The 39th RD50 Workshop
17–19 November 2021
Valencia

Results from thin silicon sensors irradiated to extreme fluence

---

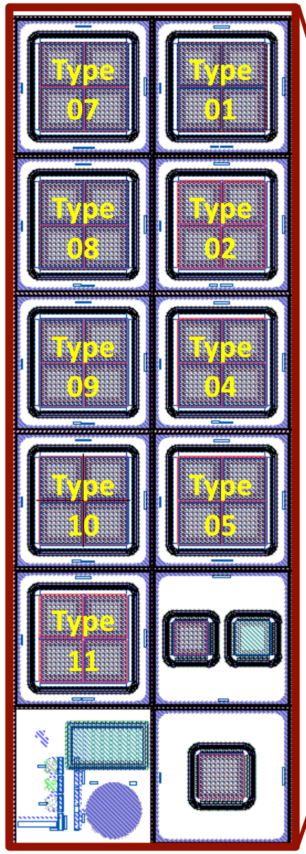
V. Sola, R. Arcidiacono, P. Asenov, G. Borghi, M. Boscardin, N. Cartiglia, M. Centis Vignali, T. Croci, M. Ferrero, G. Gioachin, S. Giordanengo, M. Mandurrino, L. Menzio, A. Morozzi, F. Moscatelli, D. Passeri, G. Paternoster, F. Siviero, M. Tornago

First Thin Wafers from FBK – EXFLU0

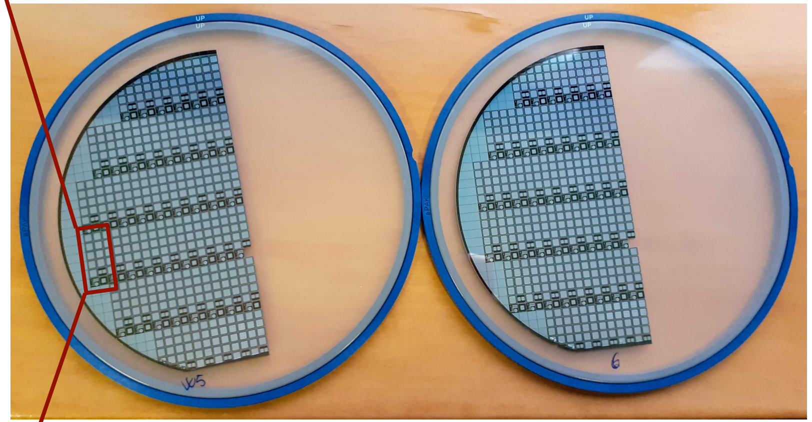
Wafer #	Thickness	Depth	Dose Pgain	Carbon	Diffusion
5	25	Standard	0.94	A	CHBL
6	35	Standard	0.94	A	CHBL

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 thicknesses: 25 & 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/

Results on Thin Sensors since last RD50

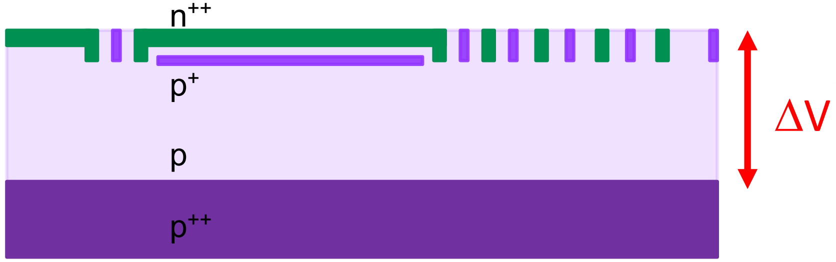
- ➢ Voltage drop on the sensor periphery
- ➢ Evolution of the inter-pad resistance with fluence
- ➢ Study of the doping profile evolution with fluence via CV and TCT measurements
- ➢ Charge collection efficiency evolution with fluence

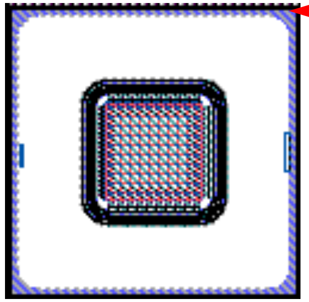
Experimental setups:

- ▻ Probe Station in Torino
  MPI TS-2000SE Probe Station with thermal chuck down to –40°C + Keysight B1505A (f_{min} = 1kHz)
- ▻ Probe Station in Perugia
  MPI TS-2000SE Probe Station with thermal chuck down to –60°C + SMU Keithley 237
  + LCR meter HP 4284A (f_{min} = 200 Hz)
- ▻ TCT in Torino
  Particulars Large Scanning TCT setup connected to Lauda chiller down to –10°C

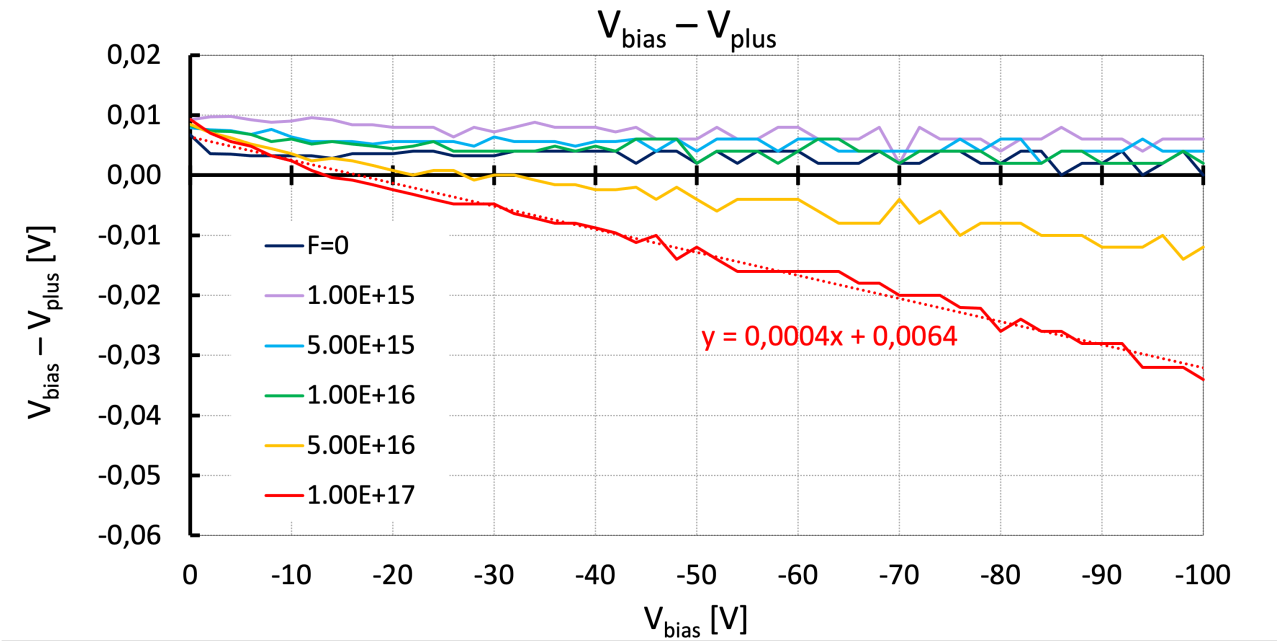
Voltage Drop on the Sensor Edge – 35 µm

Sketch not to scale





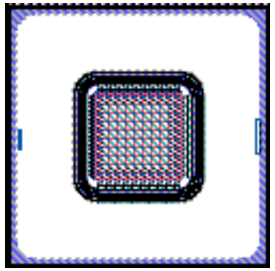
p-plus contact



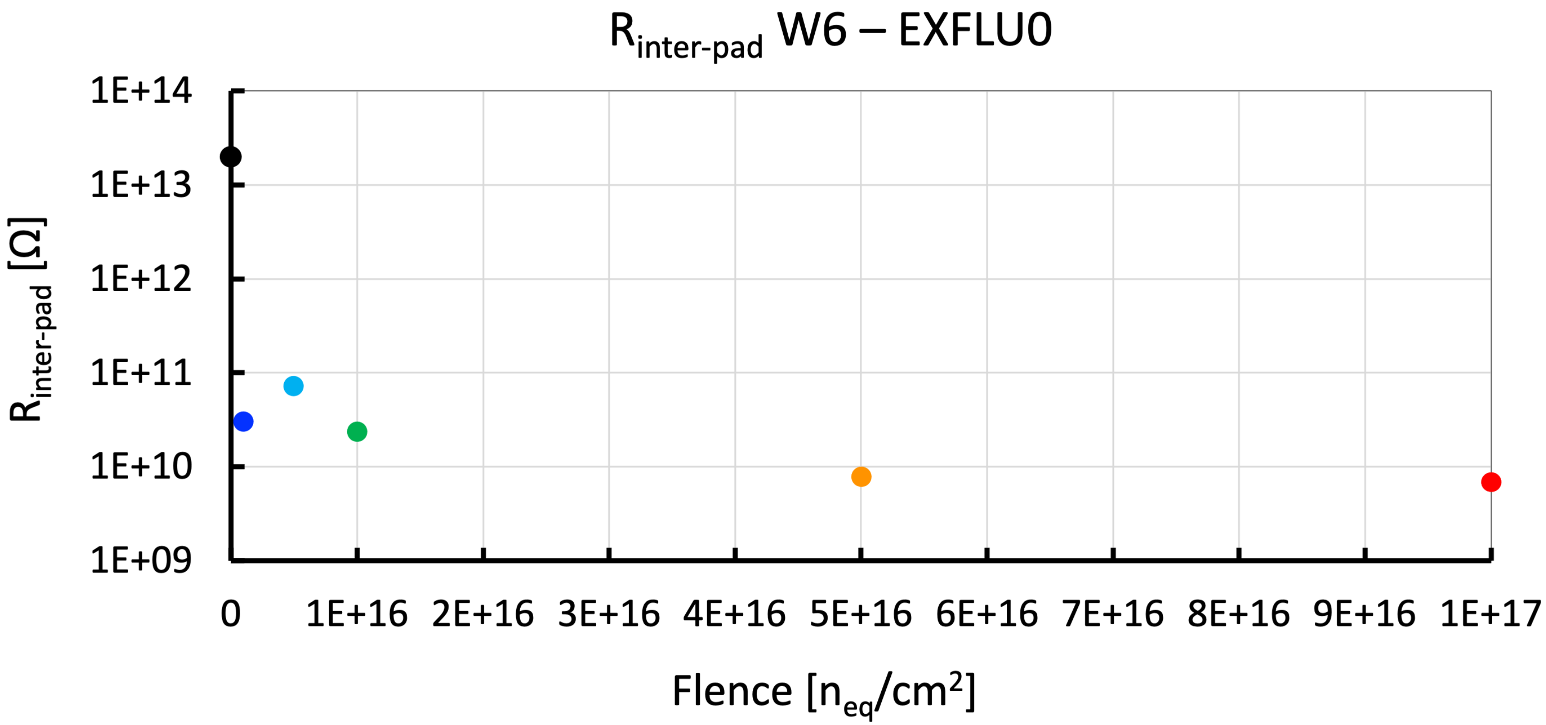
Very small difference observed above 1E16 n_{eq}/cm^2

→ 0.4 V at V_{bias} = 1000 V after a fluence of 1E17 n_{eq}/cm^2

R inter-pad – 35 µm



R inter-pad measured between the **pad** and the **guard-ring**

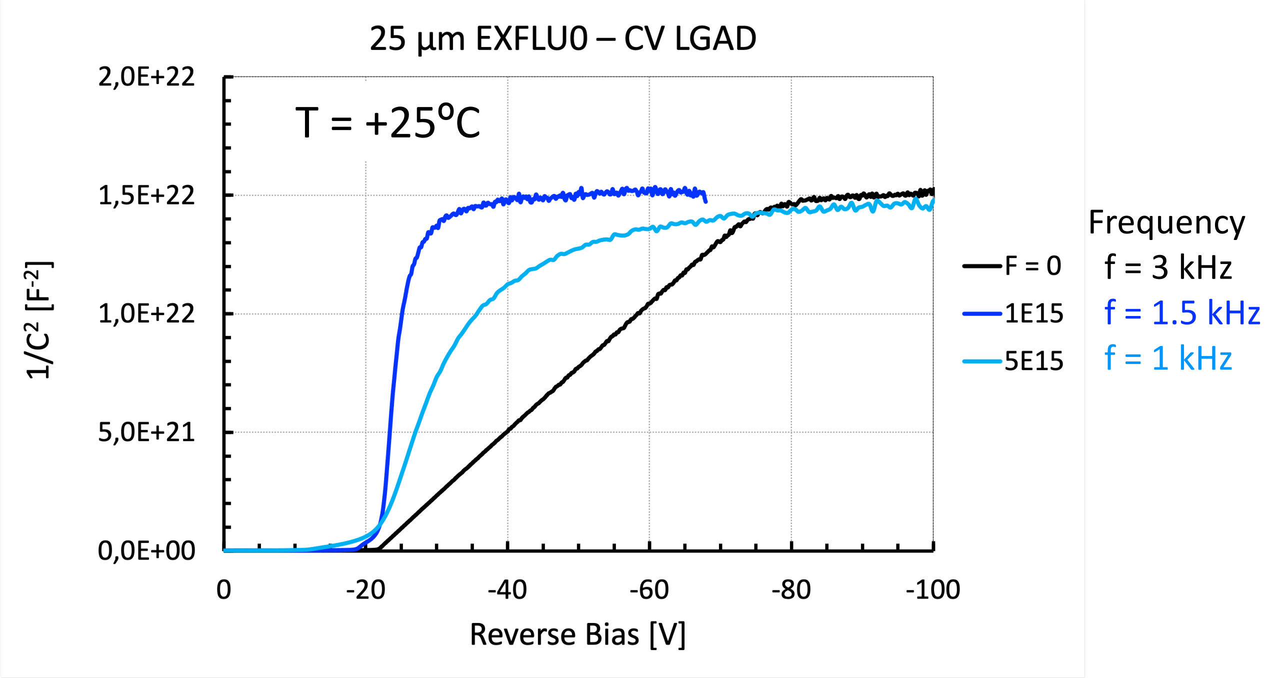


Φ [n_{eq}/cm^2]	R [GΩ]
0	2E4
1E15	30
5E15	72
1E16	23
5E16	8
1E17	7

→ Good isolation is observed at all fluences

Doping Evolution on Thin Bulk – 25 µm

25 µm thick sensors have a highly doped active substrate



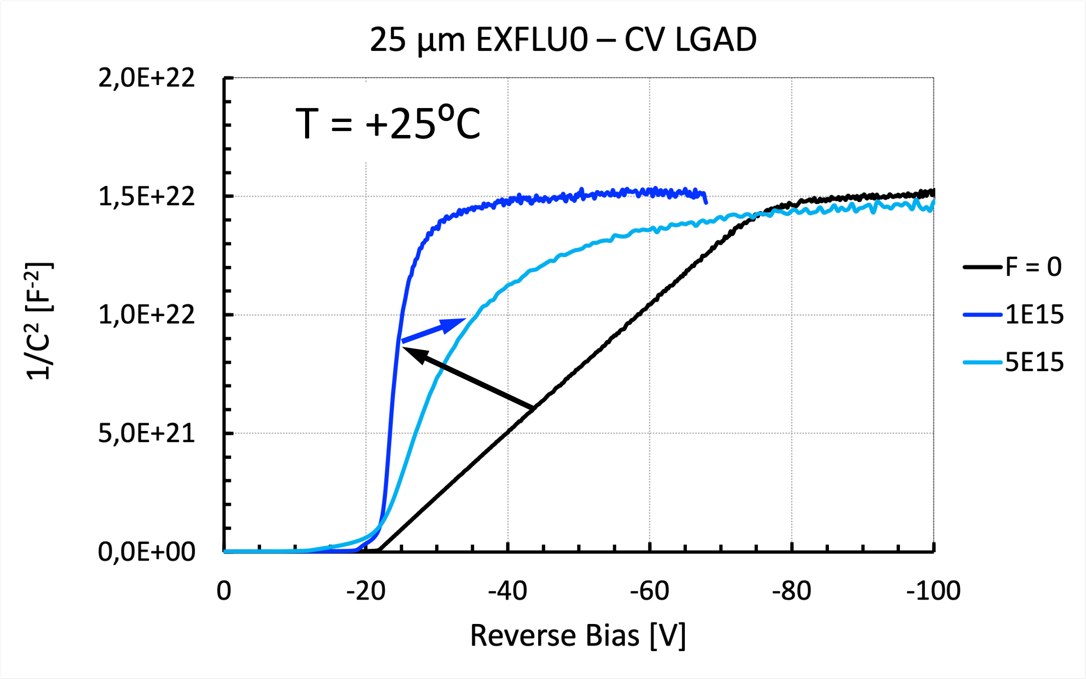
Measurements have been performed at T = +25°C

→ For higher fluences and lower temperatures, lower frequencies should be used to perform CV measurements

→ TCT measurements will be performed to estimate the voltage of full depletion of extremely irradiated sensors

Doping Evolution on Thin Bulk – 25 µm

25 µm thick sensors have a highly doped active substrate



Frequency
f = 3 kHz
f = 1.5 kHz
f = 1 kHz

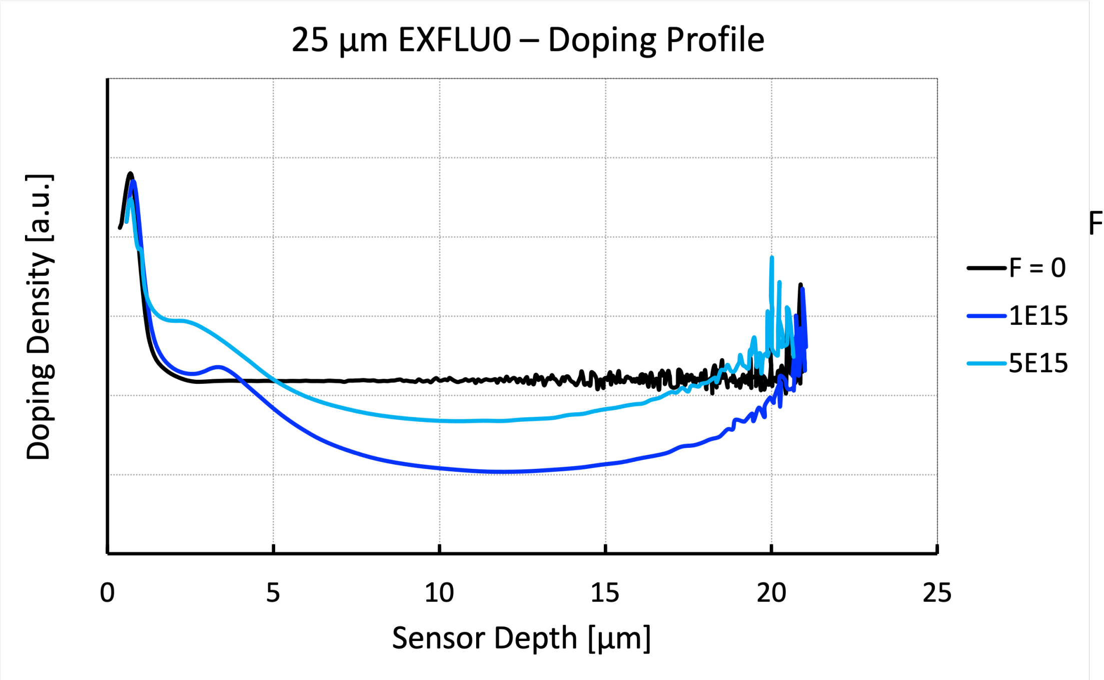
Measurements have been performed at T = +25°C

