TREDI 2023
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Advances in LGAD Technology for High Radiation Environments

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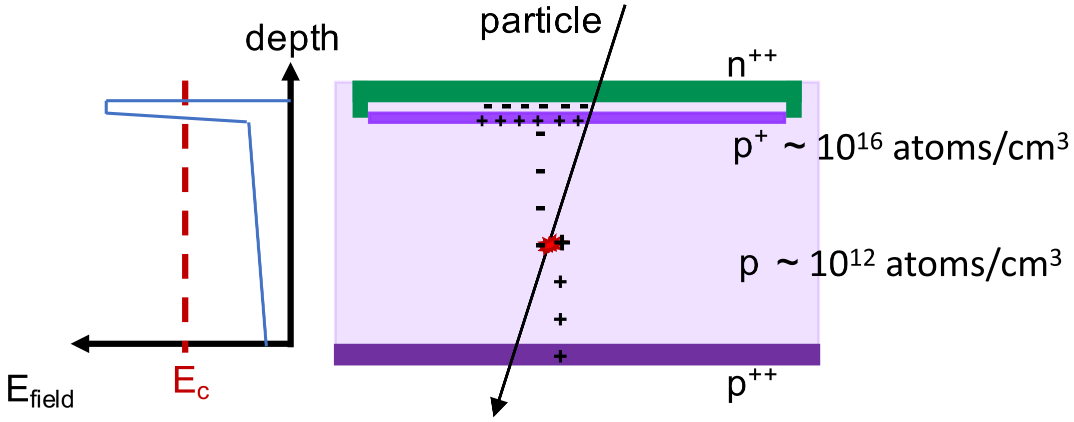
Thin LGAD for the Extreme Fluences



The idea: use thin sensors (15 – 45 μm) with internal gain

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

Minimum charge requested by the electronics

→ **~ 1 fC** for tracking

→ **≳ 5 fC** for timing

Charge from a MIP crossing thin sensors

→ **~ 0.1 fC every 10 μm**

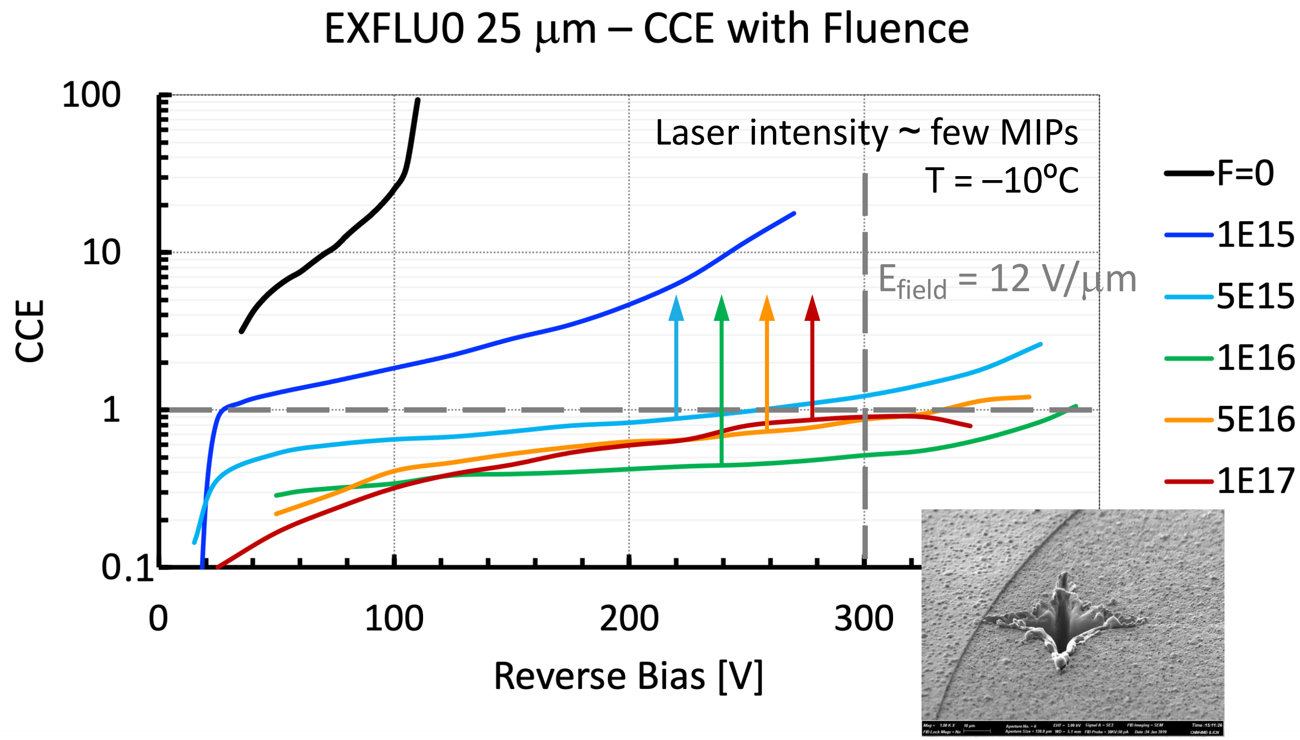
[S. Meroli et al., doi:10.1088/1748-0221/6/06/P06013]

⇒ **Need a gain of at least 5 – 10**

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

Take-Home from EXFLU0

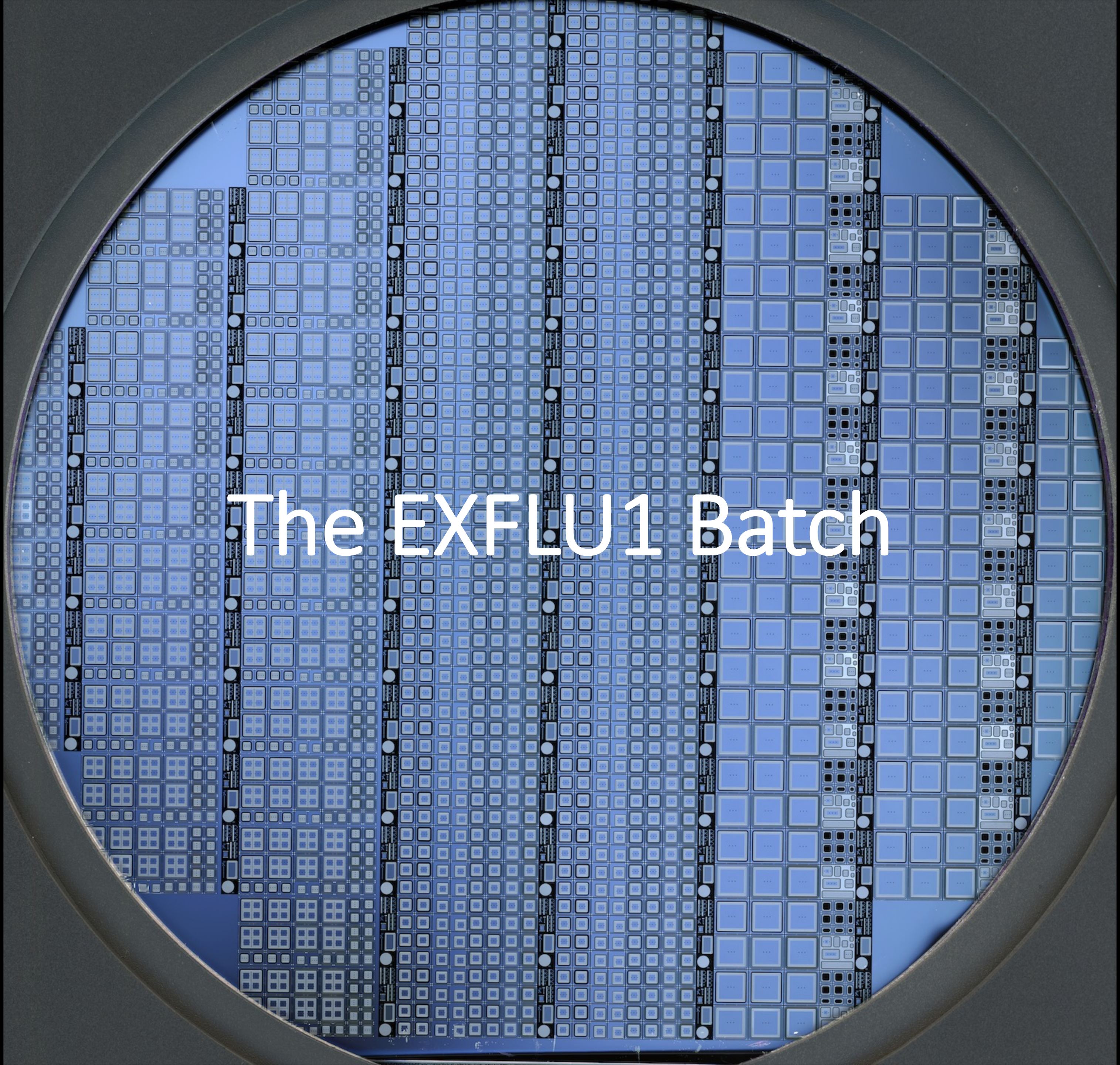
Measurements of **charge collection efficiency** (CCE) with an infra-red laser stimulus show that sensors can be operated up to the highest fluences – **25 μm thick LGADs**



- ▻ The LGAD multiplication mechanism ceases existing at ~ $5 \cdot 10^{15}$ 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 V/μm, thin silicon sensors undergo fatal death once exposed to particle beams
  → Single-Event Burnout

[indico.cern.ch/event/861104/contributions/4513238/]

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



The EXFLU1 Batch

The EXFLU1 Batch at a Glance

A new production of thin LGAD by the FBK foundry ⇒ EXFLU1

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

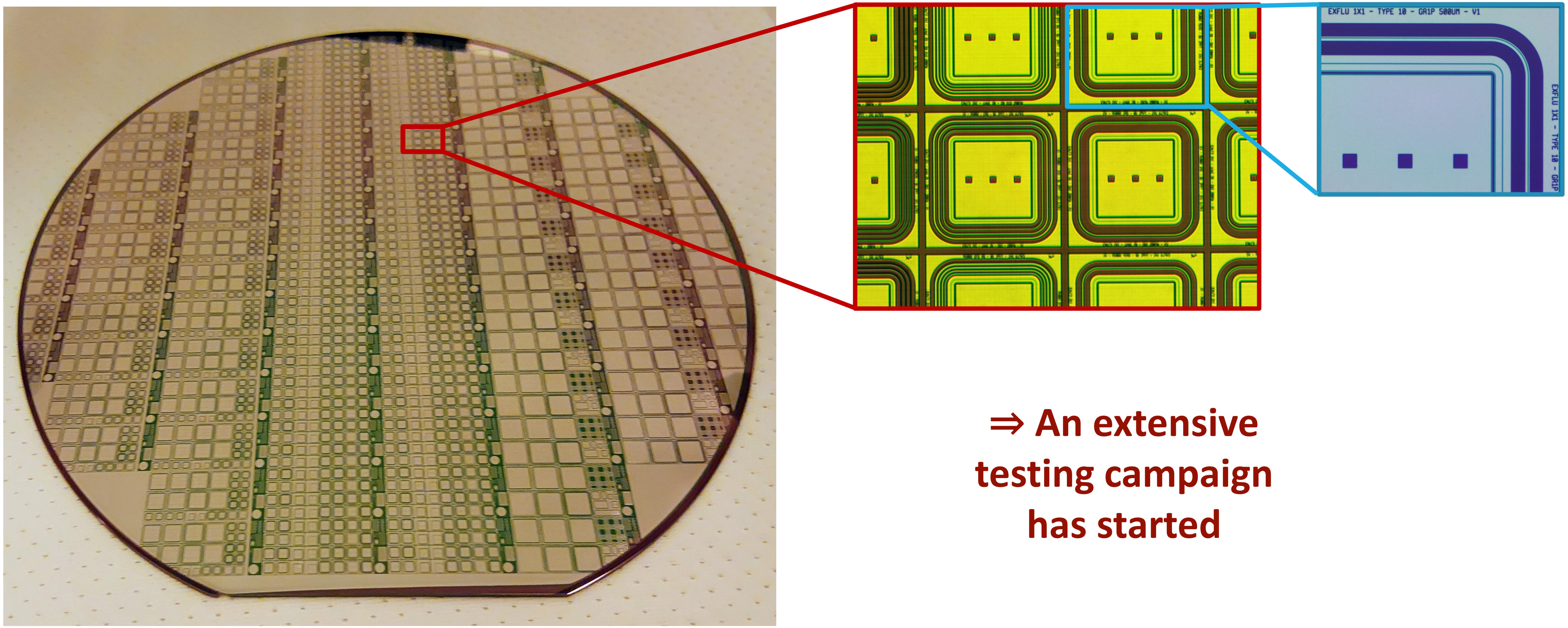
- thin substrates (15–45 µm)
- decrease of the acceptor removal – carbon shield
- signal multiplication up to the extreme fluences – compensation
- new guard ring design

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

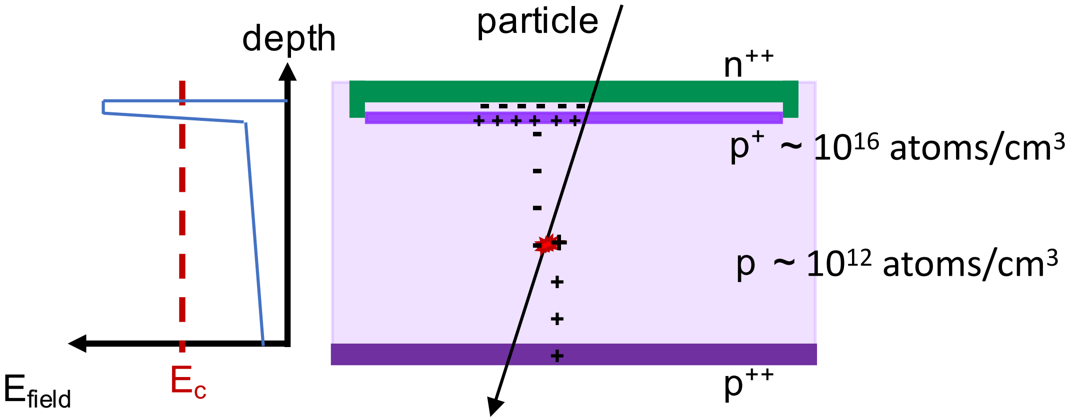
The EXFLU1 Wafers

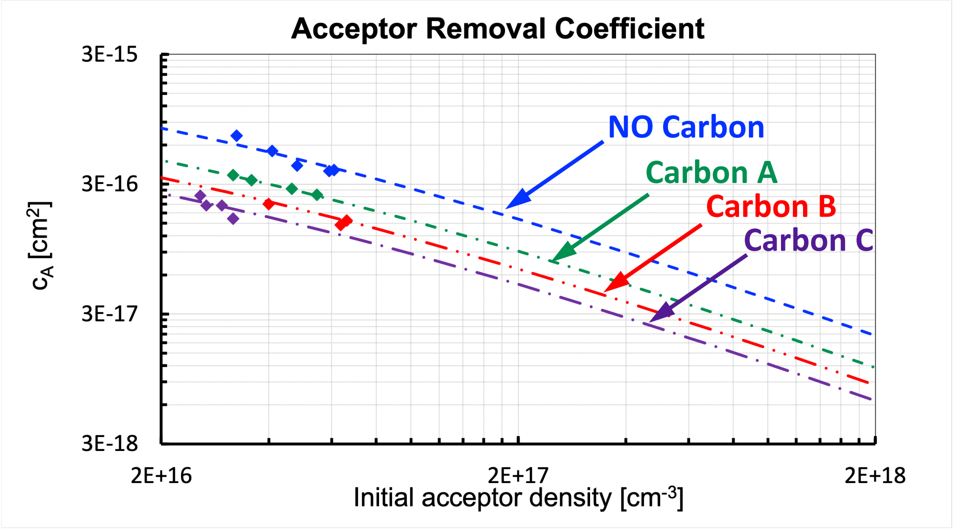
6” Wafer



⇒ An extensive testing campaign has started

Gain Removal Mechanism in LGADs





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

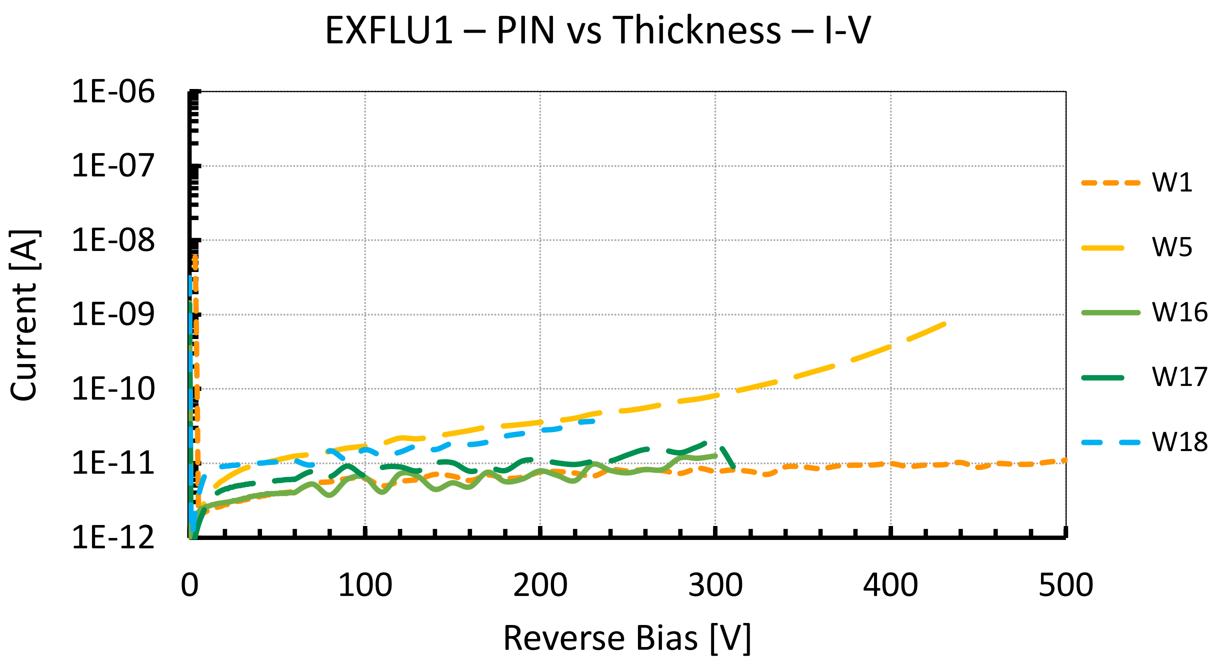
$$\mathbf{p^+(\Phi) = p^+(0)\cdot e^{-c_A\Phi}}$$

where c_A is the acceptor removal coefficient

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

Thin LGADs – I-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/cm3
16	**20**	**0.80**	**1.0**	**CHBL**	1.5E14/cm3
17	**20**	**0.96**	**1.0**	**CBL**	
18	**15**	**0.94**	**1.0**	**CBL**	



