The EXFLU1 Layout

6" Wafer Layout

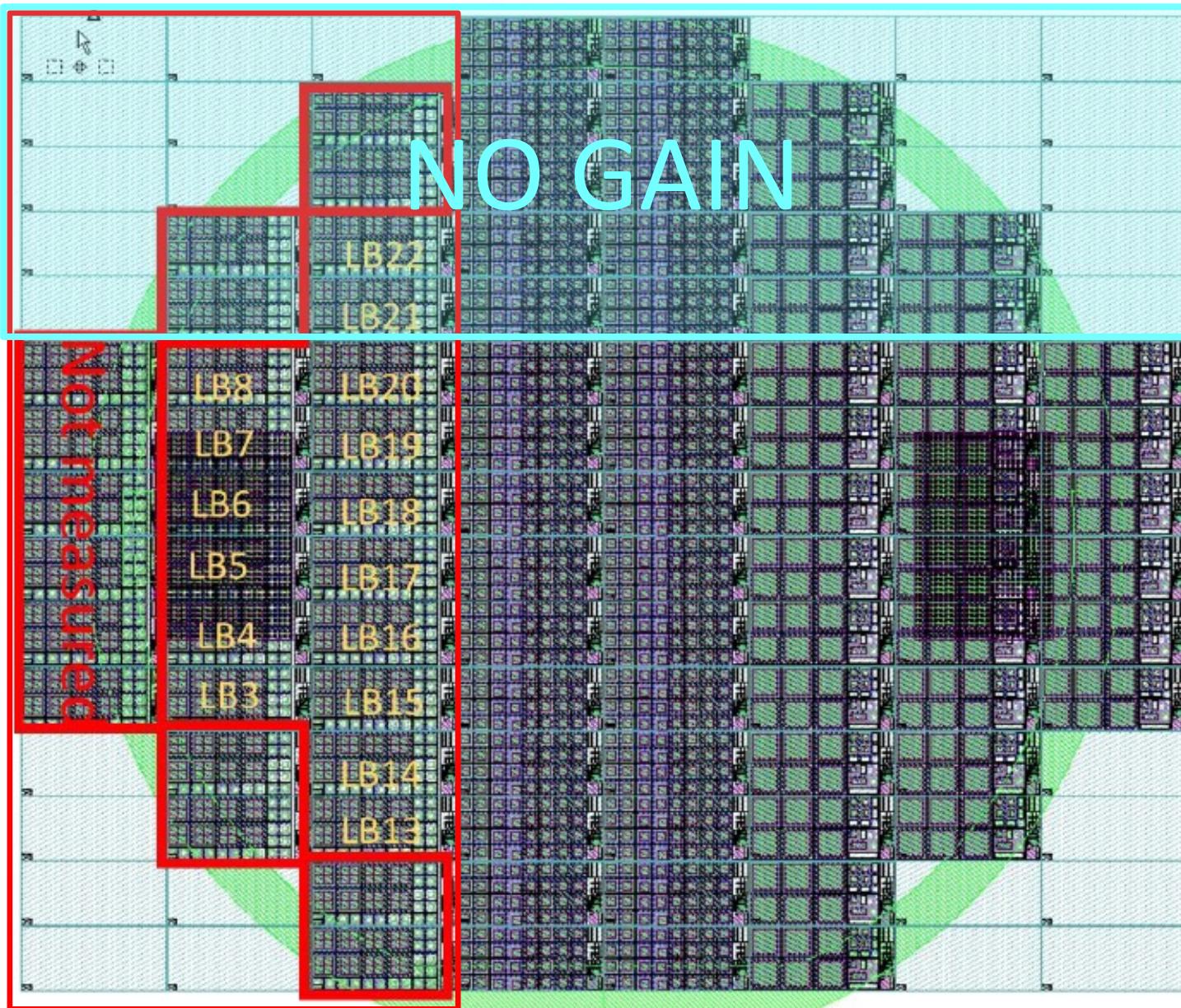


Reticle Layout



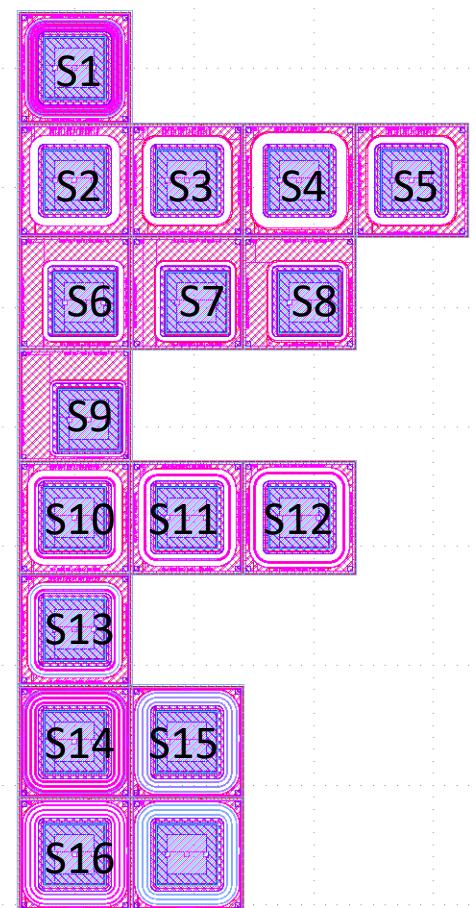
eXFlu2022_LEFT BLOCK

Measured
on wafer



EXFLU1 Guard Ring Designs

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



- S1) GR STD 500UM – à la UFSD2
- S2) GRO 500UM - V1
- S3) GRO 500UM - V2
- S4) GRO 500UM - V3
- S5) GRO 500UM - V4
- S6) GRO 300UM - V1
- S7) GRO 300UM - V2
- S8) GRO 300UM - V3
- S9) GRO 200UM - V1
- S10) GR1 500UM - V1
- S11) GR1 500UM - V2
- S12) GR1 500UM - V3
- S13) GR1P 500UM - V1
- S14) GR3 - 500UM - V1
- S15) GR3NPS - 500UM - V1
- S16) GR3PP - 500UM - V1

