Compensated LGAD
An innovative design of thin silicon sensors for very high fluences

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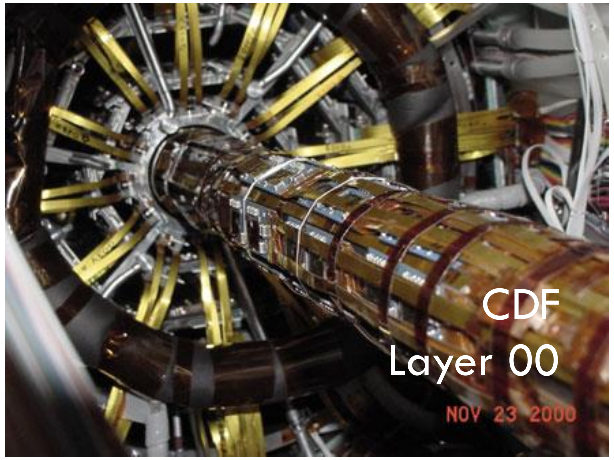
PIXEL 2024, Eleventh International Workshop on Semiconductor Pixel Detectors for Particles and Imaging

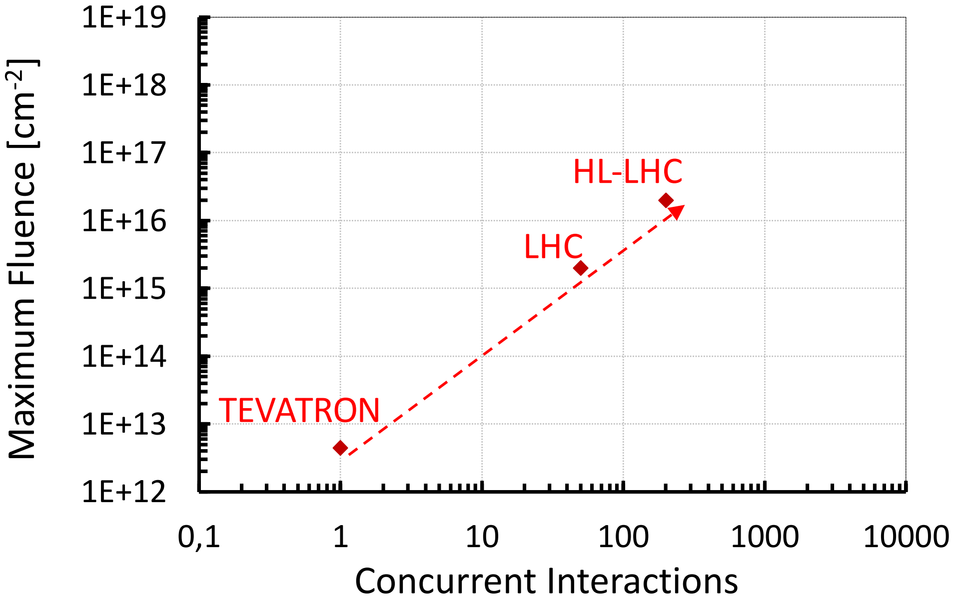
Outline

- The motivation
- The state of the art of planar silicon sensor operativity in high radiation environments
- The LGAD technology
- The CompleX strategy (compensated LGAD)
- The proof of concept of compensated-LGAD

Motivation

Silicon detectors have been enabling technology for discoveries on particle physics at colliders





State of the art of silicon sensor performance in hadron colliders:

- Precise tracking down to ~ 10 μm → 1 fC up to $2 \cdot 10^{16}$ n_{eq}/cm^2
- Precise timing down to ~ 30 ps → 5 fC up to $3 \cdot 10^{15}$ n_{eq}/cm^2

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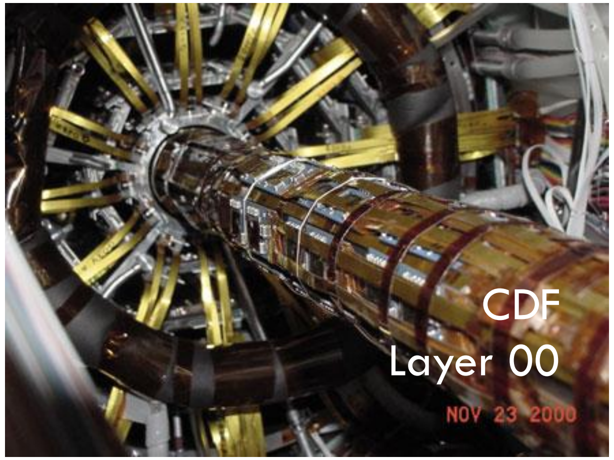

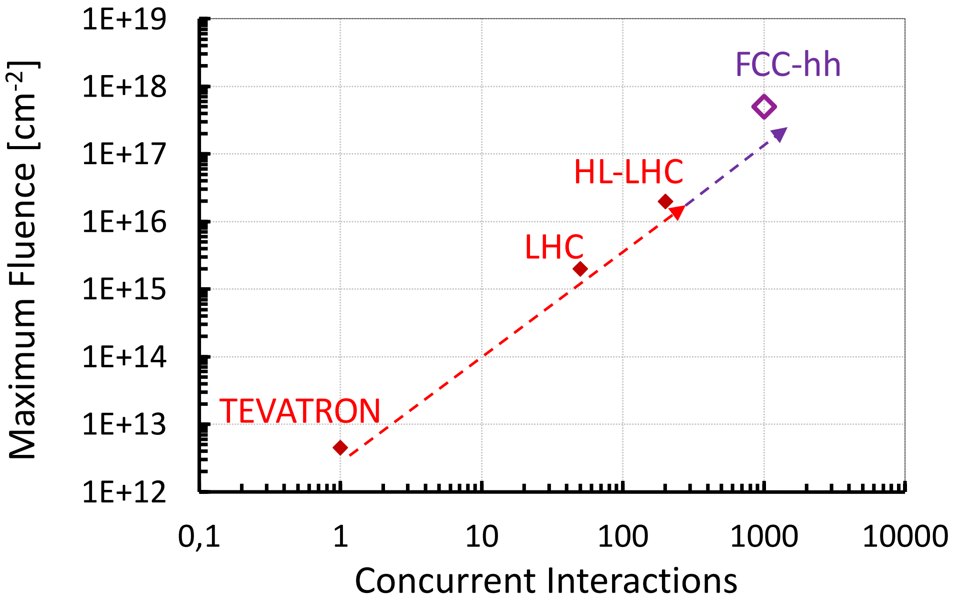

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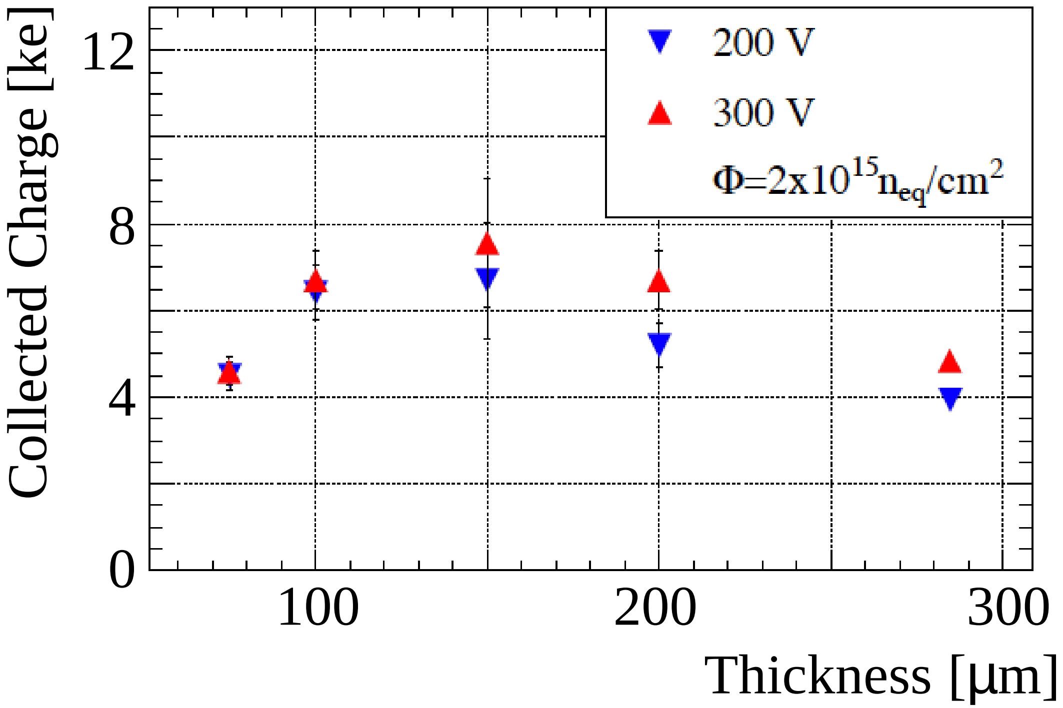
CompleX will enable 4D tracking with planar silicon sensors up to the fluence of $5 \cdot 10^{17}$ n_{eq}/cm^2

Planar silicon sensors operativity up to $1 \cdot 10^{16}$ n_{eq}/cm^2

Signals from planar silicon sensors become too small

- ➢ Non-uniformities in the electric field
- ➢ Impossible to fully deplete the sensors
- ➢ Collected charge independent from thickness

[doi: 10.1088/1748-0221/9/05/C05023]

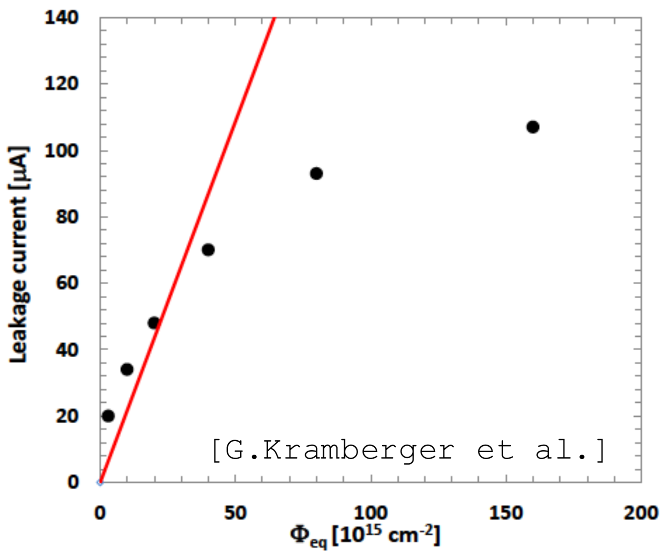


Planar silicon sensors operativity up to $1 \cdot 10^{16}\ n_{eq}/cm^2$

Macroscopic effect of radiation on silicon sensor:

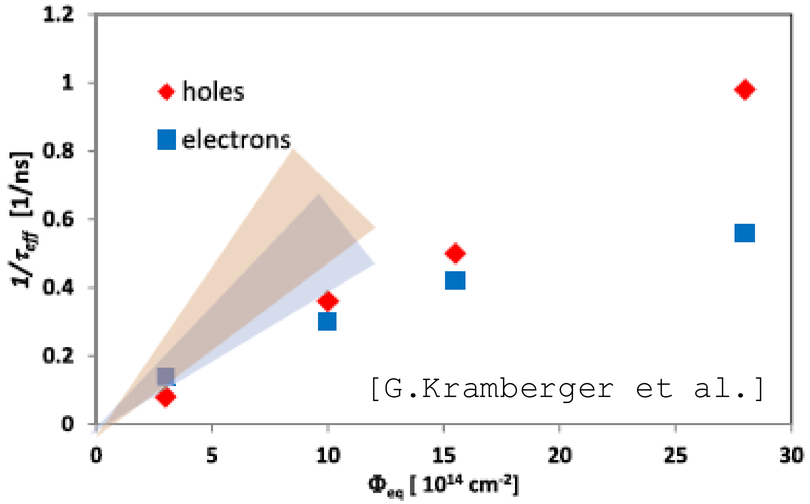
- Dark current increase is smaller than expected
- Charge collection efficiency is higher than predicted
- Slowing down of the acceptor creation rate

