16TH PISA MEETING ON ADVANCED DETECTORS La Biodola, Isola d'Elba, May 26-June 1, 2024

BANDO PRIN 2022

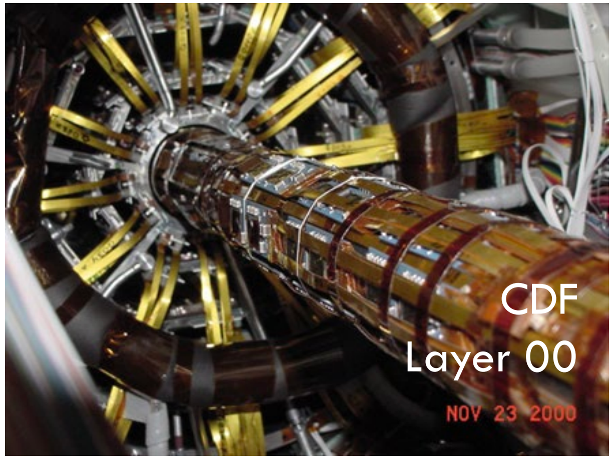
Thin silicon sensors for extreme fluences: a doping compensation strategy

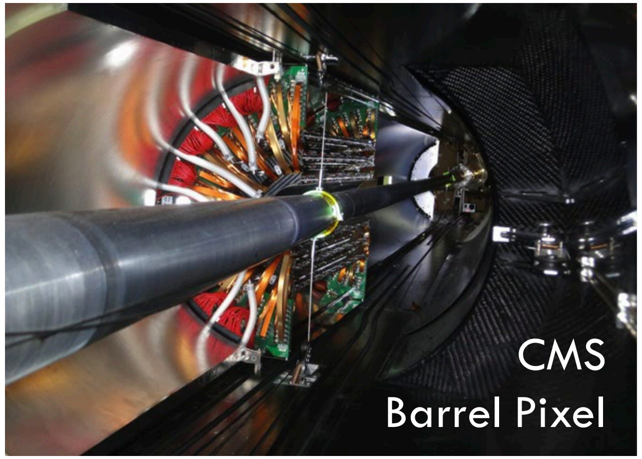
A. Morozzi, INFN Perugia

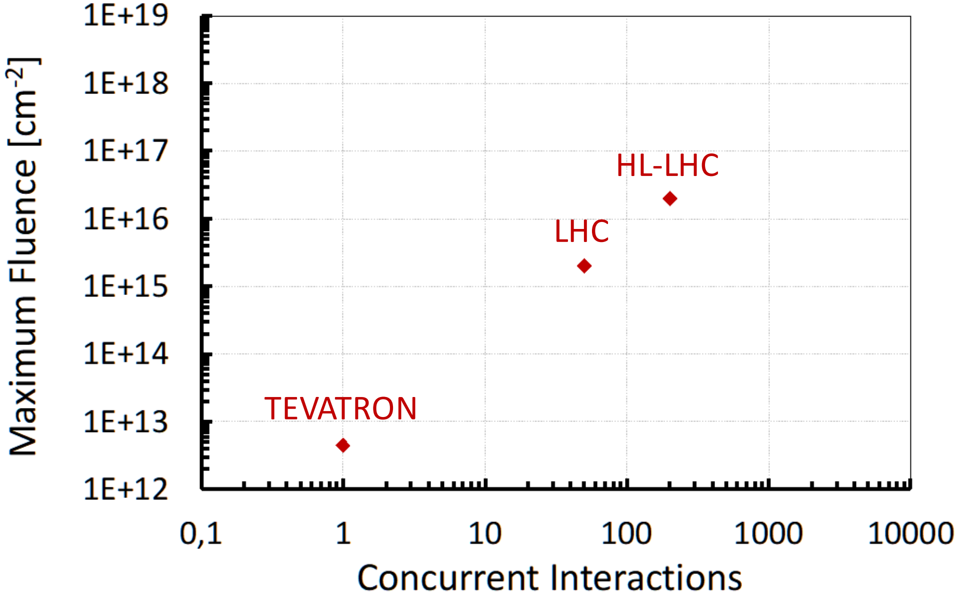
V. Sola, G. Paternoster, L. Anderlini, R. Arcidiacono, M. Barozzi, G. Borghi, M. Boscardin, N. Cartiglia,
M. Centis Vignali, M. Costa, T. Croci, M. Ferrero, F. Ficorella, A. Fondacci, S. Giordanengo, O. Hammad Ali,
C. Hanna, L. Lanteri, L. Menzio, F. Moscatelli, D. Passeri, N. Pastrone, F. Siviero, R.S. White

The Extreme Fluence Challenge

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







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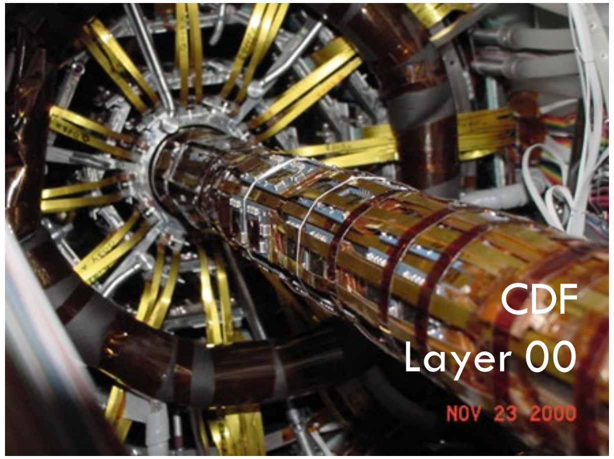

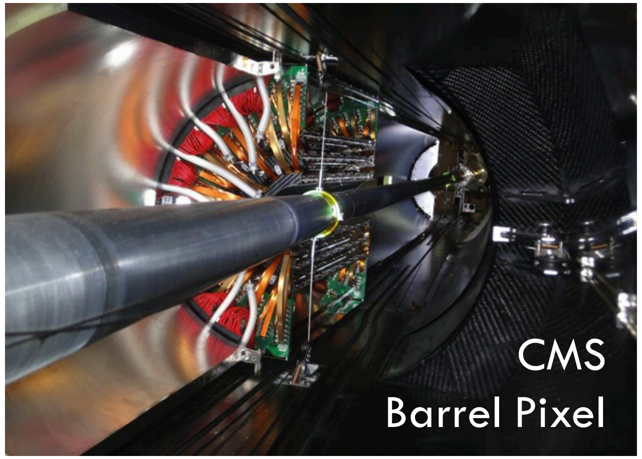

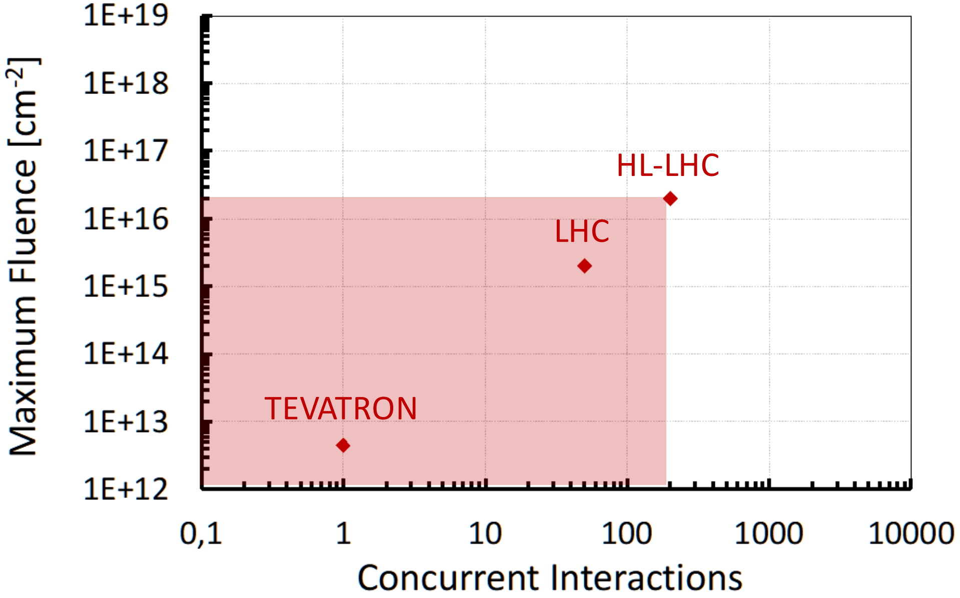

Present silicon frontier

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

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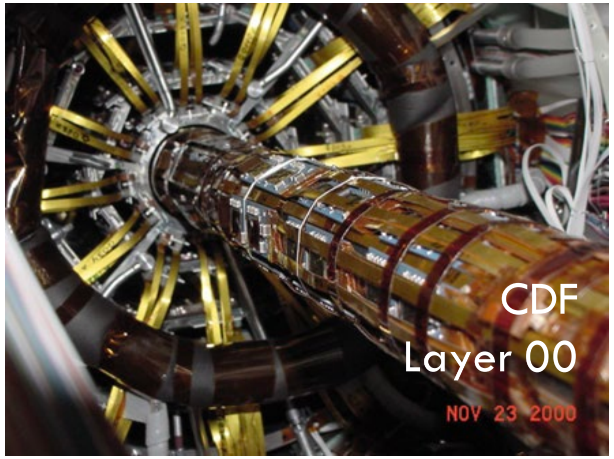

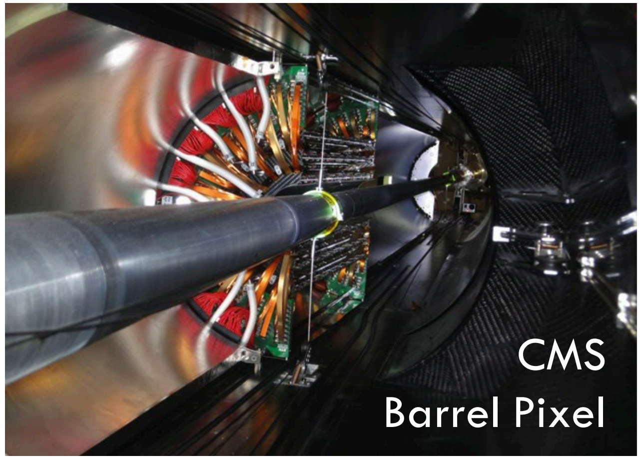

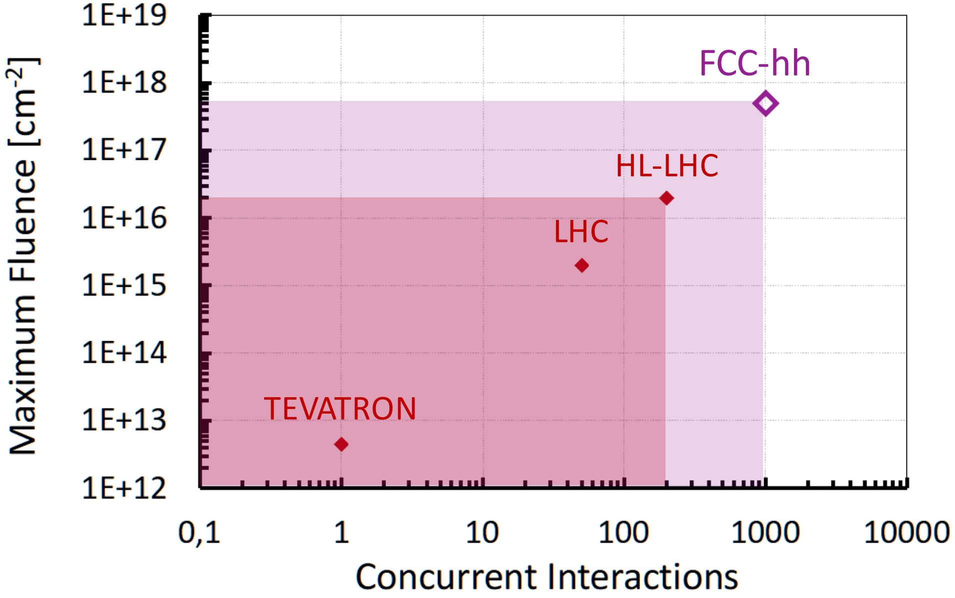

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- ▻ Precise timing down to ~ 30 ps → 5 fC up to $3 \cdot 10^{15}/\text{cm}^2$

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

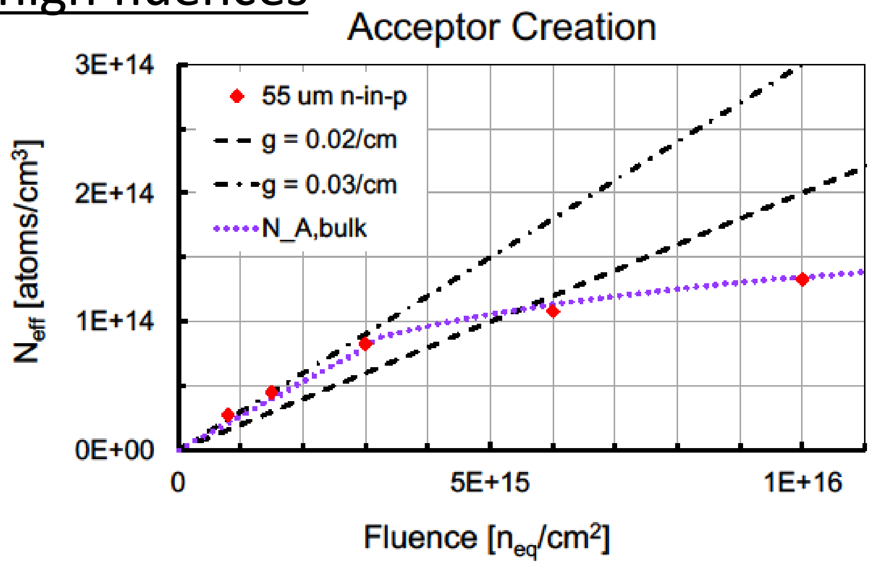
Silicon modeling at Very High Fluences

Models of the radiation damage in silicon are validated till about 10^{16}/cm^2

A mismatch between data and the predictions arises at very high fluences

- ➢ Dark current increase is smaller than expected
- ➢ Charge collection efficiency is higher than predicted
- ➢ Increase of the acceptor states slows

→ **Hints of saturation of the radiation damage effects**



Accurate modeling of silicon damage and sensor behavior at very high fluences is necessary to design the next generation of silicon detectors

TCAD simulation of LGAD devices

✓ **Physical models**

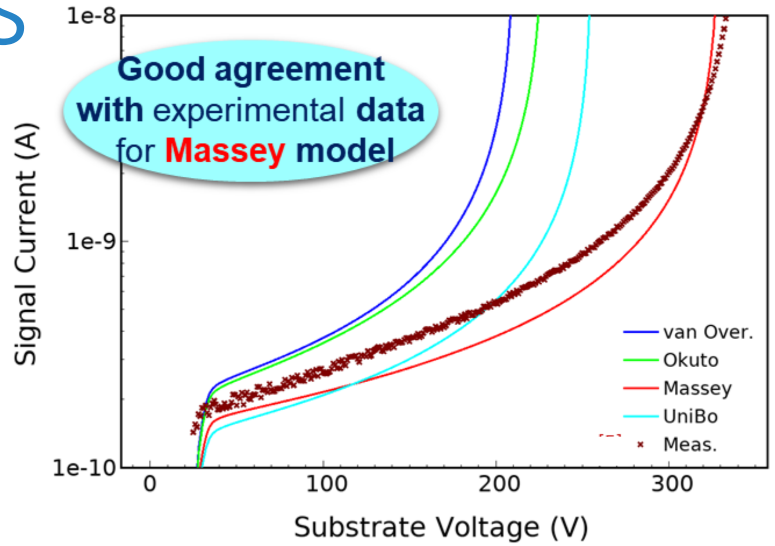
- **Generation/Recombination rate**
  - Shockley-Read-Hall, Band-To-Band Tunneling, Auger
  - **Avalanche Generation => impact ionization models,** *van Overstraeten-de Man, Okuto-Crowell, Massey*[1]*, UniBo*
- **Fermi-Dirac statistics**
- **Carriers mobility variation** doping and field-dependent
- **Physical parameters**
  - e-/h+ recombination lifetime

