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First results from thin silicon sensors irradiated to extreme fluence

V. Sola, R. Arcidiacono, P. Asenov, G. Borghi, M. Boscardin, N. Cartiglia, M. Centis Vignali, T. Croci, M. Ferrero, G. Gioachin, S. Giordanengo, M. Mandurrino, V. Monaco, A. Morozzi, F. Moscatelli, D. Passeri, G. Paternoster, F. Siviero, M. Tornago

Questions

- **Is it possible to design a silicon sensor able to work in the fluence range $10^{16} – 10^{17}$ n_{eq}/cm^2?**

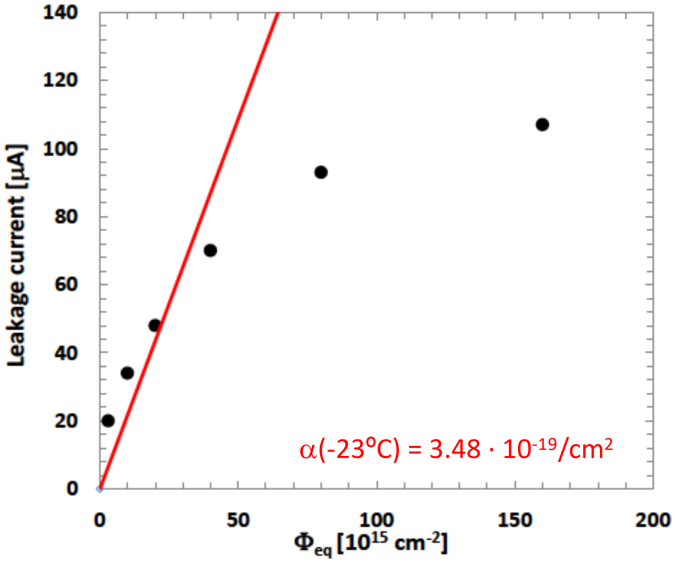
If so

- **Does such sensor generate enough charge to be used in a detector exposed to extreme fluences?**

⇒ The R&D to answer these questions is starting now

Some Optimism – Saturation

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

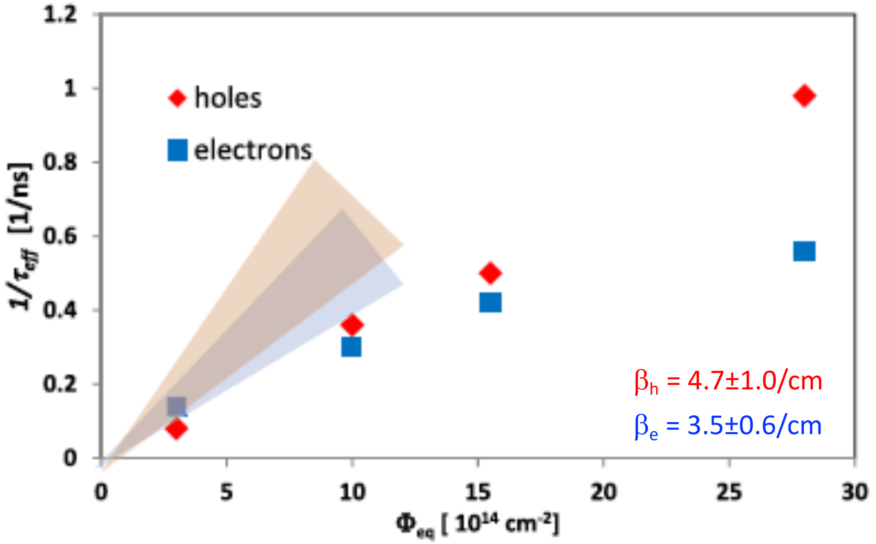


[G. Kramberger et al., doi:10.1088/1748-0221/8/08/P08004]

Leakage current saturation

$I = \alpha V \Phi$

α from linear to logarithmic

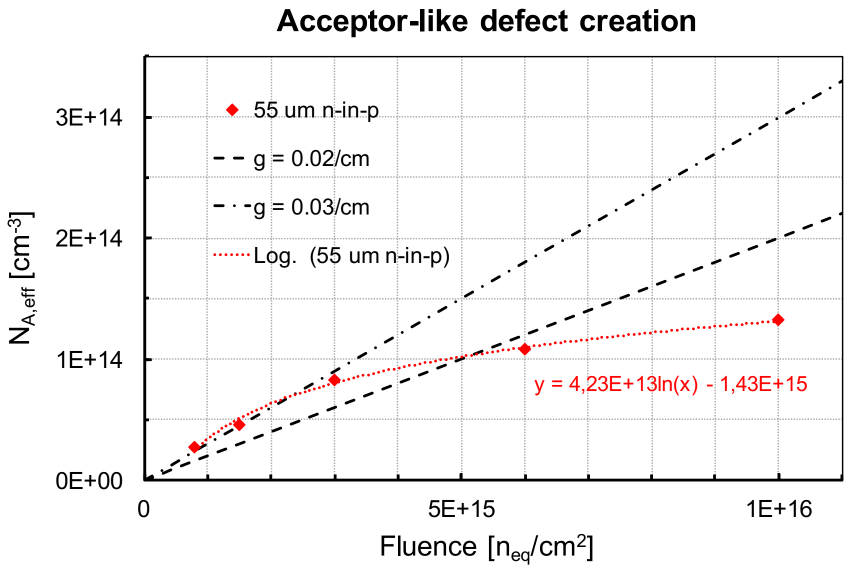


[G. Kramberger et al., doi:10.1016/j.nima.2018.08.034]

Trapping probability saturation

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

β from linear to logarithmic



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

Acceptor creation saturation

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

g_c from linear to logarithmic

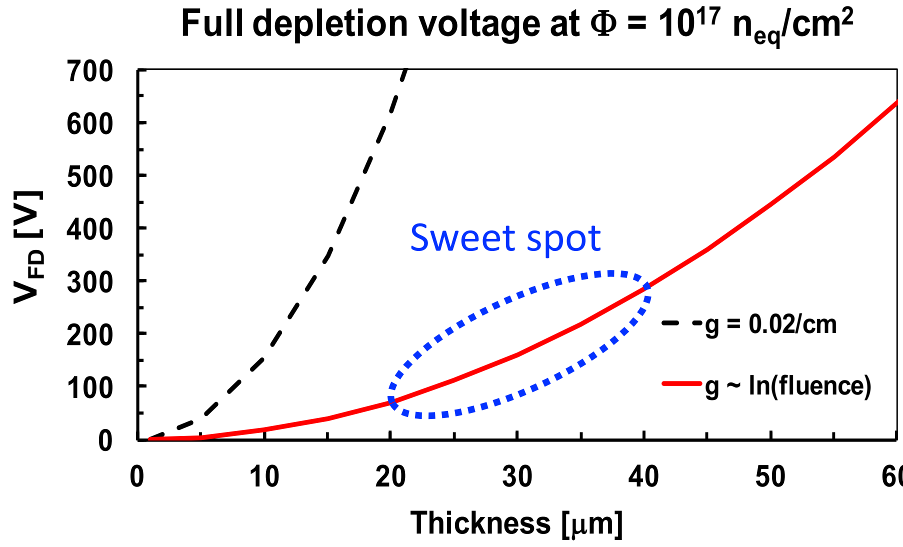
Silicon detectors irradiated at fluences $10^{16} – 10^{17}$ n_{eq}/cm^2 do not behave as expected ⟶ They behave better

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



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 ~ 0.20 fC

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

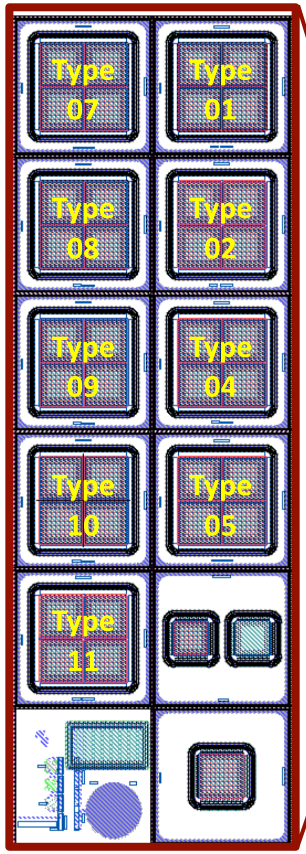
→ **Need for a gain of at least ~ 5 in order to provide enough charge**

First Thin Wafers from FBK – EXFLU0

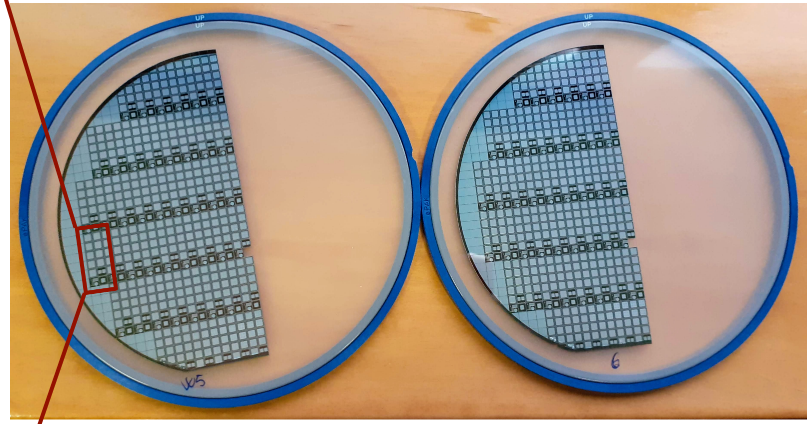
Wafer #	Thickness	Depth	Dose Pgain	Carbon	Diffusion
5	25	Standard	0.94	A	CHBL
6	35	Standard	0.94	A	CHBL

2 thin wafers have been produced at FBK
→ **EXFLU0 production**
(same layout as the FBK UFSD3.2 on 45 & 55 μm)

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



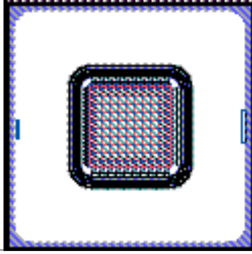
Arrived in Torino at the end of 2020



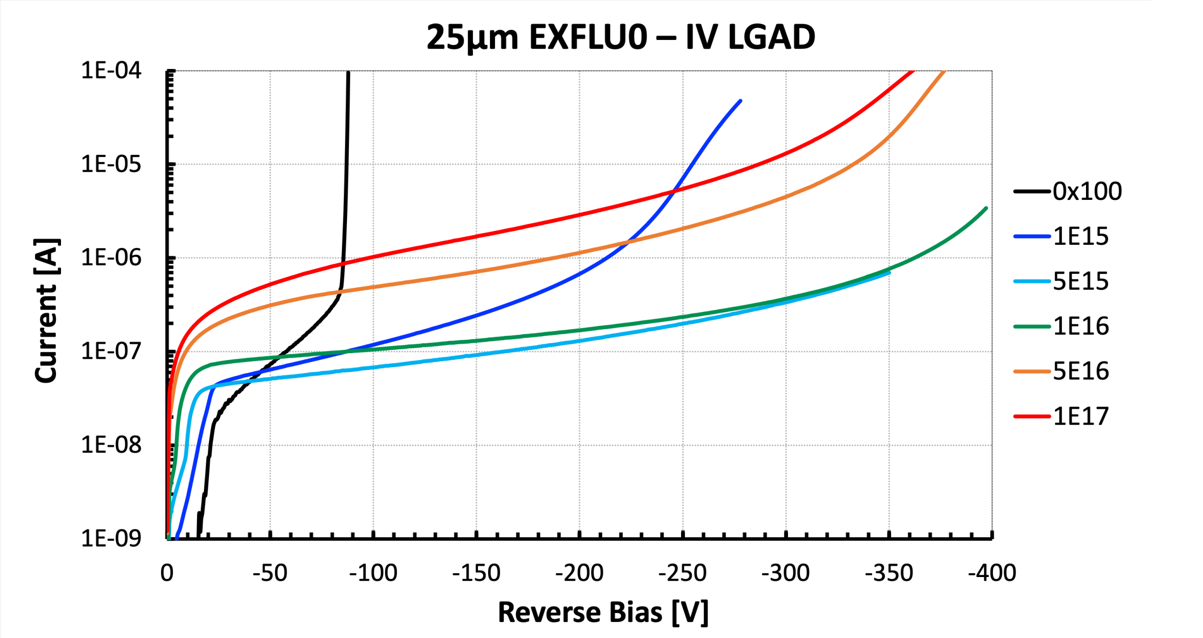
EXFLU0 sensors have been irradiated at JSI, Ljubljana, to 5 different fluences 1E15, 5E15, 1E16, 5E16, 1E17 n_{eq}/cm^2

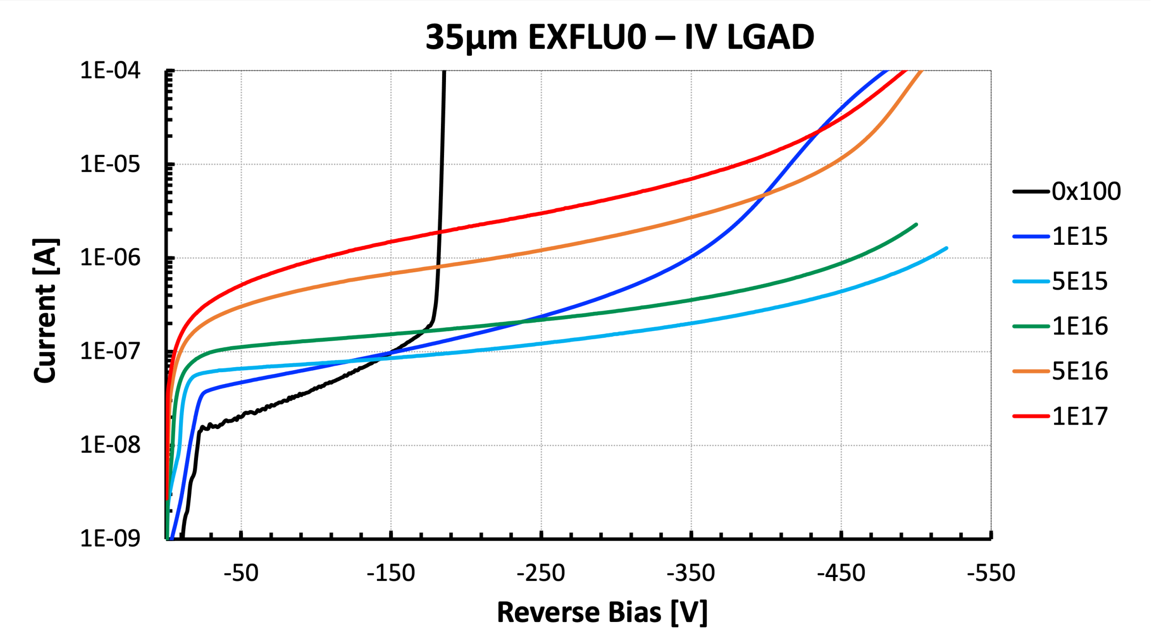
For more details see
- https://indico.cern.ch/event/896954/contributions/4106324/
- https://indico.cern.ch/event/1029124/contributions/4410341/

IV on Irradiated Thin LGAD



EXFLU0 sensors have been irradiated up to 10^{17} n_{eq}/cm^2 at the JSI neutron reactor in Ljubljana