Saturation effect of the radiation damage



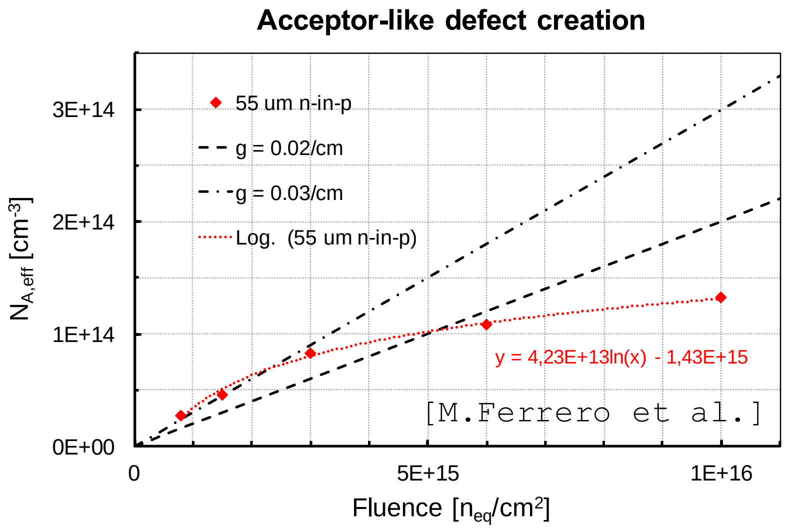
Leakage current saturation

$I = \alpha V \Phi$ **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**

The Complex project

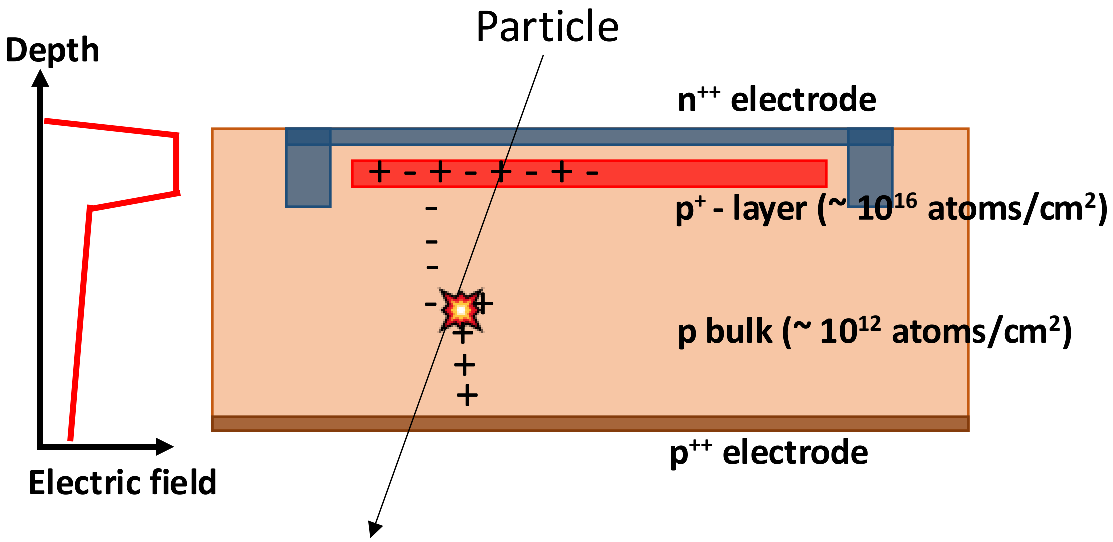
CompleX will develop a new generation of planar silicon sensors to operate in extreme fluence environment

- Exploit the saturation effect of the radiation damage
- Use this substrate (20-40 µm)
- Use sensor internal gain increase SNR

CompleX will extend the understanding and modelling of radiation damage in silicon to the fluence of $5 \cdot 10^{17}\ n_{eq}/cm^2$

Low Gain Avalanche Diodes - LGADs

LGAD sensors are planar silicon sensors main candidate to operate at extreme fluence



LGADs are n-in-p planar silicon sensors with internal moderate gain (20−30) controlled by the external bias ($E_{field} \geq 300$ kV/cm generated by gain implant)

gain implant (p^{+}-layer) obtained by the implantation of acceptor in a confined volume underneath the n^{++} electrode

LGAD performance

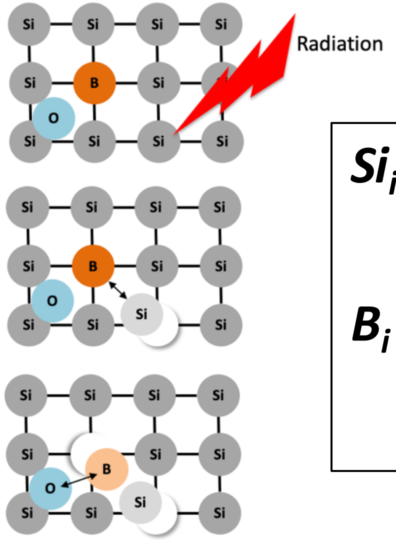
- **Timing ~ 30ps**
- **Tracking (TI-LGAD, RSD) ~ 10-20 µm**
- **Radiation resistance up to fluence of ~3E15 n_{eq}/cm^2**

LGADs - Gain Removal mechanism

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



$Si_i + B_s \rightarrow B_i$	Removal of an acceptor
$B_i + O_i \rightarrow B_iO_i$	Creation of a donor complex

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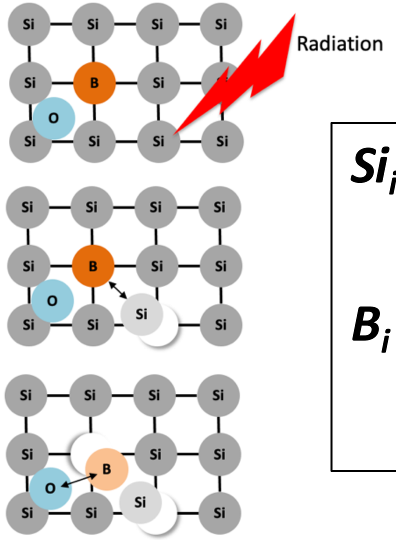

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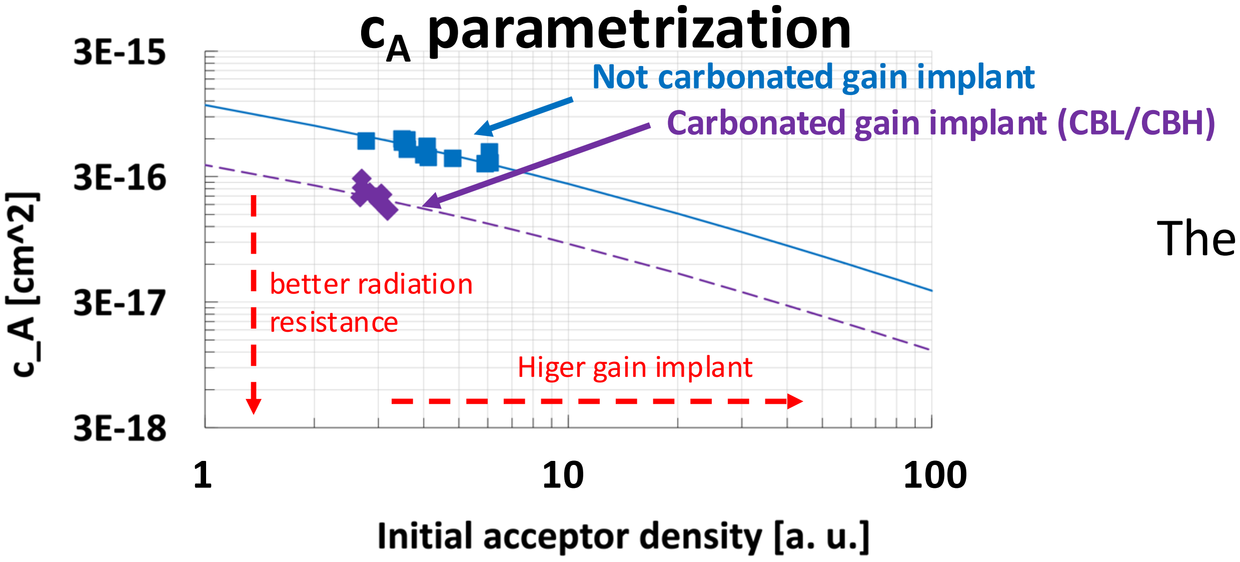
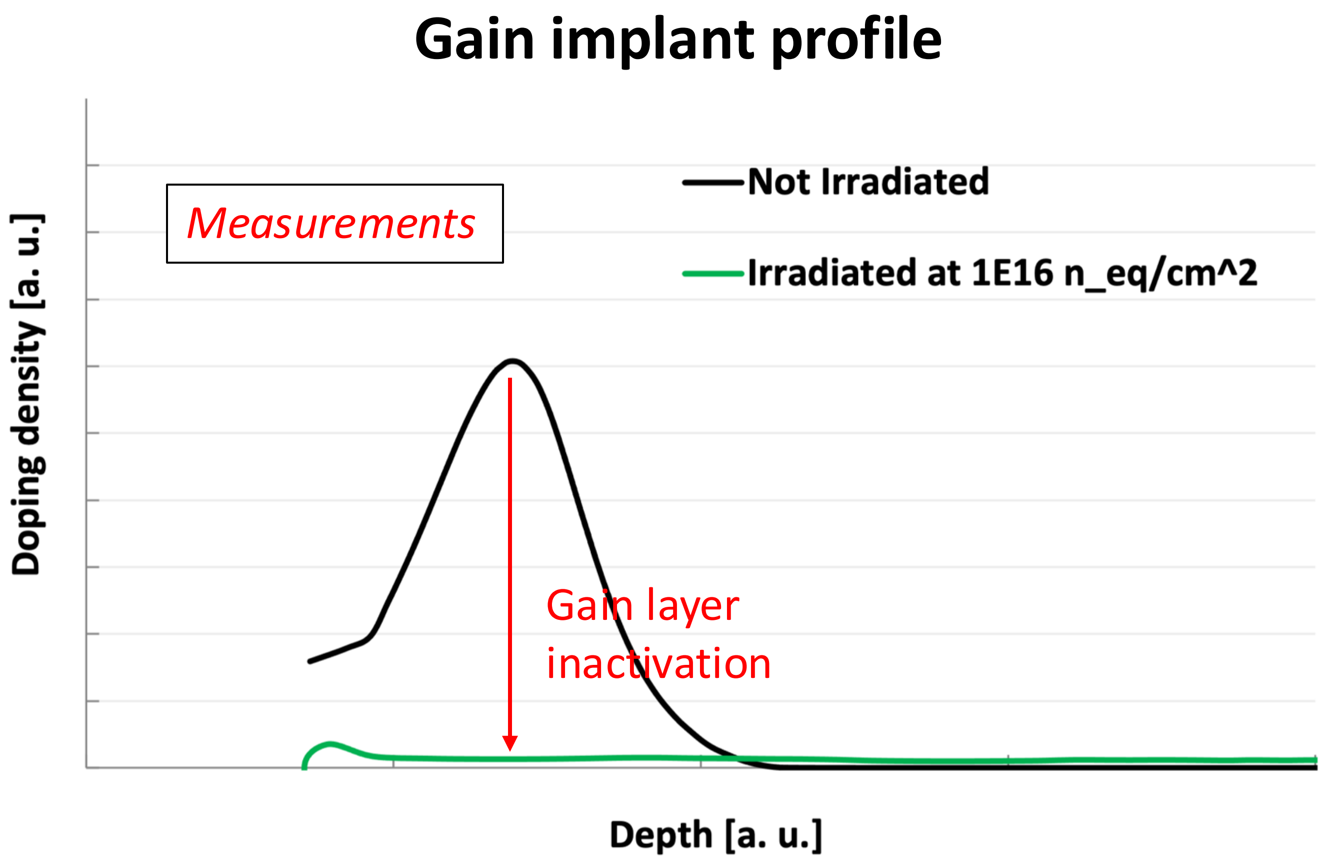

c_A parametrization

The acceptor removal coefficient depends on the initial acceptor density, $p^+(0)$

⇒ Is it possible to improve c_A further?

