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Innovations in the Design of Thin Silicon Sensors for Extreme Fluences

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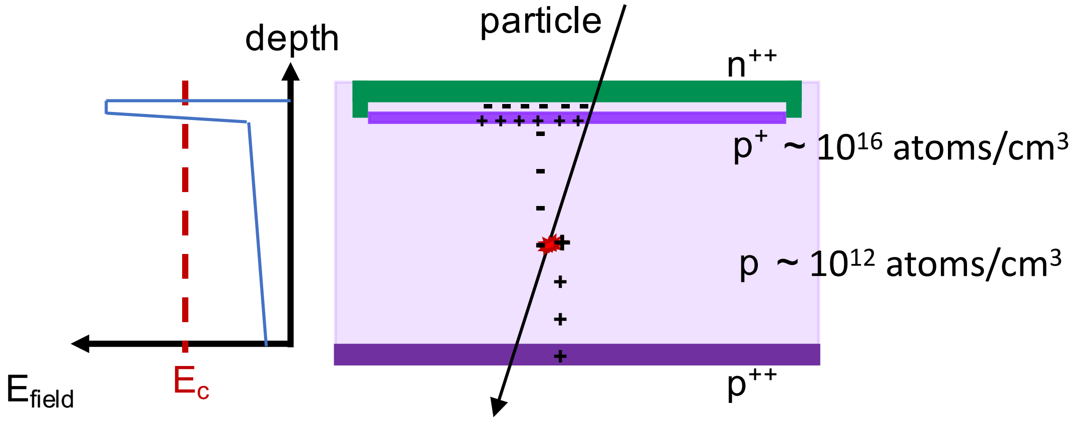
Thin LGAD for the Extreme Fluences



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

→ **$\gtrsim$ 5 fC** for timing

Charge from a MIP crossing thin sensors

→ **~ 0.1 fC every 10 μm**

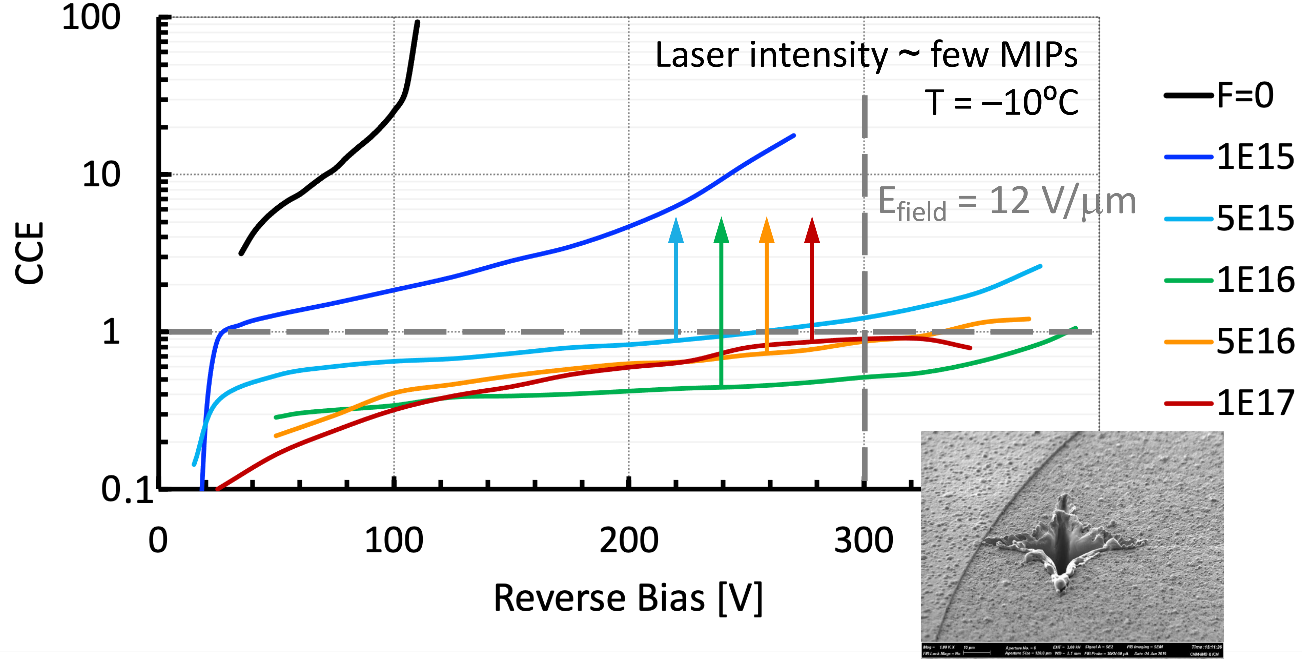
[S. Meroli et al., doi:10.1088/1748-0221/6/06/P06013]

⇒ **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**

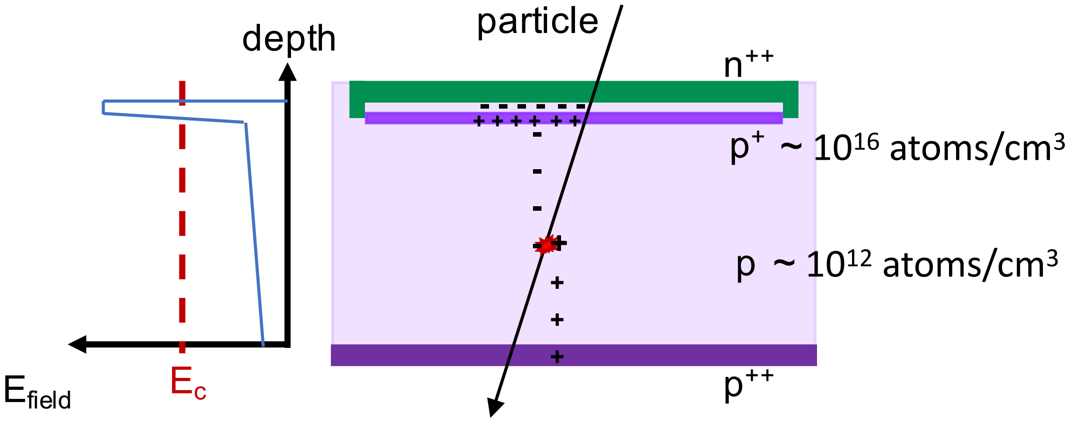

EXFLU0 25 μm – CCE with Fluence

- ▻ 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

Gain Removal Mechanism Mitigation



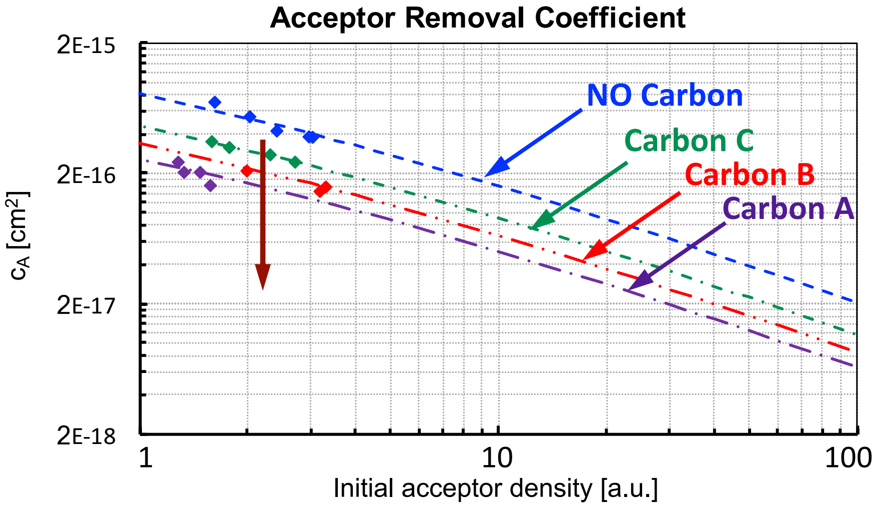
The acceptor removal mechanism deactivates the p^+-doping of the **gain layer** with irradiation according to

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

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

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



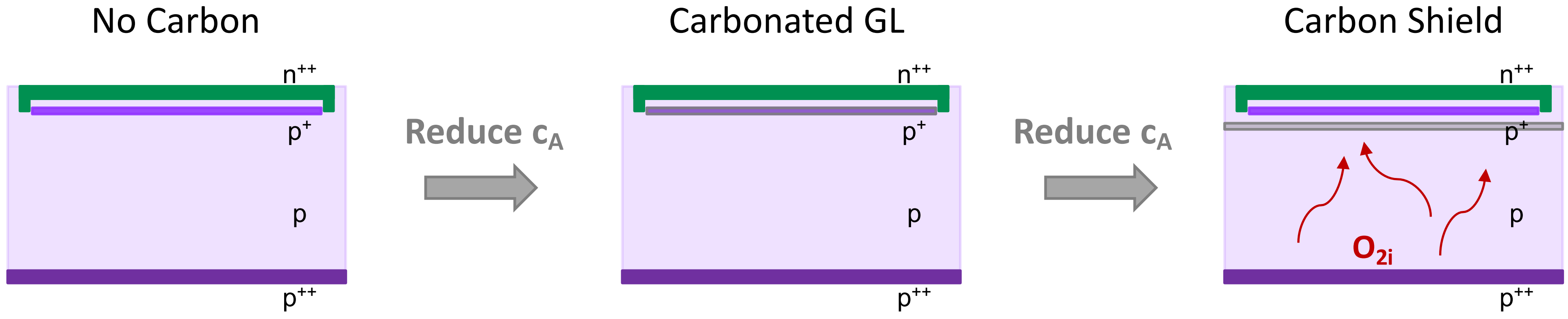
Is it possible to further reduce c_A ?