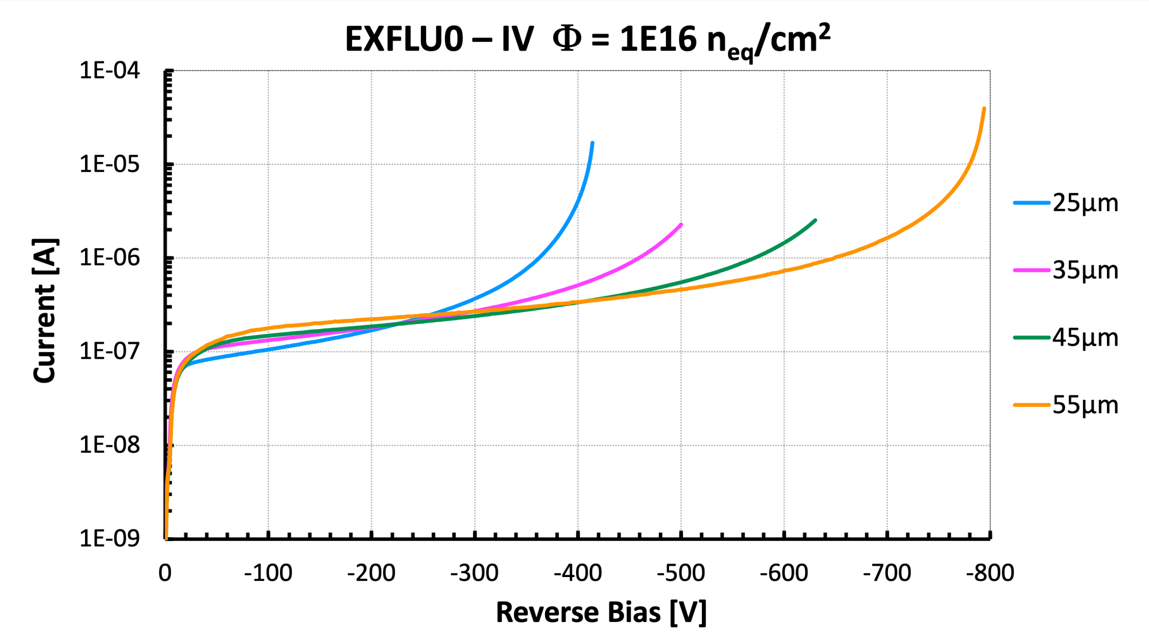
Measurements have been performed at T = -30°C

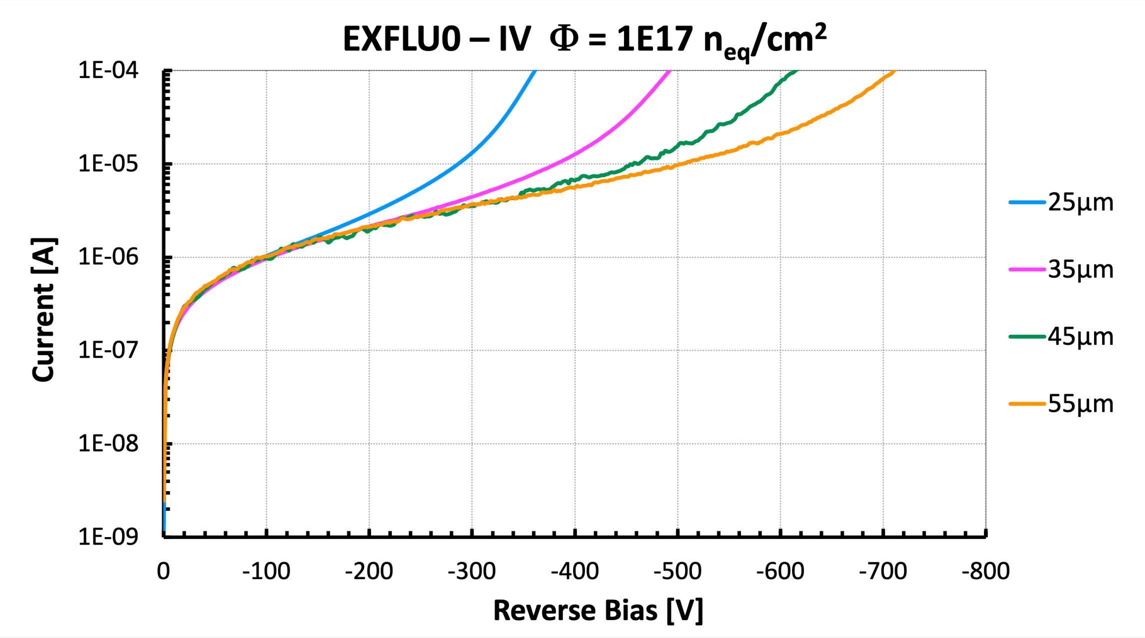
→ The knee due to gain layer depletion is visible up to 1E16 n_{eq}/cm^2

→ Sensors irradiated at 5E16 – 1E17 n_{eq}/cm^2 exhibit a higher gain w.r.t. 1E16 n_{eq}/cm^2

Reverse Current with Thickness

Irradiated sensors with different active thickness are compared





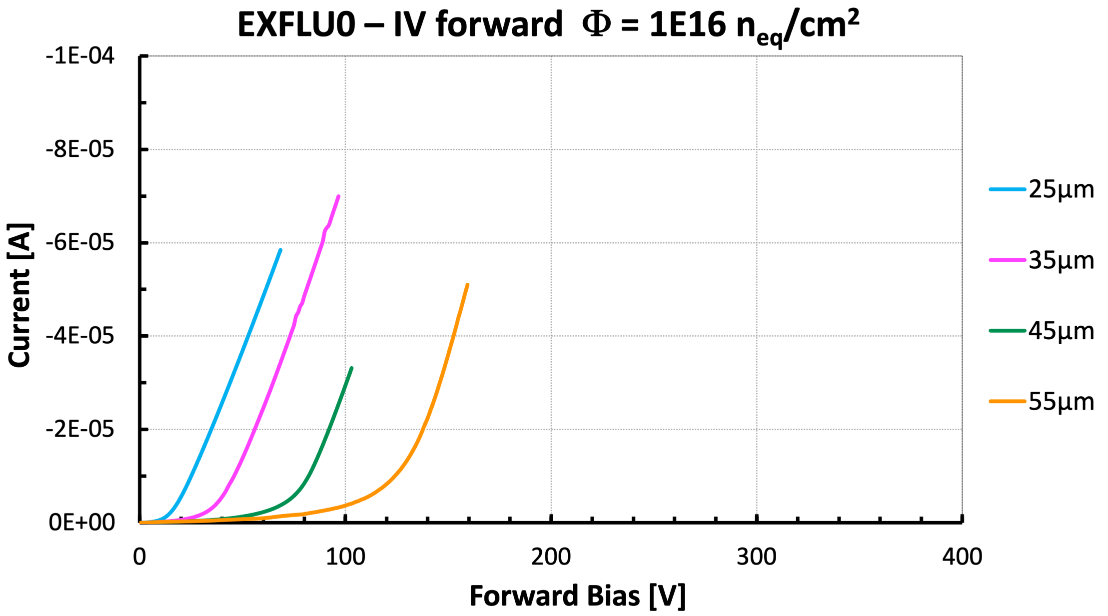
Measurements have been performed at T = -30°C

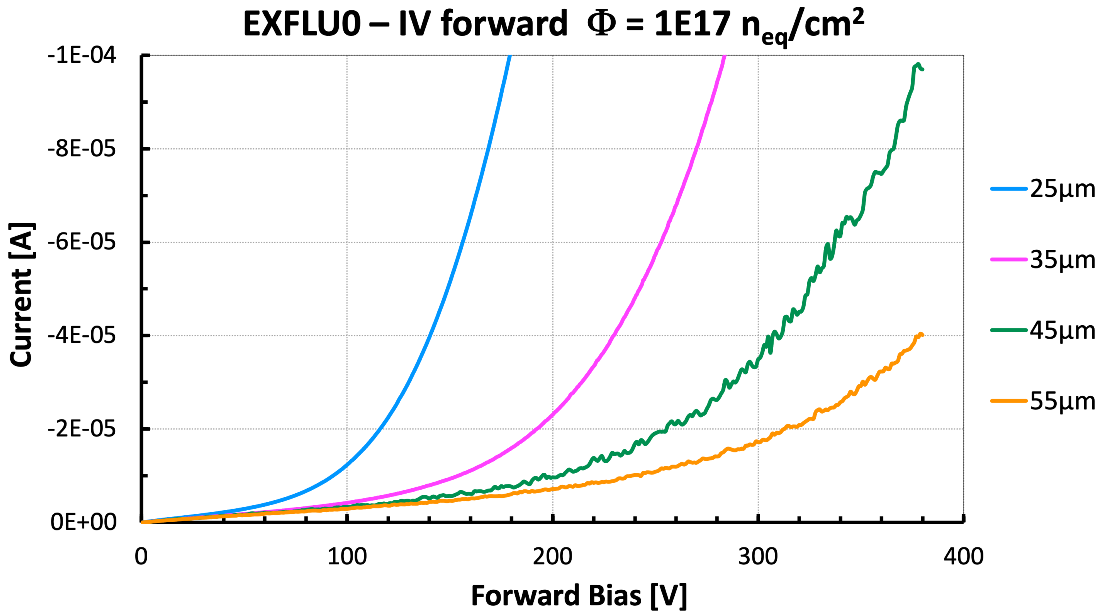
→ Forward current increase linearly scales with the sensor thickness

→ Sensors irradiated at 5E16 n_{eq}/cm^2 and above exhibit a resistance of more than 100 MΩ

Forward Current with Thickness

Sensors of different thicknesses have been tested under forward bias





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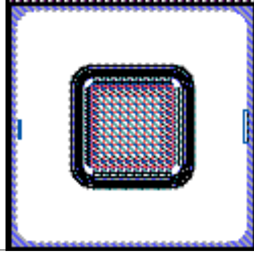
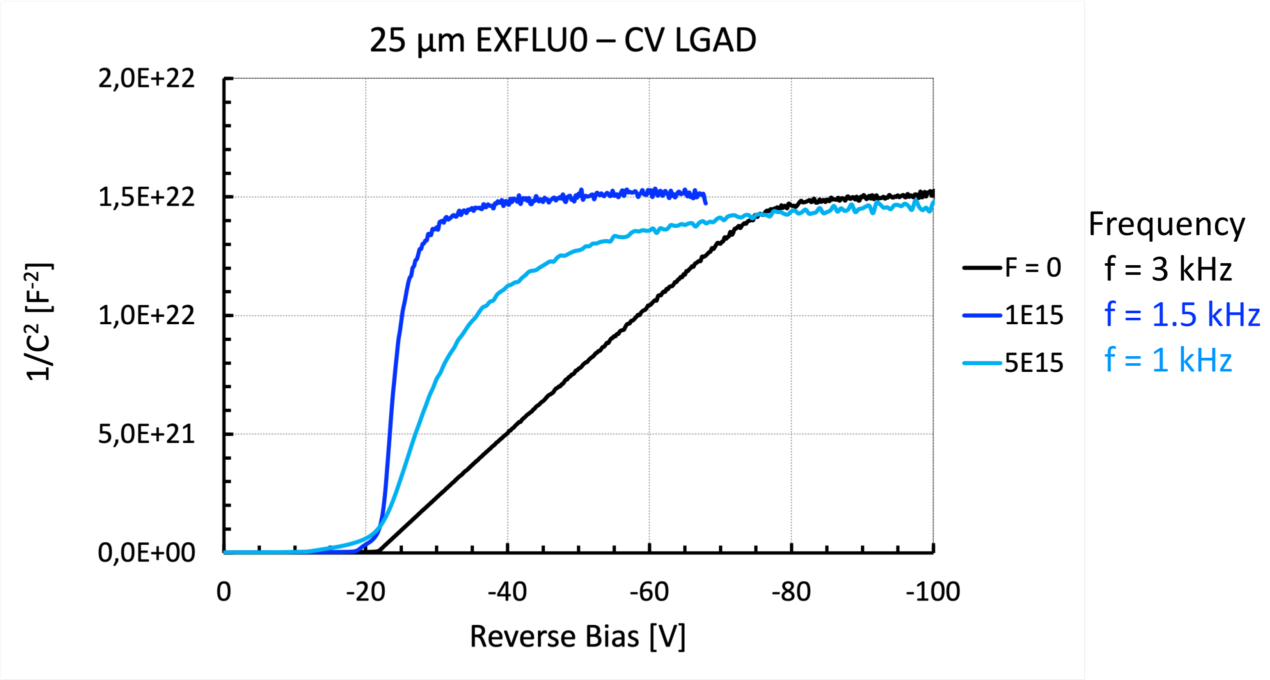
CV on Irradiated Thin LGAD – 25 µm



25 µm thick sensor have a highly doped active substrate

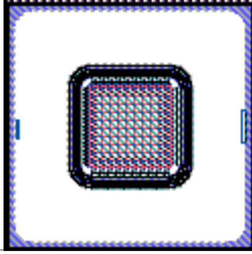


Measurements have been performed at T = +25°C

→ For higher fluence values very low frequency need to be used to perform the CV measurement

→ The Quasi-Static CV method will be used for heavily irradiated sensors to capture all the slow frequency states

CV on Irradiated Thin LGAD – 25 µm



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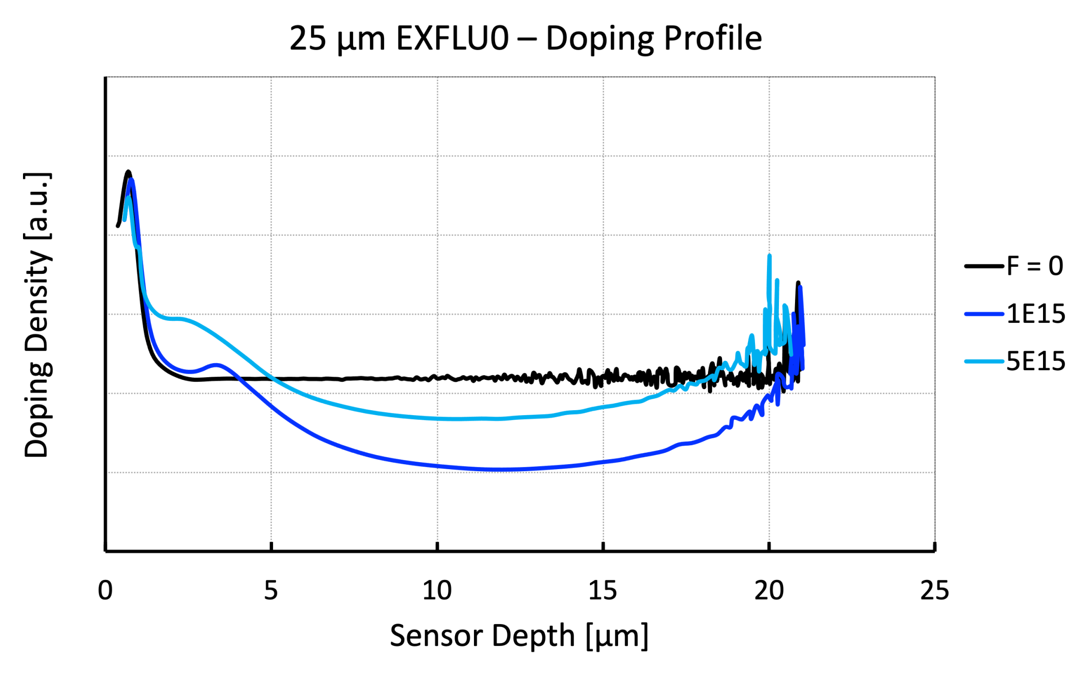