LGADs for extreme fluence

The irradiation at **$\Phi = 1\cdot10^{16}\ n_{eq}/cm^2$** causes the completed inactivation of the gain layer



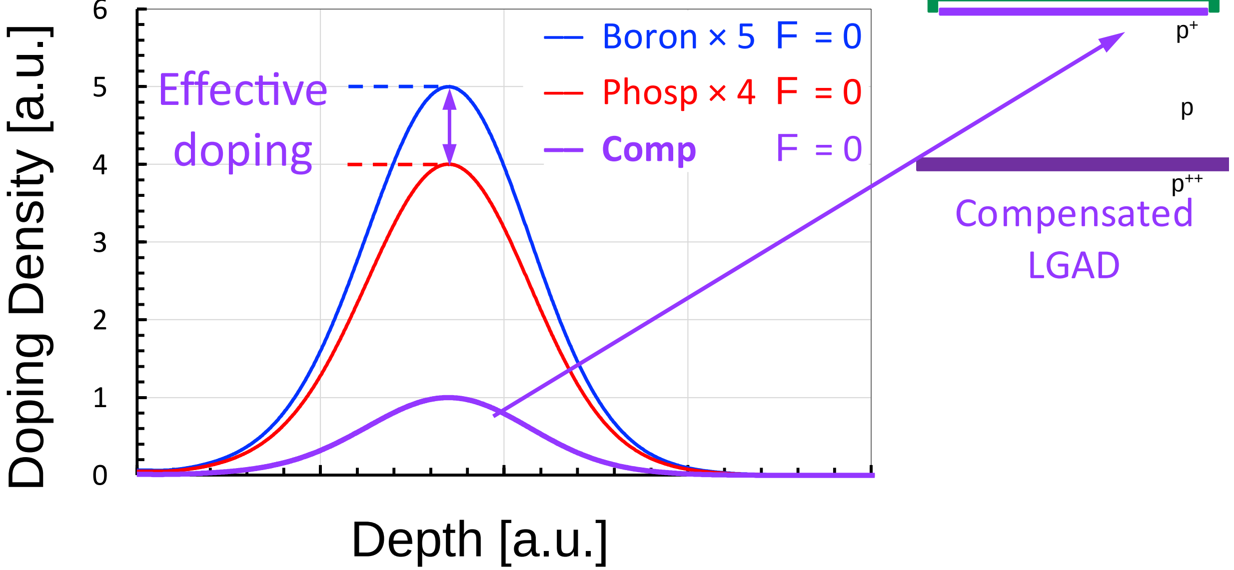
Gain layer profiles extracted from Capacitance-Voltage curves, on 50 µm-thick LGAD

Compensated LGADs for extreme fluence

Compensated LGAD

(the gain layer is obtained as difference between n^+ and a p^+ implant)

Effective doping profile



- ➢ ***B*** Implant
- ➢ ***P*** Implant
- ➢ ***B-P*** effective doping

Compensated LGADs for extreme fluence

Compensated LGAD

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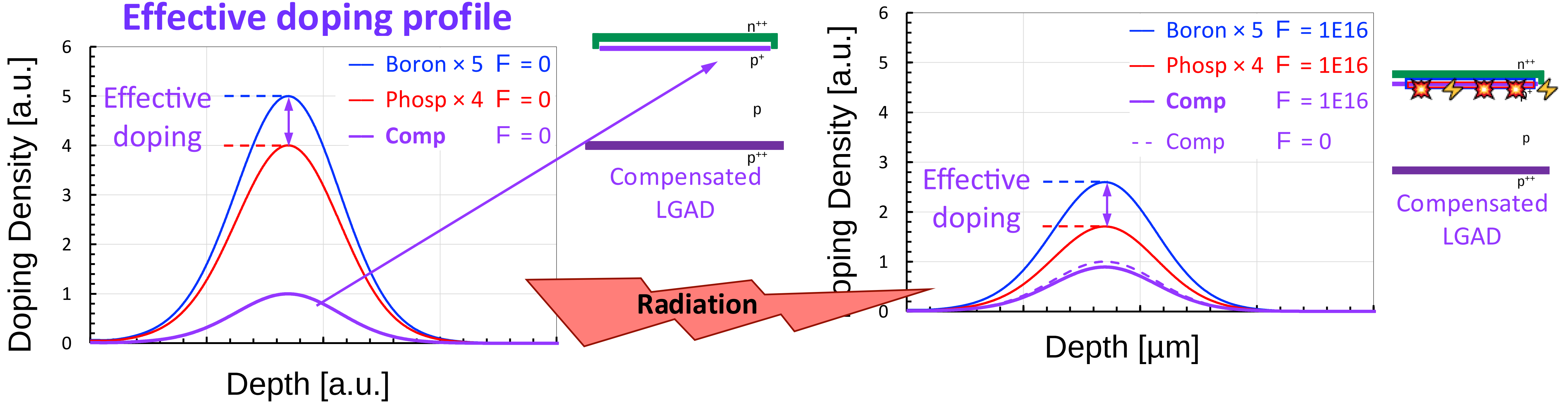
Simulation of the effect of a at $\Phi = 1 \cdot 10^{16}$ n_{eq}/cm^2 on a compensated gain layer

Effective doping profile



The compensated LGAD exploits the removal mechanism of acceptors and donors to engineer a gain implant unchangeable with radiation damage

Compensated LGADs for extreme fluence

Compensated LGAD

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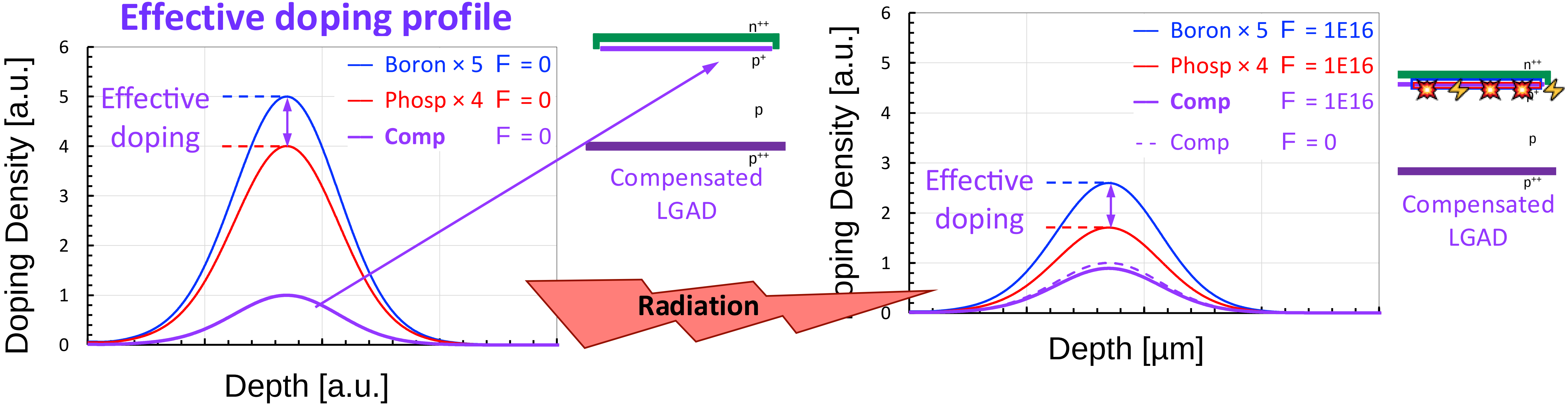

- **Acceptor removal rate is very well known**
- **Donor removal rate has never been studied**

The proof of concept of compensated LGADs - EXFLU1

The first compensated LGADs sensors have been released by FBK in 2022, in a framework of the EXFLU1 batch [V. Sola, TREDI 2024, Torino]

Split table (a < b < c)

Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30 µm	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	

3 different combinations of $p^+ - n^+$ doping:

- 2 – 1
- 3 – 2
- 5 – 4

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

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12	30	3 b	2	
13	30	3 b	2	1.0
14	30	3 c	2	
15	30	5 a	4	

3 different combinations of $p^+ - n^+$ doping:

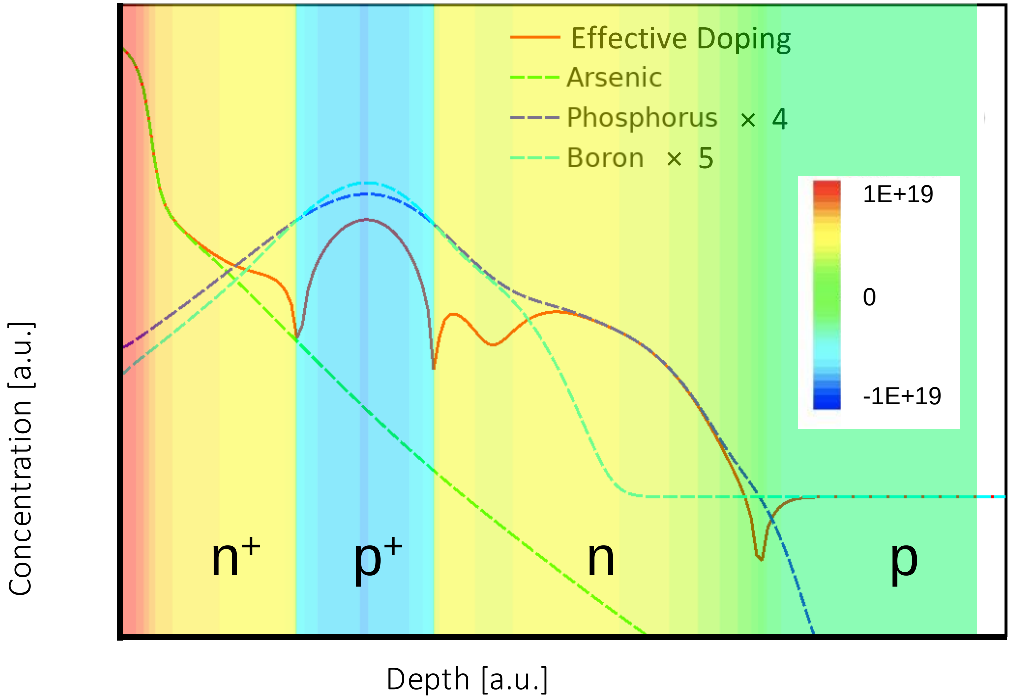
- $2 - 1$
- $3 - 2$
- $5 - 4$

The co-implantation of Carbon in the gain implant volume mitigate the acceptor removal rate

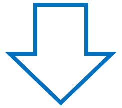
Design and preparatory studies have been performed in collaboration with the **Perugia group**

Compensated LGAD – IV Measurements

Gain Layer profile – process simulation



Different diffusion of p⁺ and n⁺ implant



Alternating of p and n doped regions

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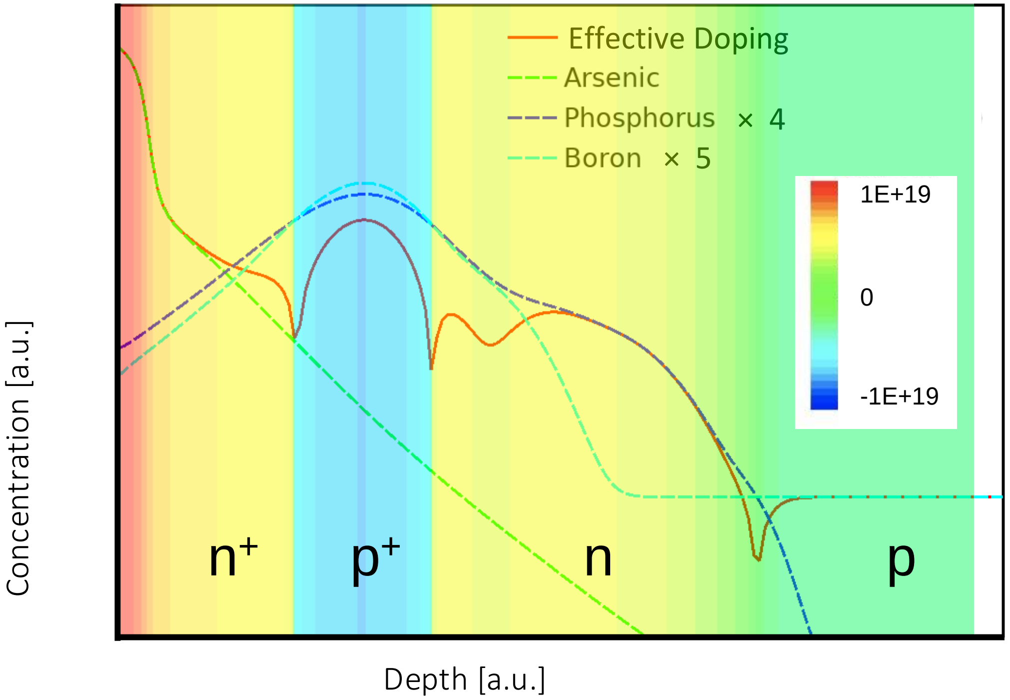

Different diffusion of p^+ and n^+ implant

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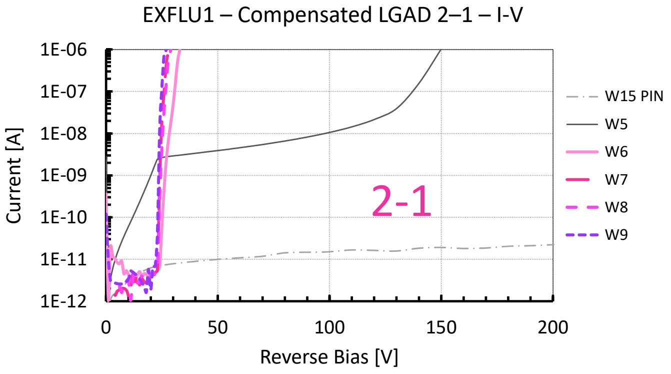
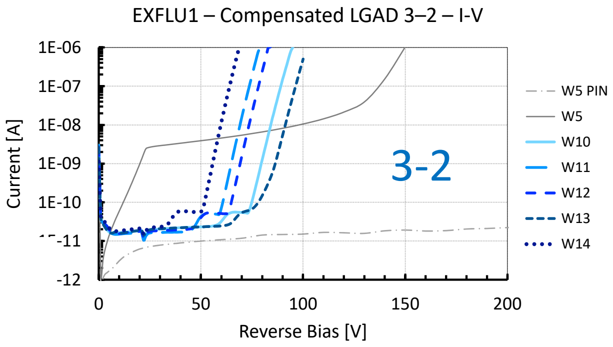
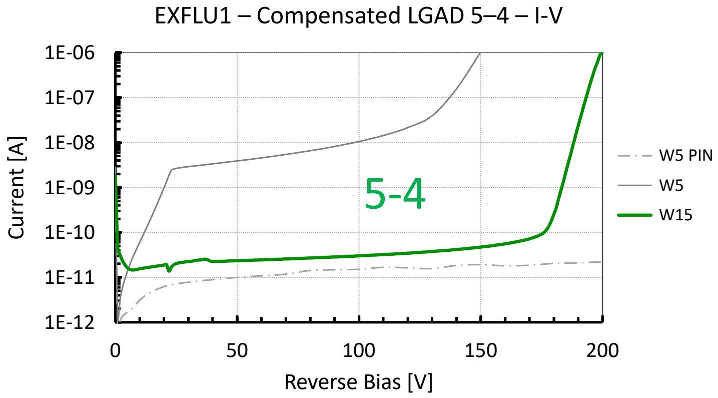
Current – Voltage measurements on wafer