Standard Gain Layer Design – Split Table

Wafer #	Thickness	p+ dose	C dose	C shield	Diffusion
1	45	1.14	1.0		CBL
2*	45	1.00		0.6	CBL
3*	45	1.16	1.0	0.6	CBL
4*	45	1.16	1.0	1.0	CBL
5	30	1.12	1.0		CBL
16	20	0.80	1.0		CHBL
17	20	0.96	1.0		CBL
18	15	0.94	1.0		CBL

Gain layer depth: shallow

p⁺ and C dose values in arbitrary units [[doi:10.1201/9781003131946](https://doi.org/10.1201/9781003131946)]

* C spray

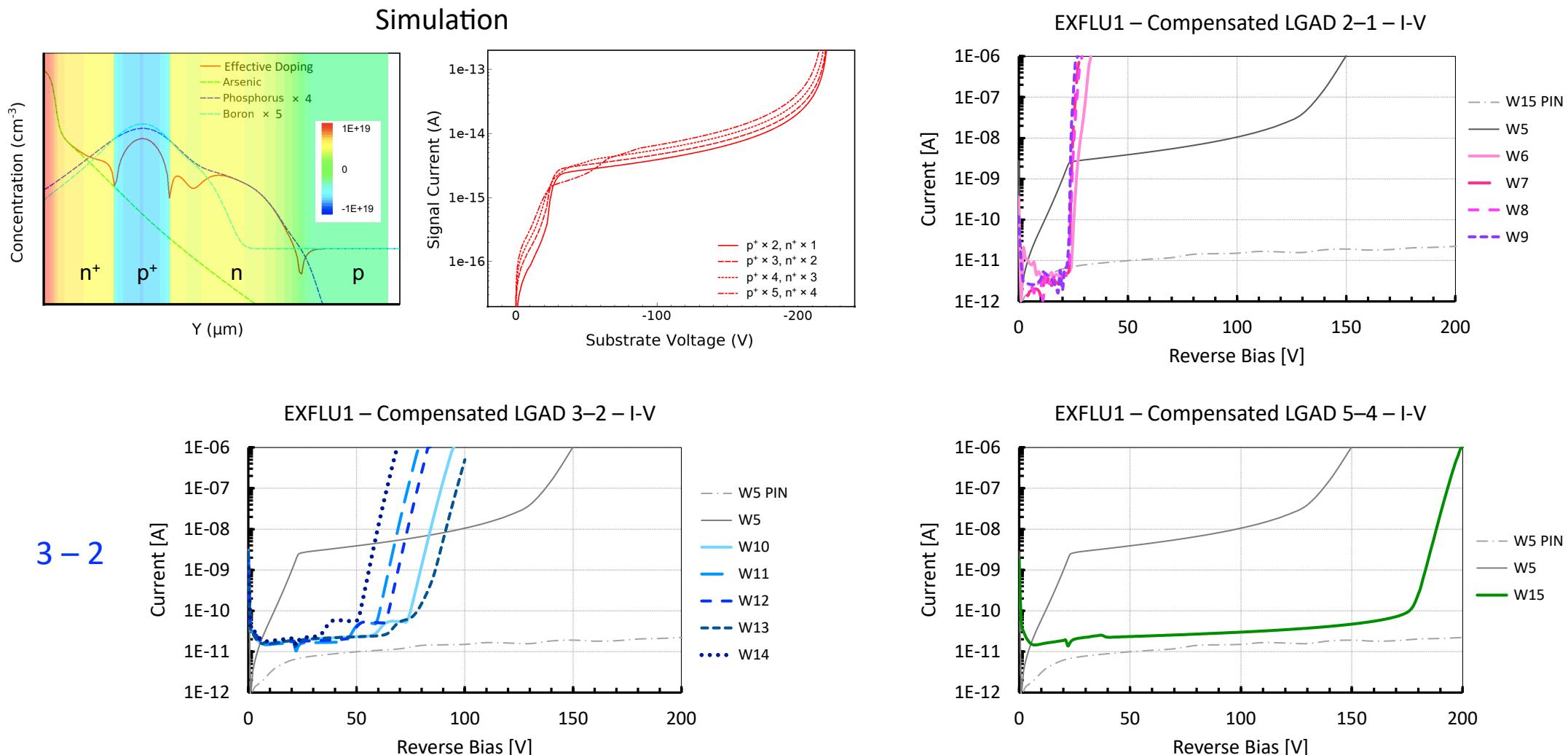
Compensated Gain Layer Design – Split Table

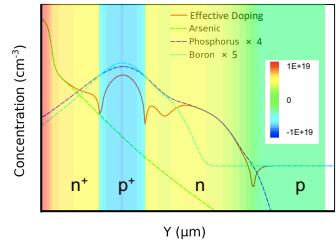
Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
7	30	2 b	1	
8	30	2 b	1	
9	30	2 c	1	
10	30	3 a	2	
11	30	3 b	2	
12	30	3 b	2	
13	30	3 b	2	1.0
14	30	3 c	2	
15	30	5 a	4	

[a < b < c]