✓ **Radiation damage models: "PerugiaModDoping"**

- **"New University of Perugia model"**
  - **Combined surface and bulk** TCAD damage modeling scheme
  - Traps generation mechanism
- **Acceptor removal mechanism** => $N_{GL}(\phi) = N_A(0)e^{-c\phi}$
  - where
    - **Gain Layer (GL)**, **c** removal rate (**Torino parameterization**)
- **Acceptor creation**

$$N_{A,bulk} = \begin{cases} N_{A,bulk}(0) + g_c\phi, & 0 < \phi < 3E15\ n_{eq}/cm^2 \\ 4.17E13 \cdot \ln(\phi) - 1.41E15, & \phi > 3E15\ n_{eq}/cm^2 \end{cases}$$

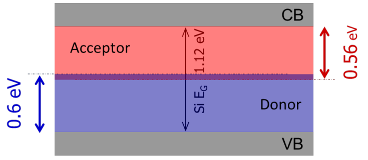
where g_c = 0.0237 cm^{-1} (**Torino acceptor creation**)



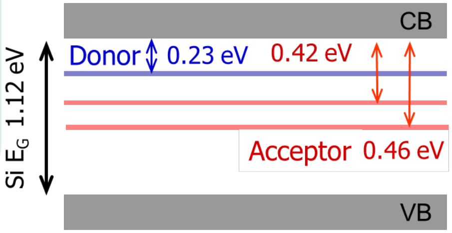
Good agreement with experimental data for Massey model

Surface damage (+ Q_{OX})

Type	Energy (eV)	Band width (eV)	Conc. (cm^{-2})
Acceptor	$E_C \leq E_T \leq E_C$-0.56	0.56	$D_{IT} = D_{IT}(\Phi)$
Donor	$E_V \leq E_T \leq E_V$+0.6	0.60	$D_{IT} = D_{IT}(\Phi)$



Bulk damage



Type	Energy (eV)	η (cm^{-1})	σ_n (cm^2)	σ_h (cm^2)
Donor	E_C - 0.23	0.006	2.3×10^{-14}	2.3×10^{-15}
Acceptor	E_C - 0.42	1.6	1×10^{-15}	1×10^{-14}
Acceptor	E_C - 0.46	0.9	7×10^{-14}	7×10^{-13}

M. Mandurrino et al., https://doi.org/ 10.1109/NSSMIC.2017.8532702. M. Ferrero et al., https://doi.org/ 10.1016/j.nima.2018.11.121.
D. Passeri, AIDA2020 report, CERN Document Server. V. Sola et al., https://doi.org/10.1016/j.nima.2018.07.060.

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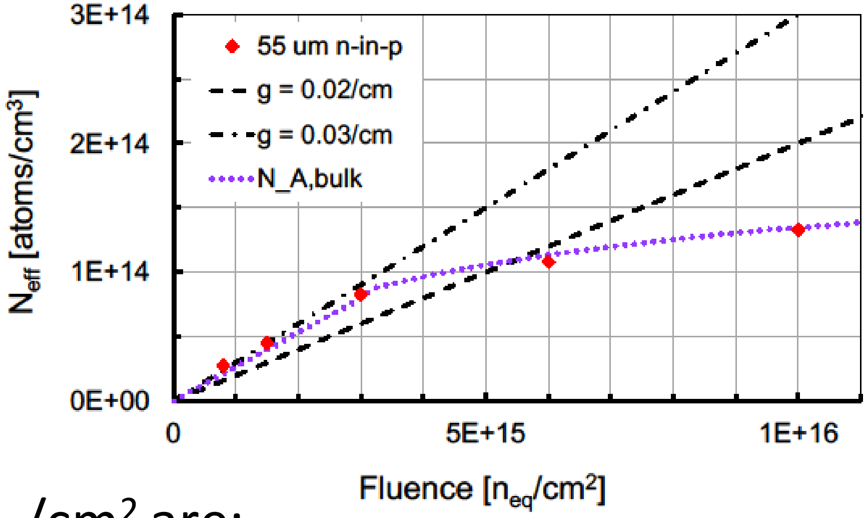
→ **Hints of saturation of the radiation damage effects**

Acceptor Creation

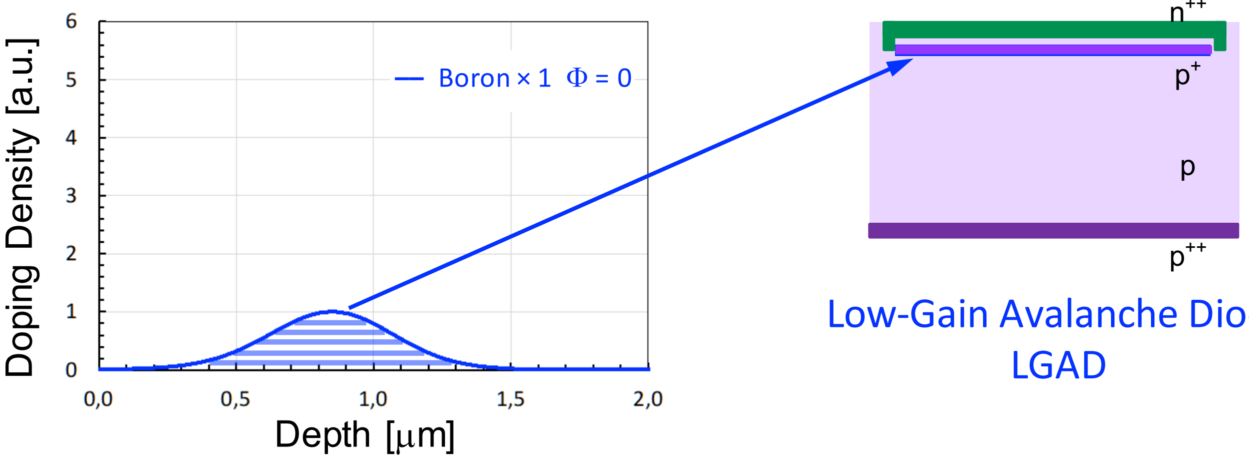


The ingredients to overcome the present limits above 10^{16} n_{eq}/cm^2 are:

- ❖ 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 → **Compensated LGADs**

Planar Silicon Sensors for eXtreme Fluences

Doping Profile – Standard LGAD



Low-Gain Avalanche Diode
LGAD

Planar Silicon Sensors for eXtreme Fluences

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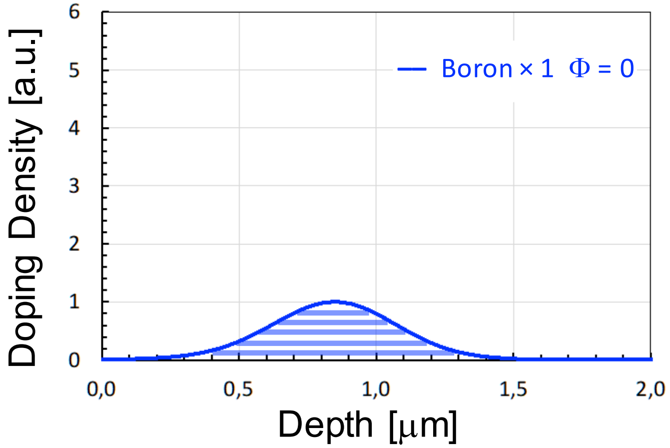
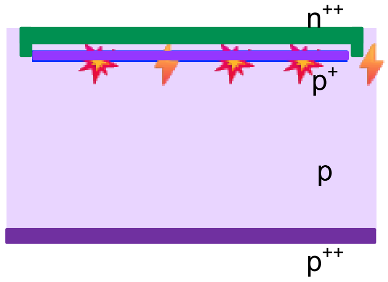
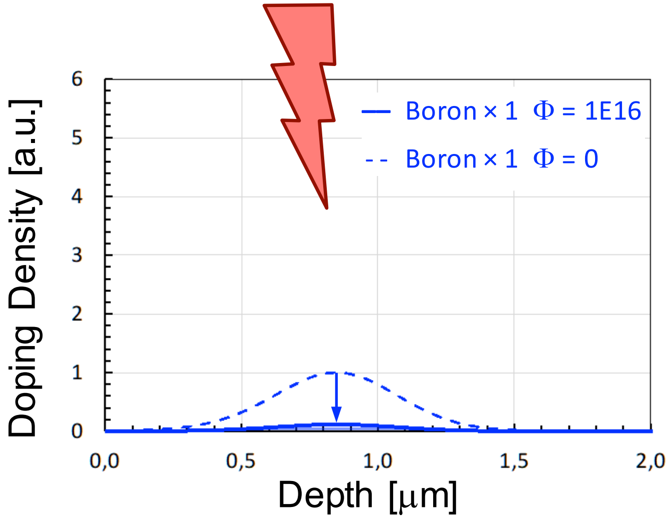




Low-Gain Avalanche Diode
LGAD

Irradiation
$\Phi = 1\times10^{16}/\text{cm}^2$



Compensated LGADs for eXtreme Fluences

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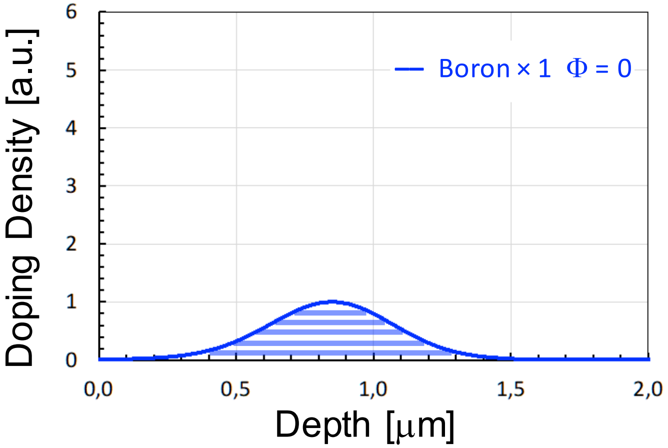


Credit: oppnest.com

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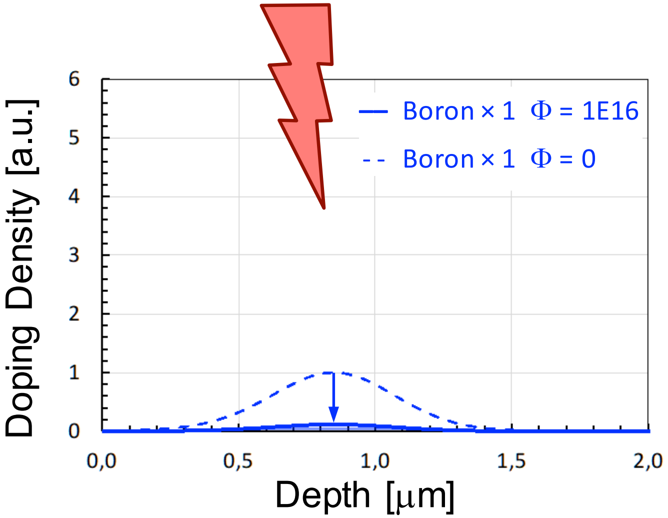

Compensated LGADs for eXtreme Fluences

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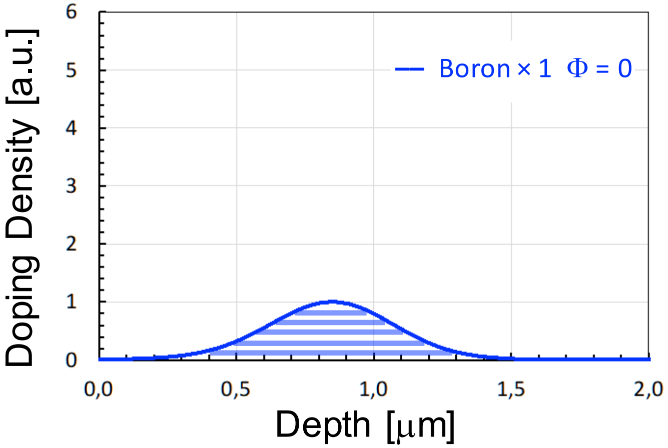
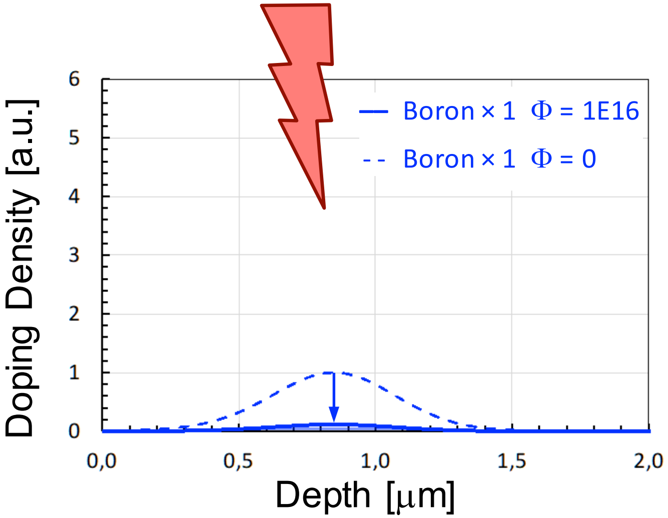