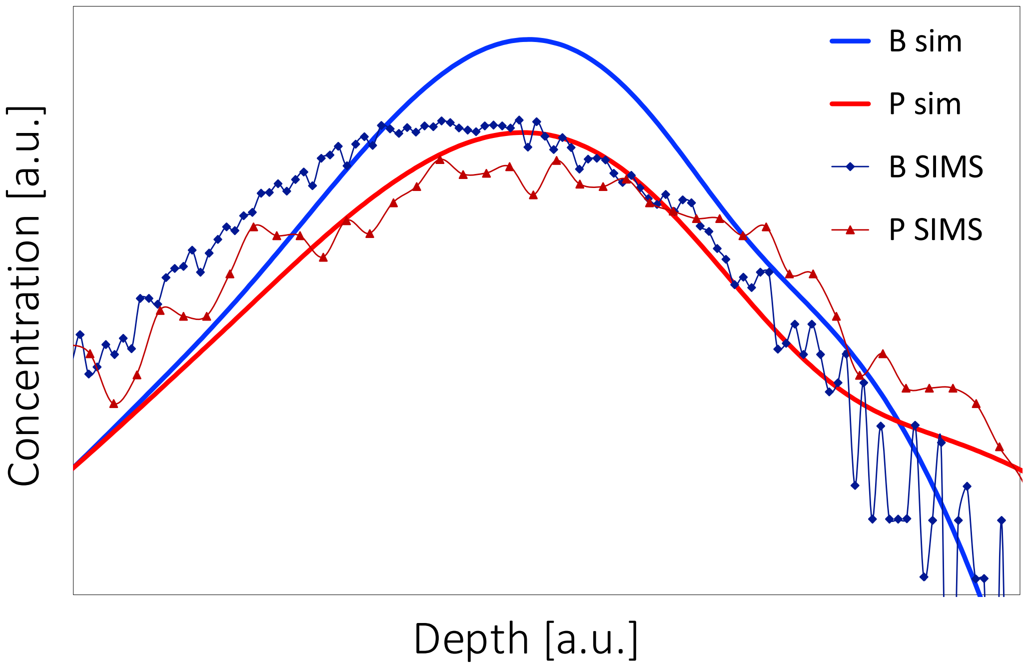




Secondary Ion Mass Spectroscopy – W15 (5-4)

Investigation of **p$^+$ (Boron)** and **n$^+$ (Phosphorus)** implants shape through SIMS technique

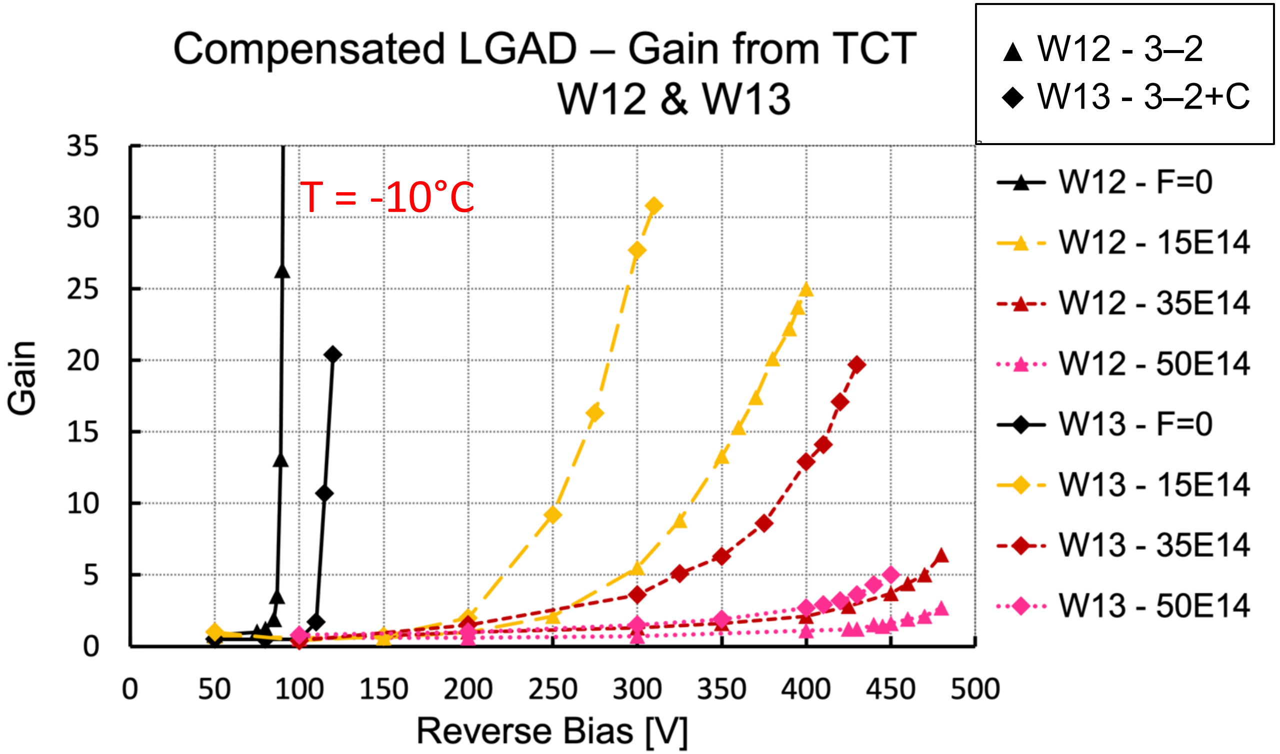
Compensated LGAD – W15 5-4
SIMS vs Process Simulation



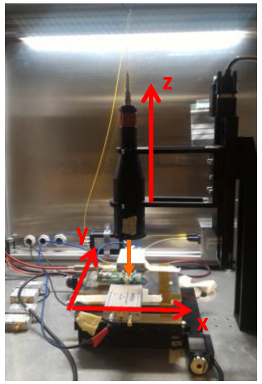
- ➢ Boron peak is shallower than phosphorus
- ➢ Boron peak is lower than predicted from simulation

1064 nm laser stimulus on Compensated-LGAD

Gain measurements



TCT setup



Gain measurements method

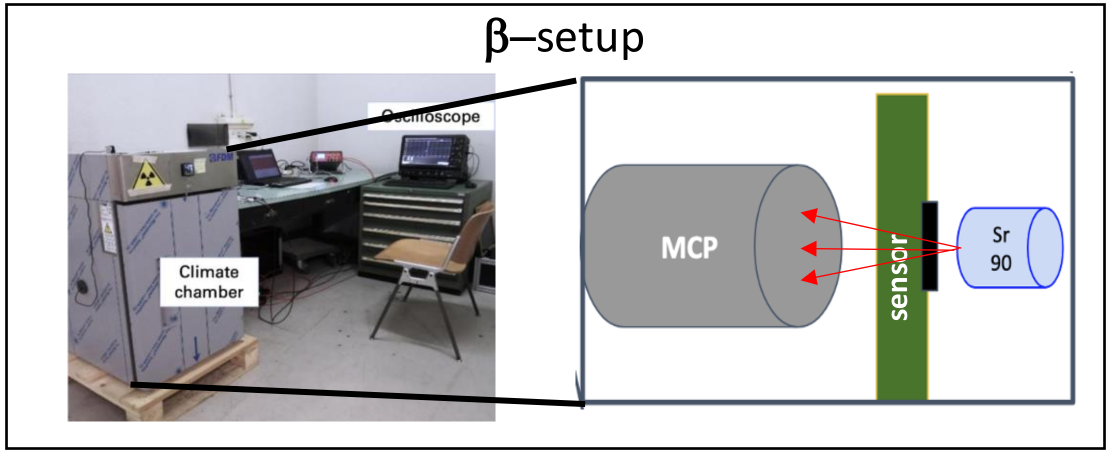
$$\mathrm{Gain} = \frac{Q_{\mathrm{LGAD}}}{< Q_{\mathrm{PiN}}^{\mathrm{No\ Gain}} >}$$

Despite not optimal **p⁺** and **n⁺** gain implants:

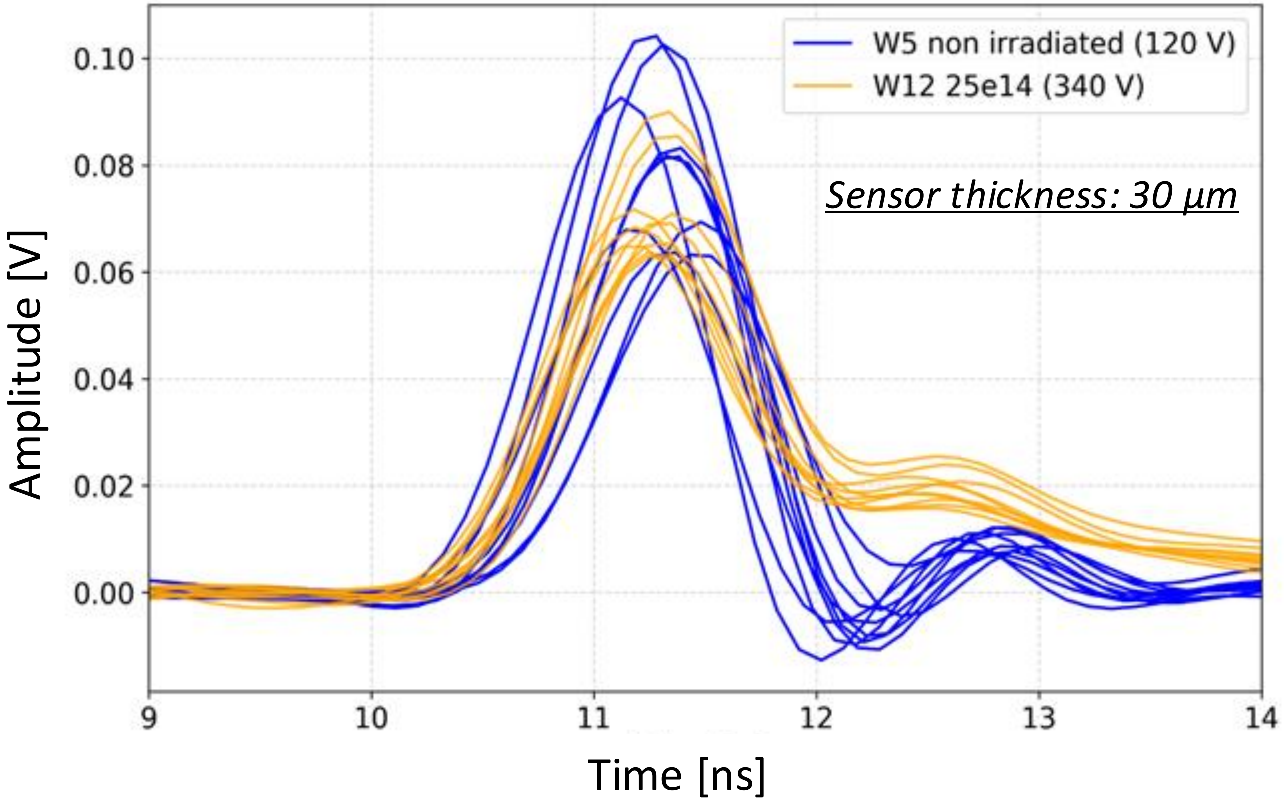
→ **Good gain behaviour of the compensated LGAD sensors after irradiation**

→ **Even in compensated LGADs, the usage of carbon mitigates the acceptor removal**

β particles on compensated LGAD – Signals


β–setup

Comparison of the signal shapes generated by β particles in compensated LGAD (W12) and a standard LGAD (W5 ExFlu1)