⇒ 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

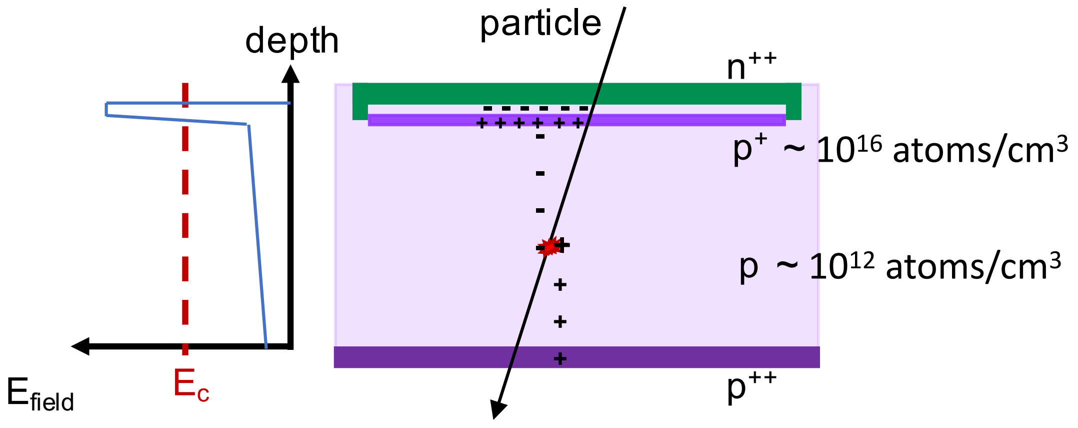
→ A **Carbon shield** will be infused below the gain layer volume to protect the gain layer from the diffusion of defect complexes from the bulk region and the support wafer



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**

Towards a Radiation Resistant Design

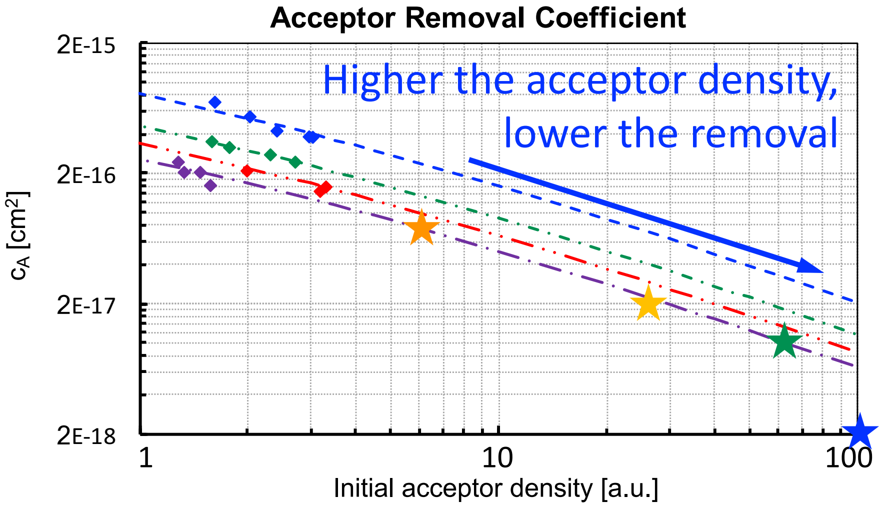


The acceptor removal mechanism deactivates the p^+-doping of the **gain layer** with irradiation according to

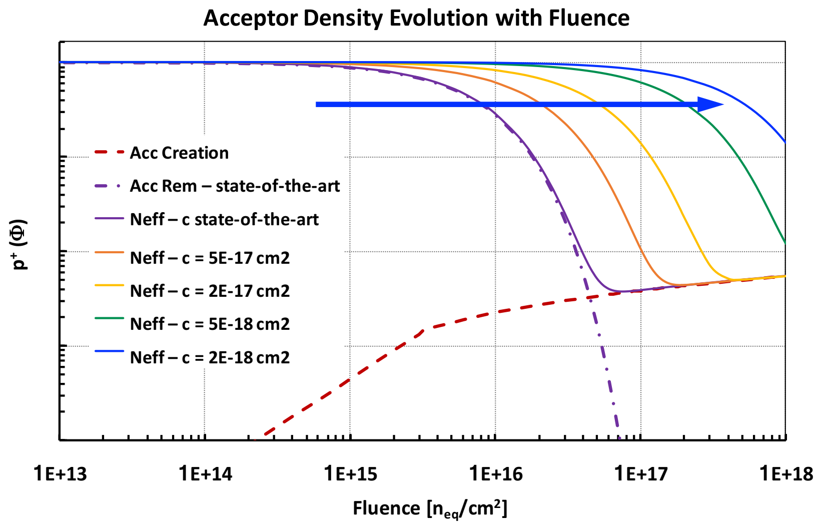
$$\mathbf{p^+(\Phi) = p^+(0) \cdot e^{-c_A \Phi}}$$

where c_A is the acceptor removal coefficient

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



Higher the acceptor density, lower the removal



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

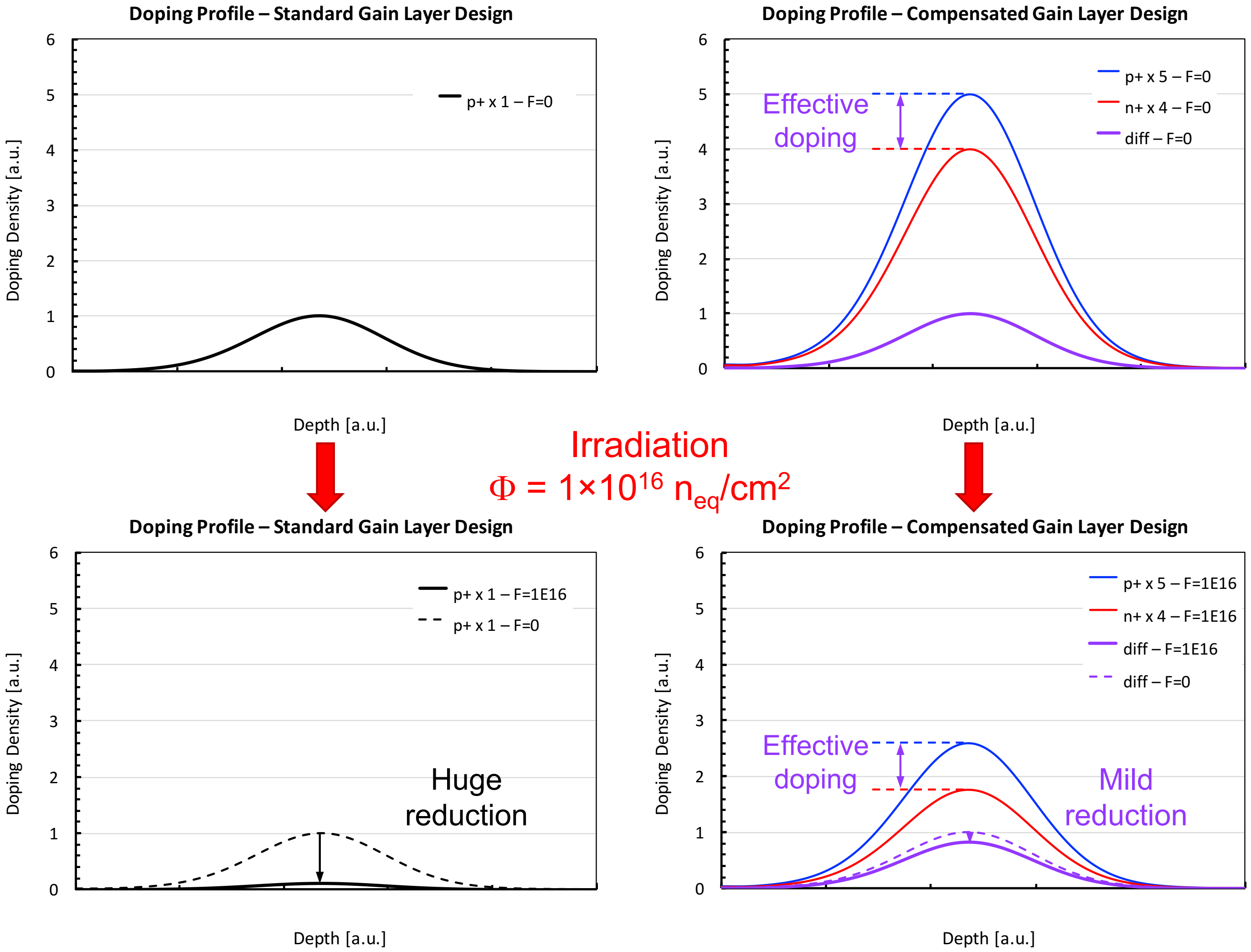
A new Paradigm – Compensation

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:

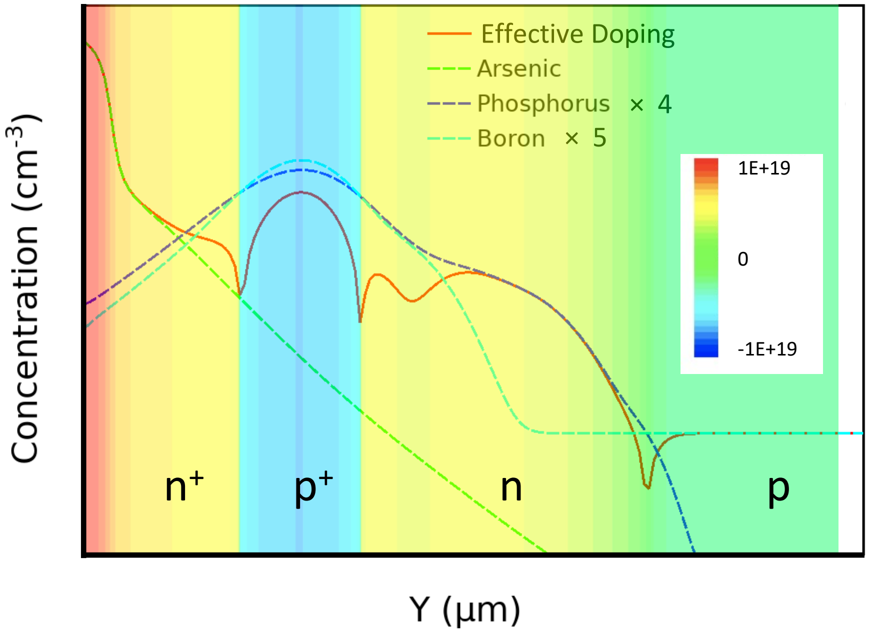
- ▻ donor removal coefficient, from $n^{+}(\Phi) = n^{+}(0)\cdot e^{-c_{D}\Phi}$
- ▻ interplay between donor and acceptor removal (c_D vs c_A)
- ▻ effects of substrate impurities on the removal coefficients