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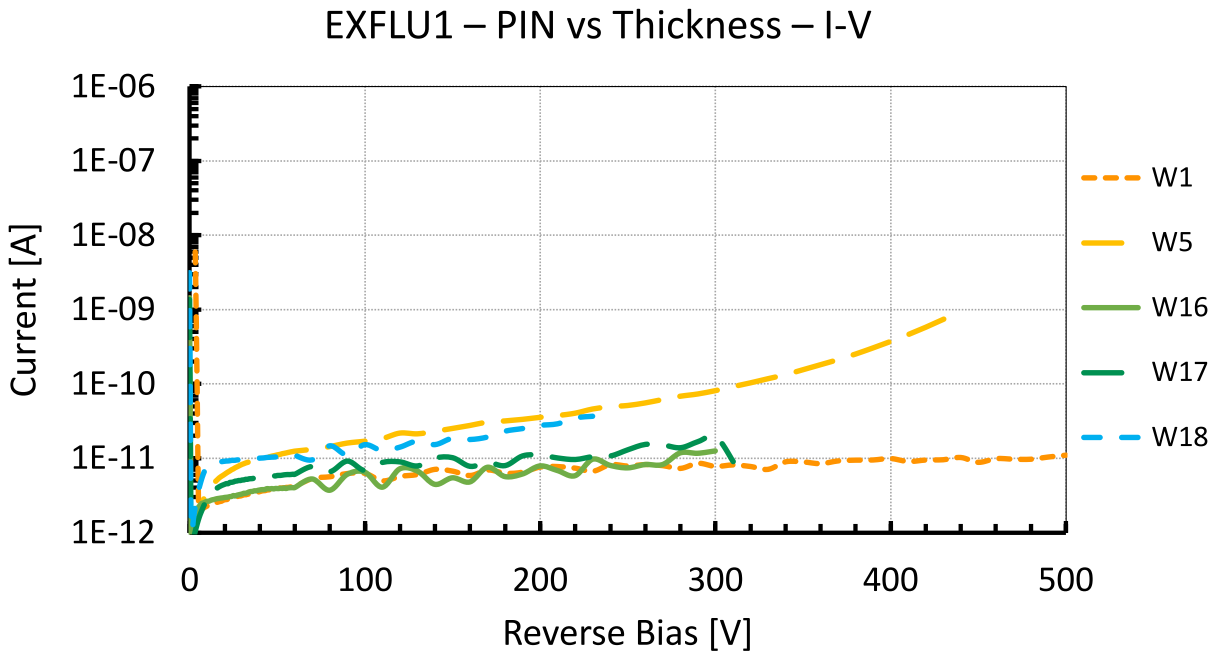
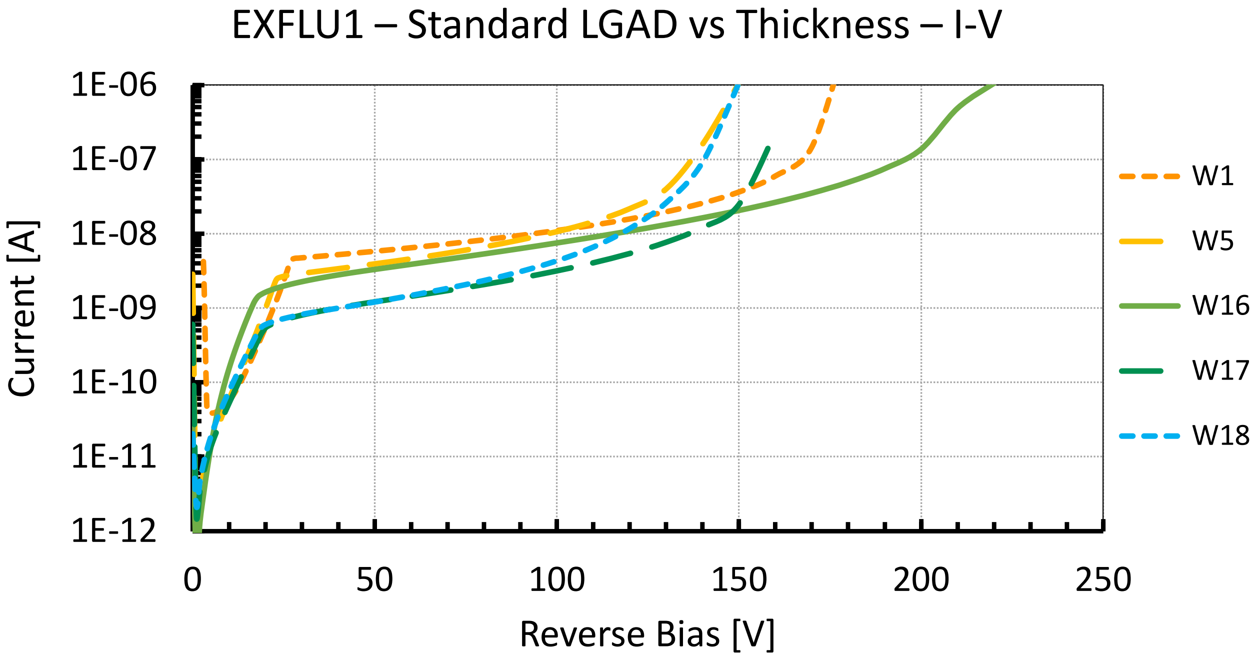
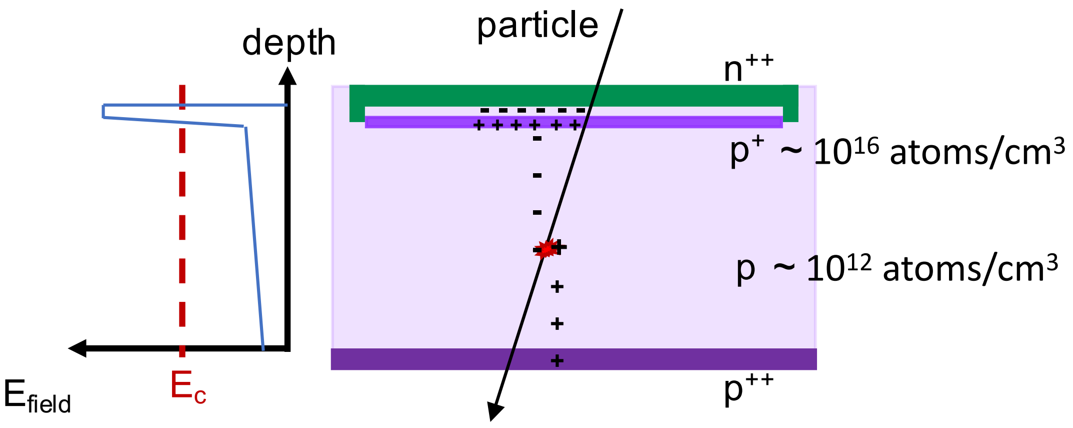
16	20	0.80	1.0	CHBL	1.5E14/cm3
17	20	0.96	1.0	CBL	
18	15	0.94	1.0	CBL	

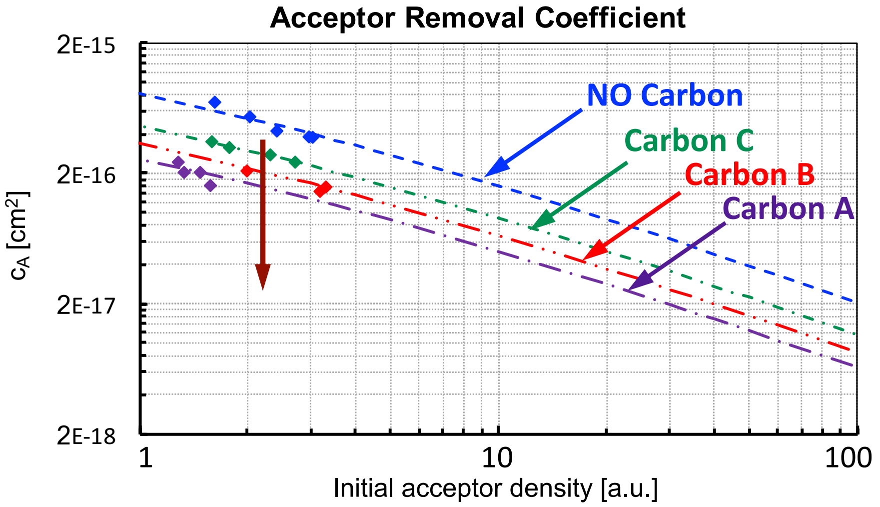
In LGAD sensors, the breakdown due to gain occurs between 150 and 220 V





Gain Removal Mechanism Mitigation





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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]`

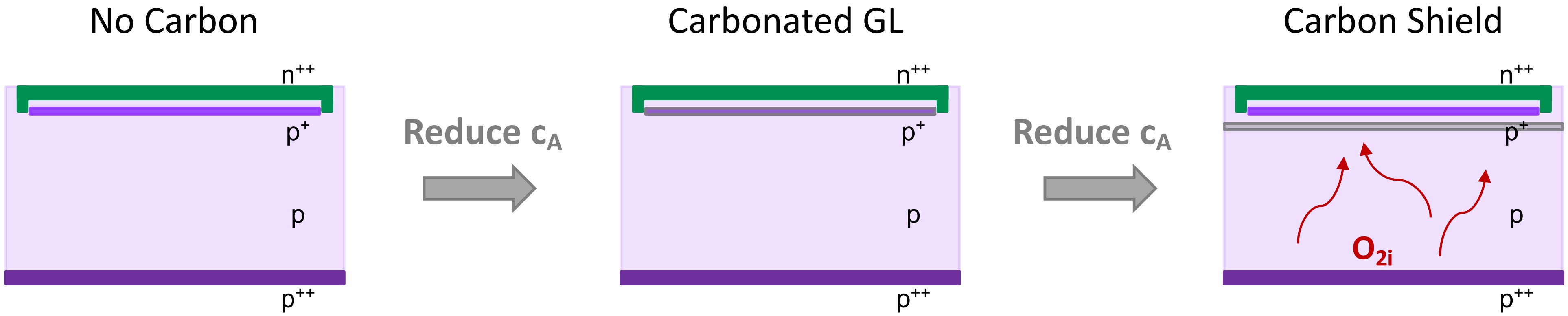
Is it possible to further reduce c_A ?

⇒ The goal is to preserve the gain up to $\Phi = 5\cdot10^{15}\ n_{eq}/cm^2$

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



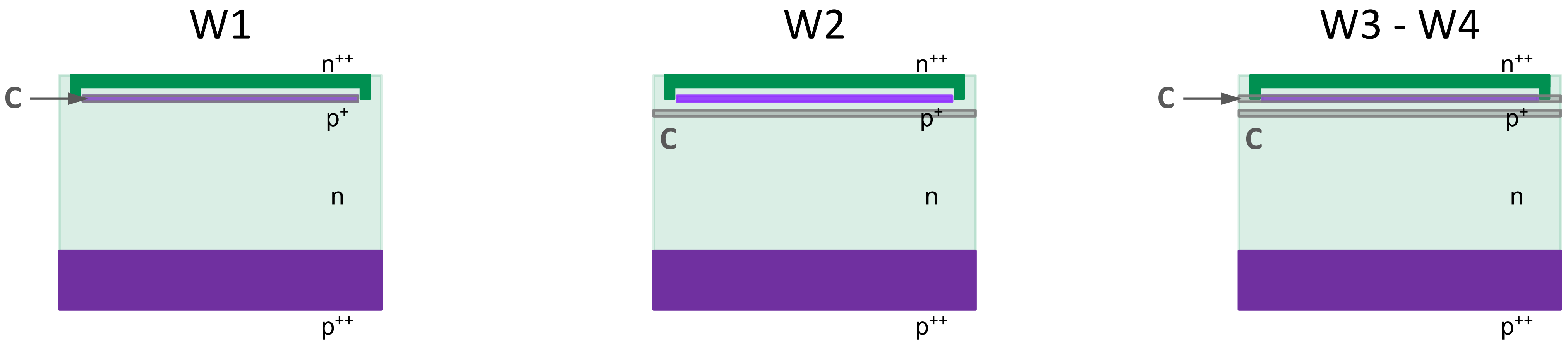
A spray of Carbon will be introduced below the gain layer region to protect the gain layer atoms from defects moving towards the n^{++} electrode during process thermal loads or exposure to particle radiation

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

LGADs 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



Production costs increase by ~ 20%

→ Expected improvement in radiation tolerance of 20 – 30%

LGADs with Carbon Shield – I-V

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1	45	1.14	1.0		CBL
2	45	1.00		0.6	CBL
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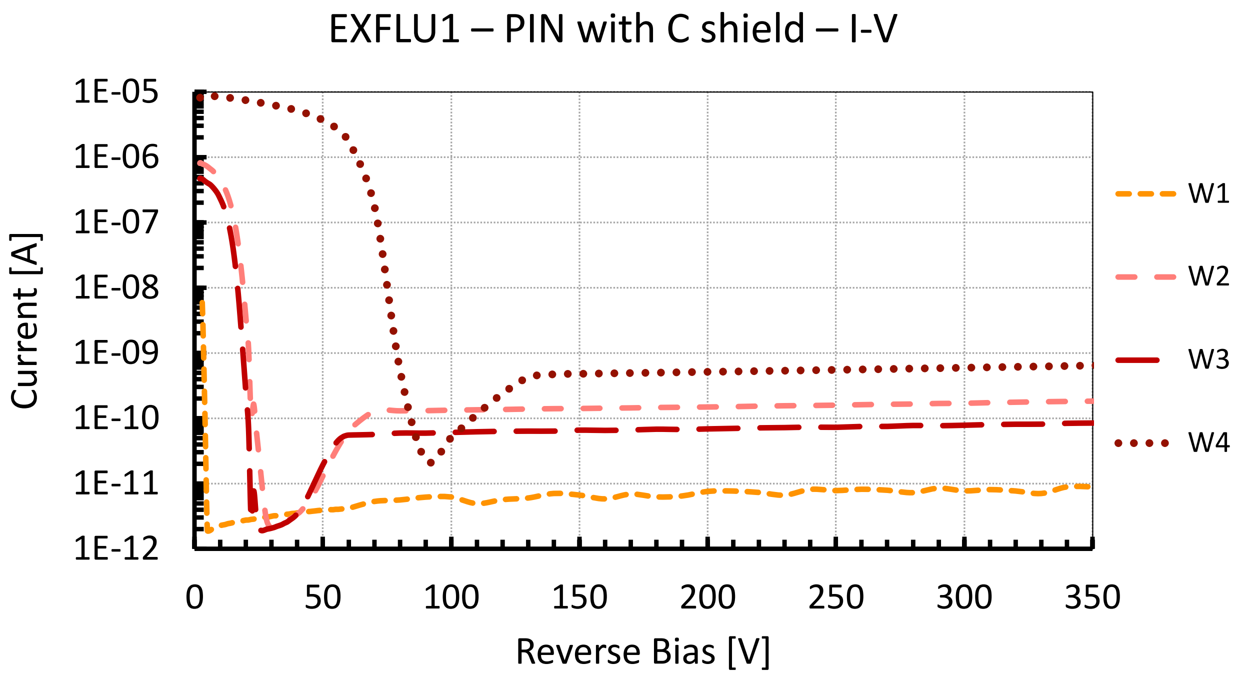