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

Compensated LGAD – I-V on wafer

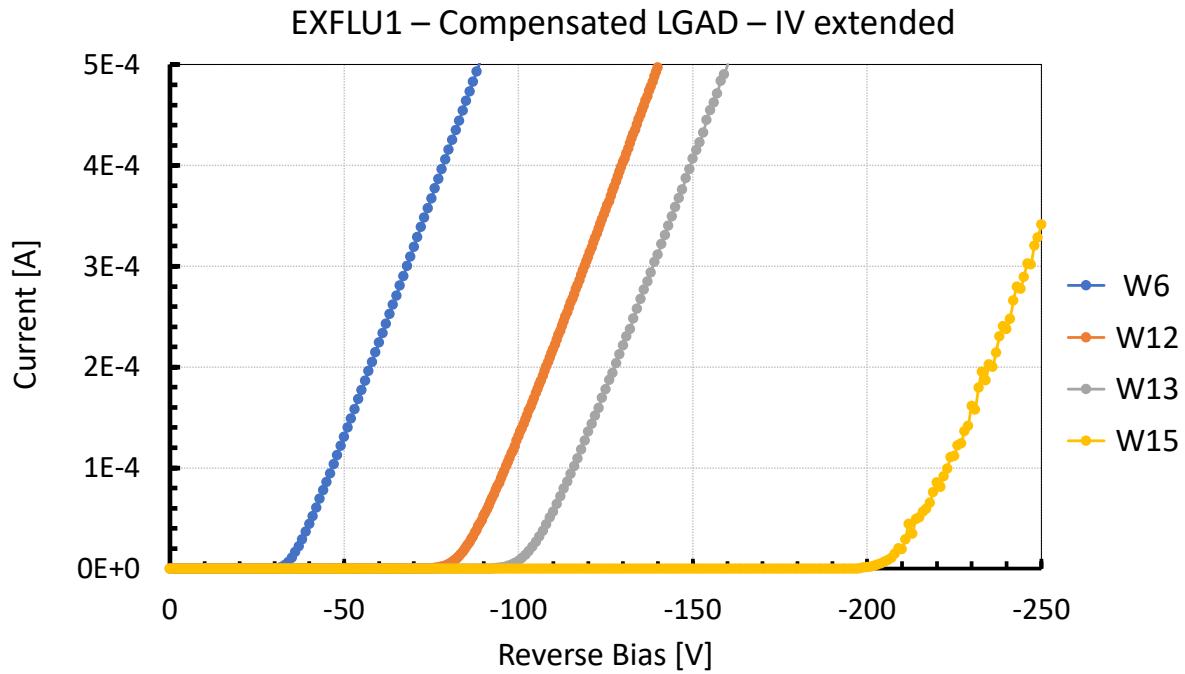
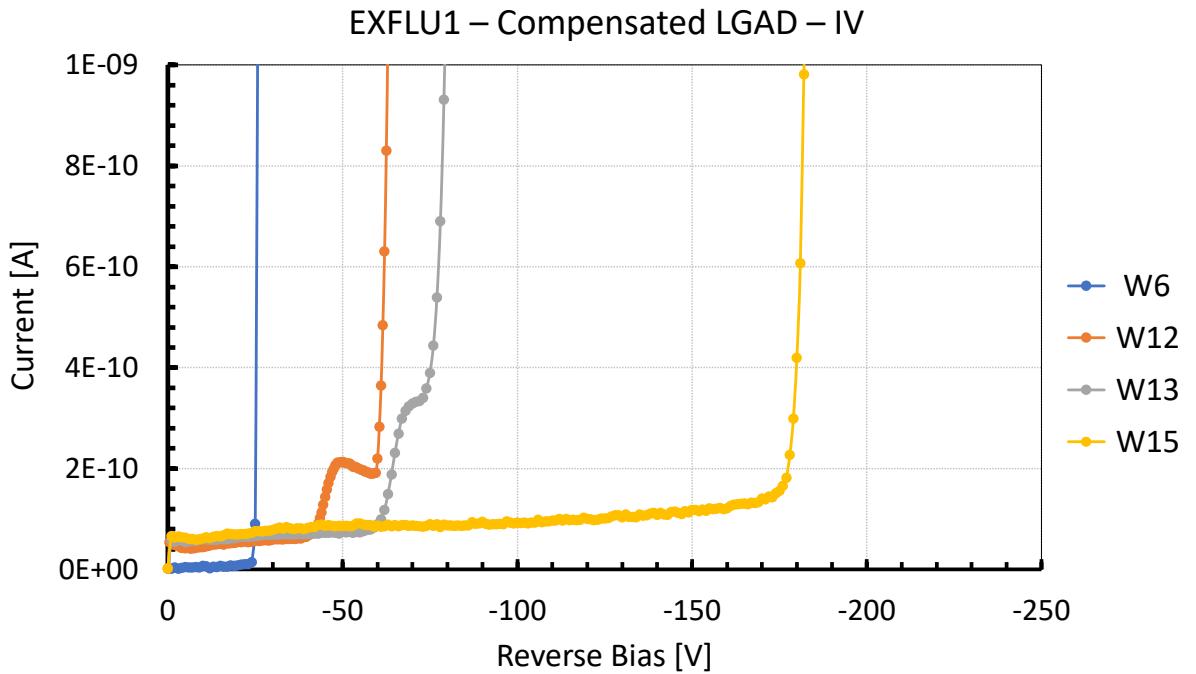




Compensated LGAD – I-V

Sensor PAD 1.3 S3 18-D

T = +25°C



Compensated LGAD produced by HPK

Presented by K. Hara at TREDI2023 [[link](#)]

Radiation tolerance improvement – trial2

How should we understand the results?