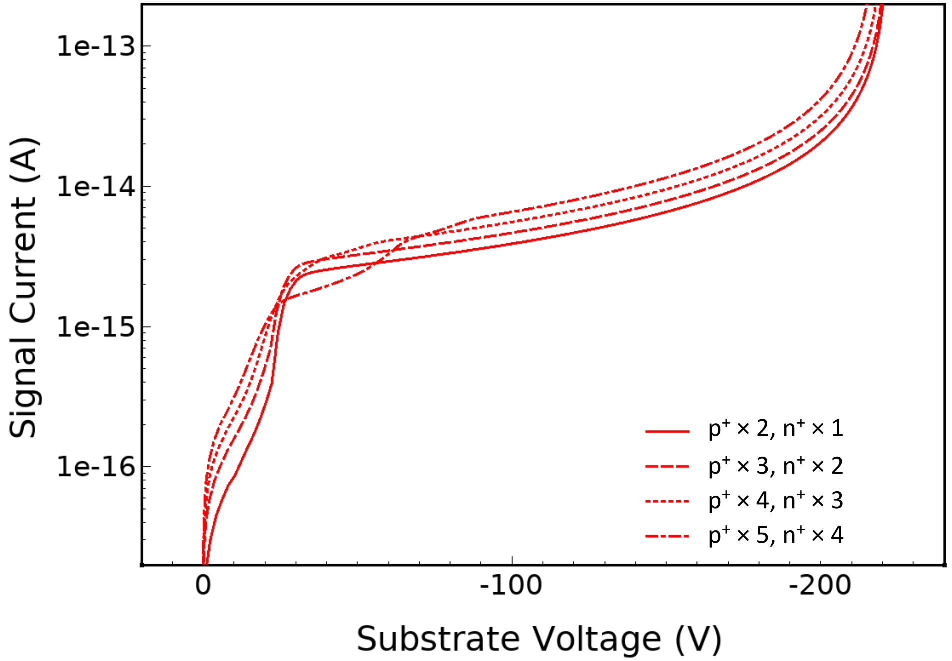
Compensation from Simulation

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

Doping Profiles from Process Simulation



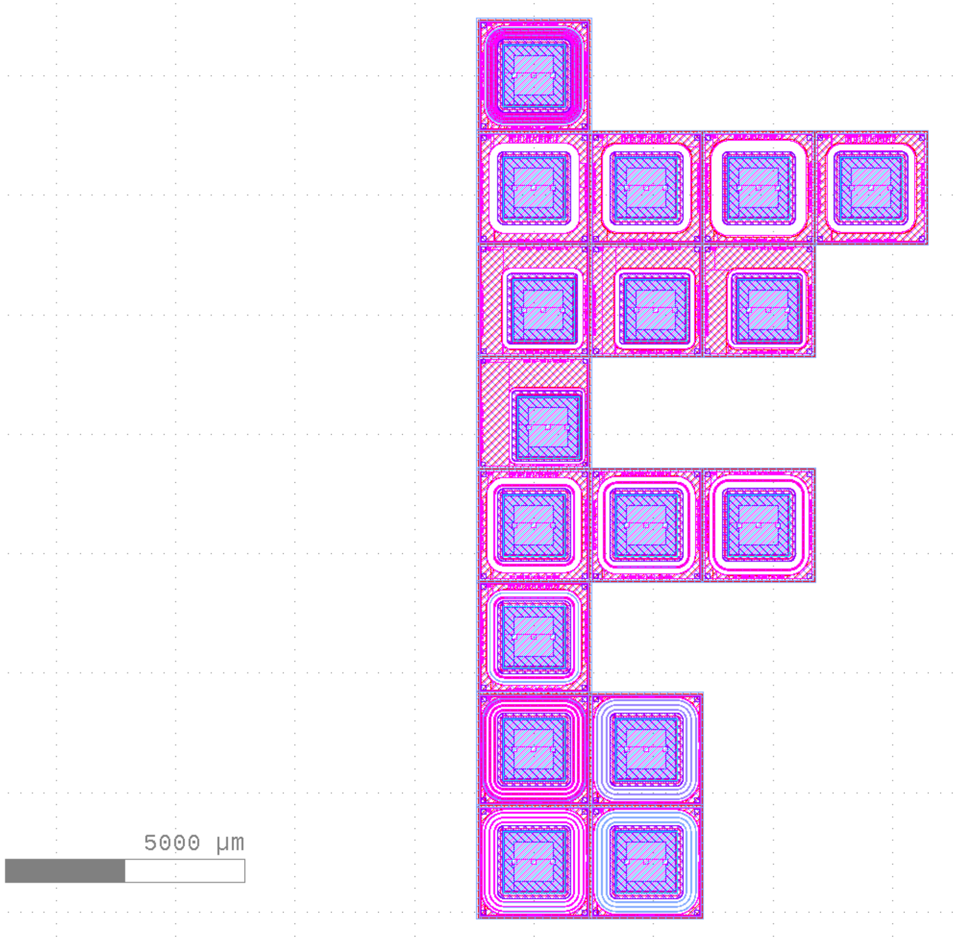
I-V from Simulation



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

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 standard design, p-stop only & n-deep only

The EXFLU1 Production Batch at a Glance

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

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

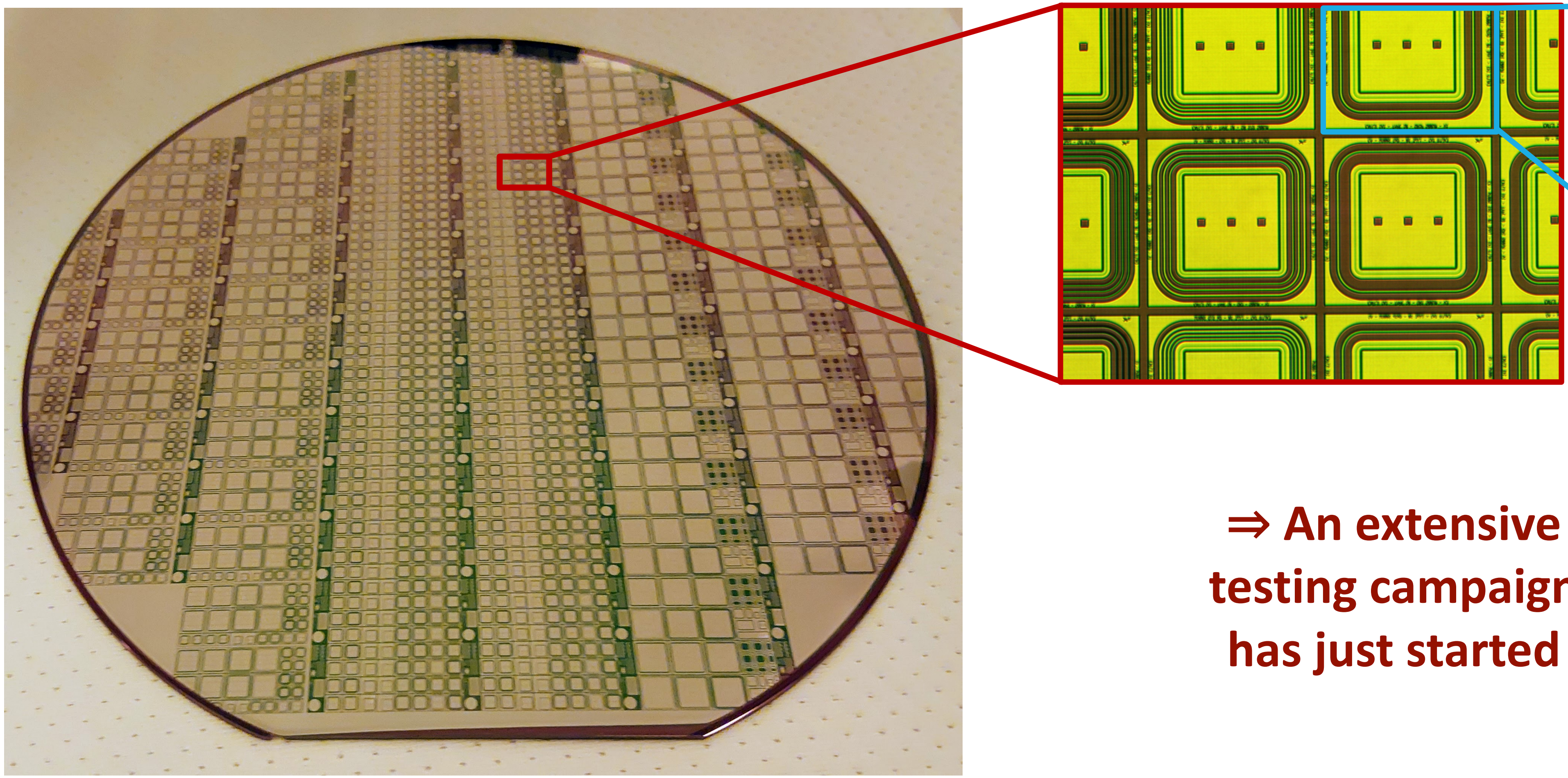
- ▻ carbon shield
- ▻ compensation
- ▻ new guard ring design
- ▻ thin substrates (15–45 µm)

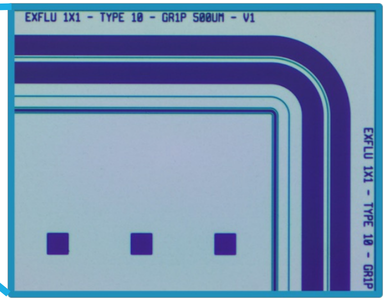
Design and preparatory studies have been performed in collaboration with the **Perugia group**

→ The EXFLU1 wafers just exited the FBK clean room

The EXFLU1 Wafers

6” Wafer





⇒ An extensive testing campaign has just started

Standard Gain Layer Design – Split Table

Wafer #	Thickness	p+ dose	C dose	C shield	Diffusion	Bulk
1	45	1.04	1.0		CBL	n-type
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	
5	30	1.02	1.0		CBL	high ρ
16	20	0.80	1.0		CHBL	low ρ
17	20	0.86	1.0		CBL	
18	15	0.84	1.0		CBL	