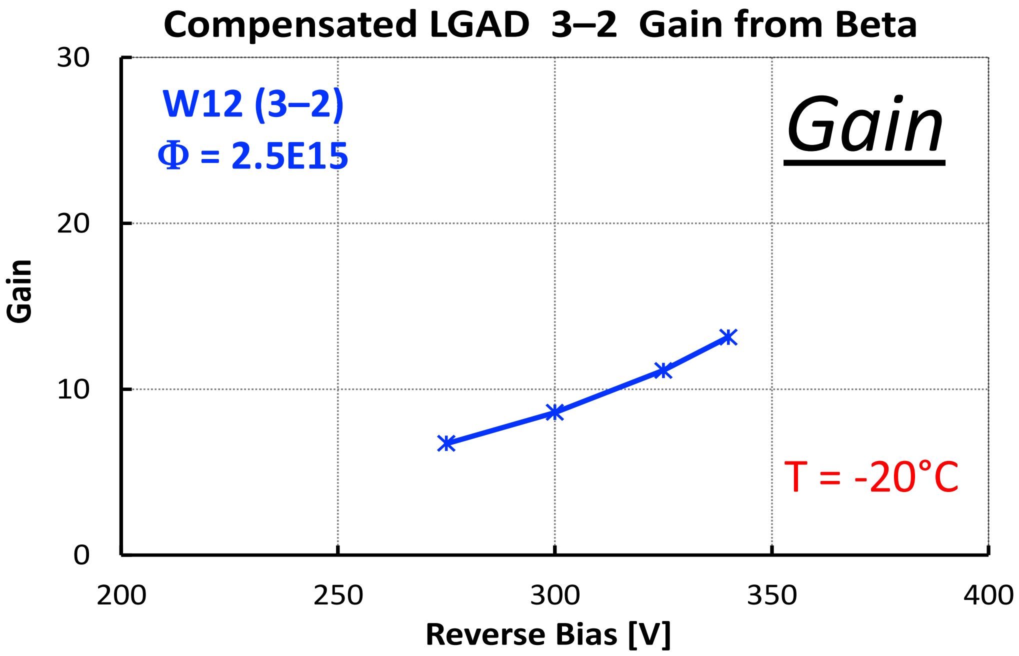


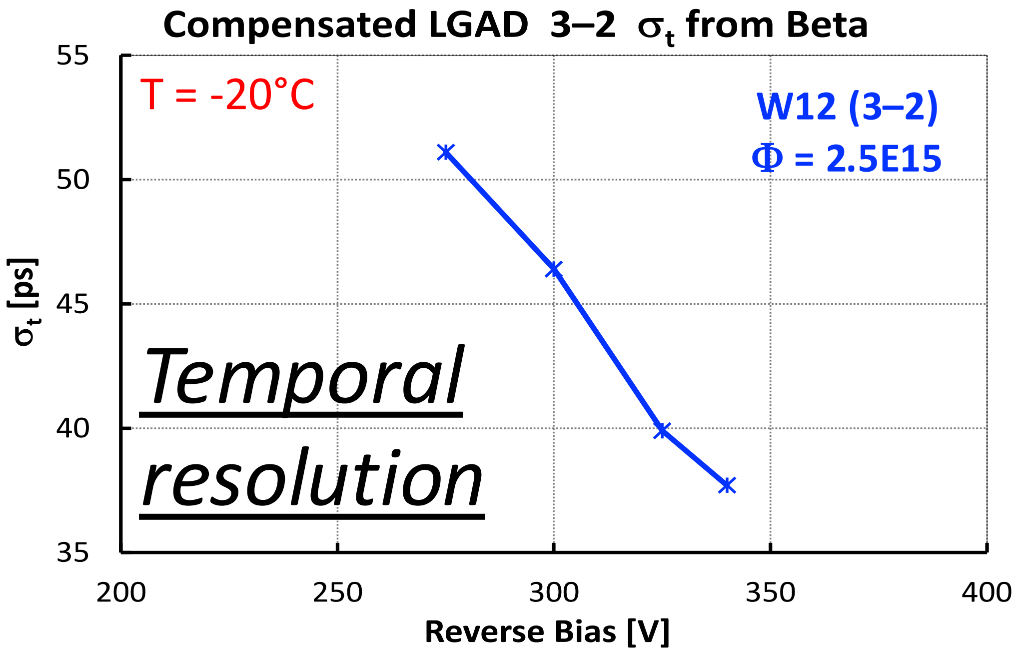
Characteristics of signals in compensated LGAD:

- Time duration ~ 2 ns
- Rise time < 1 ns

Signal from compensated-LGAD has the main characteristics of signal from standard LGAD

β particles on compensated LGAD- gain and temporal resolution





Good internal gain provide by compensated LGAD irradiated at 2.5E15 n_{eq}/cm^2

Good temporal performance of compensated LGAD irradiated at 2.5E15 n_{eq}/cm^2

→ Proof of concept of the operational capabilities of compensated LGADs

Conclusion

- **CompleX is an ERC project of 5 years with the purpose to develop a new generation of planar silicon sensors with internal gain, for 4D-tracking, to operate in extreme fluence environment**

- **3 of compensated-LGAD were planned in 5 years and they will be supported by a p-in-n LGAD batch with the purpose to study the donor removal**

- **CompleX objectives:**
  - Extend and develop a **radiation damage model** able to describe silicon behaviour, under irradiation up to $5{\cdot}10^{17}$ n_{eq}/cm^2
  - **Design LGAD silicon sensors that provide a charge of ~ 5 fC per particle hit up to fluences of $5{\cdot}10^{17}$ n_{eq}/cm^2**
  - **Define a production process to build cost-effective radiation-tolerant detectors through the p–n dopant compensation**

- **The proof of concept of compensated LGAD (EXFLU1 batch) has been released in 2022**
  - Preliminary measurements of collected charge (gain) and temporal resolution show that compensation technology for the building of a gain implant is promising

Acknowledgment

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- INFN CSN5
- RD50 and DRD3, CERN
- AIDAinnova, WP13

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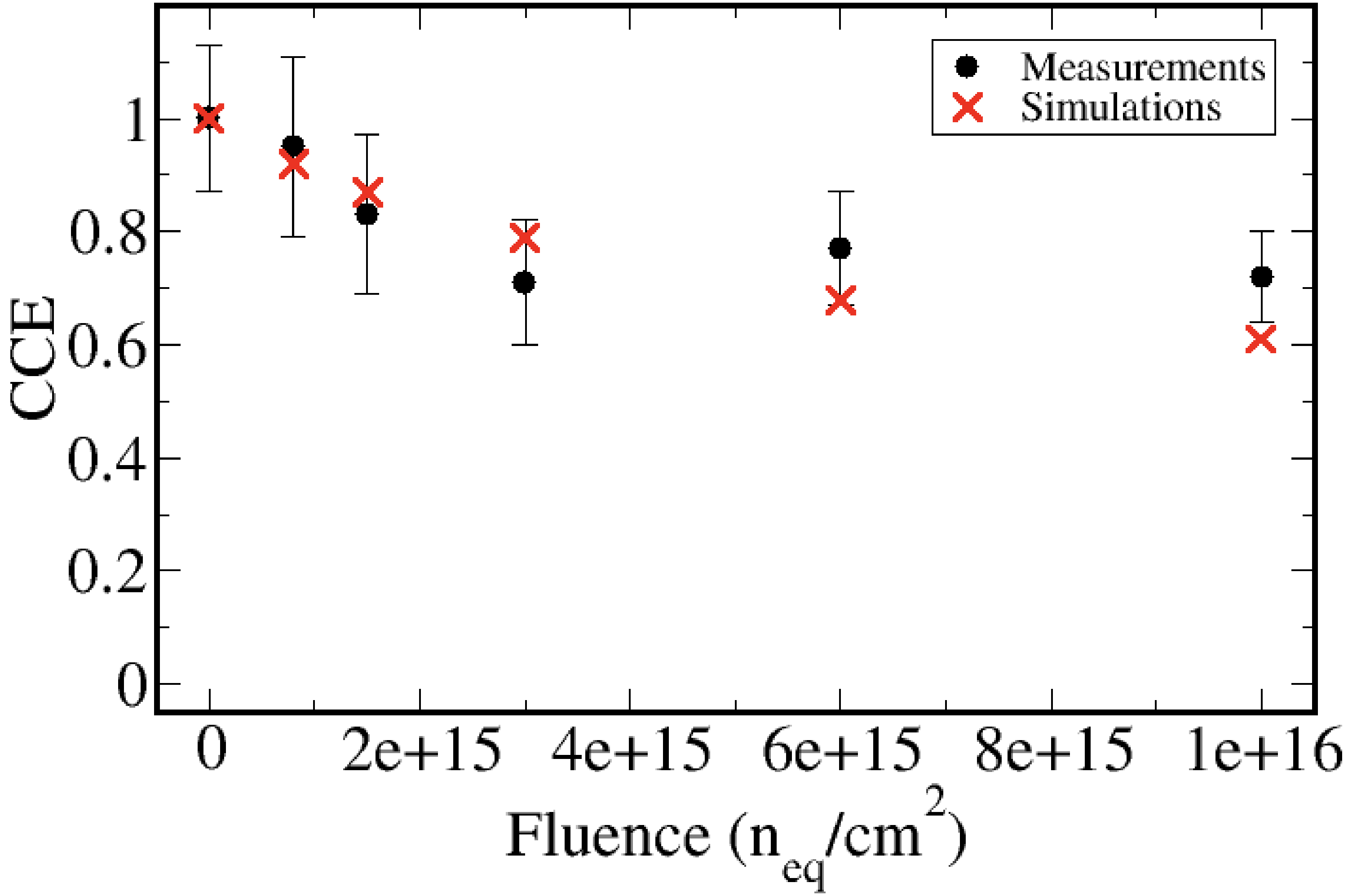
Co-funded by the European Union – Next Generation EU, Mission 4 Component 1 CUP D53D23002870001 (ComonSens)

This project is funded by the European Union (ERC 101124288 – CompeX) Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them.

Backup

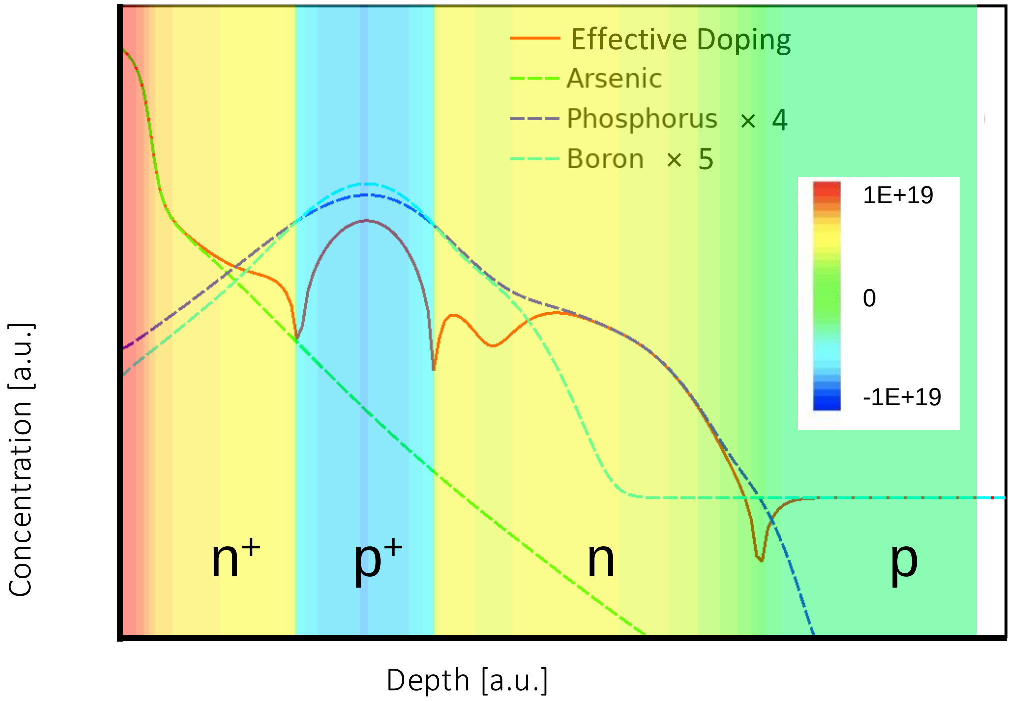
Planar silicon sensors CCE up to $1 \cdot 10^{16}$ n_{eq}/cm^2

[doi: 10.22323/1.373.0050]

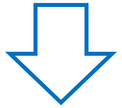


Compensated LGAD - Simulations

Gain Layer profile – process simulation

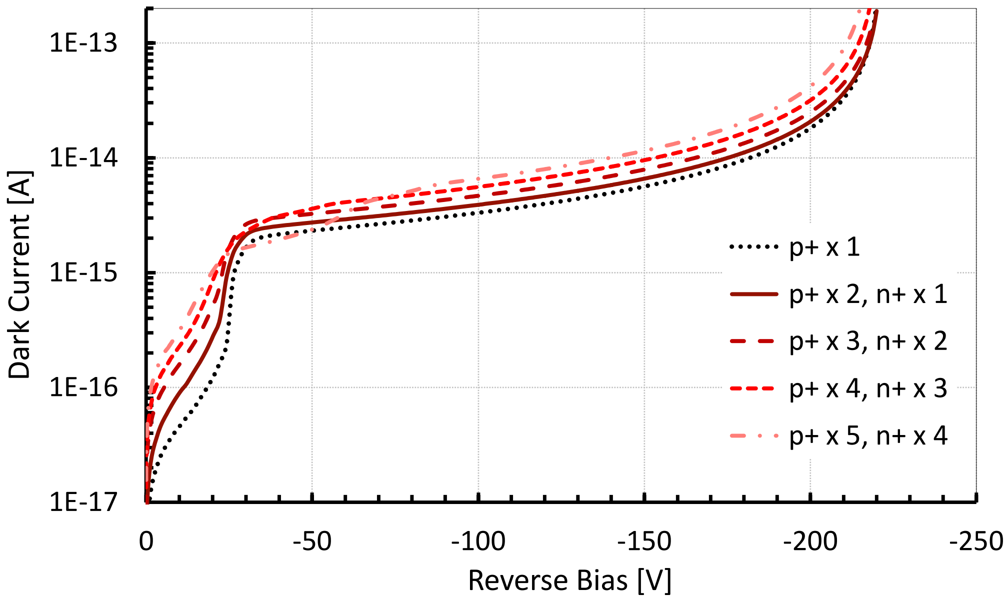


Different diffusion of p⁺ and n⁺ implant



Alternating of p and n doped regions

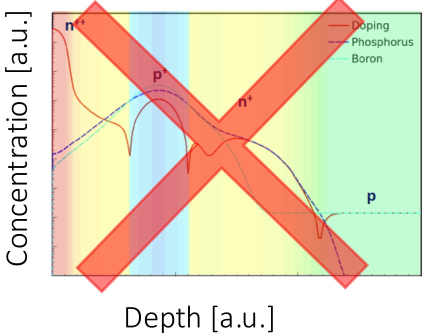
Current – Voltage simulation (TCAD)