Compensation

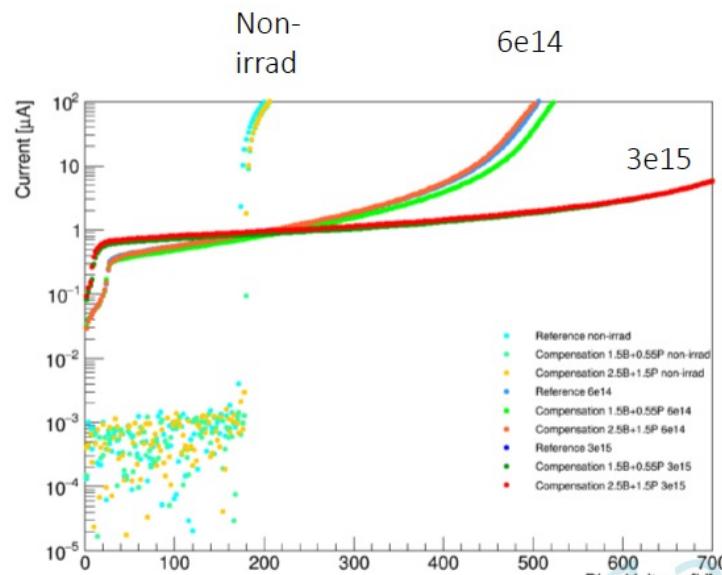
Result not promising....

Not much change by two different compensation parameters

$2.5B+1.5P$
 $1.5B+0.55P$

Initial compensation works perfect

What does this mean?



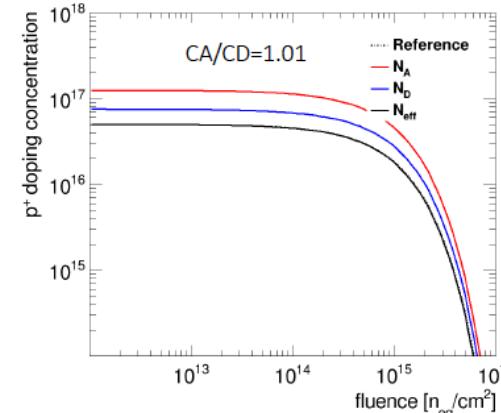
$$N_A(\emptyset) - N_D(\emptyset) = N_A(0) \cdot e^{-C_A\emptyset} - N_D(0) \cdot e^{-C_D\emptyset}$$

If $C_A = C_D$

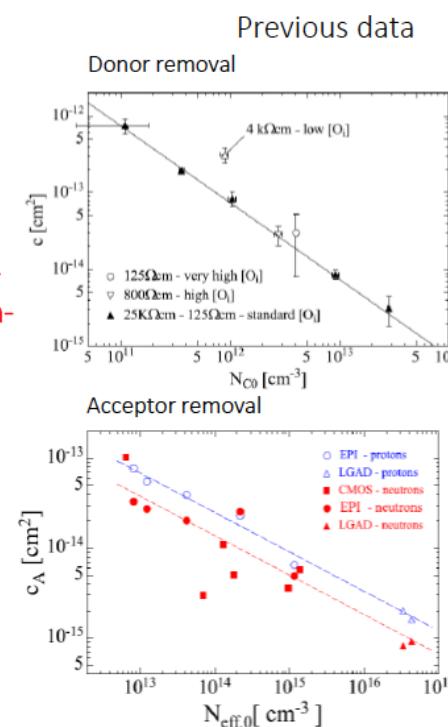
$$N_A(\emptyset) - N_D(\emptyset) = (N_A(0) - N_D(0)) \cdot e^{-C_A\emptyset}$$

