Institut Ruđer Bošković

RD50

# First results from thin silicon sensors for extreme fluences

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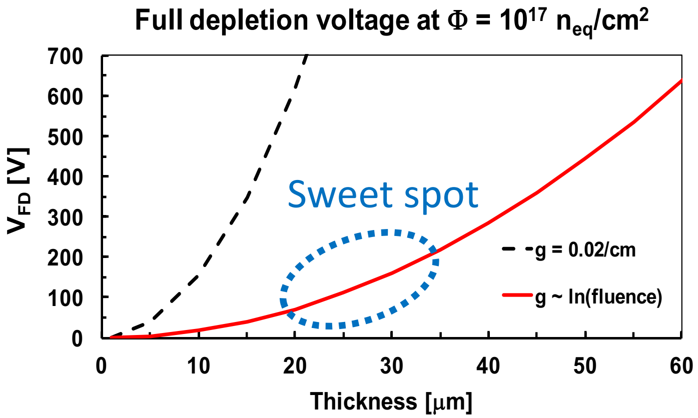
The 37th RD50 Workshop – Zagreb Online Workshop – 18-20.11.2020

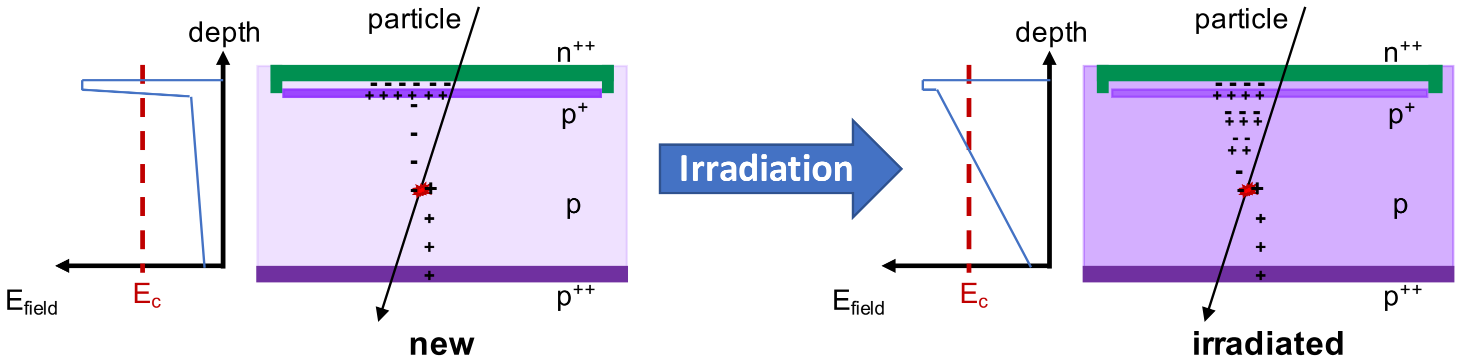
# Silicon Sensors for Extreme Fluences

eXFlu – INFN grant for Young Researchers (project duration: 2 years)
Presented at TREDI2020 [http://indico.cern.ch/event/813597/contributions/3727861/]

**eXFlu goals:**

- ▻ study radiation damage in the fluence region 1 – 10·$10^{16}$ $n_{eq}/cm^2$
- ▻ design silicon sensors able to efficiently operate up to 1·$10^{17}$ $n_{eq}/cm^2$


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

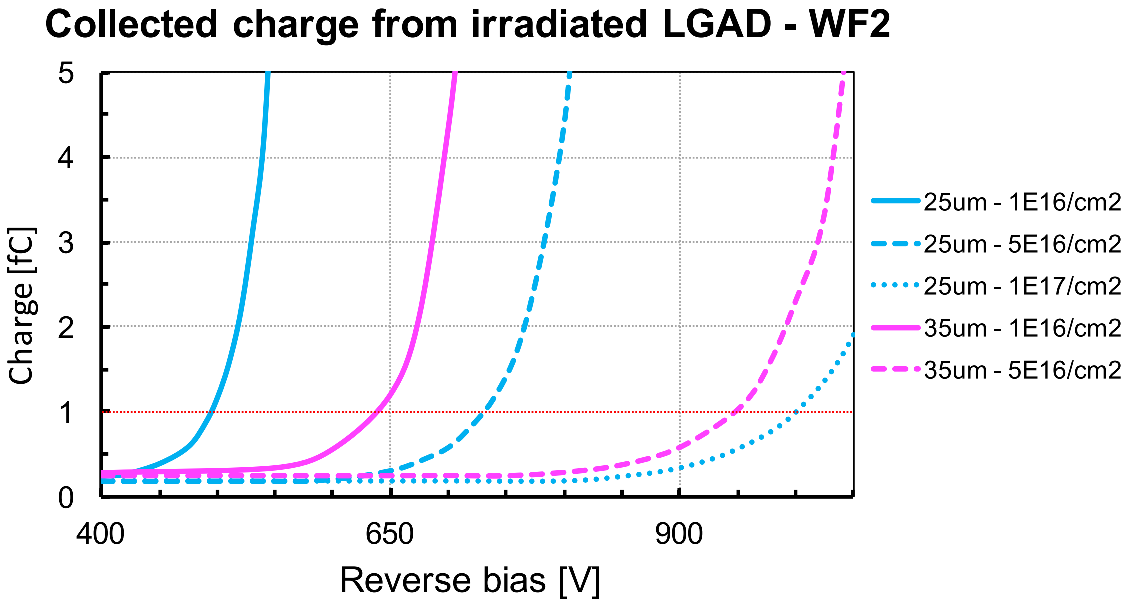


**The idea:** use thin LGAD sensors (20 – 35 µm thick) to provide 1 fC of charge

- ▻ when new, internal signal multiplication from the gain layer
- ▻ with radiation, signal multiplication progressively moves from gain layer to bulk region

More details available at l.infn.it/exflu

# PREDICTIONS



→ **Thinner sensors provide higher gain after irradiation**

**Predictions from Weightfield2** using Massey model for 25 and 35 µm thick sensors**, designed as W5 & W6 UFSD3.2**

`[WF2, l.infn.it/wf2]`

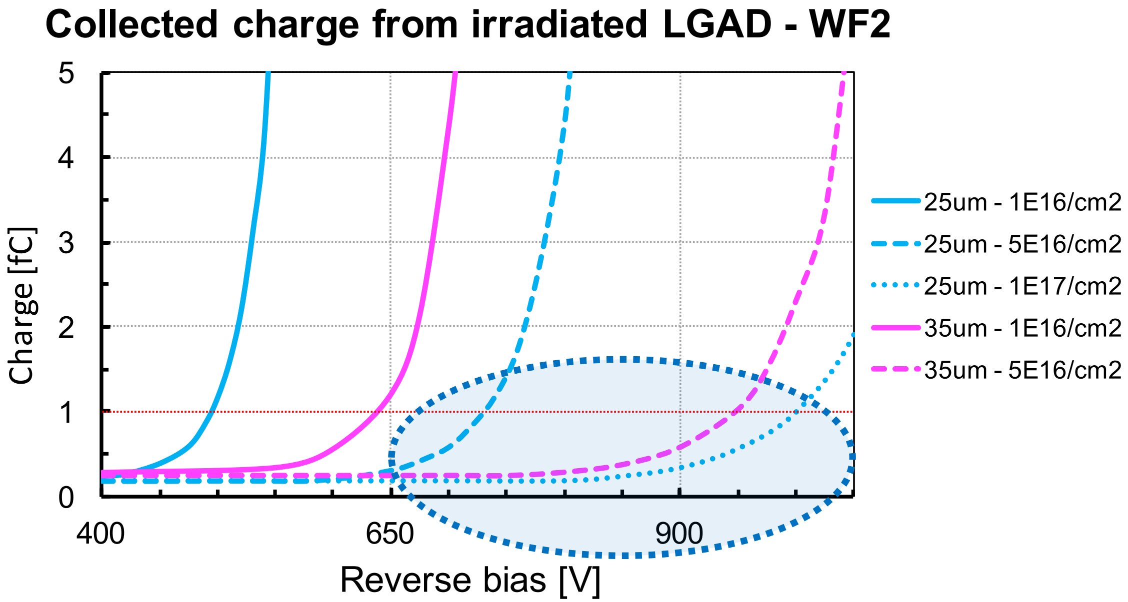
Work in progress with the Perugia group [T. Croci, A. Morozzi, F. Moscatelli, D. Passeri] to simulate thin LGAD behaviour up to extreme fluences

**Perugia model precisely describes behaviour of thin n-in-p sensors up to 1E16 $n_{eq}/cm^2$**

`[A. Morozzi et al., doi:10.22323/1.373.0050]`

→ **Does it predict thin LGAD performances up to 1E17 $n_{eq}/cm^2$ ?**

# PREDICTIONS



→ **Thinner sensors provide higher gain after irradiation**

**Predictions from Weightfield2** using Massey model for 25 and 35 µm thick sensors**, designed as W5 & W6 UFSD3.2**

`[WF2, l.infn.it/wf2]`

Data above 1E16 $n_{eq}/cm^2$ suggest some optimism:

- ▻ `I. Mandic et al., TREDI 2020`
- ▻ `J. Vaitkus et al., this Workshop`

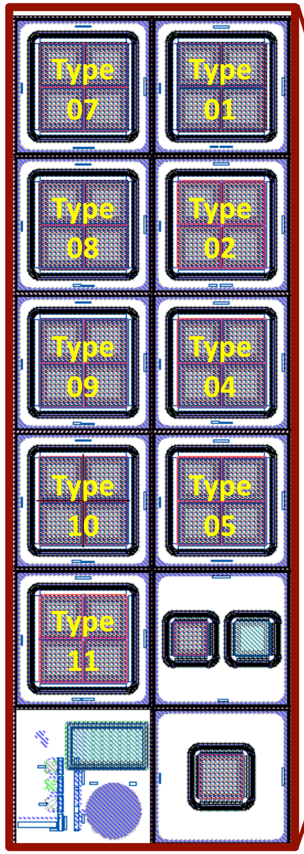
→ **To get the target charge, we need to operate extreme irradiated thin sensors at $V_{bias}$ ~ 700 – 900 V**

# FIRST THIN WAFERS FROM FBK

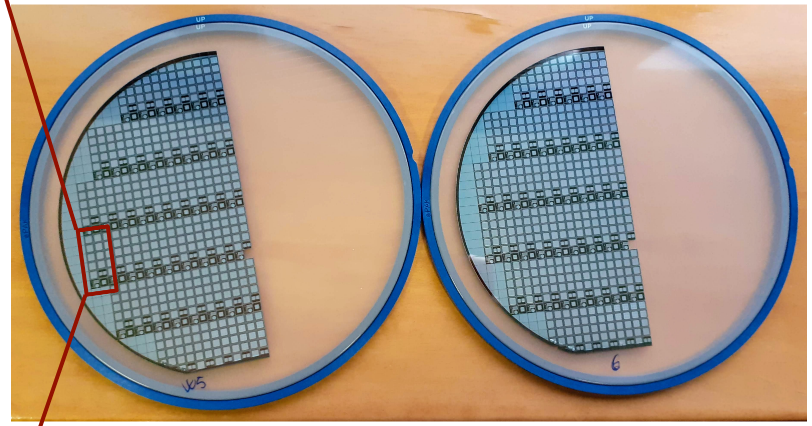
| Wafer # | Thickness | Depth | Dose Pgain | Carbon | Diffusion |
|---|---|---|---|---|---|
| 5 | 25 | Standard | 0.94 | A | CHBL |
| 6 | 35 | Standard | 0.94 | A | CHBL |

2 thin wafers have been produced at FBK (within UFSD3.2 production)

- ▻ epitaxial substrates
- ▻ 2 different wafer thickness: 25 and 35 μm
- ▻ 9 different inter-pad strategies (types)

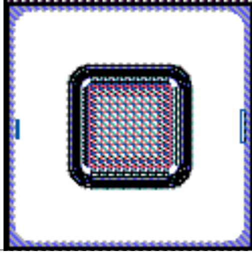


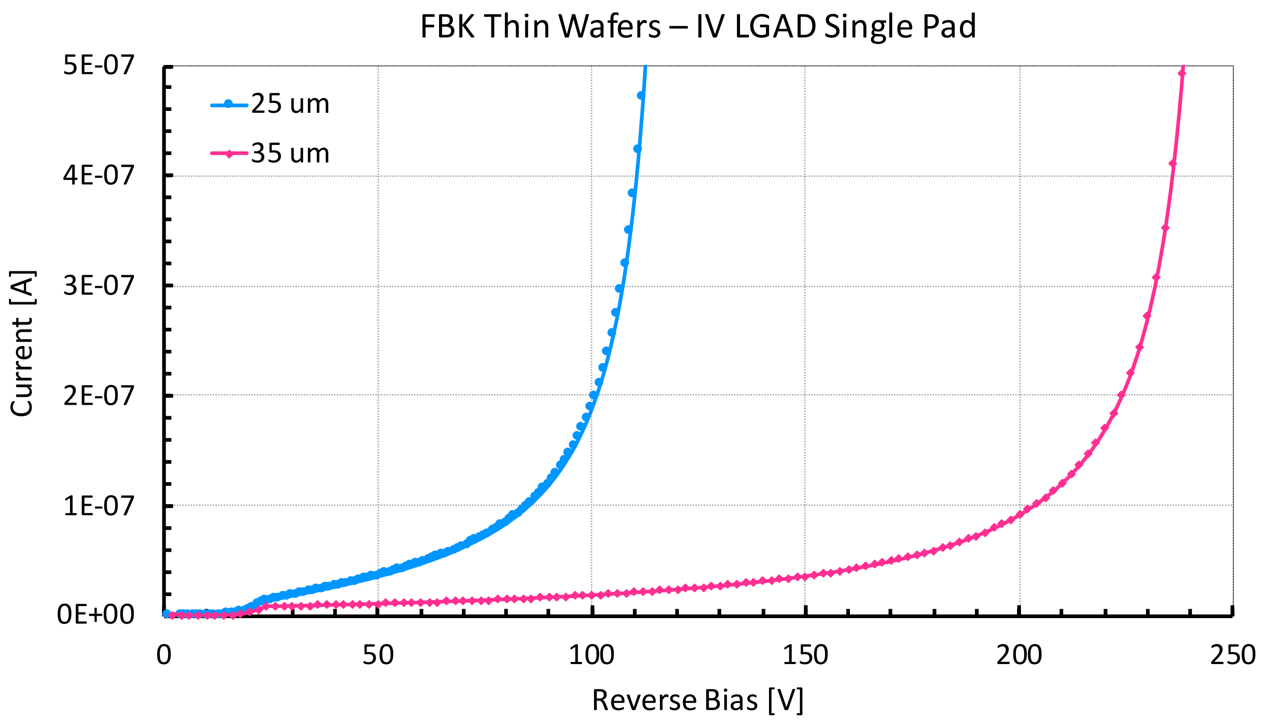
Just arrived in Torino



[Ref for types: https://indico.cern.ch/event/855994/contributions/3637004/]