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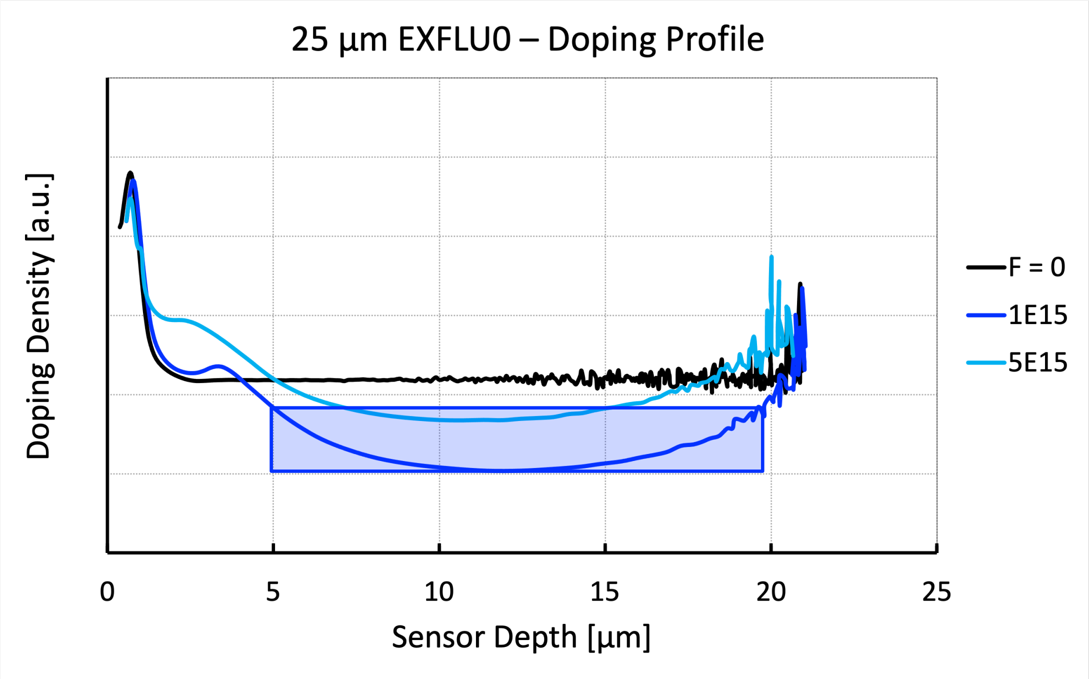

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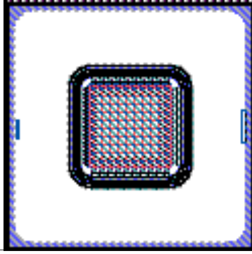

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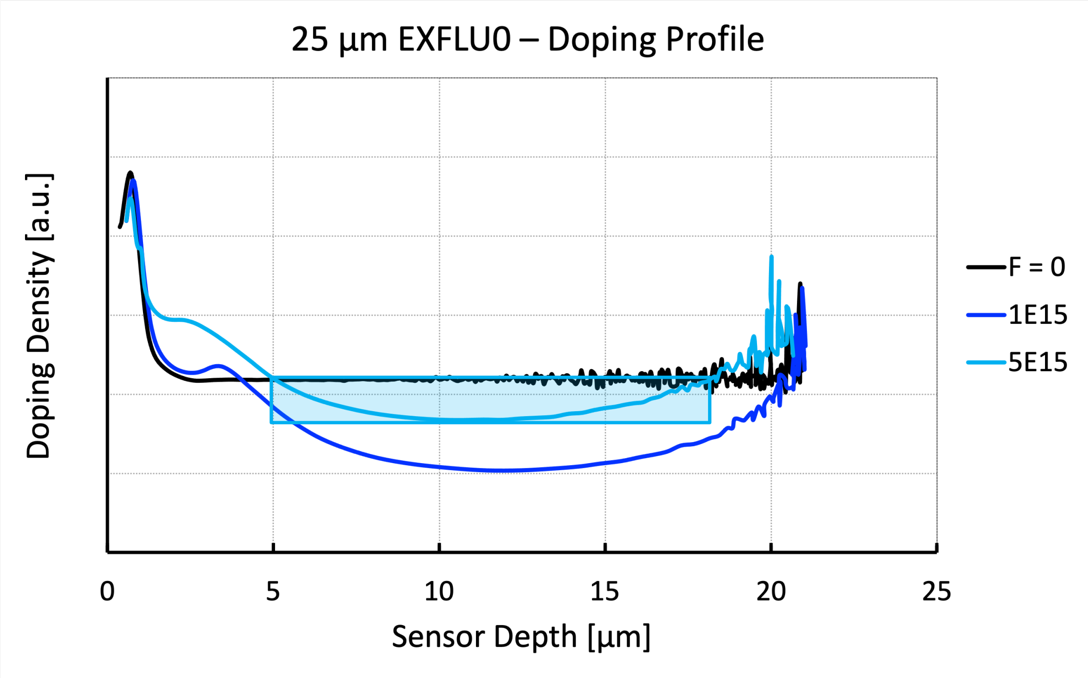

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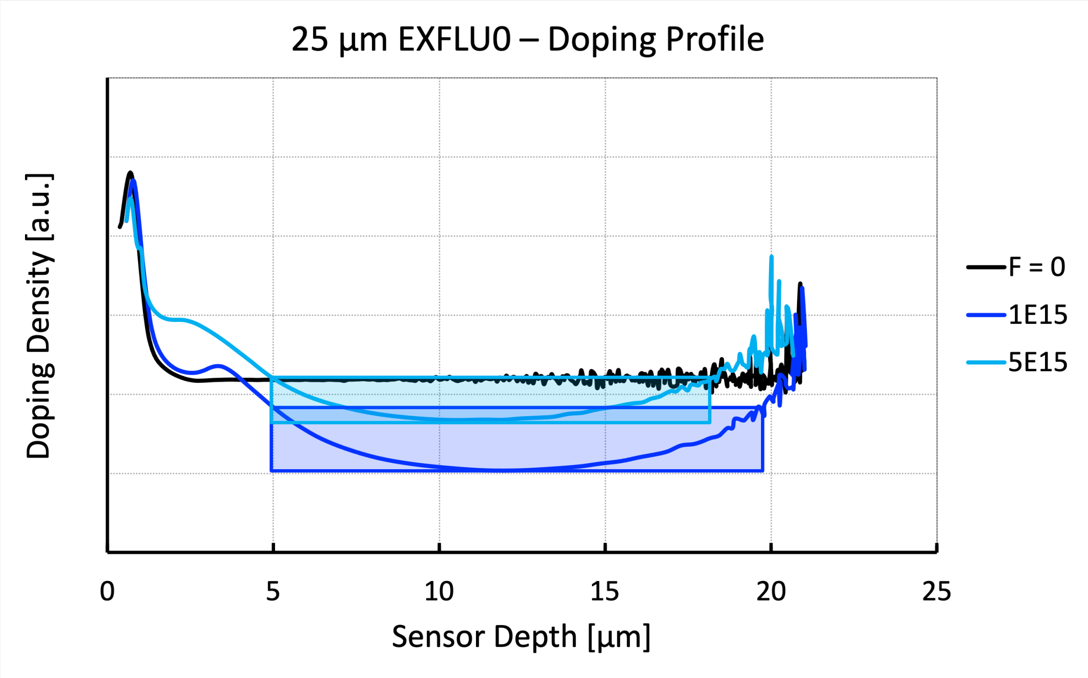
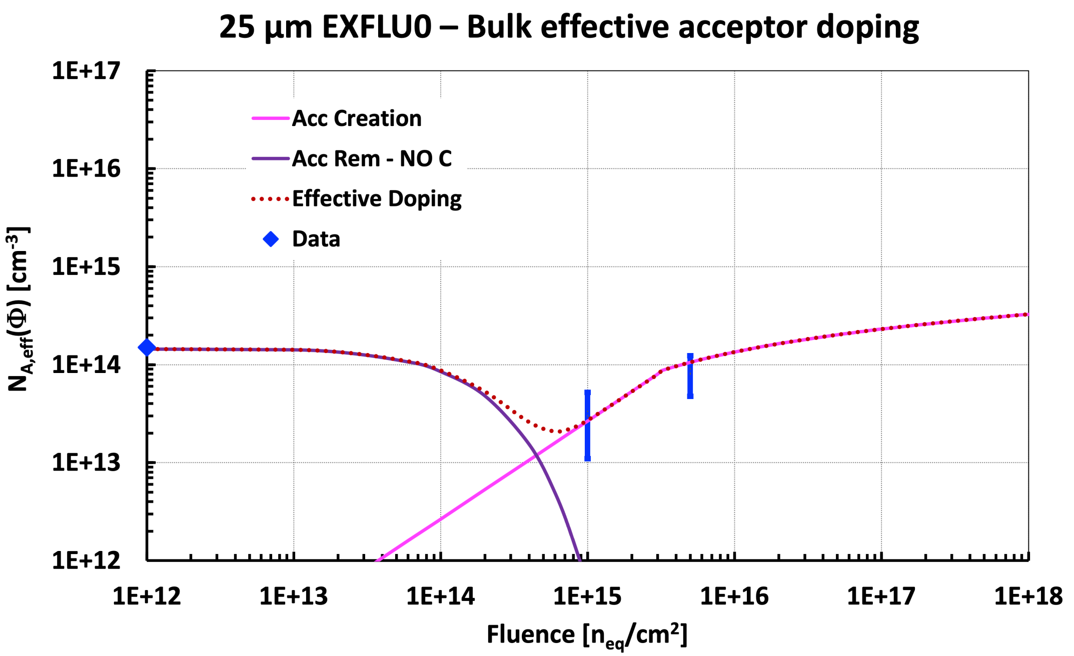
CV on Irradiated Thin LGAD – 25 µm

25 µm thick sensor 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 bulk doping is expected to evolve as follows

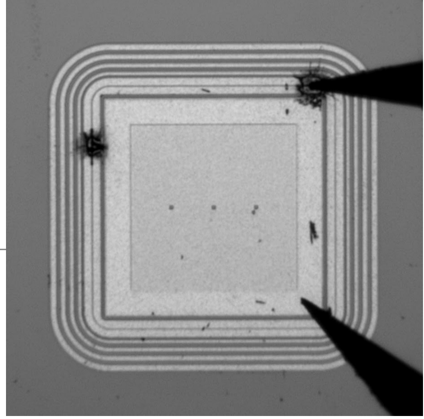


Measurements have been performed at T = +25°C

→ For higher fluence values very low frequency need to be

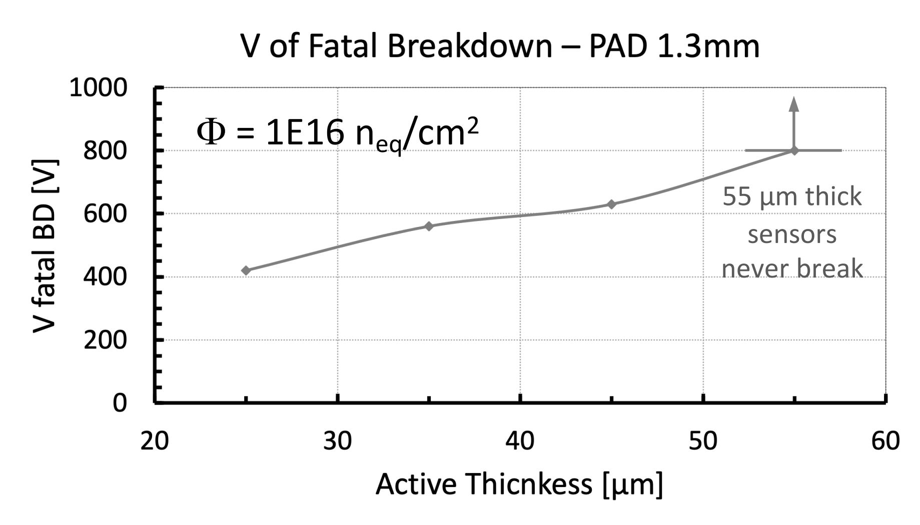
→ The Quasi-Static CV method will be used for heavily irradiated sensors to capture all the slow frequency states

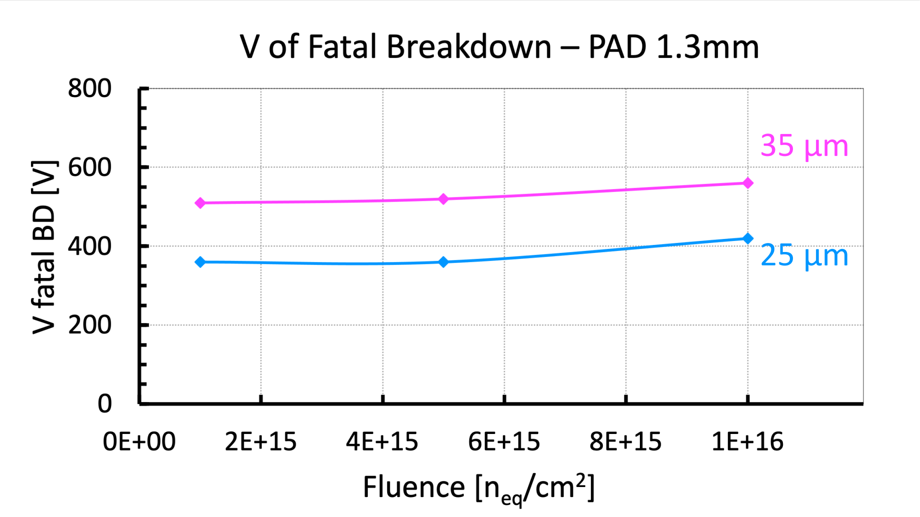
Breakdown on Thin LGAD



Guard ring structures of the EXFLU0 sensors are not optimised for thin substrates
Sensors thinner than 55 µm fatally break once a critical field is reached

T = -30^{o}C





→ The bias voltage of fatal breakdown increases with thickness and with fluence
→ For fluence values of **$\Phi \geq$ 5E16 n_{eq}/cm^2 fatal breakdown does not occur**

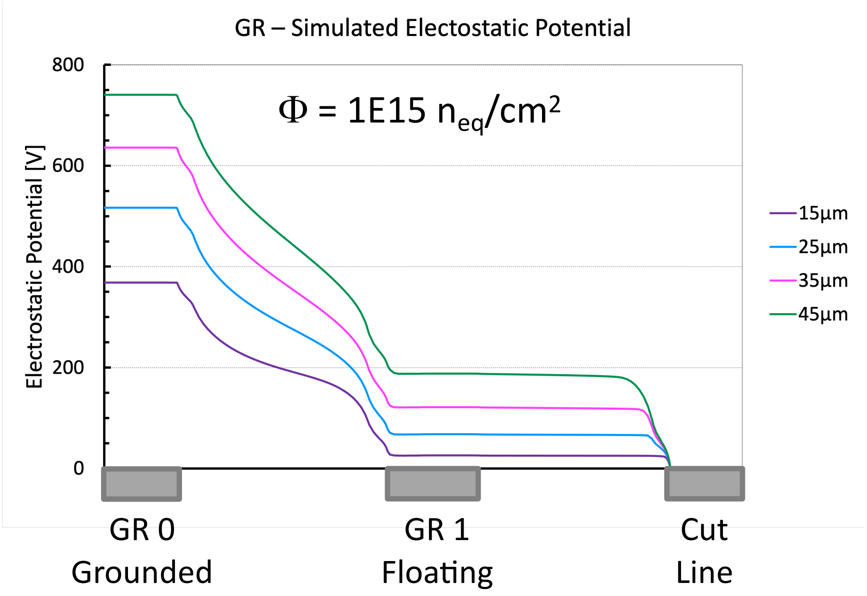
⟹ R&D on the guard-ring structures optimised for thin substrates is needed and will be pursued towards the EXFLU1 sensor production