reference

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



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



13

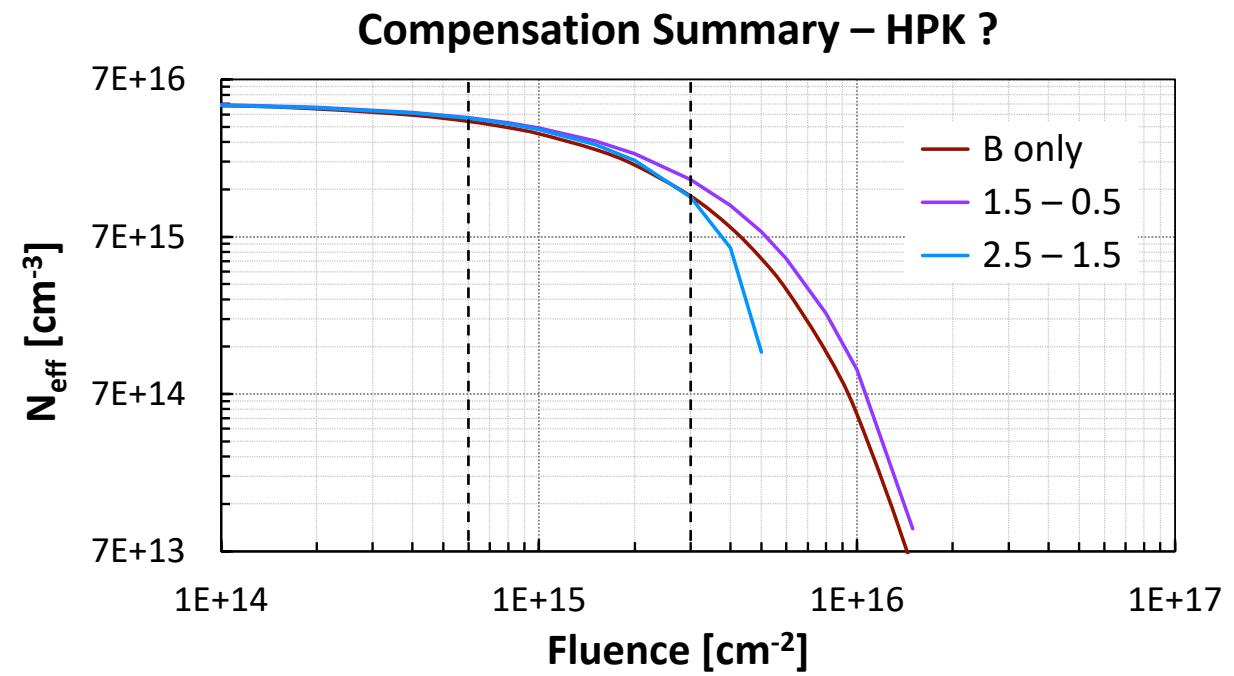
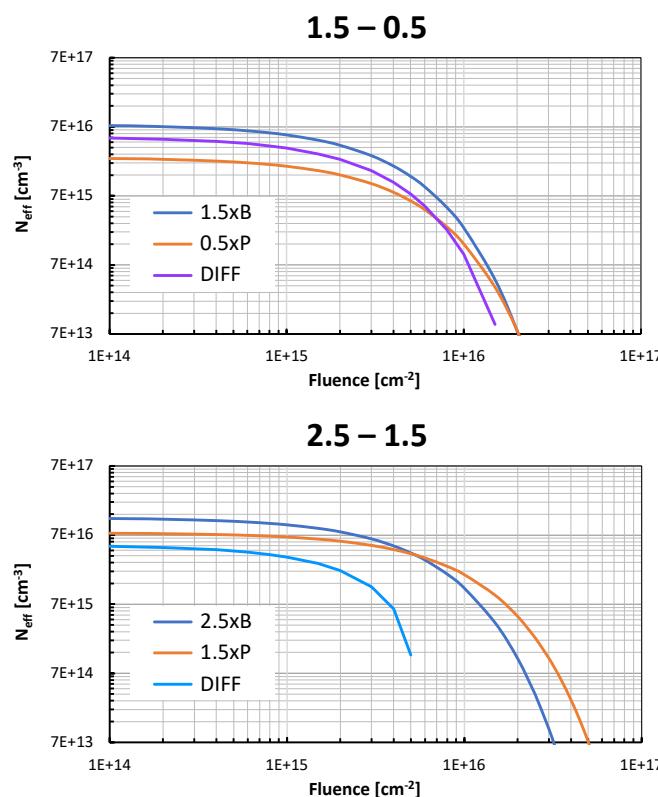
Compensated LGAD from HPK – c_A vs c_D ?

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 $6\text{E}14$ & $3\text{E}15 \text{n}_{\text{eq}}/\text{cm}^2$ → $\text{p}^+ - \text{n}^+$ compensated doping is the same as before irradiation

⇒ $c_A > c_D$?



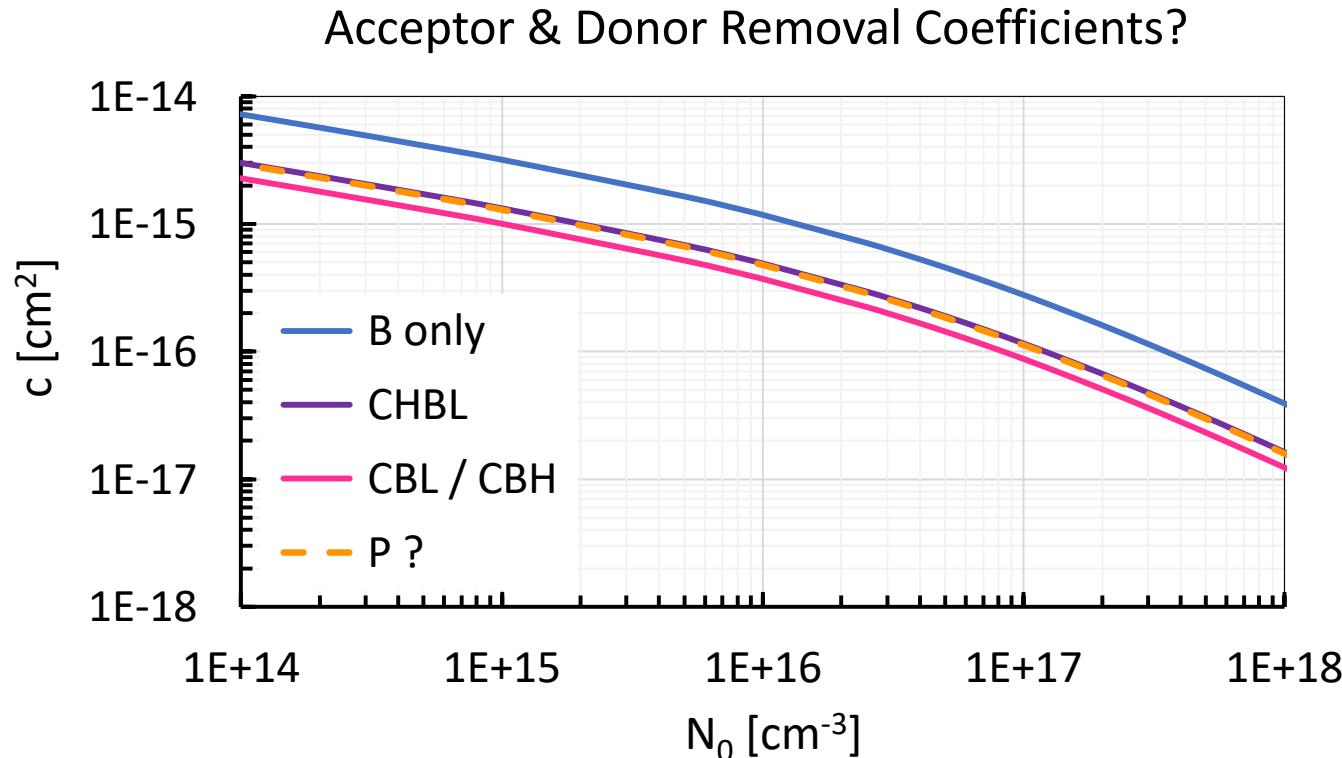
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$\Rightarrow c_A > c_D$?