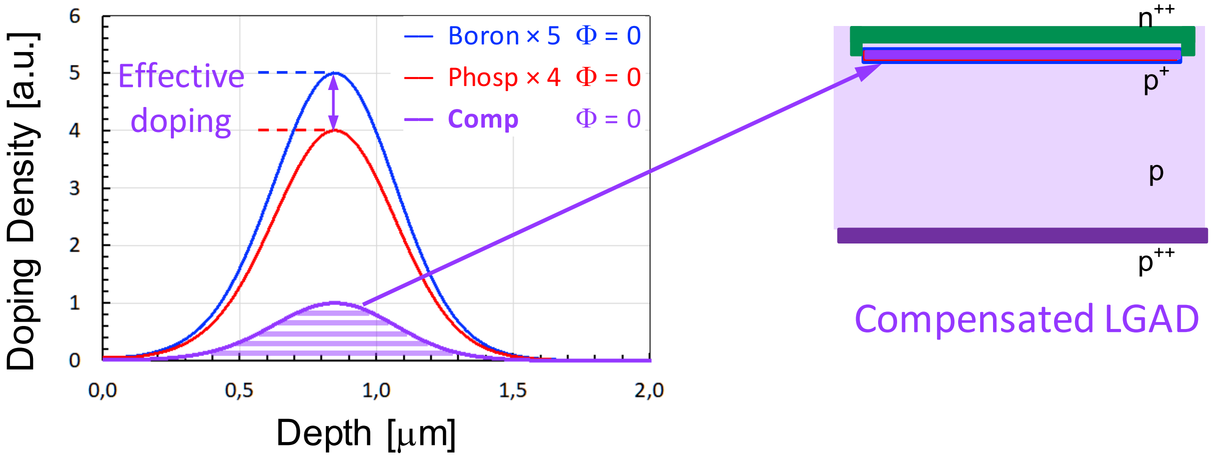

Credit: oppnest.com

Irradiation

Φ = 1×10^{16}/cm^{2}

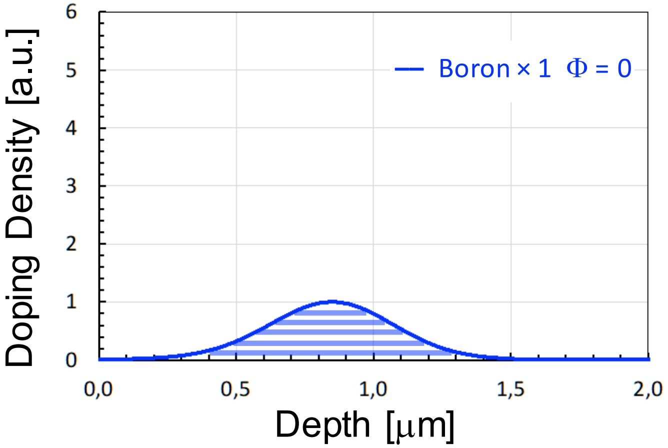


Doping Profile – Compensated LGAD



Compensated LGADs for eXtreme Fluences

Doping Profile – Standard LGAD




Credit: oppnest.com

Irradiation

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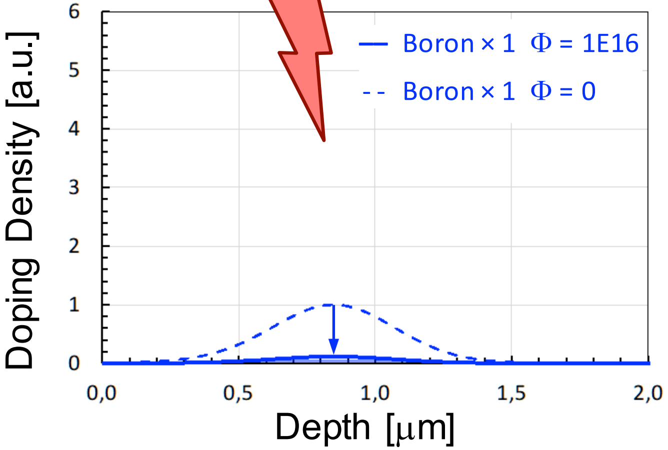

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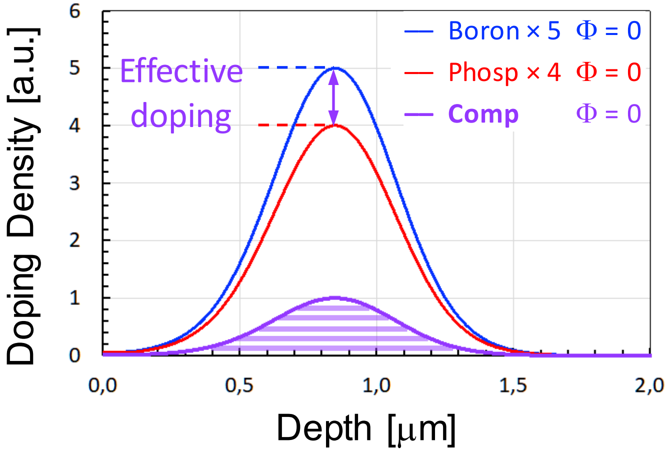
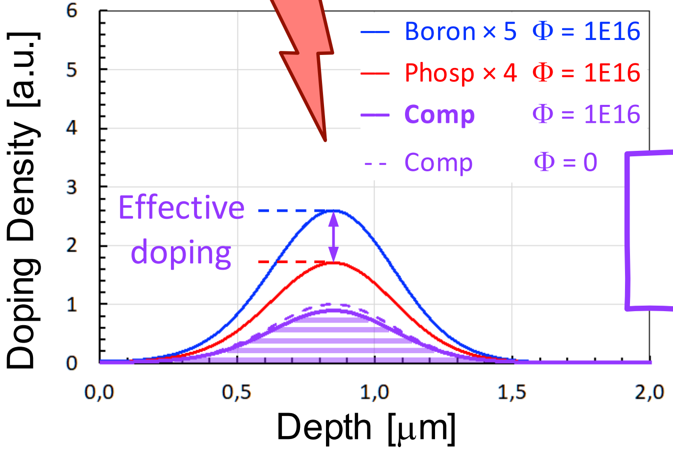
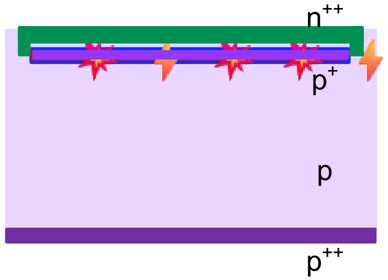






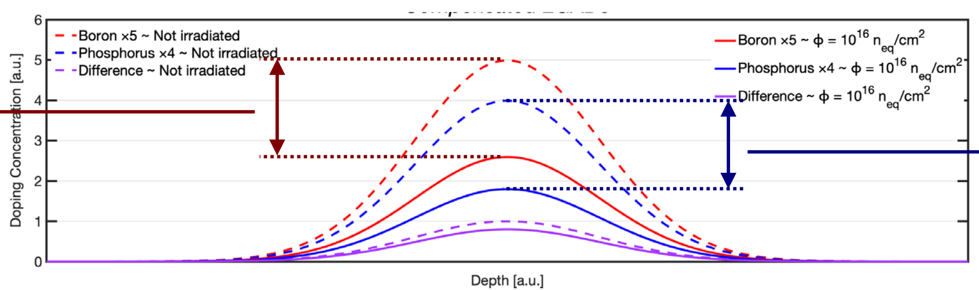
Compensated LGAD

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

CompleX target

Compensation – Doping Evolution with Fluence

Many unknowns to investigate.
A TCAD approach has been pursued.

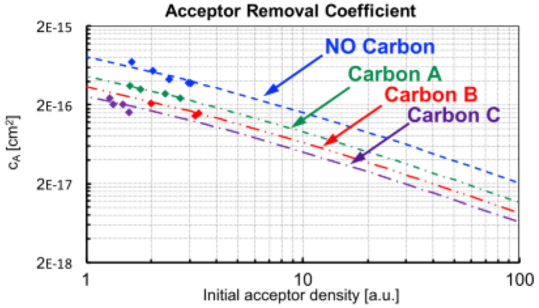


Does donor removal affect acceptor removal?

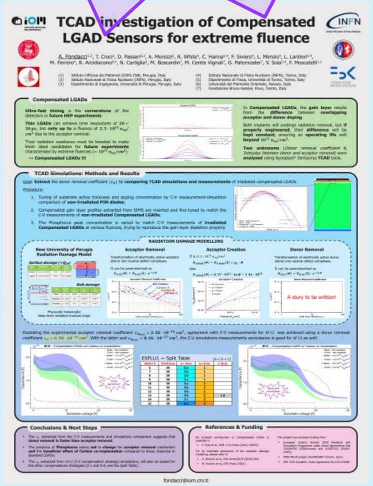
How quickly are donor atoms deactivated?

Acceptor Removal

$$N_{A,GL}(\Phi) = N_{A,GL}(0) \cdot e^{-c_A \cdot \phi}$$



POSTER A. FONDACCI
Solid State Detectors



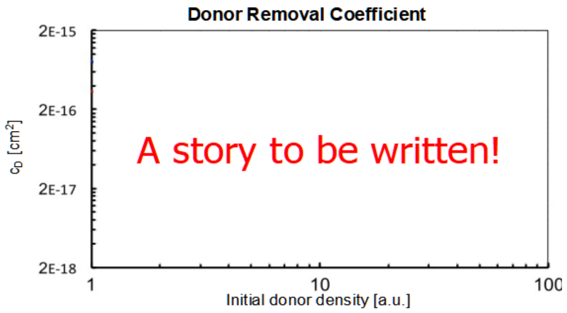
TCAD investigation of Compensated LGAD Sensors for extreme fluence

A. Fondacci[1,2], T. Croci[2], D. Passeri[3,2], A. Morozzi[2], R. White[4], C. Hanna[5,4], F. Siviero[4], L. Menzio[4], L. Lanteri[5,4], M. Ferrero[4], R. Arcidiacono[6,4], N. Cartiglia[4], M. Boscardin[7], M. Centis Vignali[7], G. Paternoster[7], V. Sola[5,4], F. Moscatelli[1,2]

Tuesday afternoon
Wednesday morning

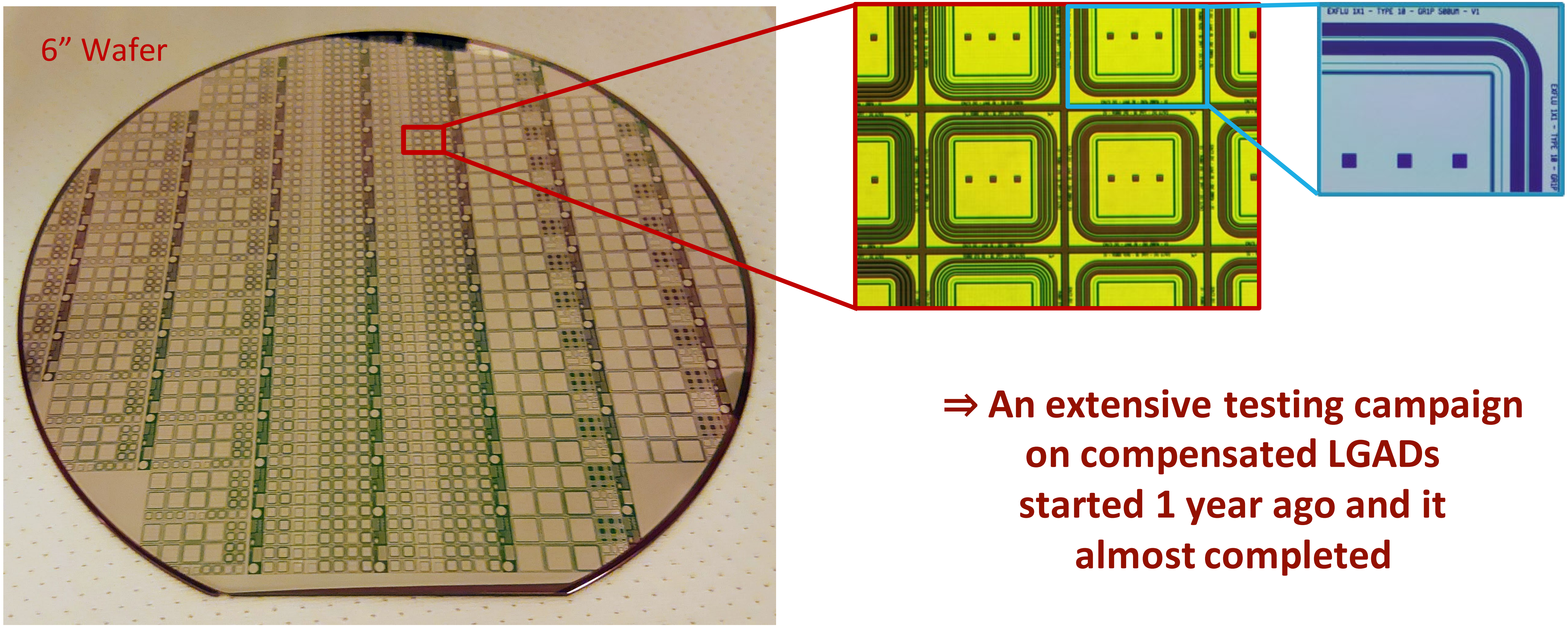
Donor Removal

$$N_{D,GL}(\Phi) = N_{D,GL}(0) \cdot e^{-c_D \cdot \phi}$$



First Compensated LGADs – EXFLU1

First production of compensated LGADs EXFLU1 batch released end of 2022 by **FBK**.



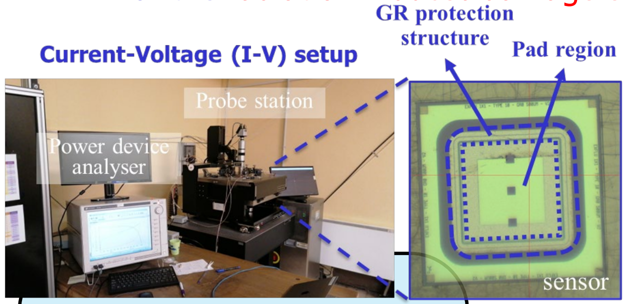
⇒ An extensive testing campaign on compensated LGADs started 1 year ago and it almost completed

Further R&D from EXFLU1 batch

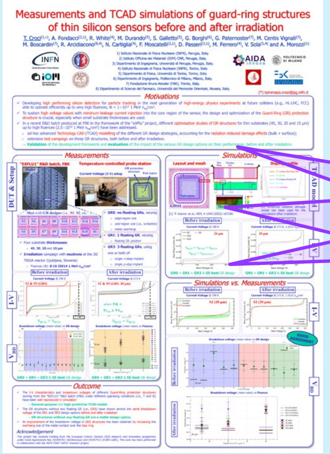
Optimization studies of GR protection structures

- ☐ Extensive test campaign on the different GR structures contained in the "EXFLU1" R&D batch (FBK).
- ☐ Ad-hoc TCAD modelling of the different GR design strategies, accounting for the radiation-induced damage effects.