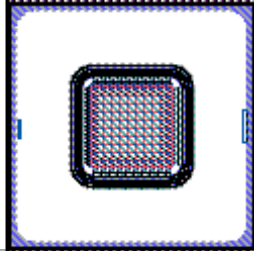
# IV ON THIN LGAD

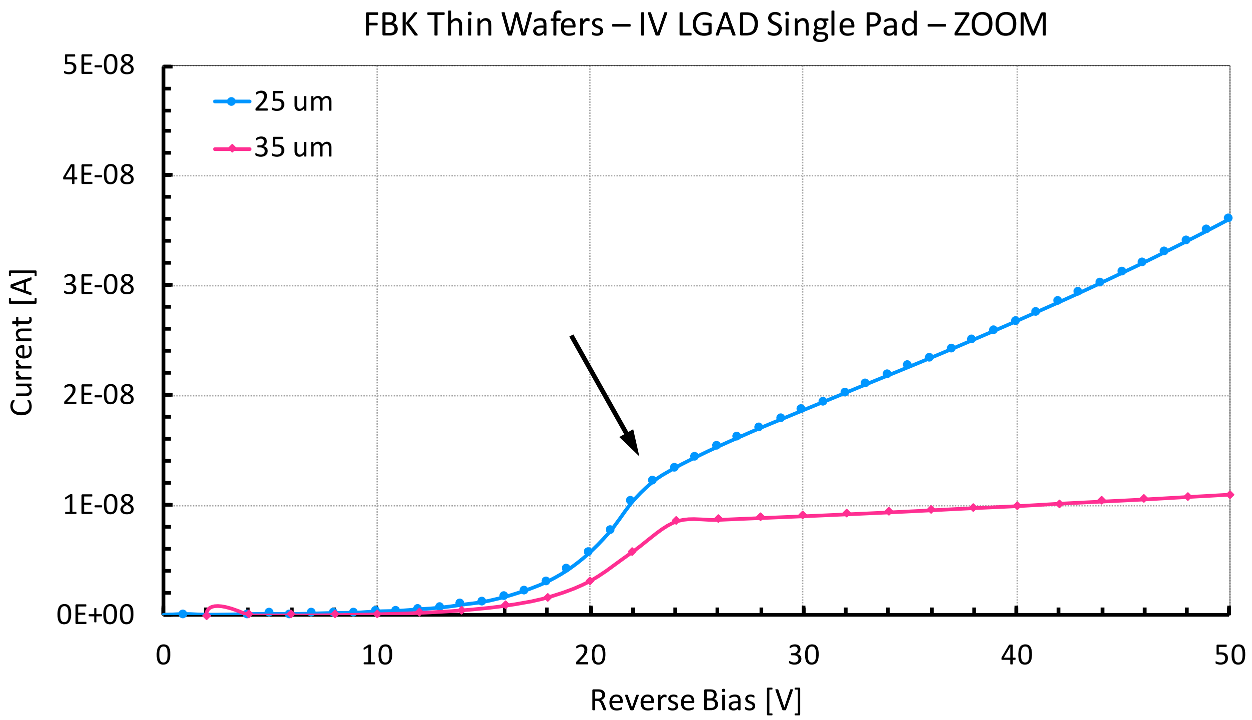




- ▻ Good electrical behaviour
- ▻ Dark current increase due to internal gain
- ▻ On thinner sensors, the same reverse bias trigger a higher gain
- ▻ Gain layer design is the same for both thicknesses

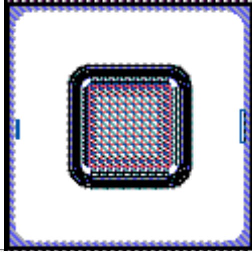
# IV ON THIN LGAD – ZOOM



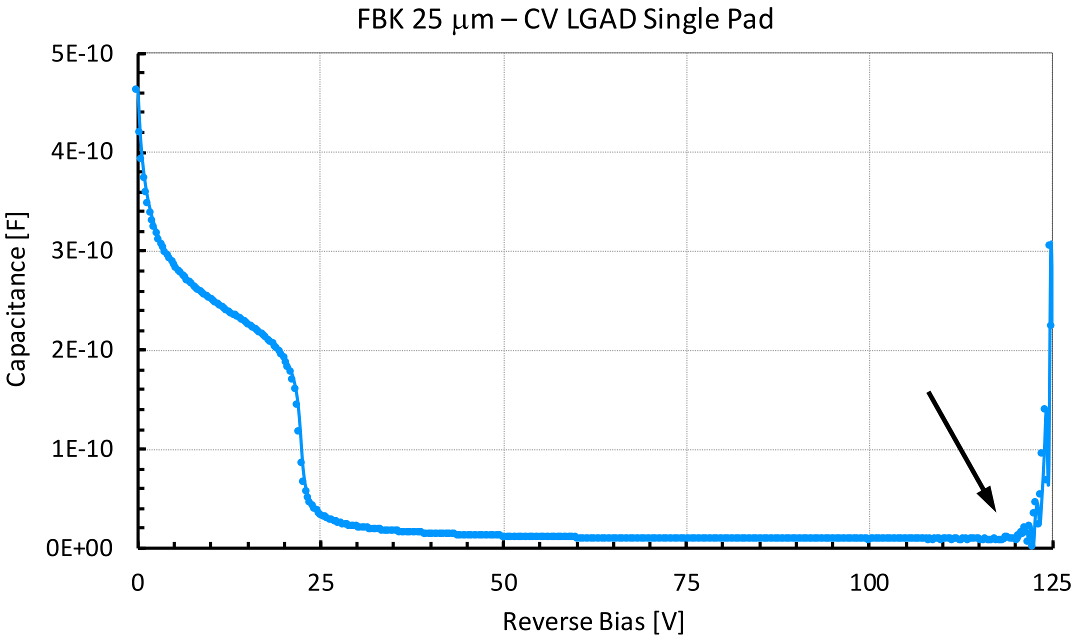


- ▻ Good electrical behaviour
- ▻ Dark current increase due to internal gain
- ▻ On thinner sensors, the same reverse bias trigger a higher gain
- ▻ Gain layer design is the same for both thicknesses
  → Gain layer depletion at ~ 22 V

# CV ON 25 μm WAFER – Low ρ

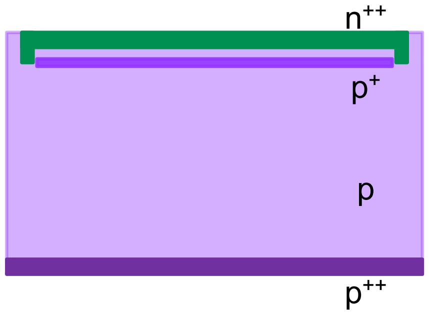


It is difficult to precisely control resistivity of thin epitaxial substrates
→ $\rho_{W5}$ ~ 75 Ω·cm

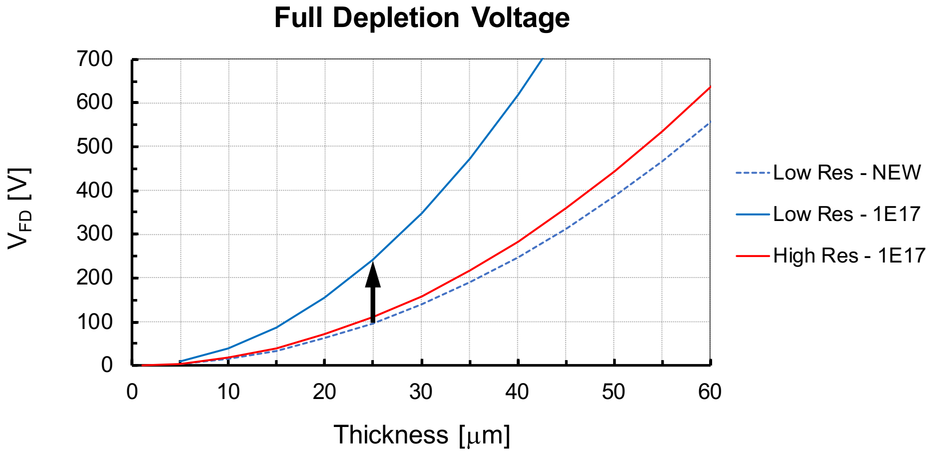


$V_{GL}$ depletion ~ 22 V
$V_{bulk}$ depletion ~ 95 V
Sensor depletion ~ 120 V

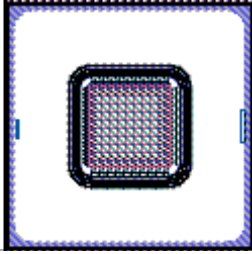
Gain at 120 V ~ 25
Gain at 130 V ~ 40



→ **Thanks to saturation $V_{FD}$ of bulk does not increase dramatically with radiation**

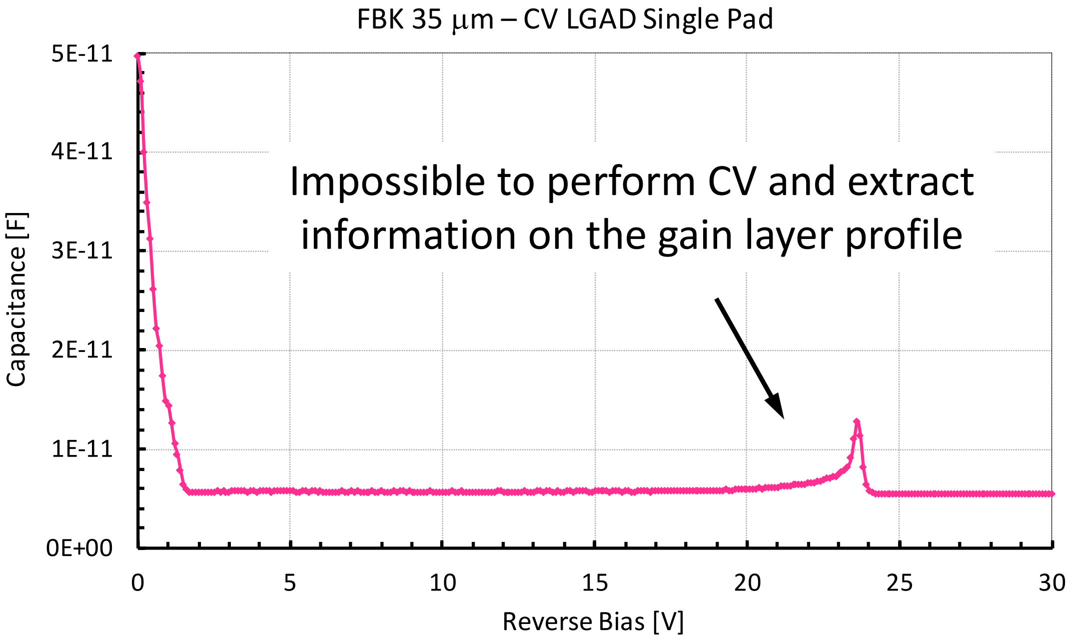


# CV ON 35 µm WAFER – High ρ

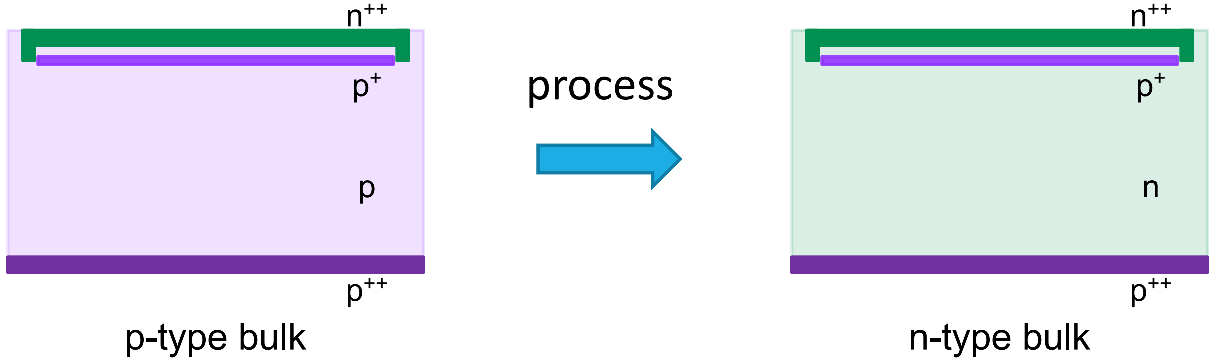


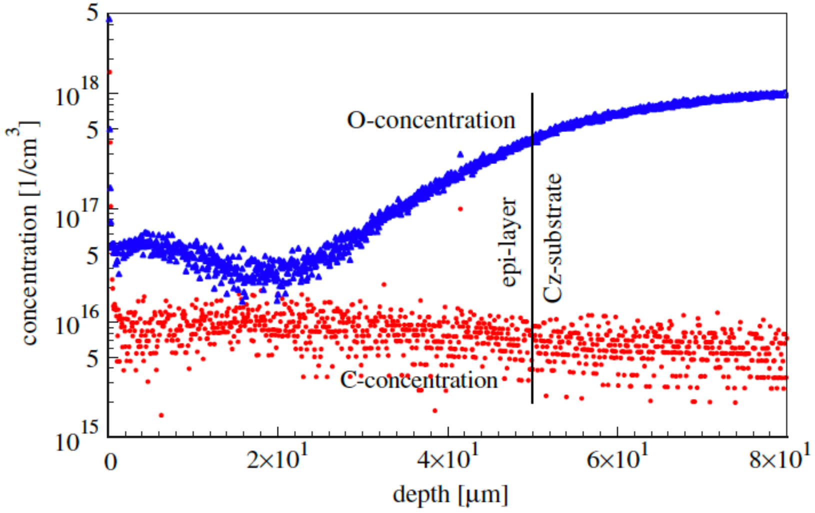
It is difficult to precisely control resistivity of thin epitaxial substrates

→ $\rho_{W6}$ ~ 3,000 Ω·cm



Impossible to perform CV and extract information on the gain layer profile





[I. Pintilie et al. (2005) doi:10.1016/j.nima.2005.10.013]

→ **Due to Oxygen diffusion from the support wafer, the active substrate undergo type inversion**