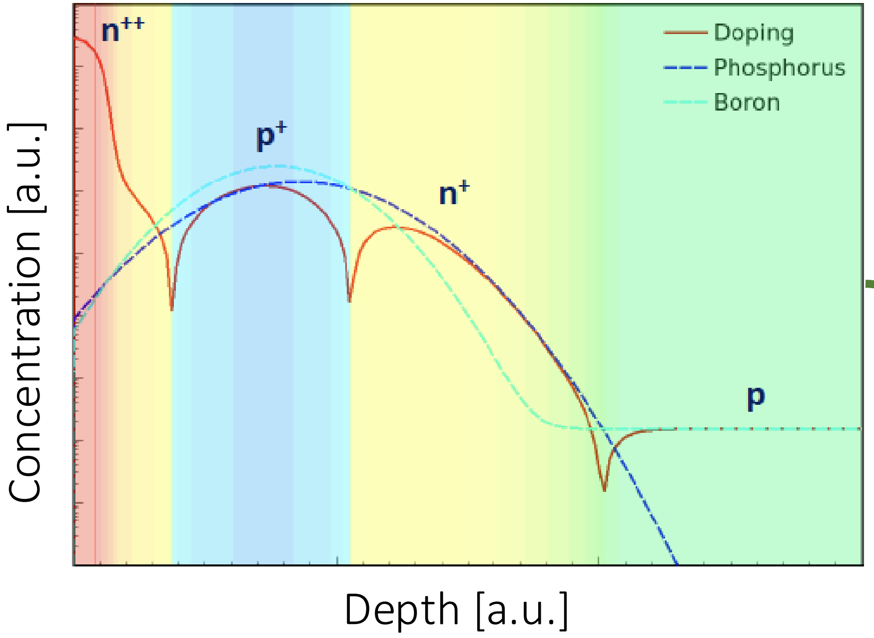
Design and preparatory studies have been performed in collaboration with the **Perugia group**

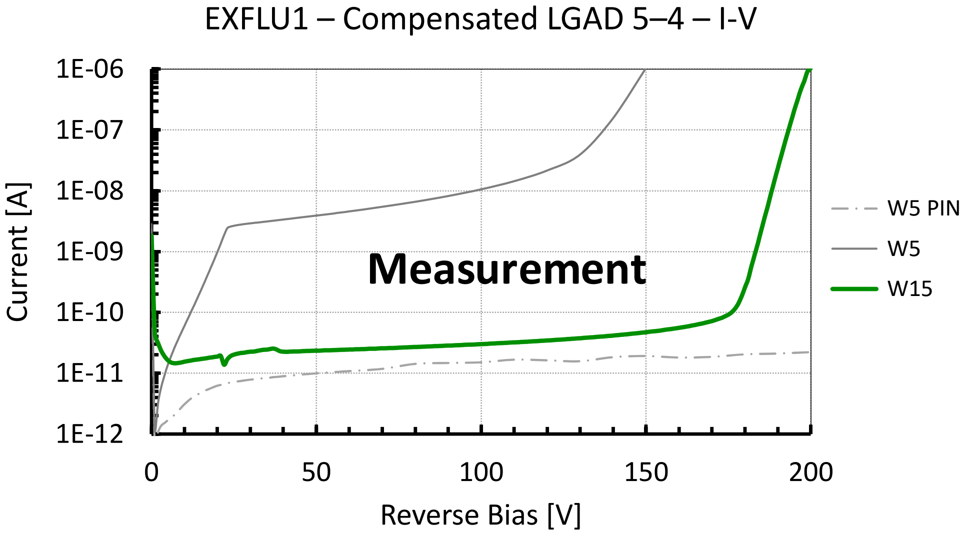
IV simulation from SIMS p^+ - n^+ profile

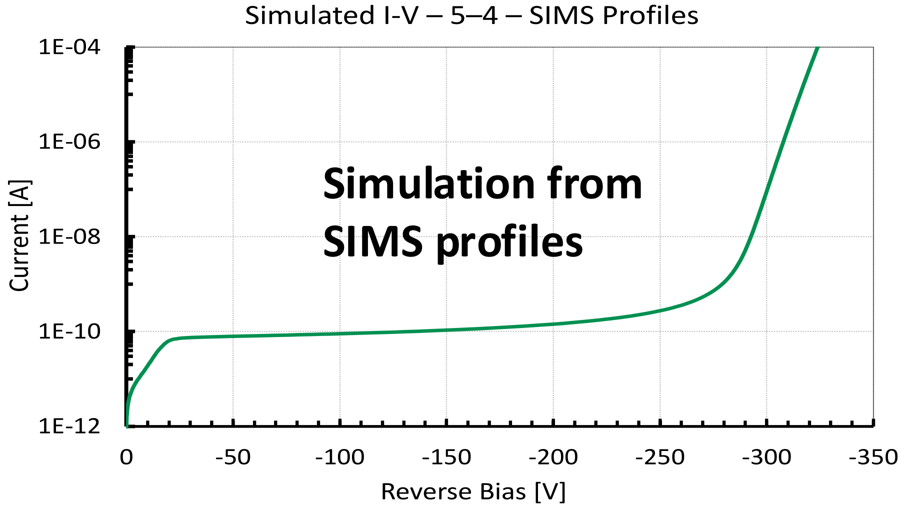
Doping Profiles
from Process Simulation



Doping Profiles from SIMS (W15)







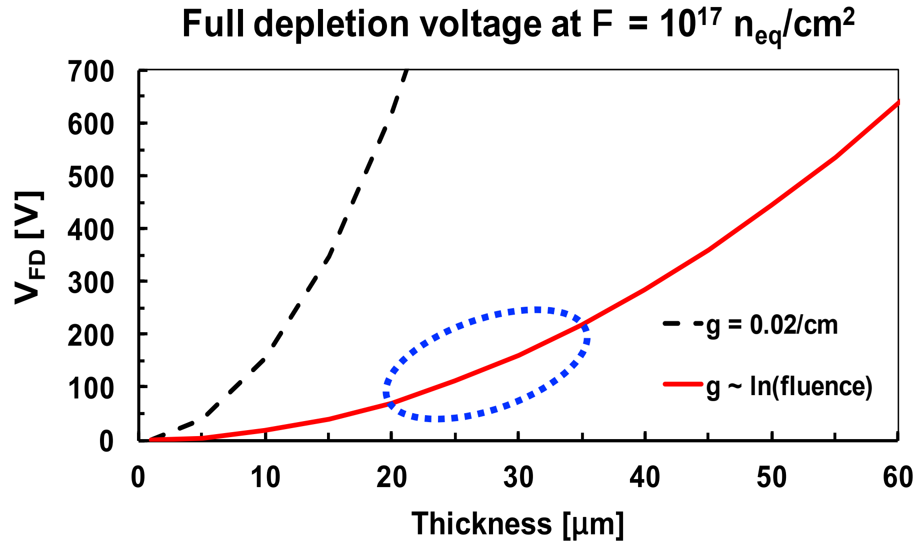
The simulated I-V using p^+ and n^+ implants extracted from SIMS reproduces the trend of the measured I-V

The advantages of this sensors

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

Saturation **Reduce thickness**

Thanks to saturation effects, thin sensors can still be depleted and operated at $V_{bias} \leq 500$ V



What does it happen to a 20 µm sensor after a fluence of $5 \cdot 10^{16}$ n_{eq}/cm^2?

- ▻ It can still be depleted
- ▻ Trapping is almost absent
- ▻ Dark current is low (small volume)

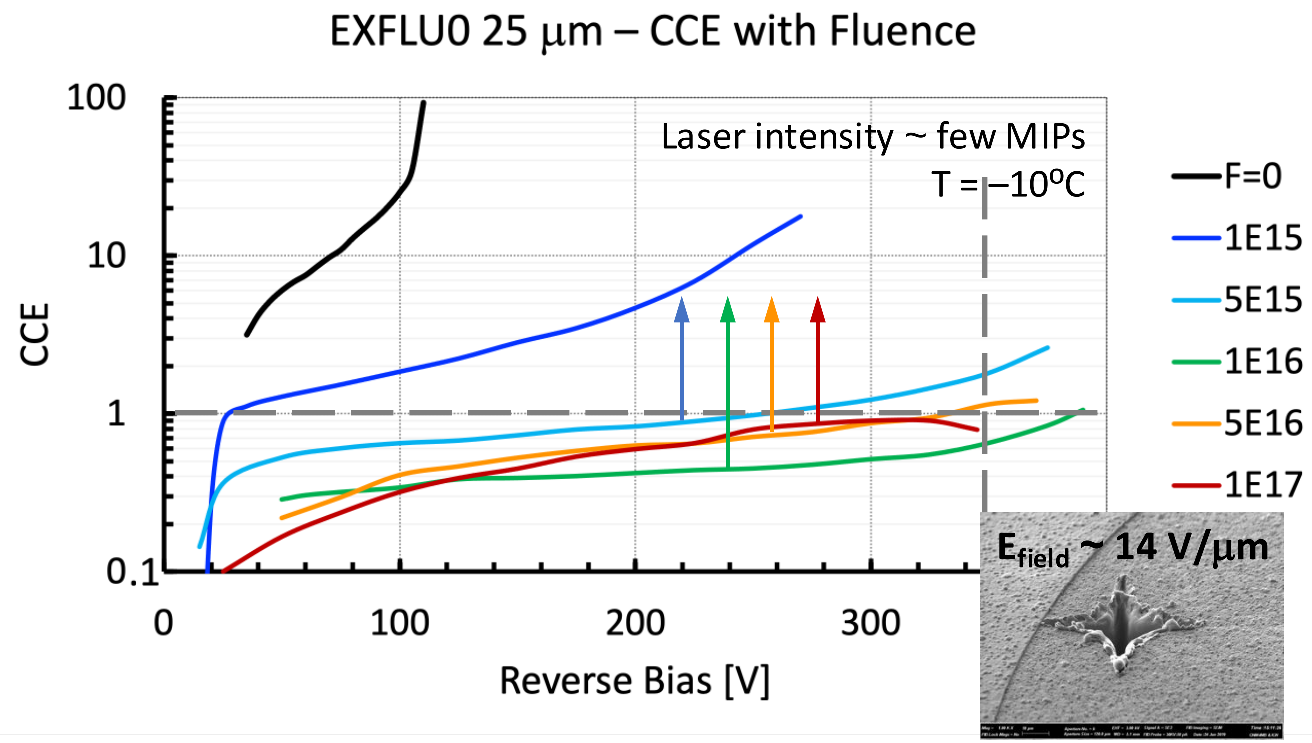
However: charge deposited by a MIP ~ 0.2 fC

→ This charge is lower than the minimum charge requested by the electronics (~ 1 fC)

→ Need a gain of at least ~ 5 in order to provide enough charge

25 µm thin LGADs

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 14 V/µm, 25 µm thick silicon sensors undergo fatal death once exposed to particle beams (SEB)

→ Necessary to increase the radiation tolerance of the gain mechanism for 5E15 n_{eq}/cm^2 and above

Single Event Burnout

Once operated at high electric field, thin sensors fatally break if exposed to particle beams

The effect is called Single Event Burnout (SEB) and apply both to LGAD and PIN sensors

Death Mechanism:

- ▻ Rare, large ionization event – Highly Ionising Particle
- ▻ Excess charge leads to highly localized conductive path
- ▻ Collapse of the depleted active thickness
- ▻ Large current flows in a narrow path – Single Event Burnout

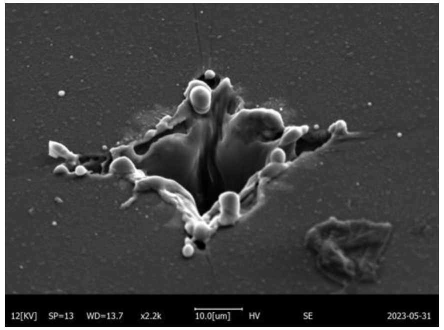
SEB consequence:

→ Impossible to operate irradiated thin sensors above the critical electric field (E_{SEB})