→ For higher fluences and lower temperatures, lower frequencies should be used to perform CV measurements

→ TCT measurements will be performed to estimate the voltage of full depletion of extremely irradiated sensors

Doping Evolution on Thin Bulk – 25 µm

25 µm thick sensors have a highly doped active substrate



Frequency
f = 3 kHz
f = 1.5 kHz
f = 1 kHz

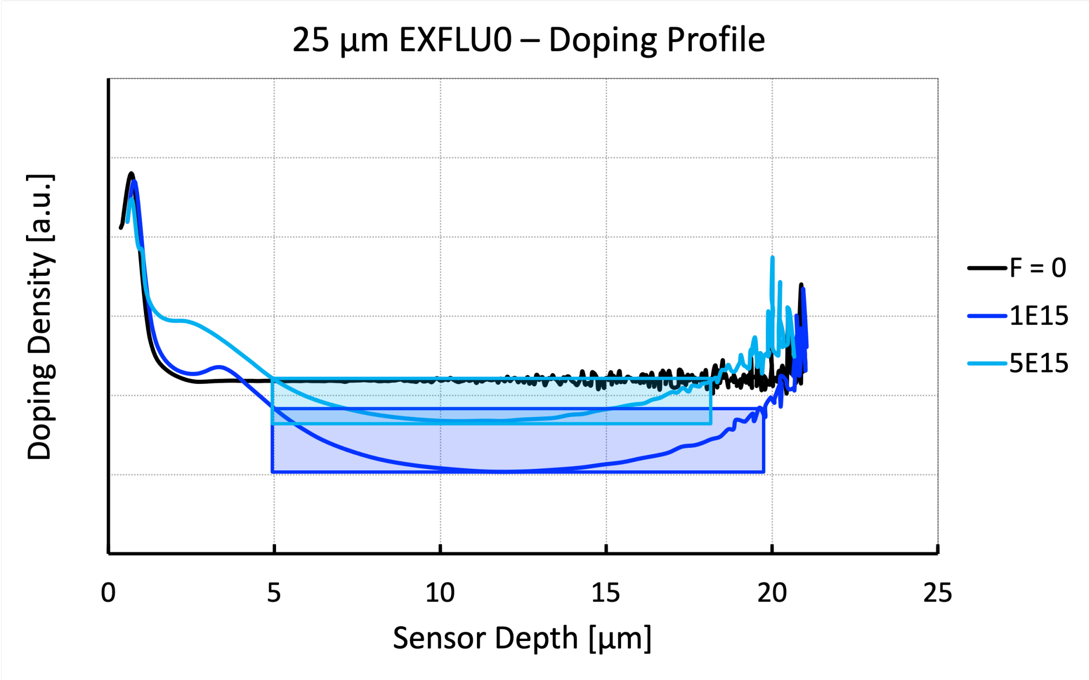
Measurements have been performed at T = +25°C

→ For higher fluences and lower temperatures, lower frequencies should be used to perform CV measurements

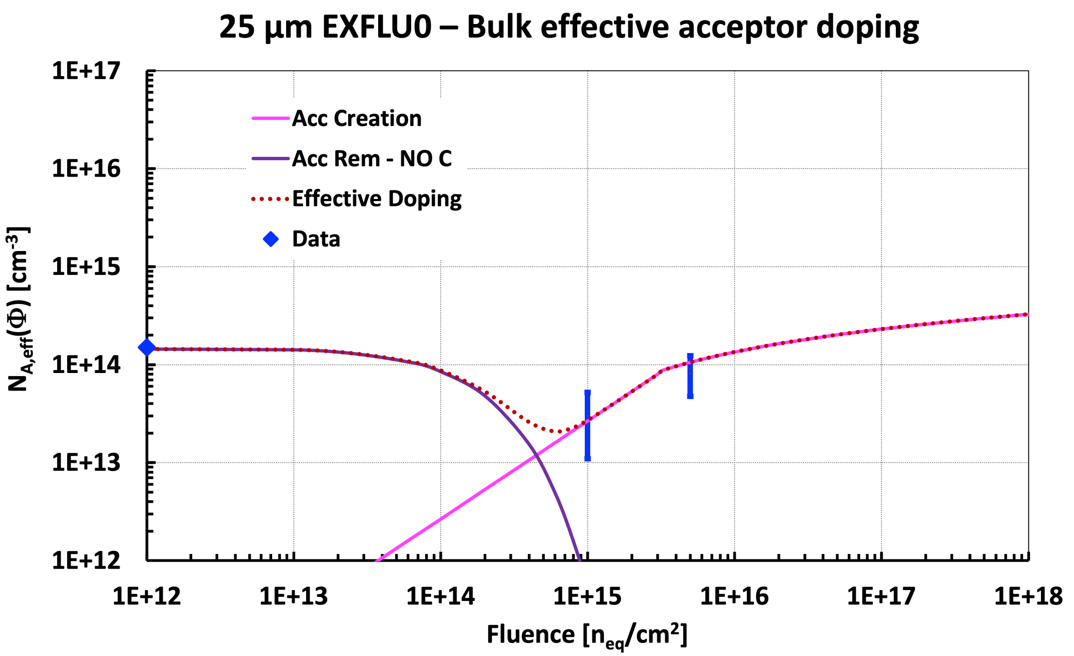
→ TCT measurements will be performed to estimate the voltage of full depletion of extremely irradiated sensors

Doping Evolution on Thin Bulk – 25 µm

25 µm thick sensors have a highly doped active substrate



From $N_{A,eff}(\Phi) = N_A(0)\cdot e^{-c\Phi} + g_c\Phi$ and considering the saturation of the acceptor creation, the W5 bulk doping is expected to evolve as follows



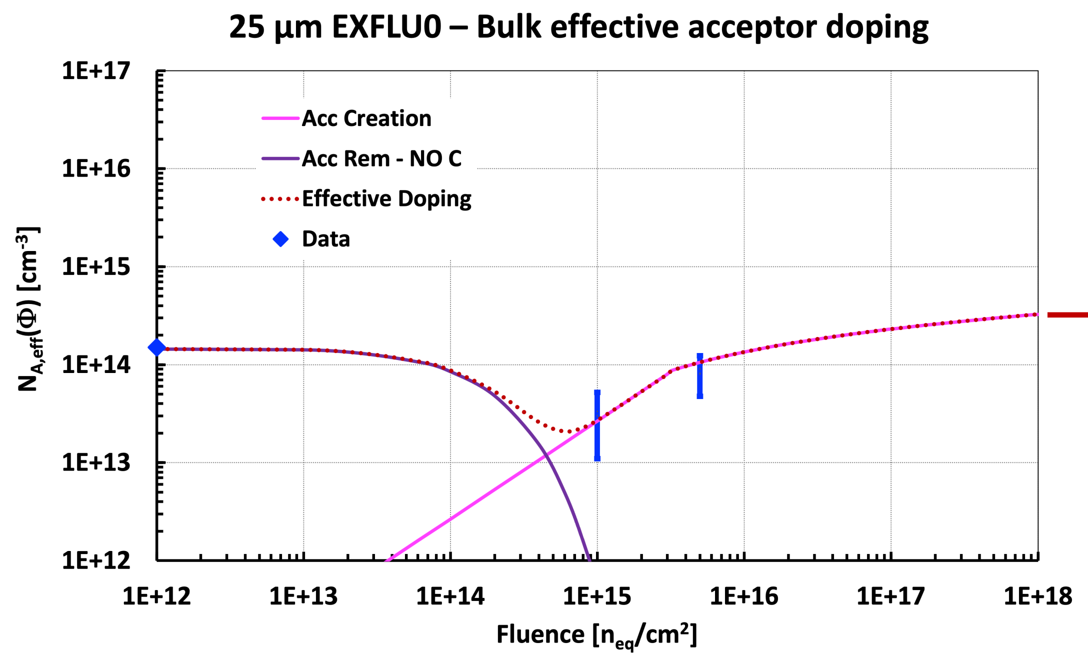
Measurements have been performed at T = +25°C

→ For higher fluences and lower temperatures, lower f

→ TCT measurements will be performed to estimate the voltage of full depletion of extremely irradiated sensors

Doping Evolution & Depletion Voltage

From $N_{A,eff}(\Phi) = N_A(0)\cdot e^{-c\Phi} + g_c\Phi$ and considering the saturation of the acceptor creation, the W5 bulk doping is expected to evolve as follows



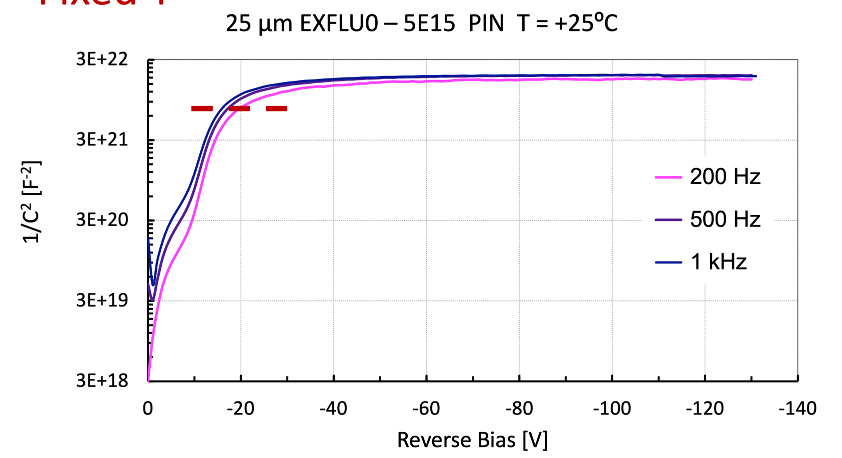
Expected bias of full depletion

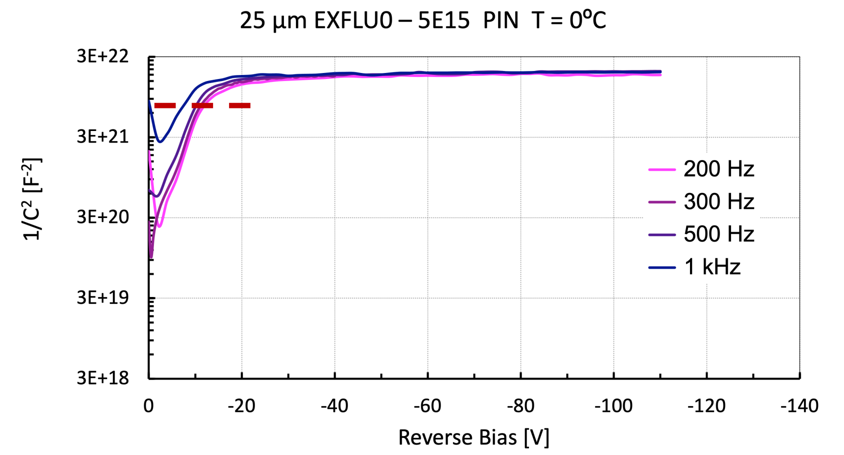
W5 EXFLU0	
Φ [n_{eq}/cm^2]	V FD [V]
0	72,5
1E+15	13,2
5E+15	51,3
1E+16	65,3
5E+16	97,7
1E+17	113,7

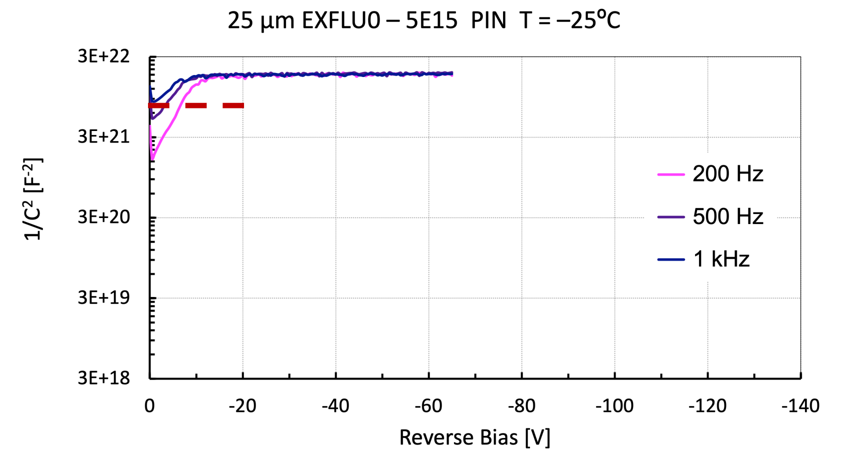
Doping Evolution Study via CV Measurements

1/C^{2}V on **PiN** @ different T & f to extract the voltage of full depletion – **5E15 n$_{eq}$/cm^2**

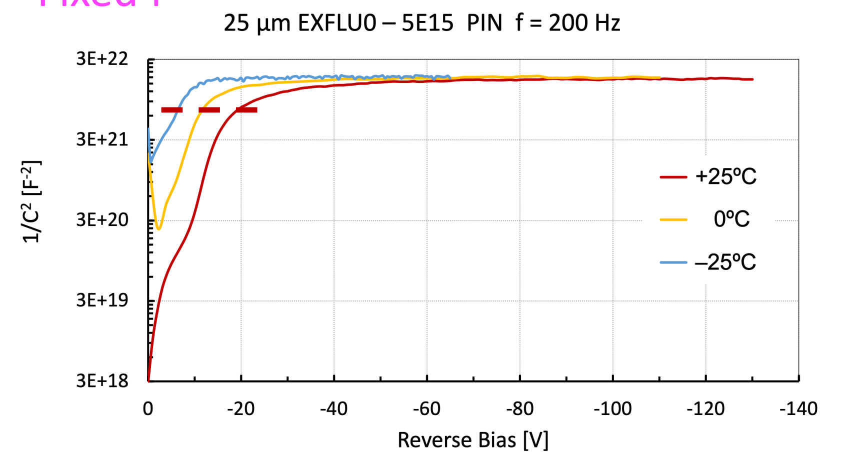
Fixed T

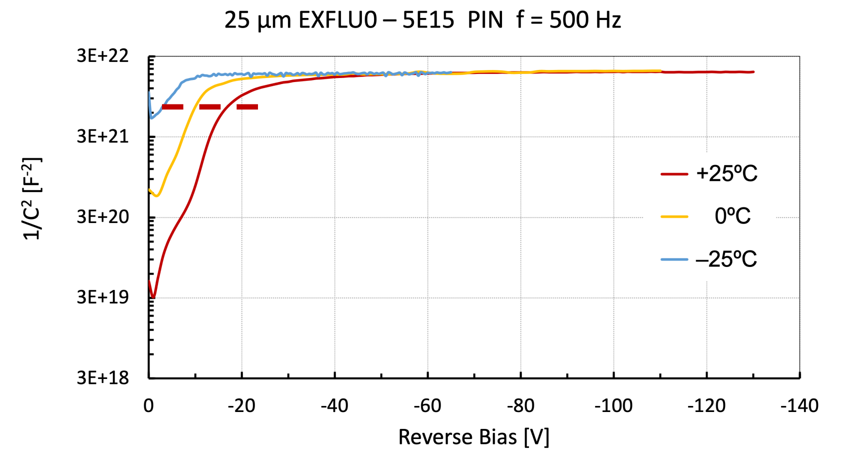


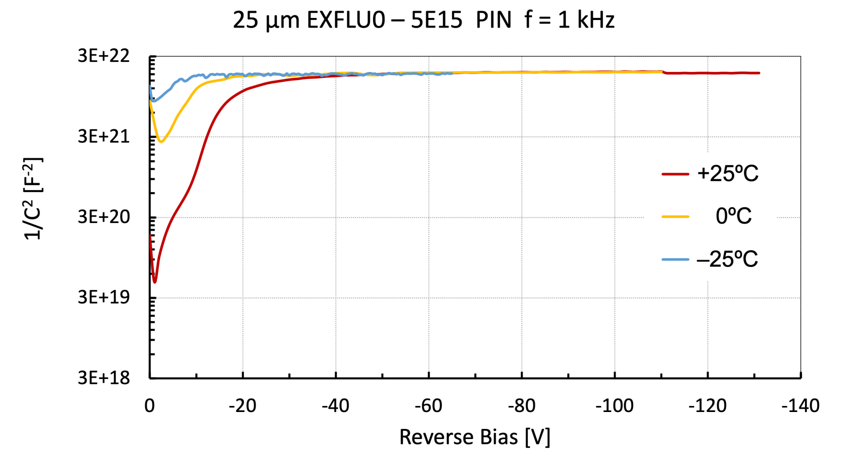




Fixed f



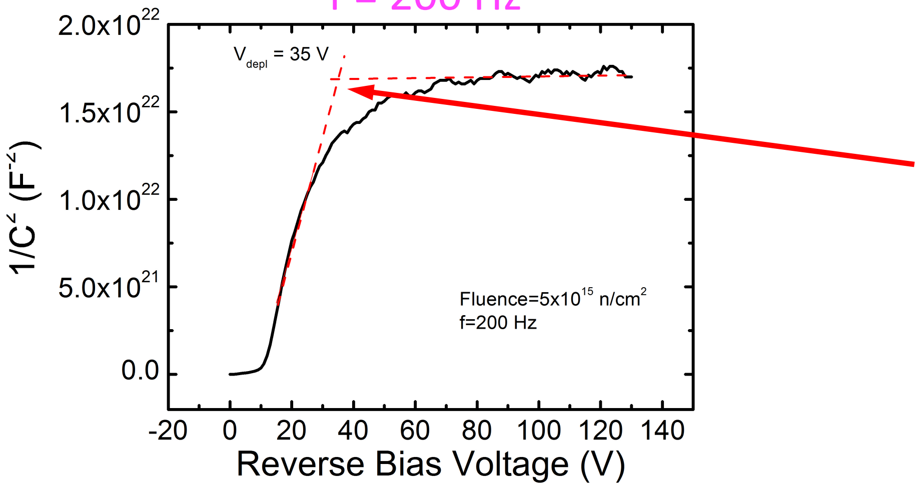




Full Depletion Voltage from $1/C^2V$ – 5E15 n_{eq}/cm^2

T = +25ºC

f = 200 Hz



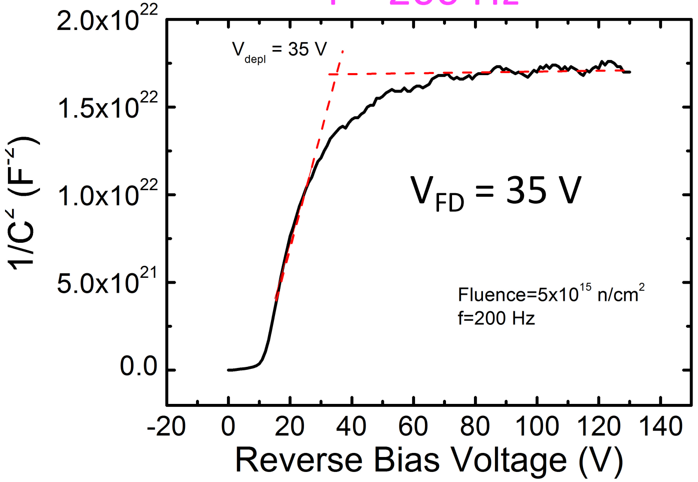
V_{FD} extracted as the intercept
of the two linear fits