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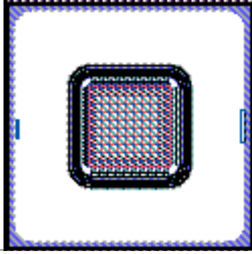
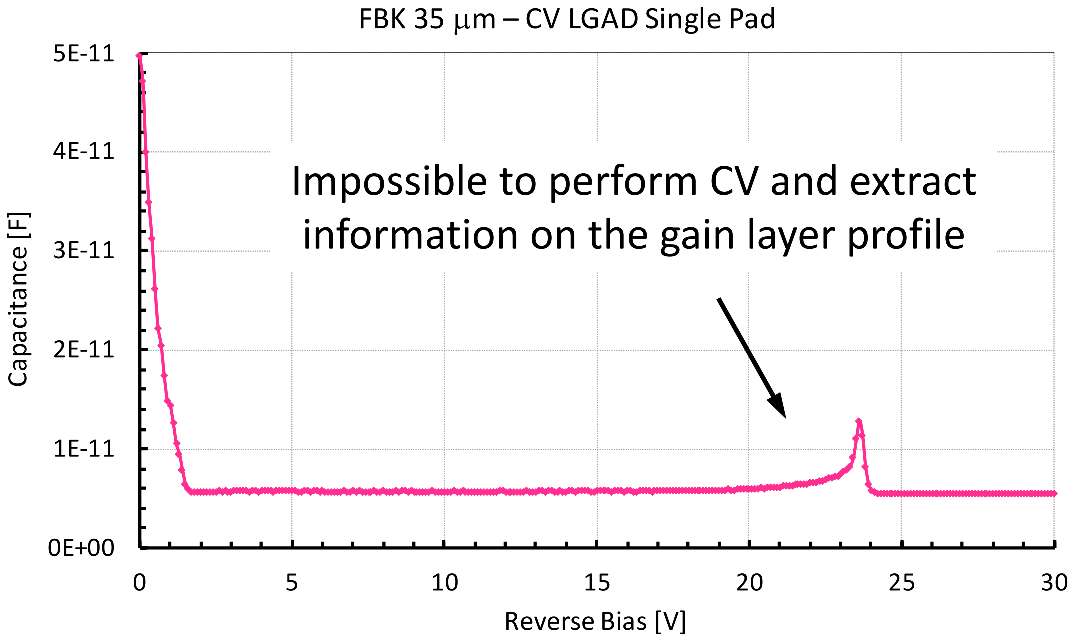


It is difficult to precisely control resistivity of thin epitaxial substrates

→ $\rho_{W6} \sim 3{,}000\ \Omega\cdot\text{cm}$



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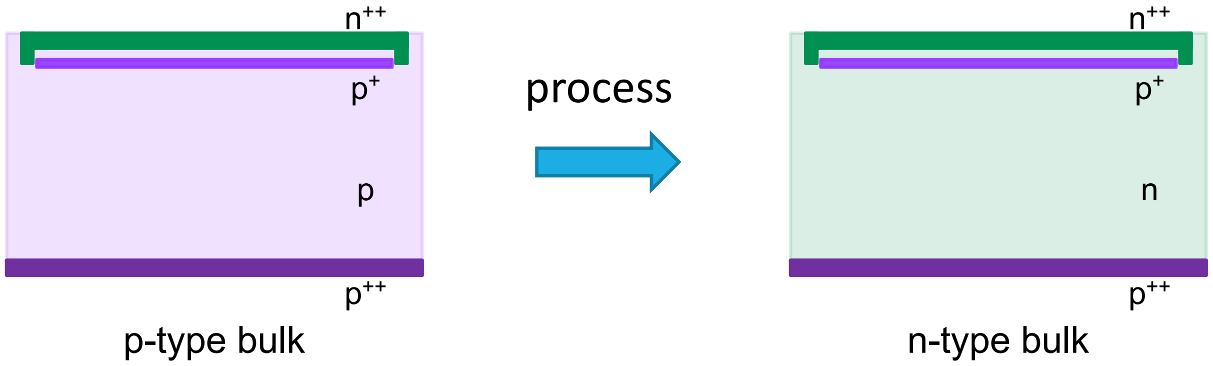

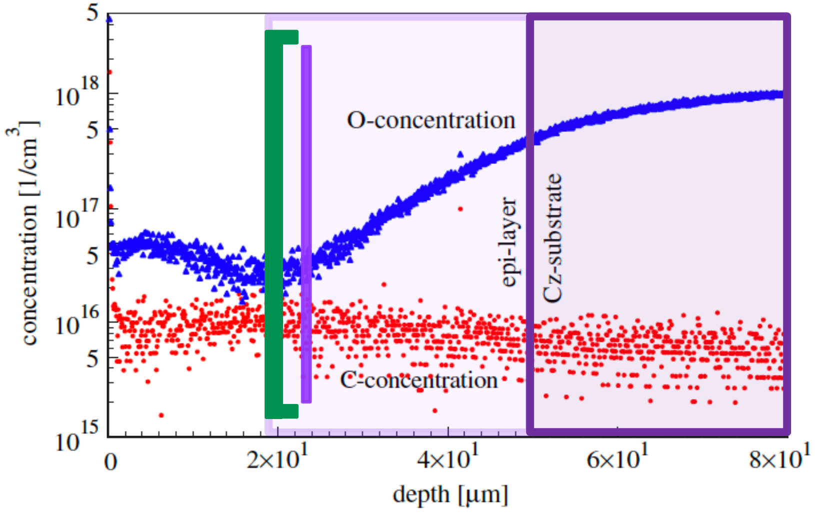

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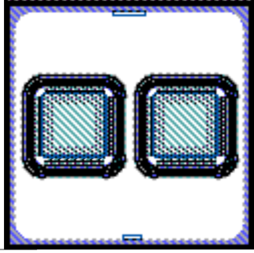
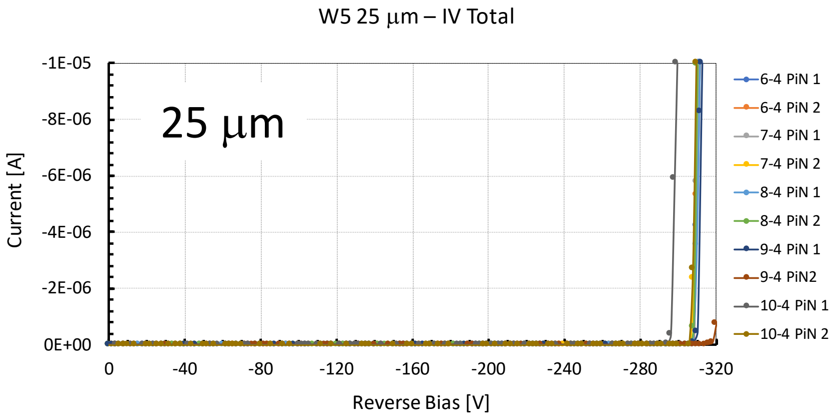
→ **Due to Oxygen diffusion from the support wafer, the active substrate undergo type inversion**

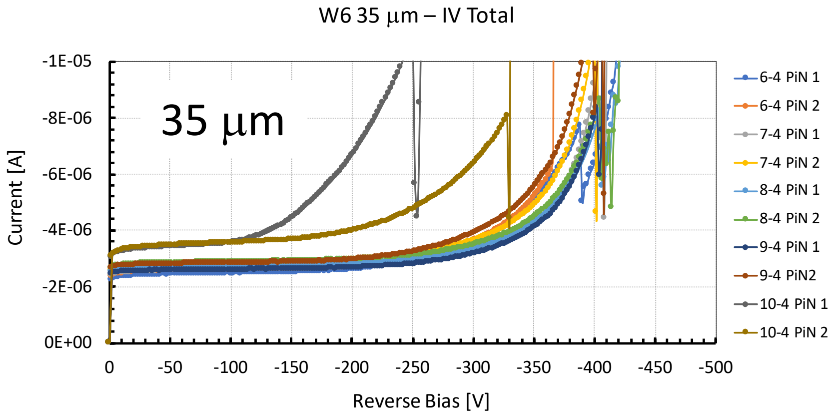
# BREAKDOWN ON THIN PiN SENSORS



On UFSD3.2 wafers, there is a row with no gain layer implantation

The breakdown has been studied on 5 PiN-PiN structures





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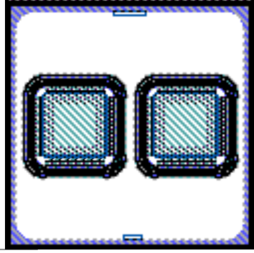

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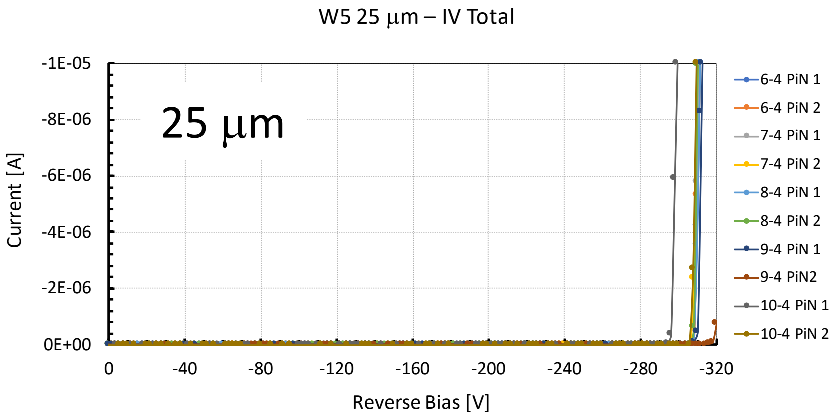
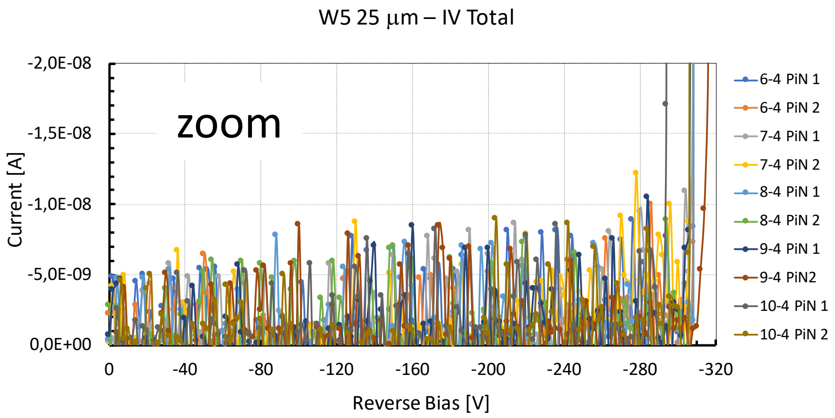

W5 25 μm – IV Total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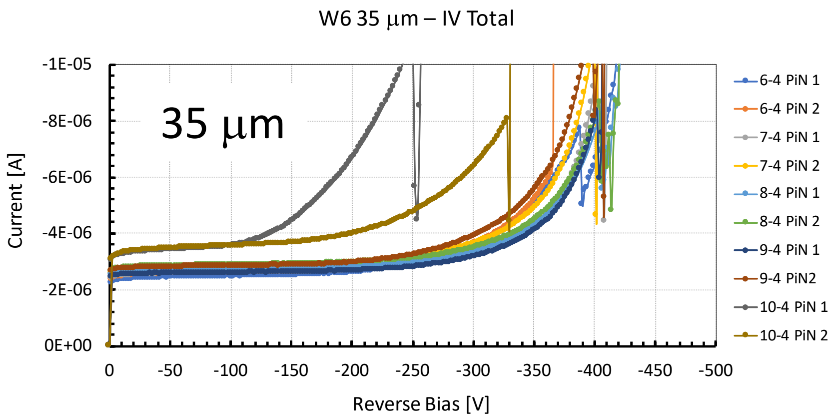
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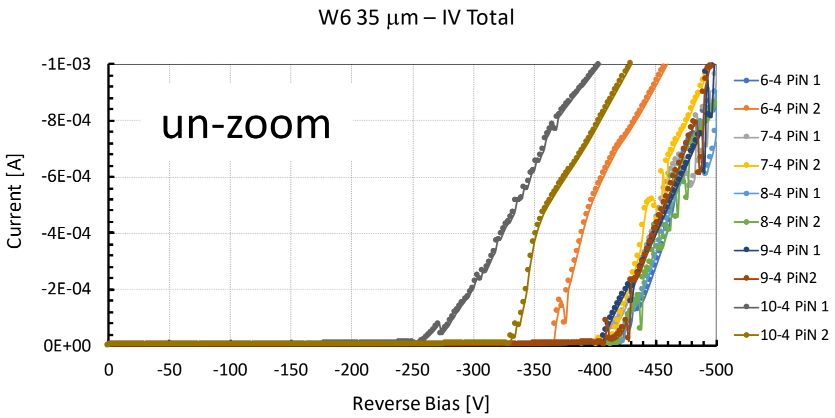
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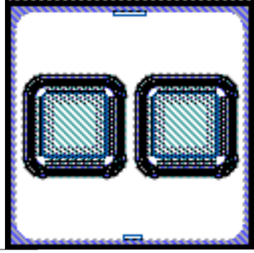

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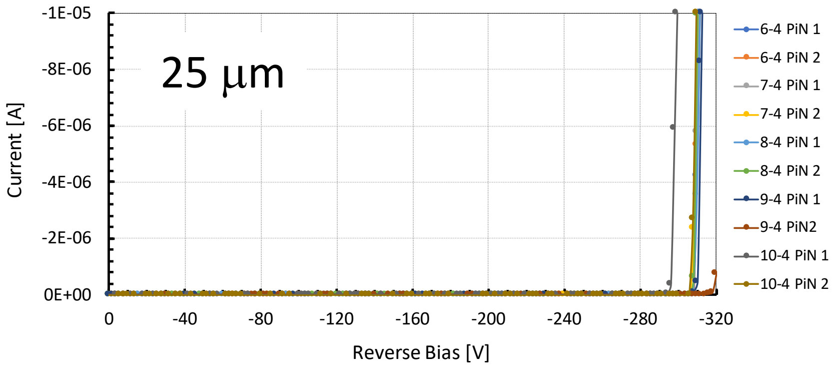

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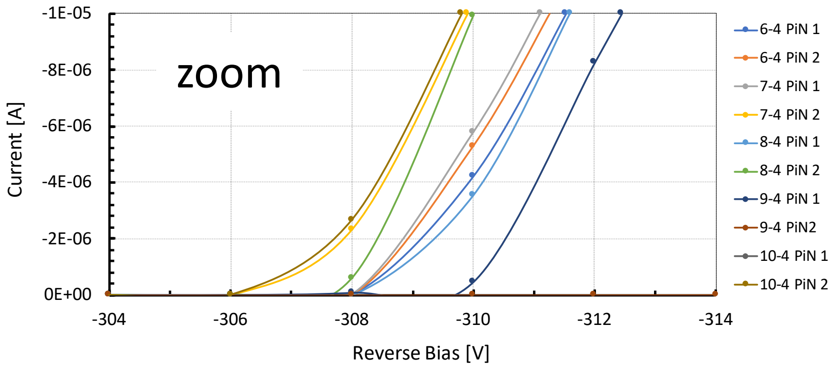