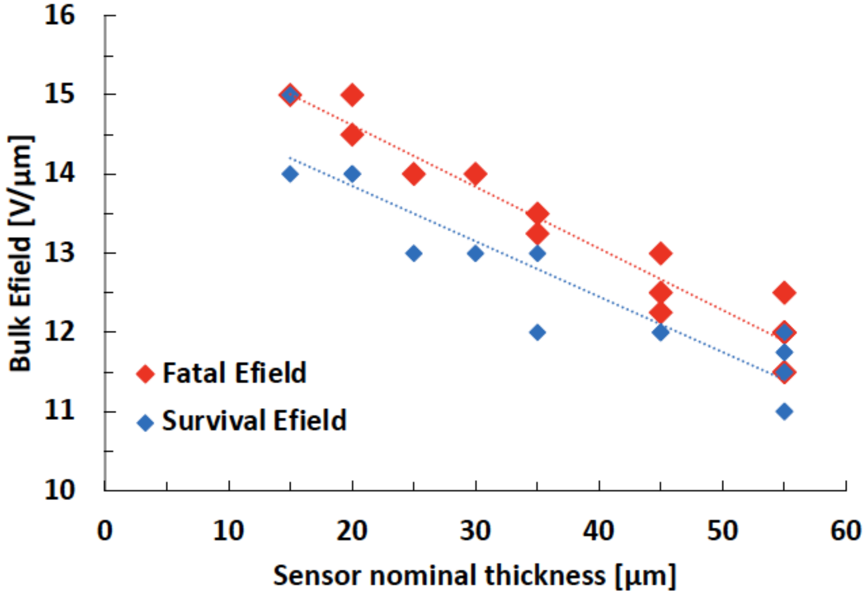
→ The E_{SEB} value is higher for thinner sensors

[M. Ferrero et al., indico.cern.ch/event/1334364/contributions/5672087]

Localized melt and vaporization of silicon



SEM picture [SSP group,UniTO]

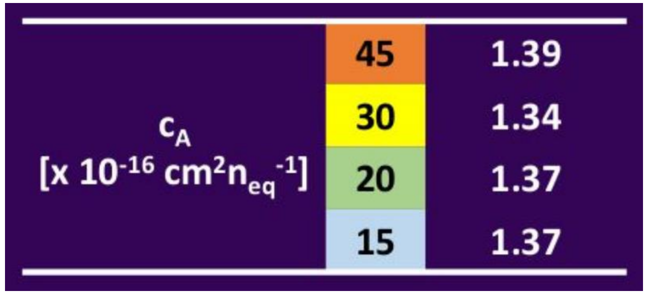


LGAD state of art in term of radiation resistance

Thin sensors from the EXFLU1 batch of FBK are the **sensors most resilient to radiation** ever produced by the FBK foundry

The technology exploits defect engineering through carbon co-implantation in the gain implant region

→ After a fluence of $2.5 \cdot 10^{15}$ n_{eq}/cm^2, all sensors maintain a gain of about 10 up to the SEB limit