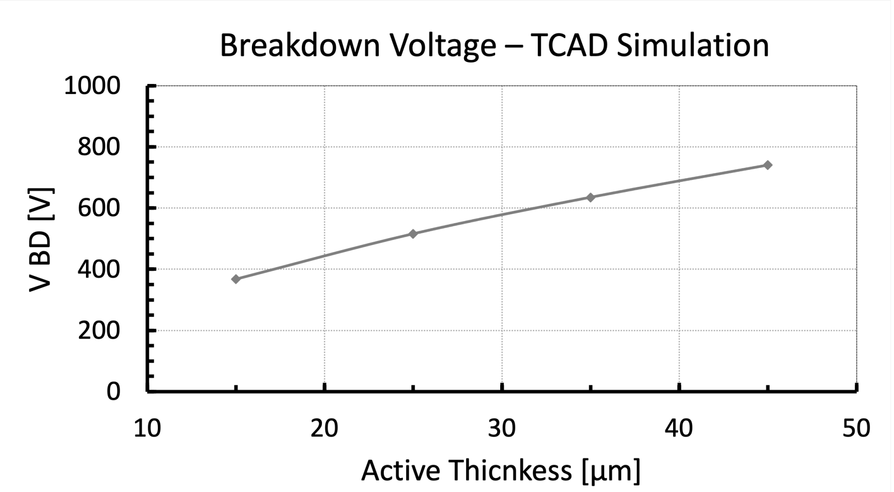
Simulated Breakdown

A guard ring structure similar to the one used for the EXFLU0 production has been simulated

Simulation at Φ = 1E15 n_{eq}/cm^2

Perugia 2020 updated model has been used to simulate the surface and bulk radiation damage



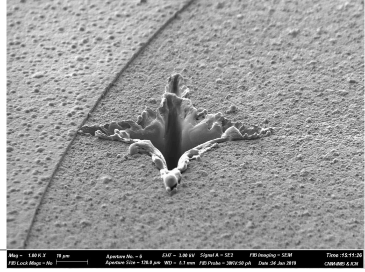


→ The simulated breakdown voltage has a trend similar to data

→ For thin sensors, the floating guard-ring experiences a potential similar to the one of the backplane

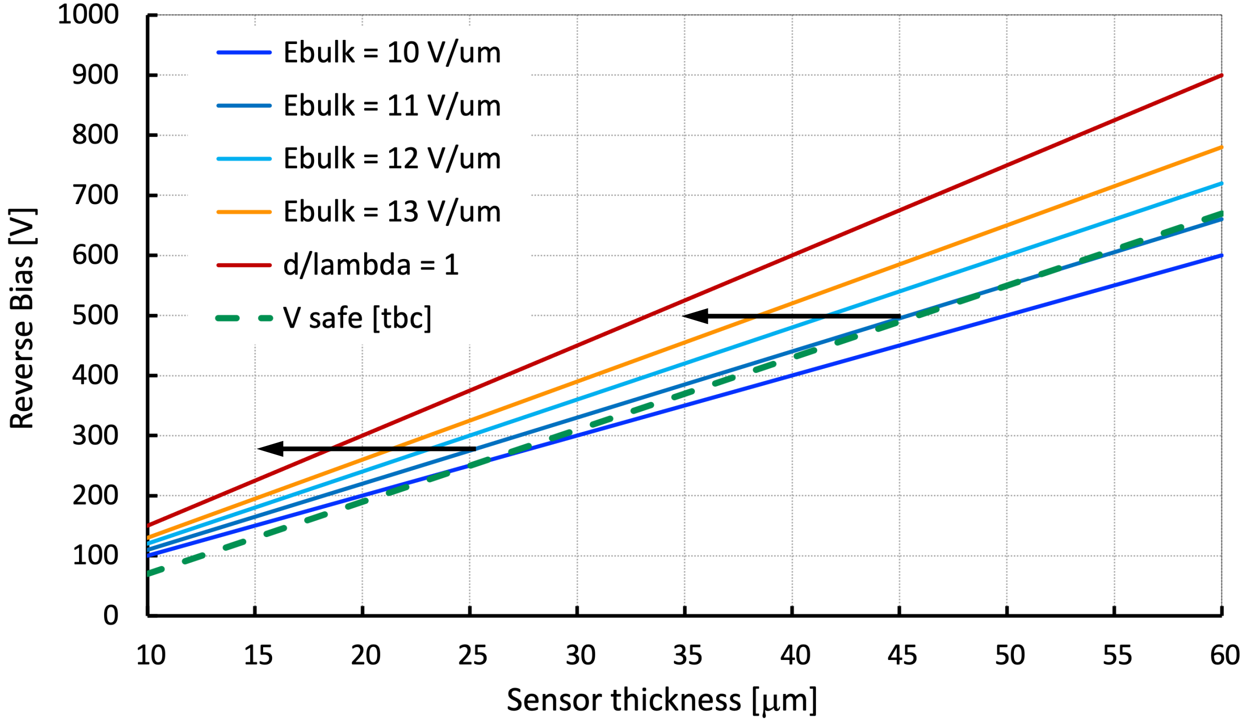
⟹ Different guard-ring designs will be simulated and tested in the EXFLU1 production

Safe Electric Field Values



Recently observed highly ionising particle effects can prevent eXFlu sensors from operating at high bias [https://indico.cern.ch/event/861104/contributions/4513238/]

From experimental data, the bulk electric field at which the sensors experience fatal break is **~ 12 V/μm**



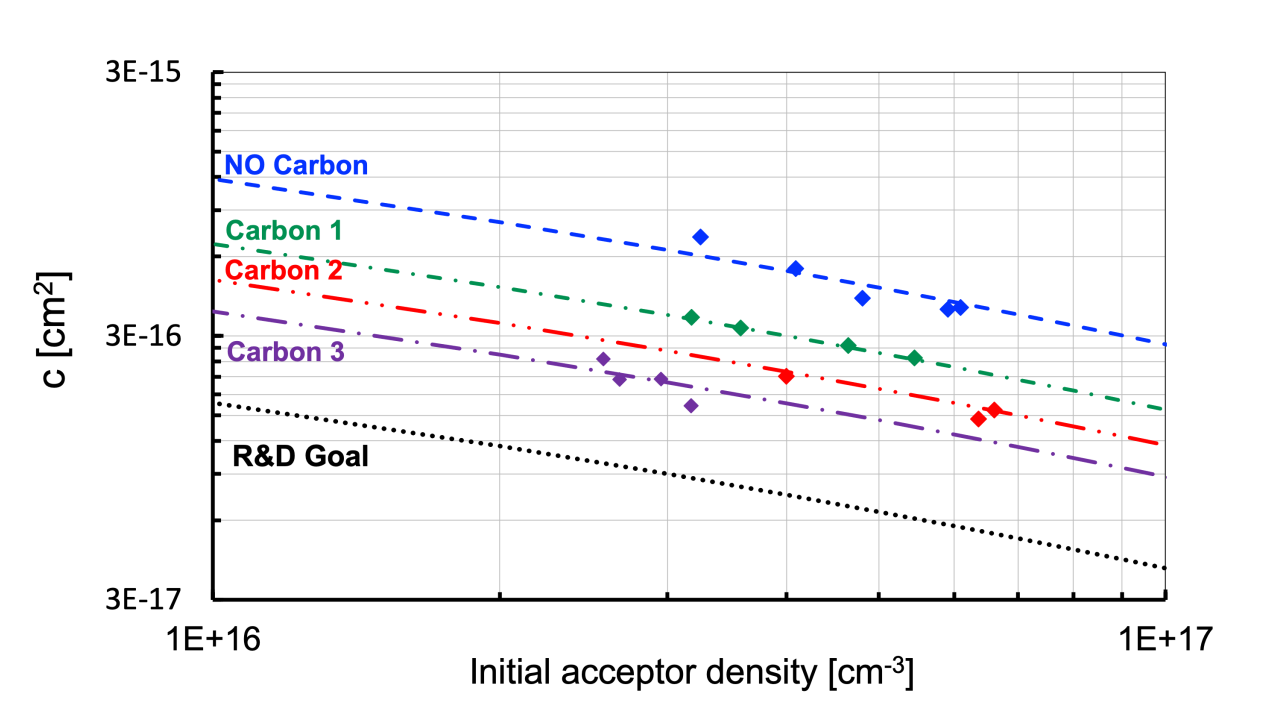
A local sensor thickness reduction can have more impact on thin sensors

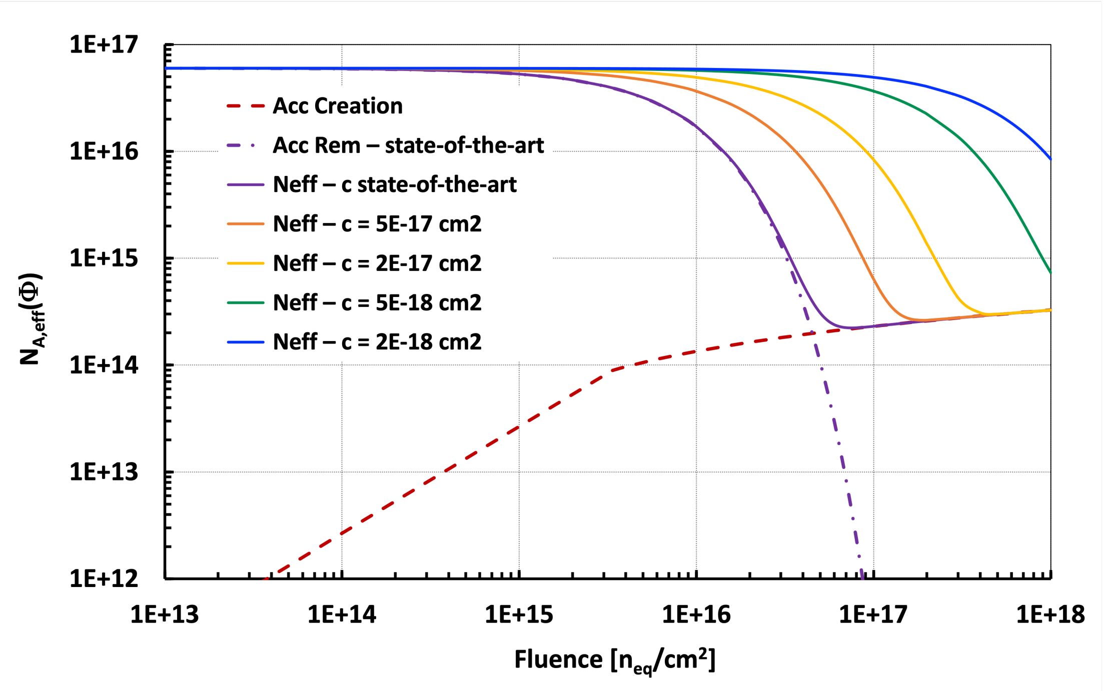
Beam test on EXFLU0 are necessary to understand the effect of highly ionising particles on thin sensors

High irradiation may mitigate the effects of highly ionising events on silicon sensors

Optimisation of the Gain Layer Design

A dedicated program of defect engineering will be pursued, to enhance the radiation tolerance of the gain layer implant, to reduce the minimum bias necessary to collect 1fC





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

Towards the EXFLU1 Production

The design of the EXFLU1 production is under finalisation

The production will include

→ different substrate active thicknesses, ranging from 15 µm to 45 µm

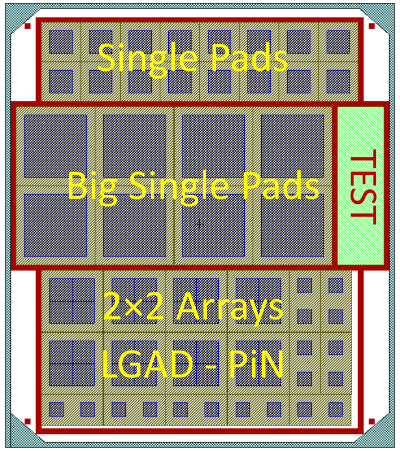
→ different design of the gain layer implant, to improve the radiation tolerance

→ defect engineering on the bulk and the gain layer regions

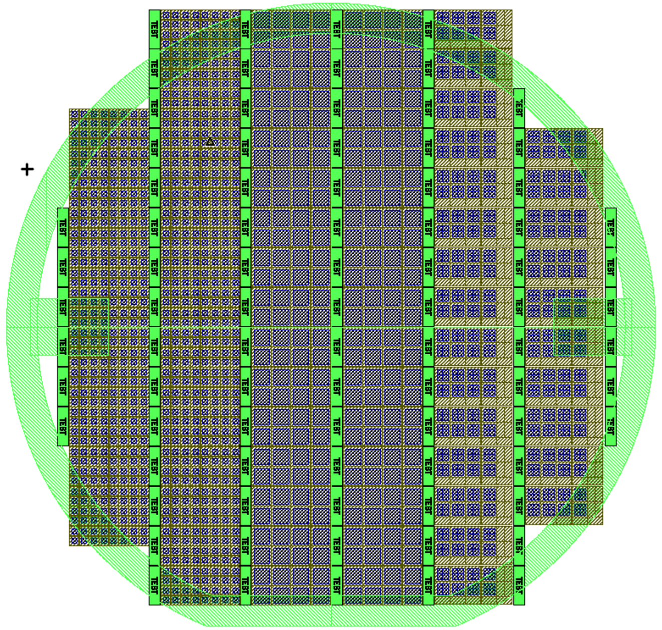
→ optimisation of the guard ring design for thin substrates

⇒ The production is expected by Spring 2022

Preliminary reticle layout

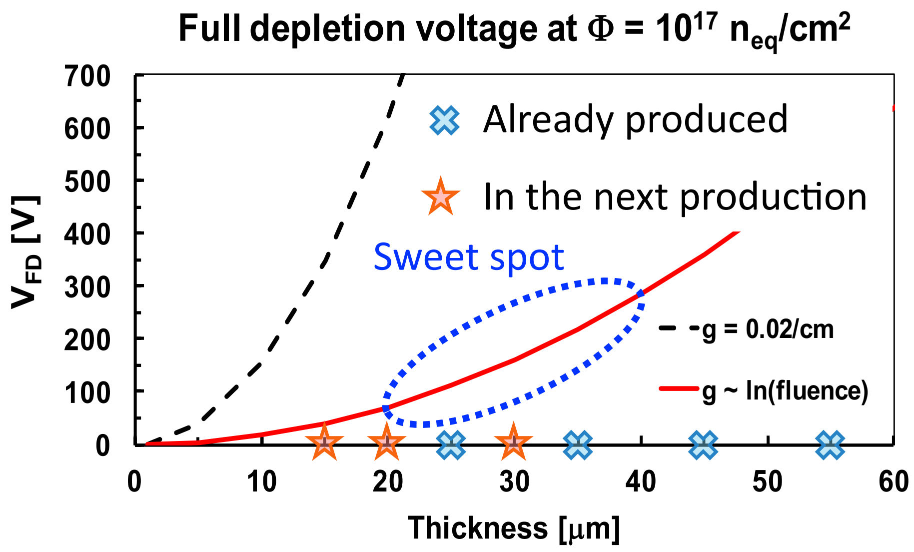


Preliminary wafer layout



Summary & Outlook

- R&D of thin silicon sensors for extreme fluences has started



- First thin LGAD have been produced at FBK and a new production on thinner substrates will follow soon