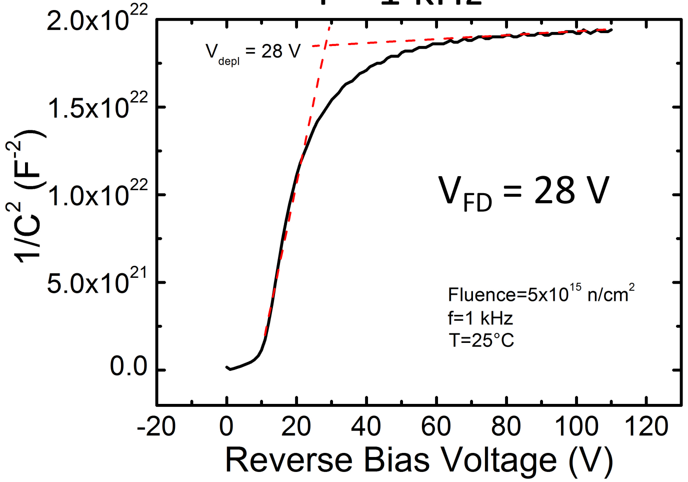
Full Depletion Voltage from $1/C^2V$ – 5E15 n_{eq}/cm^2

f = 200 Hz

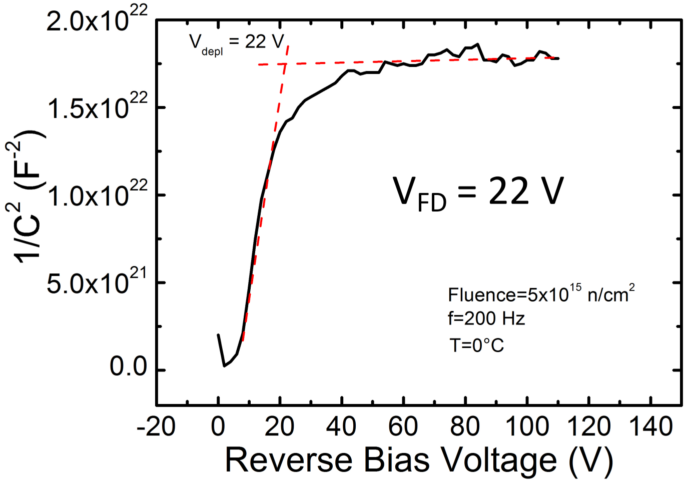
f = 1 kHz

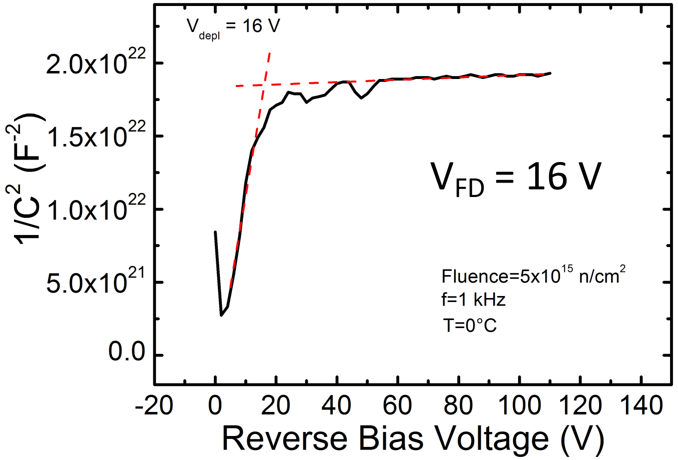
T = +25°C





T = 0°C

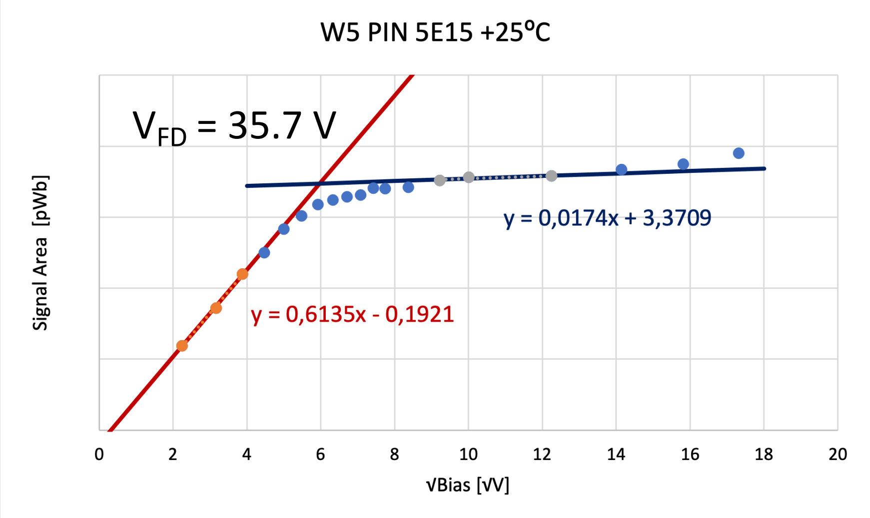


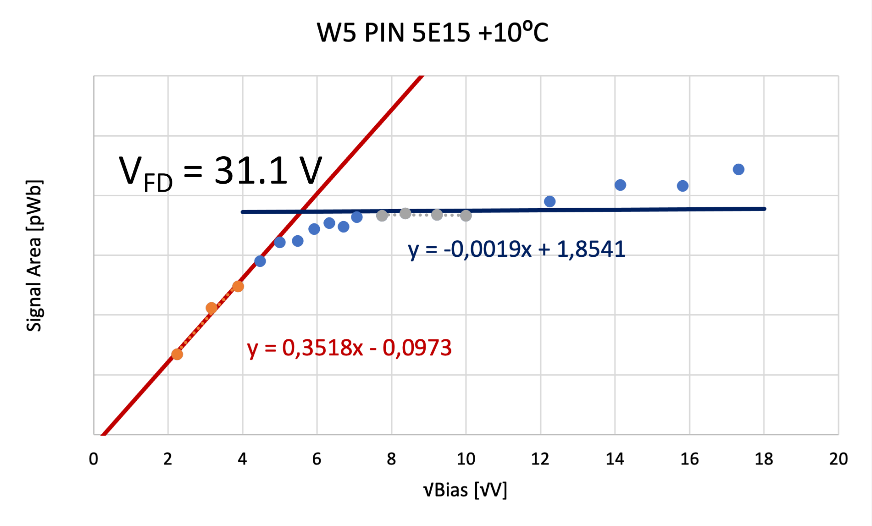


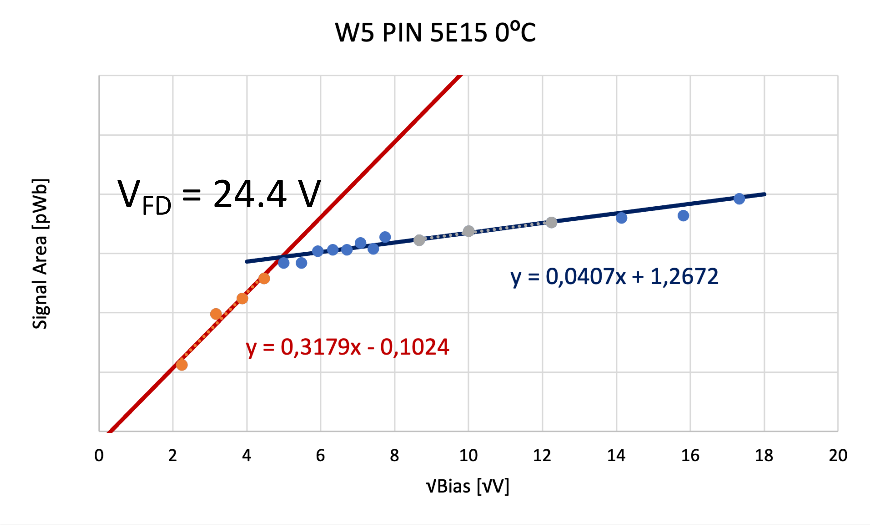
Full Depletion Voltage from TCT – 5E15 n_{eq}/cm^2

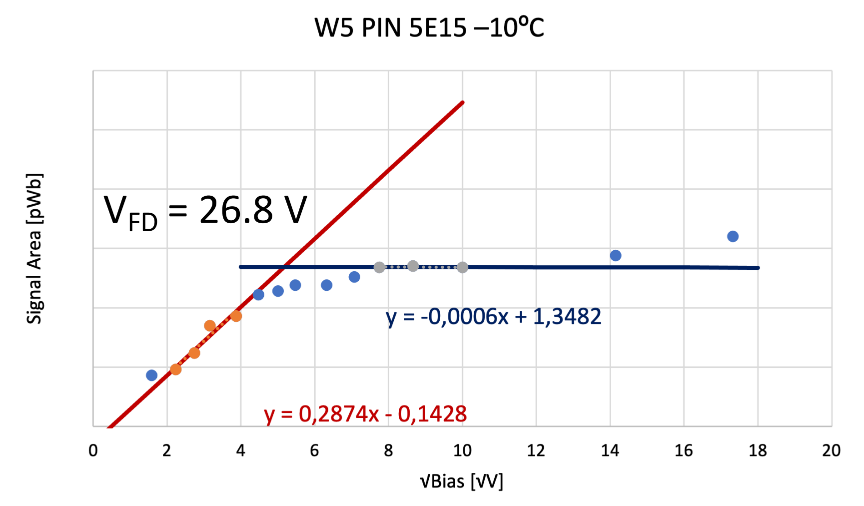
TCT on PiN @ different T to extract the voltage of full depletion 5E15 n_{eq}/cm^2

Laser intensity many MIPs


W5 PIN 5E15 +25°C


W5 PIN 5E15 +10°C


W5 PIN 5E15 0°C


W5 PIN 5E15 –10°C

V_{FD} of PiN @ 5E15

TCT

T [°C]	V_{FD} [V]
+25	35.7
+10	31.1
0	24.4
-10	26.8

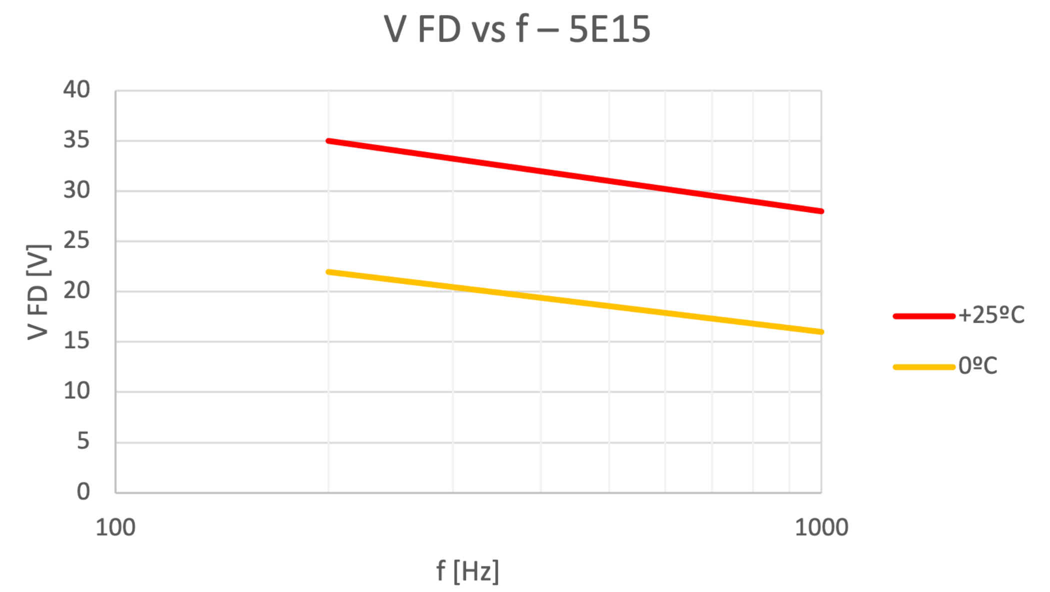
$1/C^2V$

T = +25°C

f [Hz]	V FD [V]
200	35
1000	28

T = 0°C

f [Hz]	V FD [V]
200	22
1000	16



TCT data agree better with $1/C^2V$ results taken at f = 200 Hz

The slope of bias of full depletion as a function of log(f/1kH) remain constant at different temperatures, as for D. Campbell et al., [doi:10.1016/S0168-9002(02)01353-0](https://doi.org/10.1016/S0168-9002(02)01353-0)