Gain layer depth: shallow

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

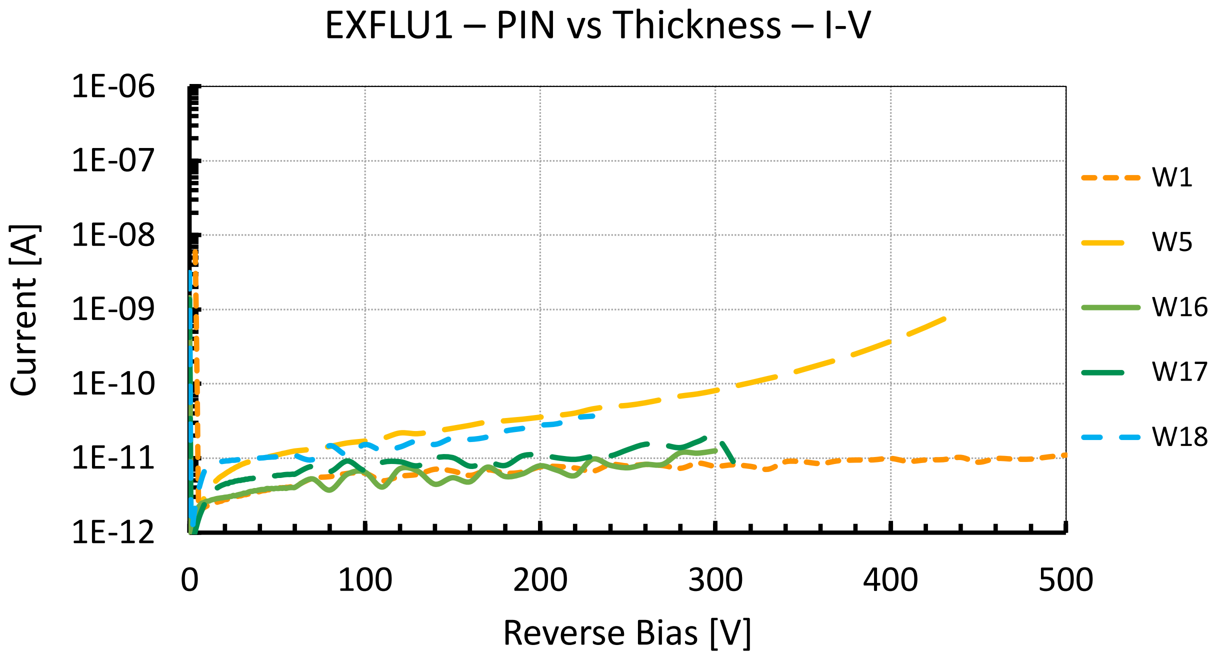
I-V measurements have been performed on wafer on LGAD-PIN structures

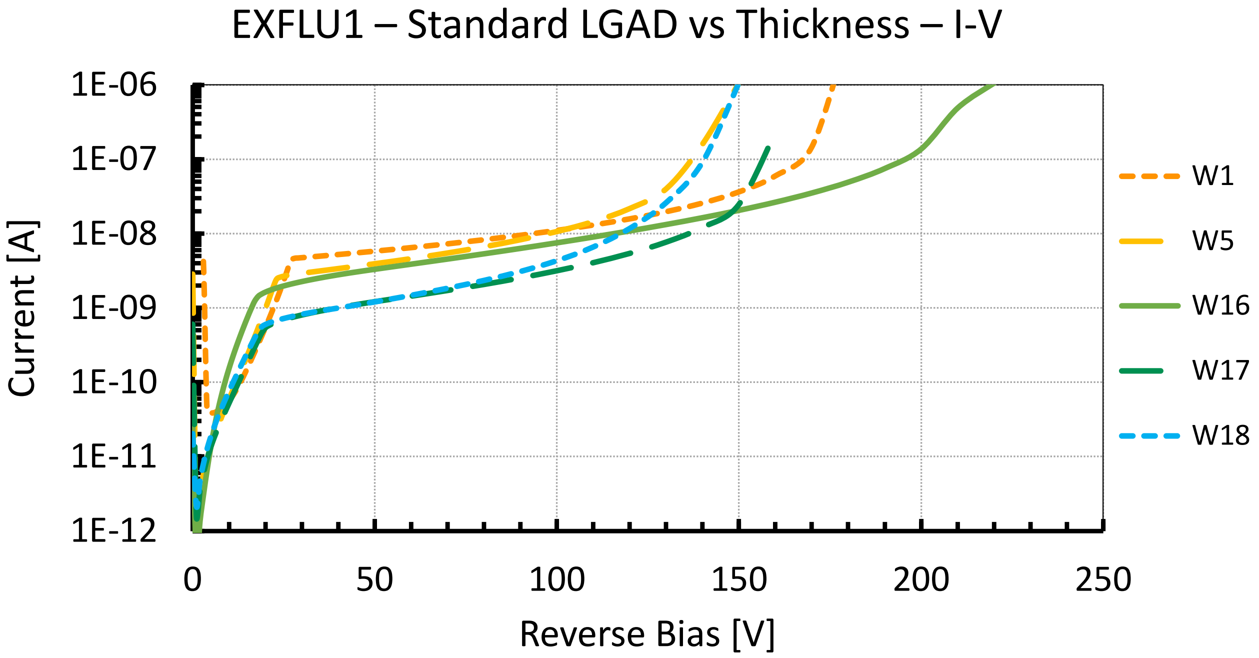
Standard LGAD – I-V at Different Thickness

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

Bulk
n-type
high ρ
TBC
low ρ

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

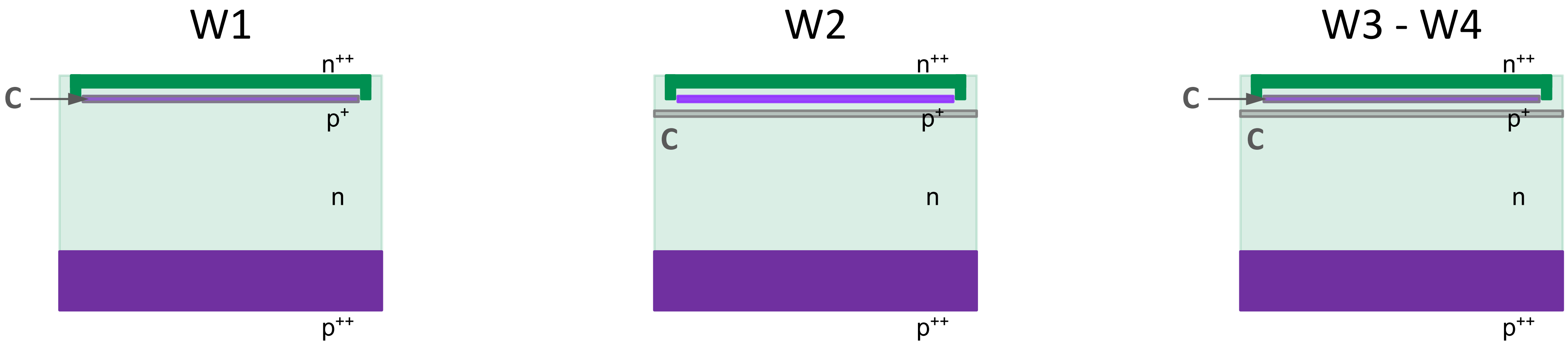




Standard LGAD with Carbon Shield

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



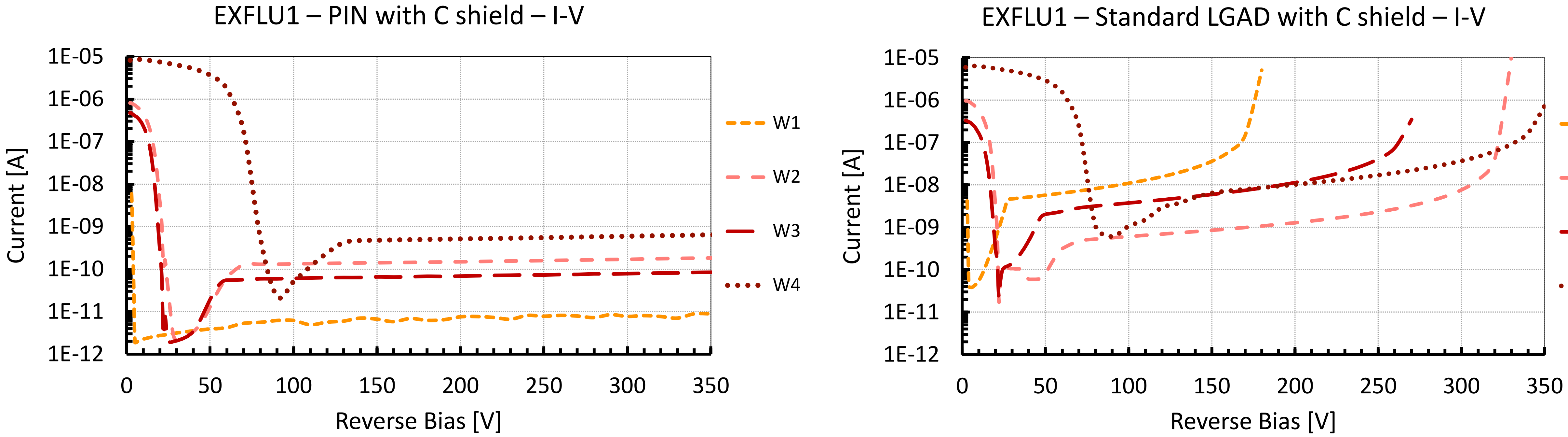
Production costs increase by ~ 20%

→ 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



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

Compensated Gain Layer Design – Split Table

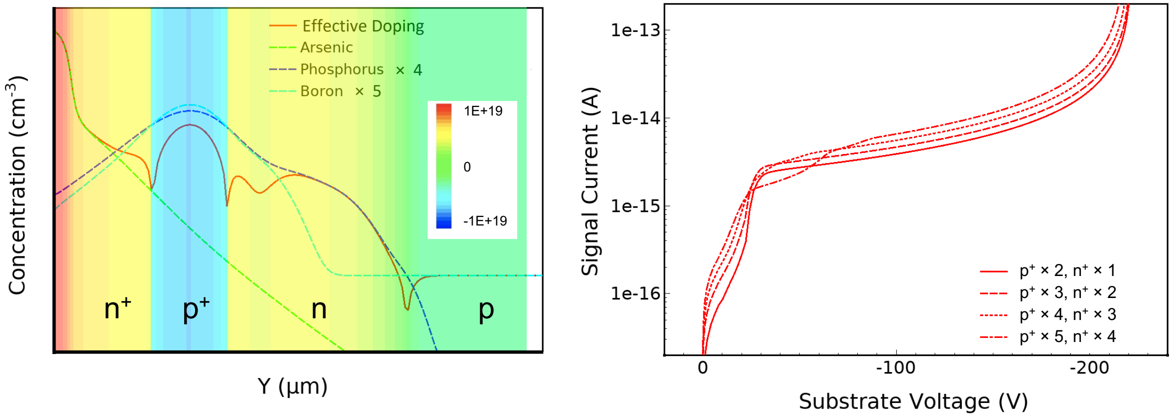
Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
7	30	2 b	1	
8	30	2 b	1	
9	30	2 c	1	
10	30	3 a	2	
11	30	3 b	2	
12	30	3 b	2	
13	30	3 b	2	1.0
14	30	3 c	2	
15	30	5 a	4	