Current-Voltage (I-V) setup



- ✓ **GR0**: **no floating GRs**, varying
  - *edge* region size
  - *void* region size (i.e., scribeline)
  - metal *overhang*
- ✓ **GR1**: **1 floating GR**, varying
  - floating GR *position*
- ✓ **GR3**: **3 floating GRs**, using one or both of:
  - single *n-deep* implant
  - single *p-stop* implant


Measurements and TCAD simulations of guard-ring structures of thin silicon sensors before and after irradiation

POSTER T. CROCI
Solid State Detectors

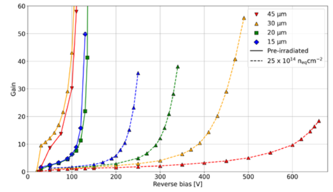
Tuesday afternoon
Wednesday morning

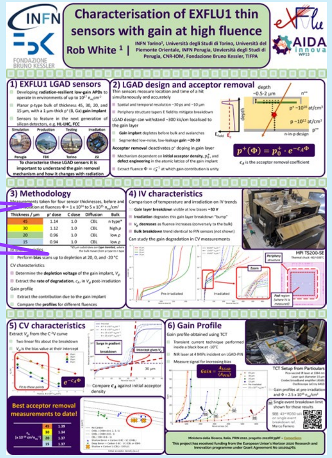
EXFLU1 thin sensors with gain at high fluence

- ☐ Planar p-type bulk of thickness 45, 30, 20, and 15 μm, with a 1 μm-thick p+ (B, Ga) gain implant
- ☐ Characterizationin terms of I-V, C-V, Gain-V up to 2.5×10^{15} n_{eq}/cm^2

Measurements taken for four sensor thicknesses, before and after irradiation at fluences $\Phi = 1 \times 10^{14}$ to 5×10^{15} n_{eq}/cm^2

Thickness / μm	p^+ dose	C dose	Diffusion	Bulk
45	1.14	1.0	CBL	n type*
30	1.12	1.0	CBL	high ρ
20	0.96	1.0	CBL	low ρ
15	0.94	1.0	CBL	low ρ




Characterisation of EXFLU1 thin sensors with gain at high fluence

Rob White

POSTER R. WHITE
Solid State Detectors

Tuesday afternoon
Wednesday morning

Compensated Gain Layer Design – Split Table

Active thickness 30 μm

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	

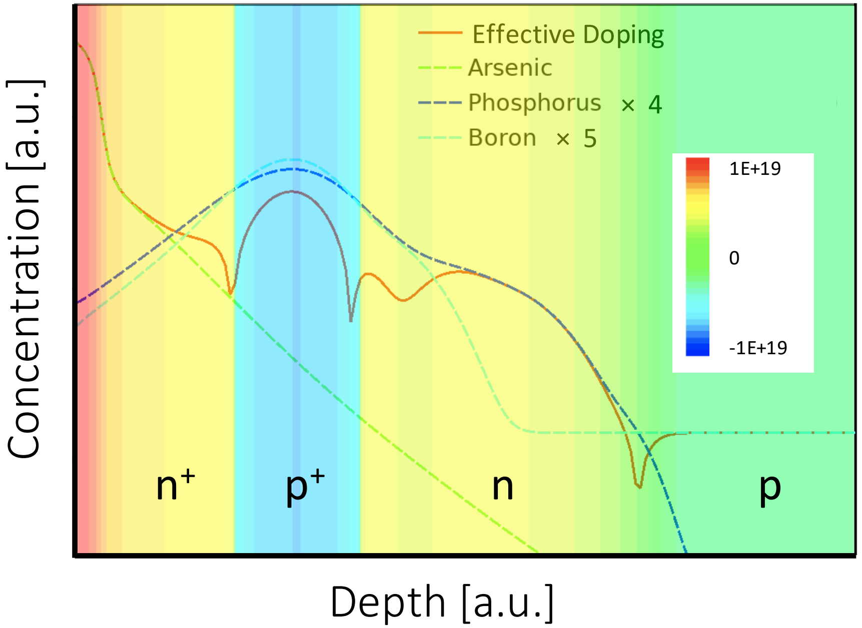
[a < b < c]

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

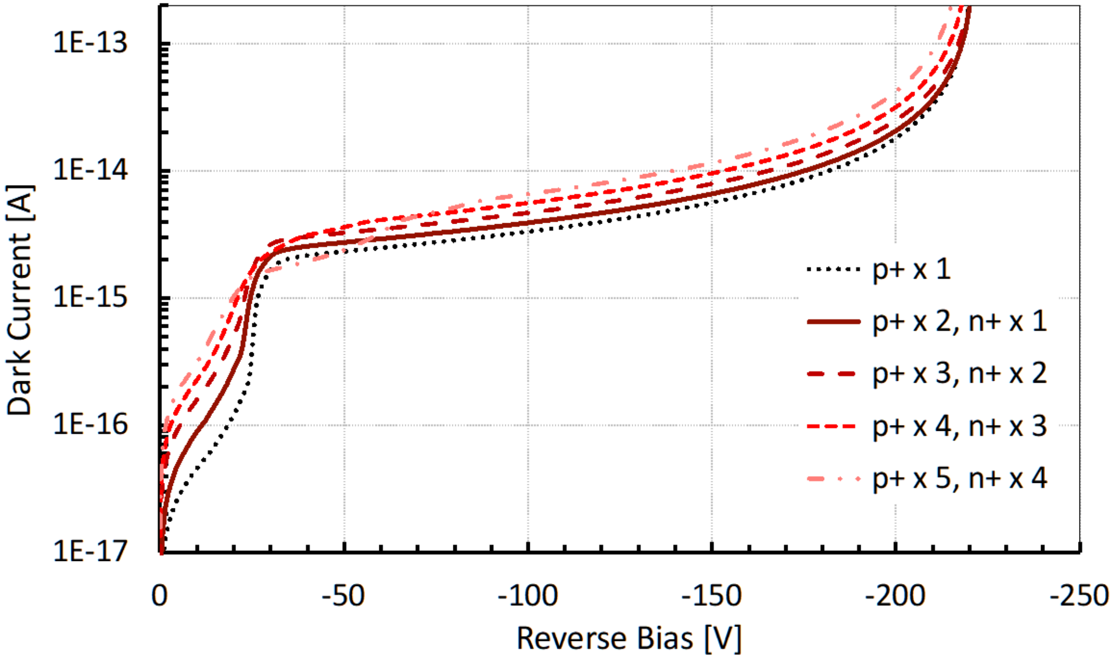
Compensation from Simulation

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

Doping Profiles from Process Simulation



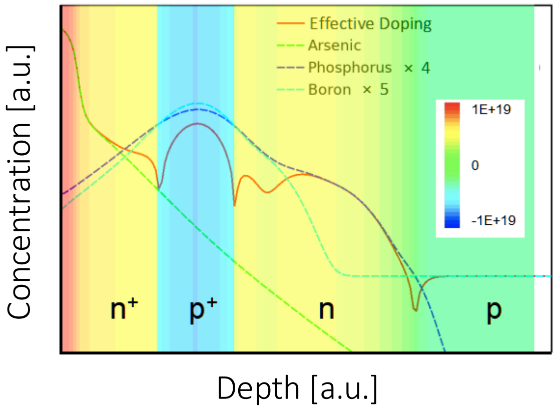
Compensated LGAD – I-V from Simulation

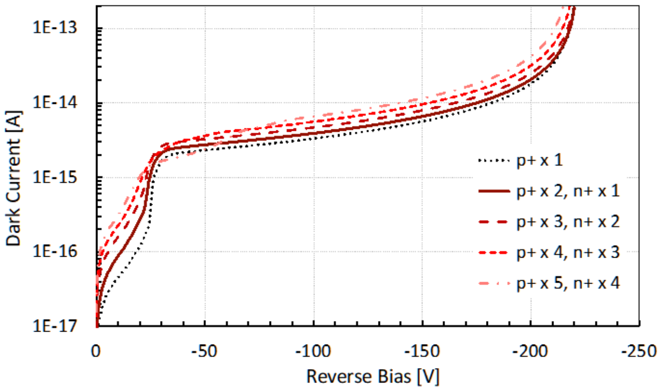


→ The simulation of the electrostatic behaviour shows that it is possible to reach similar multiplication for different initial concentrations of p^+ and n^+ dopants