Full Depletion Voltage from $1/C^2V$ – 1E16 n_{eq}/cm^2

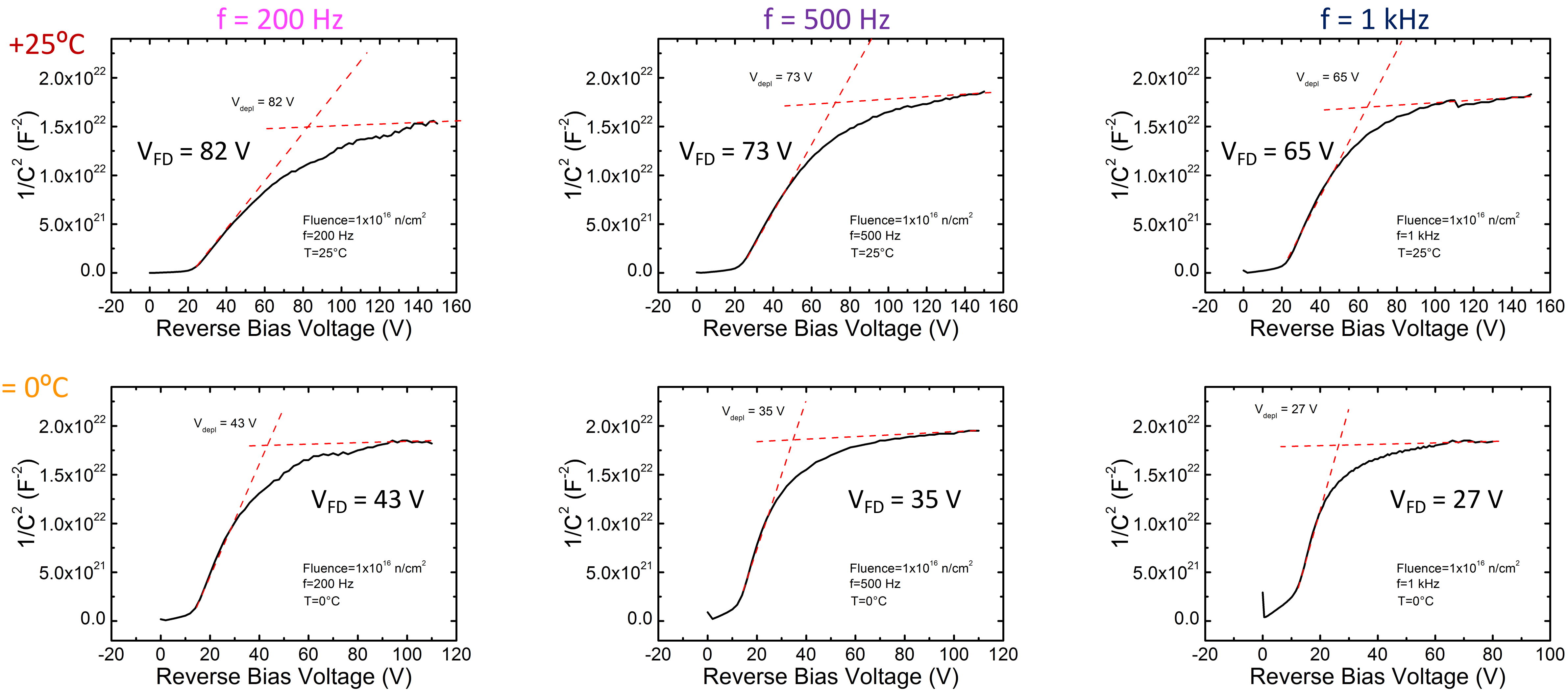
f = 200 Hz

f = 500 Hz

f = 1 kHz

T = +25°C

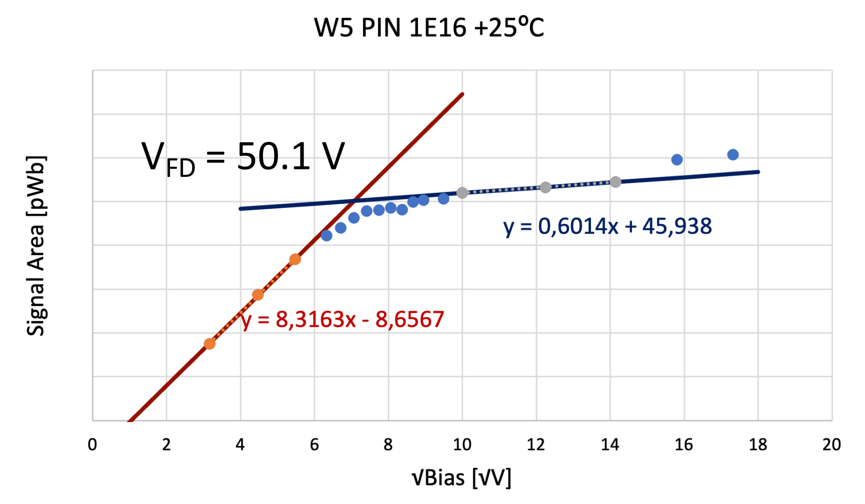
T = 0°C

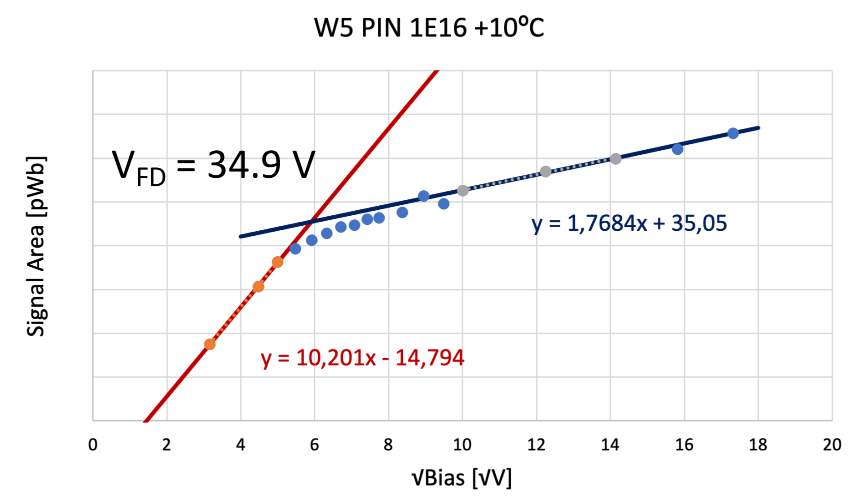


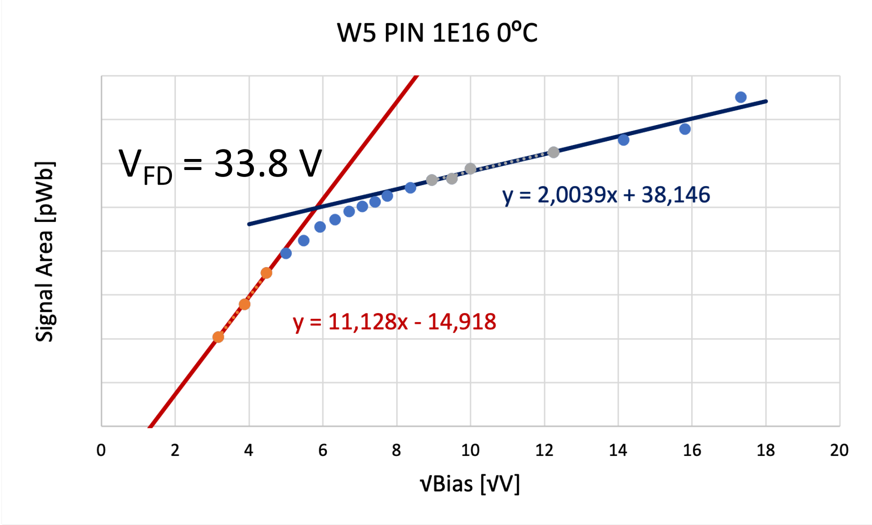
Full Depletion Voltage from TCT – 1E16 n_{eq}/cm^2

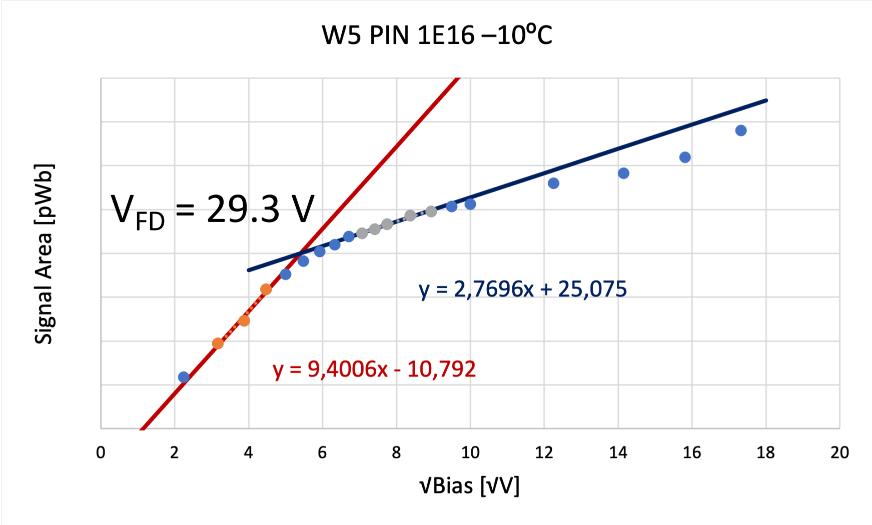
TCT on PiN @ different T to extract the voltage of full depletion 1E16 n_{eq}/cm^2

Laser intensity many MIPs









V_{FD} of PiN @ 1E16

TCT

T [°C]	V_{FD} [V]
+25	50.1
+10	34.9
0	33.8
-10	29.3

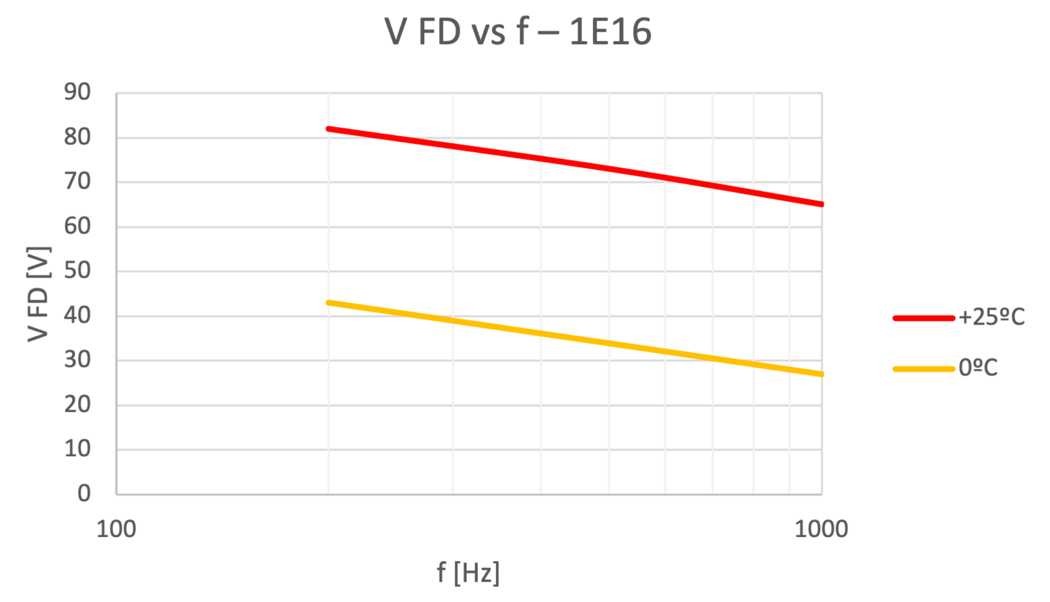
$1/C^2V$

T = +25°C

f [Hz]	V FD [V]
200	82
500	73
1000	65

T = 0°C

f [Hz]	V FD [V]
200	43
500	35
1000	27



TCT data underestimate $1/C^2V$ results taken at f = 200 Hz
[to be cross checked with further measurements]

The slope of bias of full depletion as a function of log(f/1kH) remain constant at different temperatures, as for D. Campbell et al., doi:10.1016/S0168-9002(02)01353-0

V_{FD} of PiN @ 5E16 n_{eq}/cm^2 & 1E17 n_{eq}/cm^2 ?

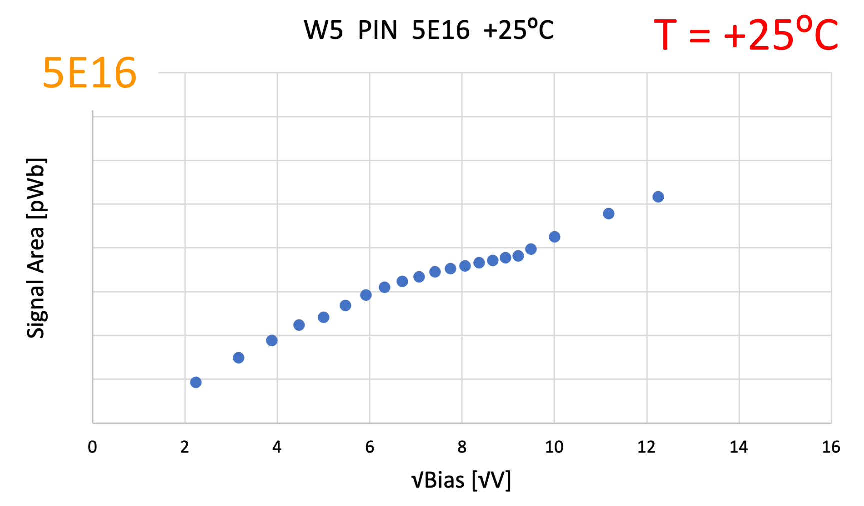
TCT on PiN @ different T on PiN irradiated to 5E16 & 1E17 n_{eq}/cm^2

Laser intensity many MIPs

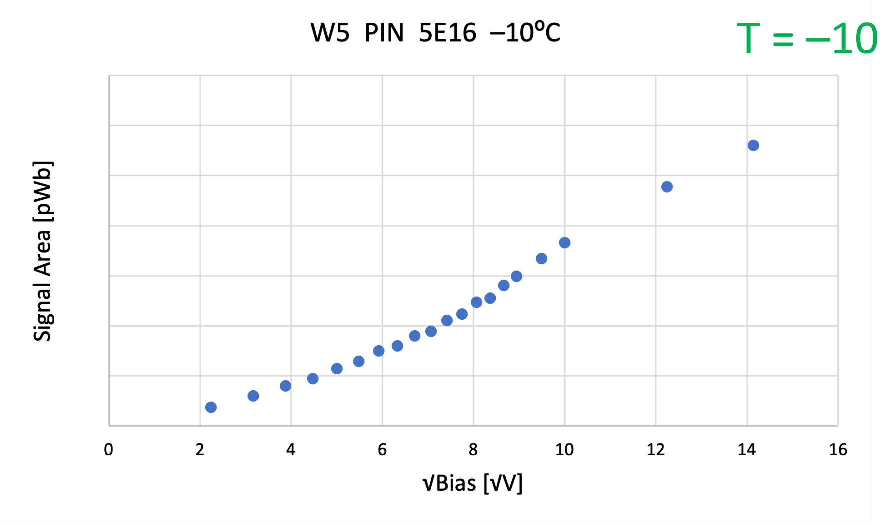
Very difficult to extract full depletion voltage from TCT data from PiN irradiated at 5E16 n_{eq}/cm^2 and above

T = +25°C

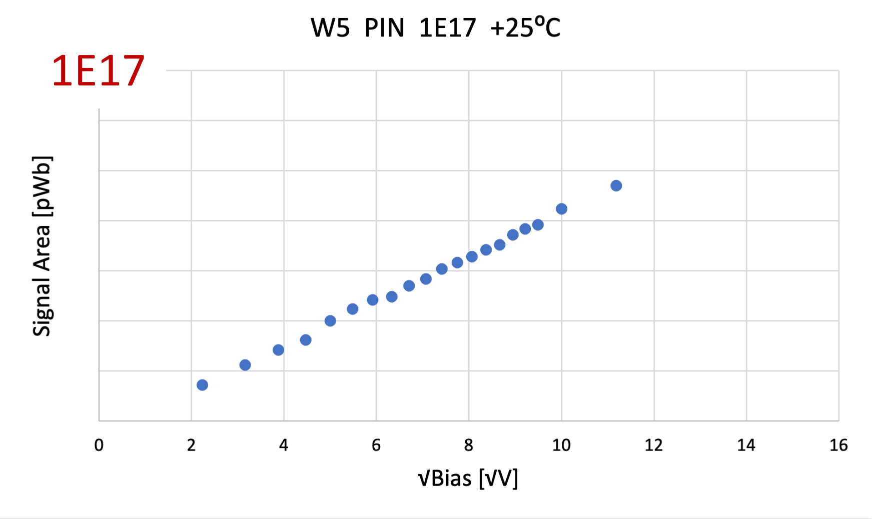
5E16

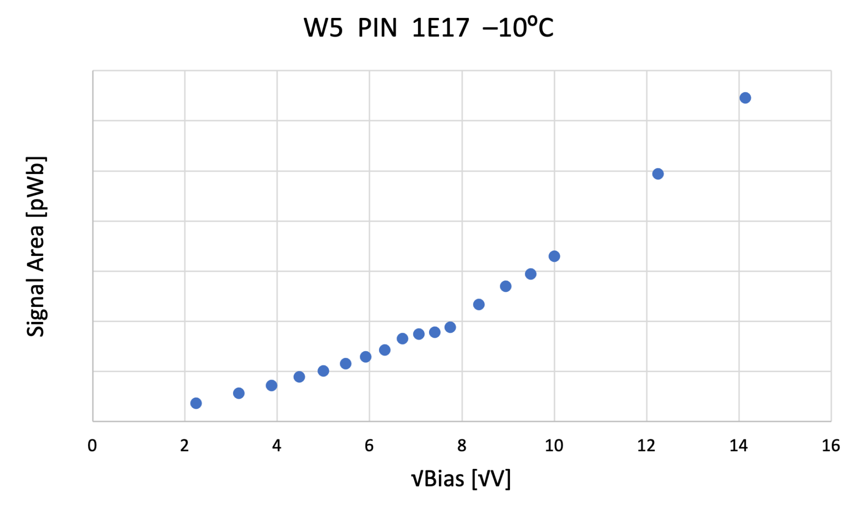


T = –10°C

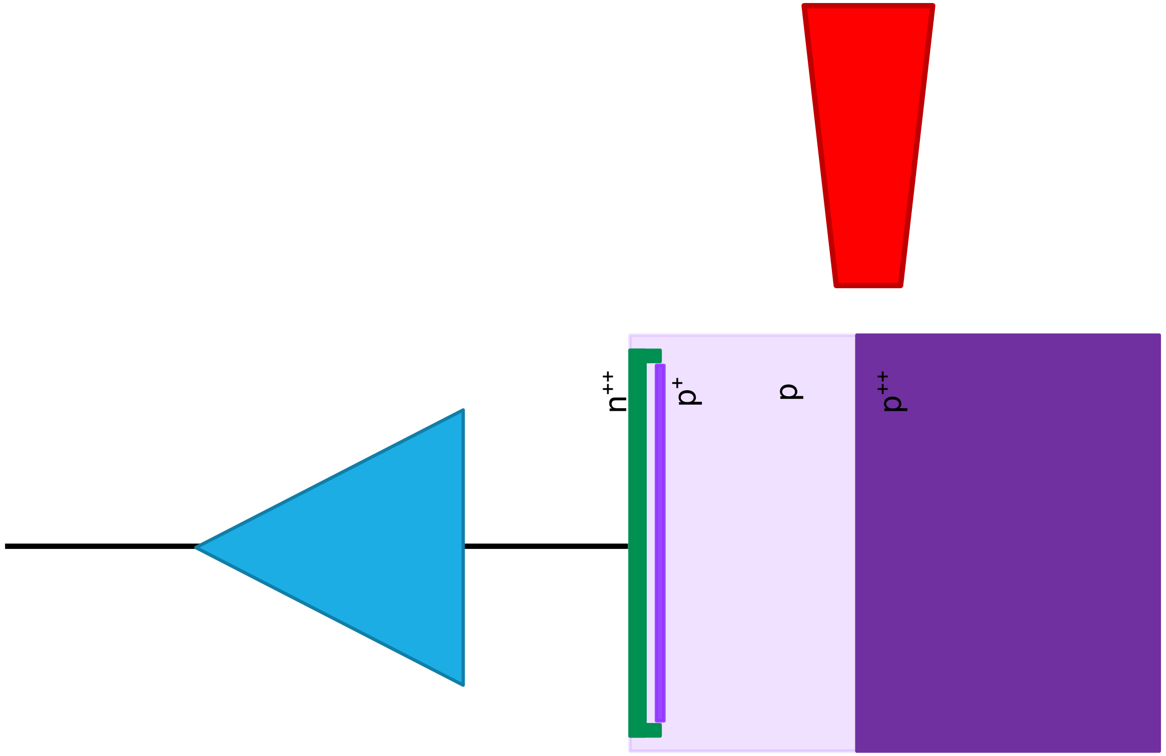


1E17





Edge TCT or TPA to extract V_{FD}?



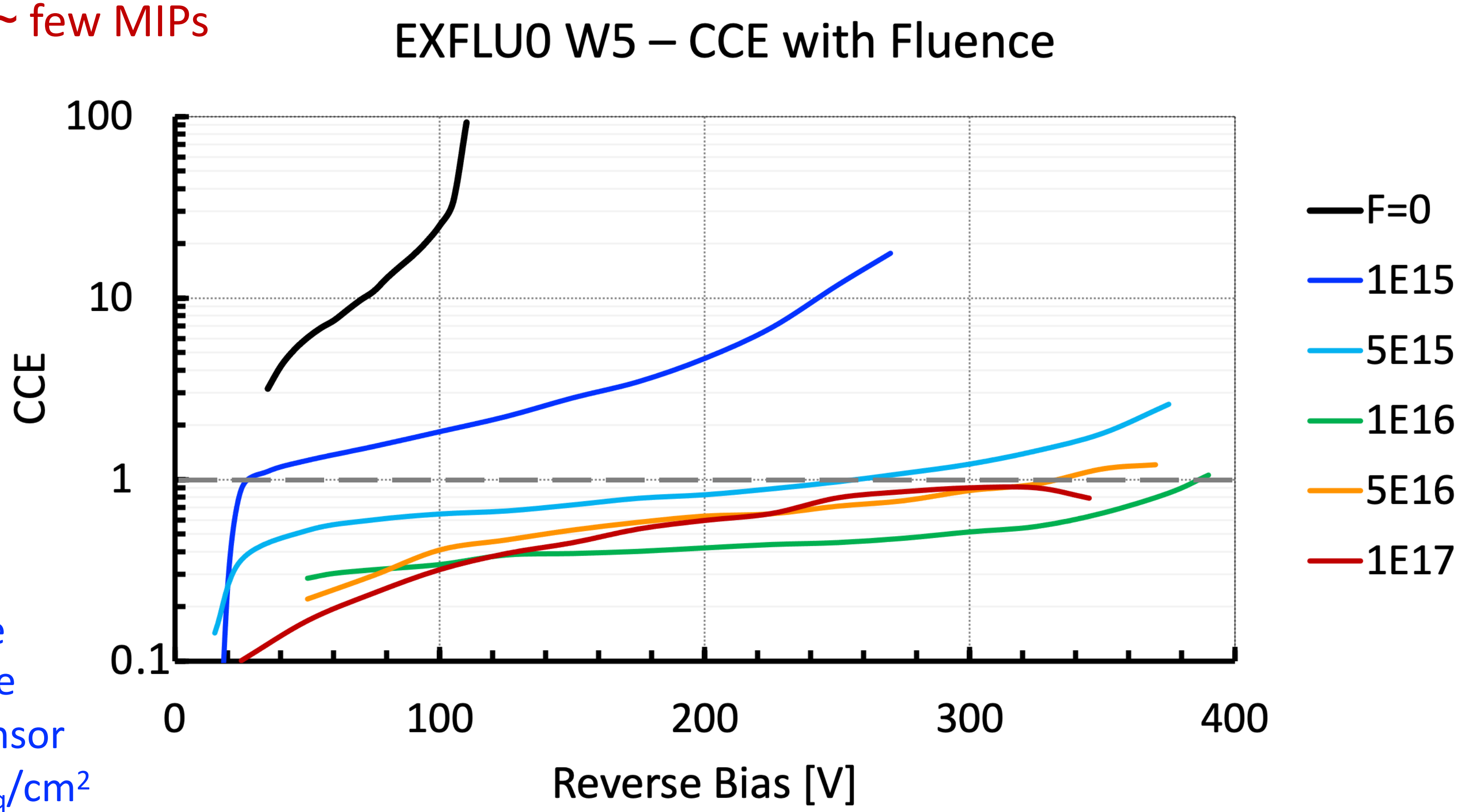
Can edge TCT be exploited to extract the bias of full depletion?