[a < b < c]

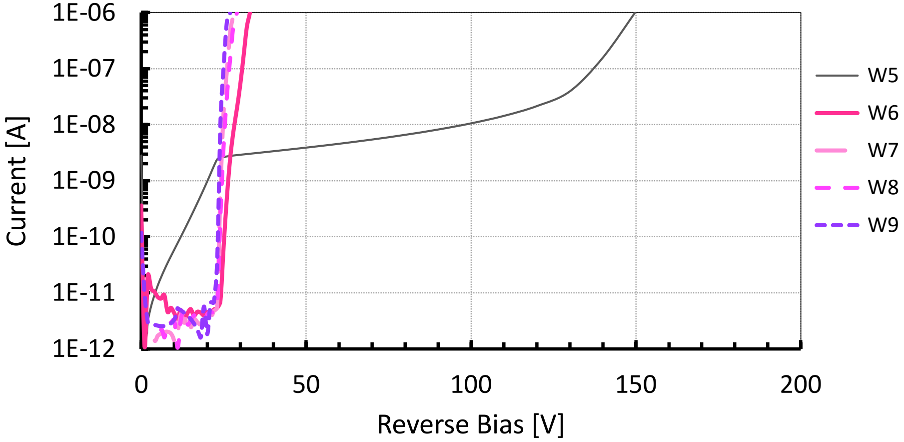
3 different combinations of $p^+ - n^+$ doping: 2 – 1, 3 – 2, 5 – 4

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

Simulation

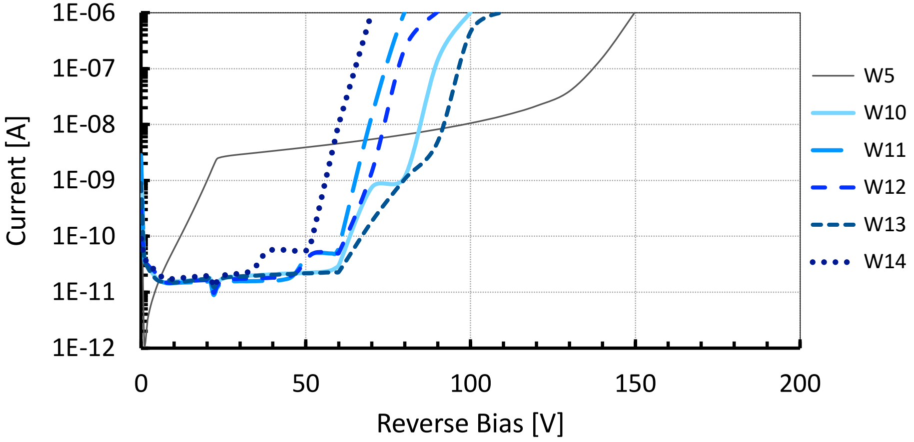


EXFLU1 – Compensated LGAD 2–1 – I-V



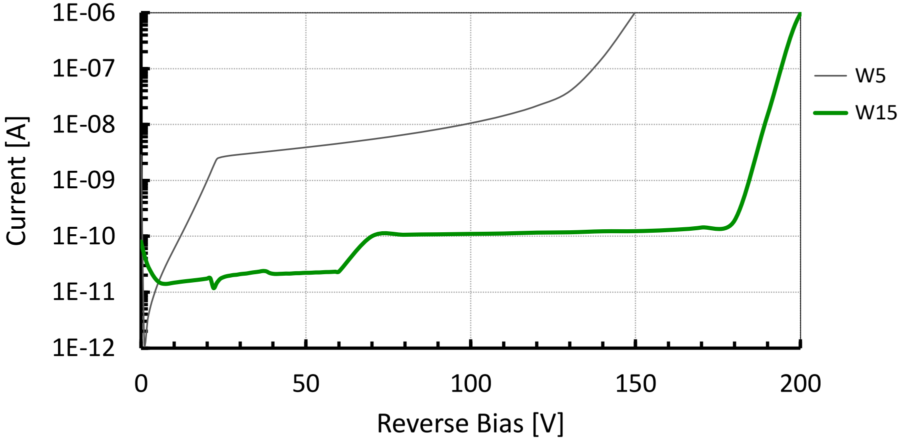
2 – 1

EXFLU1 – Compensated LGAD 3–2 – I-V



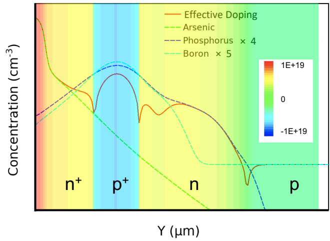
3 – 2

EXFLU1 – Compensated LGAD 5–4 – I-V



5 – 4

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

Summary & Outlook

The EXFLU1 production batch has been completed

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

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


MERSI takk obrigado благодаря mesi ありがとう
MOLTE GRAZIE ARIGATO
danke TEŞEKKÜR EDERIM
PALDIES grazas THANK YOU
спасибо muchas gracias どうも 多謝
merci danke schön DANKU
DANK U THANKS GRACIAS GRAZZI qujan
謝謝 TACK
ARIGATO MOLTE GRAZIE MERSI obrigado takk
THANK YOU
gracias TAK hvala
danke schön GO RAIBH MAITH AGAT muchas gracias
감사합니다 どうも grazie DZIĘKI
muchas gracias OBRIGADO obrigado
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- 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

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

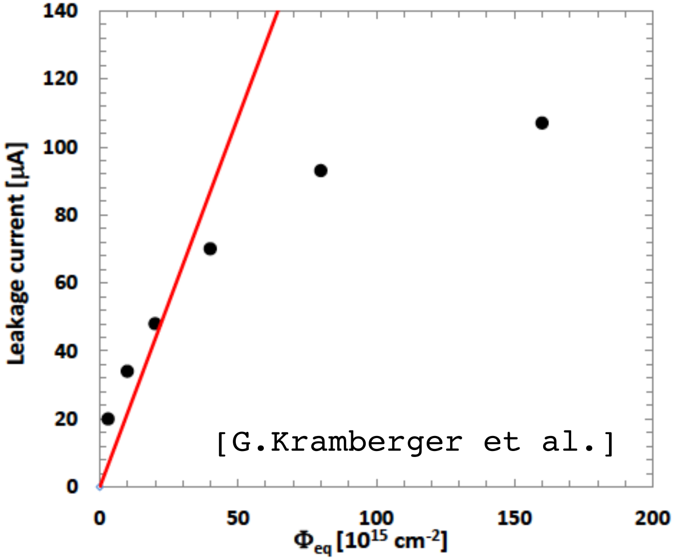
Backup

The Goals

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

Saturation

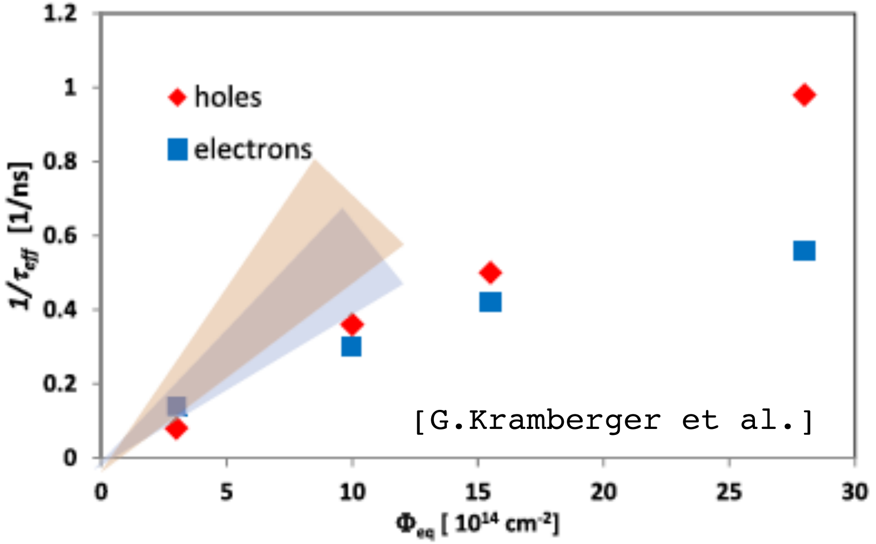
At fluences above $5 \cdot 10^{15}$ cm^{-2} → **Saturation of radiation effects observed**