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

The eXFlu Project

In 2020, INFN awarded for funding a 2 years grant for young researchers
to develop, produce, irradiate and study thin silicon sensors
→ **The *Silicon Sensor for Extreme Fluences (eXFlu)* project**

Thin LGAD wafers have been produced at FBK

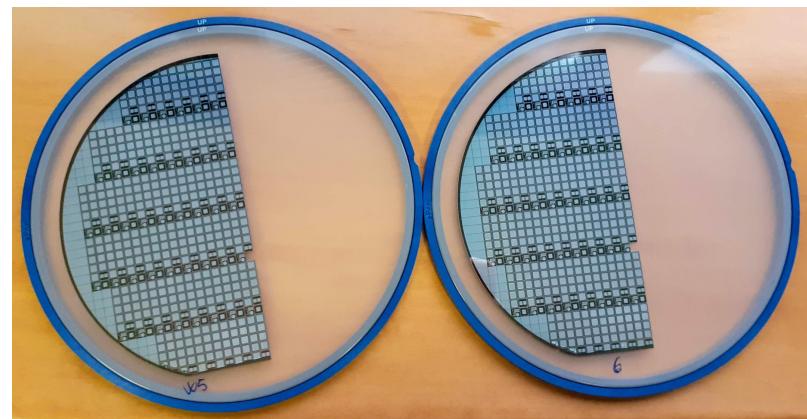
→ **EXFLU0 production**

- ▷ 2 different wafer thicknesses: **25 & 35 µm**
- ▷ epitaxial substrates
- ▷ **single pads** and **2x2 arrays**

For more details see

- ⇒ 1.infn.it/exflu
- ⇒ indico.cern.ch/event/896954/contributions/4106324/
- ⇒ indico.cern.ch/event/1074989/contributions/4601953/

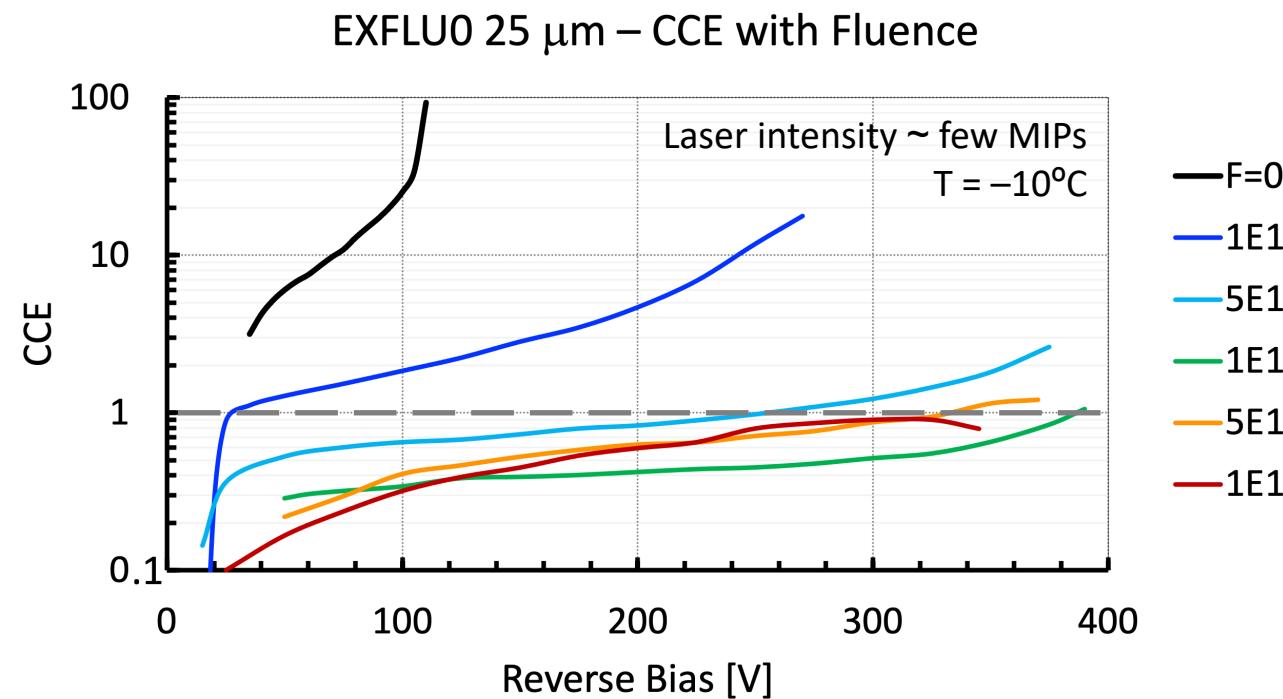
Released at the end of 2020



**EXFLU0 sensors have been irradiated
at JSI, Ljubljana, to 5 different fluences
 10^{15} , $5 \cdot 10^{15}$, 10^{16} , $5 \cdot 10^{16}$, 10^{17} n_{eq}/cm²**