- Simulation of thin LGAD behaviour under irradiation is ongoing and a comparison with data will be available soon

⇒ 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

Acknowledgements

We kindly acknowledge the following funding agencies, collaborations:

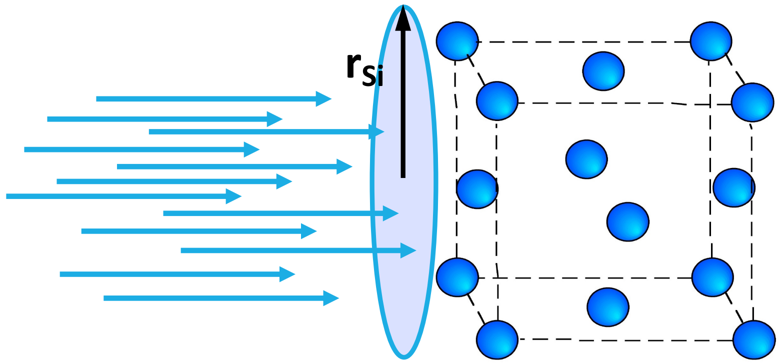
- ▻ RD50, CERN
- ▻ Horizon 2020, grant UFSD669529
- ▻ AIDA-2020, grant agreement no. 654168
- ▻ MIUR, Dipartimenti di Eccellenza (ex L. 232/2016, art. 1, cc. 314, 337)
- ▻ Ministero della Ricerca, Italia, PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
- ▻ Ministero della Ricerca, Italia, FARE, R165xr8frt_fare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

BACKUP

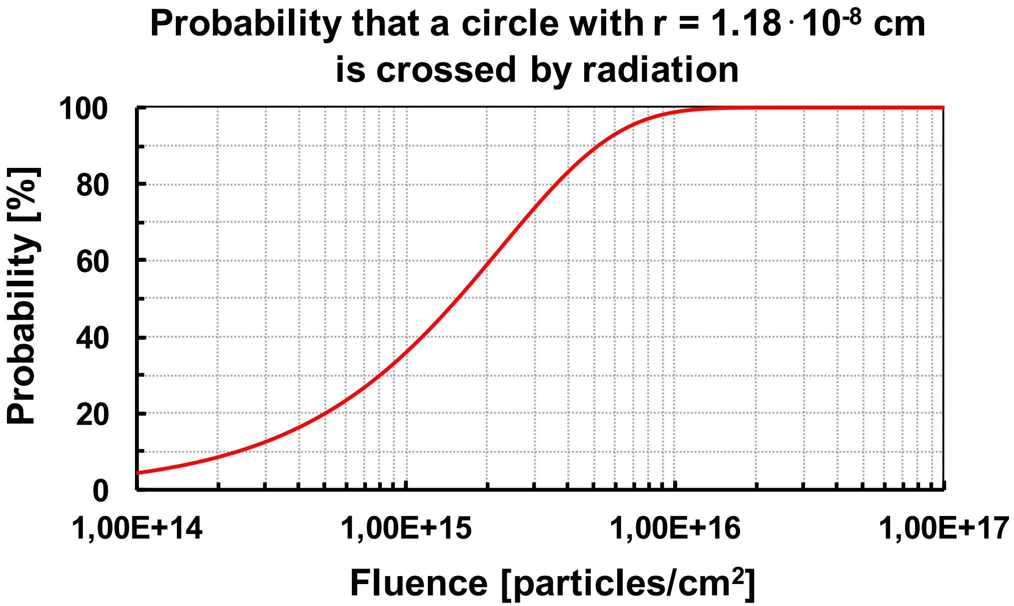
WHY SATURATION?

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



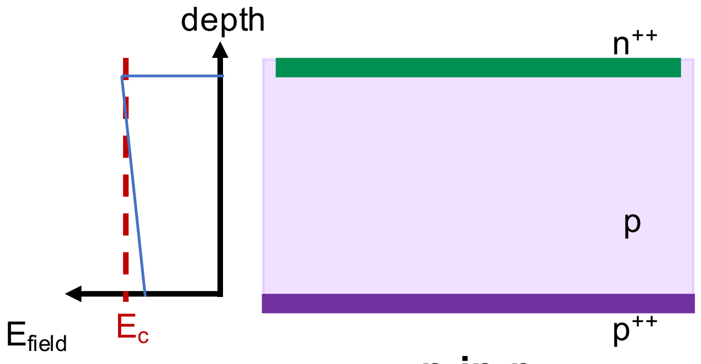
Above 10^{16} particles/cm^2:
damage happening on already damaged Silicon might be different

SENSOR CHOICE

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

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

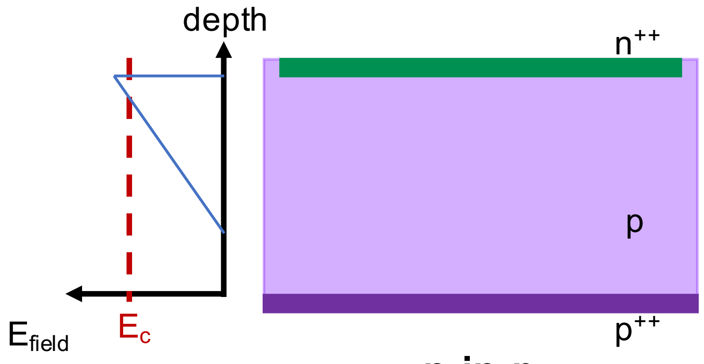
1) **$E_{field} > E_c$ for a short distance**
2) **This length is controlled by applied V_{bias}**



n-in-p
p ~ 10^{12} cm^{-3}

E_{field} above E_c
over long distance

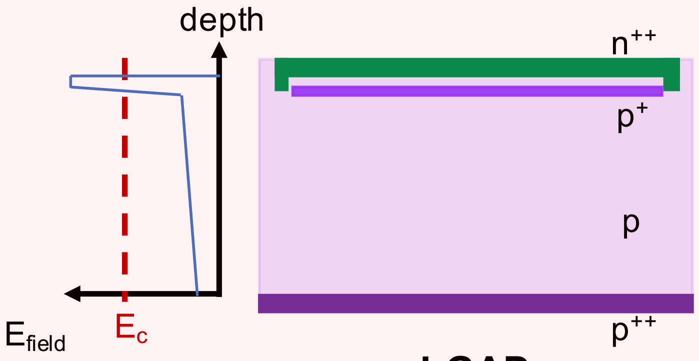
AVALANCHE



n-in-p
p ~ 10^{14} cm^{-3}

Difficult to precisely
control E_{field}

RISK OF AVALANCHE



LGAD
p ~ 10^{12} cm^{-3}, p^{+} ~ 10^{16} cm^{-3}

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

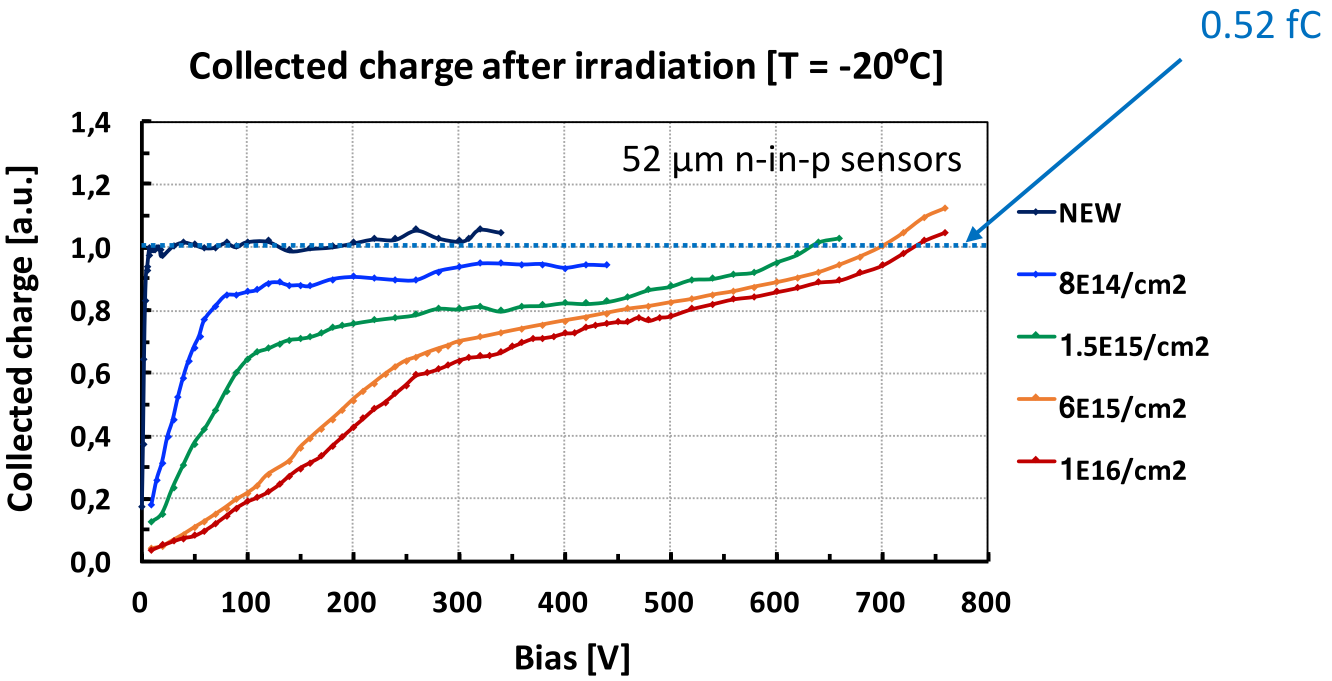
CONTROLLED GAIN

HOW THIN?

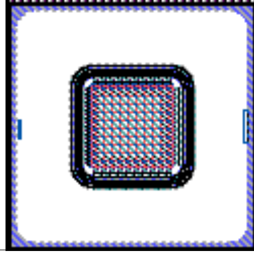
To efficiently record a hit, electronics require al least **1 fC**

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

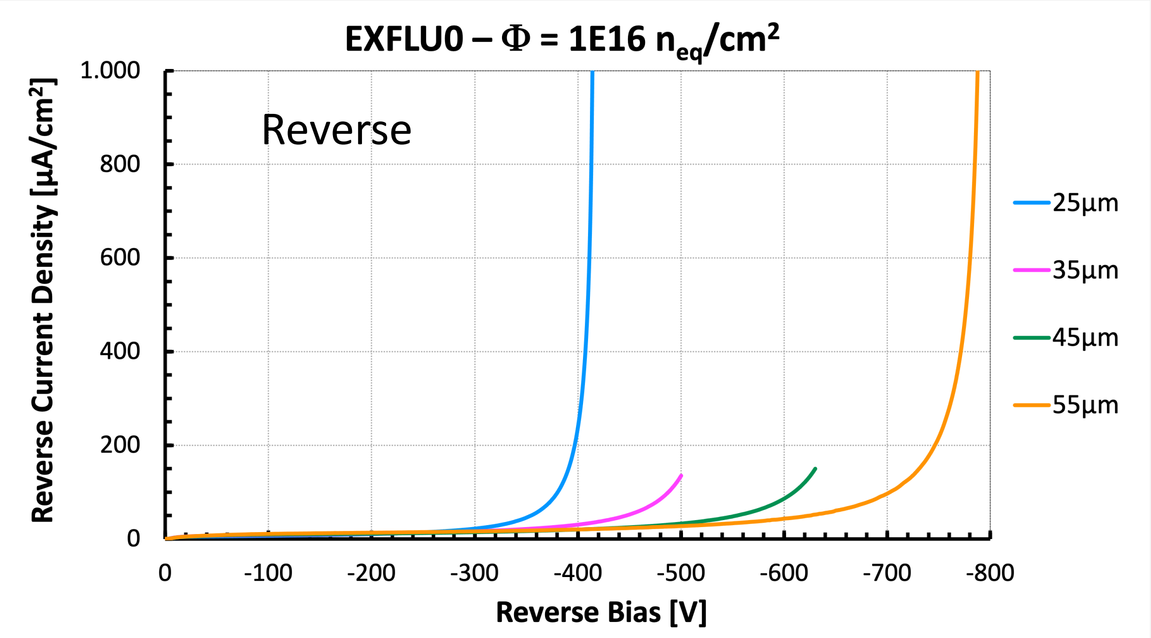
Signal multiplication by a factor of 5-10 is needed

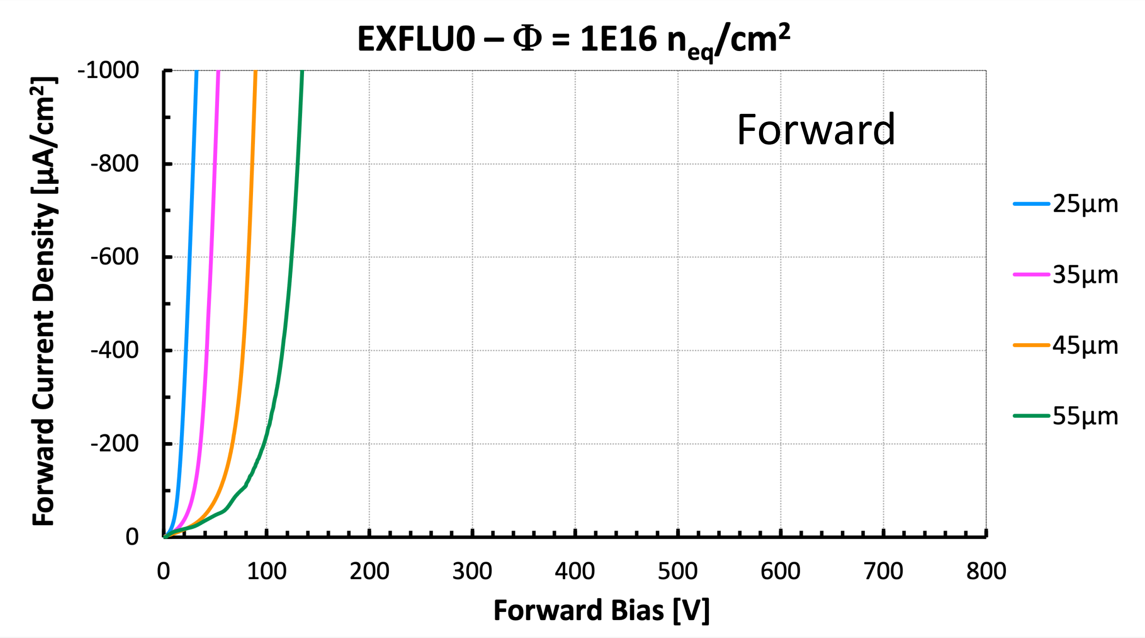


CURRENT DENSITY – Φ = 1E16 n_{eq}/cm^2



Reverse and forward current densities are shown for different sensor thicknesses





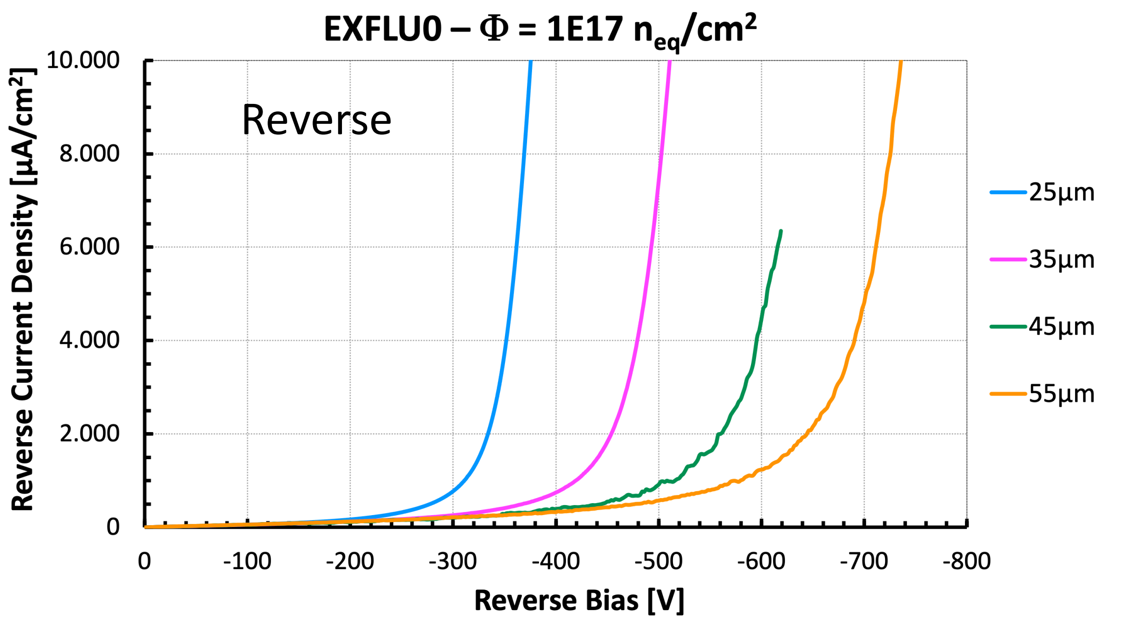
Measurements have been performed at T = -30ºC