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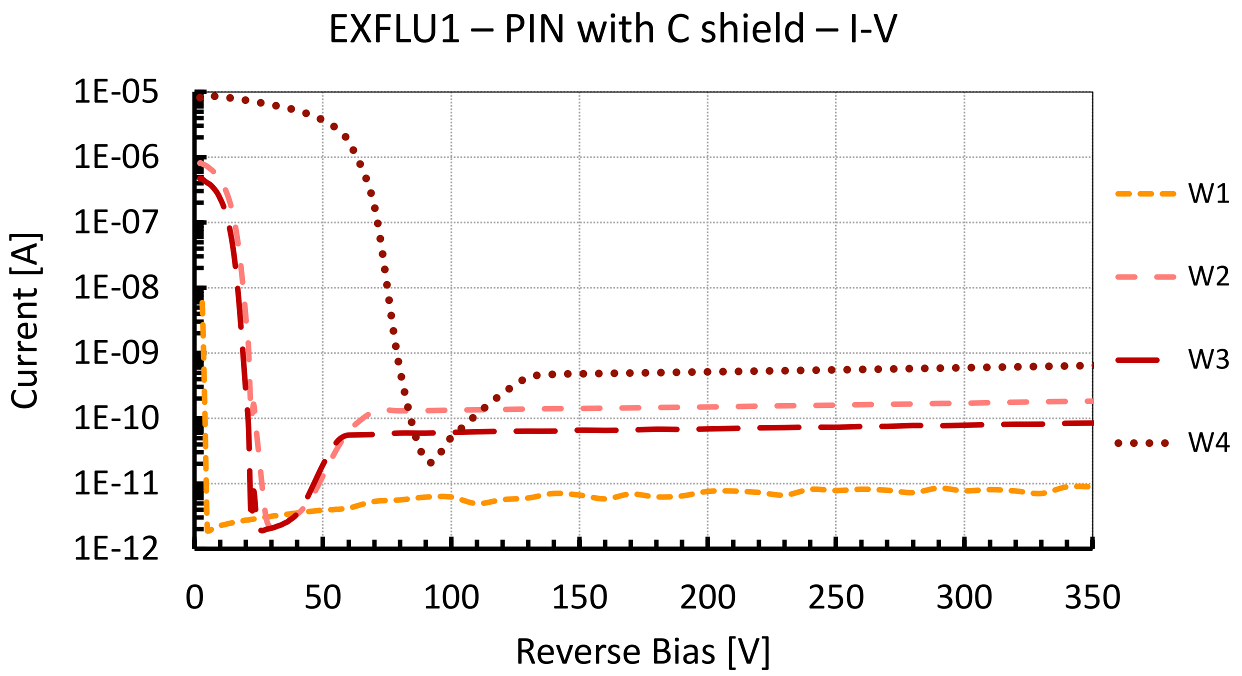
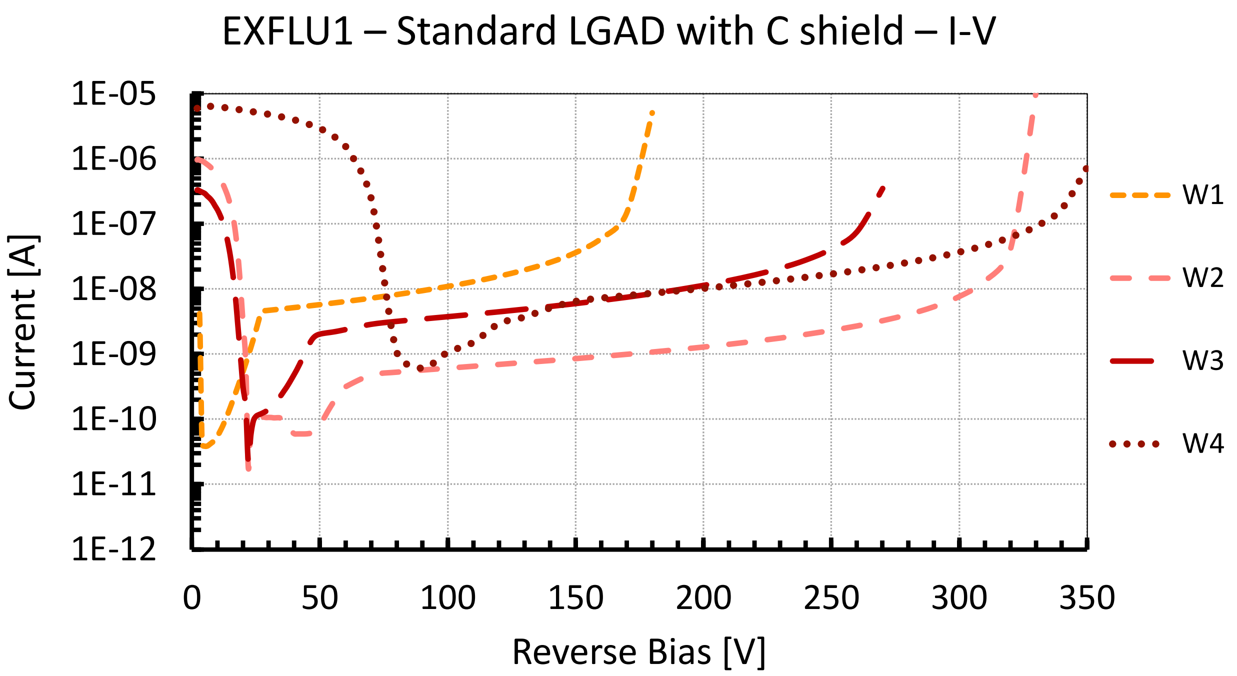
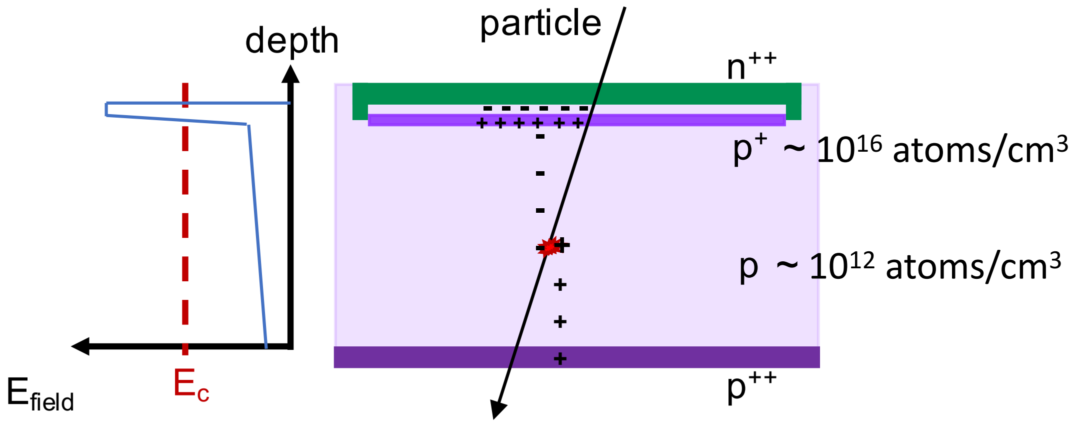
4	45	1.16	1.0	1.0	CBL

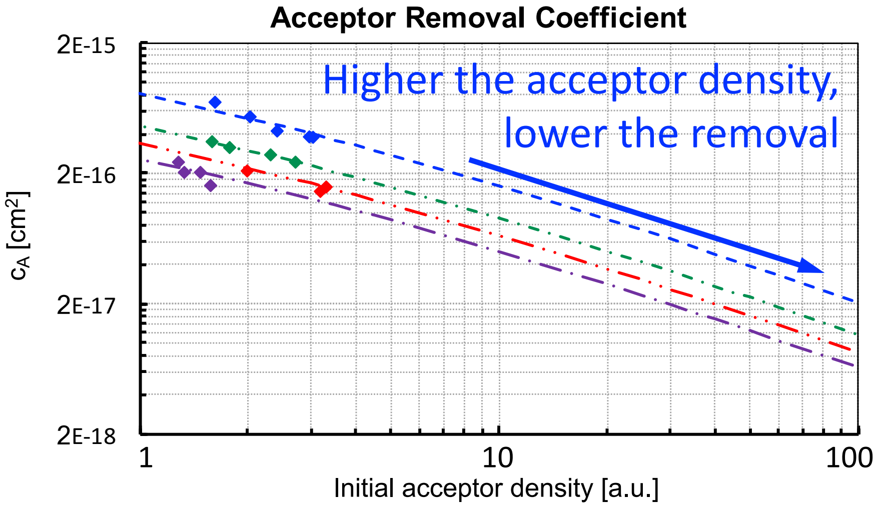
Carbon shield shifts
the breakdown voltage
to higher values of bias





Towards a Radiation Resistant Design





Higher the acceptor density, lower the removal

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

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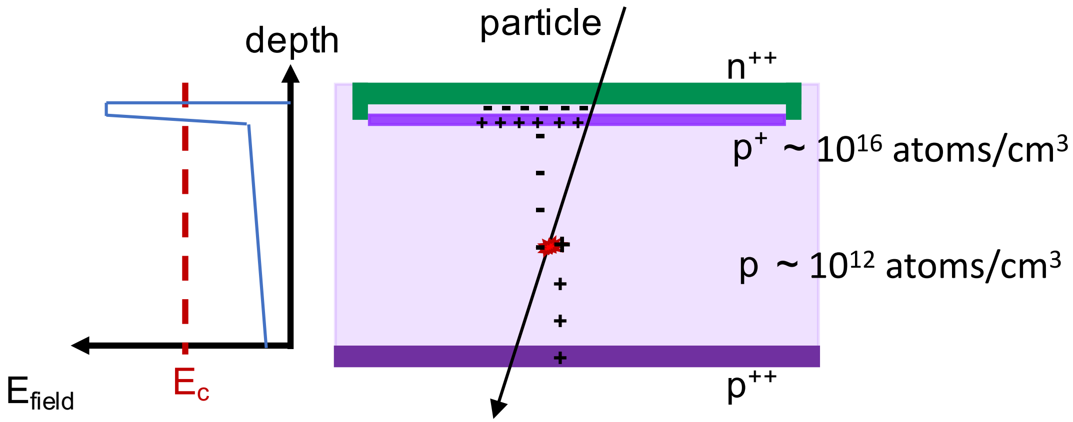

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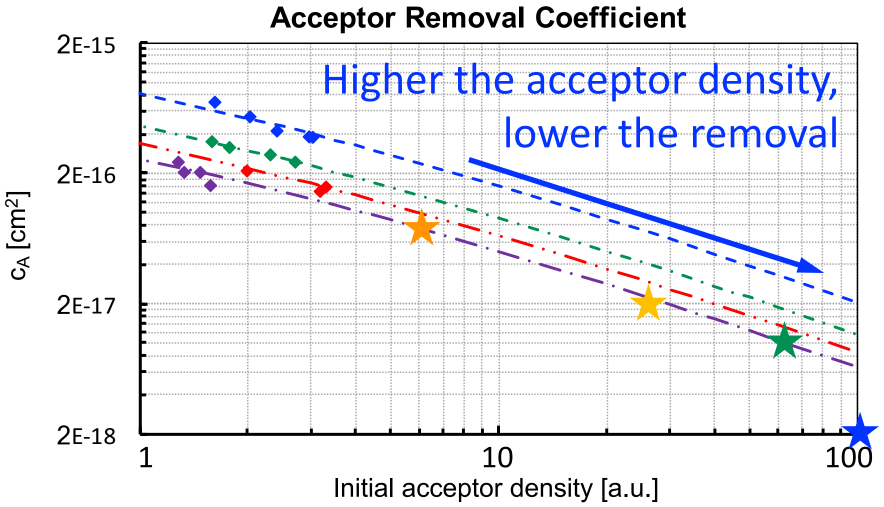
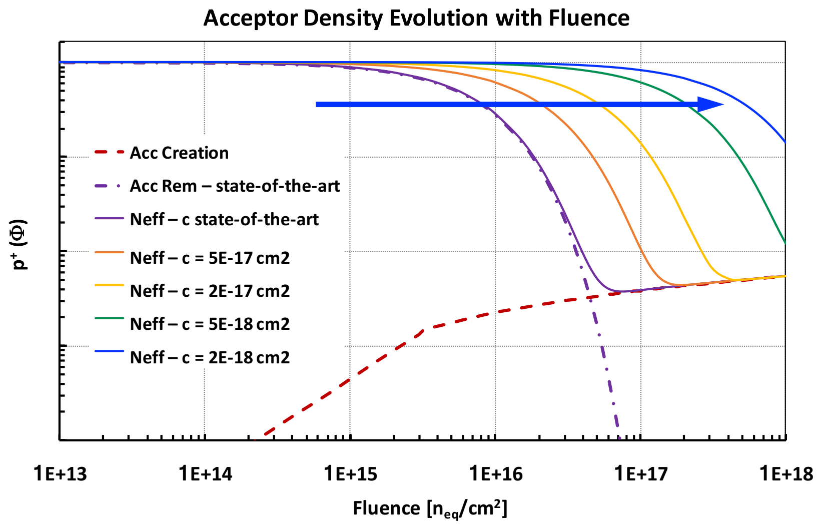




Lowering c_A can extend the gain layer survival up to $\Phi \geq 10^{17}$ n_{eq}/cm²

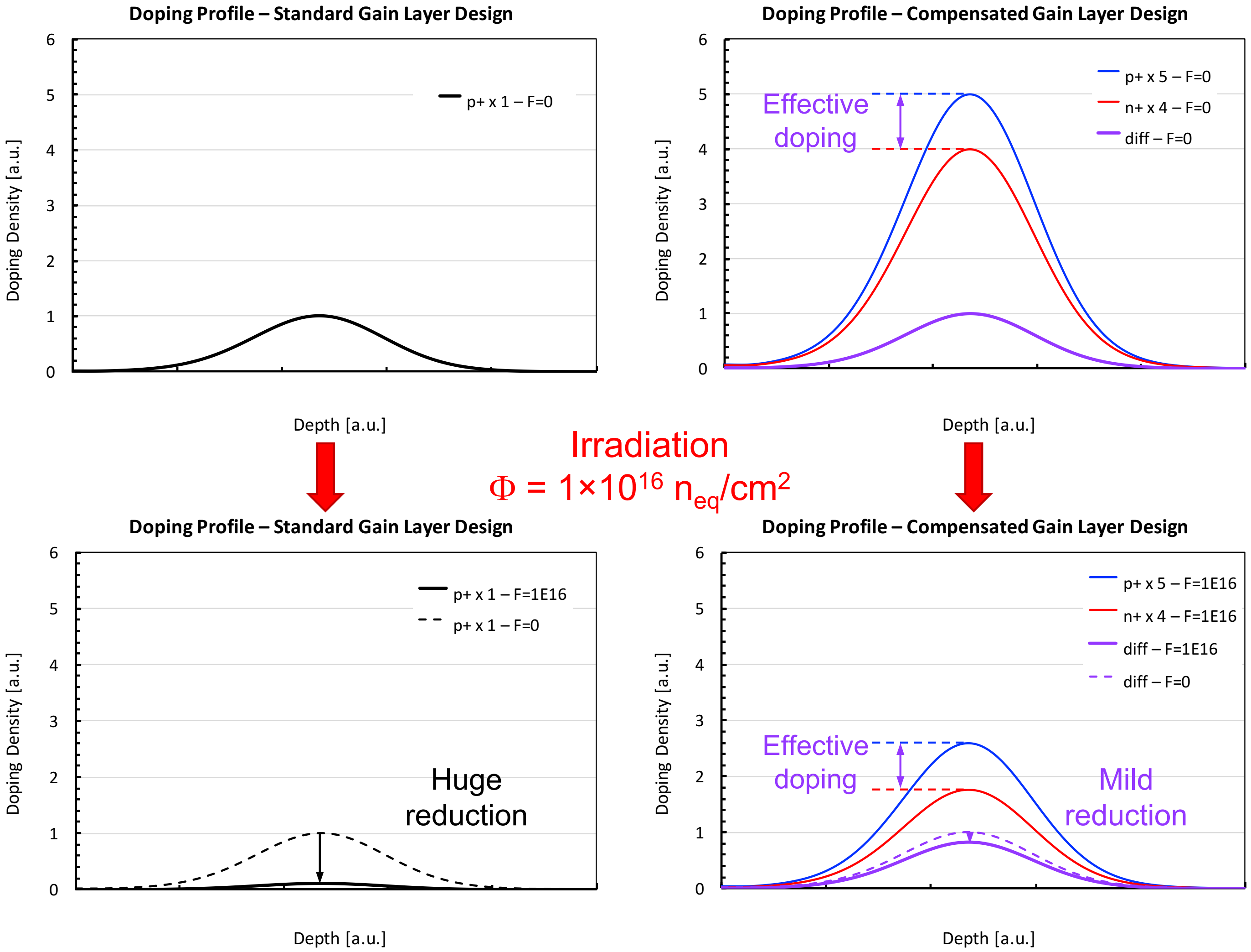
A new Paradigm – Compensation

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:

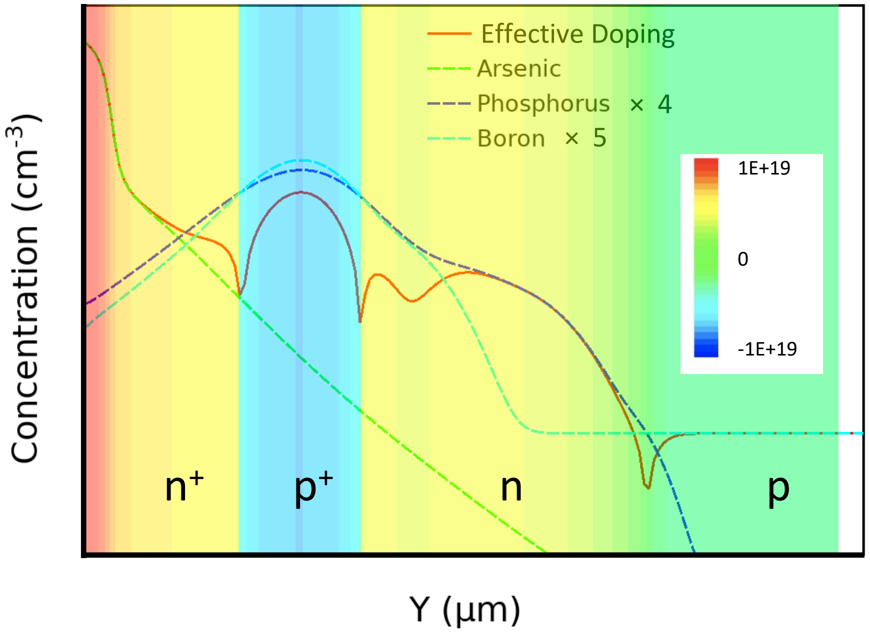
- donor removal coefficient, from $n^+(\Phi) = n^+(0)\cdot e^{-c_D\Phi}$
- interplay between donor and acceptor removal (c_D vs c_A)
- effects of substrate impurities on the removal coefficients