Is TPA position resolution precise enough to study V_{FD} up to the highest fluences?

CCE on LGAD @ different Fluences

Laser intensity ~ few MIPs

T = –10°C



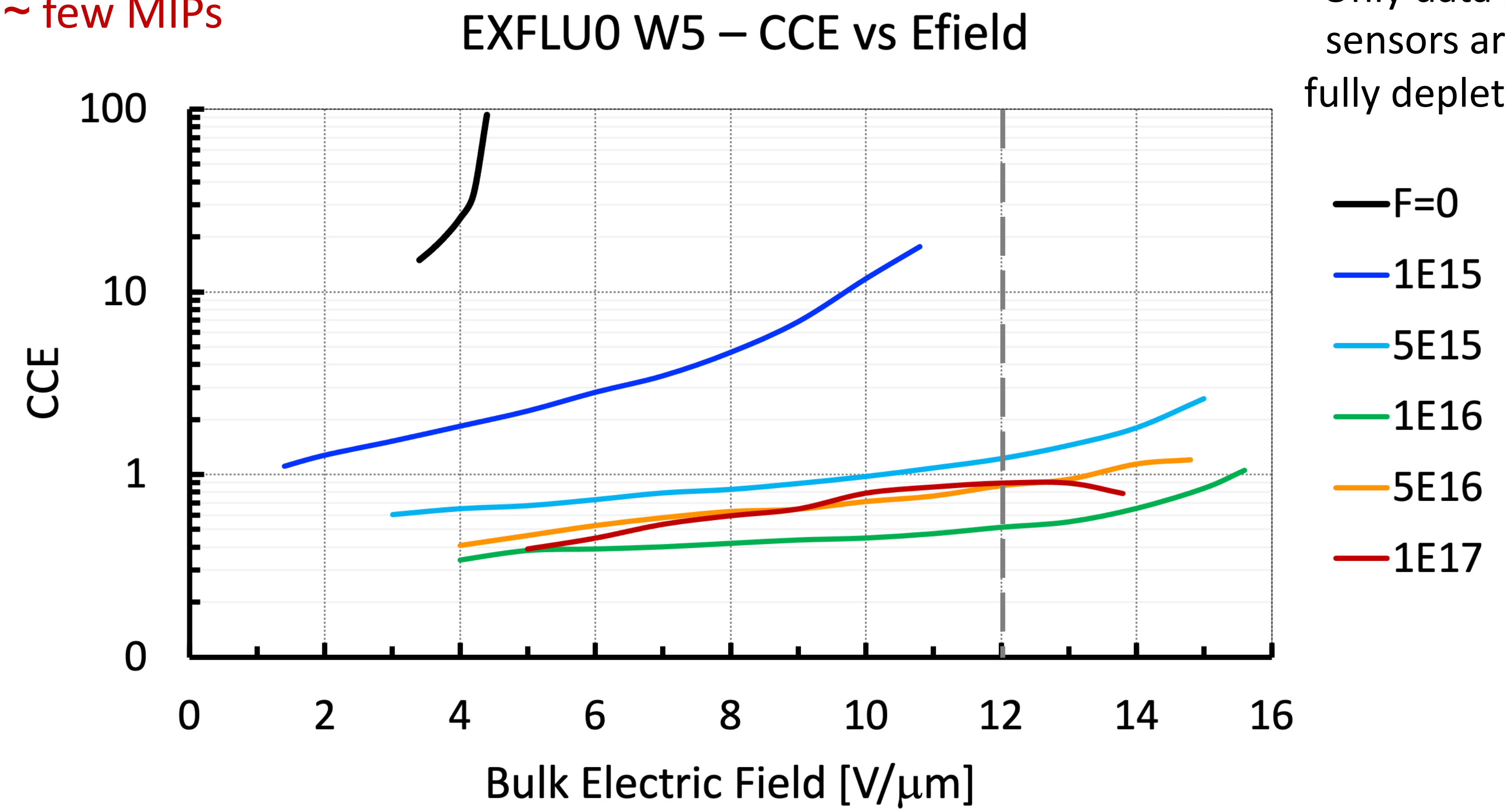
Collected charge normalised to the depletion of the sensor irradiated to 1E15 n_{eq}/cm^2

Increase of CCE with bias visible for all the fluences

CCE on LGAD – Electric Field Dependence

Laser intensity ~ few MIPs

T = –10ºC



Only data points where the sensors are expected to be fully depleted are considered

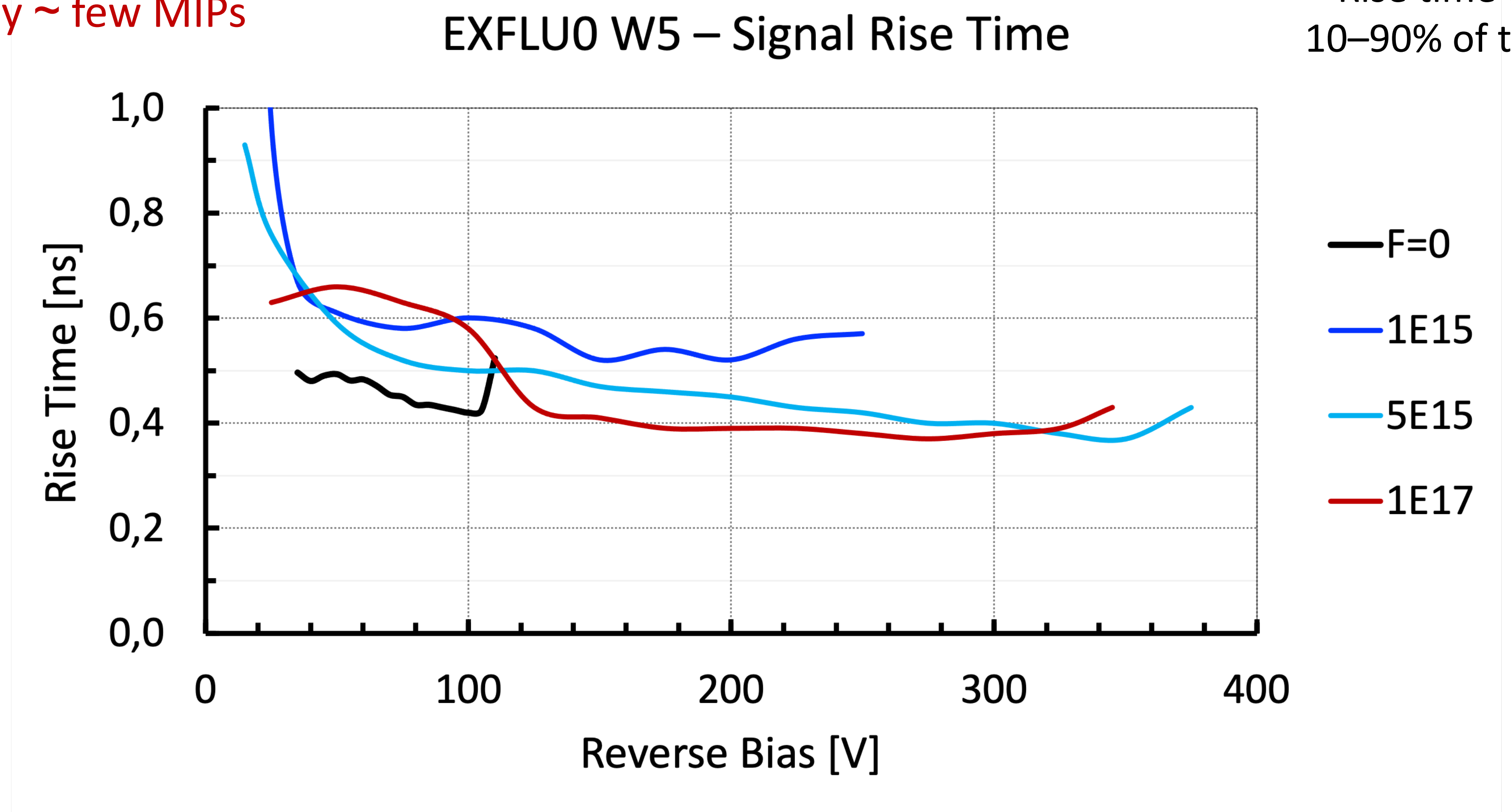
→ Try to enhance CCE below 12 V/µm in future R&D

Rise Time of LGAD @ different Fluences

Laser intensity ~ few MIPs

T = –10°C

Rise time defined as the
10–90% of the leading edge



Signals exhibit a fast rise at all fluences

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

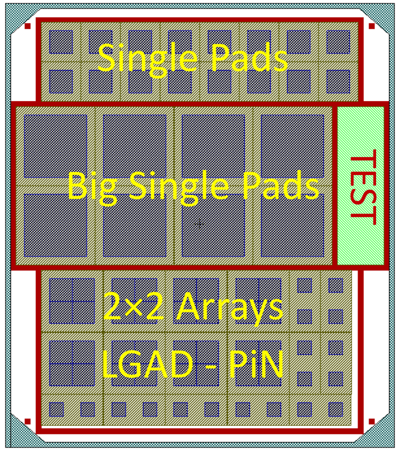
⟶ different design of the gain layer implant, to improve the radiation tolerance

⟶ optimisation of the carbon implantation in the gain layer region

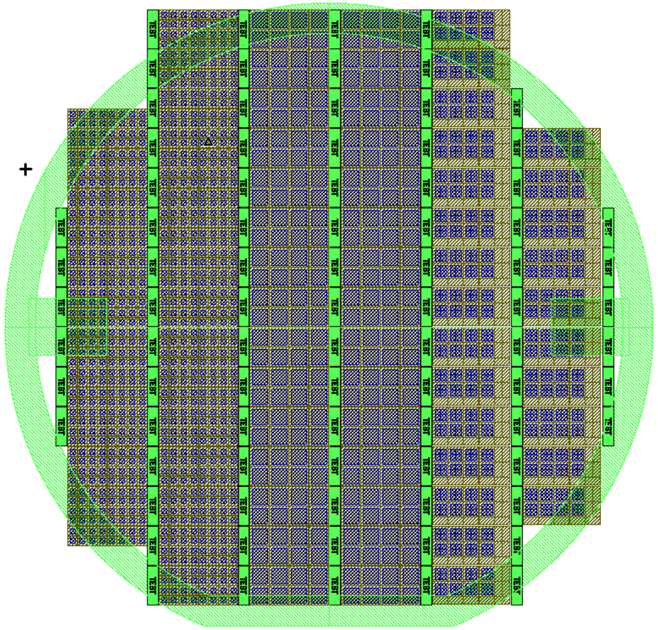
⟶ optimisation of the guard ring design for thin substrates

⇒ The production is expected by Spring 2022

Preliminary reticle layout

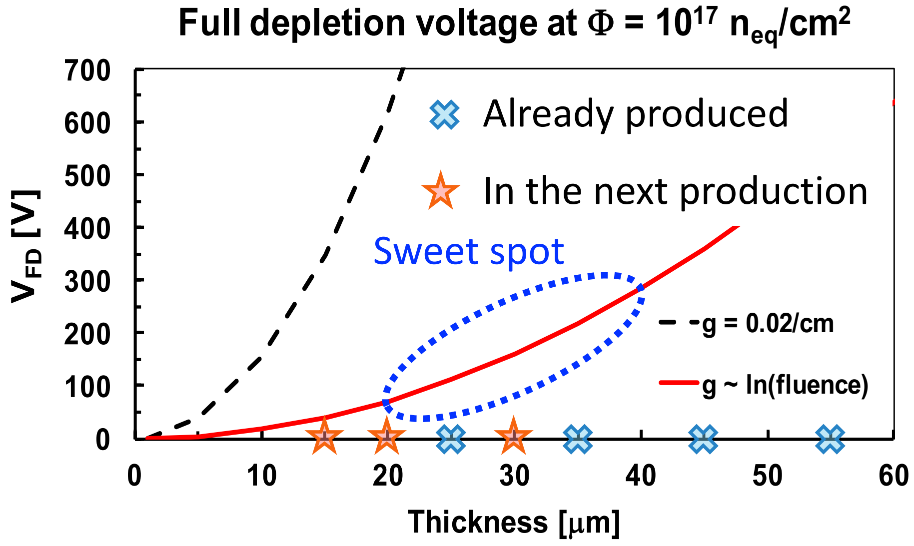


Preliminary wafer layout



Summary & Outlook

- ▻ **Characterisation of the first production of thin LGAD sensors is ongoing**
- ▻ **Tests on thin sensors irradiated up to 1E17 n_{eq}/cm^2 showed good operation performances**
- ▻ **A new LGAD production on thin substrates will be released the next Spring**



⇒ 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

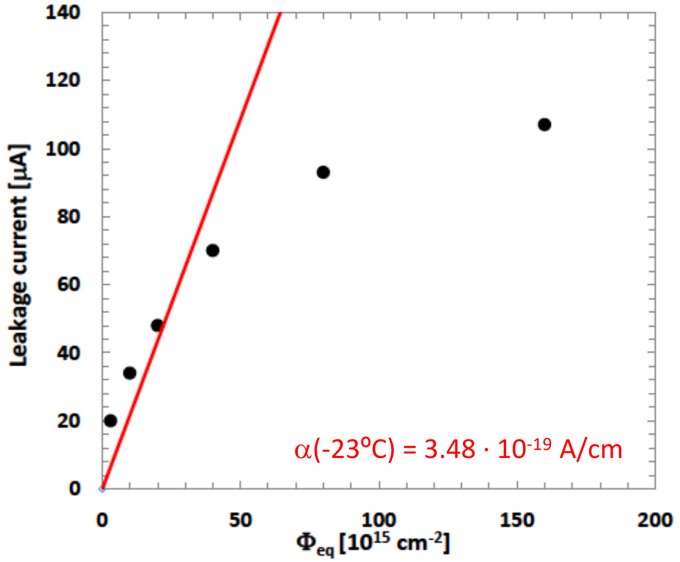
We kindly acknowledge the following funding agencies, collaborations:

- ▻ 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

SATURATION

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

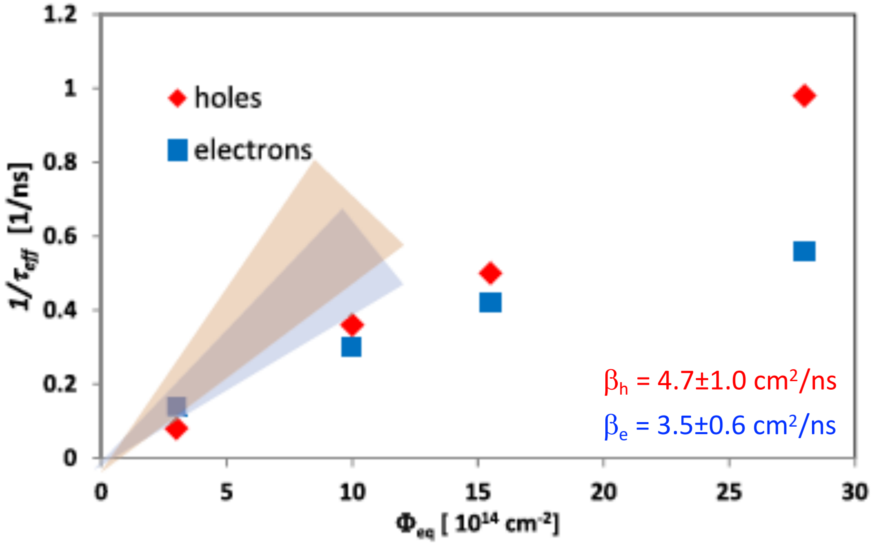


[G. Kramberger et al., doi:10.1088/1748-0221/8/08/P08004]

Leakage current saturation

$I = \alpha V \Phi$

α from linear to logarithmic

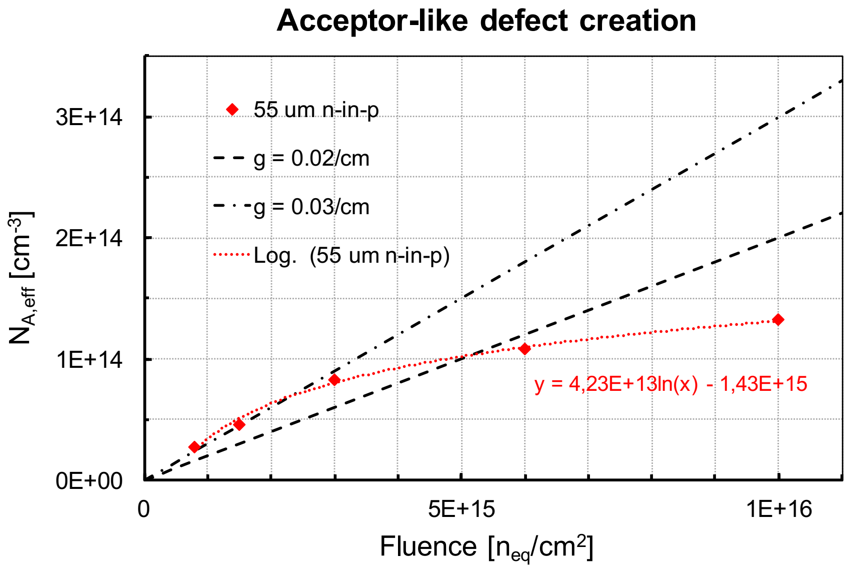


[G. Kramberger et al., doi:10.1016/j.nima.2018.08.034]

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

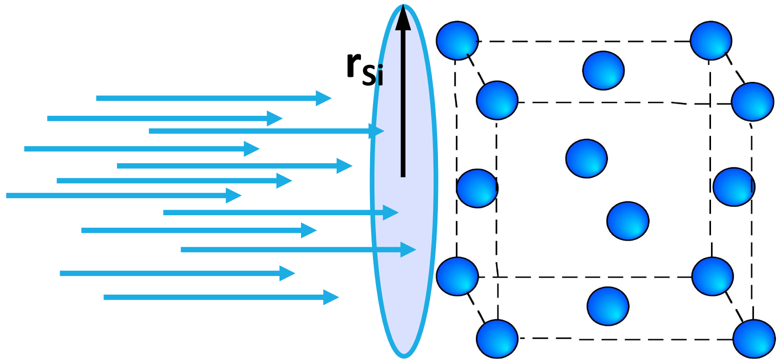
Silicon detectors irradiated at fluences $10^{16} – 10^{17}\ n_{eq}/cm^2$ do not behave as expected → They behave better

WHY SATURATION?