c_A [x 10^{-16} $cm^2 n_{eq}^{-1}$]	45	1.39
	30	1.34
	20	1.37
	15	1.37

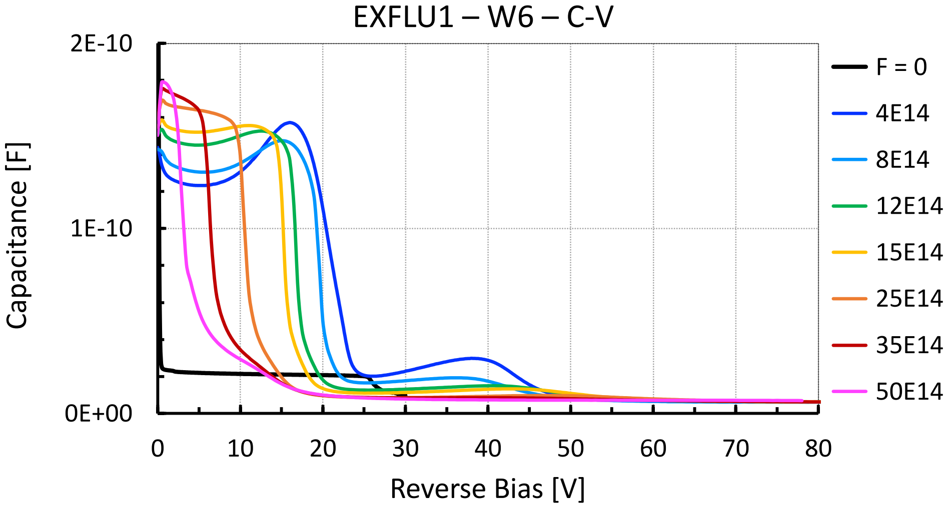
CV from irradiated Compensated LGAD

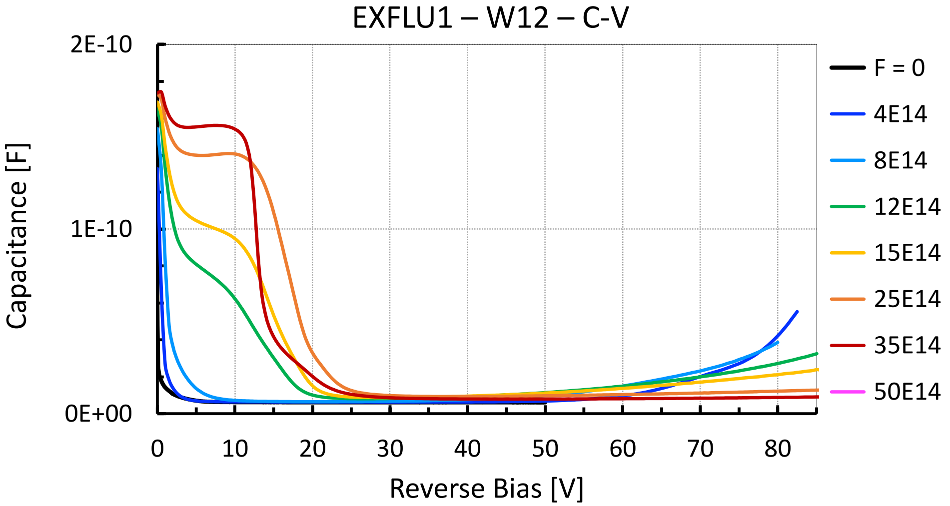
[Φ] = n_{eq}/cm^2

T = + 20ºC

f = 2k Hz

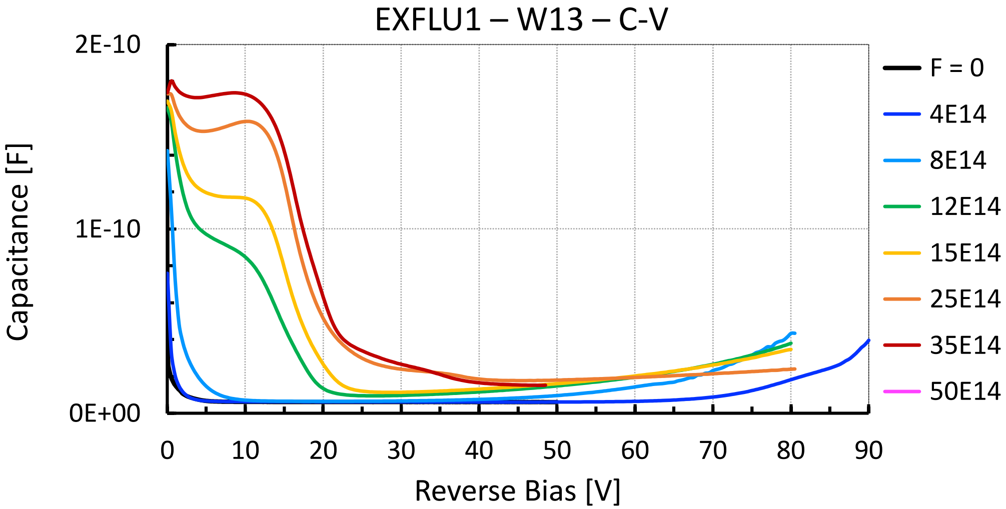
W6
2 – 1

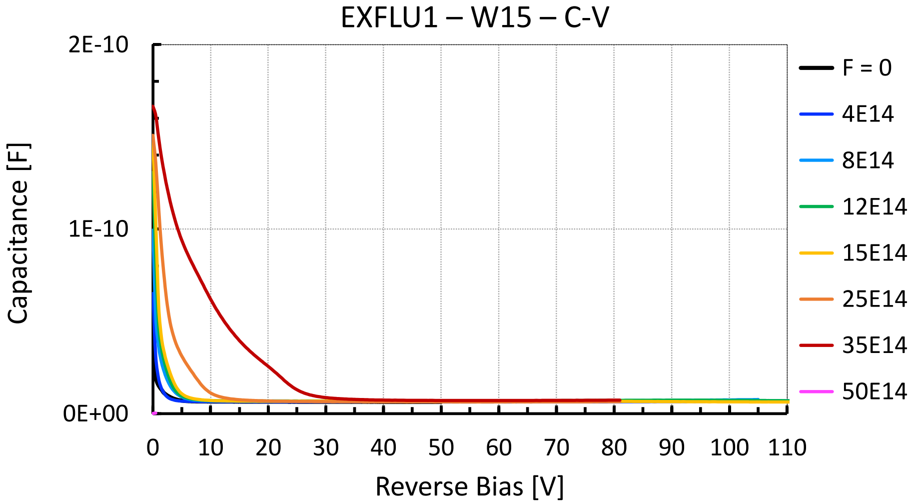

EXFLU1 – W6 – C-V


EXFLU1 – W12 – C-V

W12
3 – 2

W13
3 – 2 + C


EXFLU1 – W13 – C-V

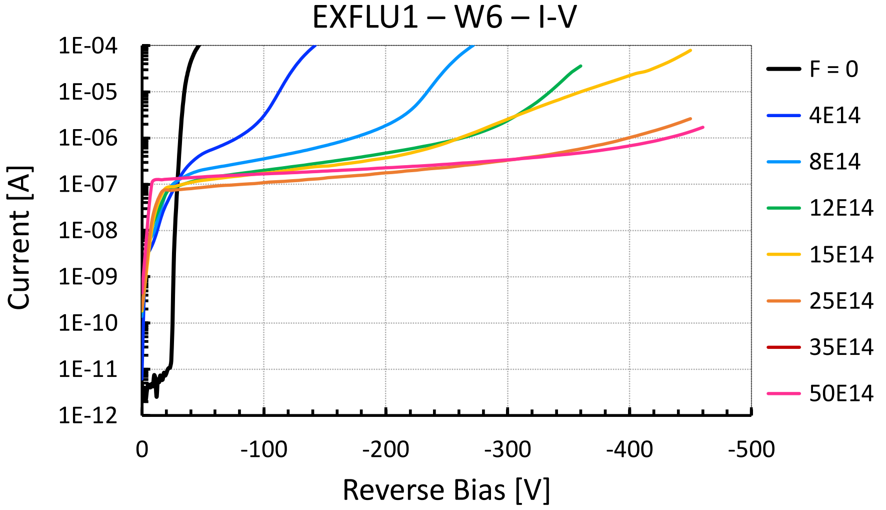

EXFLU1 – W15 – C-V

W15
5 – 4

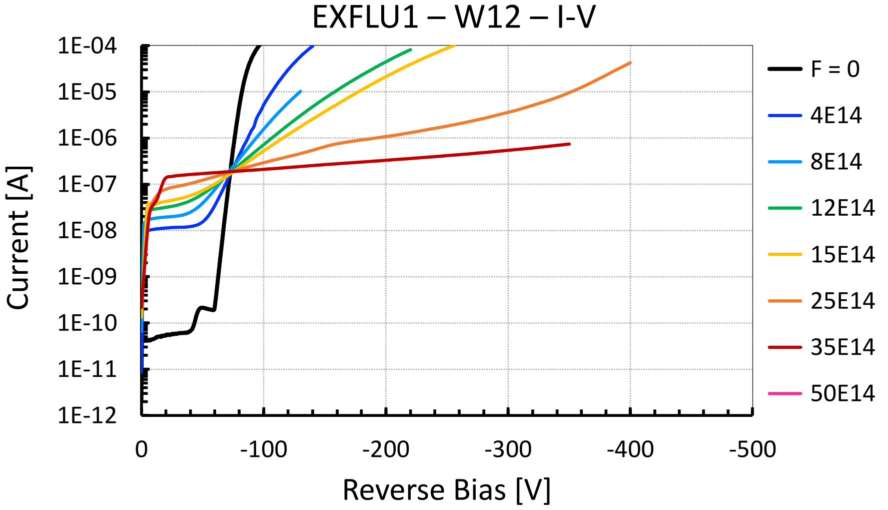
IV from irradiated Compensated LGAD

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

W6
2 – 1



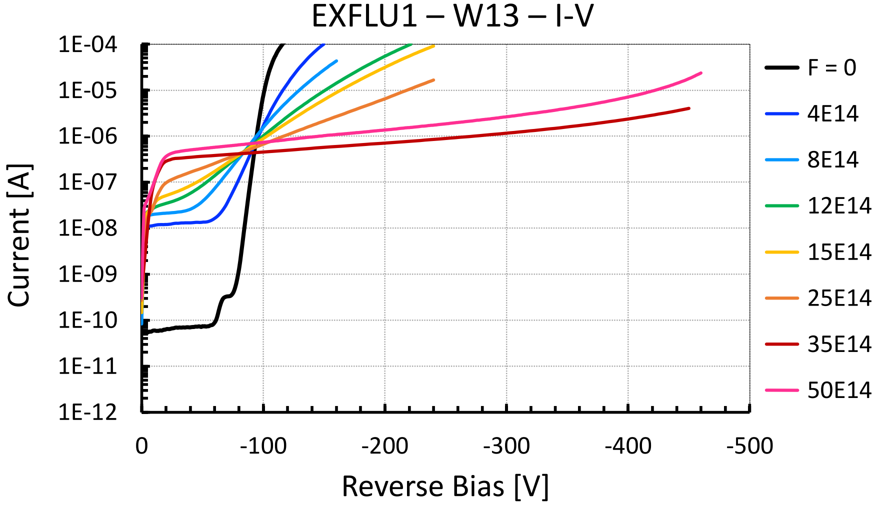
EXFLU1 – W6 – I-V



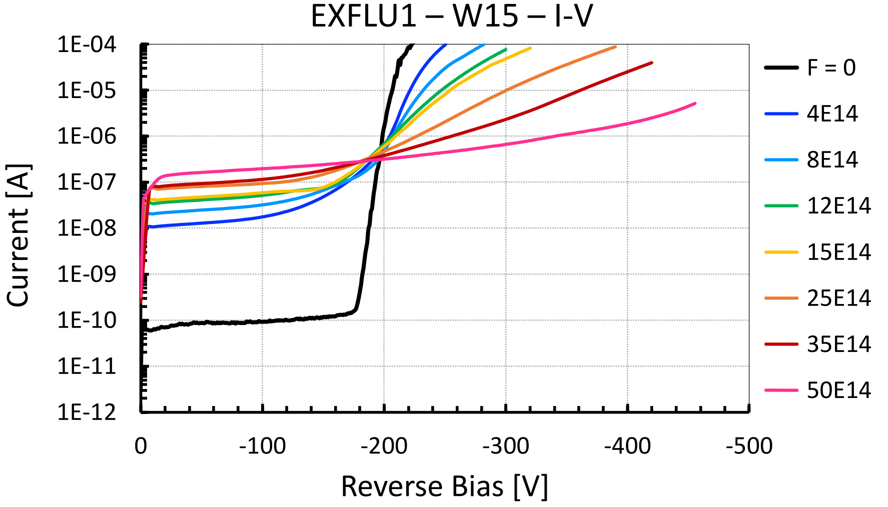
EXFLU1 – W12 – I-V

W12
3 – 2

W13
3 – 2 + C



EXFLU1 – W13 – I-V



EXFLU1 – W15 – I-V

W15
5 – 4

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

$T_{F=0} = +\ 20^oC$

$T_{IRR} = -\ 20^oC$

TCT setup

TCT Setup from Particulars

Pico-second IR laser at 1064 nm

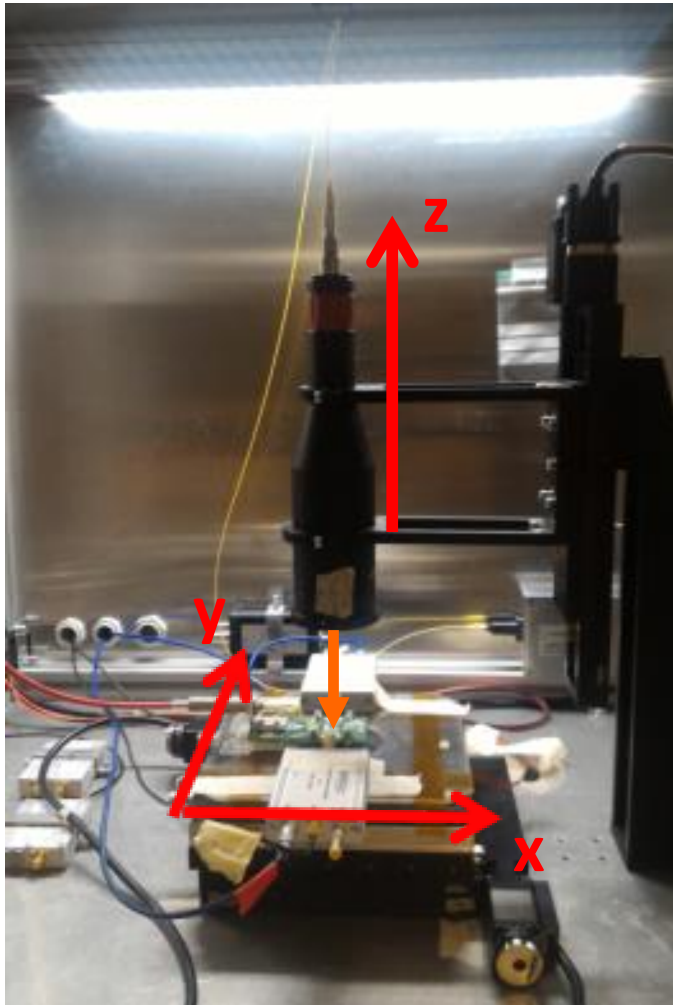
Laser spot diameter ~ 10 µm

Cividec Broadband Amplifier (40dB)

Oscilloscope LeCroy 640Zi

Laser intensity ~ 4 MIPs

T = -10°C



β setup

β Setup

Oscilloscope: LeCroy 9254M (2.5GHz - 40Gs/s)

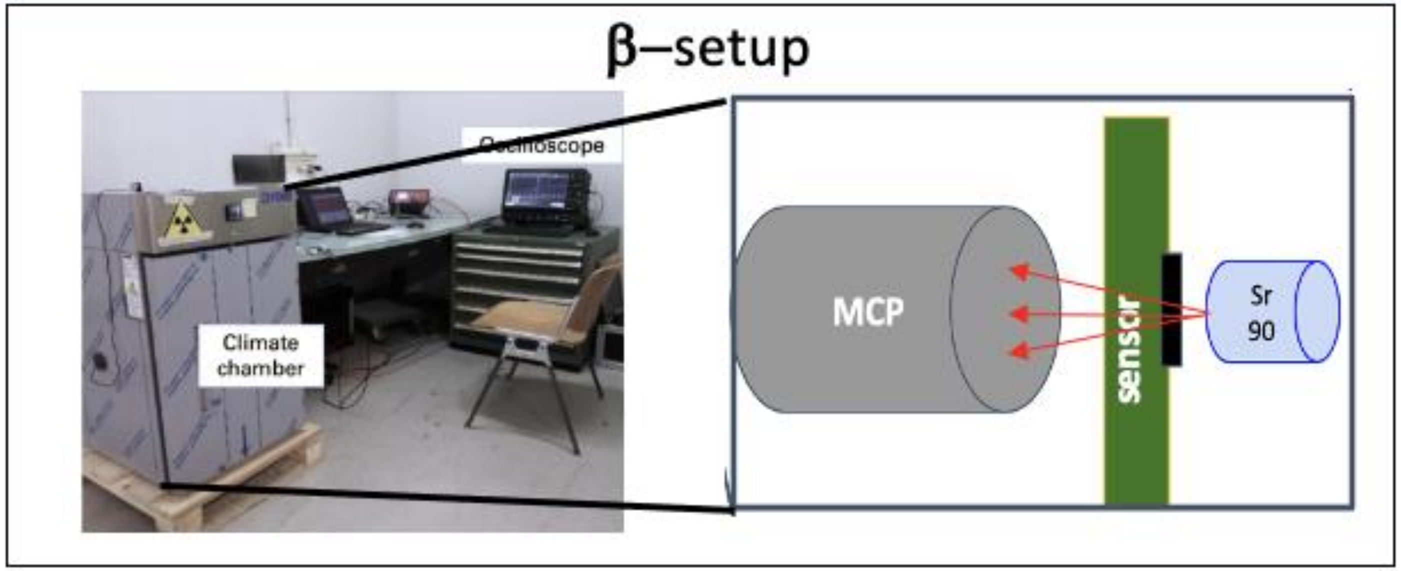
HV Power supply: CAEN DT1471ET

UCSC Board + Cividec Broadband Amplifier (20dB)

Time reference: Photonis MCP-PMT – $\sigma_t \sim 15$ ps

β source: Sr90 – activity ~ 37 kBq

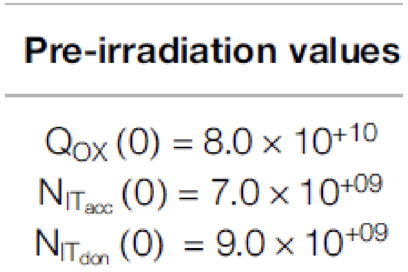
T = -25°C



Simulation setup

Physical models

- ✓ **Standard drift-diffusion model**
  - => Fermi-Dirac statistics
- ✓ **Generation/Recombination rate**
  - => Shockley-Read-Hall (SRH)
  - => Band-To-Band Tunneling (BTBT)
  - => Auger
  - => Massey impact ionization model
- ✓ **Carriers mobility variation**
  - => doping and field dependent
- ✓ **Bandgap narrowing model**
  - => OldSlotboom
- ✓ **Physical parameters**
  - => s_0 = 0 cm/s (surface recomb. velocity)
  - => $\tau_n = \tau_p$ = 1E-3 s (e-/h+ recomb. lifetime)



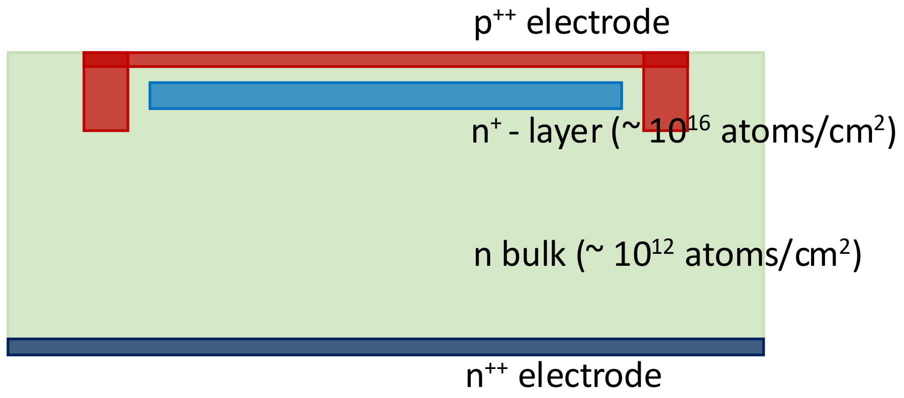
Pre-irradiation values

$Q_{OX}(0) = 8.0 \times 10^{+10}$

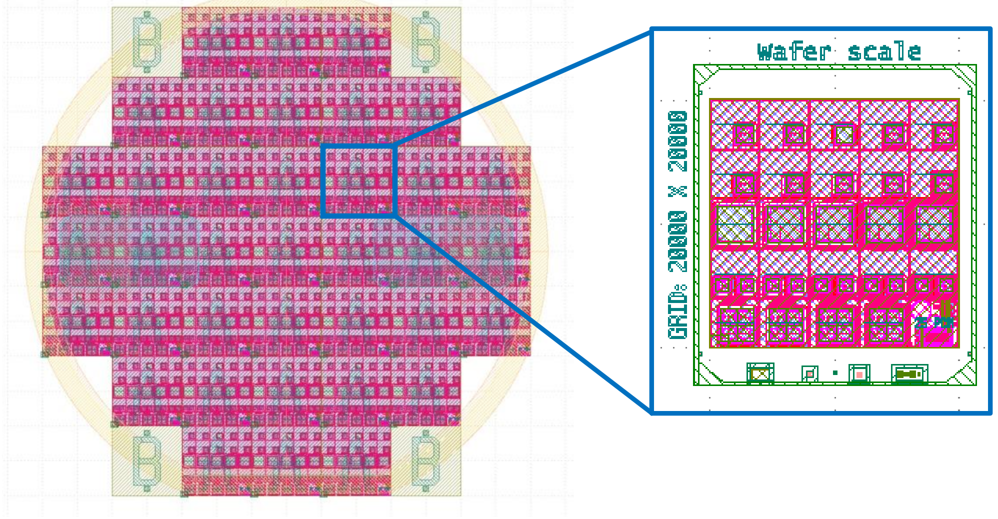
$N_{IT_{acc}}(0) = 7.0 \times 10^{+09}$

$N_{IT_{don}}(0) = 9.0 \times 10^{+09}$

Towards compensated LGAD – Donor removal investigation



Wafer layout of the p-in-n LGAD batch



The study of donor removal will be conducted on a p-in-n LGAD batch

- Donor removal has been studied for doping densities of $10^{12} – 10^{14}$ atoms/cm^3
- **We will study donor removal for concentrations of ~ $10^{15} – 10^{17}$ atoms/cm^3**
- The production of the p-in-n LGAD batch is planned to start by the end of 2024