Compensated LGAD – I-V on wafer

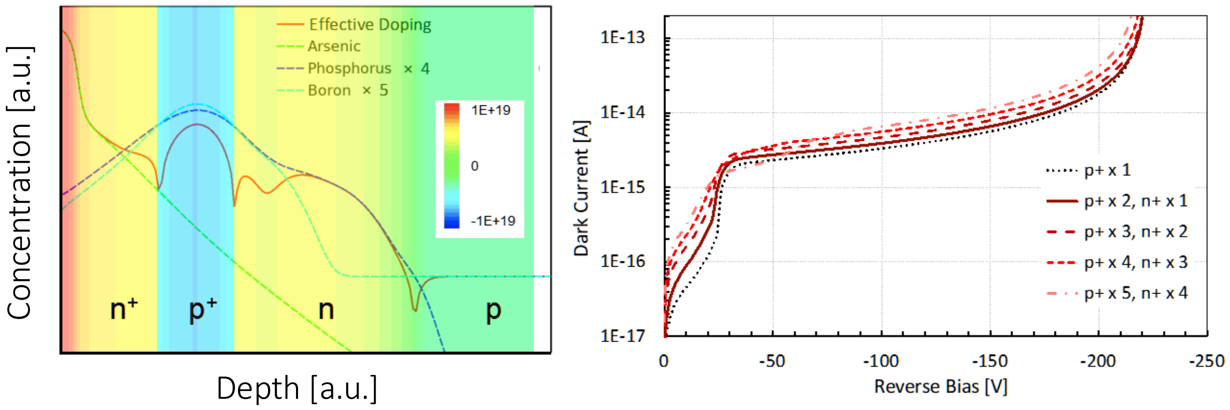
Simulation



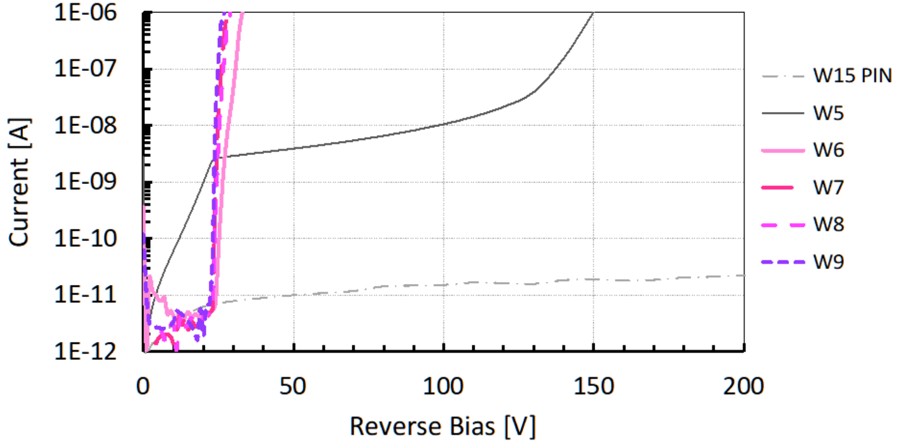


Compensated LGAD – I-V on wafer

Simulation



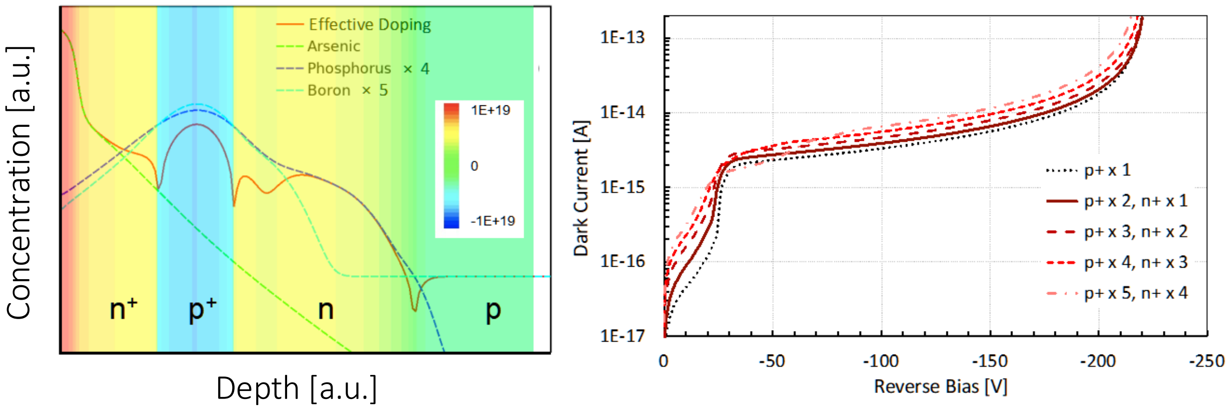
EXFLU1 – Compensated LGAD 2–1 – I-V



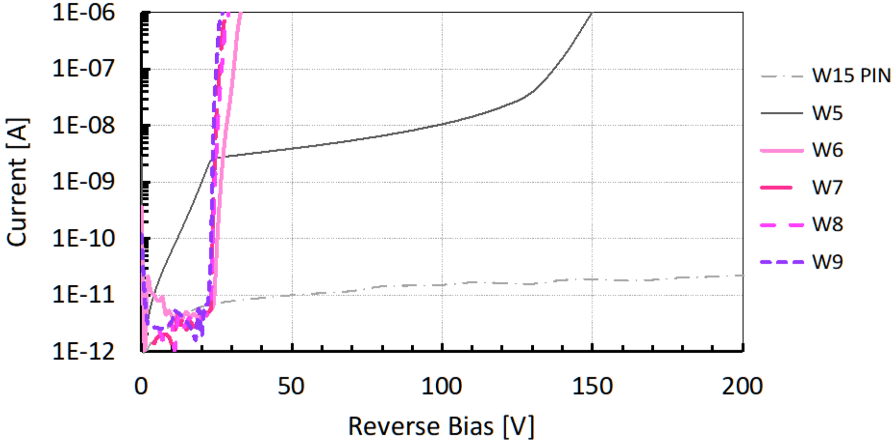
2 – 1

Compensated LGAD – I-V on wafer

Simulation



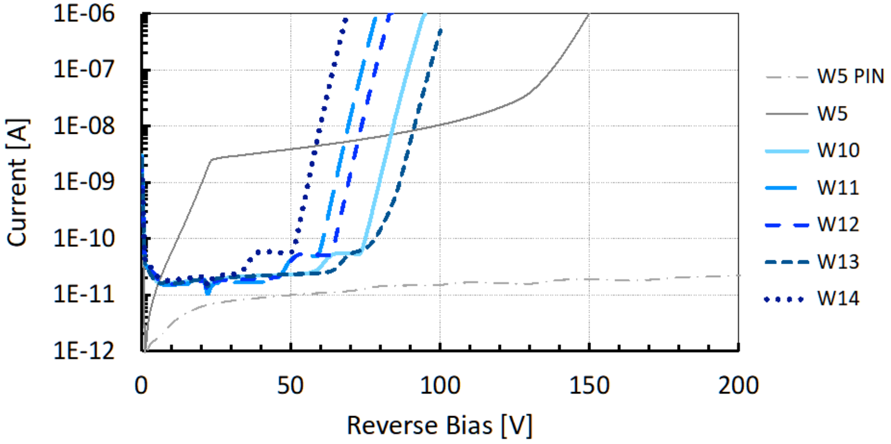
EXFLU1 – Compensated LGAD 2–1 – I-V



2 – 1

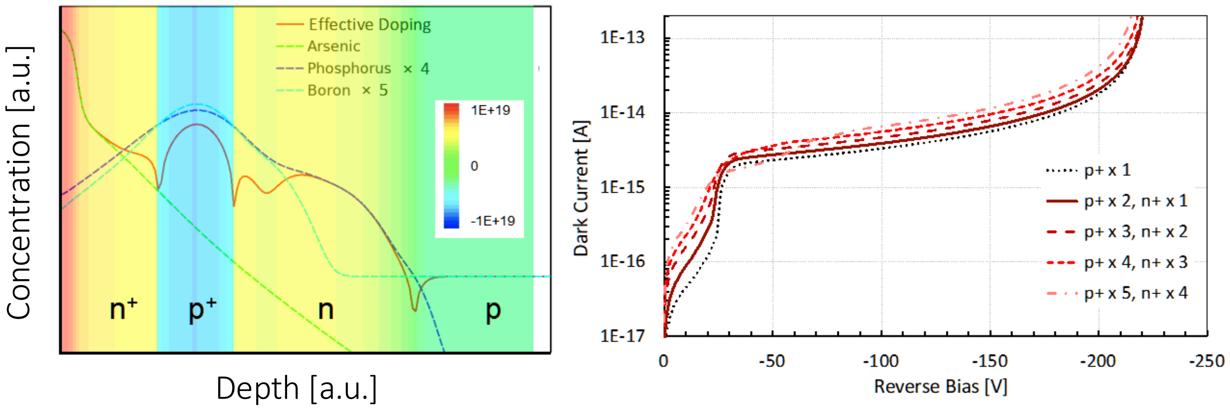
3 – 2

EXFLU1 – Compensated LGAD 3–2 – I-V

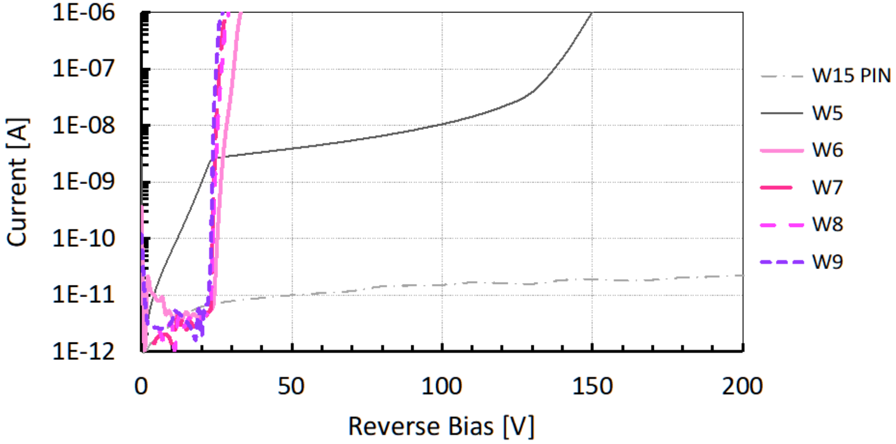


Compensated LGAD – I-V on wafer

Simulation



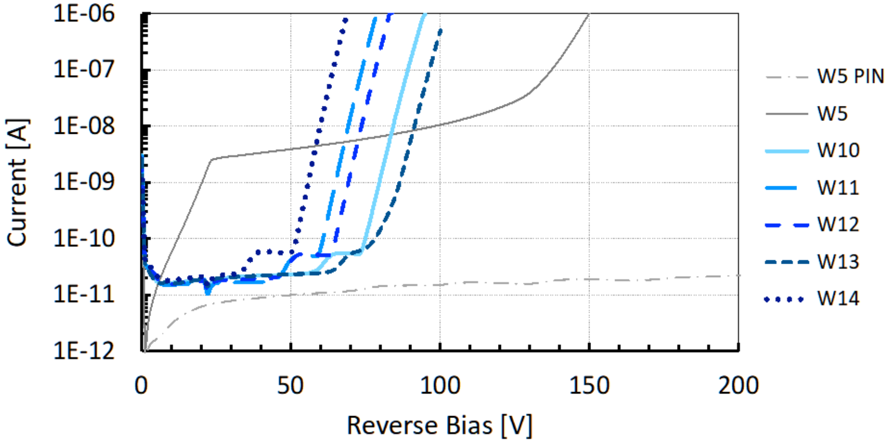
EXFLU1 – Compensated LGAD 2–1 – I-V



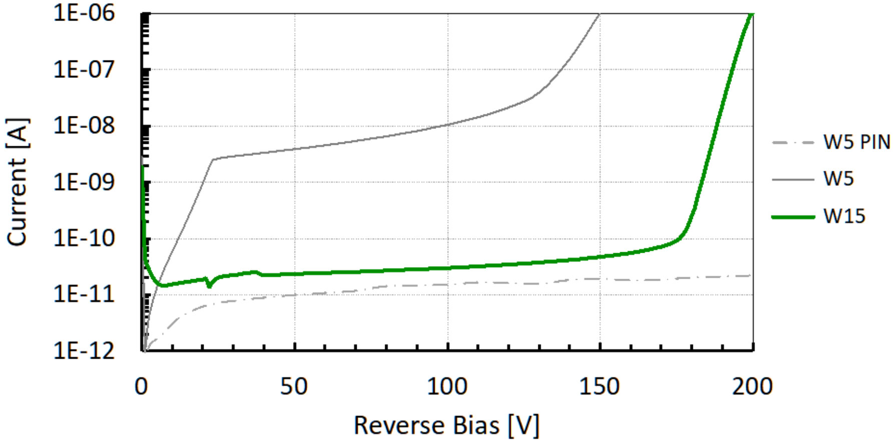
2 – 1

EXFLU1 – Compensated LGAD 3–2 – I-V

3 – 2

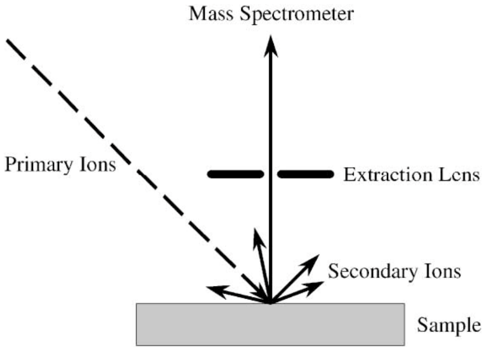


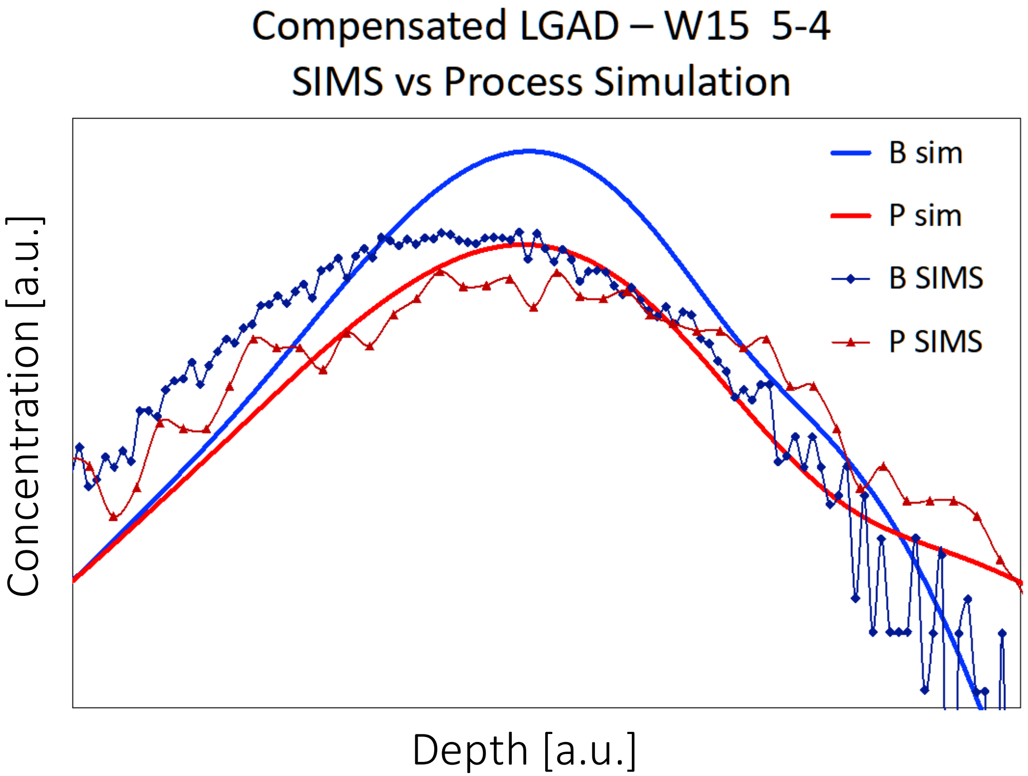
EXFLU1 – Compensated LGAD 5–4 – I-V



5 – 4

Secondary Ion Mass Spectroscopy – W15





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

IR Laser Stimulus on Compensated LGAD

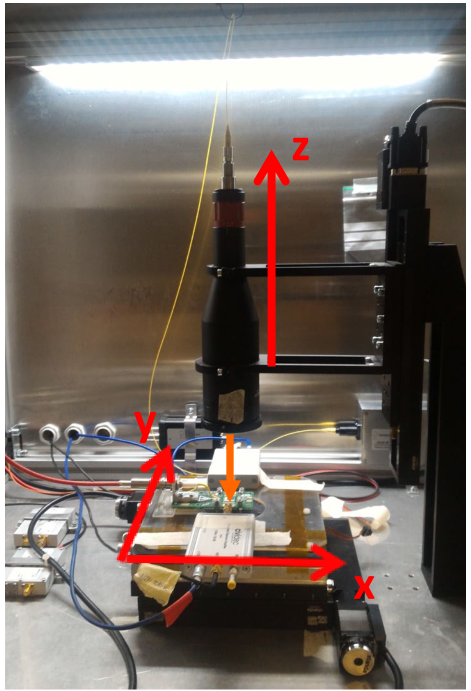
TCT Setup from Particulars

Pico-second IR laser at 1064 nm

Laser spot diameter ~ 10 µm

Cividec Broadband Amplifier (40dB)

Oscilloscope LeCroy 640Zi



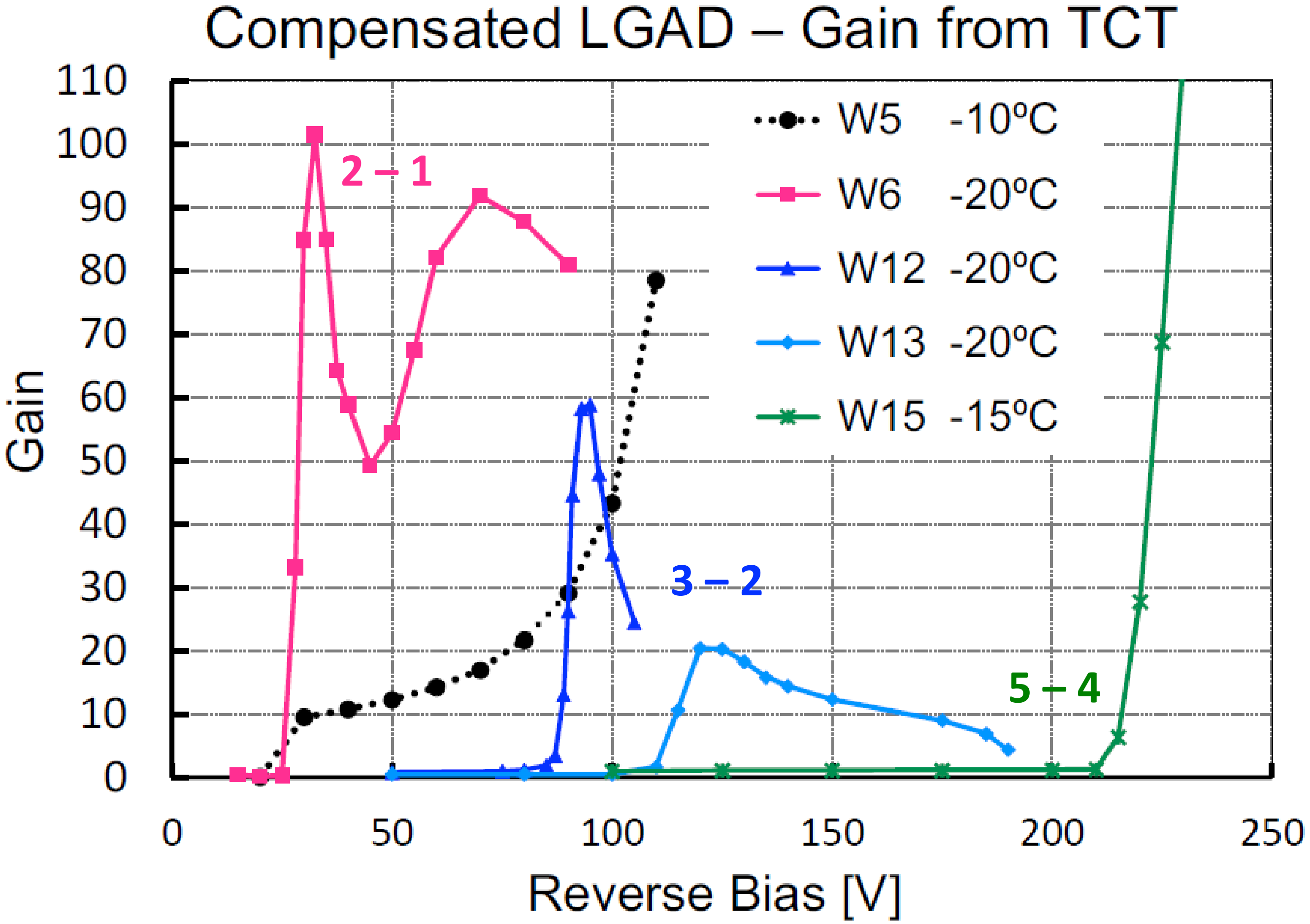
Laser stimulus on LGAD-PiN structures

$$\boxed{\mathbf{Gain} = \frac{\mathbf{Q_{LGAD}}}{< \mathbf{Q_{PiN}} >}}$$

Laser intensity

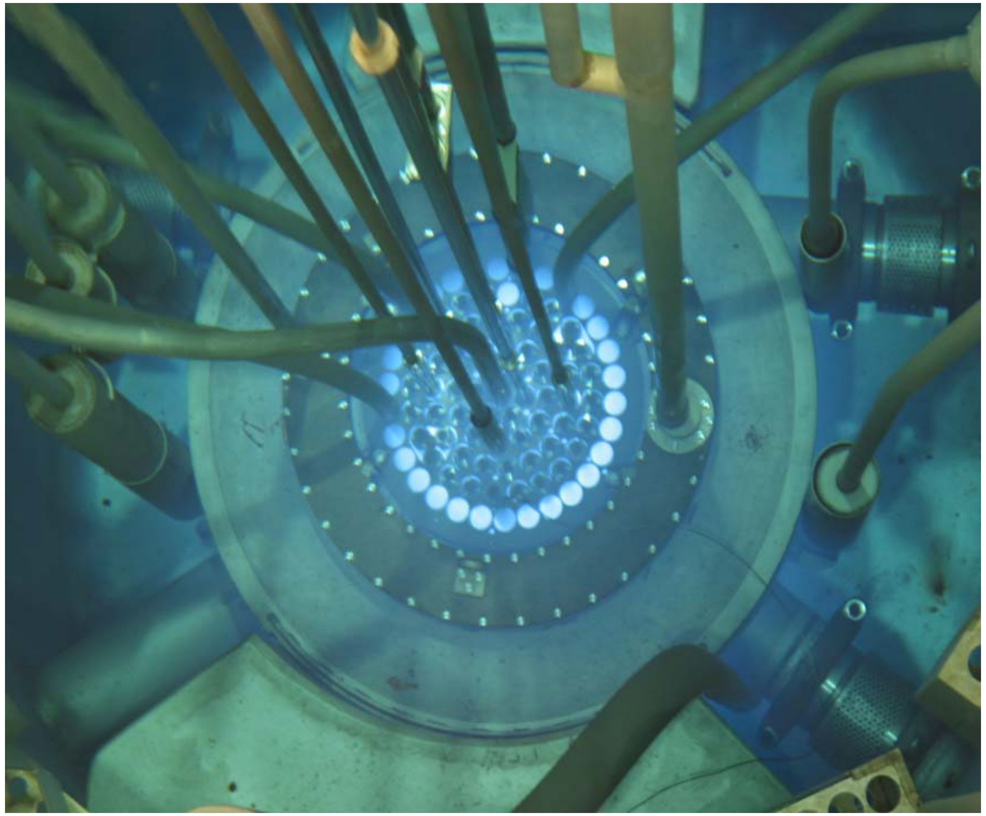
~ 4 MIPs

$\Phi = 0$



→ **Not trivial to operate compensated LGAD sensors**

Neutron Irradiation of Compensated LGADs



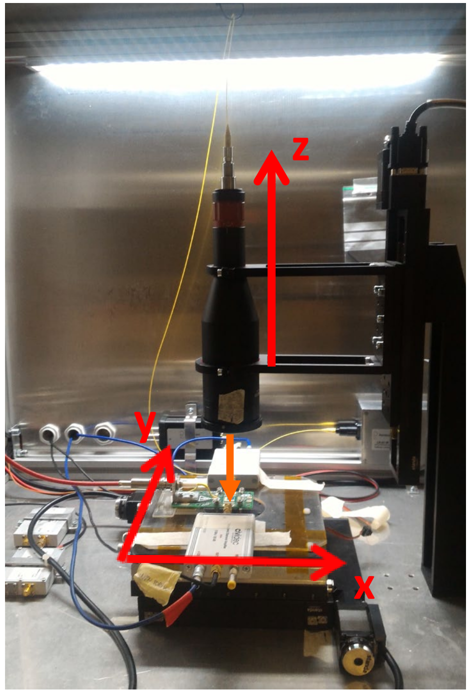
Compensated LGAD sensors have been irradiated with neutrons at the JSI TRIGA Reactor Irradiation Facility (Ljubljana)