Possible explanation:

The distance between two atoms, the so-called Silicon radius, is

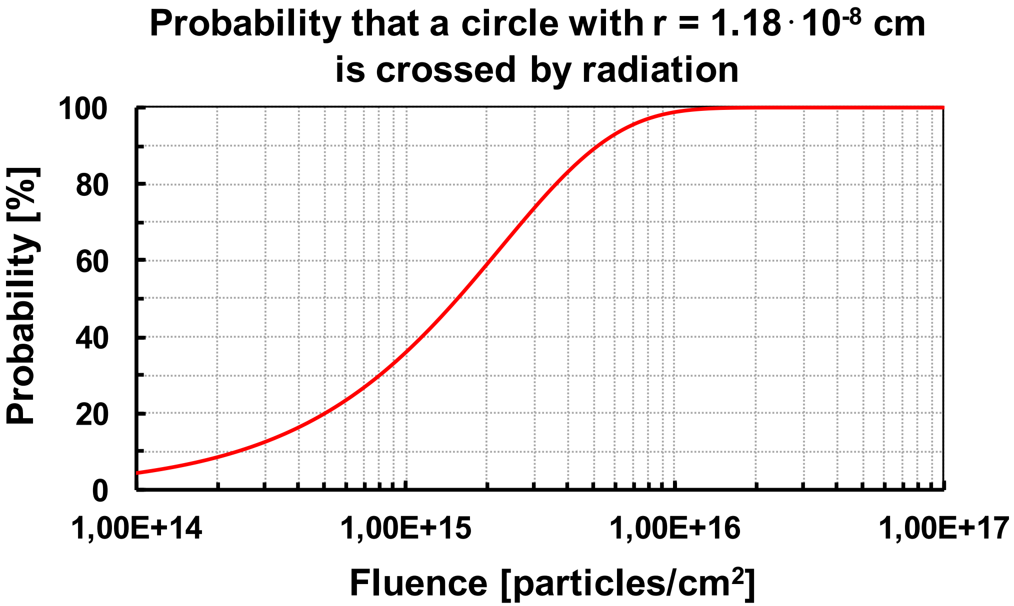
$r_{Si} = 1.18 \cdot 10^{-8}$ cm



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



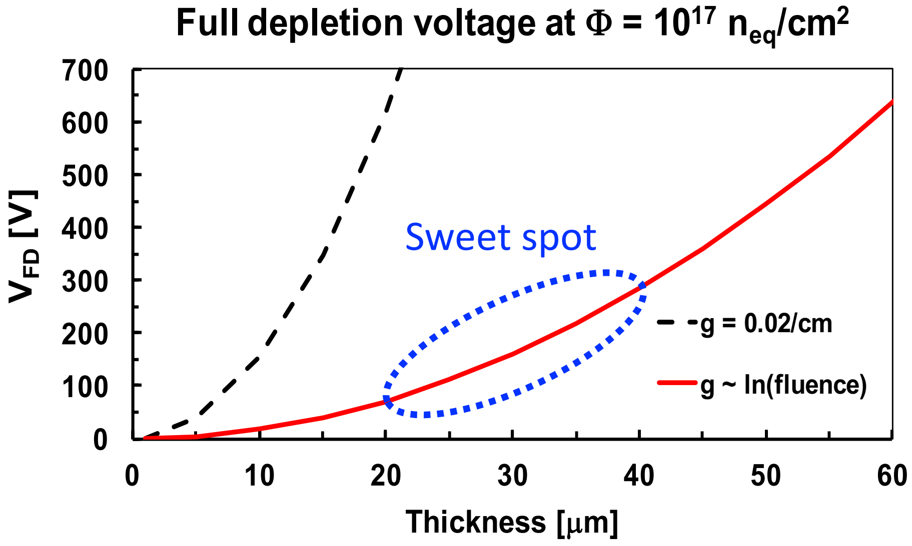
Thin Planar Sensors for Extreme Fluences

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

Saturation of $N_{A,eff}$ creation

Reduced 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 limited
- 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)

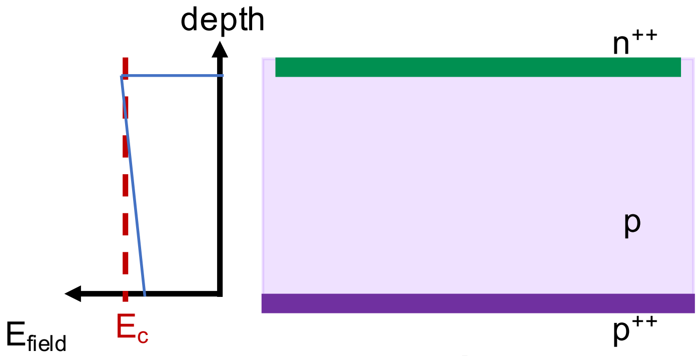
→ Need for a gain of at least ~ 5 in order to provide enough charge

SENSOR CHOICE

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

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

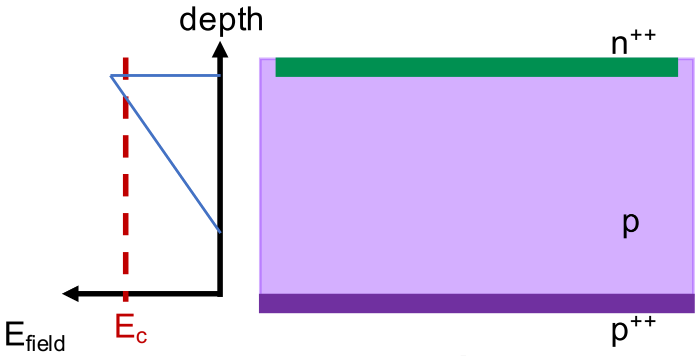
1) **$E_{field} > E_c$ for a short distance**
2) **This length is controlled by applied V_{bias}**



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

E_{field} above E_c
over long distance

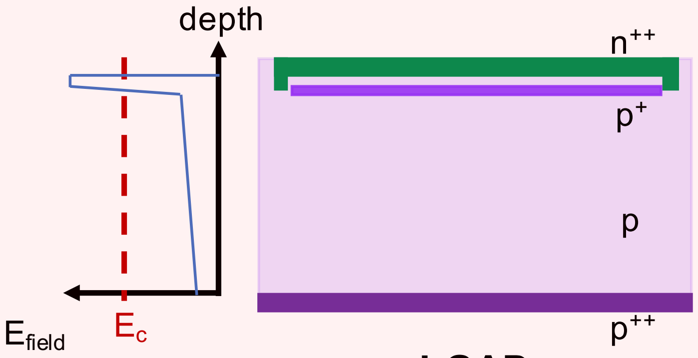
AVALANCHE



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}

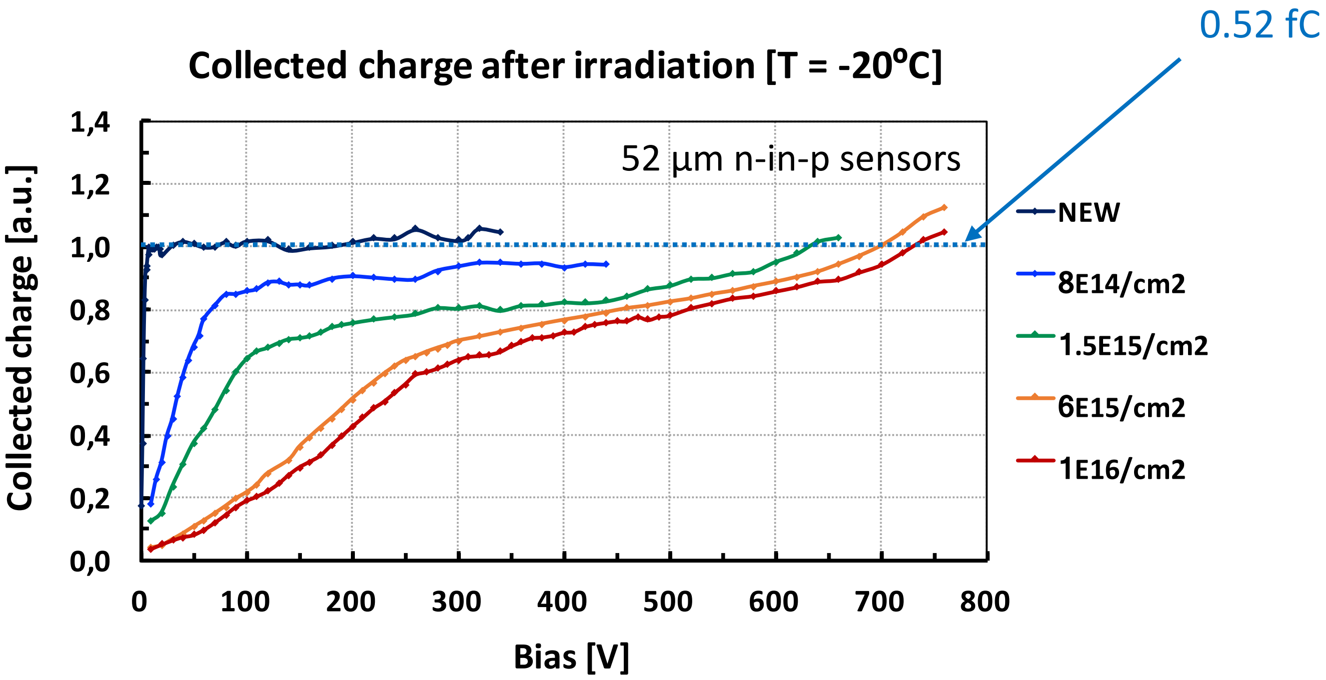
CONTROLLED GAIN

HOW THIN?

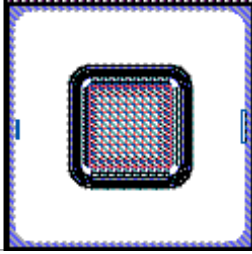
To efficiently record a hit, electronics require al least **1 fC**

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

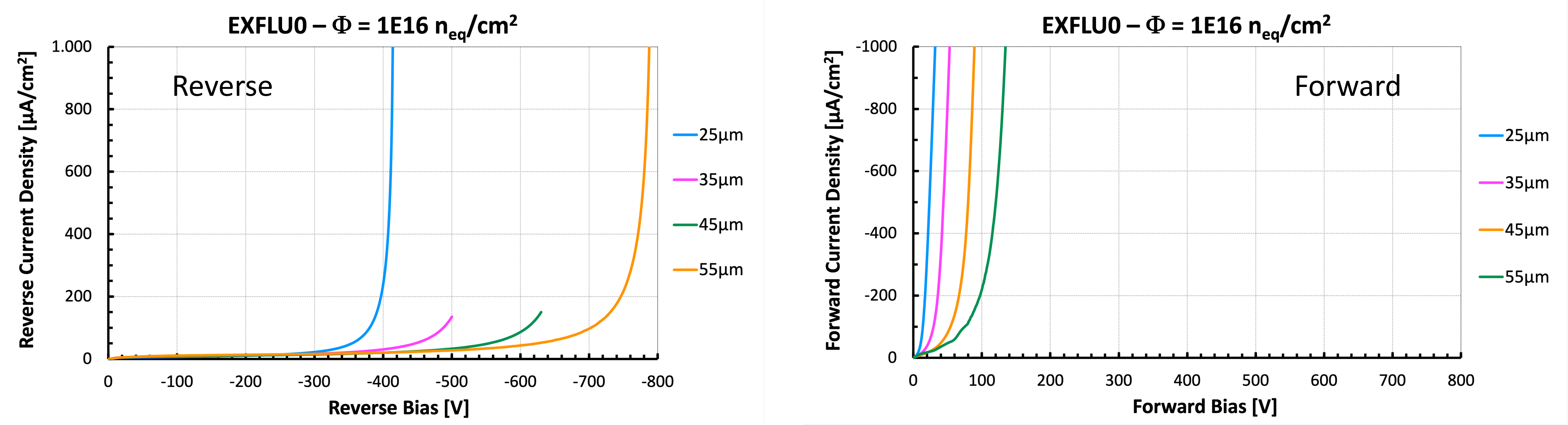
Signal multiplication by a factor of 5-10 is needed



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



Reverse and forward current densities are shown for different sensor thicknesses

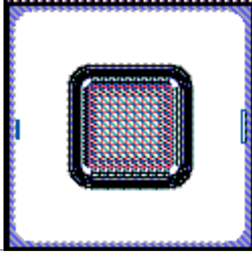


Measurements have been performed at T = -30°C

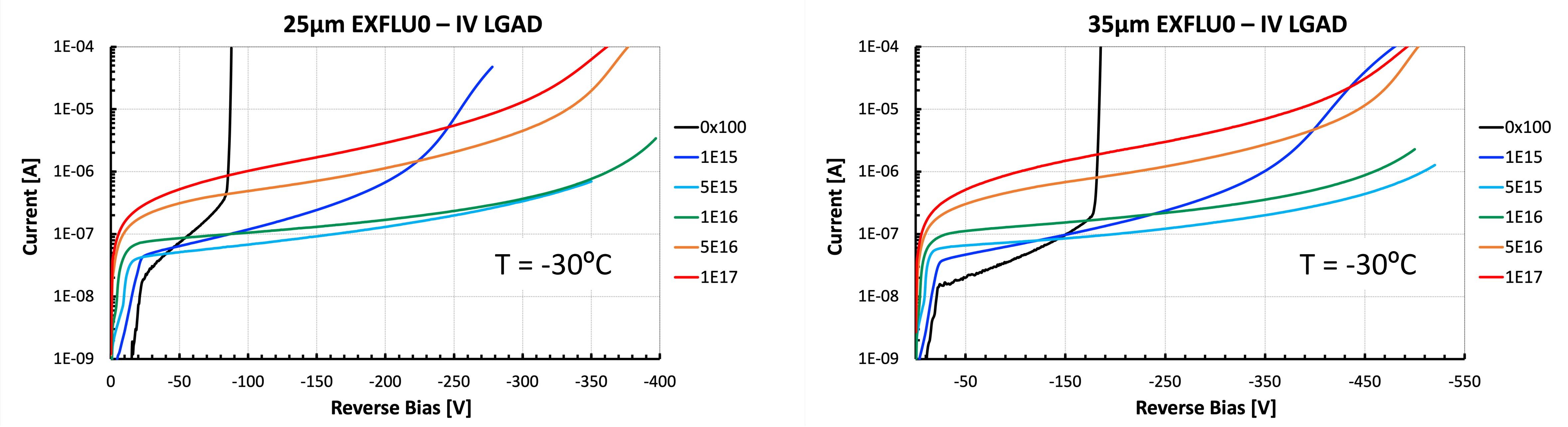
→ Reverse and forward current densities linearly scales with thickness

→ Forward current density shows an abrupt increase for all thicknesses

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



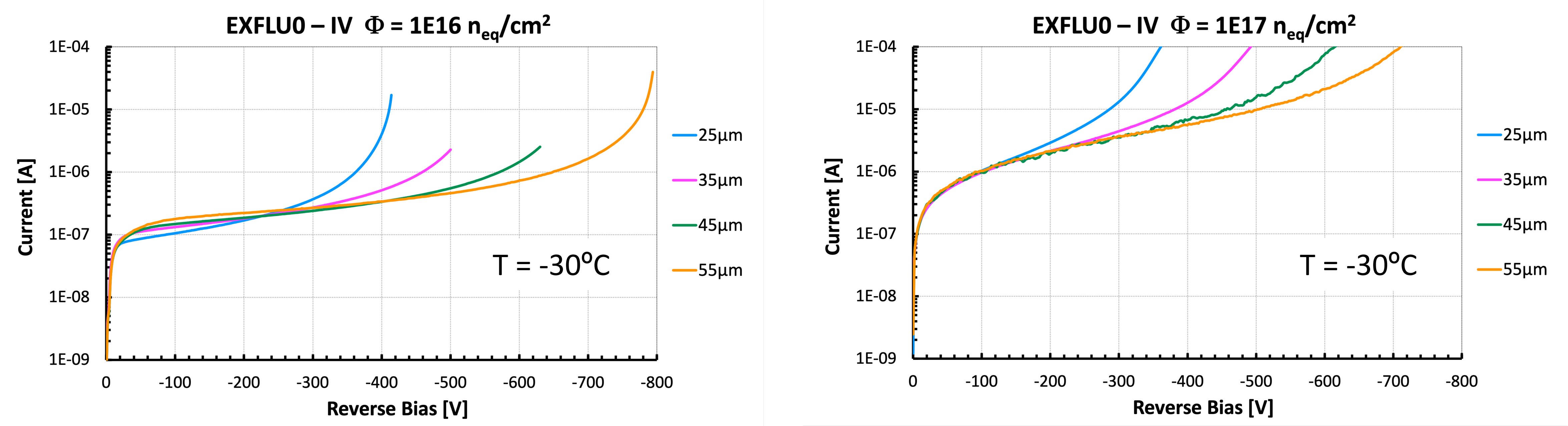
Measurements have been performed at T = -30ºC