Compensation from Simulation

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

Doping Profiles from Process Simulation



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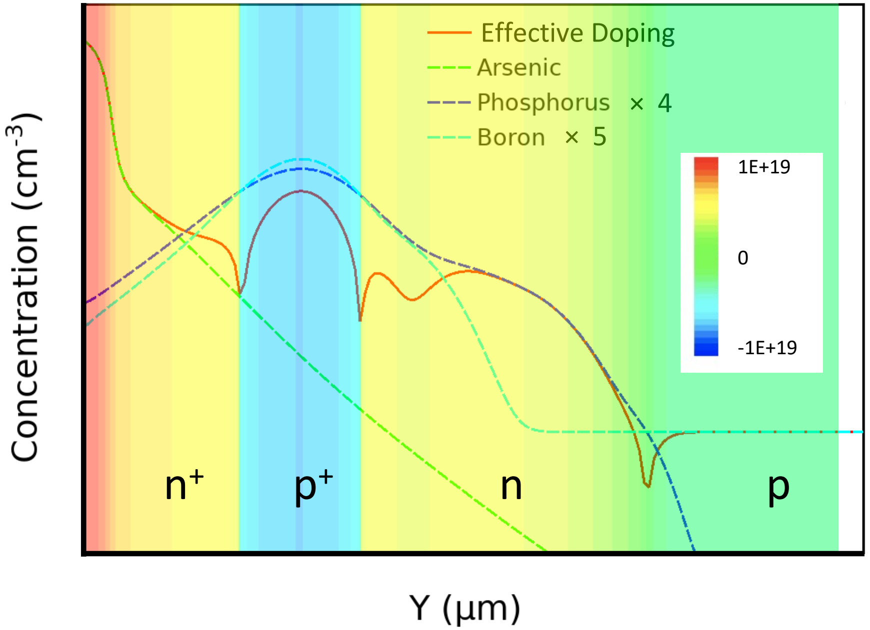
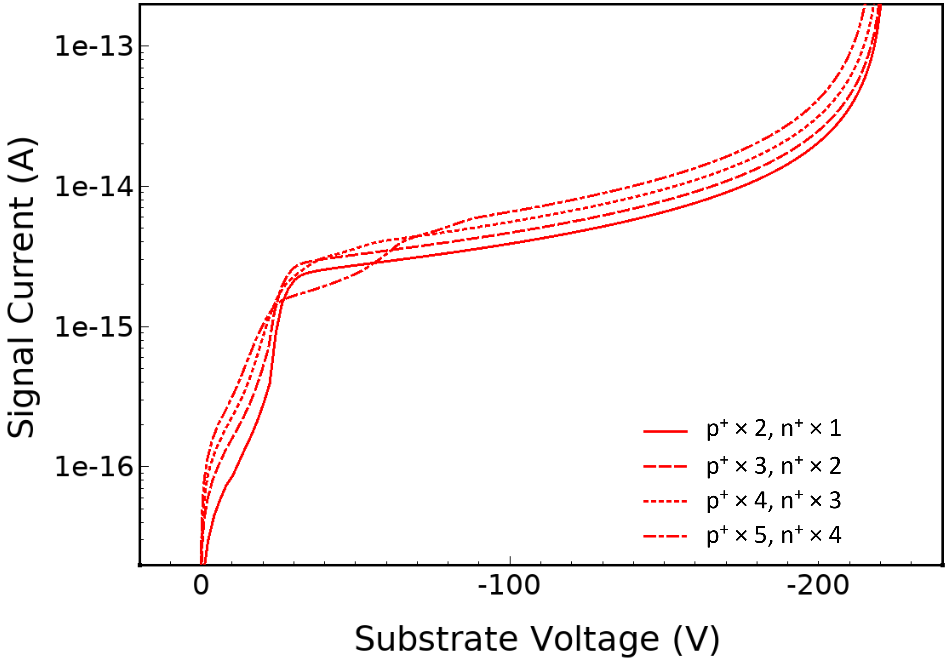


I-V from Simulation



→ 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

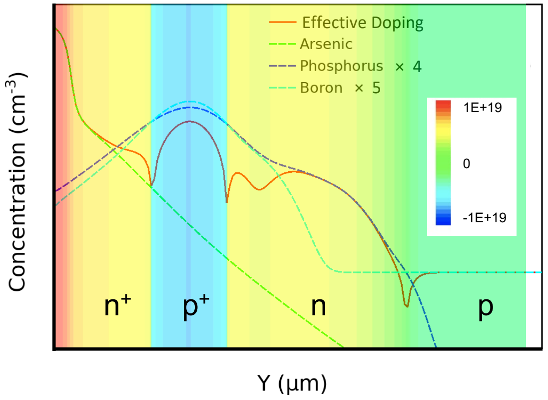
Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
7	30	2 b	1	
8	30	2 b	1	
9	30	2 c	1	
10	30	3 a	2	
11	30	3 b	2	
12	30	3 b	2	
13	30	3 b	2	1.0
14	30	3 c	2	
15	30	5 a	4	

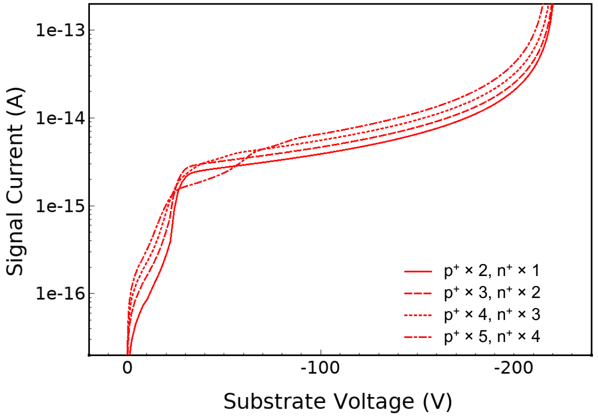
[a < b < c]

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

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

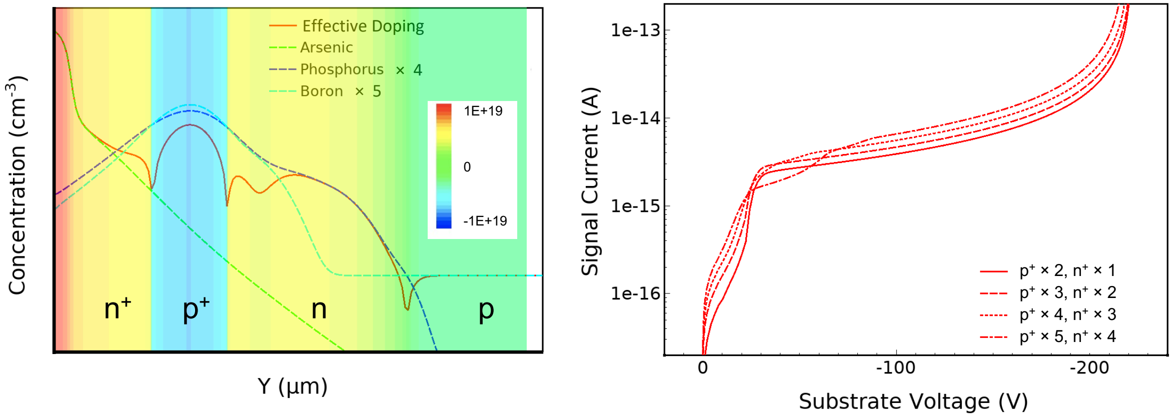
Simulation



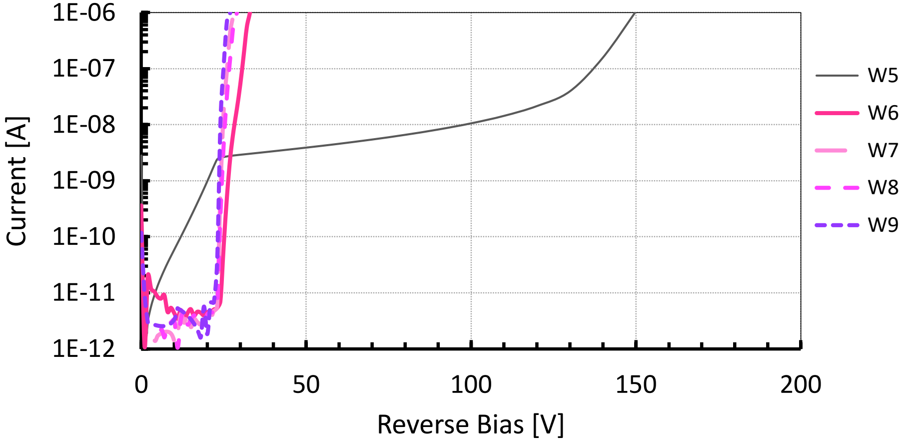


Compensated LGAD – I-V for different $p^+ – n^+$

Simulation



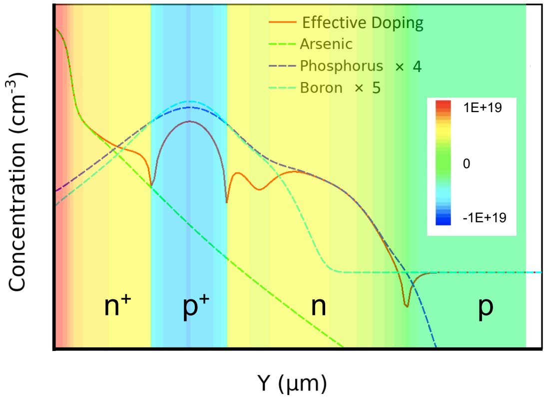
EXFLU1 – Compensated LGAD 2–1 – I-V

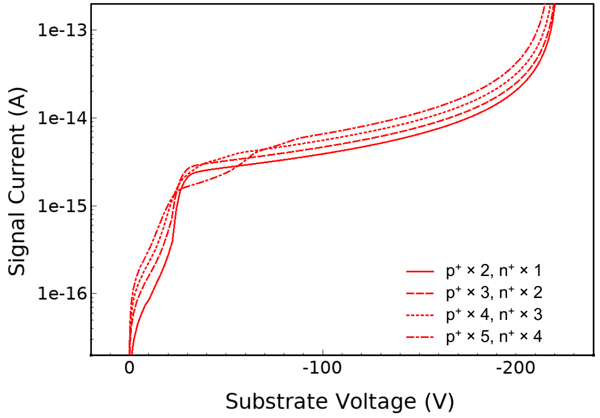


2 – 1

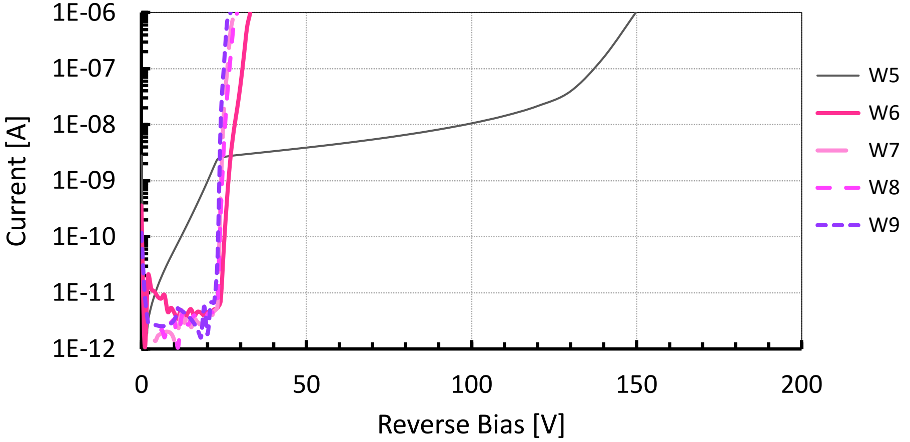
Compensated LGAD – I-V for different $p^+ – n^+$