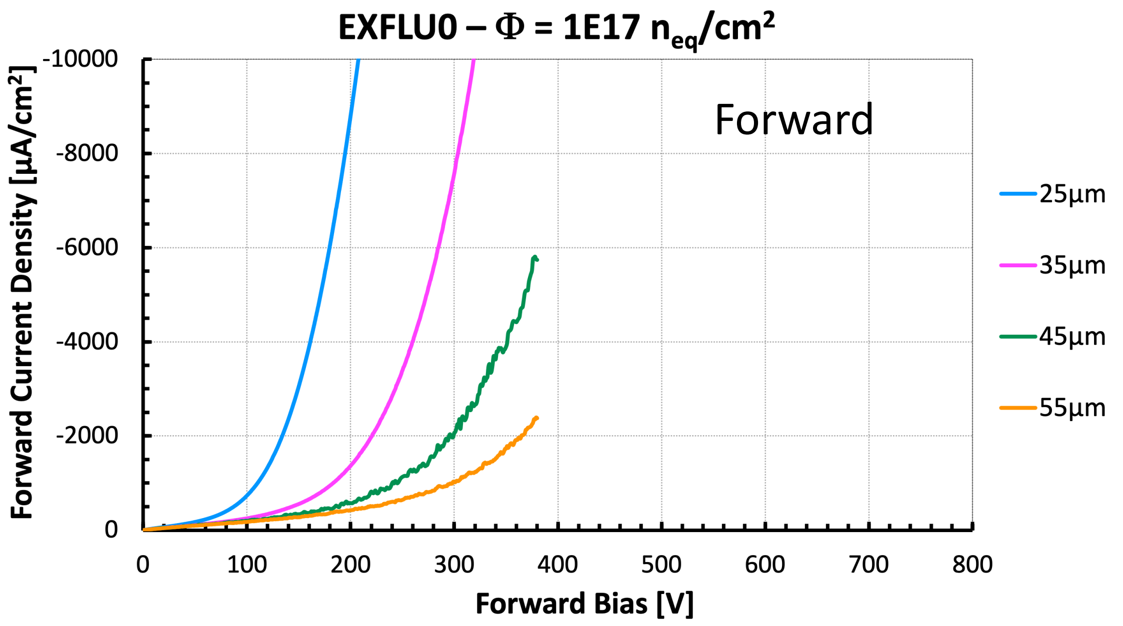
→ Reverse and forward current densities linearly scales with thickness

→ Forward current density shows an abrupt increase for all thicknesses

CURRENT DENSITY – $\Phi = 1E17\ n_{eq}/cm^2$

Reverse and forward current densities are shown for different sensor thicknesses



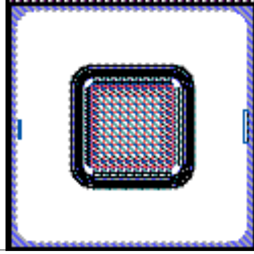


Measurements have been performed at T = -30°C

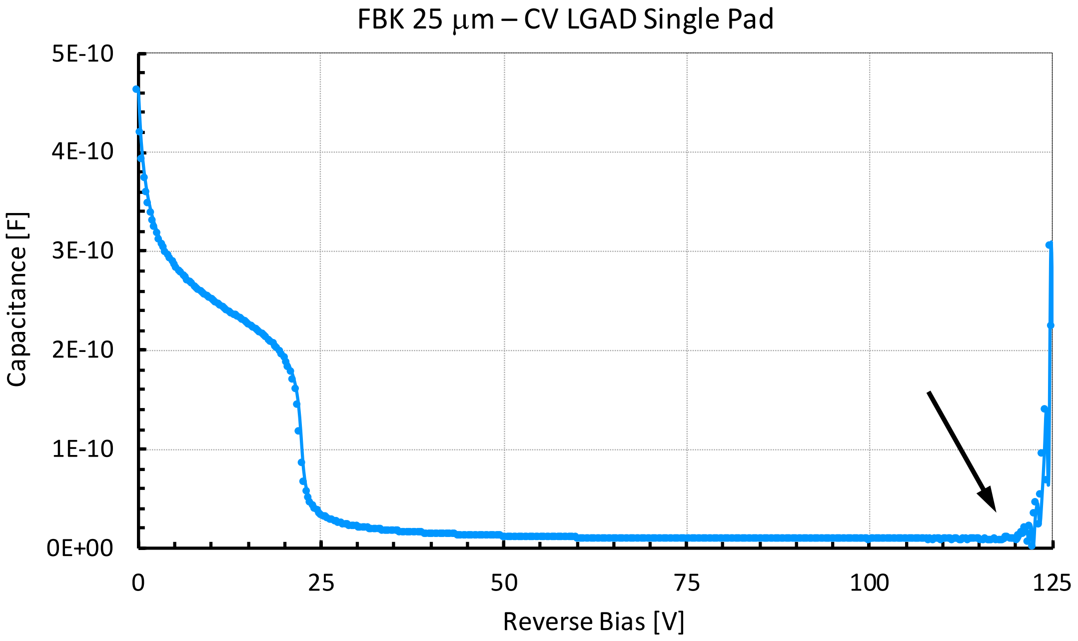
→ Reverse and forward current densities linearly scales with thickness

→ Forward current density extends towards higher values of bias

CV ON 25 μm WAFER – Low ρ

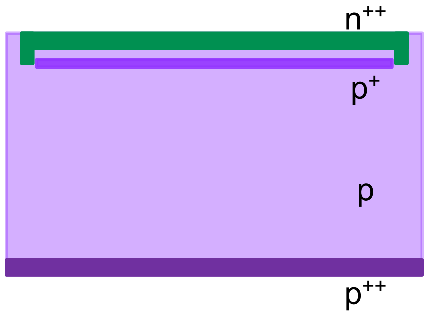


It is difficult to precisely control resistivity of thin epitaxial substrates
→ ρ_{W5} ~ 75 Ω·cm

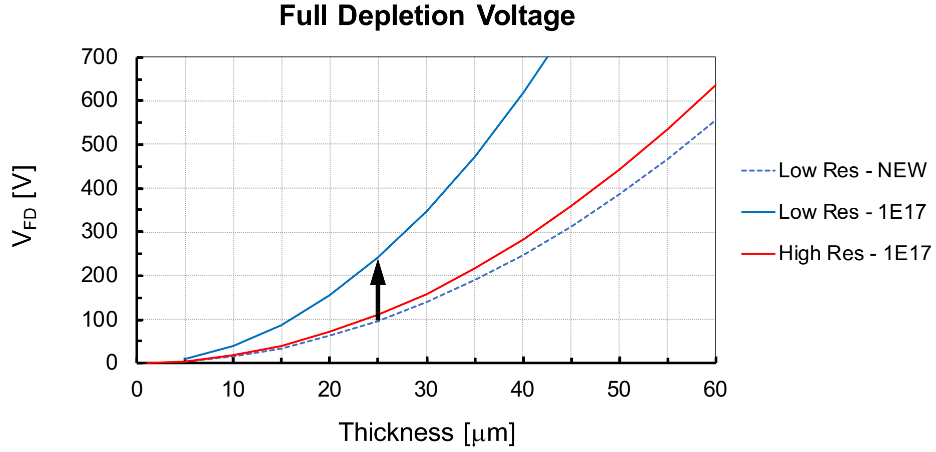


V_{GL} depletion ~ 22 V
V_{bulk} depletion ~ 95 V
Sensor depletion ~ 120 V

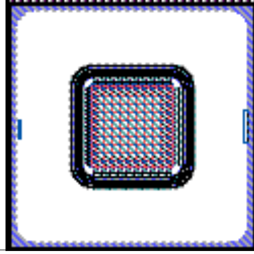
Gain at 120 V ~ 25
Gain at 130 V ~ 40



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

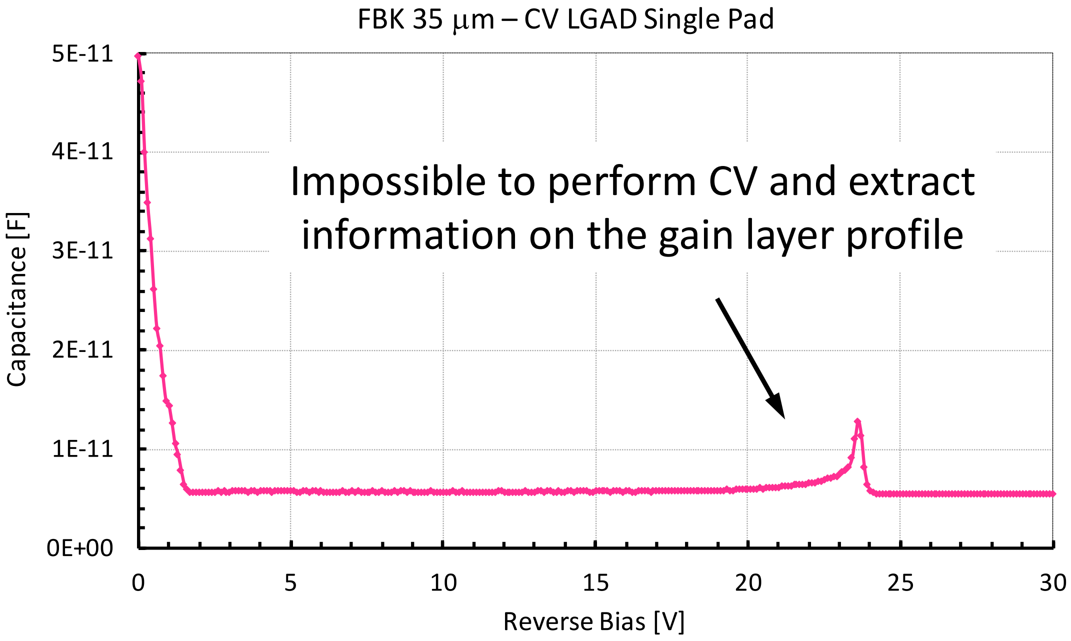


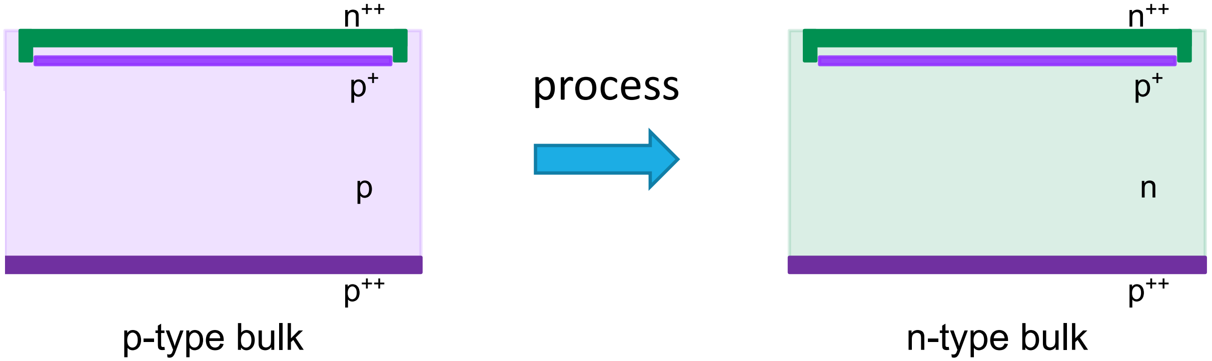
CV ON 35 μm WAFER – High ρ

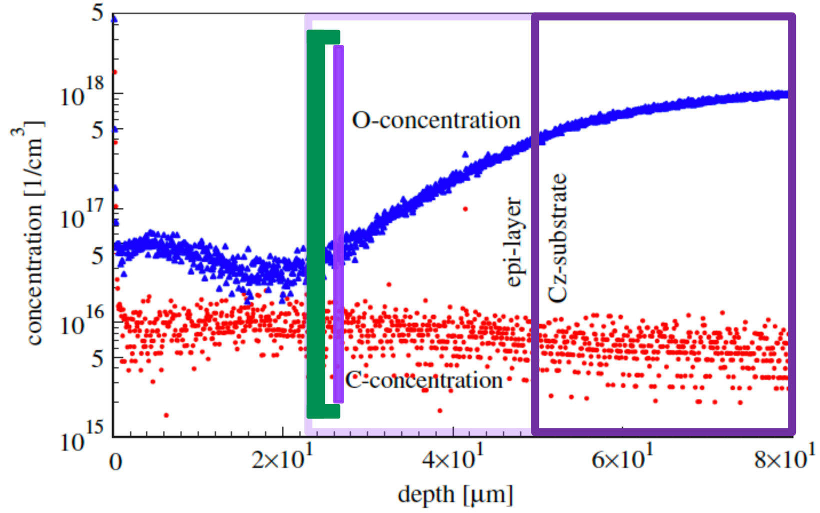


It is difficult to precisely control resistivity of thin epitaxial substrates

→ ρ_{W6} ~ 3,000 Ω·cm





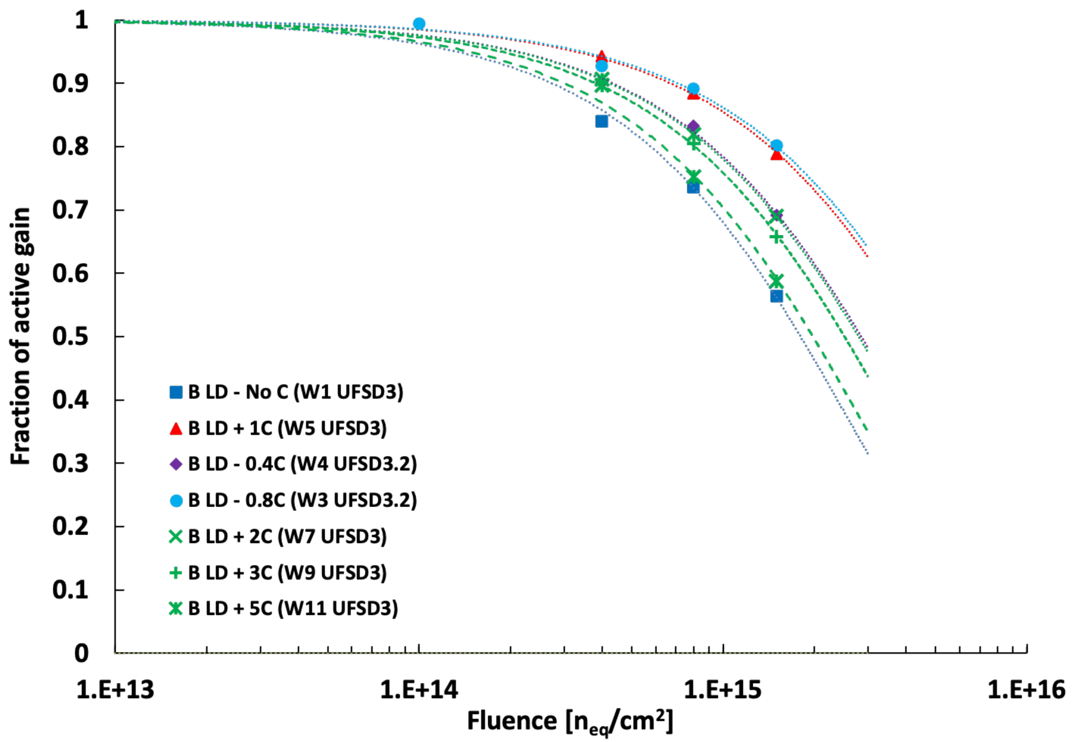


[I. Pintilie 2005 et al., doi:10.1016/j.nima.2005.10.013]