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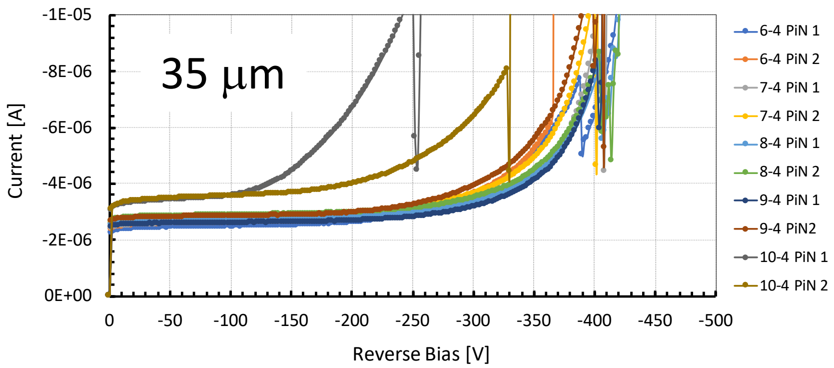
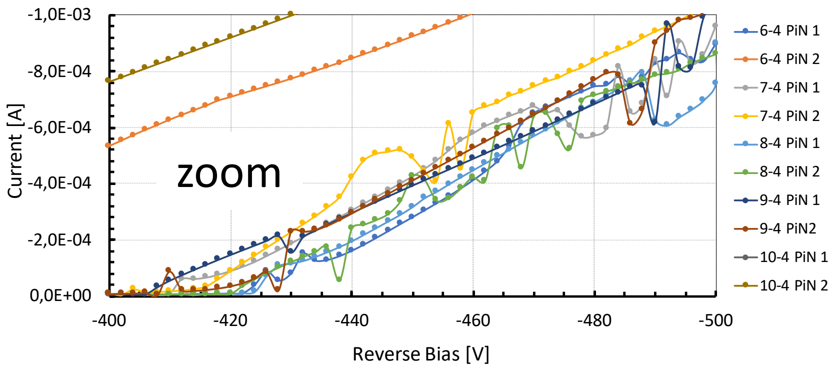


W6 35 µm – IV Difference



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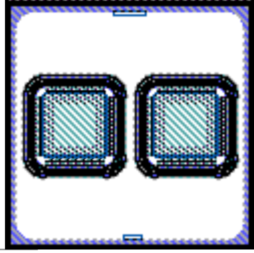

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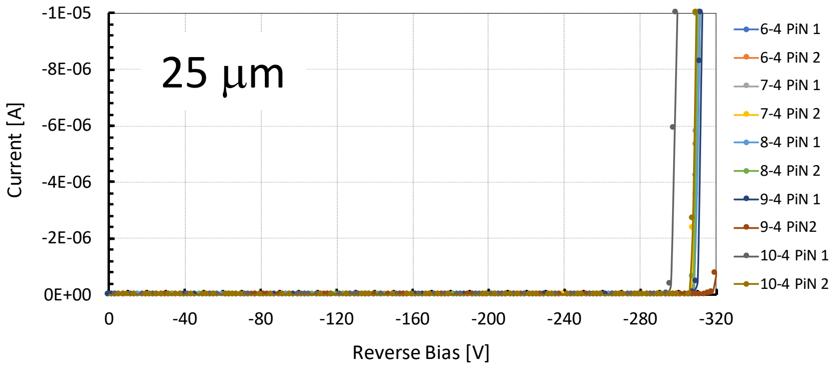
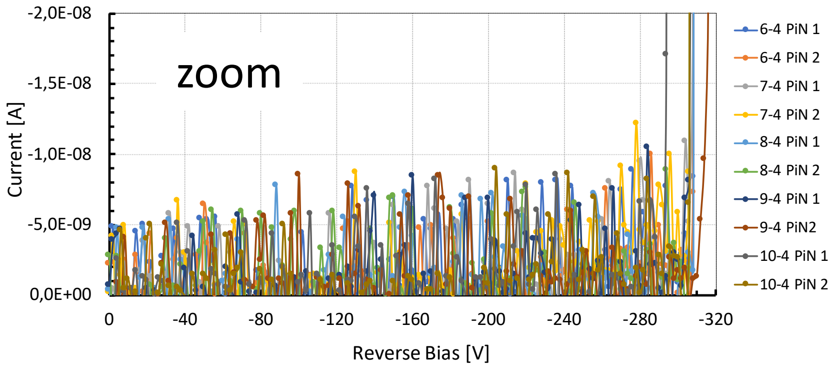
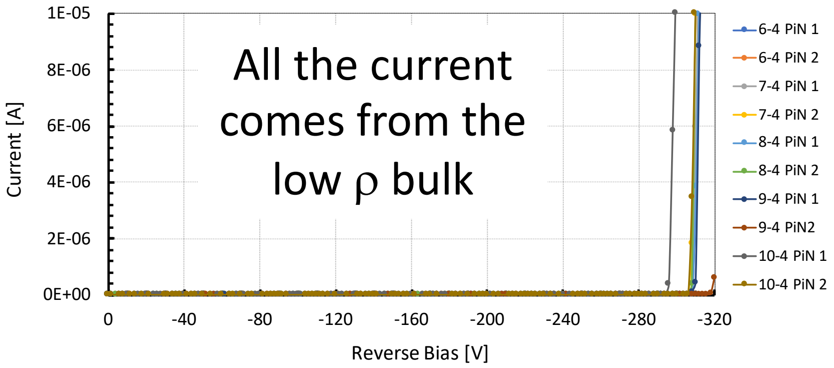

W5 25 μm – IV Total

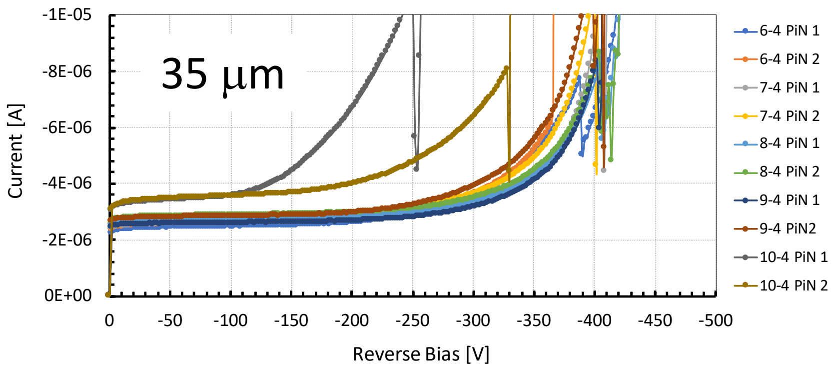
25 μm


W5 25 μm – IV Total

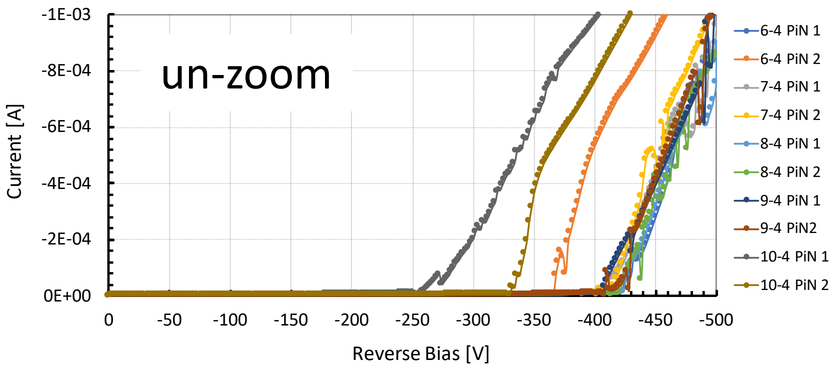
zoom


W5 25 μm – IV on PAD

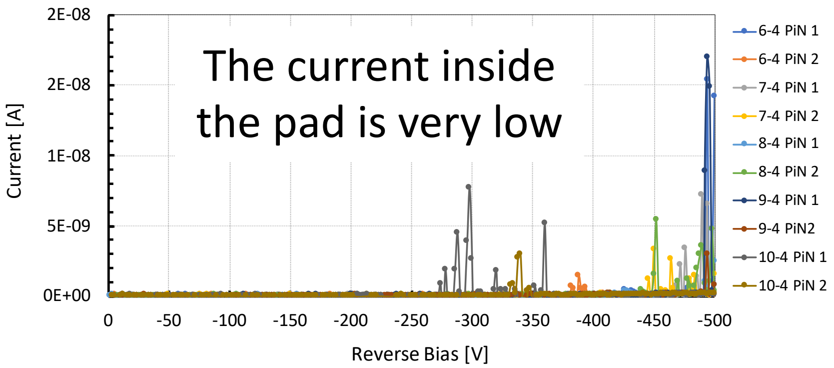
All the current comes from the low ρ bulk


W6 35 μm – IV Total

35 μm


W6 35 μm – IV Total

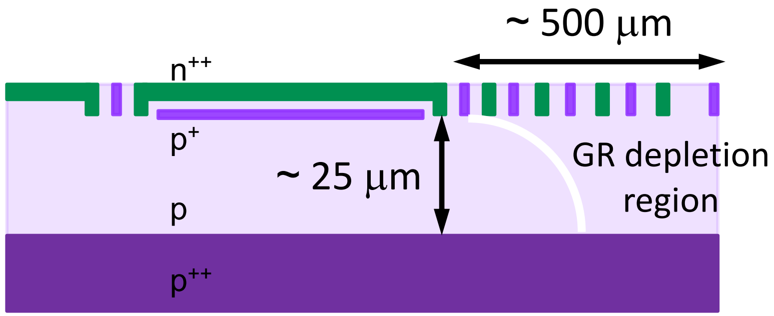
un-zoom


W6 35 μm – IV on PAD

The current inside the pad is very low

# GUARD-RING DESIGN FOR THIN SENSORS

Sketch not
to scale



→ **R&D on guard-ring structures is mandatory**

For UFSD3.2 PiN sensors, before irradiation $V_{BD} > 500$ V
When new, $V_{BD}$ on PiN occurs at a higher bias than $V_{BD}$ due to gain and do not limit sensor operation
→ **UFSD3.2 guard rings work nicely before irradiation**

Once irradiated at 1E17 $n_{eq}/cm^2$, guard rings need to sustain ~ 800 V over a thickness of ~ 25 μm
→ **Is it possible?**

Guard-ring needs a new design for extreme irradiated thin substrates:
- **How many rings do we need on ~ 25 μm thick structures?**
- **How far should be the pad from the physical sensor edge?**

# NEXT STEPS

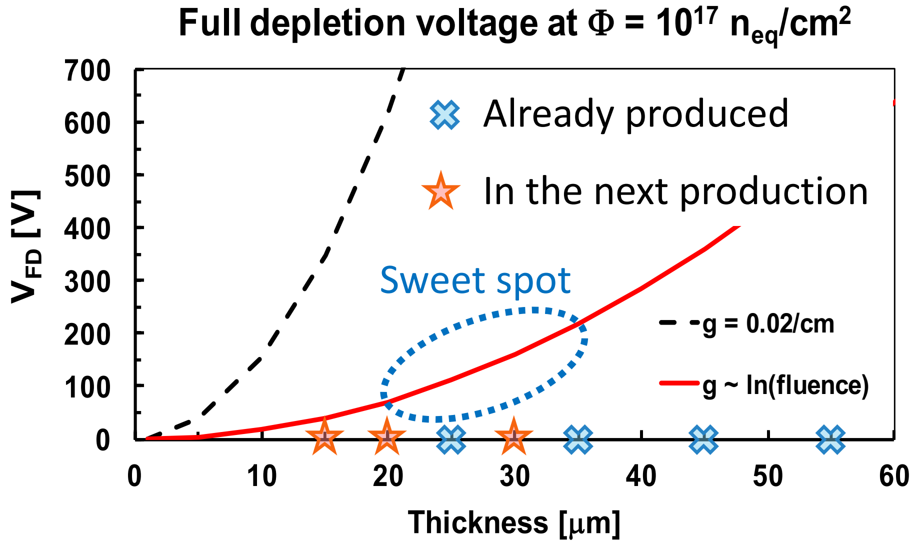
- **Irradiate thin UFSD3.2 sensors up to 1E17 $n_{eq}/cm^2$ and measure the irradiation effects on thin substrates**

- **Optimise the gain-layer and guard-ring design for the next thin wafer production**

  15, 20, and 30 μm thick epitaxial wafers in production

  ⟶ 15 & 20 μm thick substrate requested ρ = 75 Ω·cm

  ⟶ 30 μm substrate requested ρ > 200 Ω·cm (intrinsic)



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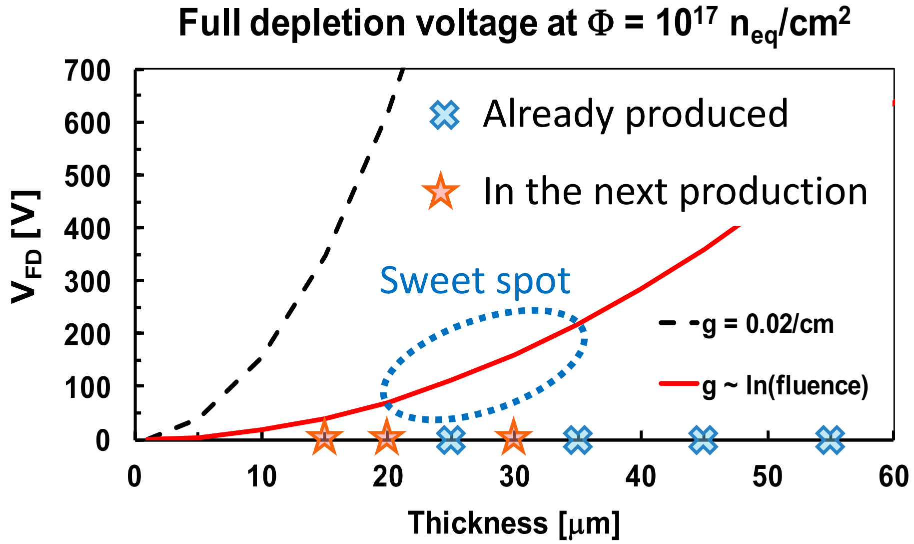

**Thank you for your attention**

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# ACKNOWLEDGEMENTS

We kindly acknowledge the following funding agencies, collaborations:

- RD50, CERN
- Horizon 2020, grant UFSD669529
- AIDA-2020, grant agreement no. 654168
- MIUR, Dipartimenti di Eccellenza (ex L. 232/2016, art. 1, cc. 314, 337)
- Ministero della Ricerca, Italia, PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
- Ministero della Ricerca, Italia, FARE, R165xr8frt_fare
- INFN CSN5

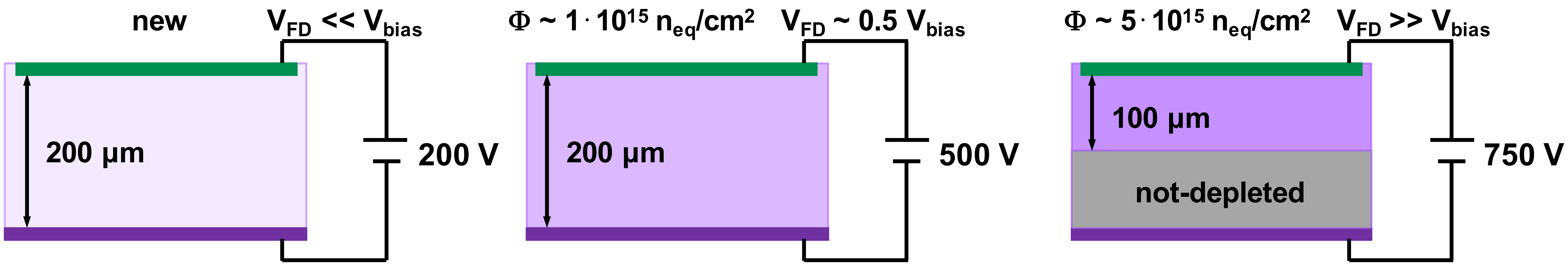
# BACKUP

# EFFECTS OF RADIATION ON SILICON SENSORS

**Irradiation results in 3 main effects:**

- ▻ Decrease of the collected charge due to trapping effects
- ▻ Increase of the dark current
- ▻ Change in effective doping
  - → increase of the reverse bias to operate the sensor
  - → distortion of the electric field inside the sensor