Irradiation fluences from 1E14 to 5E15 n_{eq}/cm^2

Fluence uncertainty ± 5%

IR Laser Stimulus on Compensated LGAD

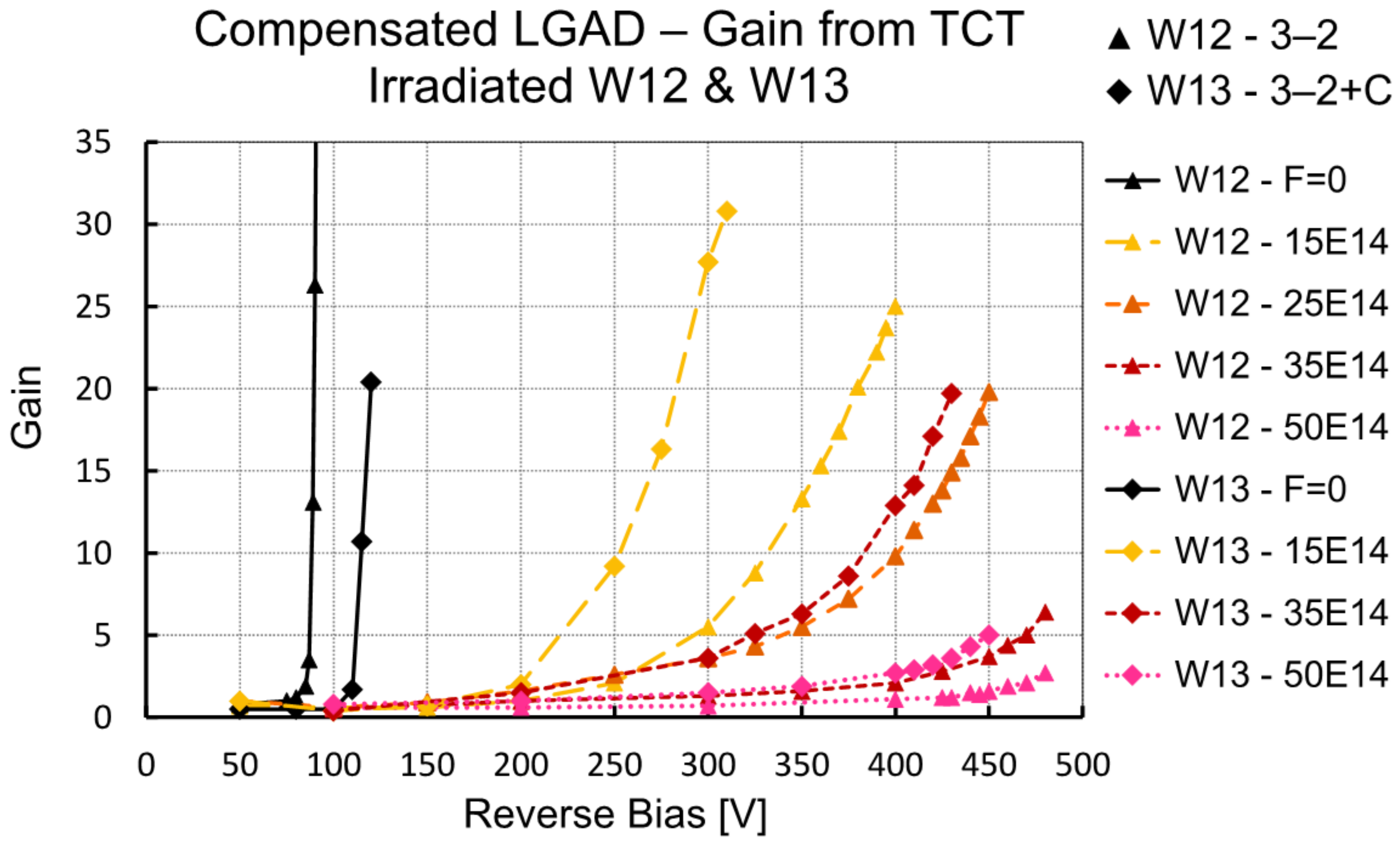
TCT Setup from Particulars
Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
Room temperature



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

→ Good gain behavior of the compensated LGAD sensors after irradiation

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



β Particles on Compensated LGAD

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

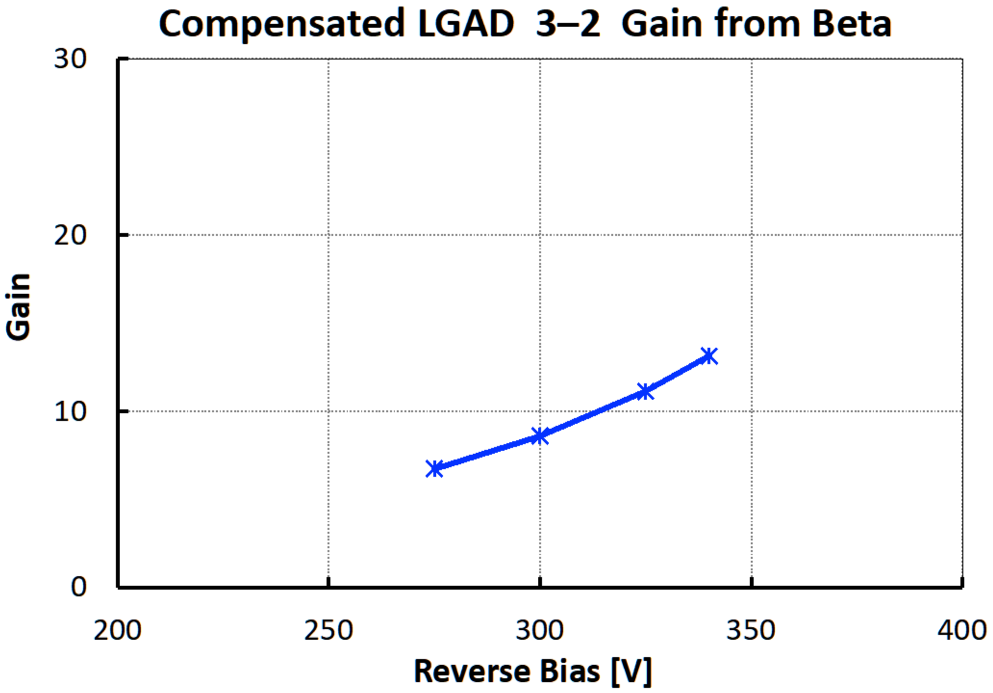
3–2 compensated LGAD from W12 irradiated to $2.5 \cdot 10^{15}$ n_{eq}/cm^2 has been tested with beta particles

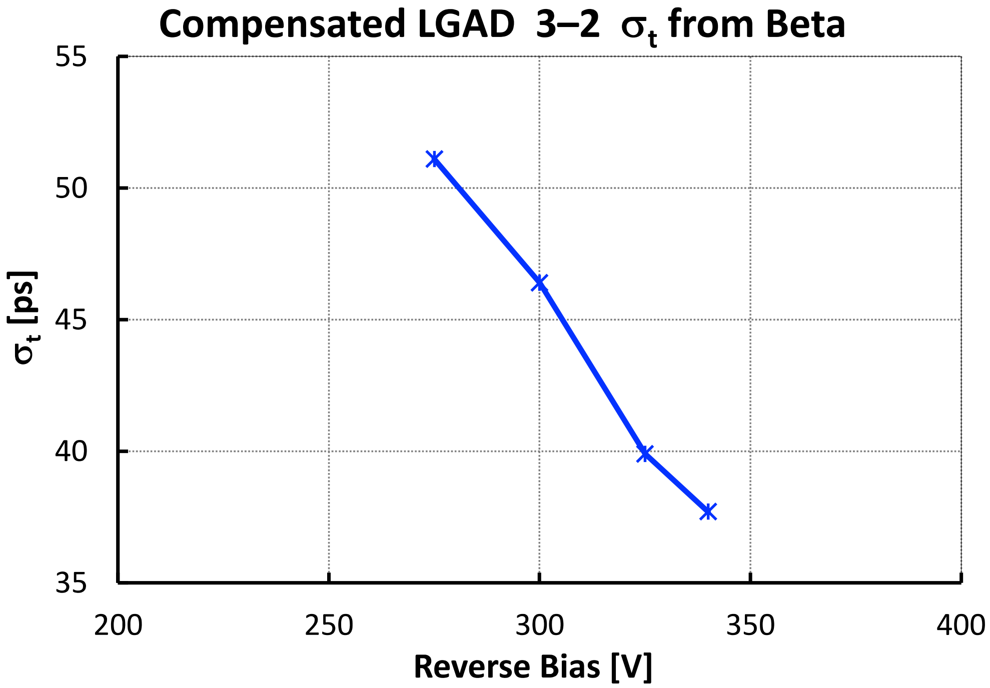
→ **Good timing performances of compensated LGAD sensors irradiated to $2.5 \cdot 10^{15}$ n_{eq}/cm^2**

W12

3–2

$\Phi = 2.5E15$





Compensated LGAD – State-of-the-Art

Lesson from the first batch of compensated LGAD sensors:

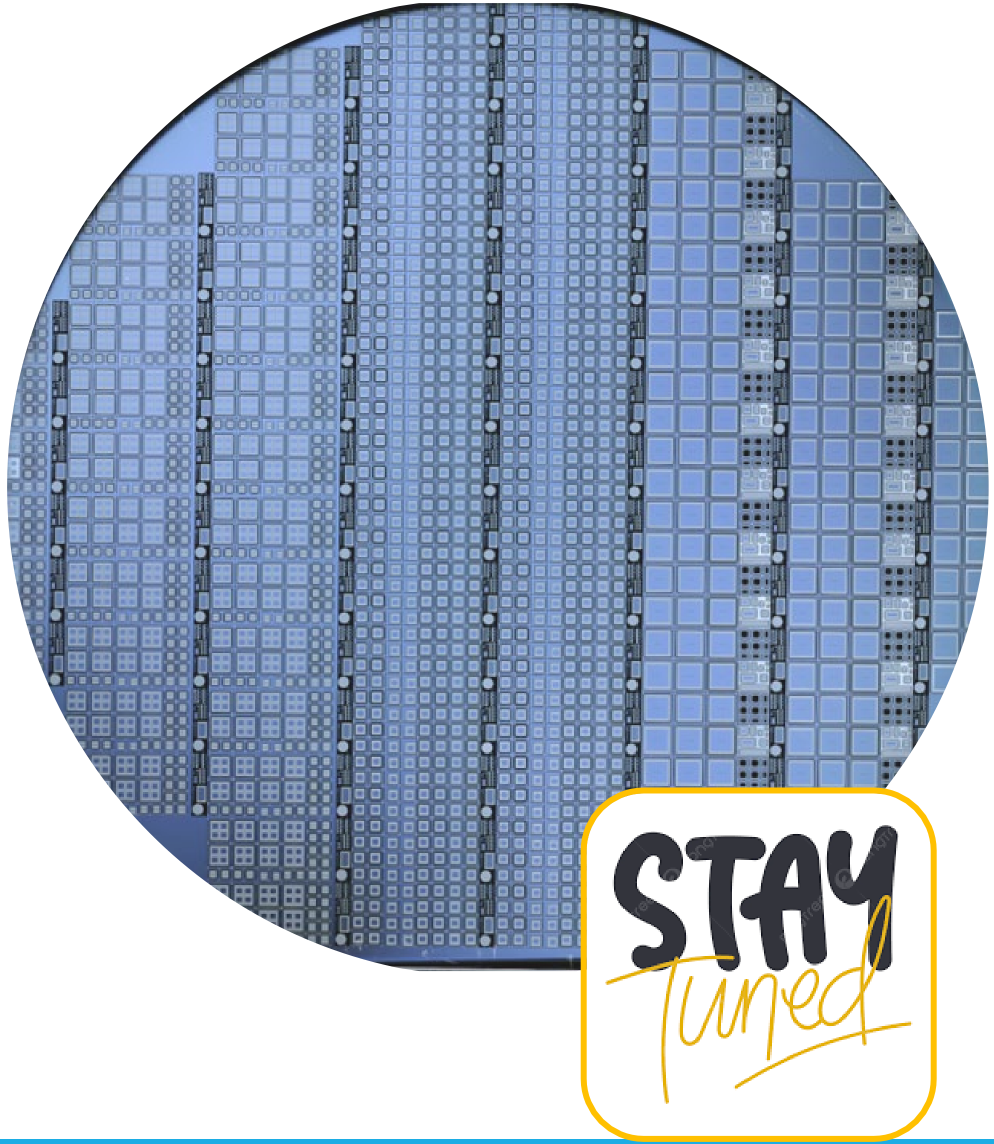
- ▻ Difficult to control the shape and the peak concentration of two different elements
  ⟶ **Necessary to carefully tune all the process parameters**

- ▻ After irradiation, possible to successfully operate compensated LGAD sensors
  ⟶ **Good gain and timing performances after irradiation**

- ▻ Co-implantation of Carbon in the same volume of Boron and Phosphorus
  ⟶ **Same effect as in standard LGAD, a reduction of a factor of ~ 3 of the Acceptor removal**

- ▻ Simulation effort in progress to replicate I-V, C-V, and gain behavior after irradiation
  ⟶ **Possible to extract Acceptor and Donor removal by comparing data and simulations**
  ⟶ **Reliable TCAD highly predictive model for the GR structures to improve the V_{BD} of LGADs**

➢ **Compensated LGADs represent the sensor technology for the extreme fluences**



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- RD50, CERN
- AIDAinnova, WP13
- Compagnia di San Paolo
- Ministero della Ricerca, Italia, PRIN 2022, progetto 2022RK39RF – ComonSens

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An ERC Consolidator Grant awarded to further develop compensated LGAD sensors

Doping Compensation in Thin Silicon Sensors:
the pathway to Extreme Radiation Environments
CompleX

Co-funded by the European Union

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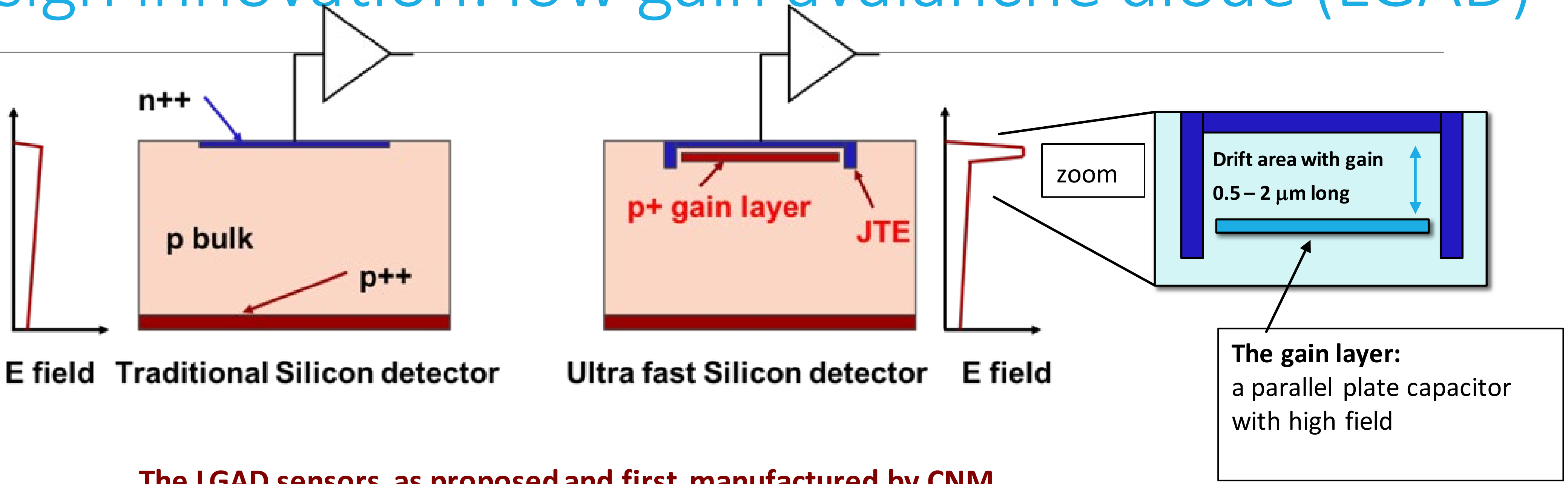
Thank you

Backup

First design innovation: low gain avalanche diode (LGAD)



The gain layer:
a parallel plate capacitor with high field

The LGAD sensors, as proposed and first manufactured by CNM

(National Center for Micro-electronics, Barcelona):

High field obtained by adding an extra doping layer

E ~ 300 kV/cm, closed to breakdown voltage

- The low-gain mechanism, obtained with a moderately doped p-implant, is the defining feature of the design.