25 μm LGAD Signal at Different Fluences

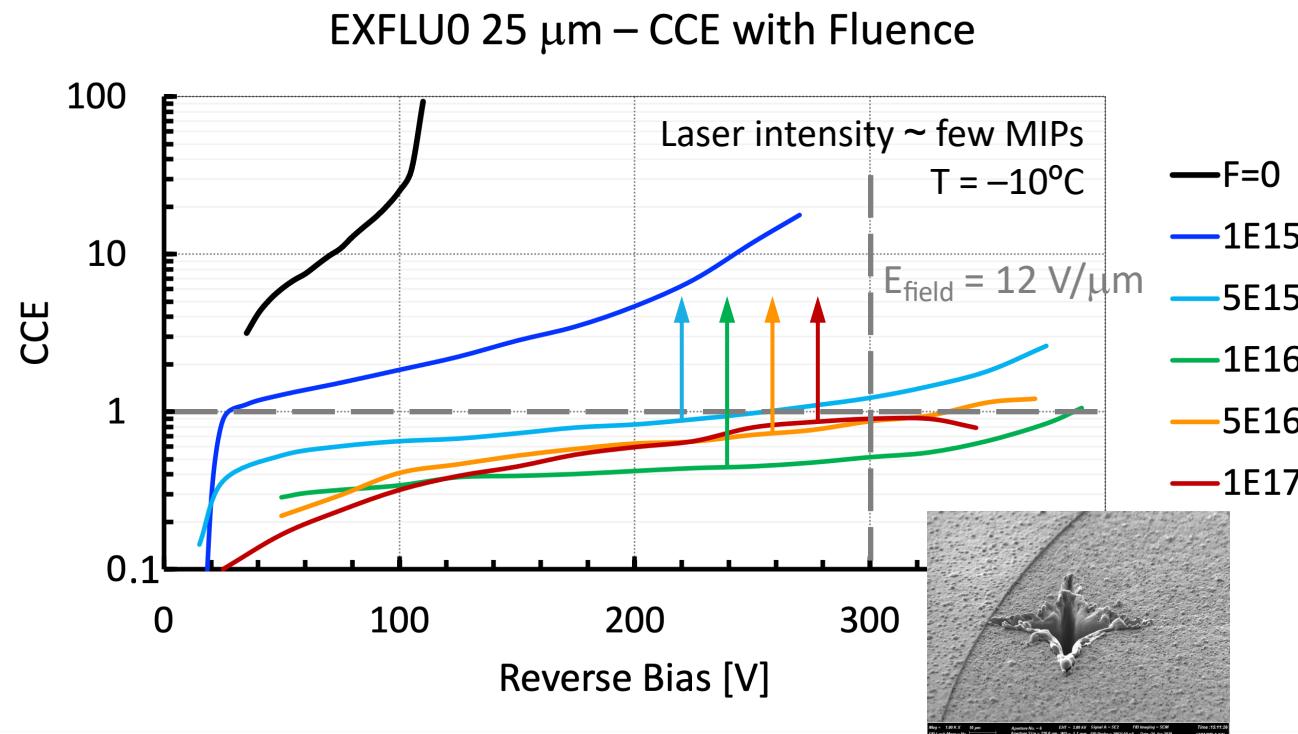
Measurements of charge collection efficiency (CCE) with an infra-red laser stimulus show that sensors can be operated up to the highest fluences



- ▷ The LGAD multiplication mechanism ceases existing at $\sim 5 \cdot 10^{15} n_{eq}/cm^2$
- ▷ From 10^{16} to $10^{17} n_{eq}/cm^2$ 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

Take-Home from EXFLUO

Measurements of **charge collection efficiency (CCE)** with an infra-red laser stimulus show that sensors can be operated up to the highest fluences – **25 μm thick LGADs**



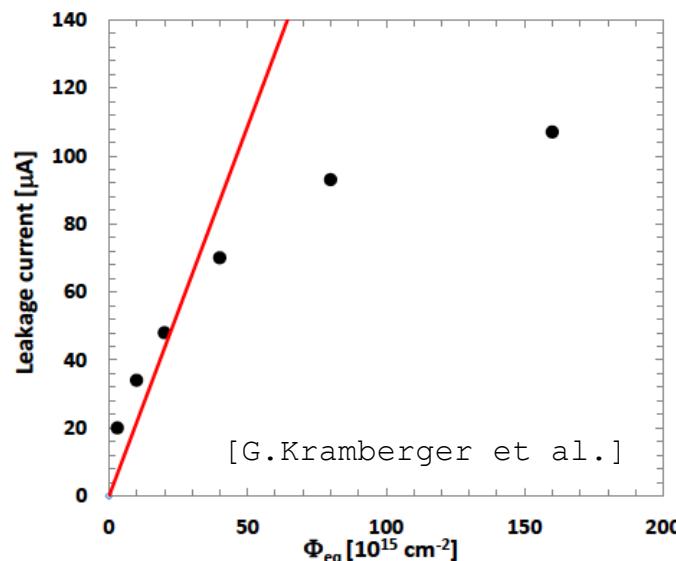
- ▷ The LGAD multiplication mechanism ceases existing at $\sim 5 \cdot 10^{15} n_{eq}/cm^2$
- ▷ From 10^{16} to $10^{17} n_{eq}/cm^2$ the collected signal is roughly constant
- ▷ For electric fields above $12 \text{ V}/\mu\text{m}$, thin silicon sensors undergo fatal death once exposed to particle beams
→ Single-Event Burnout

[[indico.cern.ch/event/861104/
contributions/4513238/](https://indico.cern.ch/event/861104/contributions/4513238/)]

→ Necessary to increase the radiation tolerance of the gain mechanism above $10^{15} n_{eq}/cm^2$