Leakage current saturation

$I = \alpha V \Phi$

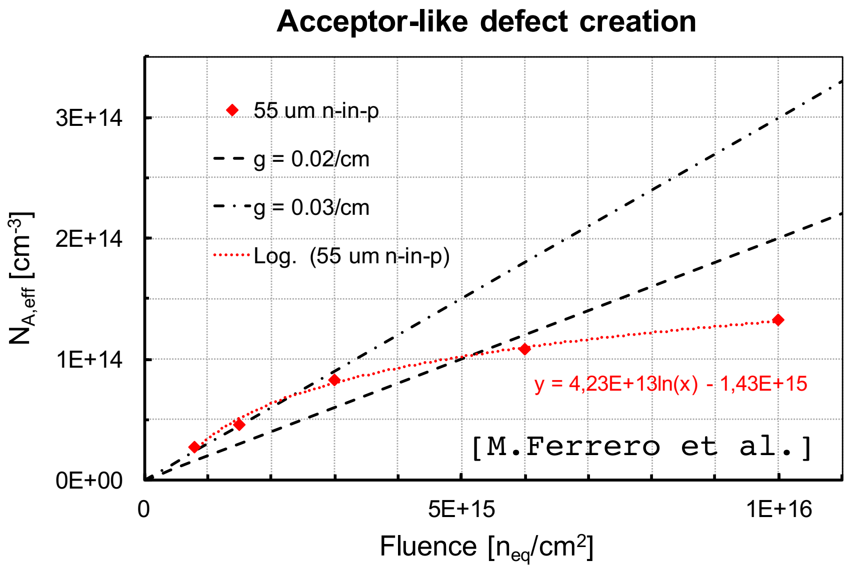
α from linear to logarithmic



Trapping probability saturation

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

β from linear to logarithmic



Acceptor creation saturation

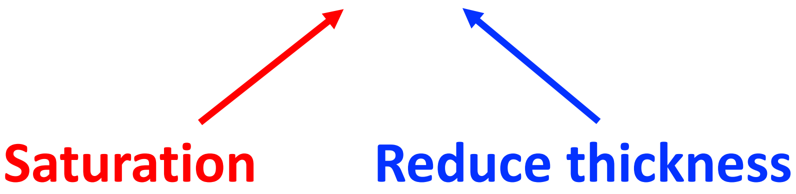
$N_{A,eff} = g_c \Phi$

g_c from linear to logarithmic

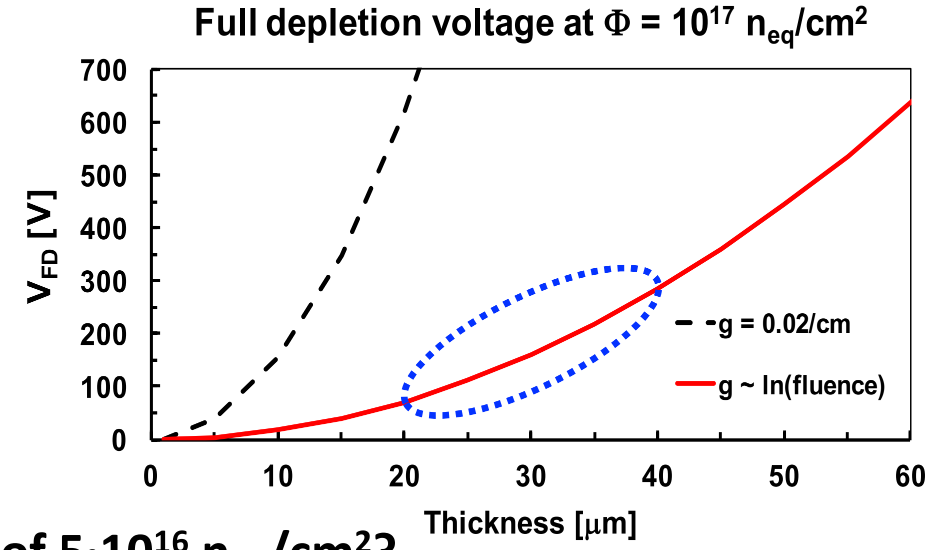
Silicon detectors irradiated at fluences 10^{16} – 10^{17} n_{eq}/cm^2 do not behave as expected → They behave better

Thin Substrates

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


Saturation **Reduce thickness**

At high fluences, only thin substrates can be fully depleted



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

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

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

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

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

Optimal candidate:
LGAD sensors

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:

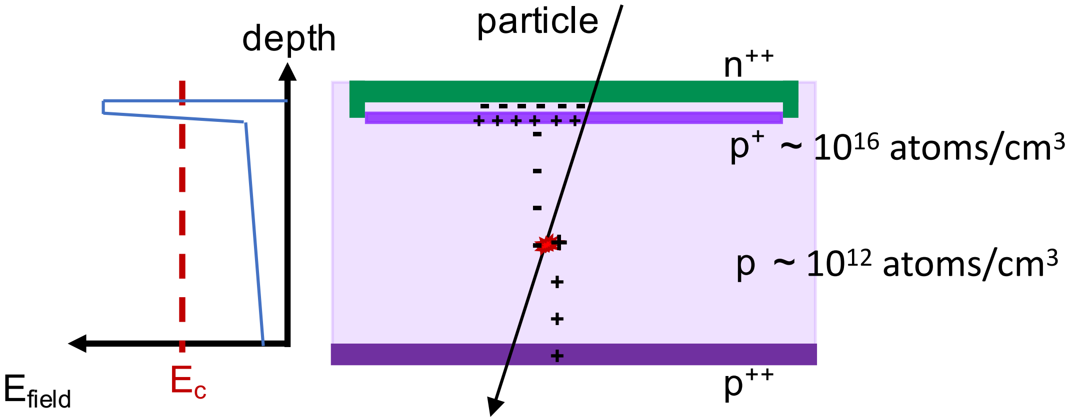
- defects in the silicon lattice structure → increase of the dark current
- trapping of the charge carriers → decrease of the charge collection efficiency
- change in the bulk effective doping → impossible to fully deplete the sensors

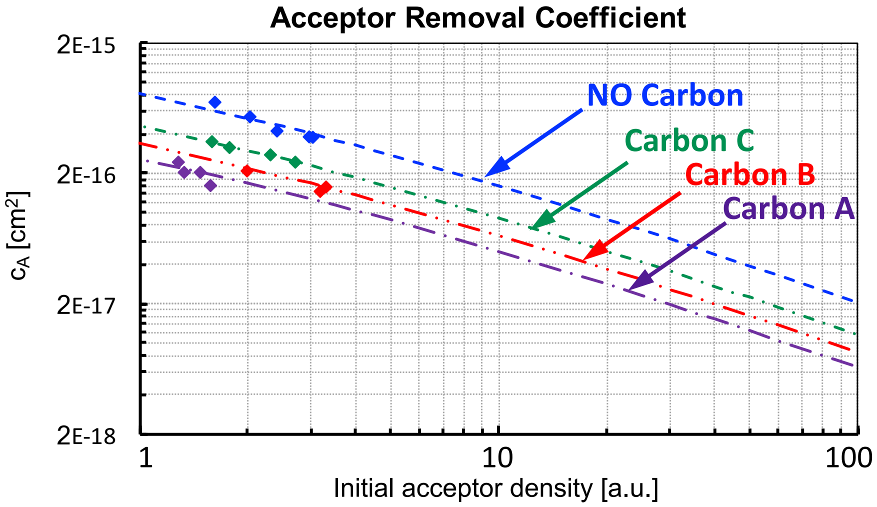
The ingredients to overcome the present limits above 10^{16} n_{eq}/cm^2 are:

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

Gain Removal Mechanism in LGADs





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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

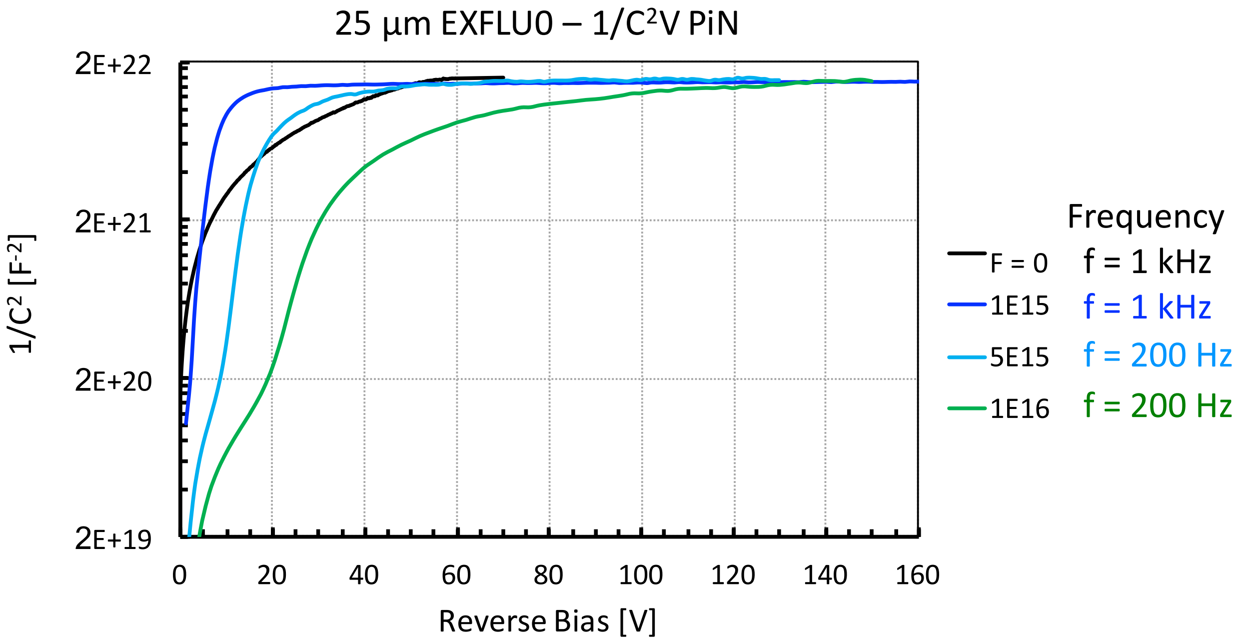
[M. Ferrero et al., doi:10.1201/9781003131946]