Low gain is the key ingredient to good temporal resolution

First Compensated LGADs – EXFLU1

First compensated LGAD sensors have been released by FBK in the framework of the EXFLU1 batch

Other R&D paths pursued by the EXFLU1 batch to extend the radiation tolerance of the LGAD sensors:

- new guard ring design
- decrease of the acceptor removal – carbon shield
- thin substrates (15–45 µm)

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

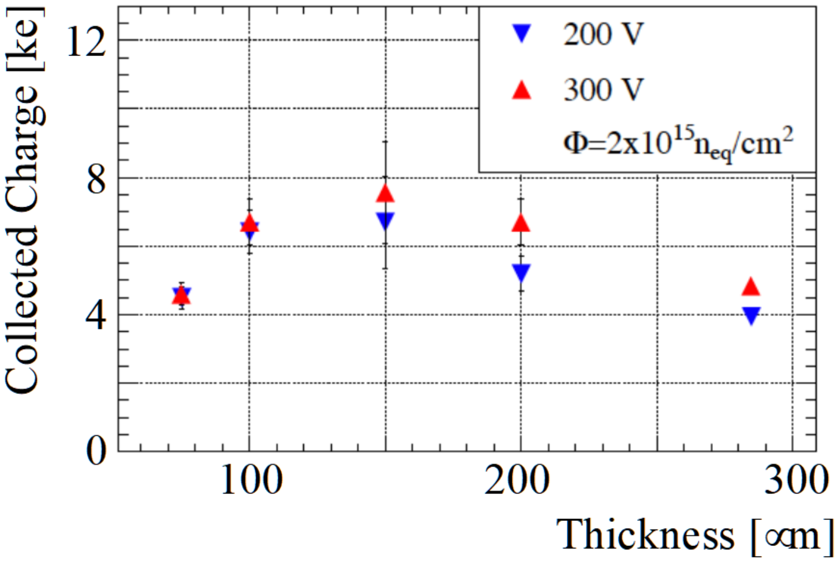
[V. Sola, TREDI 2023, Trento]

Towards the eXtreme Fluences – CompleX

Planar silicon sensors can operate up to $10^{16}/\mathrm{cm}^2$

<u>Signals from planar silicon sensors become too small</u>

- ➢ 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]

<u>CompleX will design a new generation of silicon sensors</u>

- ▻ exploit saturation of the radiation damage
- ▻ use thin substrates (20 – 40 μm)
- ▻ use internal gain to enhance the signal

→ CompleX will develop a new generation of planar silicon sensors with gain to operate in extreme fluence environments