**Irradiation models developed in the fluence range $10^{14} – 10^{15}$ $n_{eq}/cm^2$ predict standard silicon detectors (~ 200 $\mu$m) are almost impossible to operate**



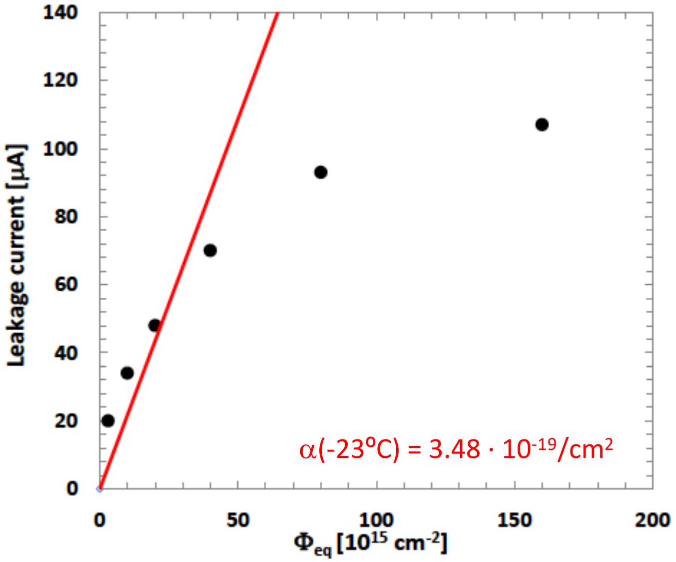
Fully depleted at low $V_{bias}$

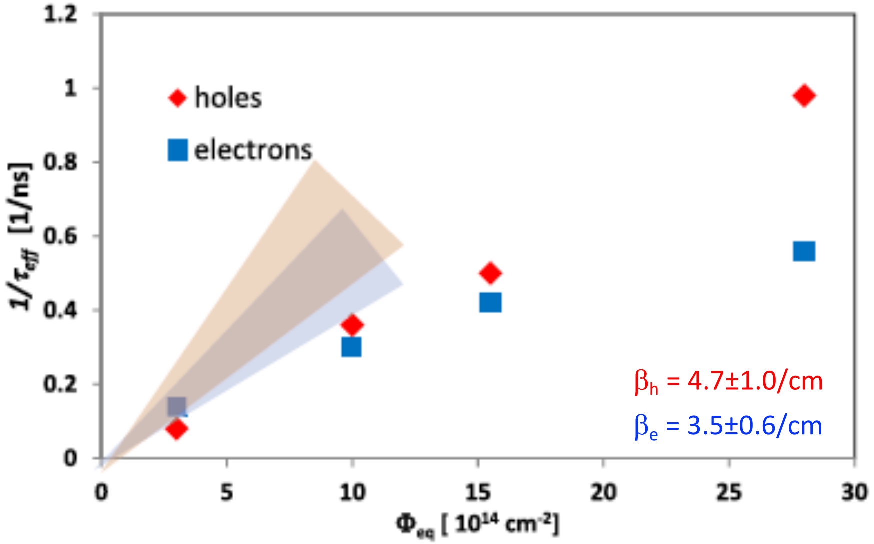
Fully depleted at high $V_{bias}$

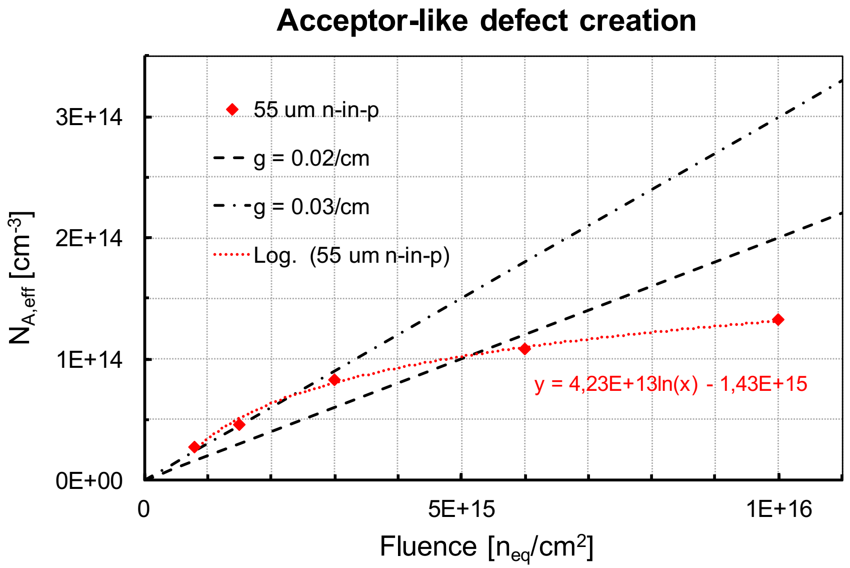
Partially depleted at very high $V_{bias}$

# SOME OPTIMISM – SATURATION

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







[G. Kramberger et al., doi:10.1088/1748-0221/8/08/P08004]

[G. Kramberger et al., doi:10.1016/j.nima.2018.08.034]

[M. Ferrero et al., 34th RD50 Workshop, Lancaster, UK]

**Leakage current saturation**

$I = \alpha V \Phi$

**$\alpha$ from linear to logarithmic**

**Trapping probability saturation**

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

**$\beta$ 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**

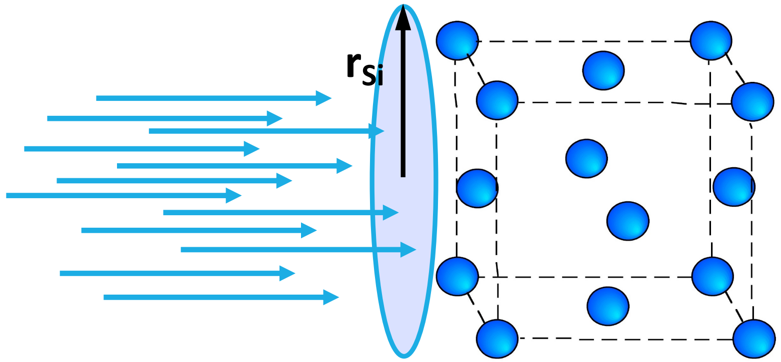
# WHY SATURATION?

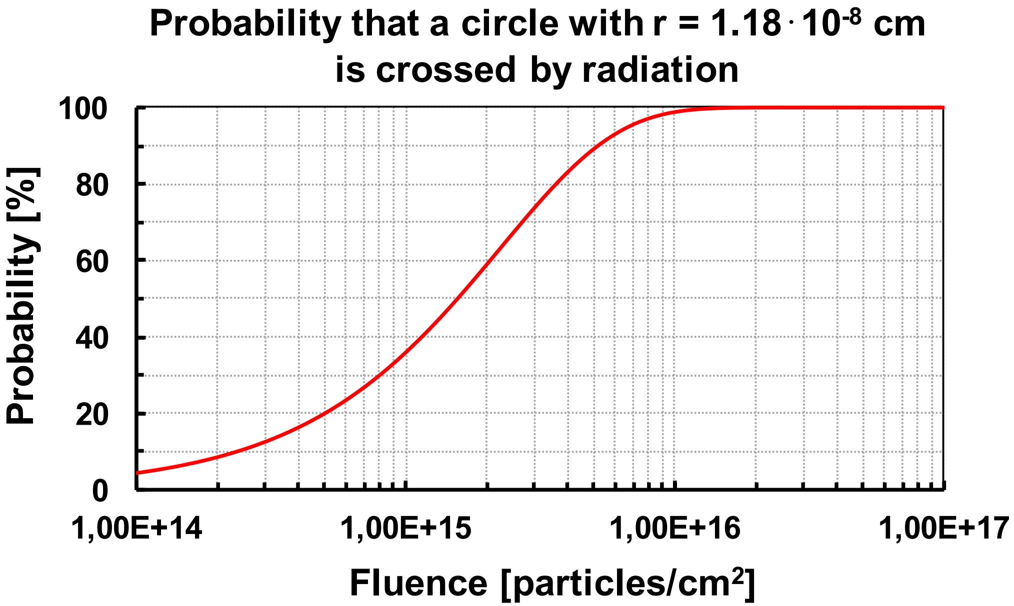
**Possible explanation:**

The distance between two atoms,
the so-called Silicon radius, is
**$r_{Si} = 1.18 \cdot 10^{-8}$ cm**

**The probability that a circle of radius $r_{Si}$ has been crossed by a particle becomes 1 at $10^{16}$ particles/cm$^2$**

**Above $10^{16}$ particles/cm$^2$:**
damage happening on already damaged Silicon might be different



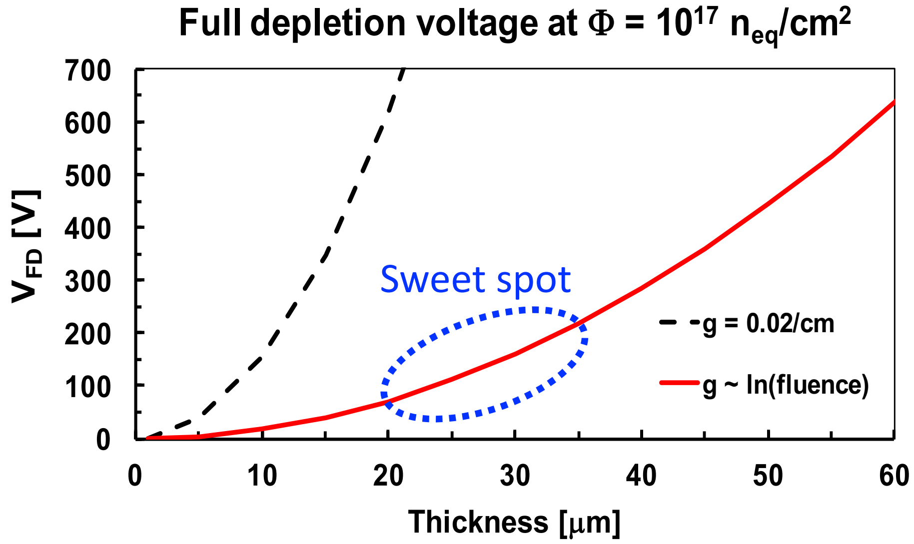


# GO THIN

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

**Saturation** **Reduce thickness**

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


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 almost absent
- ▻ 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)**

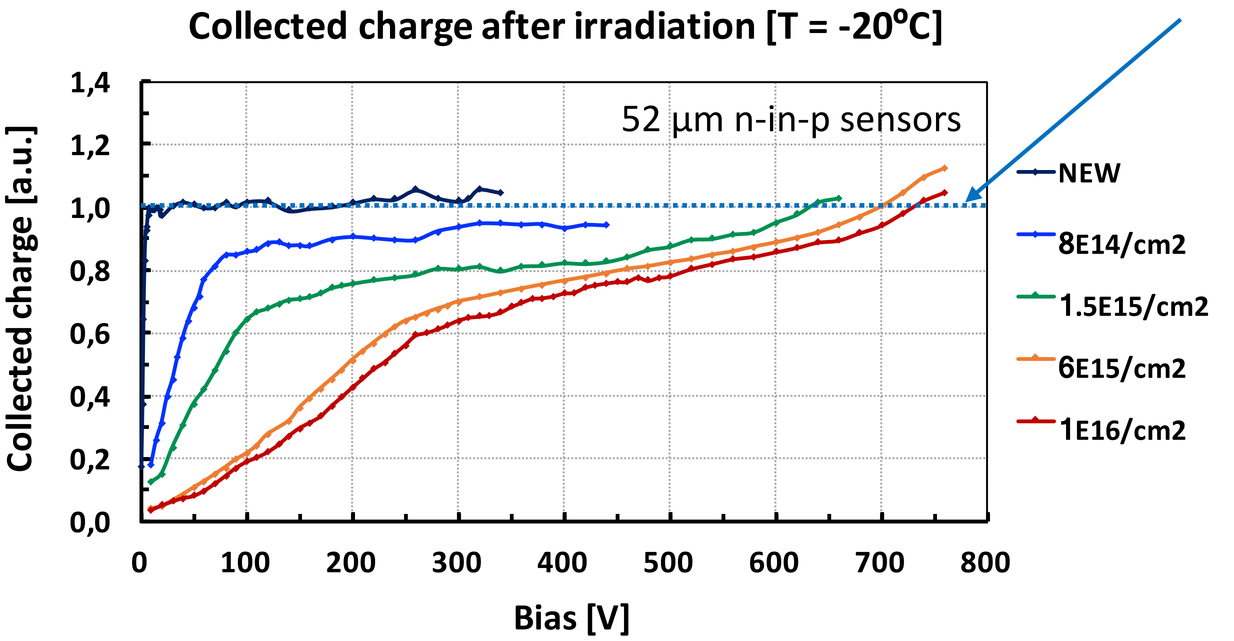
→ **Need a gain of at least ~ 5 in order to provide enough charge**

# HOW THIN?

To efficiently record a hit, electronics require al least **1 fC**

MPV charge from a MIP crossing silicon ~ 75 e-h/µm
52 µm thick → 0.52 fC
25 µm thick → 0.25 fC

**Signal multiplication by a factor of 5-10 is needed**

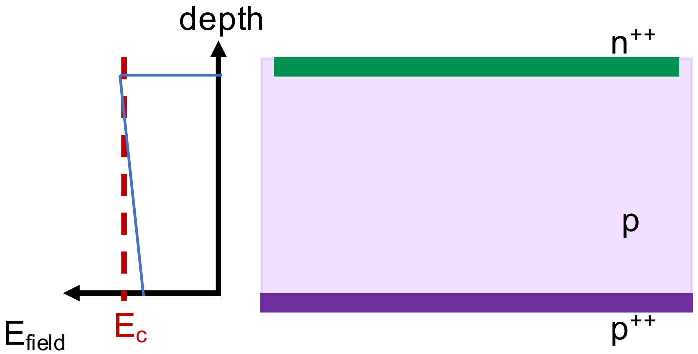


# SENSOR CHOICE

**Impact ionisation occurs when $E_{field} > E_c = 250$ kV/cm**

**→ How to get internal multiplication of 5-10? Stable gain if:**

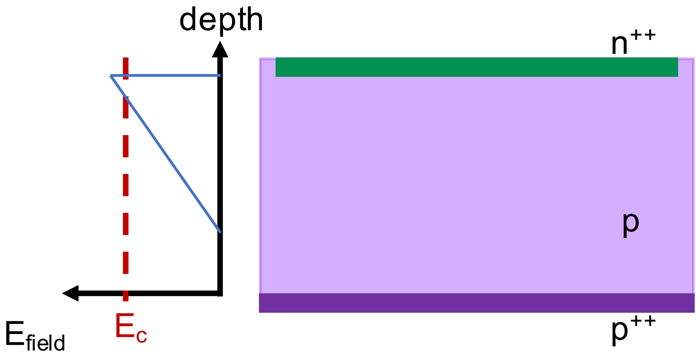
1) **$E_{field} > E_c$ for a short distance**
2) **This length is controlled by applied $V_{bias}$**