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}/cm²

Doping Evolution on Thin Bulk – 25 µm

25 µm thick sensors have a highly doped active substrate



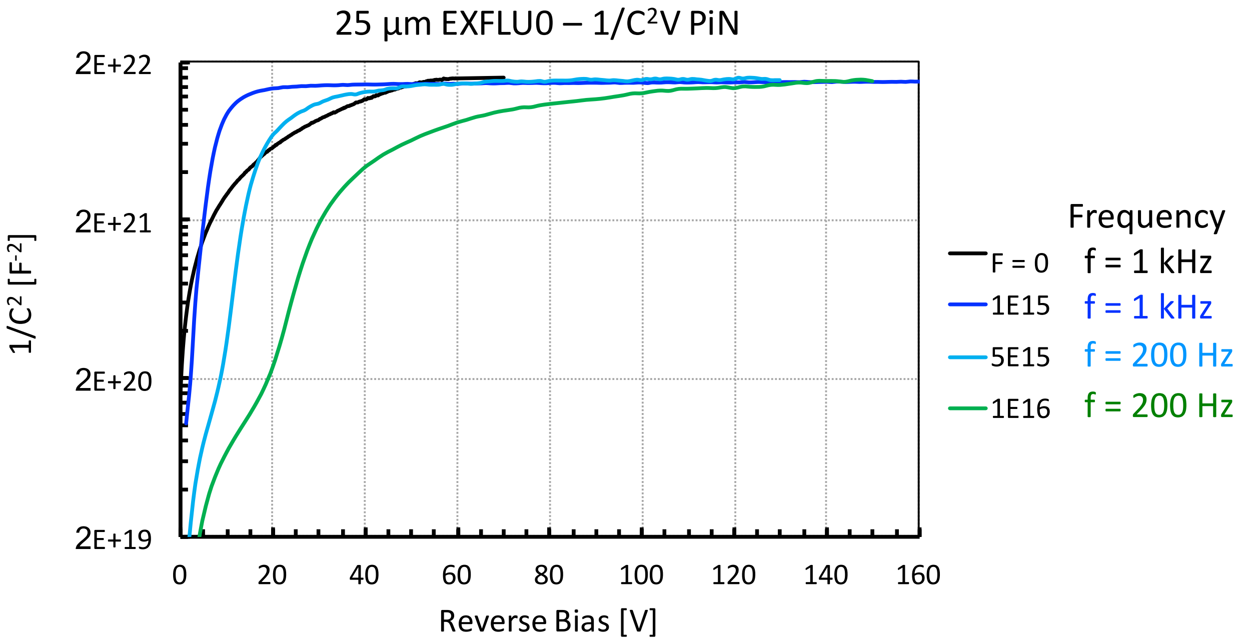
Φ [n_{eq}/cm^2]	V_{FD} from CV [V]	V_{FD} from TCT [V]
0	53	–
$1 \cdot 10^{15}$	6	–
$5 \cdot 10^{15}$	35	36
$1 \cdot 10^{16}$	82	50

Measurements have been performed at T = +25°C

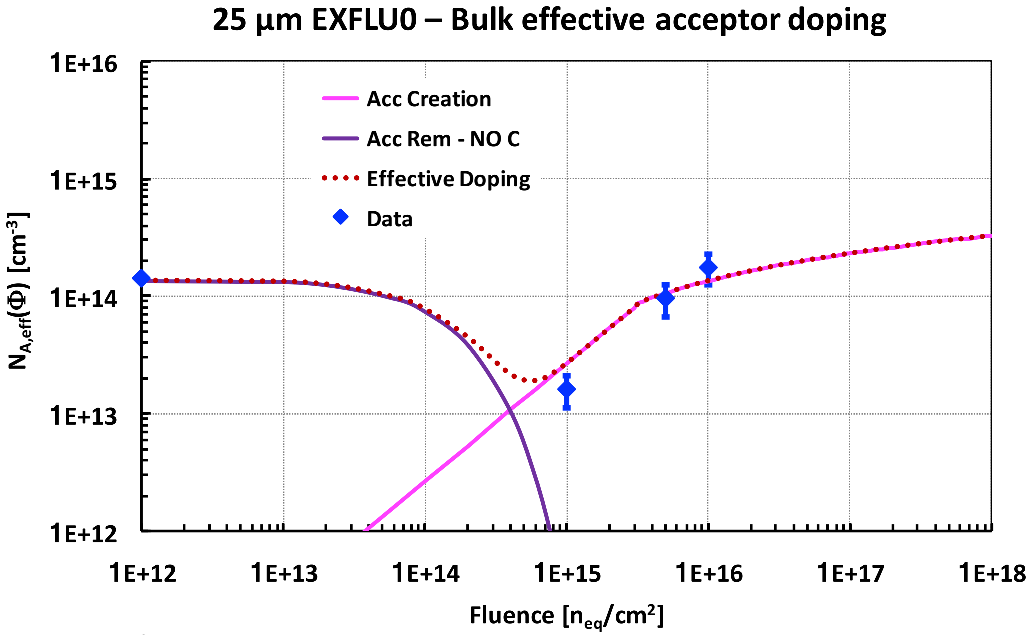
→ The average of V_{FD} from CV and TCT is used to extract the effective doping

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 Activity

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

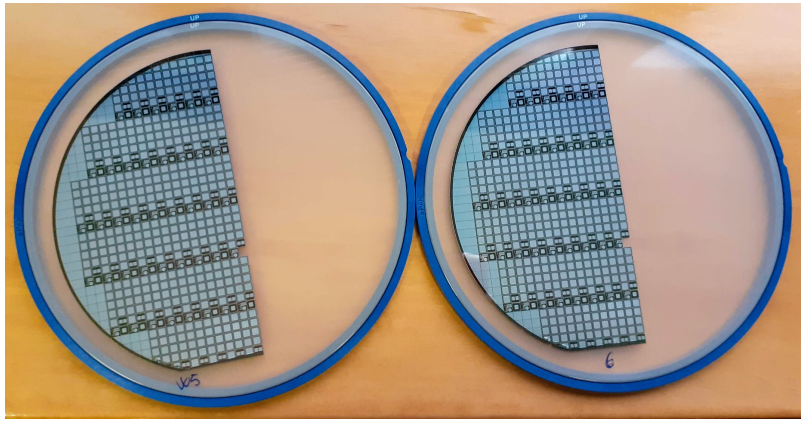
→ The *Silicon Sensor for Extreme Fluences (eXFlu)* project

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



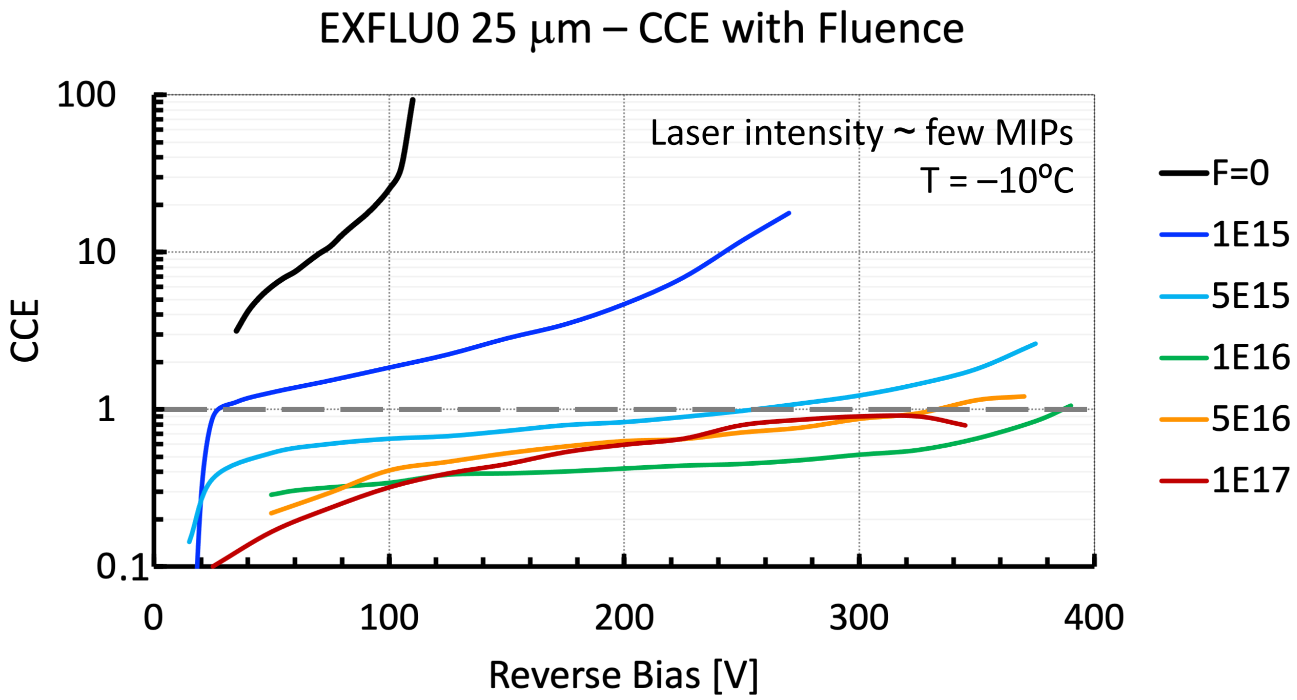
EXFLU0 sensors have been irradiated at JSI, Ljubljana, to 5 different fluences 10^{15}, $5\cdot10^{15}$, 10^{16}, $5\cdot10^{16}$, 10^{17} n_{eq}/cm^2

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

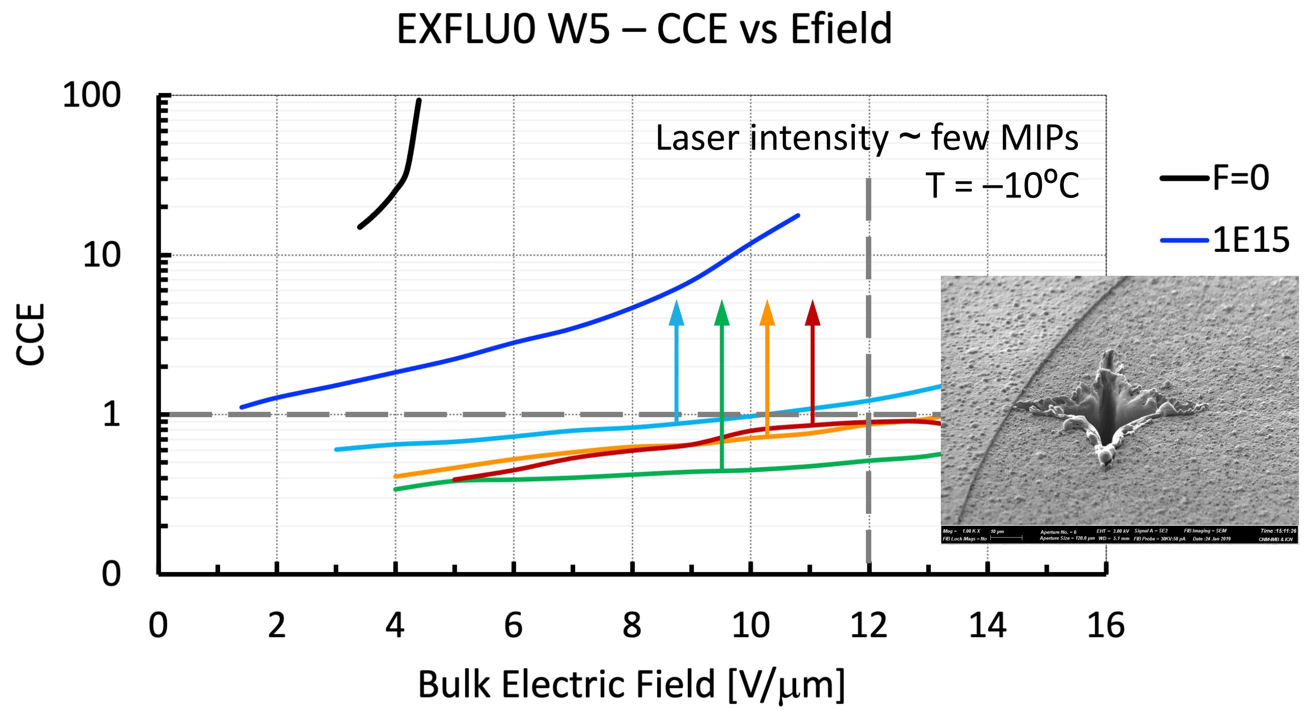
Measurements of charge collection efficiency (CCE) with an infra-red laser stimulus show that sensors can be operated up to the highest fluences