Saturation

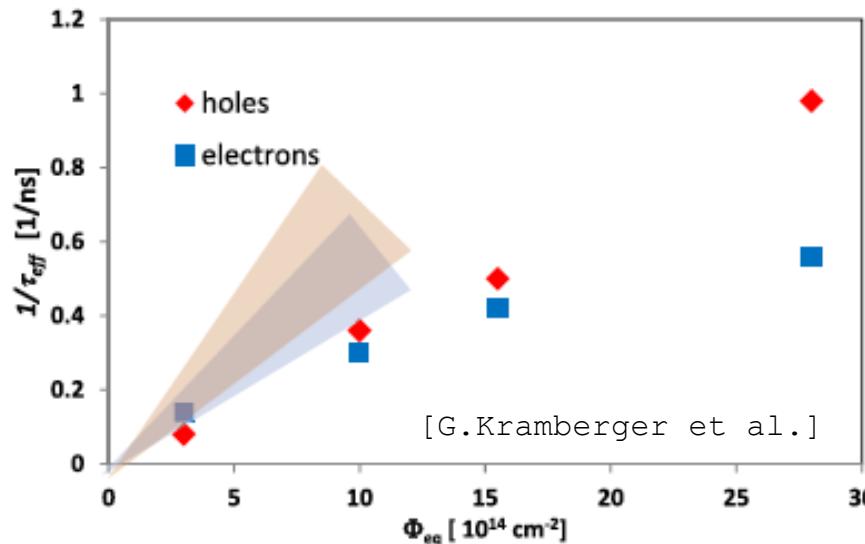
At fluences above $5 \cdot 10^{15} \text{ cm}^{-2}$ → **Saturation of radiation effects observed**



Leakage current saturation

$$I = \alpha V \Phi$$

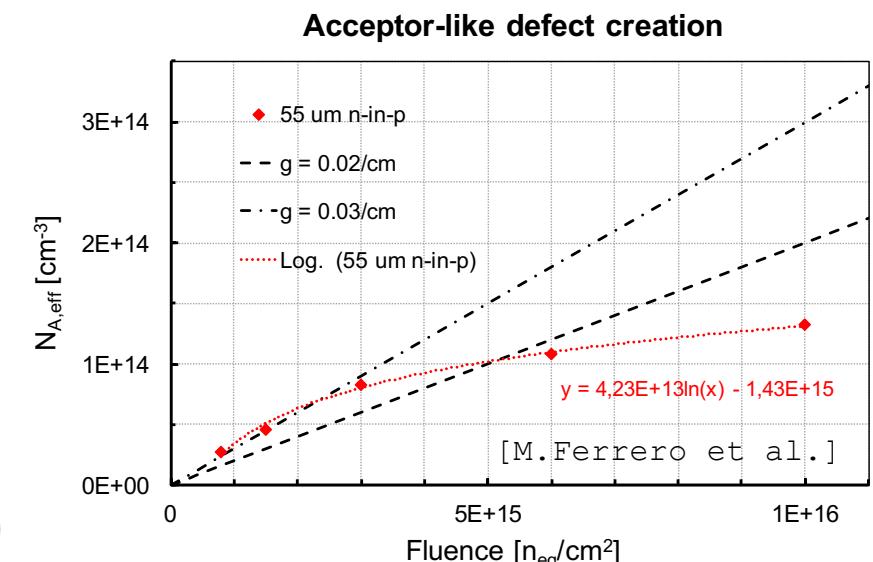
α from linear to logarithmic



Trapping probability saturation

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

β from linear to logarithmic



Acceptor creation saturation

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

g_c from linear to logarithmic

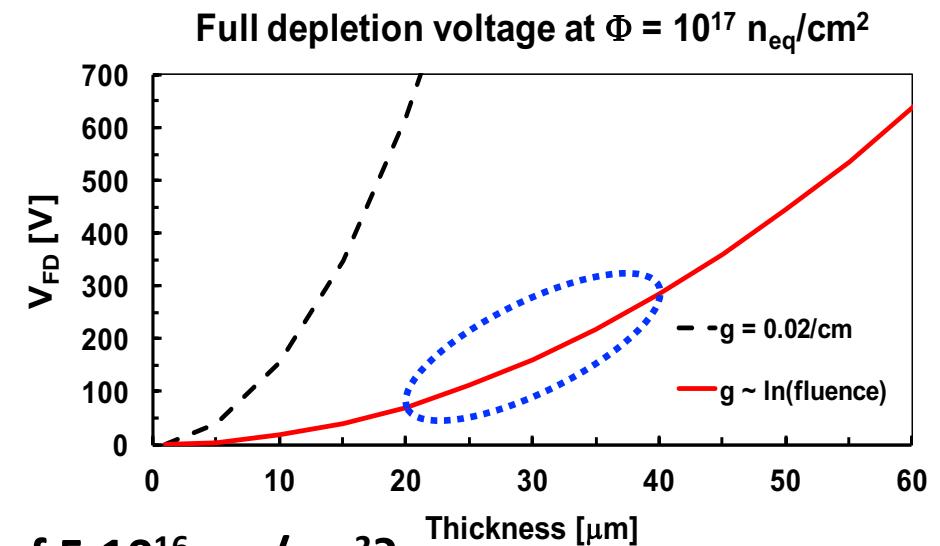
Silicon detectors irradiated at fluences $10^{16} - 10^{17} \text{ n}_{\text{eq}}/\text{cm}^2$ do not behave as expected → **They behave better**

Thin Substrates

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

Saturation **Reduce thickness**

At high fluences, only thin substrates can be fully depleted



What does it happen to a $25 \mu m$ 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 $\sim 0.25 fC$

- This charge is lower than the minimum charge requested by the electronics ($\sim 1 fC$ for tracking, $\gtrsim 5 fC$ for timing)
- Need a gain of at least ~ 5 in order to efficiently record a hit

Optimal candidate:
LGAD sensors