I-V from Compensated LGAD – Irradiated

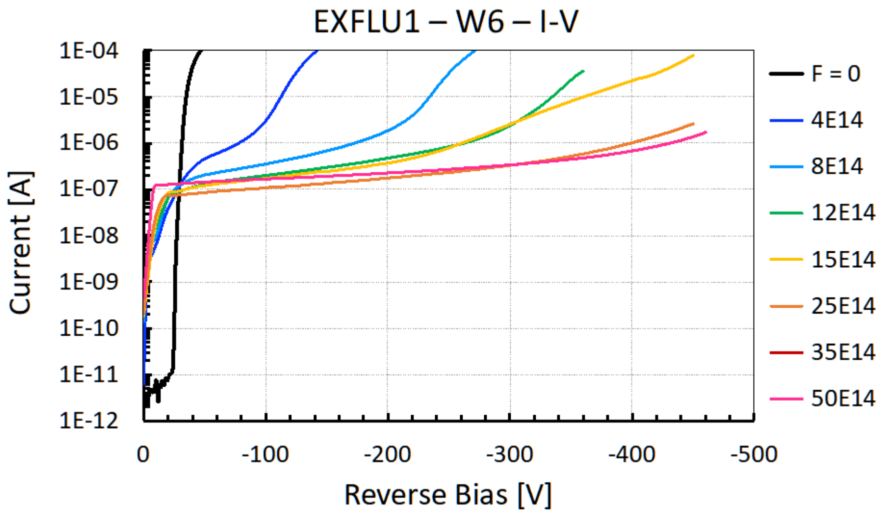
$[\Phi] = n_{eq}/cm^2$

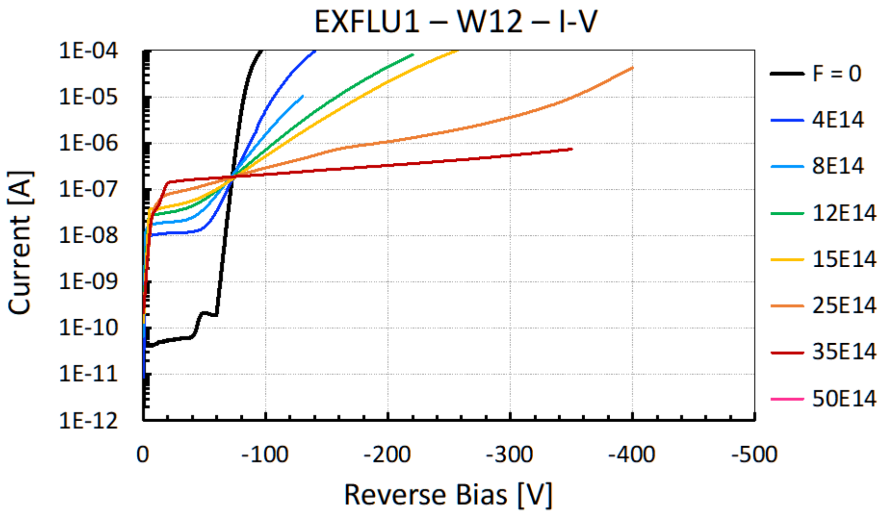
$T_{\phi=0} = + 20^oC$

$T_{IRR} = - 20^oC$

W6

2 – 1



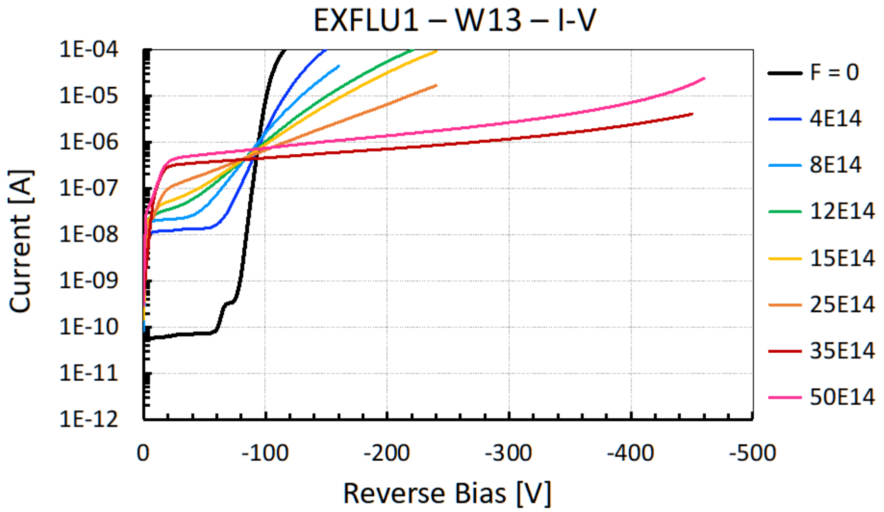


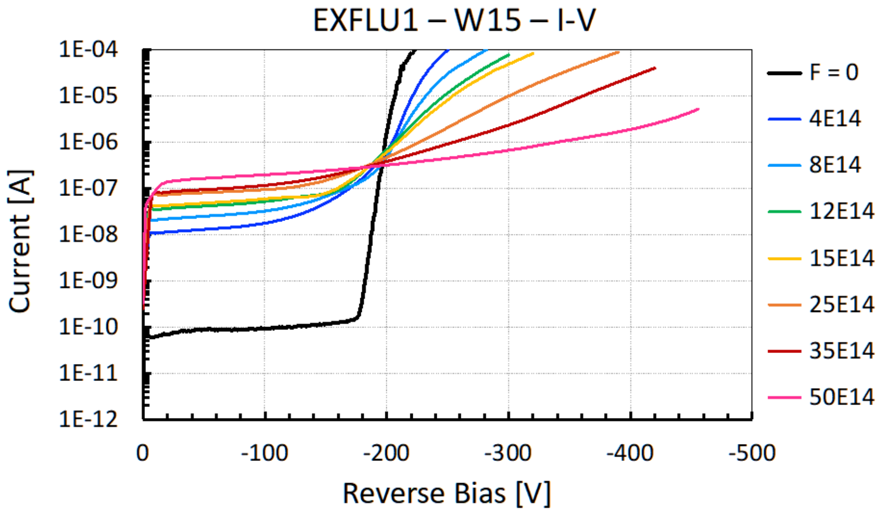
W12

3 – 2

W13

3 – 2 + C





W15

5 – 4

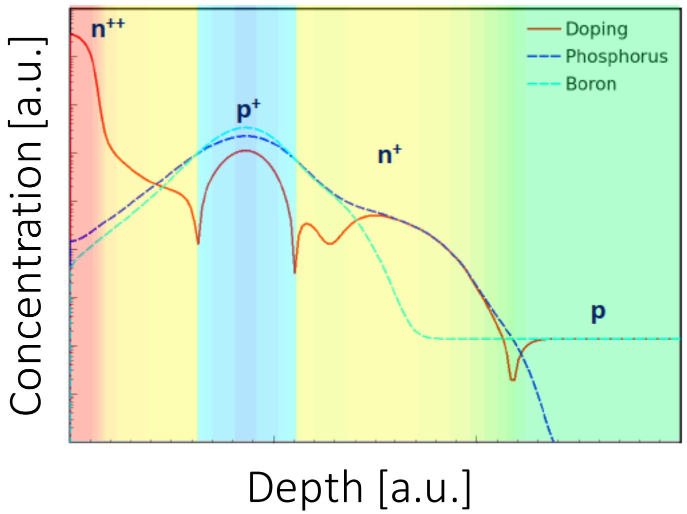
$[\Phi] = n_{eq}/cm^2$

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

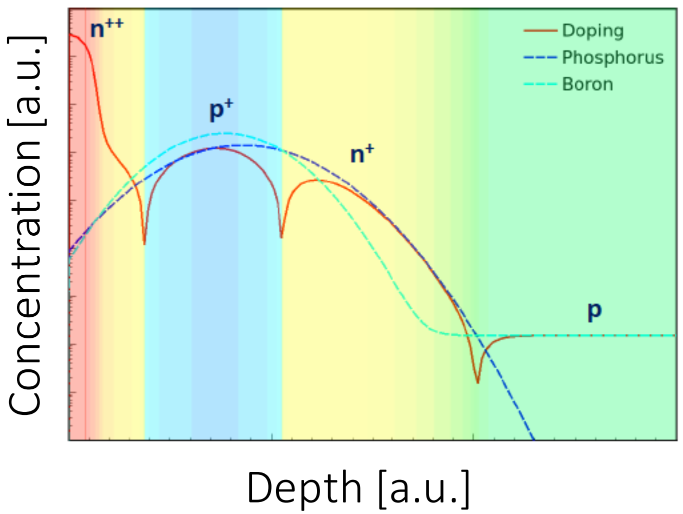
$T_{IRR} = - 20^oC$

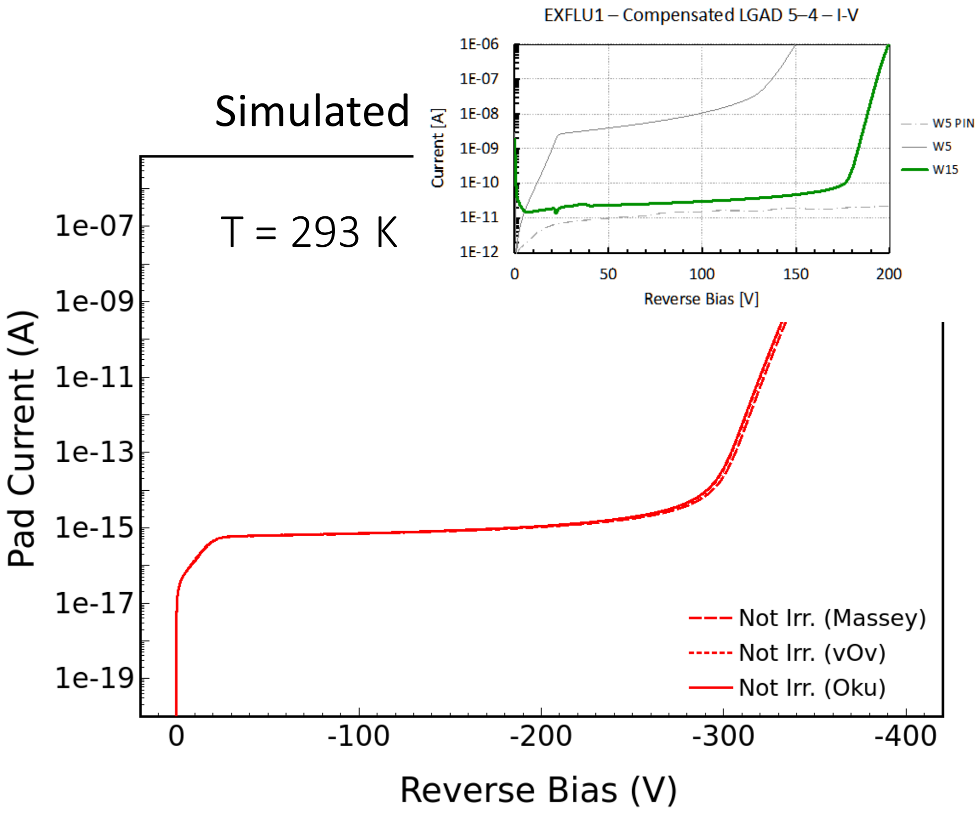
SIMS Profile & I-V – 5–4

Doping Profiles
from Process Simulation



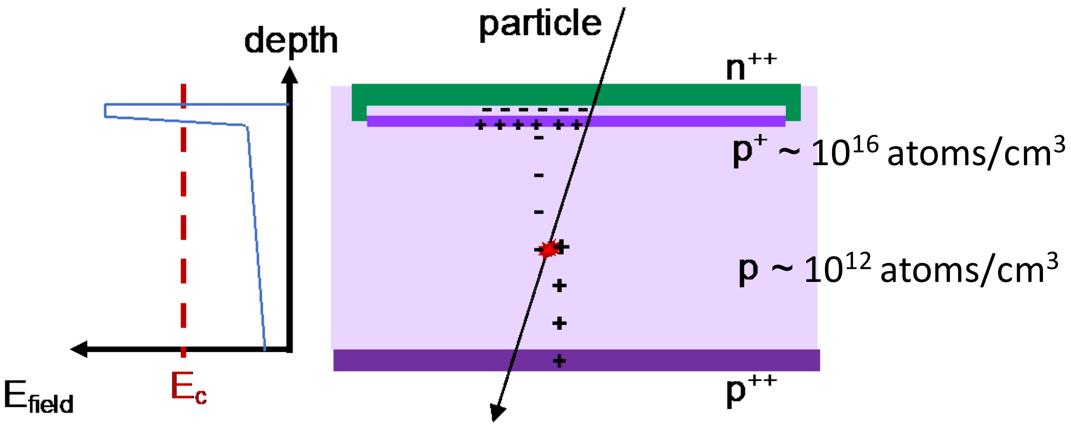
Doping Profiles
from SIMS

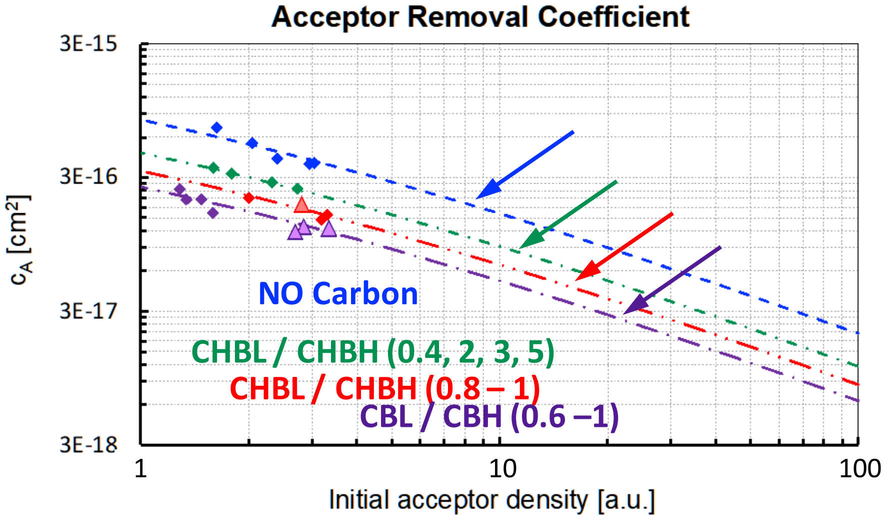




→ **The simulated I-V reproduces the trend of the measured I-V from W15**

Gain Removal Mechanism in LGADs





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

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

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

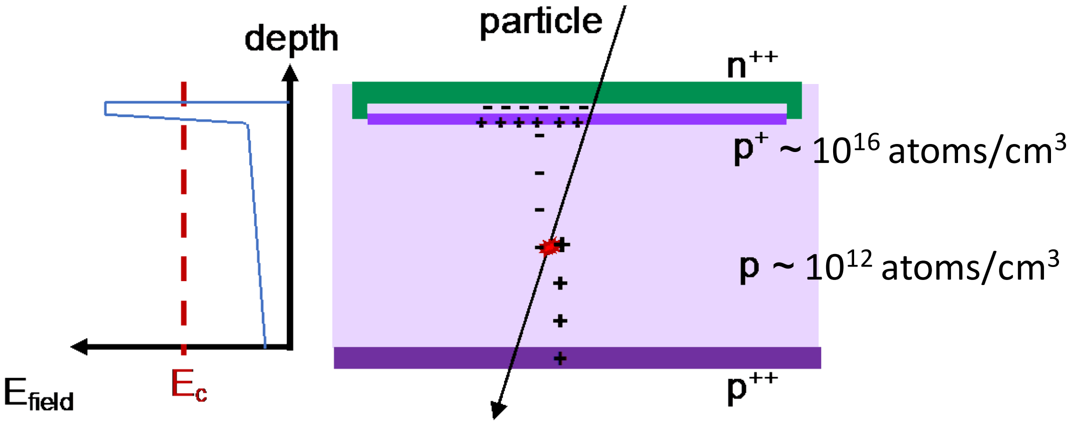
$\Phi_0 = 1/c_A \sim$ the fluence at which multiplication power of the gain implant reaches unity

▲ thin sensors from the EXFLU1 batch

[R.S. White, 43rd RD50 Workshop (2023) CERN]

⇒ Is it possible to reduce c_A further?

Towards a Radiation Resistant Design of LGADs

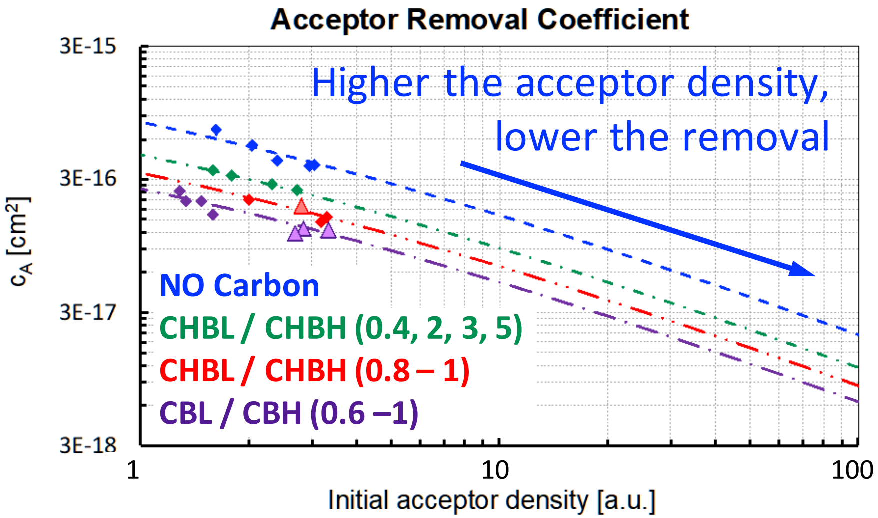


The acceptor removal mechanism deactivates the p^+-doping of the **gain implant** with irradiation as

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

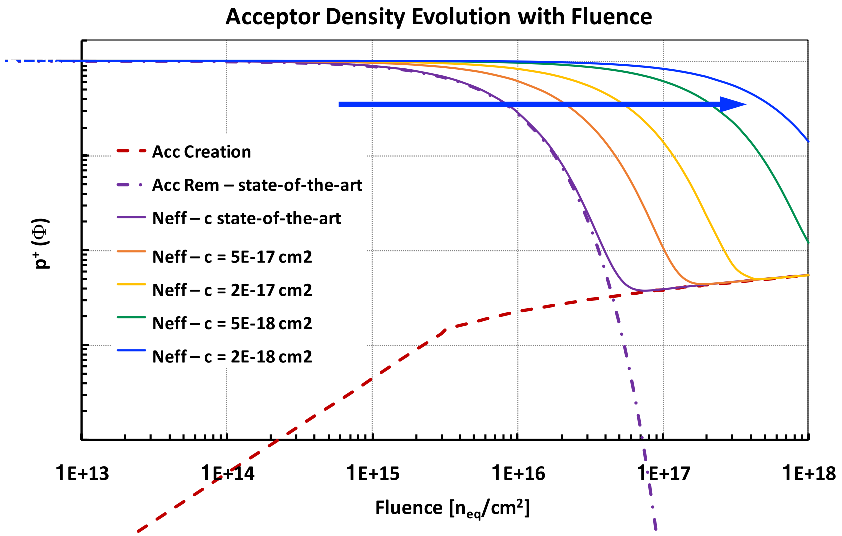
where c_A is the acceptor removal coefficient

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



Higher the acceptor density, lower the removal

NO Carbon
CHBL / CHBH (0.4, 2, 3, 5)
CHBL / CHBH (0.8 – 1)
CBL / CBH (0.6 –1)



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

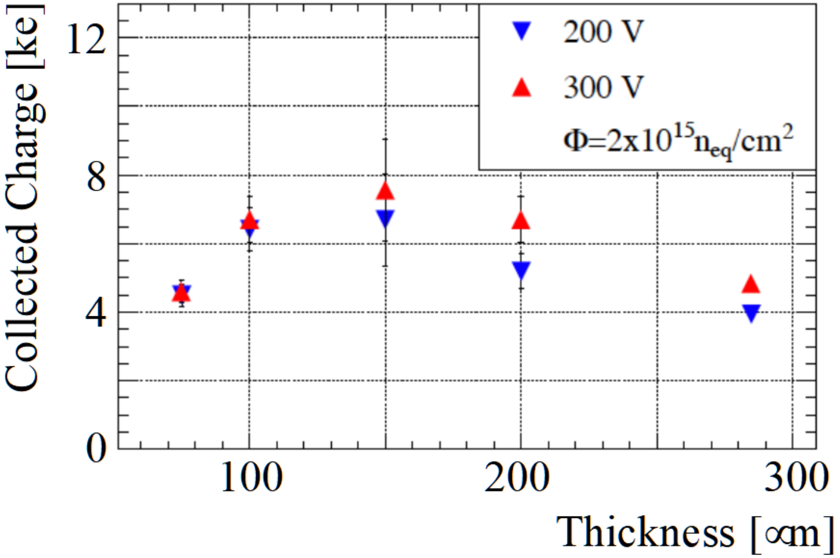
→ compensation

Sensor design the eXtreme Fluences

Planar silicon sensors can operate up to 10^{16}/cm²

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



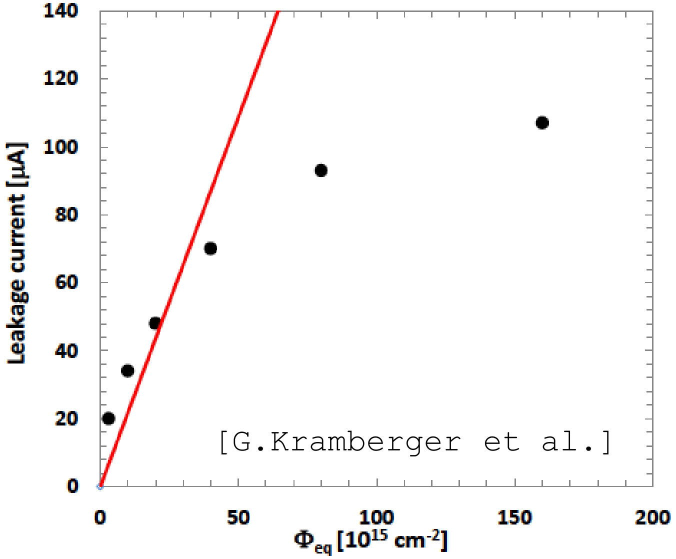
[doi: 10.1088/1748-0221/9/05/C05023]

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

- ❖ 1. **saturation** of the radiation damage effects above $5\cdot10^{15}$ 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 → **Compensated LGADs**

Saturation

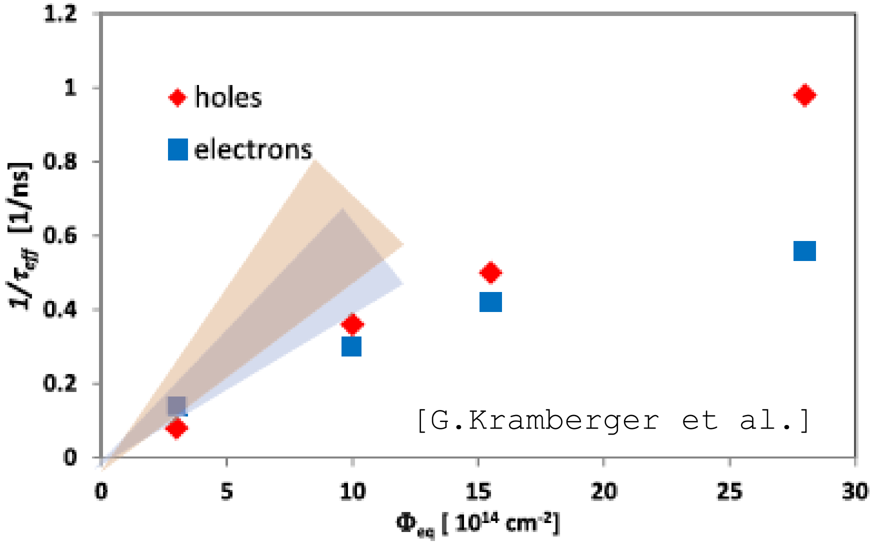
At fluences above $5 \cdot 10^{15}$ cm^{-2} → **Saturation of radiation effects observed**



Leakage current saturation

$I = \alpha V \Phi$

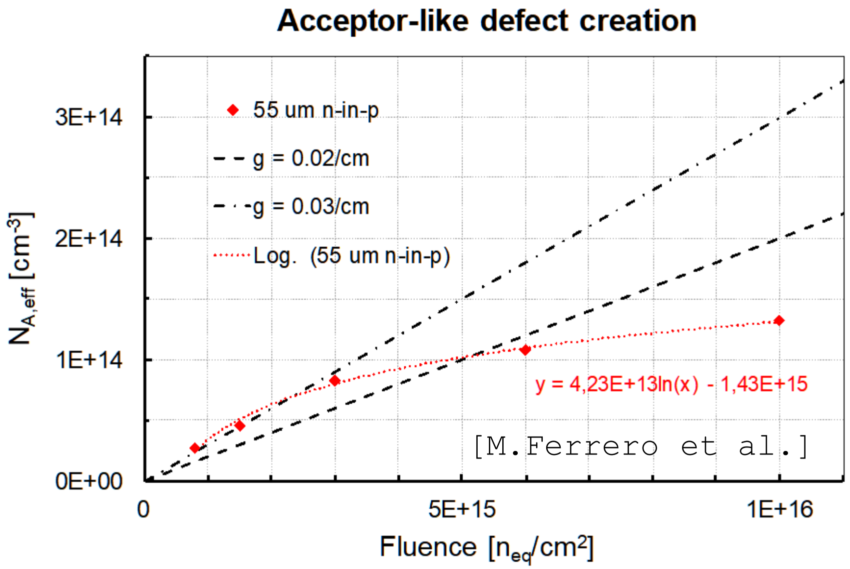
α from linear to logarithmic



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