- ▻ 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


EXFLU0 W5 – CCE vs Efield

- ▻ 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

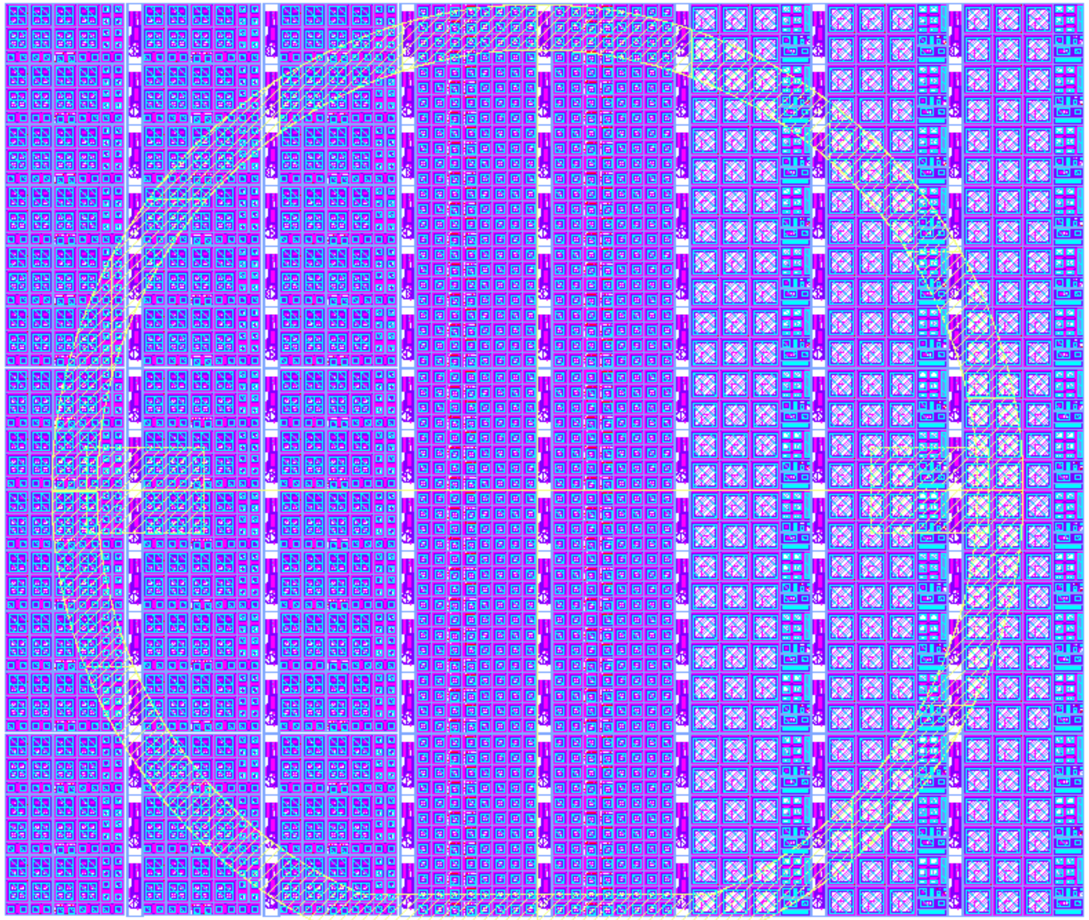
  → Single-Event Burnout

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

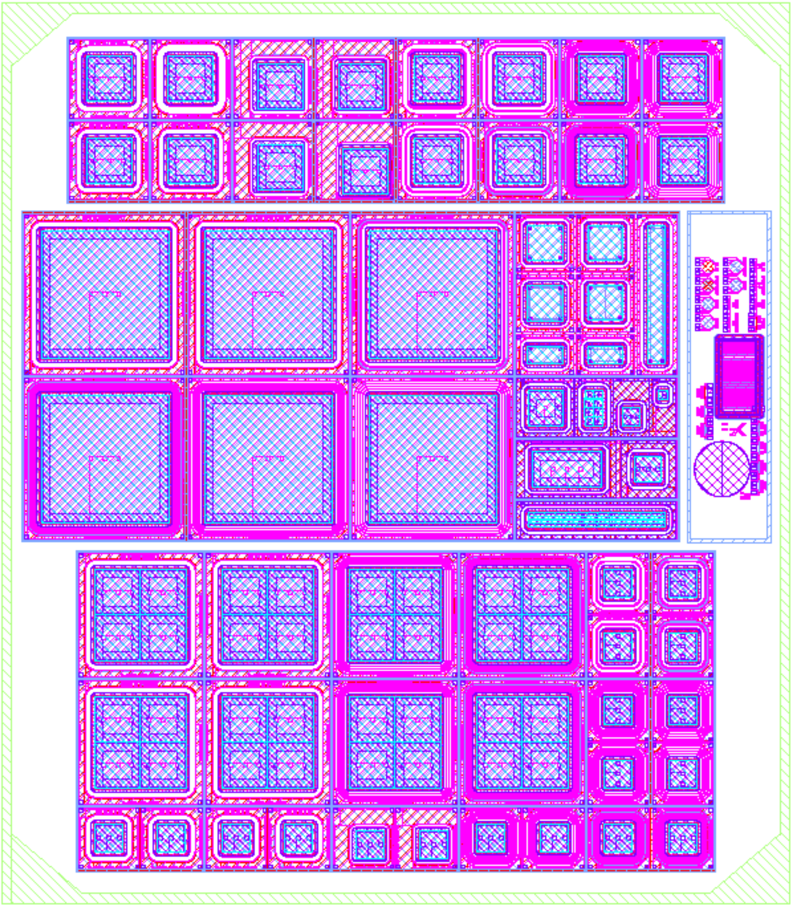
→ Necessary to increase the radiation tolerance of the gain mechanism above 10^{15} n_{eq}/cm^2

The EXFLU1 Layout

6” Wafer Layout

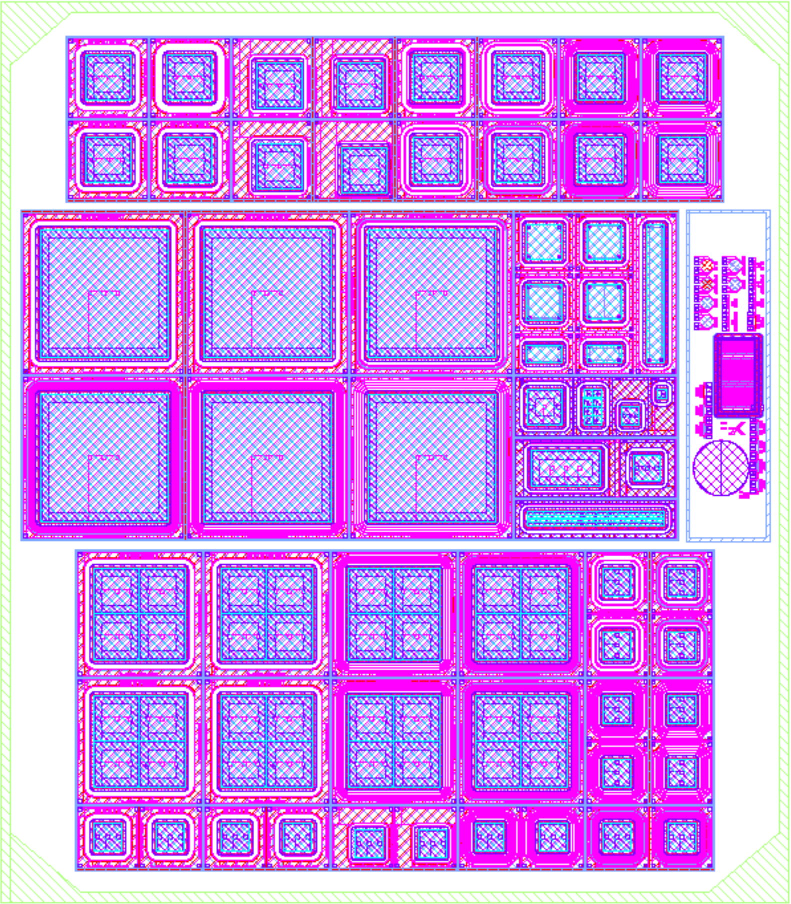


Reticle Layout



The EXFLU1 Layout

Reticle Layout



- ▻ Single Pads with 16 different guard-ring designs
- ▻ Big Single Pads
- ▻ 2×2 Arrays & LGAD-PiNs

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

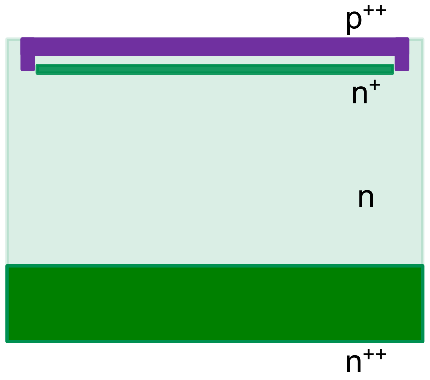
Donor Removal Characterisation

A p-in-n LGAD production batch is needed to study the donor removal coefficient, c_D

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

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

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



p-in-n LGAD

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