**n-in-p**
**$p \sim 10^{12}$ cm$^{-3}$**

$E_{field}$ above $E_c$
over long distance

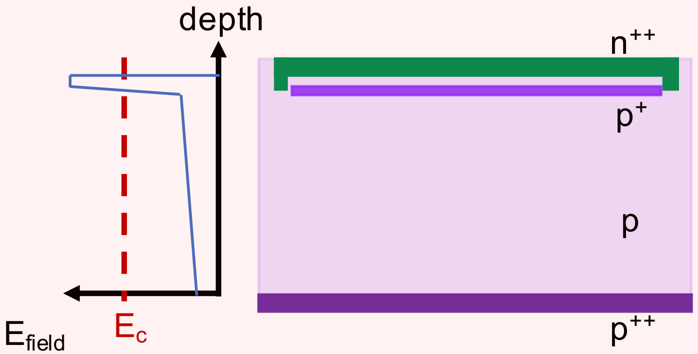
**AVALANCHE**



**n-in-p**
**$p \sim 10^{14}$ cm$^{-3}$**

Difficult to precisely
control $E_{field}$

**RISK OF AVALANCHE**

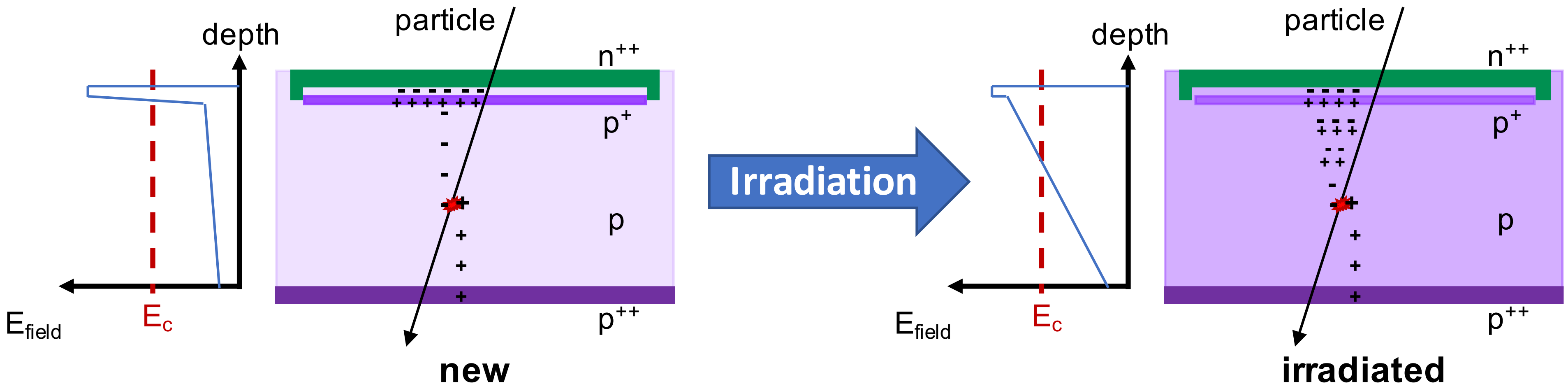


**LGAD**
**$p \sim 10^{12}$ cm$^{-3}$, $p^+ \sim 10^{16}$ cm$^{-3}$**

$E_{field}$ above $E_c$
for short distance
well controlled by $V_{bias}$

**CONTROLLED GAIN**

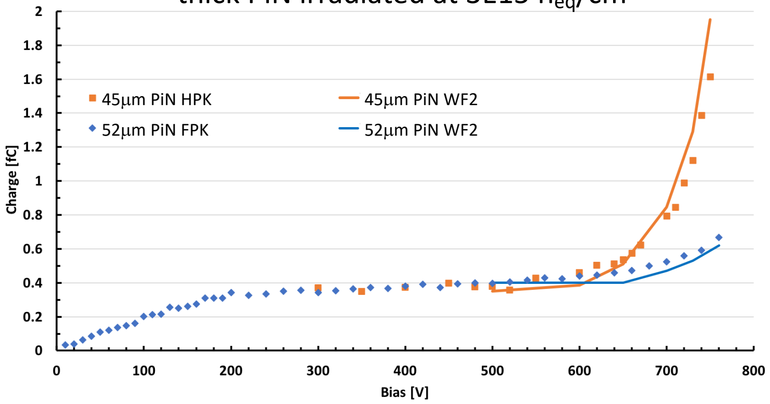
# IRRADIATED LGAD



- Start with a thin LGAD, 20 – 35 μm thick (to be optimized)
- **$2\cdot10^{15} – 5\cdot10^{15}$ $n_{eq}/cm^2$**: with increasing fluence, the gain layer is deactivated
- **$5\cdot10^{15} – 10^{16}$ $n_{eq}/cm^2$**: compensate the decrease power of the gain layer by shifting the multiplication region to the bulk
- **$10^{16} – 10^{17}$ $n_{eq}/cm^2$**: rely solely on bulk multiplication

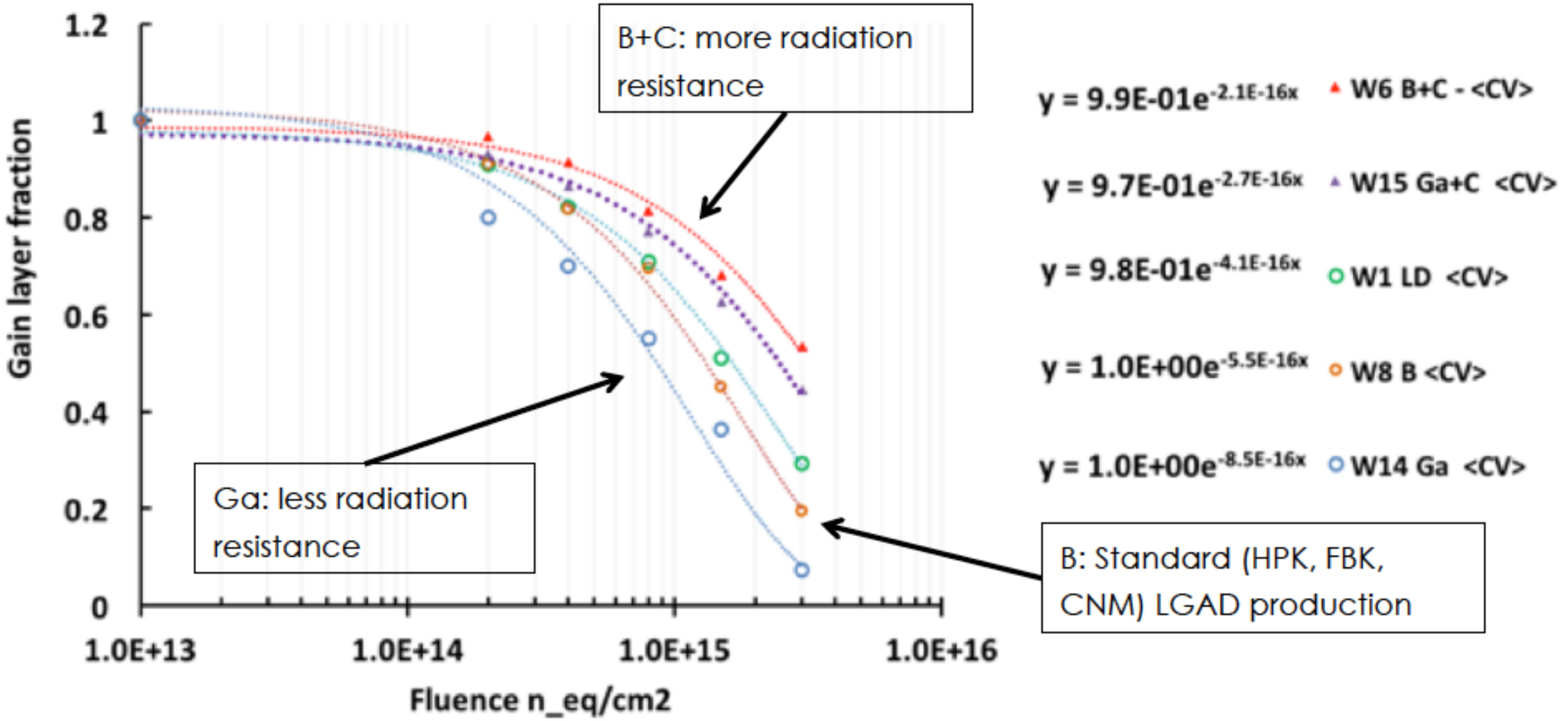
  → **Does bulk multiplication exist at these fluences?**

Collected charge for 45μm and 52μm thick PiN irradiated at 3E15 $n_{eq}/cm^2$



# GAIN LAYER RADIATION TOLERANCE

UFSD suffer for gain reduction due to irradiation
FBK used both Boron and Gallium as gain layer dopant, and added Carbon in the gain layer volume



B+C: more radiation resistance

Ga: less radiation resistance

B: Standard (HPK, FBK, CNM) LGAD production

**⇒ The usage of Carbon double the radiation hardness of UFSD**

# GAIN LAYER RADIATION TOLERANCE

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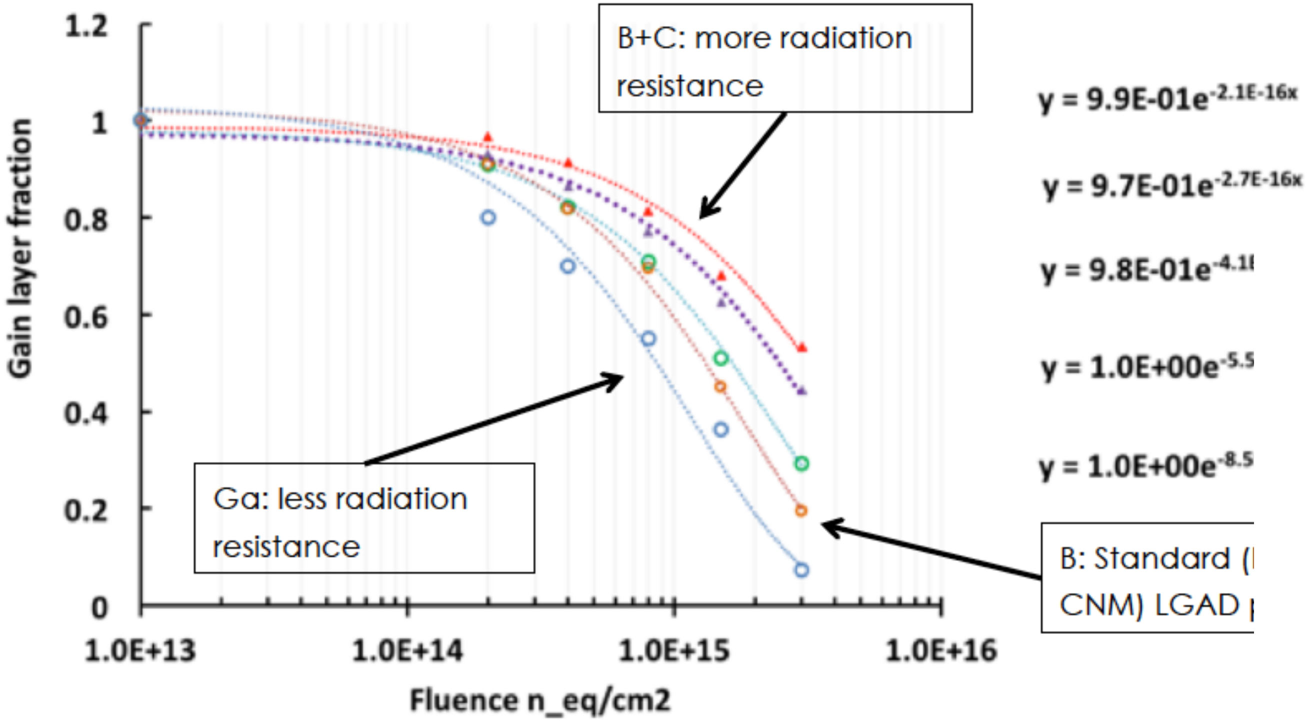