Simulation





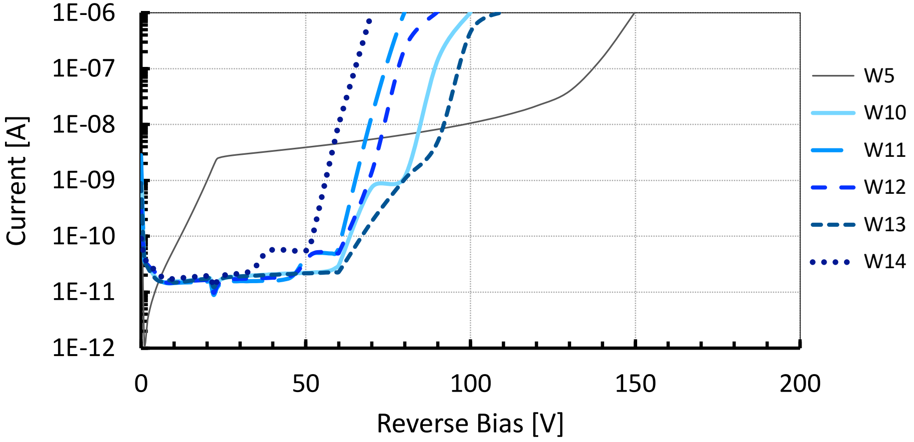
EXFLU1 – Compensated LGAD 2–1 – I-V



2 – 1

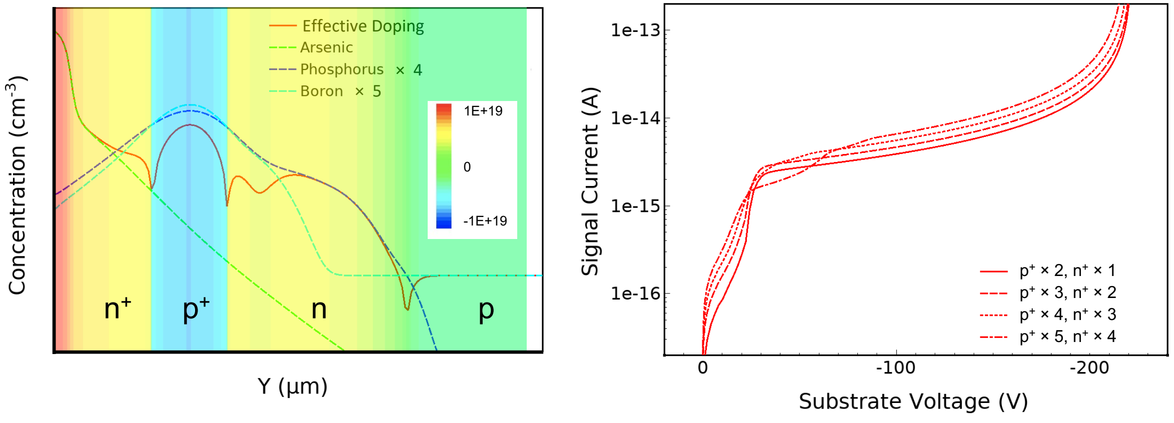
EXFLU1 – Compensated LGAD 3–2 – I-V

3 – 2

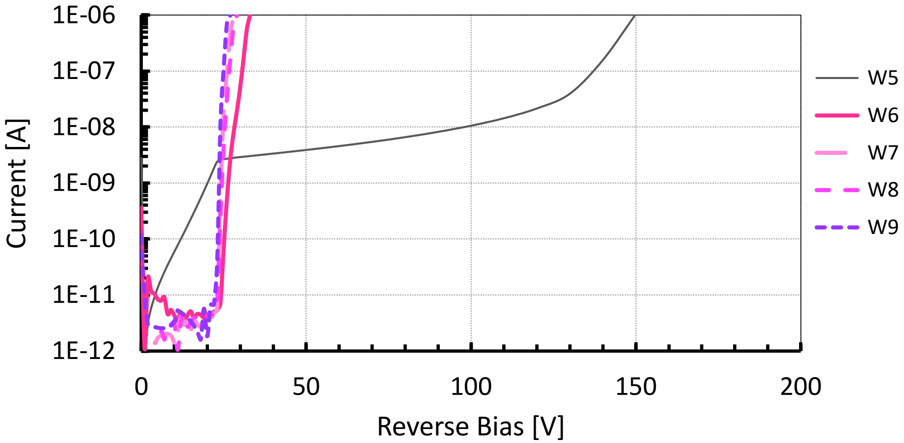


Compensated LGAD – I-V for different $p^+ – n^+$

Simulation



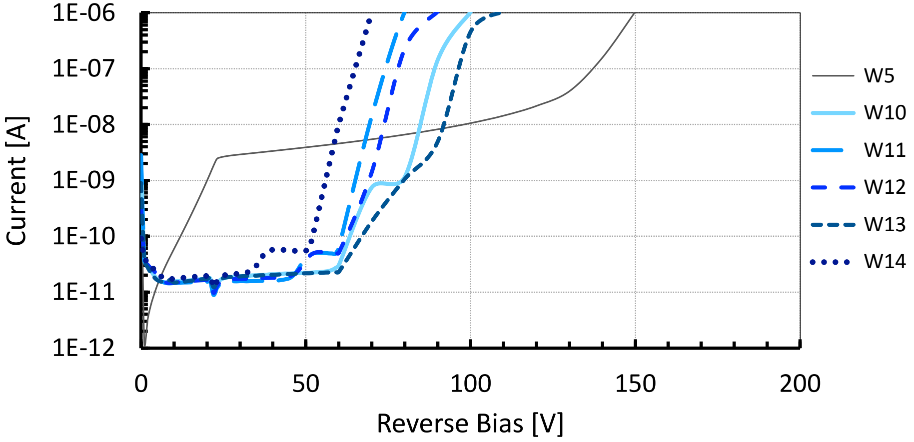
EXFLU1 – Compensated LGAD 2–1 – I-V



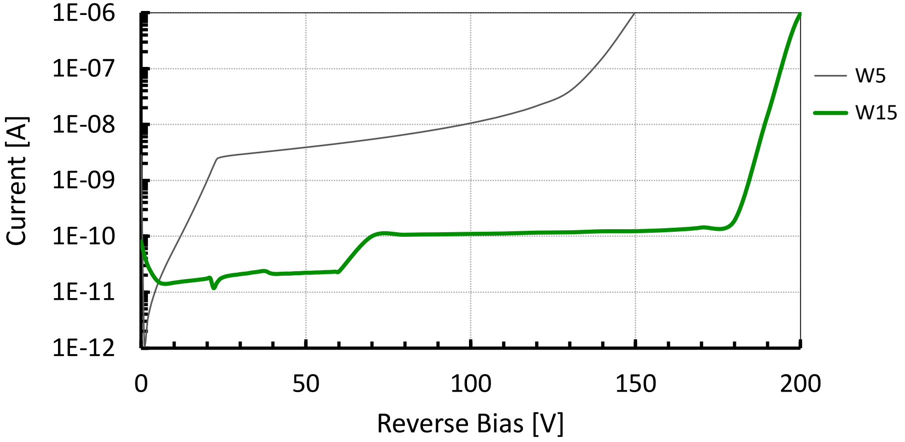
2 – 1

3 – 2

EXFLU1 – Compensated LGAD 3–2 – I-V



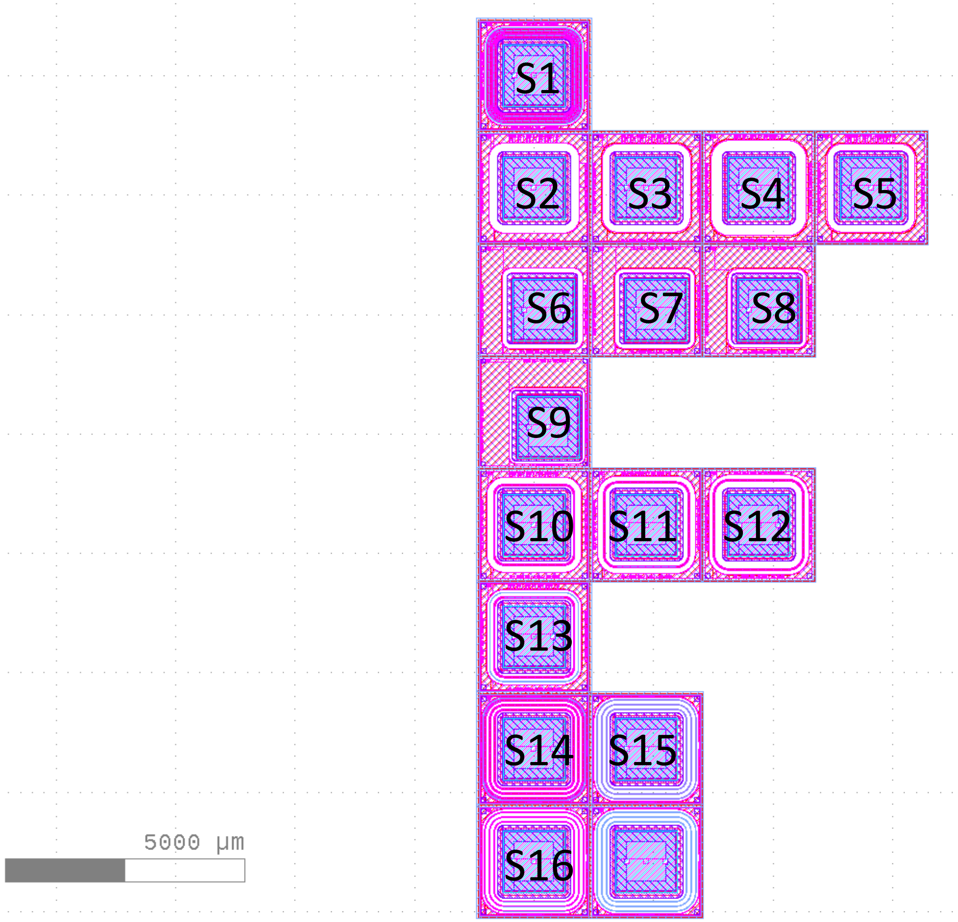
EXFLU1 – Compensated LGAD 5–4 – I-V



5 – 4

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:

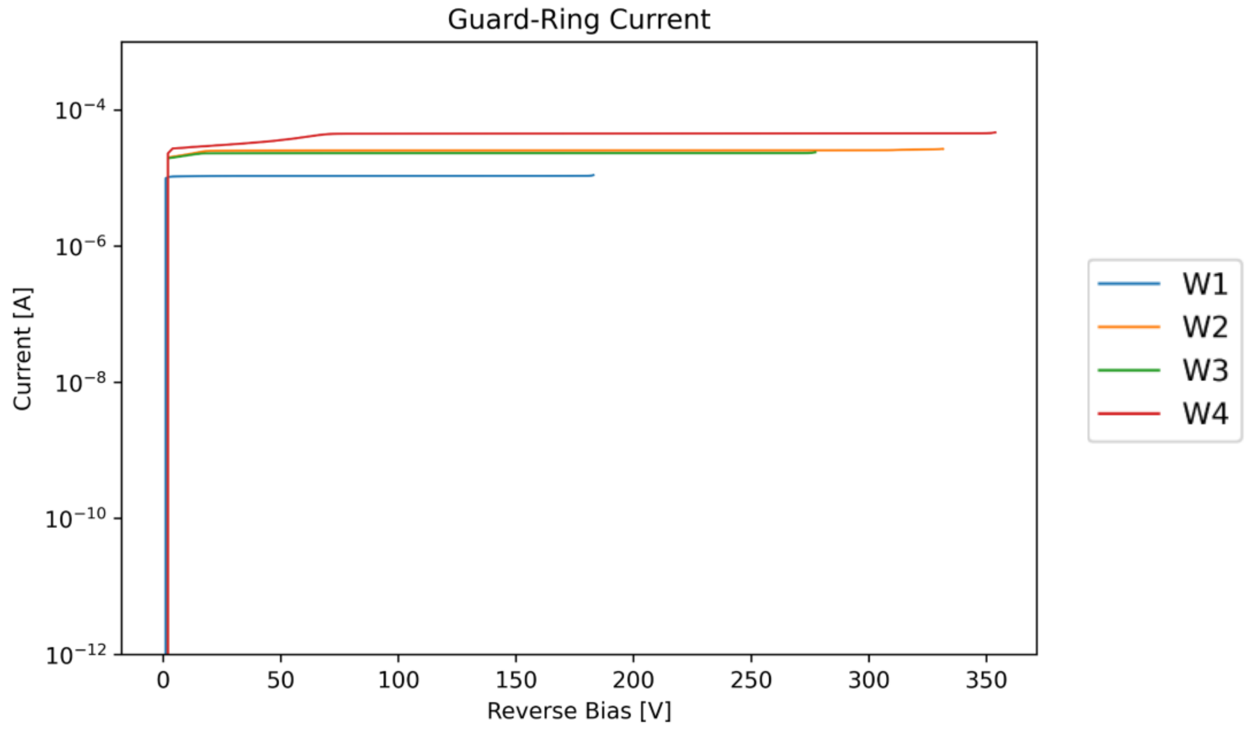
- ▻ 0 GR floating, varying the edge size
  - – different size of the 'empty' region
  - – different size of the edge region: 500, 300 & 200 µm
- ▻ 1 GR floating, varying the GR position
- ▻ 3 GR floating with different designs

[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

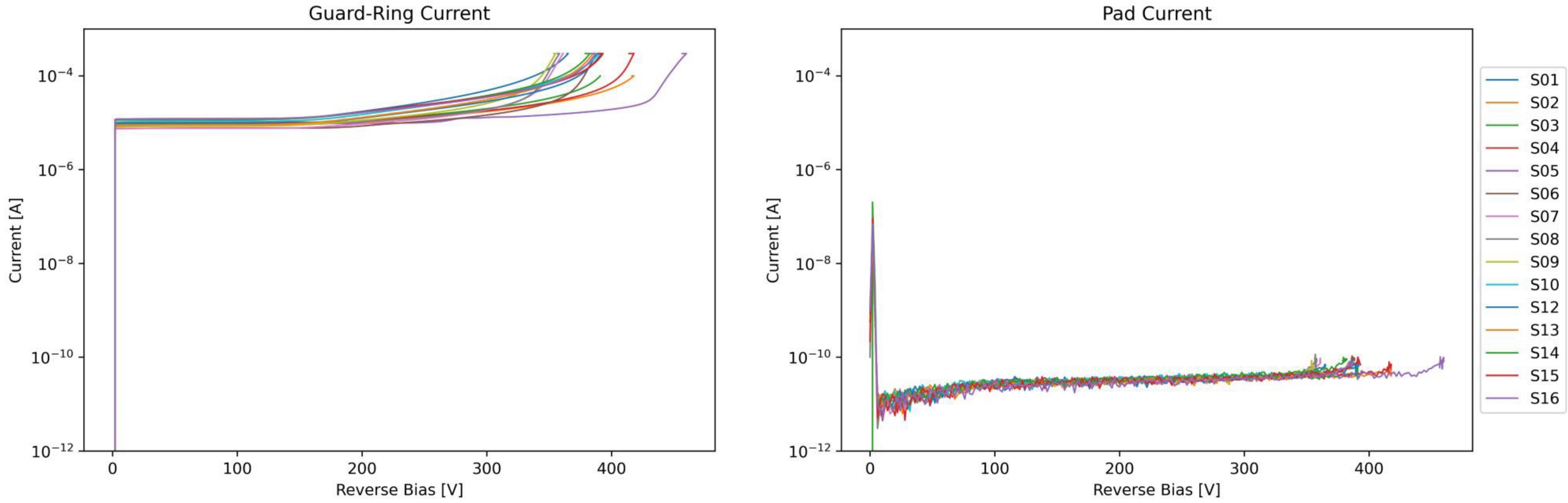


→ Due to the substrate doping, the guard ring current is high and almost constant

Optimised Guard Ring Design on 45 µm

45 µm substrates converted to n-type

EXFLU1 – 45 µm PIN



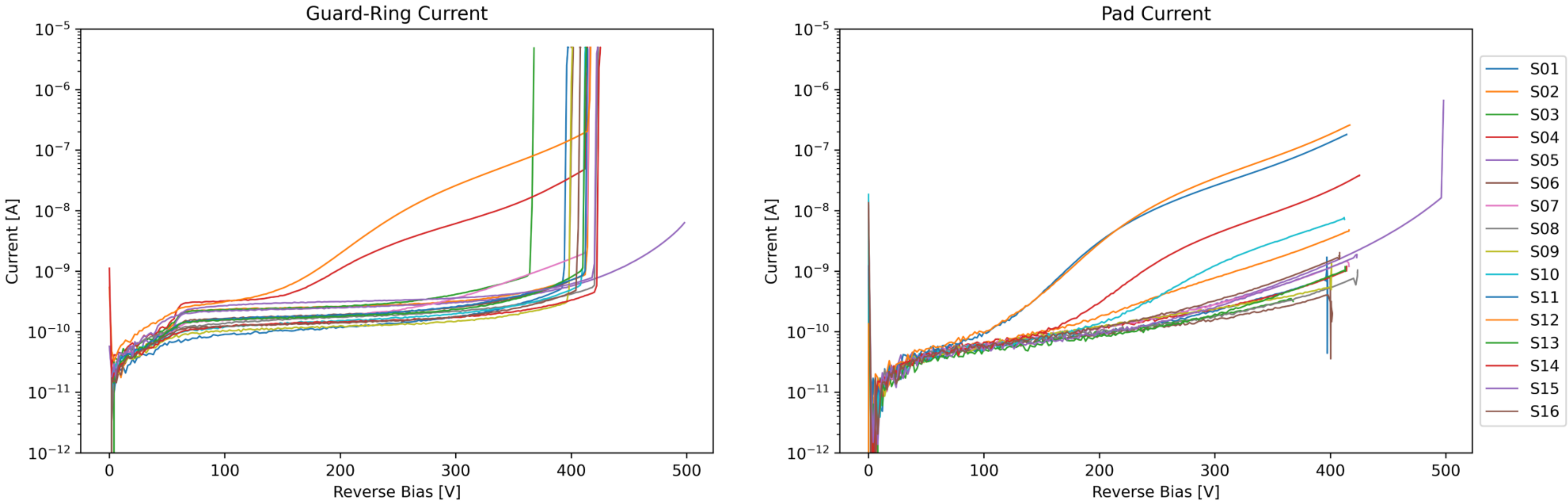
→ Due to the substrate doping, the guard ring current increases above 350 V

→ 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



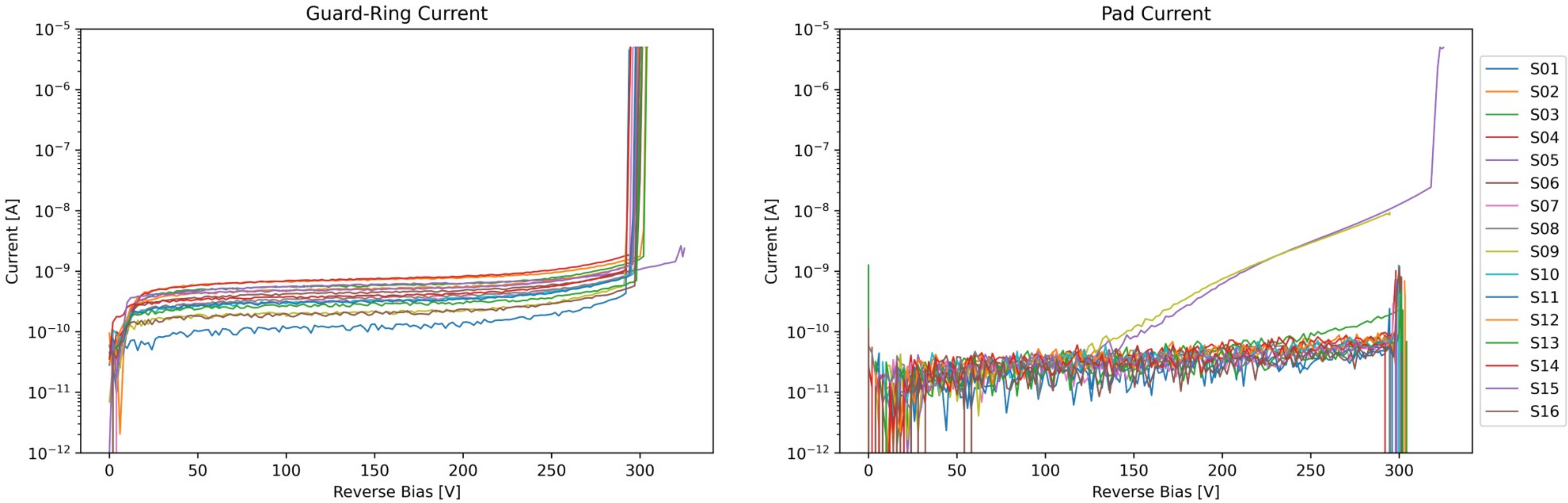
→ Most of the guard rings exhibit a breakdown at ~ 400 V (E_{field} ~ 14 V/µm), except S5

→ 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



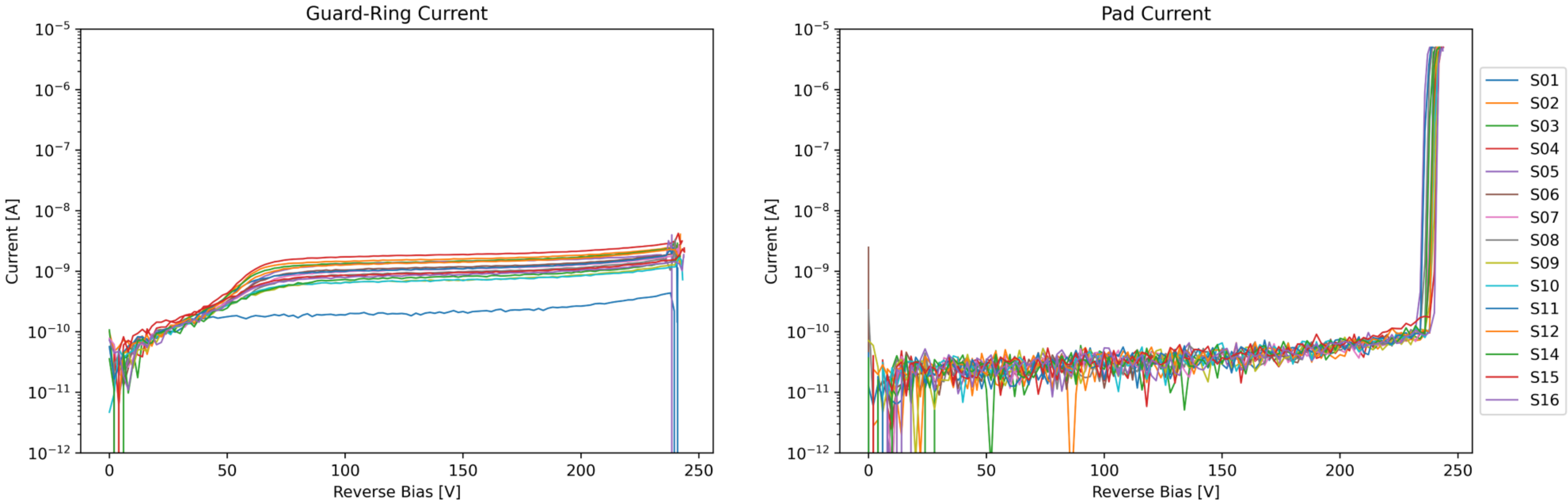
→ Most of the guard rings exhibit a breakdown at ~ 300 V (E_{field} ~ 15 V/µm), except S5