→ 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



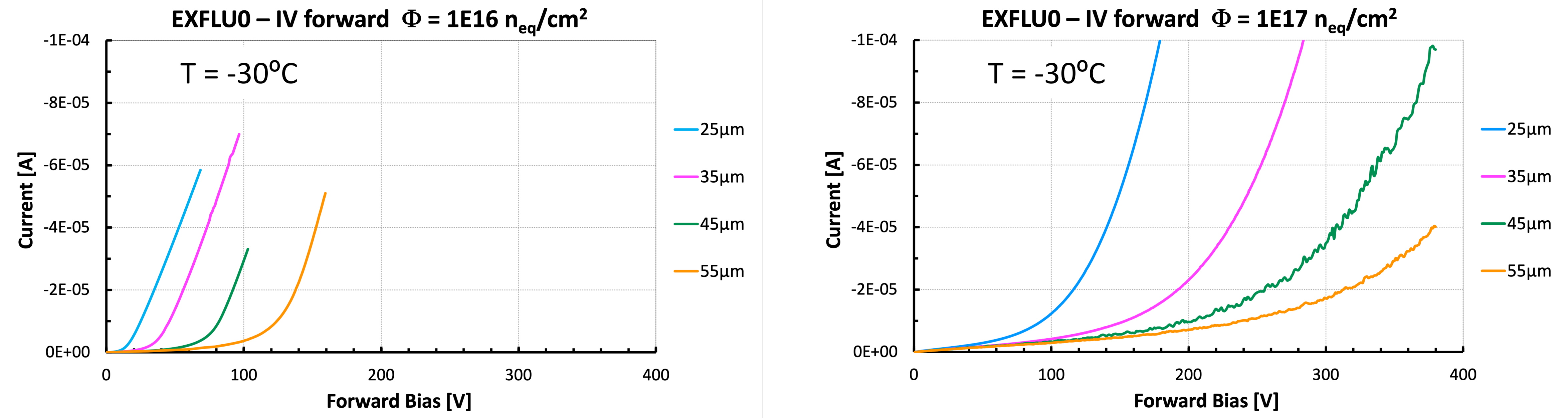
Measurements have been performed at T = -30°C

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

⟶ The breakdown voltage due to internal multiplication linearly shifts to higher values in thicker sensors

Forward Current with Thickness

Sensors of different thicknesses have been tested under forward bias

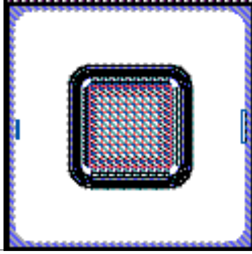


Measurements have been performed at T = -30°C

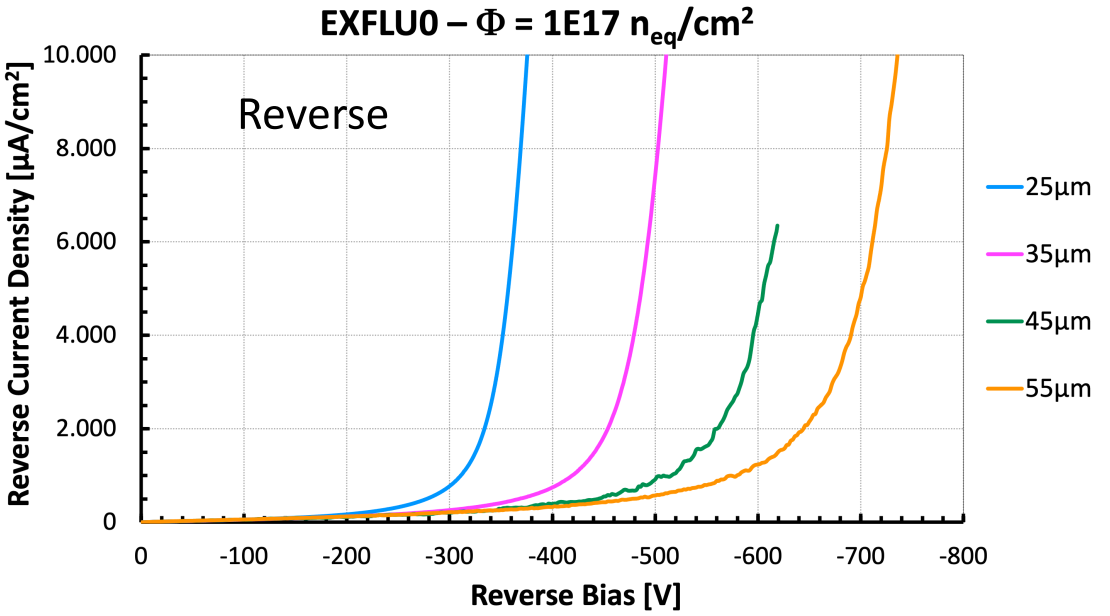
→ Forward current increase linearly scales with the sensor thickness

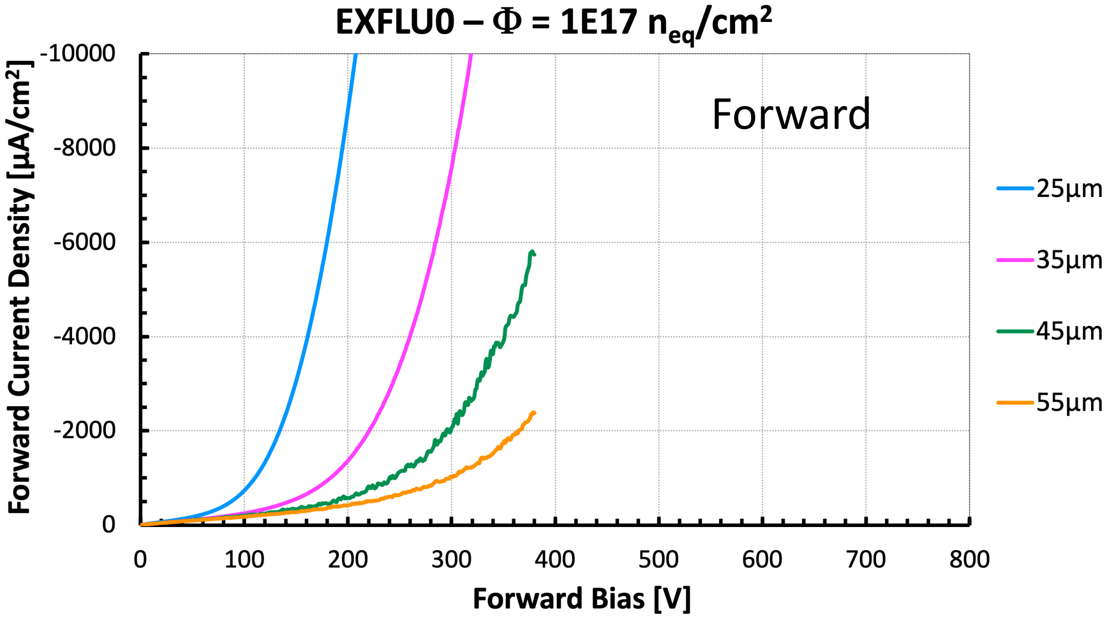
→ Sensors irradiated at 5E16 n_{eq}/cm^2 and above exhibit a resistance of more than 100 MΩ

Current Density – Φ = 1E17 n_{eq}/cm^2



Reverse and forward current densities are shown for different sensor thicknesses



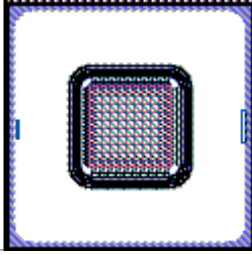


Measurements have been performed at T = -30°C

→ Reverse and forward current densities linearly scales with thickness

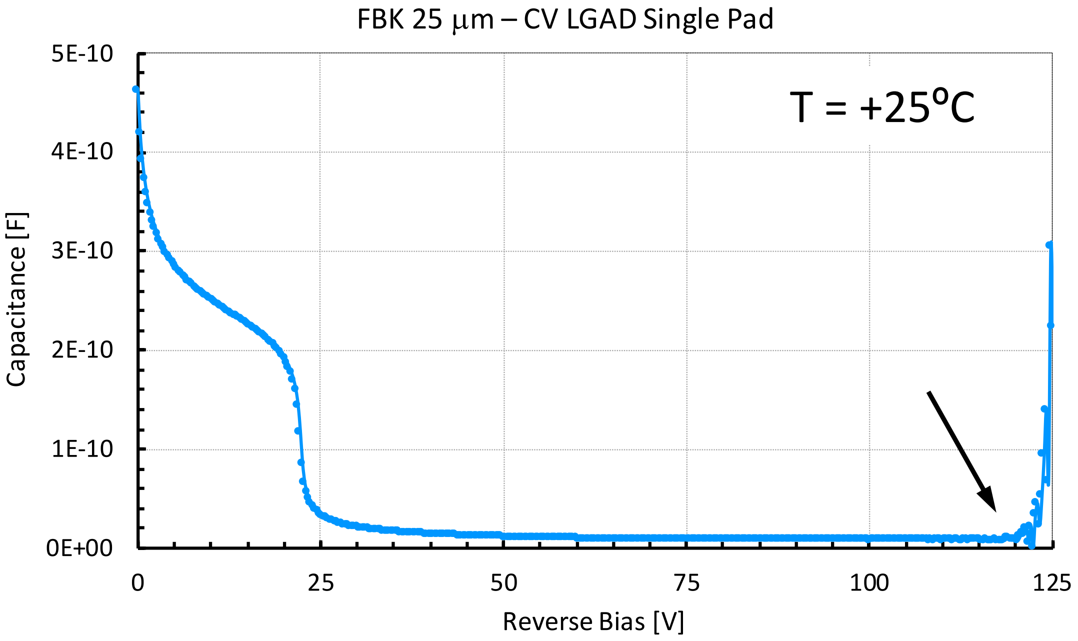
→ Forward current density extends towards higher values of bias

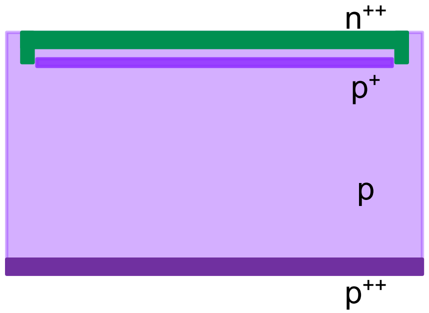
CV ON 25 μm WAFER – Low ρ



It is difficult to precisely control resistivity of thin epitaxial substrates

→ ρ_{W5} ~ 75 Ω·cm





V_{GL} depletion ~ 22 V

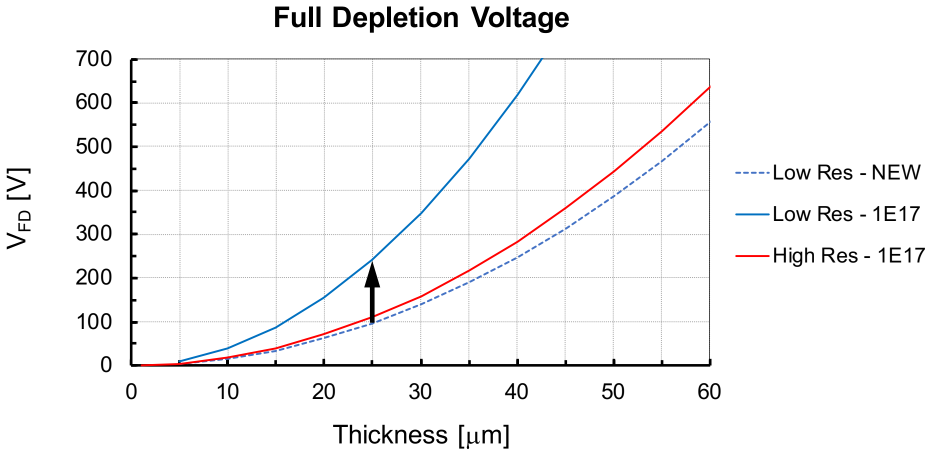
V_{bulk} depletion ~ 95 V

Sensor depletion ~ 120 V

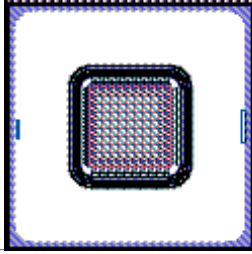
Gain at 120 V ~ 25

Gain at 130 V ~ 40

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

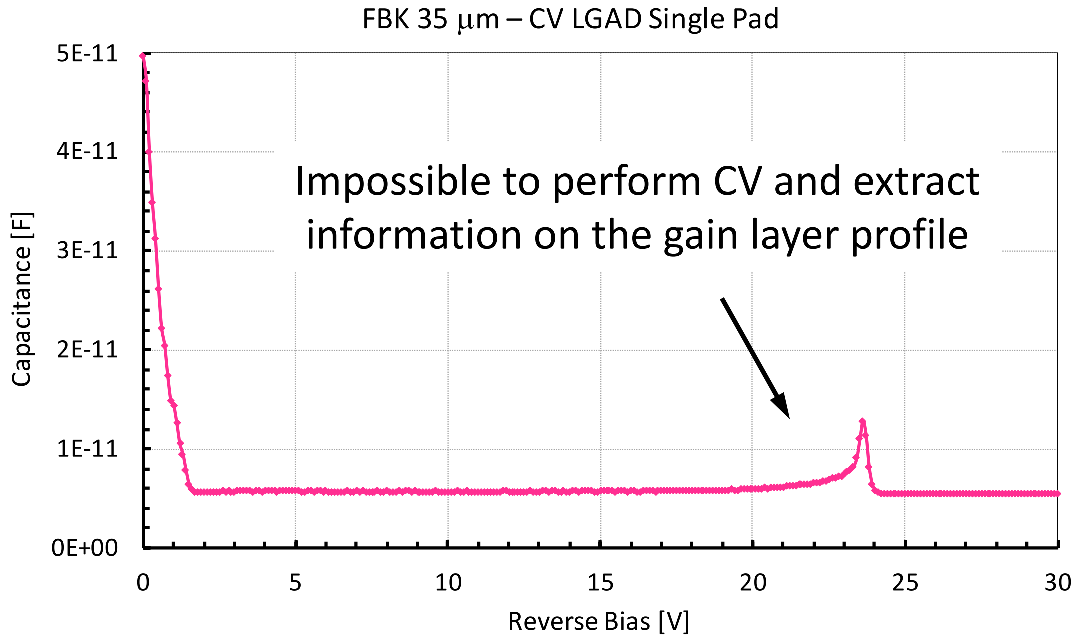


CV ON 35 μm WAFER – High ρ

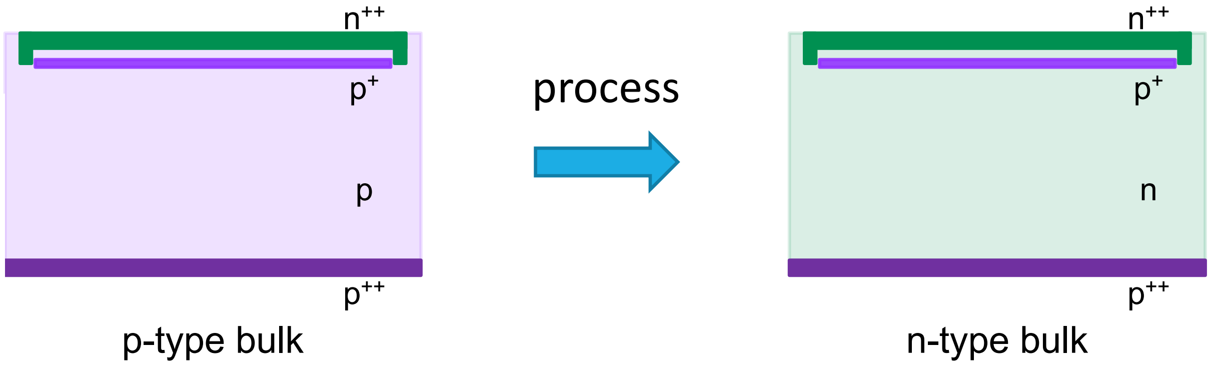


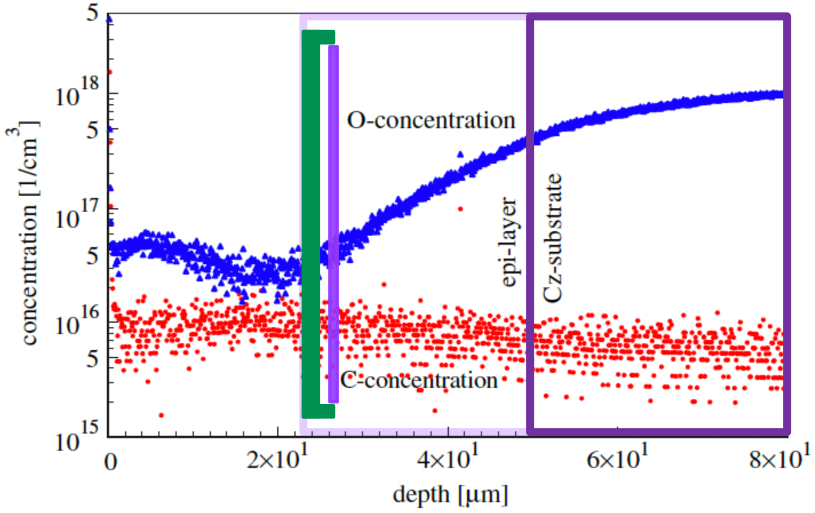
It is difficult to precisely control resistivity of thin epitaxial substrates