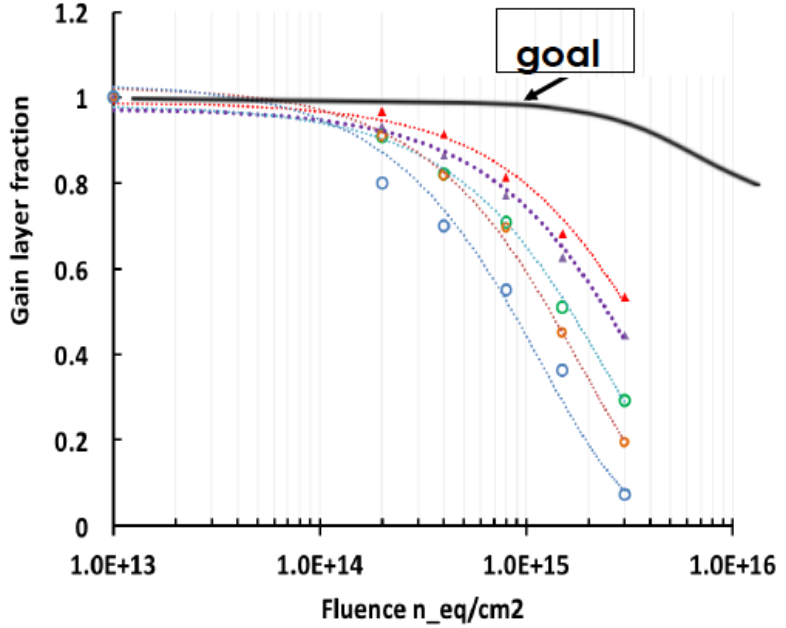
→ **Due to Oxygen diffusion from the support wafer, the active substrate undergo type inversion**

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



Future R&D



⇒ The usage of Carbon enhances the radiation hardness of UFSD

GAIN LAYER RADIATION TOLERANCE

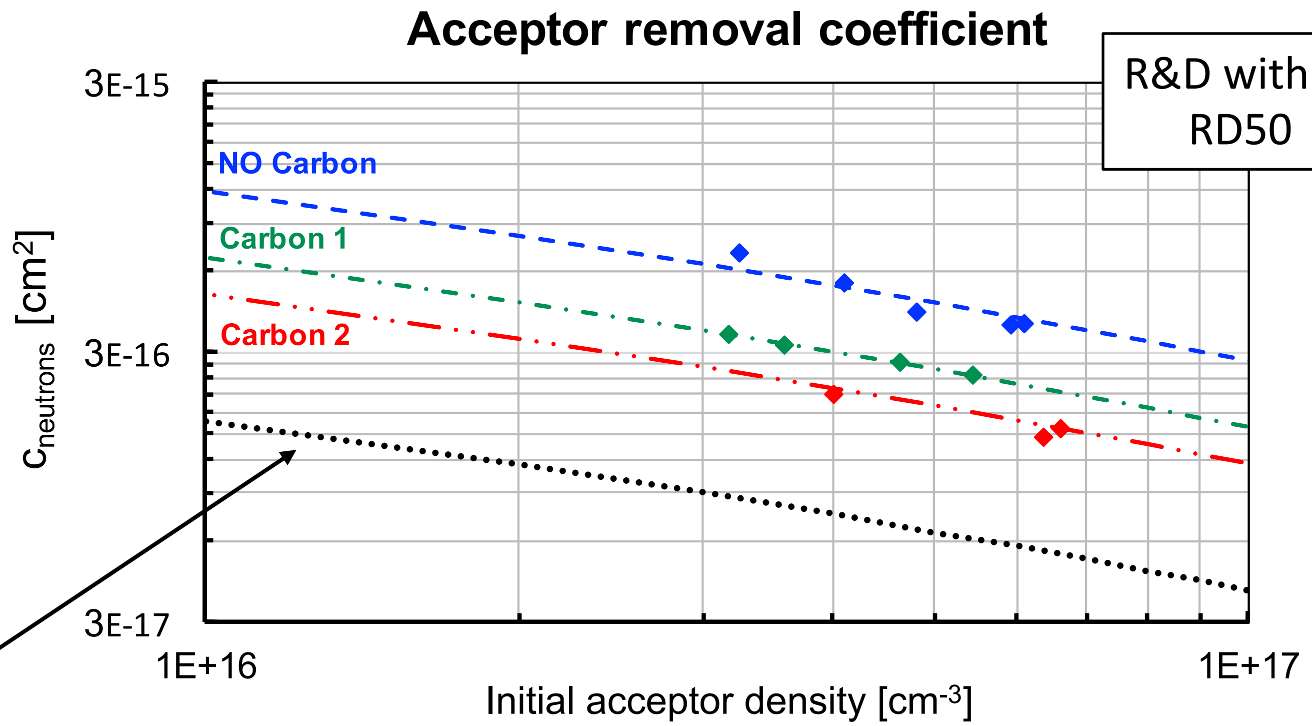
Goal: retard multiplication transition from the gain layer to the bulk region

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**



R&D within RD50

Possible?

[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:

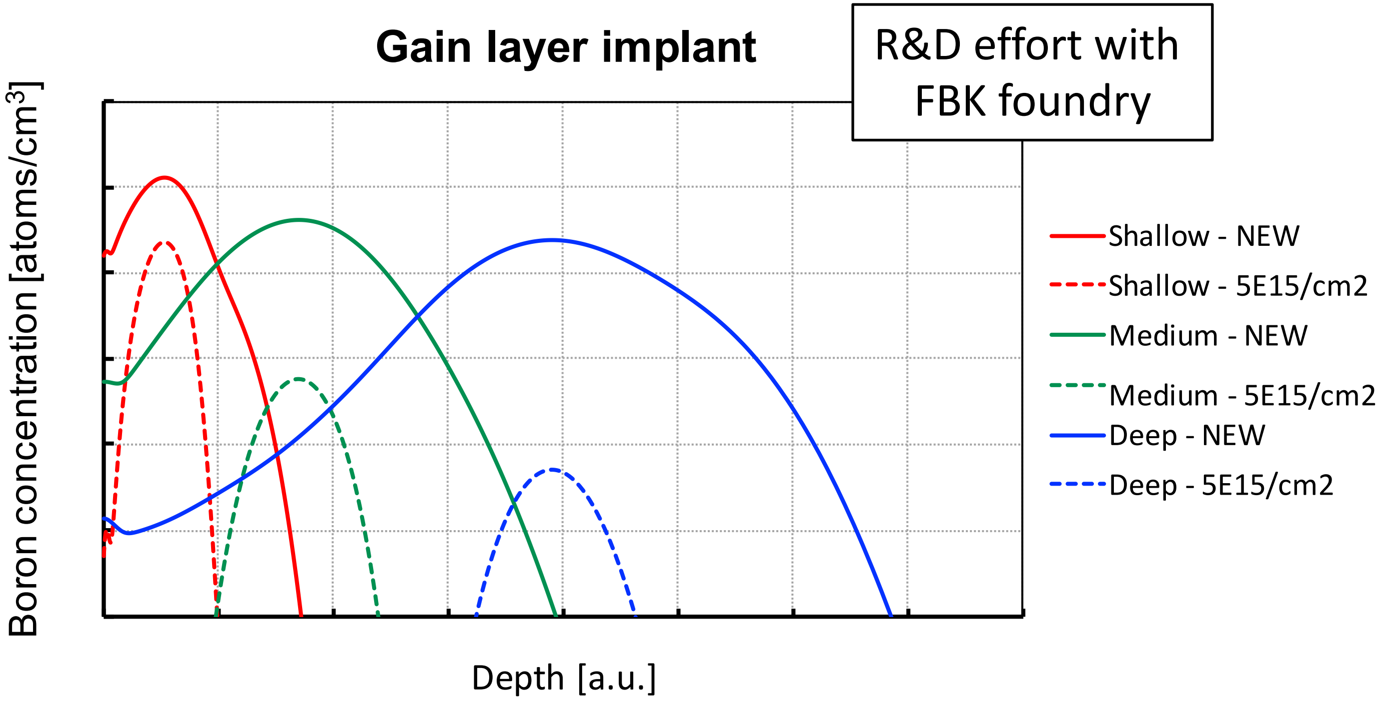
$$N_{A,eff} = N_{A,0} \cdot e^{-c\Phi}$$

Defect engineering and different gain layer implantation strategies will be investigated