→ 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

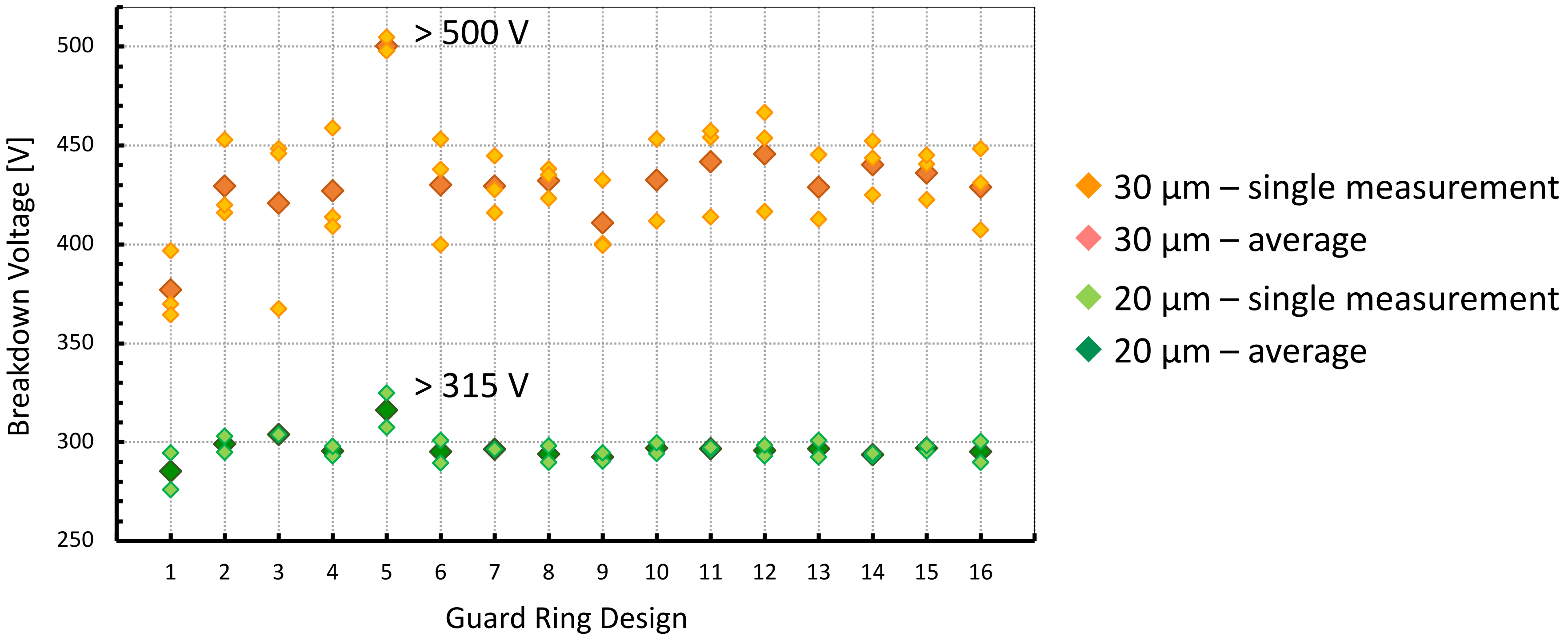
EXFLU1 – 15 µm PIN



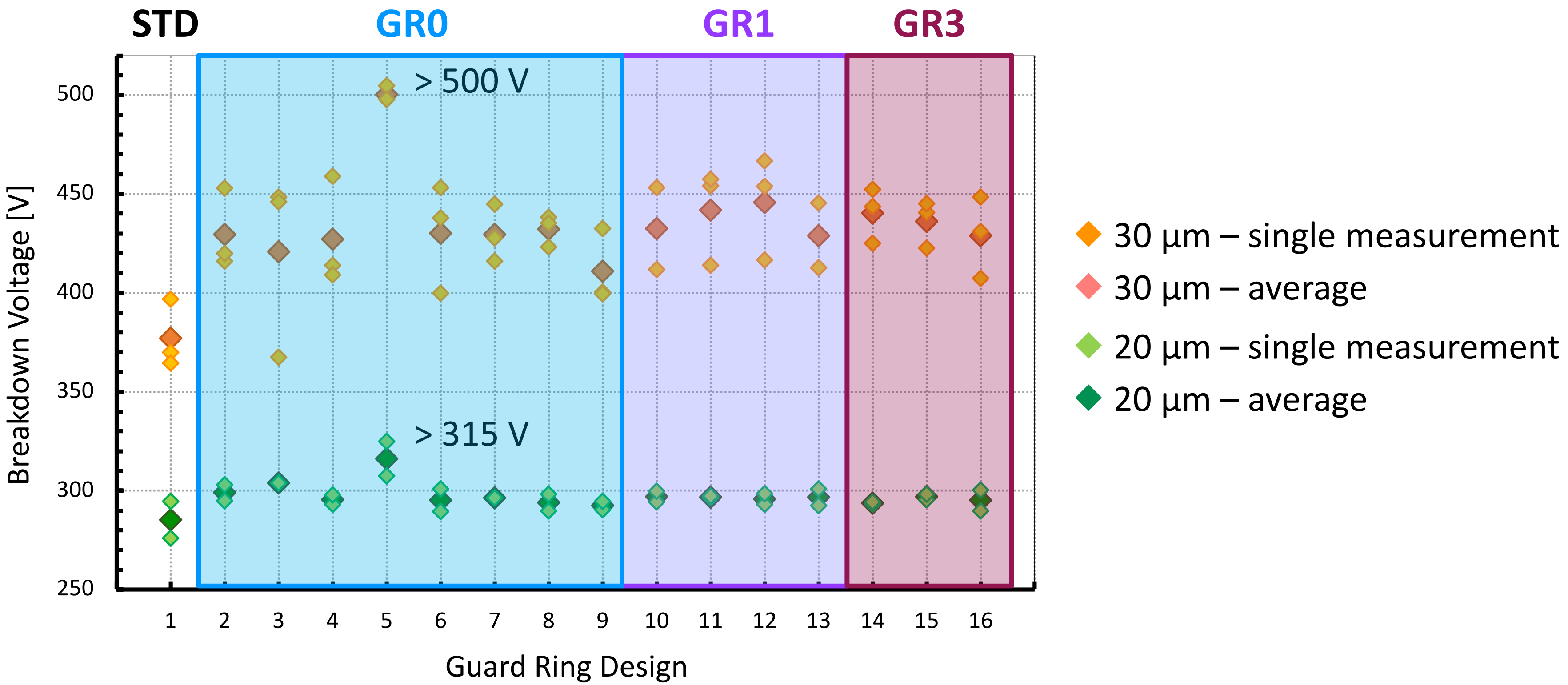
→ No breakdown on guard rings is observed up to 240 V (E_{field} ~ 16 V/µm)

→ 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

Summary & Outlook

The EXFLU1 production batch has been completed

- ➢ **Investigation of thin substrates**
- ➢ **Carbon shield to protect the gain implant from acceptor removal**
- ➢ **First LGAD with compensated gain implant have been produced**
- ➢ **Extensive R&D on guard ring structures for thin substrates**

⟹ An extensive measurement campaign before and after irradiation is ahead of us

Grazie

Acknowledgements

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- 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 esterme (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

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

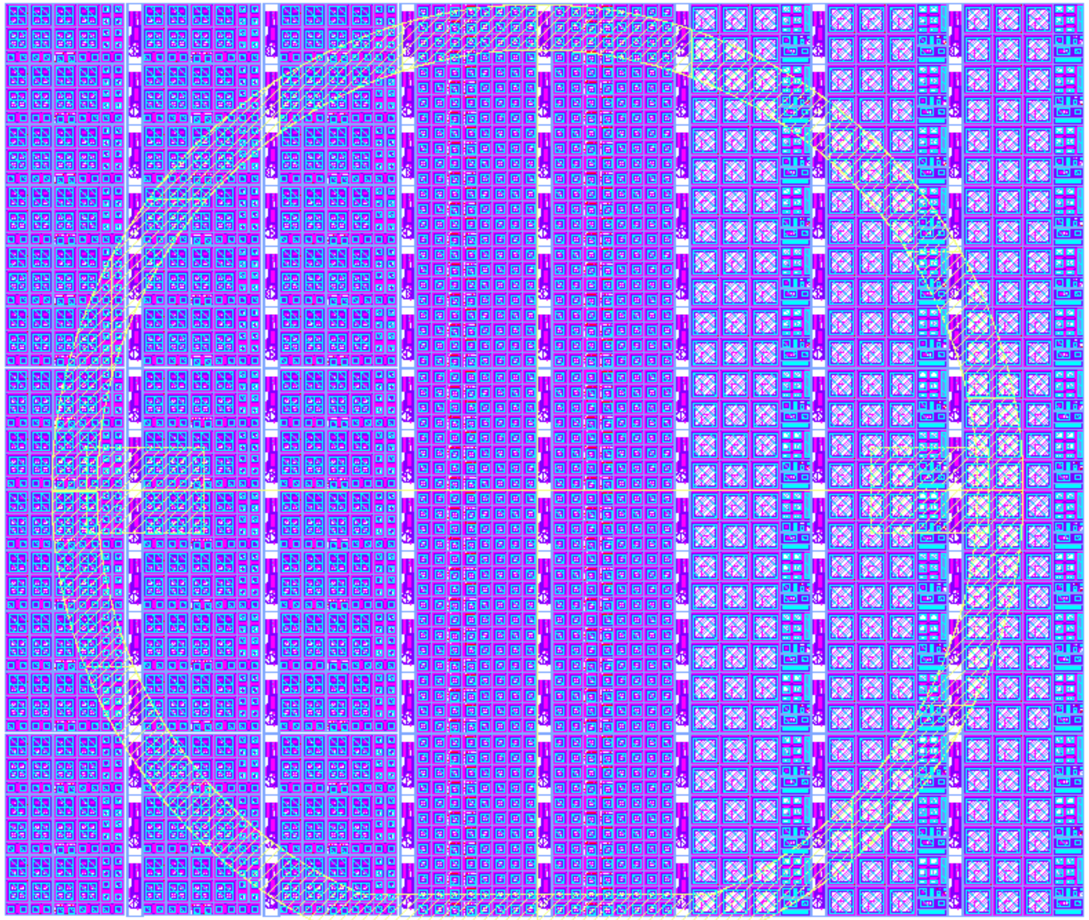
Gain layer depth: shallow

p^+ and C dose values in arbitrary units [`doi:10.1201/9781003131946`]

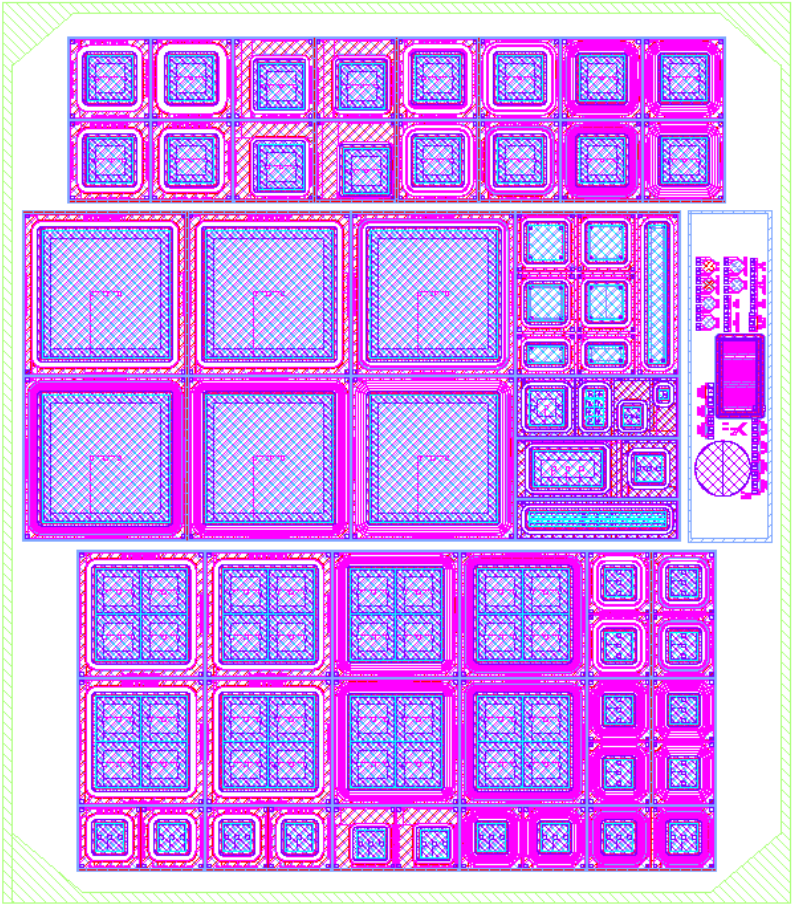
I-V measurements have been performed on wafer on LGAD-PIN structures