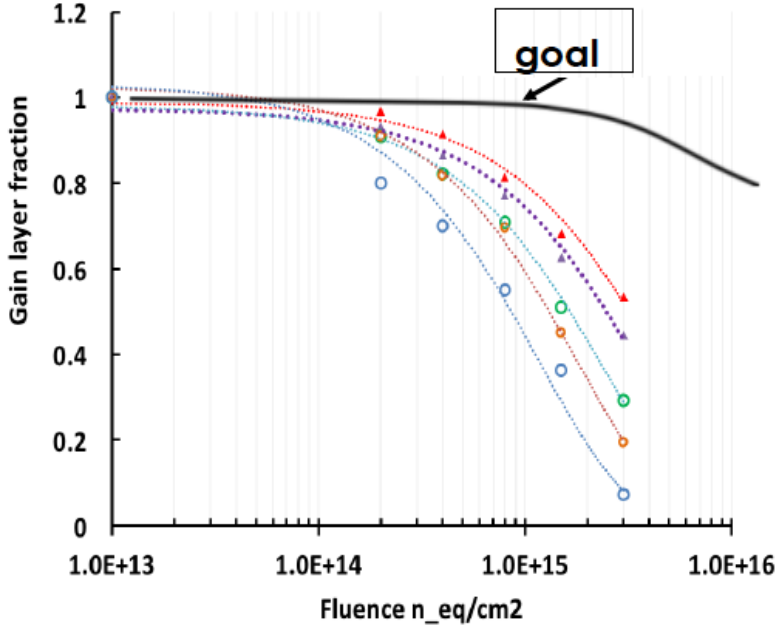
B+C: more radiation resistance

Ga: less radiation resistance

B: Standard (

CNM) LGAD

## Future R&D



⇒ **The usage of Carbon double the radiation hardness**

# GAIN LAYER RADIATION TOLERANCE

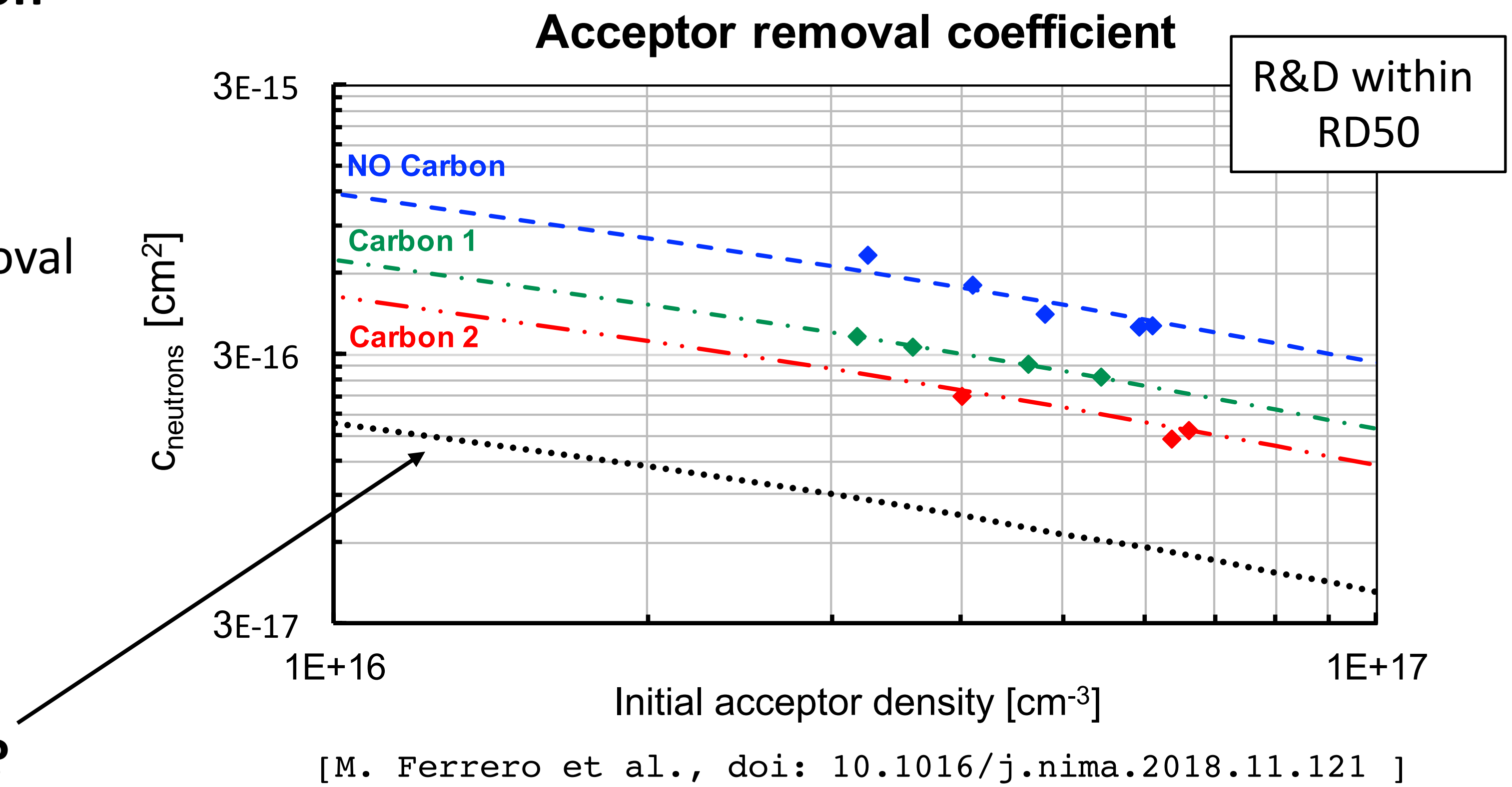
**Goal: retard multiplication transition from the gain layer to the bulk region**

Acceptor removal:

$$N_{A,eff} = N_{A,0} \cdot e^{c\Phi}$$

Adding carbon protects boron from removal
Different carbon concentrations have different impact on boron protection

→ **Gain layer engineering to extend its contribution to $5 \cdot 10^{16}$ $n_{eq}/cm^2$**



[M. Ferrero et al., doi: 10.1016/j.nima.2018.11.121 ]

# GAIN LAYER RADIATION TOLERANCE

**Goal: retard multiplication transition from the gain layer to the bulk region**

Acceptor removal:

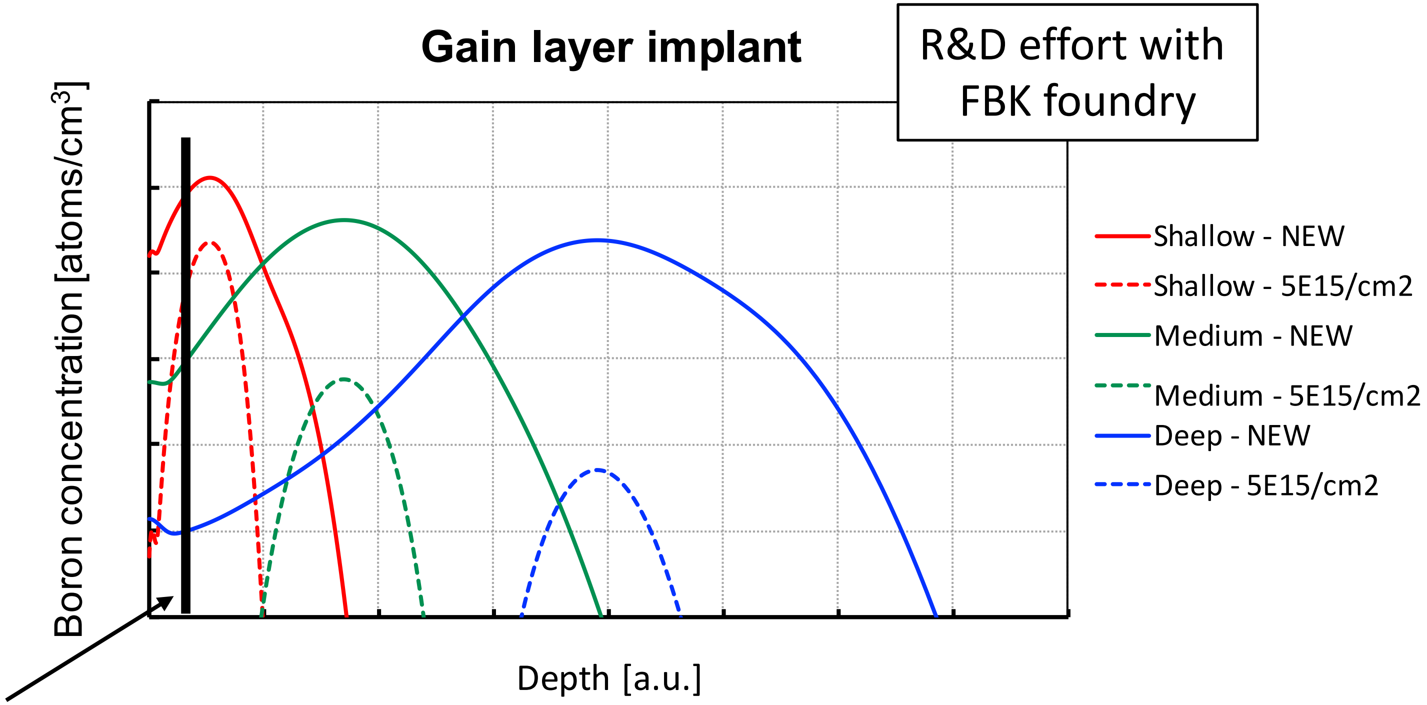
$$N_{A,eff} = N_{A,0} \cdot e^{c\Phi}$$

Defect engineering and different gain layer implantation strategies will be investigated

$$\mathbf{c \cdot N_{A,0} = 60\ cm^{-1} \rightarrow\ < 10\ cm^{-1}}$$

for $N_{A,0} = 10^{17}$ atoms/cm$^3$

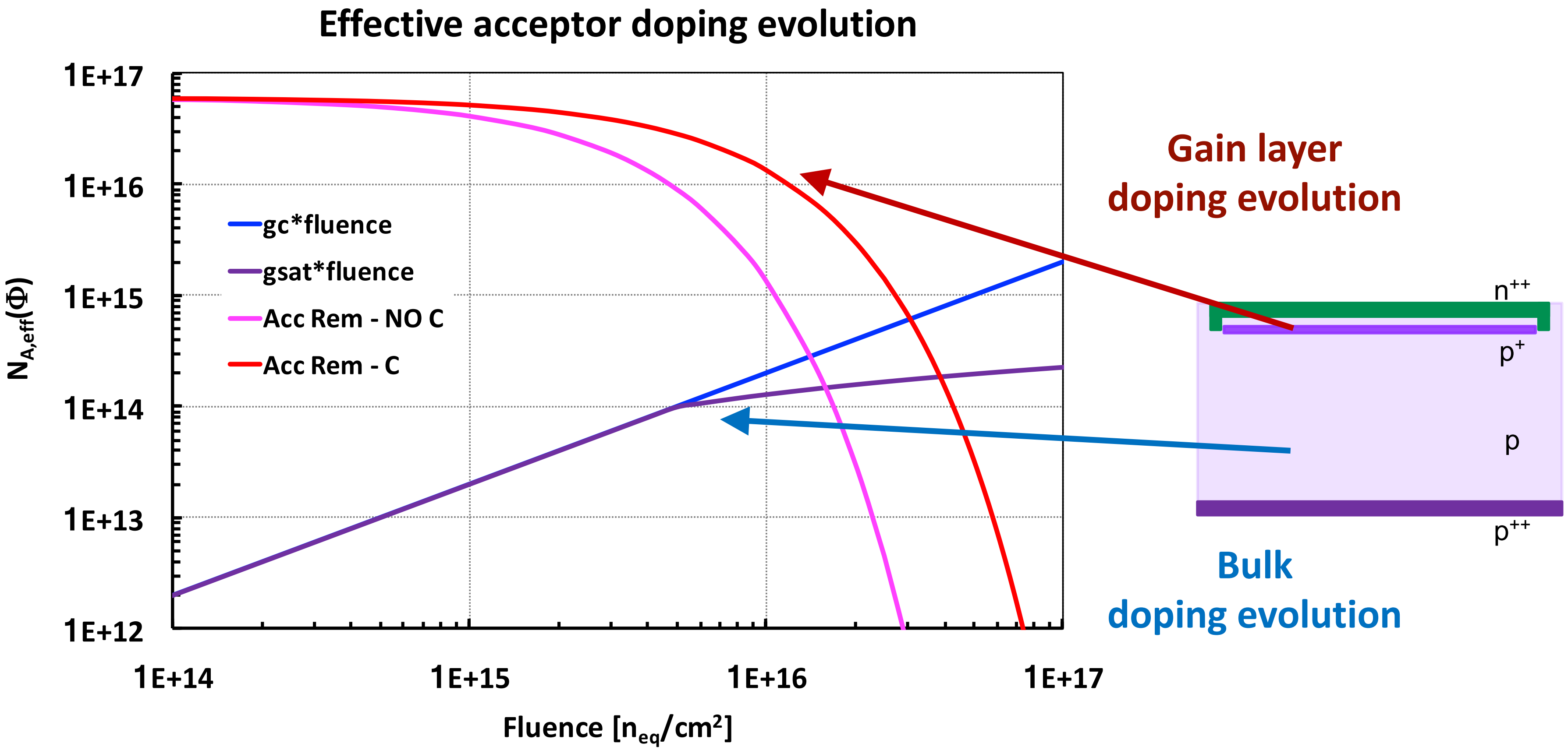
R&D effort with FBK foundry



**Possible?**

# ACCEPTOR DOPING EVOLUTION WITH Φ

$$N_{A,eff}(\Phi) = g_c \cdot \Phi + N_A(0) \cdot e^{-c \cdot \Phi}$$



**Gain layer doping evolution**

**Bulk doping evolution**

# GAIN SIMULATION ON THIN PiN

To nicely reproduce data, a quenching factor on bulk gain need to be introduced (Massey model is used)

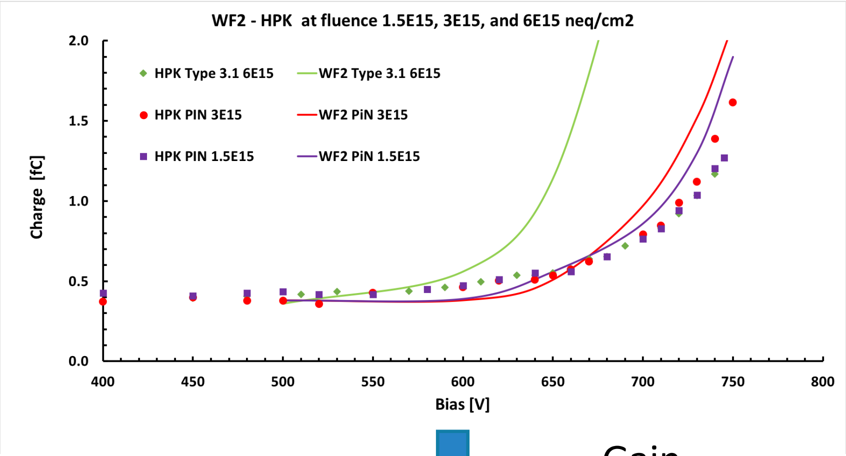
$$G \propto e^{\alpha(E,T)*d}$$

$$\alpha \propto e^{-(a+b*T+c*\emptyset)/E}$$

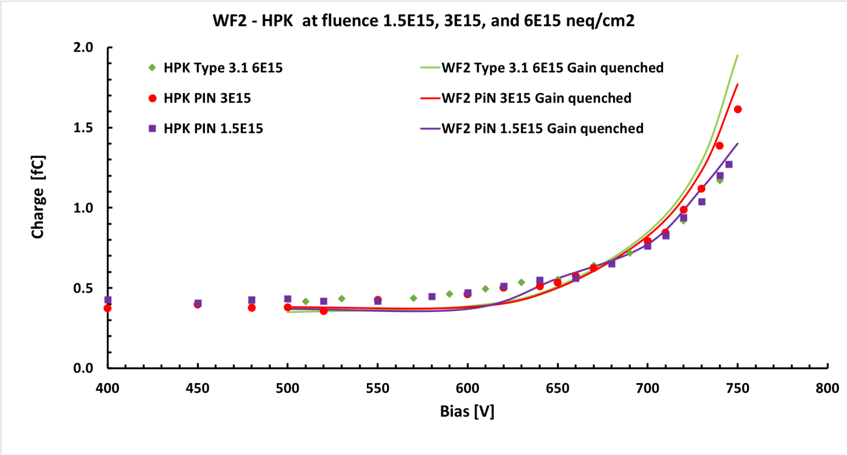
Using data on charge multiplication in PiN and the measured bulk doping, a value of c can be determined

$$c = 2 * 10^{-11}\ \mathrm{V}/\emptyset$$

[N. Cartiglia, https://indico.cern.ch/event/812761/contributions/3459057]