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

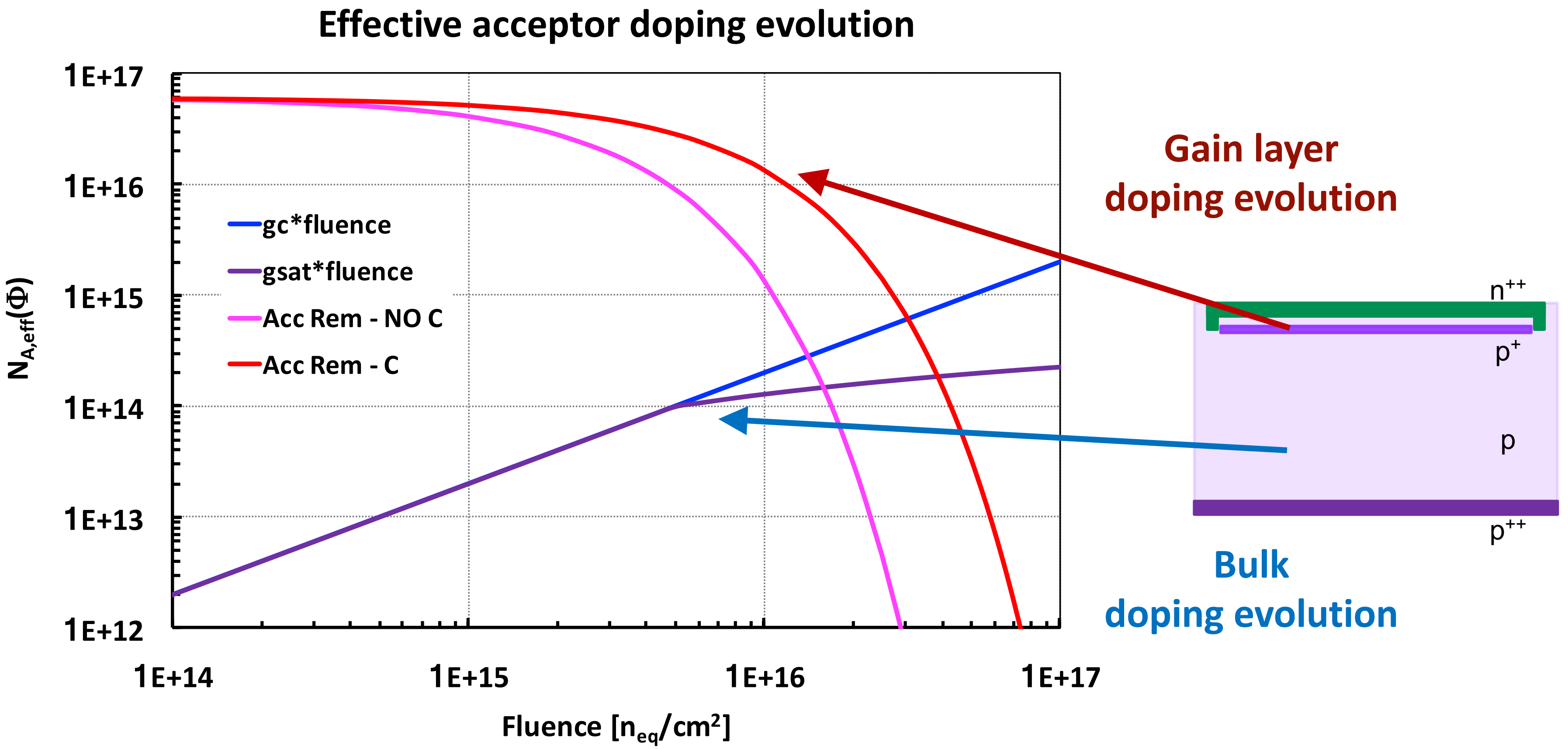
for $N_{A,0} = 10^{17}$ atoms/cm^3

R&D effort with FBK foundry



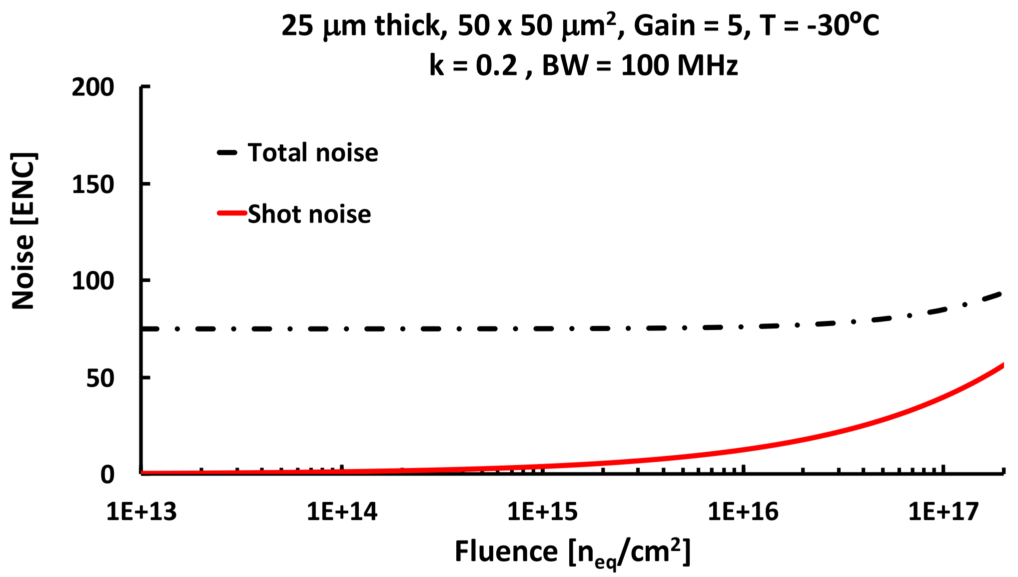
ACCEPTOR DOPING EVOLUTION WITH Φ

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



SHOT NOISE

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



For LGAD sensors, shot noise is given by

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

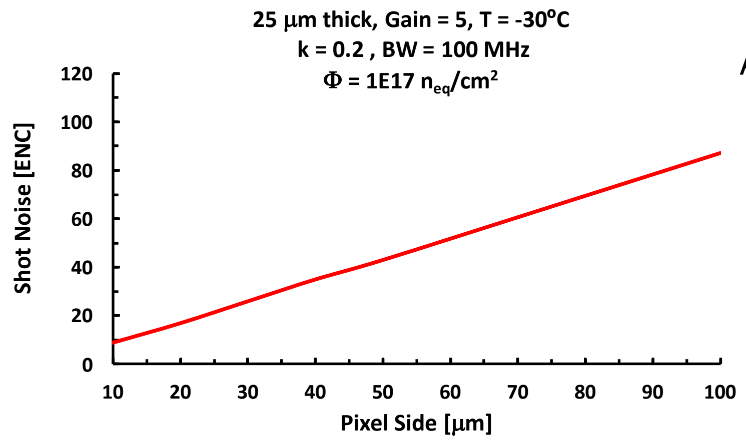
G = gain

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

Δf = bandwidth interval

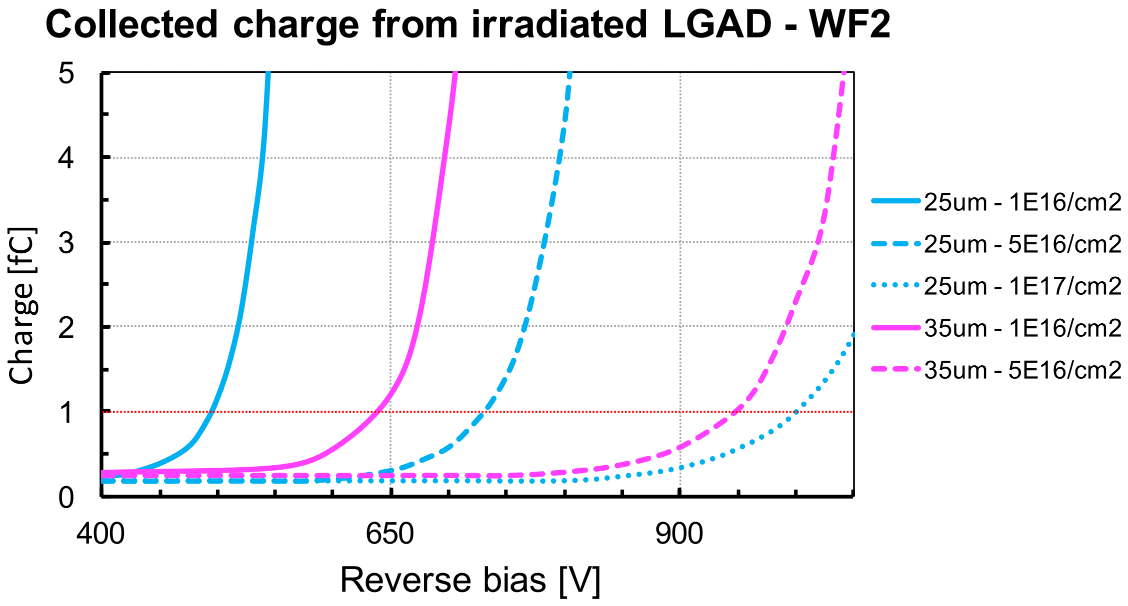
Shot noise is compared to RD53 chip performances
`[https://rd53.web.cern.ch/]`

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



Assuming squared pixels

TOWARD THE EXTREME FLUENCES



→ **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**

[l.infn.it/wf2]

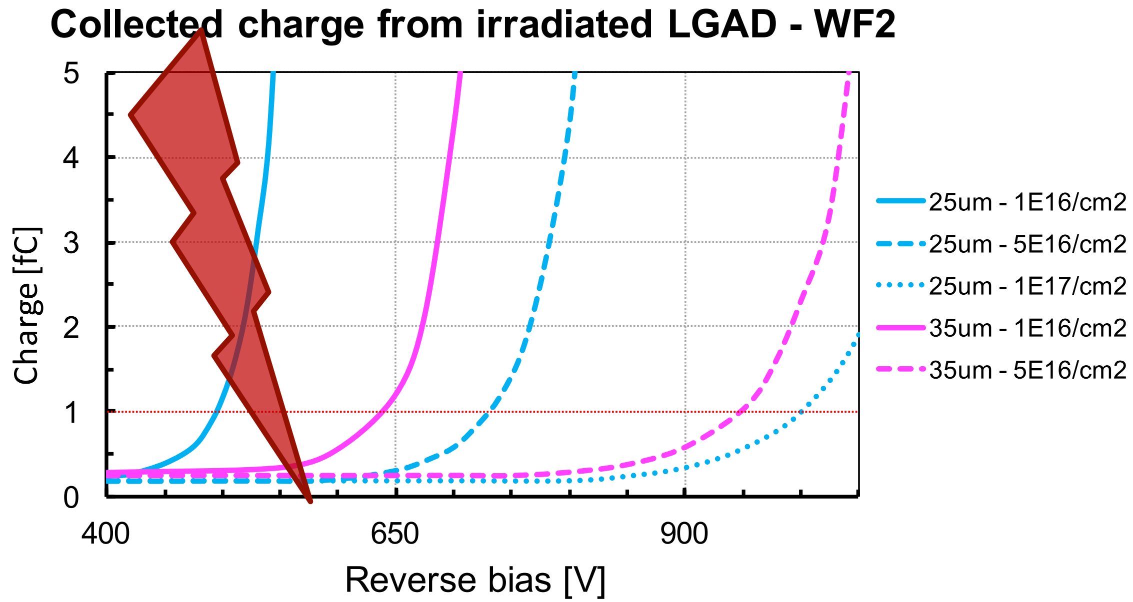
Simulation in progress with the Perugia group to find the optimal sensor design for the next production on thin wafers – EXFLU1

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

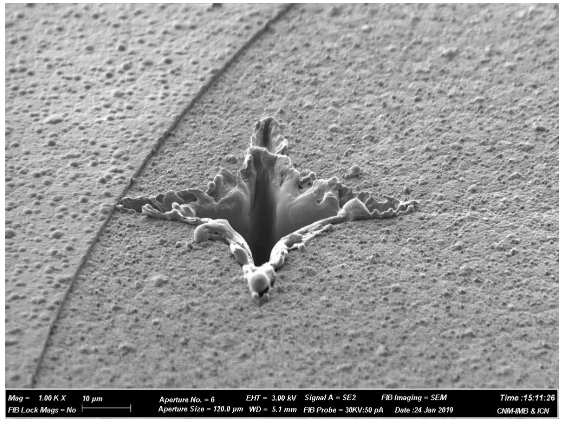
[A. Morozzi et al., doi:10.22323/1.373.0050]

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

HIGHLY IONISING EVENTS ON THIN SENSORS



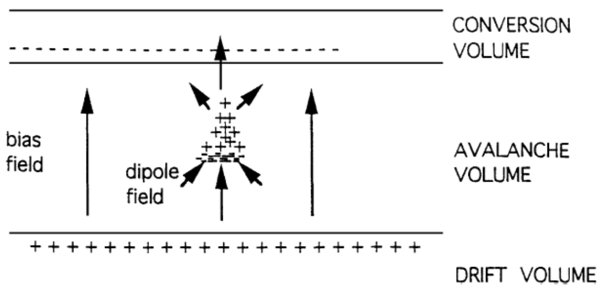
What happens if the sensor experiences a fatal highly ionising particle at a bias lower to the one necessary to collect 1fC?



The observed mortality of thin LGAD sensors on beam can be even more severe for the thinner EXFLU sensors

[See R. Heller contribution at this workshop for more details]

HIGHLY IONISING PARTICLE EFFECTS

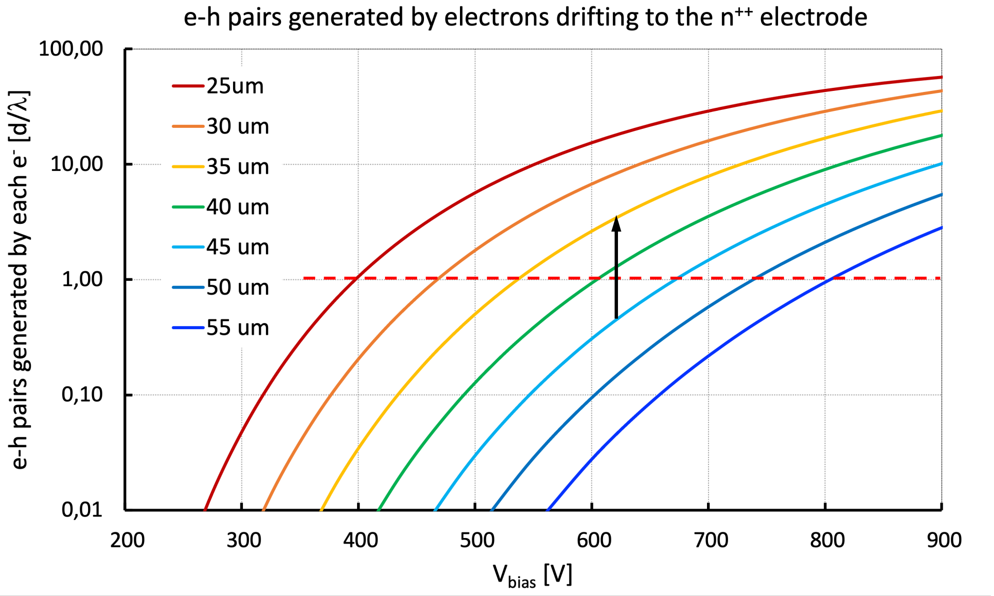


Same effect was observed in APD
[G. Anzivino et al. NIM A 430 (1999) 100]

A reasonable picture of a highly ionising event is that the high charge carrier density induces a local collapse of the electric field causing a local reduction of the sensor thickness

Considering the impact ionisation mechanism $N(x) = N_0 \cdot e^{\alpha(E)x}$

$\lambda = 1/\alpha$ is the mean free path needed by a charge carrier to acquire enough kinetic energy to create an additional electron-hole pair



Reducing the sensor thickness the probability of generating secondary e-h pairs in the bulk at V_{bias} = 630 V increases

45 µm ⟶ $2^{0.5}$ = 1.4

40 µm ⟶ $2^{1.7}$ = 3.2

35 µm ⟶ $2^{3.8}$ = 14

30 µm ⟶ $2^{9.1}$ = 549

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 irradiated 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

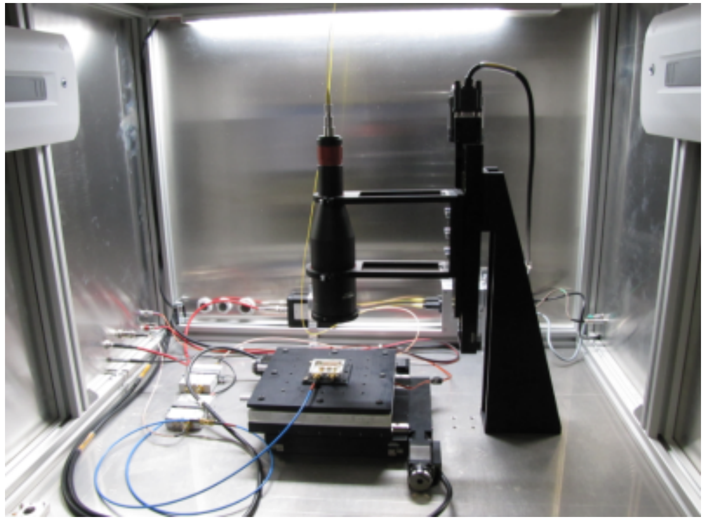
COOL SYSTEMS

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 +300°C
will arrive soon in Torino Laboratory

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

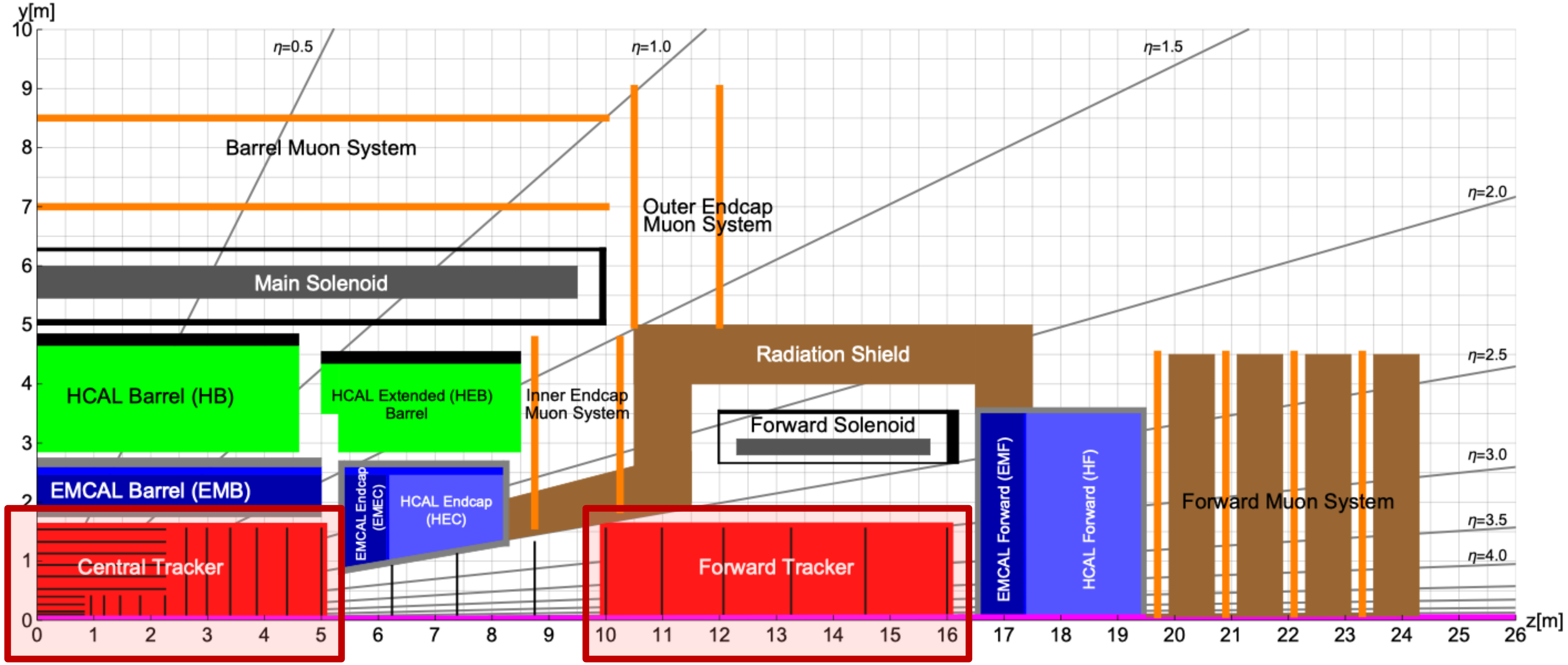


Particulars Large Scanning TCT setup
connected to Lauda chiller down to -20°C
available in Torino Laboratory

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 σ_z ~ 44 mm, σ_t ~ 165 ps
- Average distance between vertices at z = 0 is 125 μm

Tracker requirements:

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

RADIATION BUDGET- TRACKER VOLUME

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

Courtesy of M.I. Besana