The EXFLU1 Layout

6” Wafer Layout

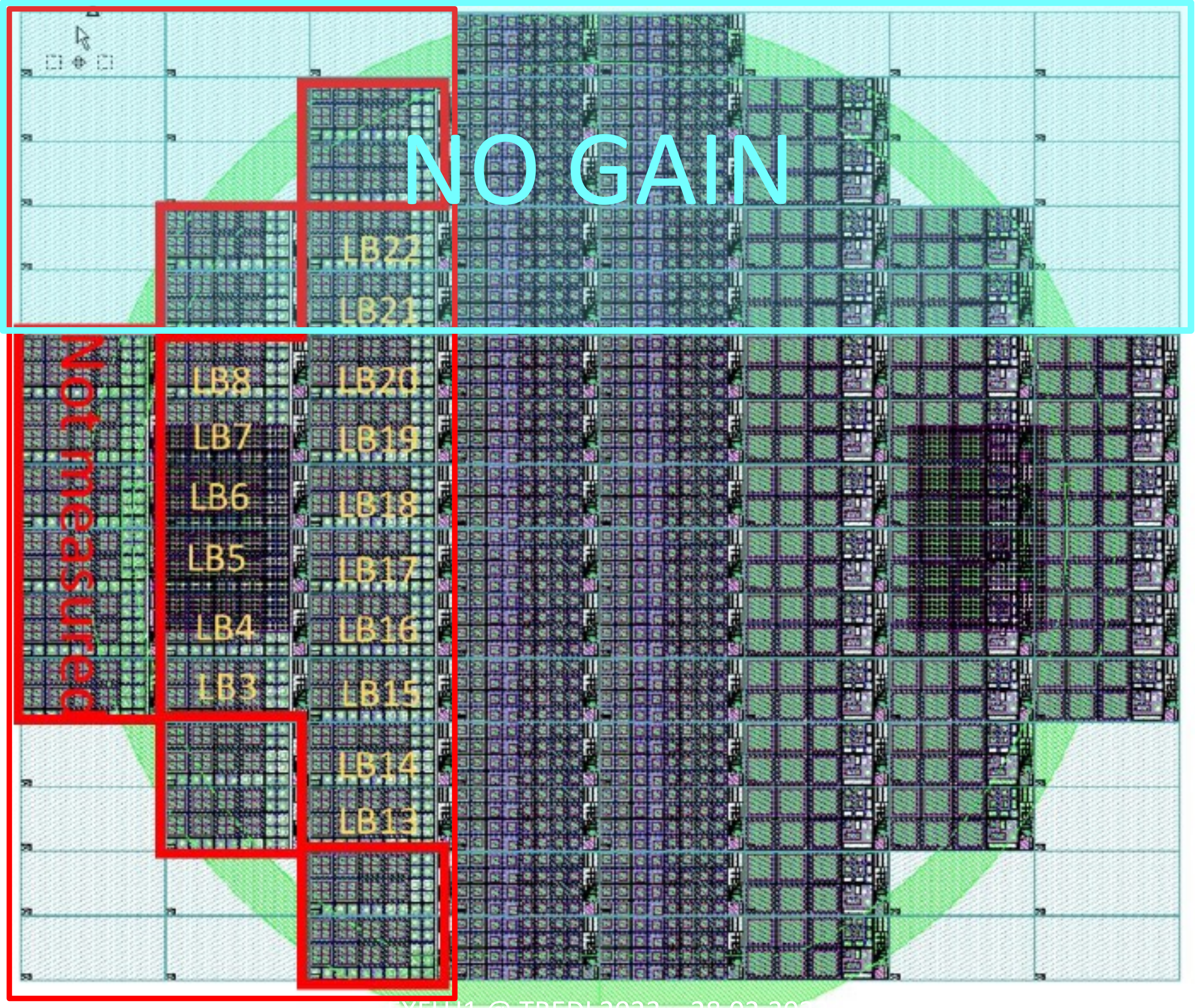


Reticle Layout



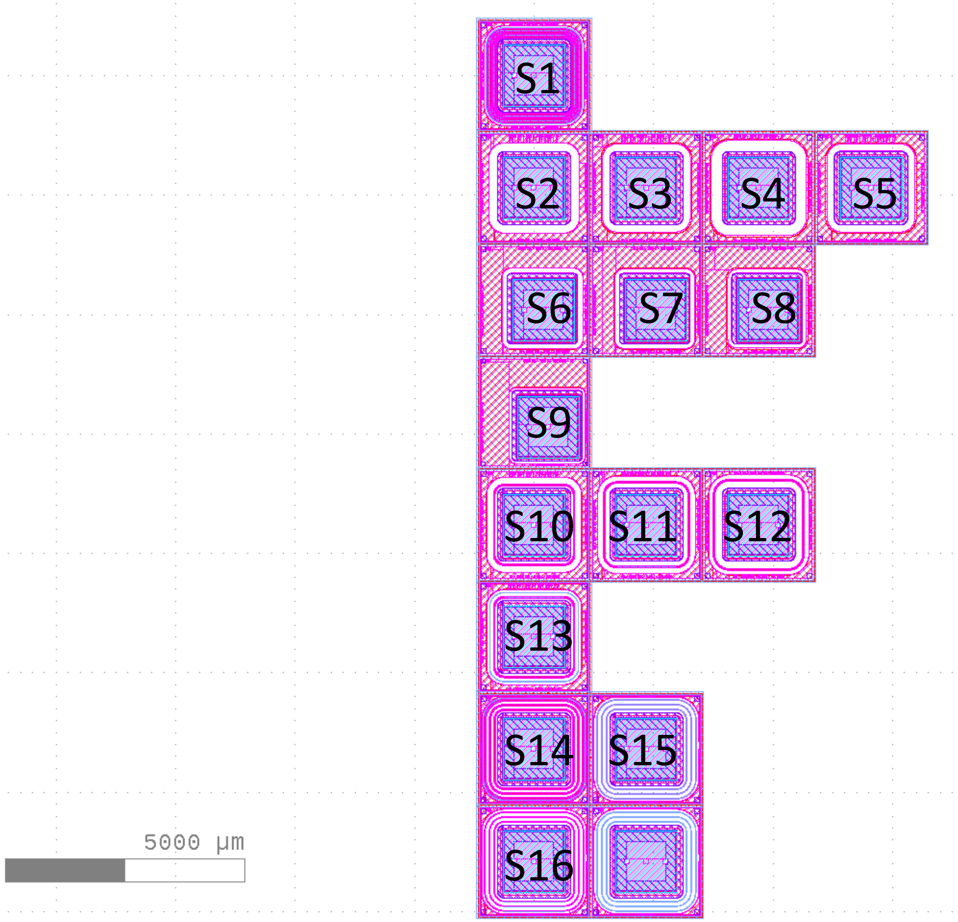
eXFlu2022_LEFT BLOCK

Measured
on wafer



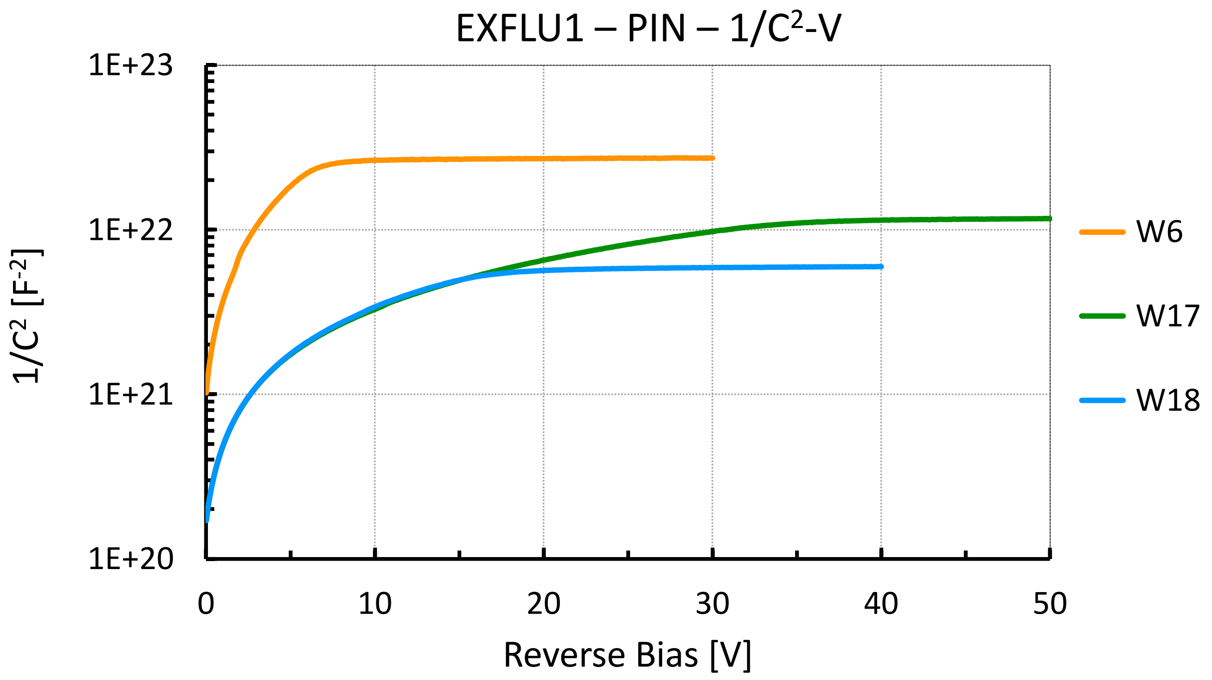
EXFLU1 Guard Ring Designs

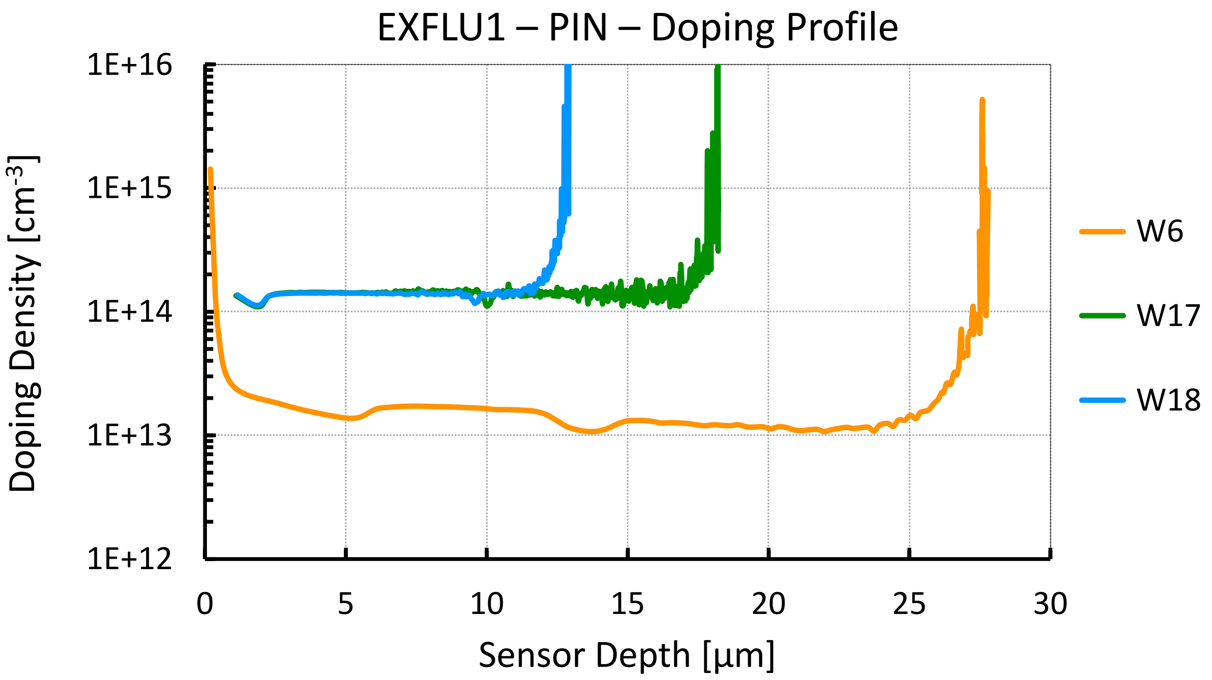
16 different guard rings have been designed, optimised for thin substrates and extreme fluences



S1) GR STD 500UM – à la UFSD2
S2) GR0 500UM - V1
S3) GR0 500UM - V2
S4) GR0 500UM - V3
S5) GR0 500UM - V4
S6) GR0 300UM - V1
S7) GR0 300UM - V2
S8) GR0 300UM - V3
S9) GR0 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

EXFLU1 – Doping Profile of Thin Substrates





Tests on LGAD with Carbon Shield

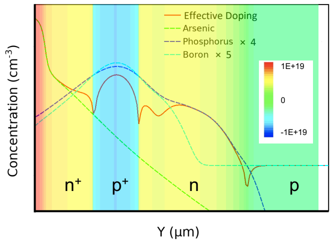
Observations from C-shielded sensors:

- ▻ C shield reduces the boron activation of the gain implant
- ▻ C shield increases the dark current both in PIN and LGAD sensors
- ▻ A sharp increase of the dark current at low bias values is observed both in PIN and LGAD sensors
  - → is it correlated to the n-type bulk?
    - ⇒ **irradiation will solve this question** (n-type bulk will invert into p-type at relatively low Φ)

Investigation of the acceptor removal mechanism:

- ▻ Before irradiation I-V measurement will be used to extract V_{GL} (gain layer depletion bias)
- ▻ After irradiation above 10^{14} n_{eq}/cm^2, bulk type inversion will occur, and C-V measurements will be used to extract the V_{GL} evolution
- ▻ TCT measurements before and after irradiation will be used to study the signal shape evolution

Tests on Compensated LGAD



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 good gain performance, similar to standard LGAD (W5)
- 5–4 sensors exhibit smaller gain with respect to standard LGAD

  → **A correct tuning of the p$^+$–n$^+$ doping densities will be extrapolated by the EXFLU1 sensors**

Investigation of the gain implant doping evolution:

- The shape and doping density of the gain implant will 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

Compensation – Doping Evolution with Φ

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

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

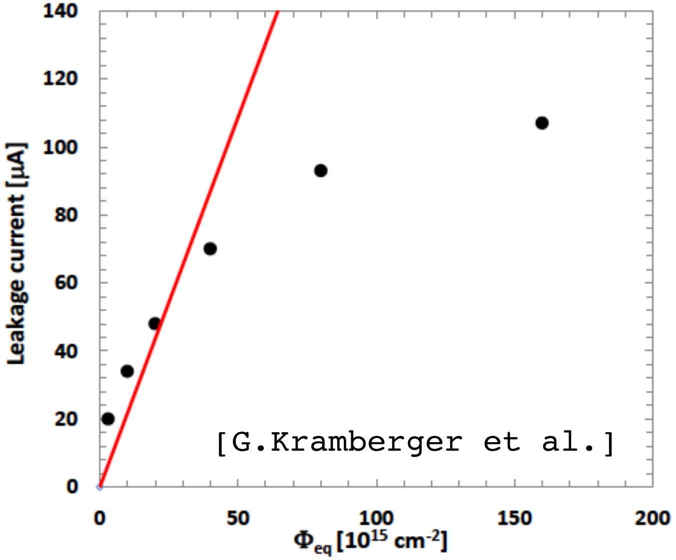
The ingredients to overcome the present limits above 10^{16} n_{eq}/cm^2 are:

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

⇒ The whole research program is performed in collaboration with the FBK foundry

Saturation

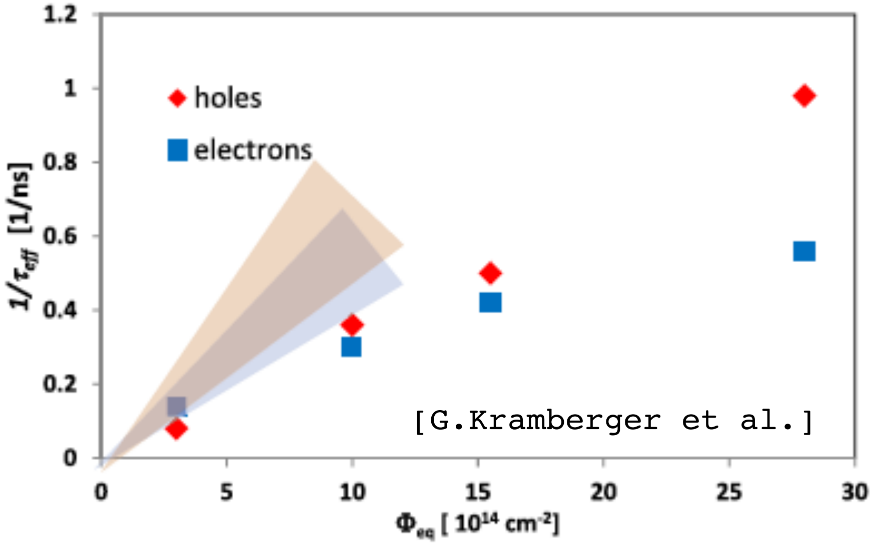
At fluences above $5 \cdot 10^{15}$ cm^{-2} → **Saturation of radiation effects observed**



Leakage current saturation

$I = \alpha V \Phi$

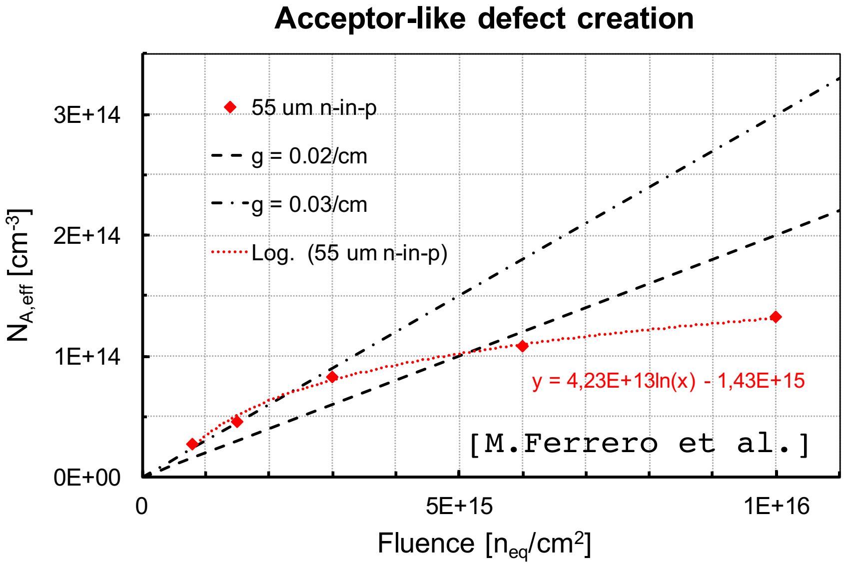
α from linear to logarithmic



Trapping probability saturation

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

β from linear to logarithmic



Acceptor creation saturation

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

g_c from linear to logarithmic

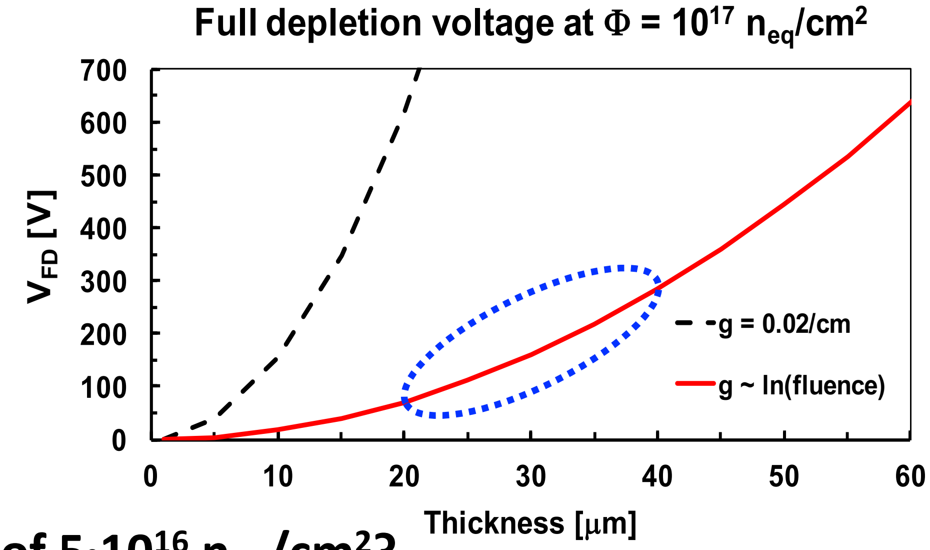
Silicon detectors irradiated at fluences $10^{16} – 10^{17}$ n_{eq}/cm^2 do not behave as expected → They behave better

Thin Substrates

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

Saturation **Reduce thickness**

At high fluences, only thin substrates can be fully depleted


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

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

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

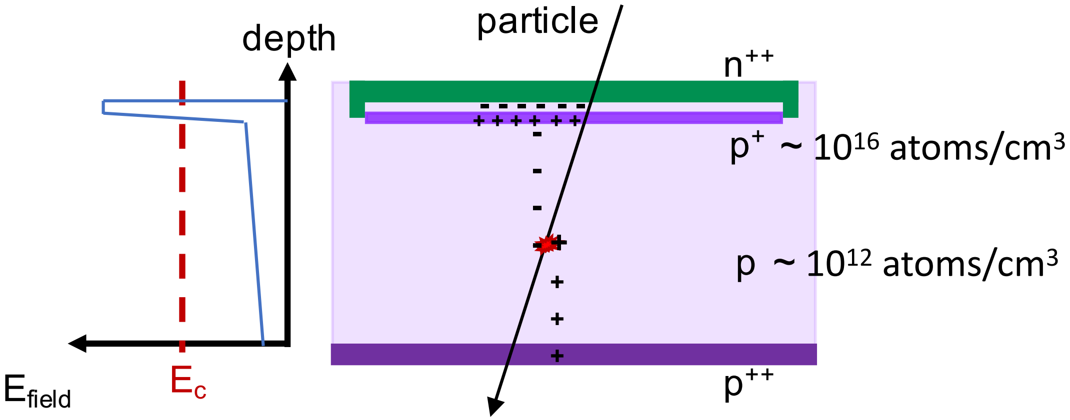
However: **charge deposited by a MIP ~ 0.25 fC**