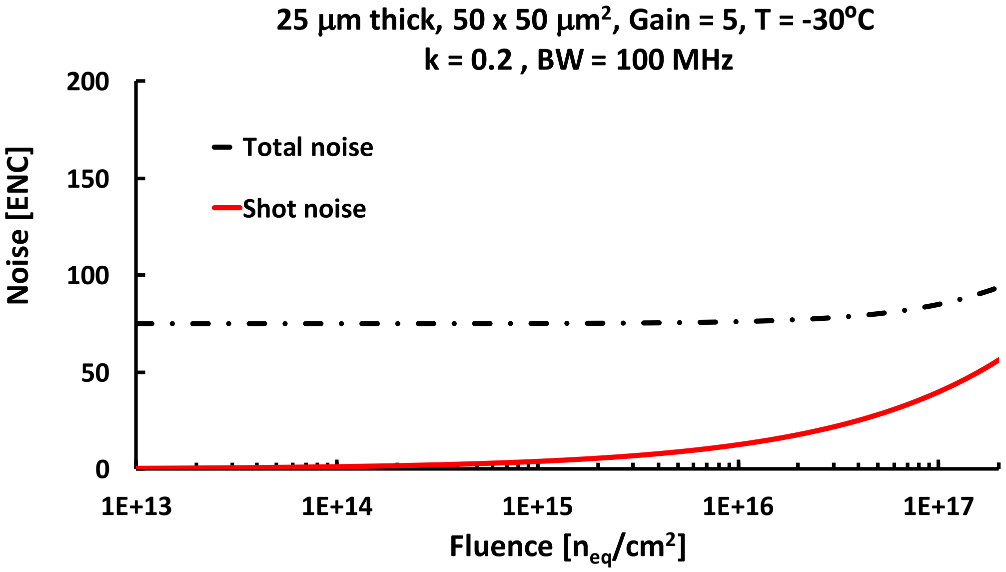


Gain quenching



# SHOT NOISE

**It is crucial to study the interplay between irradiated thin sensors and the electronics**



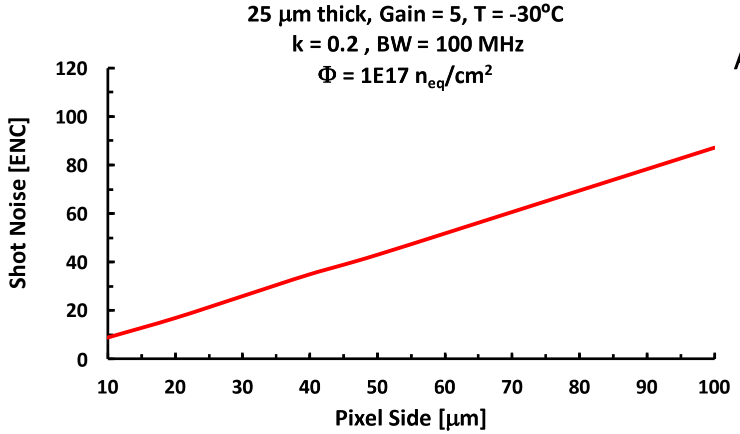
For LGAD sensors, shot noise is given by

$$\sigma_{shot} = \sqrt{2q\left(I_{surface} + I_{bulk} G^2 F\right)\Delta f}$$

G = gain

F ~ $G^x$ = excess noise factor (0 < x < 1)

$\Delta$f = bandwidth interval



Assuming squared pixels

Shot noise is compared to RD53 chip performances
`[https://rd53.web.cern.ch/]`

→ To further reduce the shot noise it is possible to decrease the detector operating temperature and the pixel size

# eXFlu PROJECT

**INFN awarded for funding the *Silicon Sensor for Extreme Fluences (eXFlu)* project[*] to develop, produce, irradiate and study thin silicon sensors (V. Sola as PI)**

The eXFlu project aims to

→ Optimise the design of thin silicon sensors

→ Measure the onset and the magnitude of saturation effects in thin sensors

→ Map the shift of multiplication from the gain layer to the bulk

→ Study the signal multiplication mechanism in highly irradiated sensors – does it disappear at very high fluences?

→ Collaborate with colleagues to extend radiation damage models (RD50, Perugia, ...)

[*] Award funding for one over six projects presented by young researchers in the fields of research and technological development carried out by the Institute (Announcement No.21188)

# eXFlu IN A GLANCE

- **Involved institutes:**
  INFN Torino and FBK

- **Work Packages:**
  WP1: sensor simulation and design
  WP2: sensor production
  WP3: irradiation (n, p, π ...)
  WP4: laboratory characterisation and signal analysis
  WP5: beam test

- **Total budget:**
  ~ 130k euro

# eXFlu EXPECTED OUTCOMES

- **Measure silicon properties in an unexplored region of radiation fluences**
- **Study of saturation of radiation effects in thin silicon sensors**
- **Understanding of impact ionisation mechanism in highly irradiated sensors**
- **Contribute to building models for very irradiates silicon detectors**

**⇒ The ultimate goal is to pave the way for the design of silicon sensors able to efficiently record charged particles up to $10^{17}$ $n_{eq}/cm^2$ and beyond**

# eXFlu TEAM

The eXFlu project consists of 2 Research Units: one centered on the sensor design, irradiation and test (INFN – Torino) while the other on the sensor fabrication (FBK)

- **INFN, Torino**
  - **Valentina Sola** (PI), particle physicist expert both in data analysis and detector R&D, involved in the development and characterisation of Ultra-Fast Silicon Detectors, actively participating to laboratory and beam tests, organisation of irradiation campaign, and supervision of students
  - **Simona Giordanengo**, researcher at INFN Torino; **Ennio Monteil**, technician at the Physics Department of the University of Torino; **Marta Tornago**, Ph.D. student at Torino University
- **FBK, Trento**
  - **Maurizio Boscardin**, senior researcher at Fondazione Bruno Kessler in Trento; **Giacomo Borghi**, researcher at Fondazione Bruno Kessler in Trento

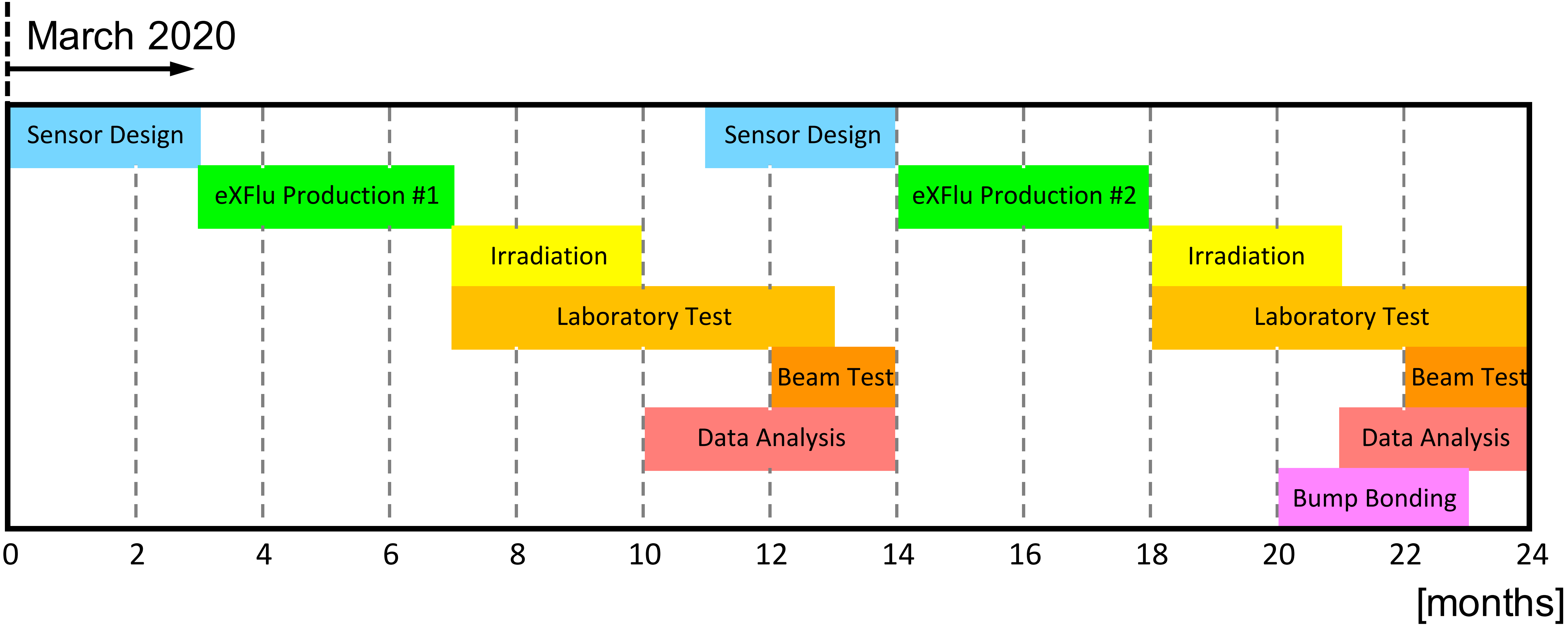
→ **The team includes a diverse composition of expertise, well fitted to the project**

→ **The project can rely on a fully functional laboratory**

# eXFlu BUDGET TABLE

| **Item** | **First year** | | **Second year** | | **Total (Euros)** |
|---|---|---|---|---|---|
| | **Cost per unit (Euros)** | **Units** | **Cost per unit (Euros)** | **Units** | |
| **Wafers (Epitaxial)** | 80 | 25 | | | 2.000 |
| **Wafers (Si-Si DWB FZ)** | 300 | 20 | | | 6.000 |
| **LGAD Production** | 30.000 | 1 | 30.000 | 1 | 60.000 |
| **Chiller** | 30.000 | 1 | | | 30.000 |
| **Irradiation** | 3.000 | | 3.000 | | 6.000 |
| **Bump-bonding** | | | 10.000 | | 10.000 |
| **Read-out boards** | | | 400 | 10 | 4.000 |
| **Travel** | 3.000 | | 10.000 | | 13.000 |
| **Total** | **74.000** | | **57.000** | | **131.000** |

# eXFlu TIMELINE



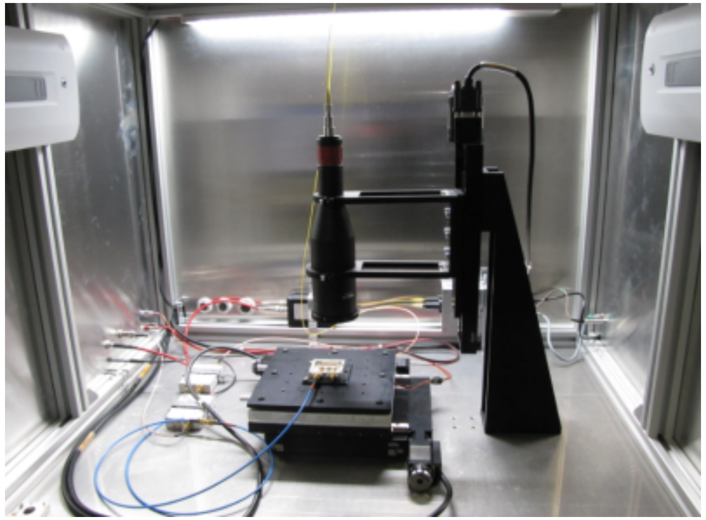
# COOL SYSTEMS

**A key aspect of eXFlu project is to be able to perform measurement on irradiated sensors at low temperatures**

→ Preparation of cold setups in progress

MPI TS200-SE Manual Probe Station
with temperature range from -40 to +300ºC
will arrive soon in Torino Laboratory

Vötsch VCL4010 Test Chamber
with temperature range from -40 to +180ºC
available in Torino Laboratory

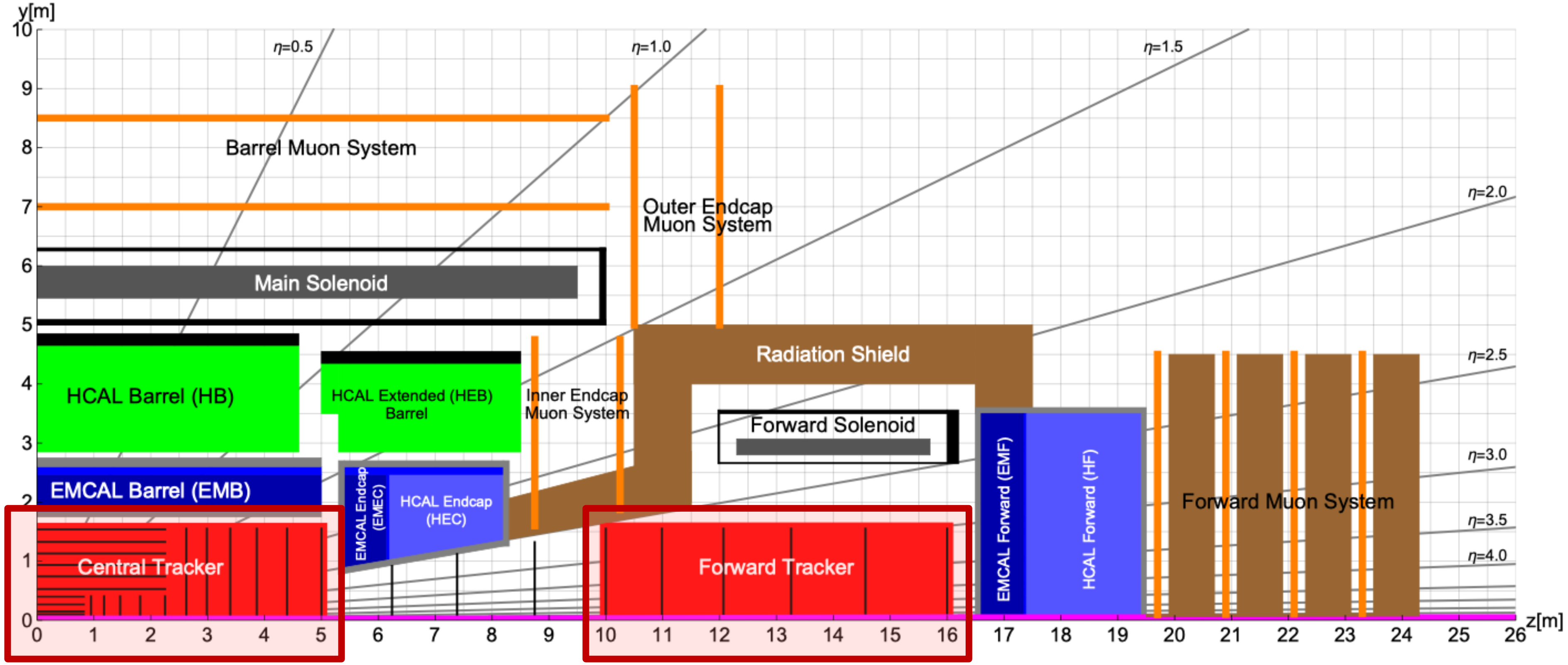


Particulars Large Scanning TCT setup
connected to Lauda chiller down to -20ºC
available in Torino Laboratory

# TRACKING AT FUTURE HADRON COLLIDER

Next generation high-energy and high-intensity hadronic collider ⟶ FCC-hh

**FCC-hh reference detector**



**The tracker**

[http://cds.cern.ch/record/2651300]

**Running conditions:**

- Pile-up per bunch crossing ~ 1000
- Vertex region $\sigma_z \sim 44$ mm, $\sigma_t \sim 165$ ps
- Average distance between vertices at z = 0 is 125 μm

**Tracker requirements:**

- $\sigma_{r\phi} = 7.5 - 9.5\ \mu m$
- Low material budget $N_{layers} = 12$
- Effective pile-up = 1 $\sigma_t = 5$ ps

# RADIATION BUDGET - TRACKER VOLUME

Fluence foreseen at $L_{int}$ = 30 $ab^{-1}$

**Courtesy of M.I. Besana**