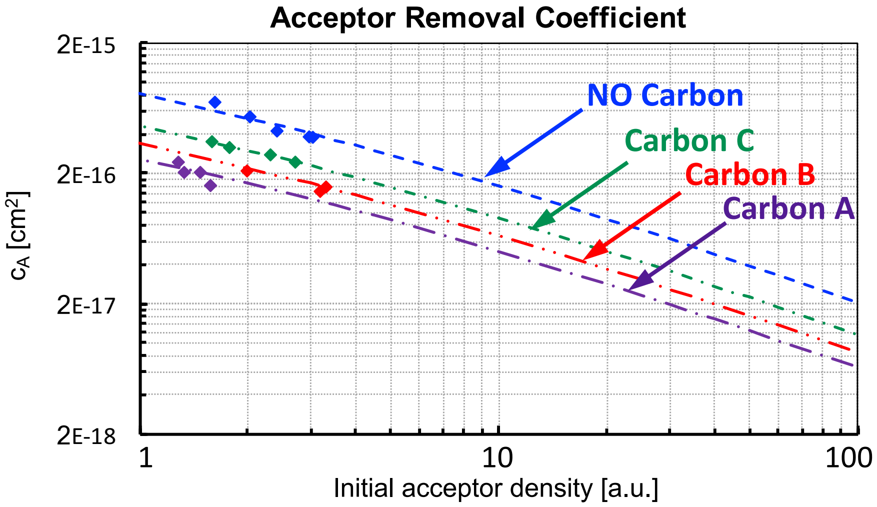
→ This charge is lower than the minimum charge requested by the electronics (**~ 1 fC** for tracking, **≳ 5 fC** for timing)

→ **Need a gain of at least ~ 5** in order to efficiently record a hit

Optimal candidate:
LGAD sensors

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

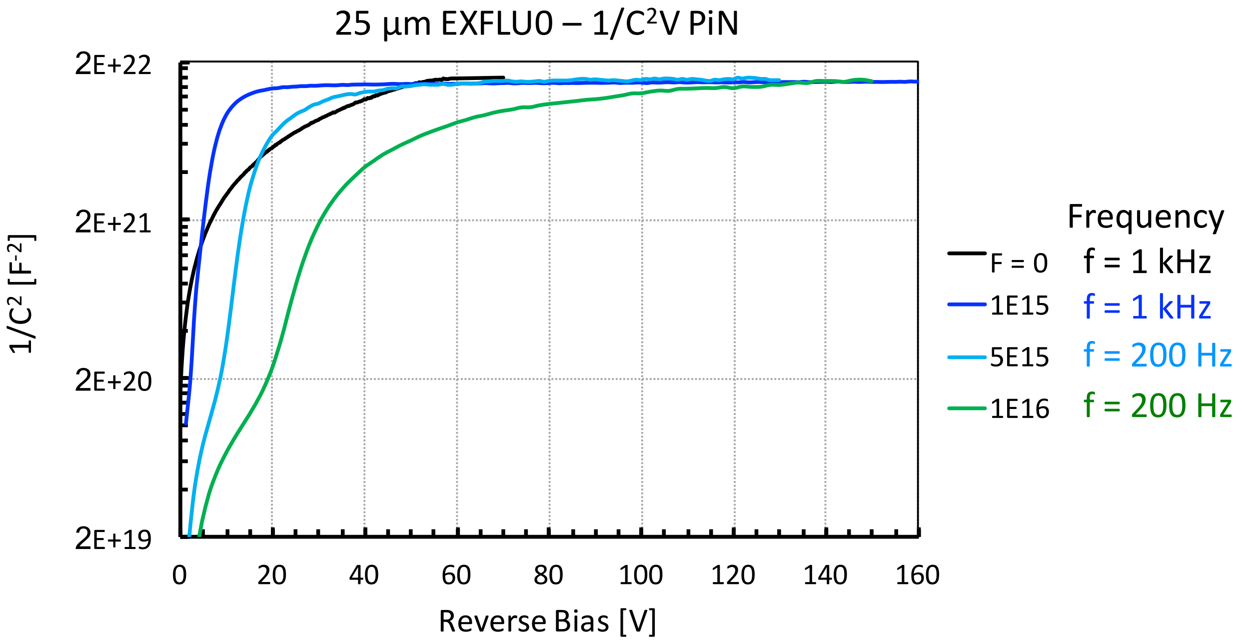
[M. Ferrero et al., doi:10.1201/9781003131946]

Thanks to the R&D performed within FBK acceptor removal reduced by a factor of 3

⇒ LGAD performances unchanged up to Φ = 2E15 n_{eq}/cm^2

Doping Evolution on Thin Bulk – 25 µm

25 µm thick sensors have a highly doped active substrate



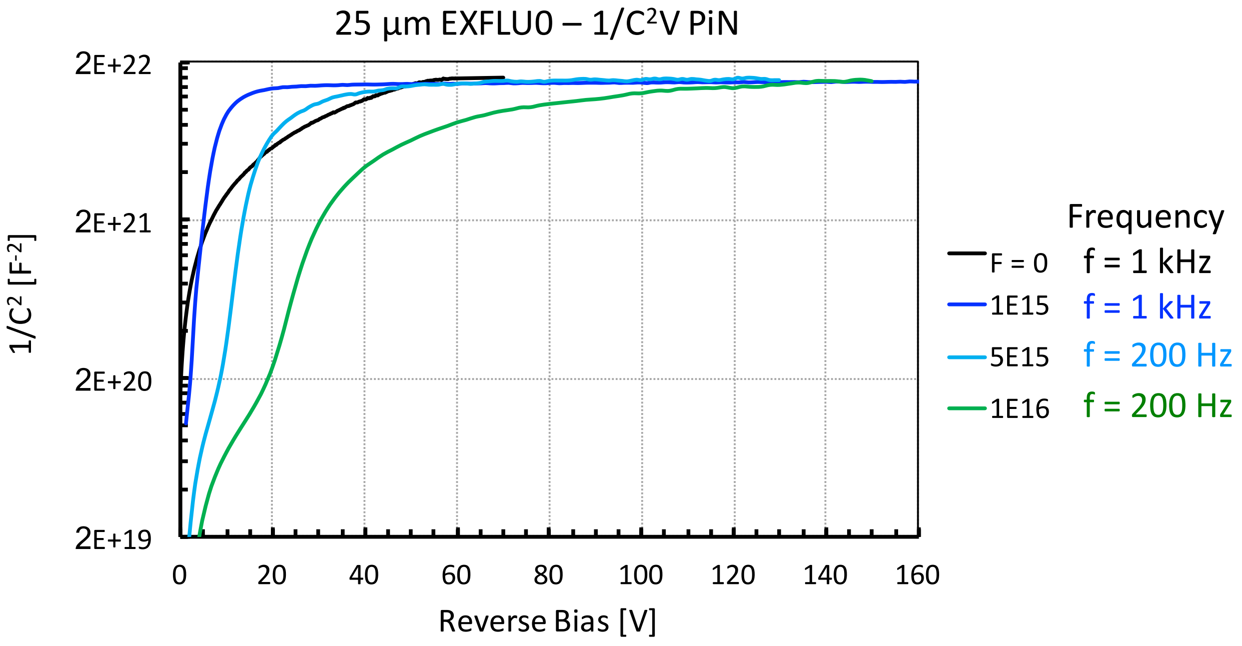
Φ [n_{eq}/cm^2]	V_{FD} from CV [V]	V_{FD} from TCT [V]
0	53	–
$1\cdot10^{15}$	6	–
$5\cdot10^{15}$	35	36
$1\cdot10^{16}$	82	50

Measurements have been performed at T = +25°C

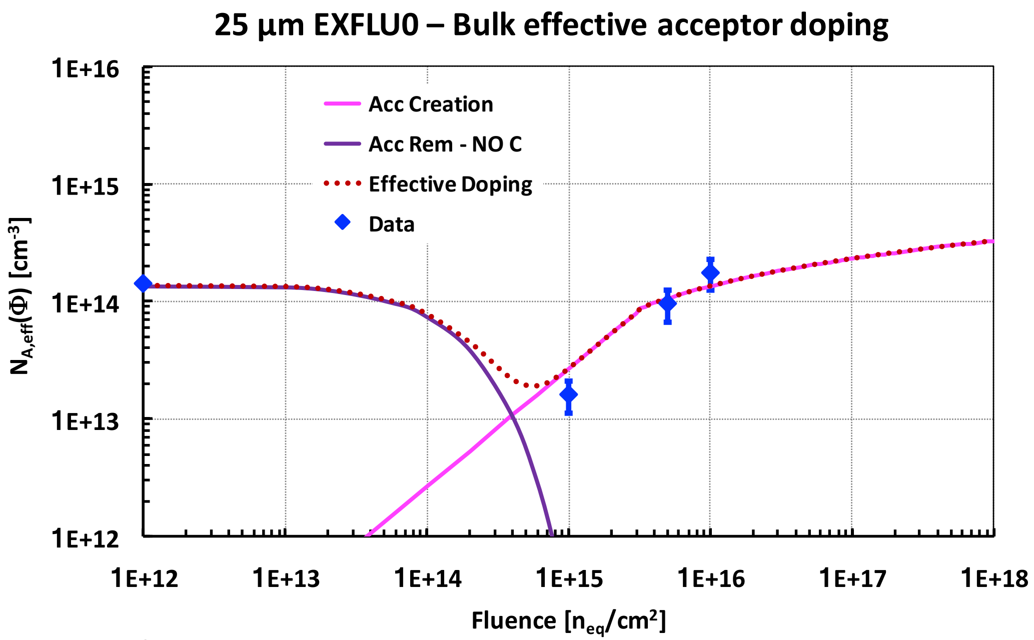
→ The average of V_{FD} from CV and TCT is used to extract the effective doping

Doping Evolution on Thin Bulk – 25 µm

25 µm thick sensors have a highly doped active substrate



From $N_{A,eff}(\Phi) = N_A(0)\cdot e^{-c\Phi} + g_c\Phi$ and considering the saturation of the acceptor creation, the 25 µm bulk doping is expected to evolve as follows



Measurements have been performed at T = +25°C

→ The average of V_{FD} from CV and TCT is used to extract the effective doping

→ Difficult to assess the voltage of full depletion above 10^{16} n_{eq}/cm^2 ⇒ Possible to use signal shape information?

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**

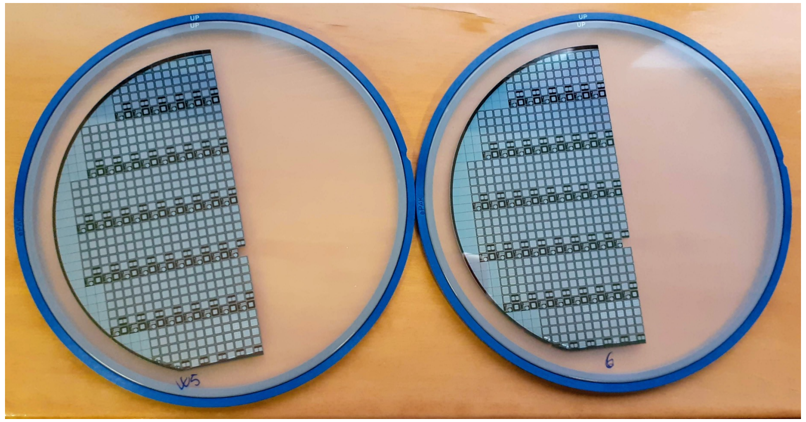
→ The *Silicon Sensor for Extreme Fluences (eXFlu)* project

Thin LGAD wafers have been produced at FBK

→ EXFLU0 production

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

Released at the end of 2020



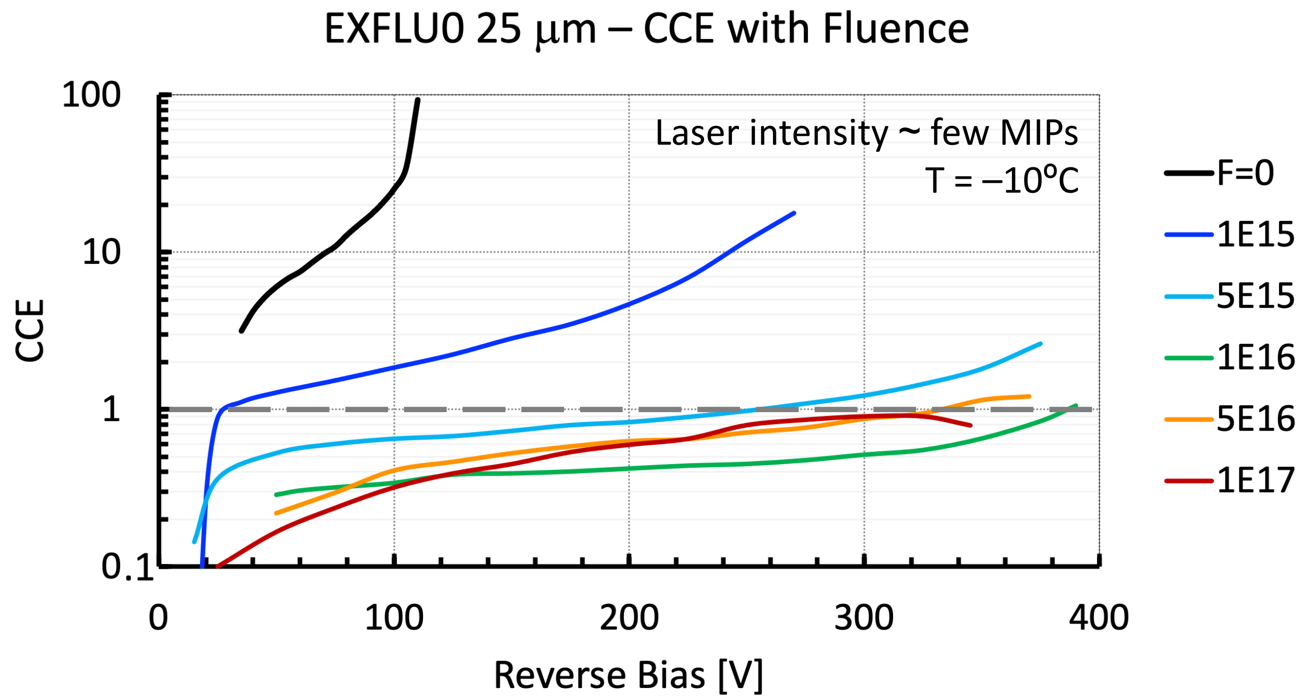
EXFLU0 sensors have been irradiated at JSI, Ljubljana, to 5 different fluences 10^{15}, $5 \cdot 10^{15}$, 10^{16}, $5 \cdot 10^{16}$, 10^{17} n_{eq}/cm^2

For more details see

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

25 μm LGAD Signal at Different Fluences

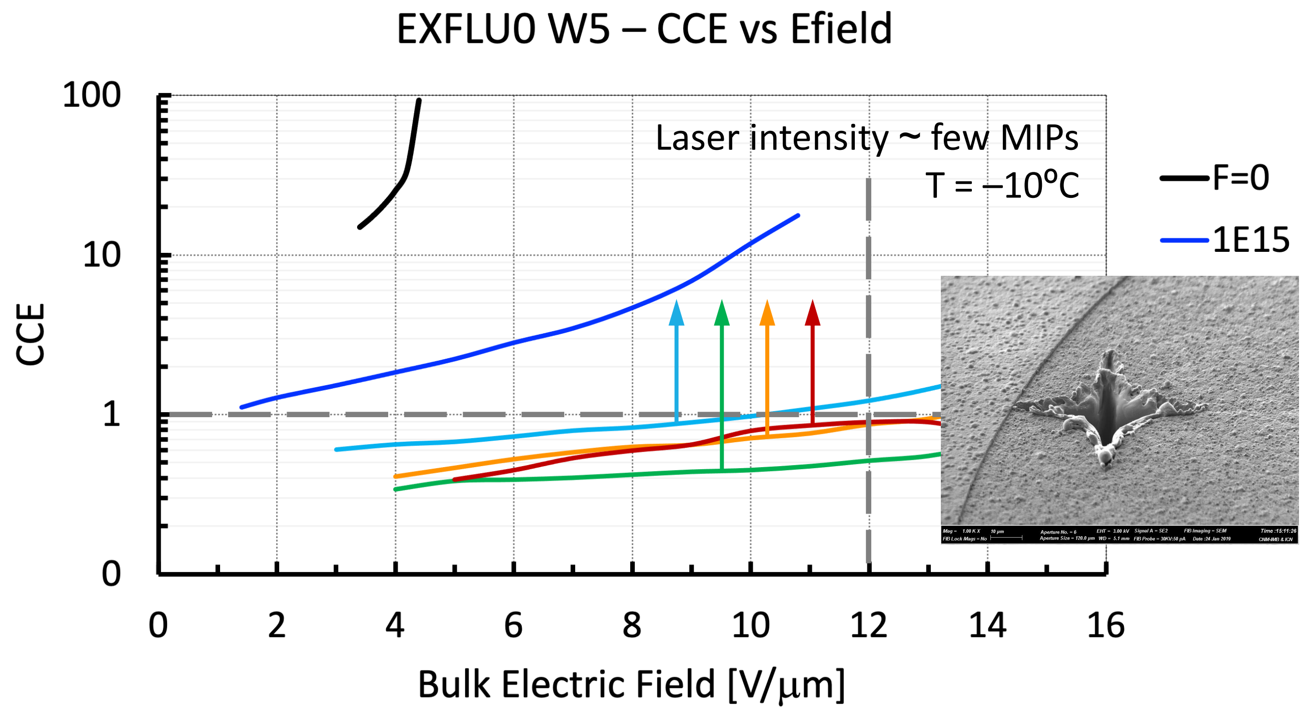
Measurements of charge collection efficiency (CCE) with an infra-red laser stimulus show that sensors can be operated up to the highest fluences



- ▻ The LGAD multiplication mechanism ceases existing at ~ $5 \cdot 10^{15}$ 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

25 µm LGAD Signal vs Electric Field

Measurements of charge collection efficiency (CCE) with an infra-red laser stimulus as a function of the electric field in the depleted bulk region



- ▻ Only data points where the sensors are fully depleted are considered here
- ▻ For electric fields above 12 V/µm, thin silicon sensors undergo fatal death once exposed to particle beams

  → Single-Event Burnout

  [indico.cern.ch/event/861104/contributions/4513238/]

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