→ ρ_{W6} ~ 3,000 Ω·cm



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



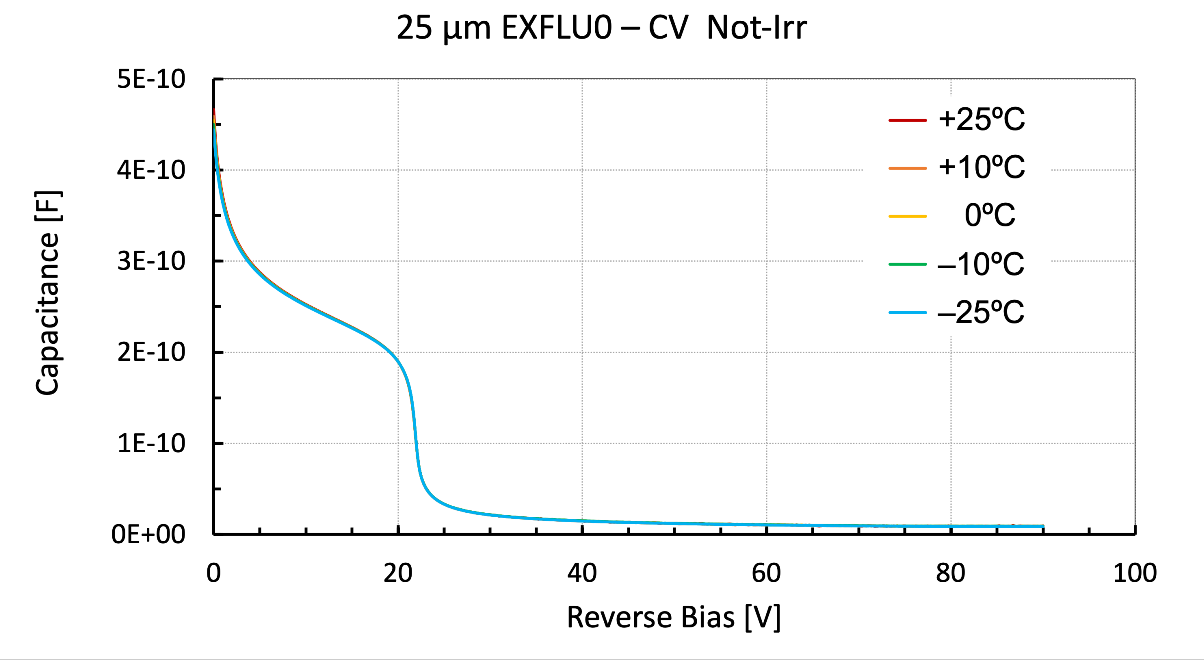


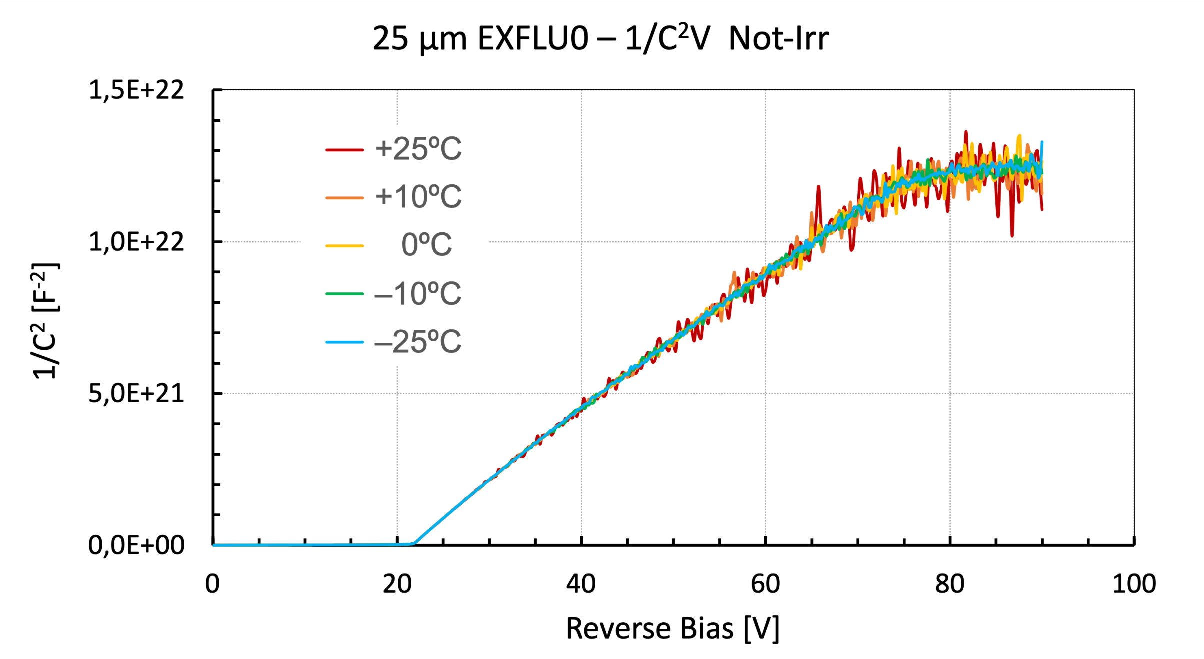
[I. Pintilie 2005 et al., doi:10.1016/j.nima.2005.10.013]

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

CV on 25 µm LGAD – Φ = 0

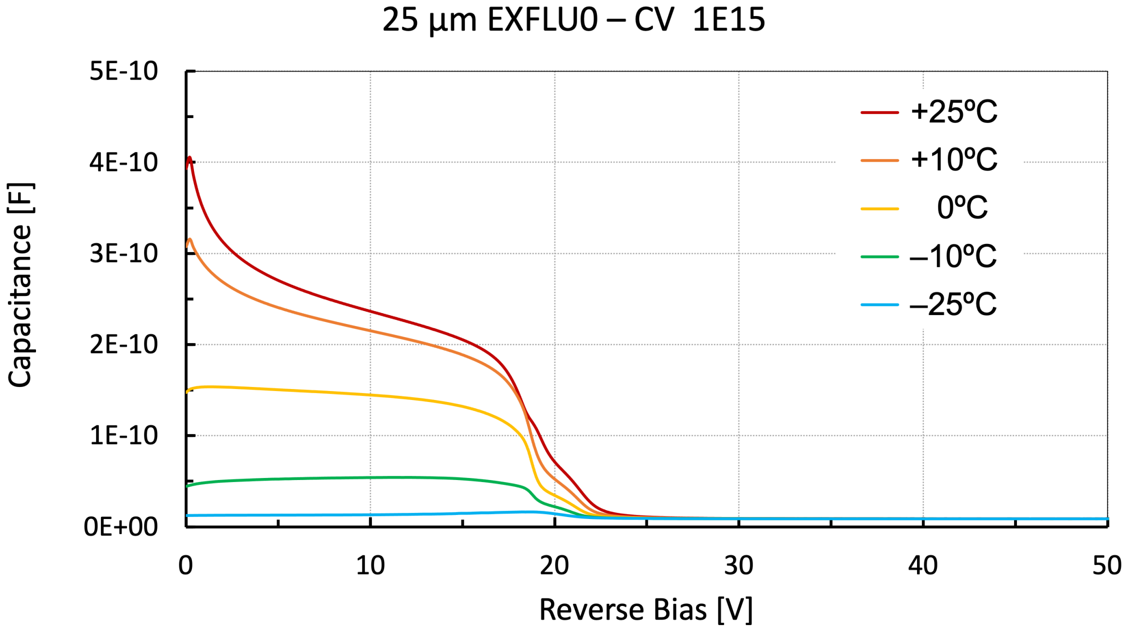
HF-CV with Keysight B1505A – f = 1 kHz

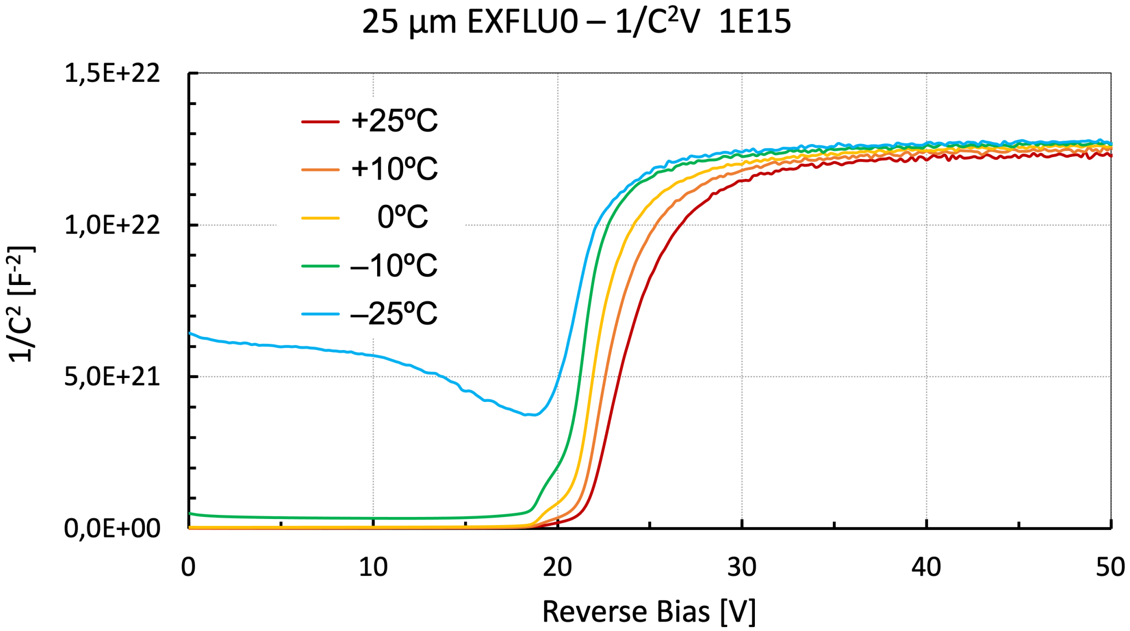




CV on 25 μm LGAD – $\Phi = 1E15\ n_{eq}/cm^2$

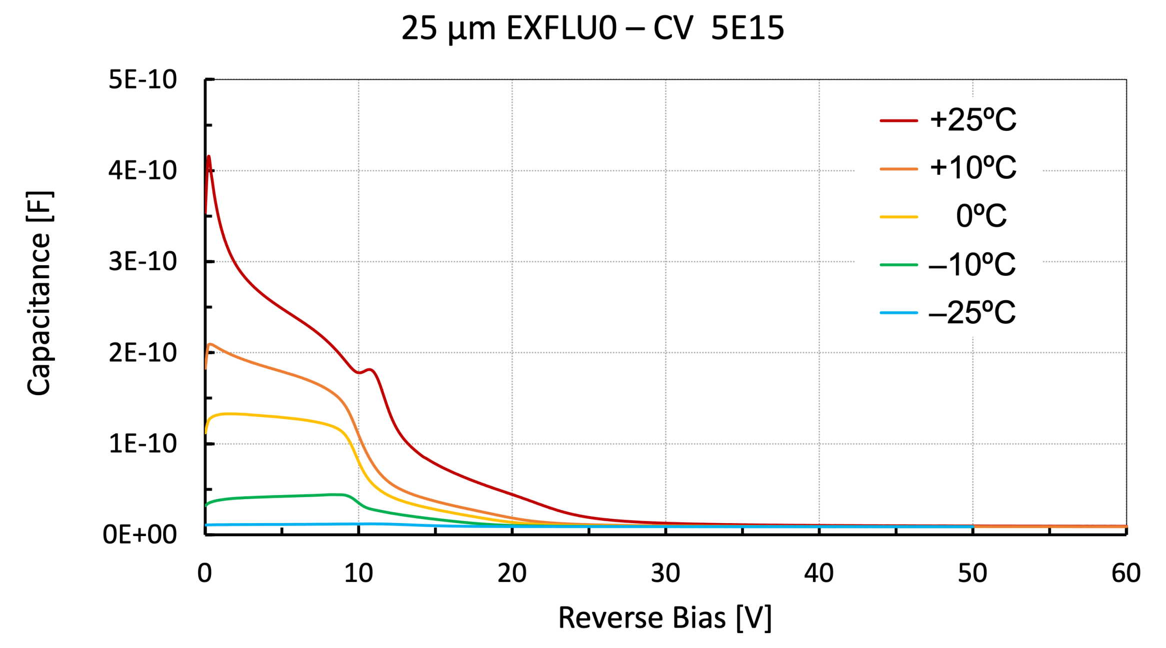
HF-CV with Keysight B1505A – f = 1 kHz

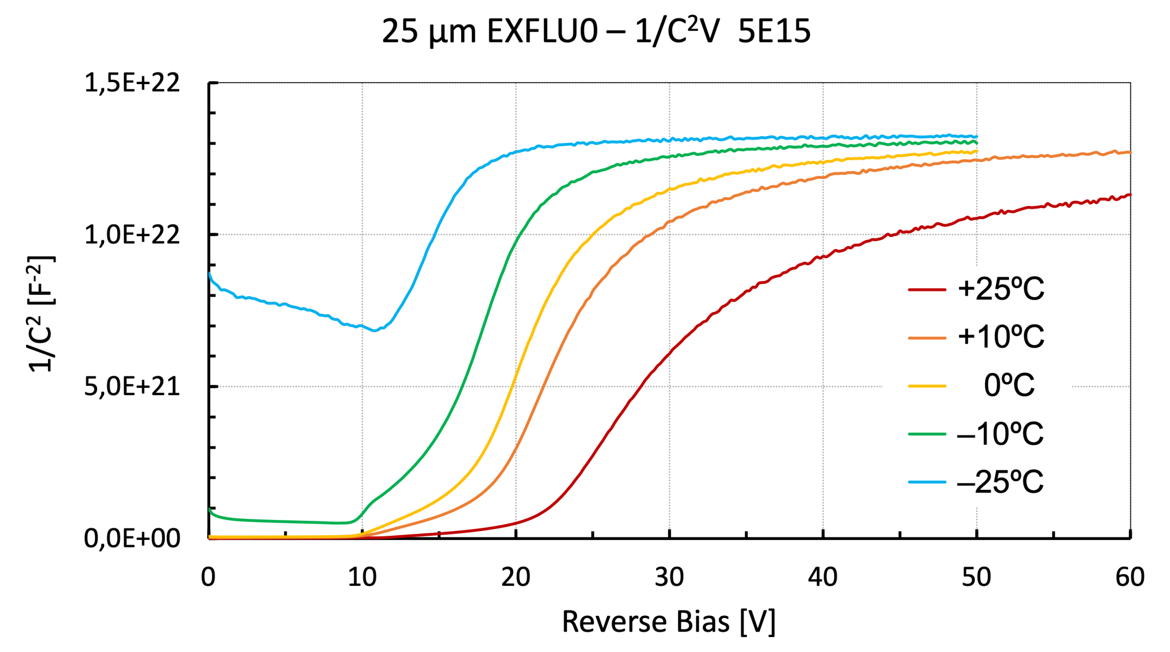




CV on 25 μm LGAD – Φ = 5E15 n_{eq}/cm^2

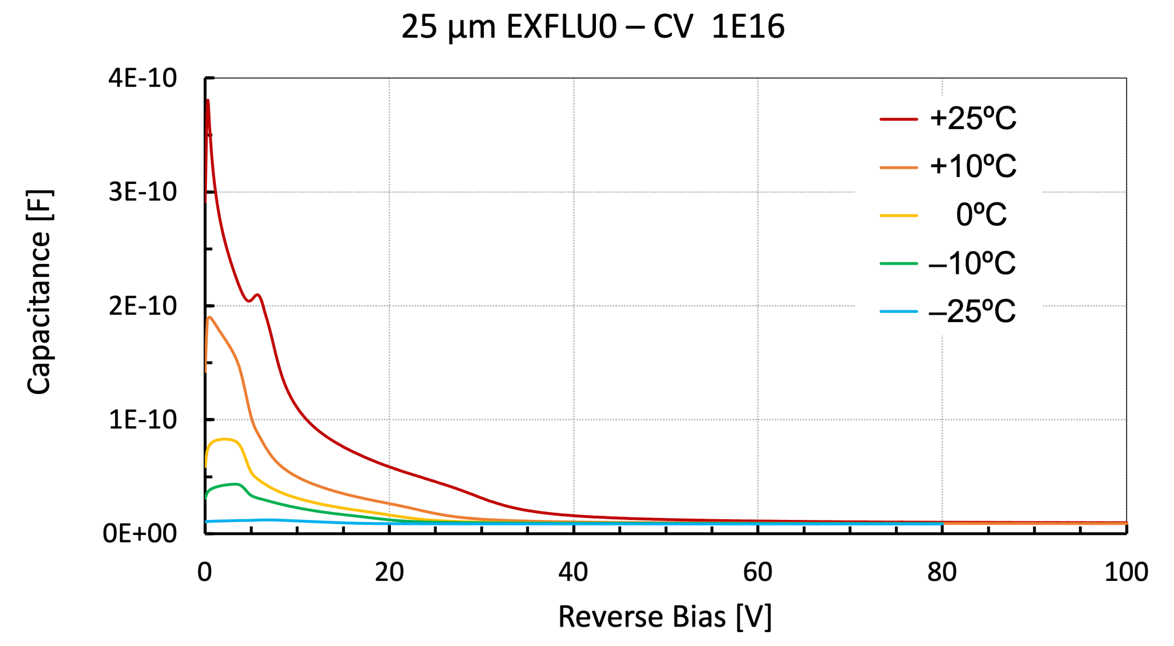
HF-CV with Keysight B1505A – f = 1 kHz

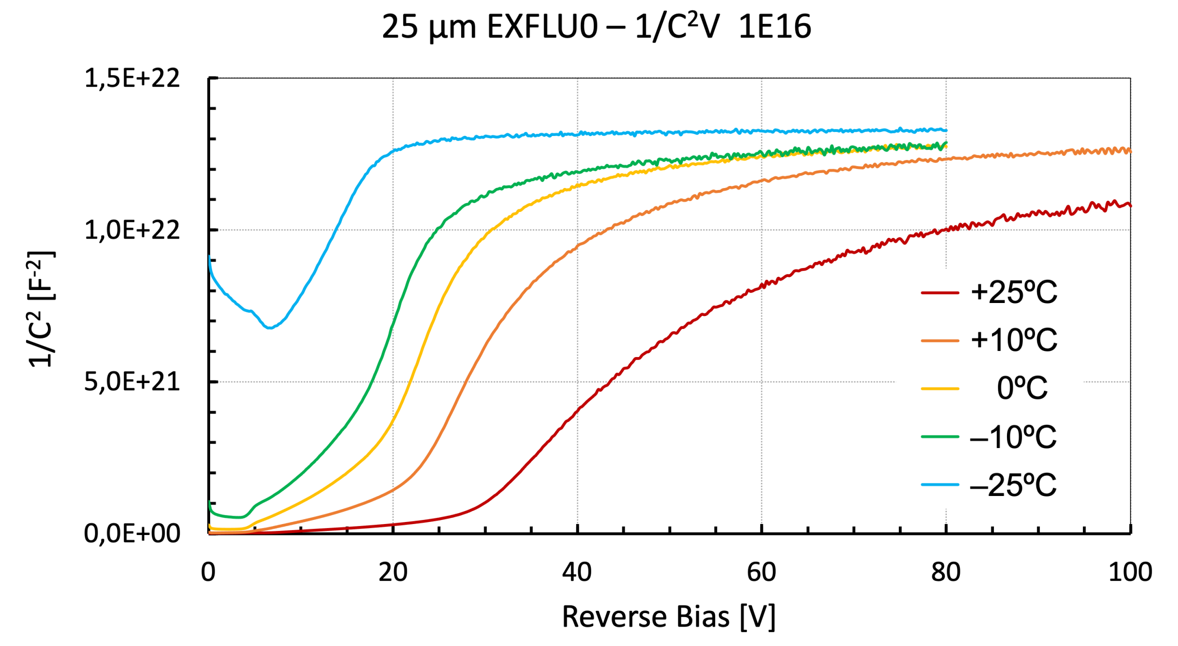




CV on 25 µm LGAD – Φ = 1E16 n_{eq}/cm^2

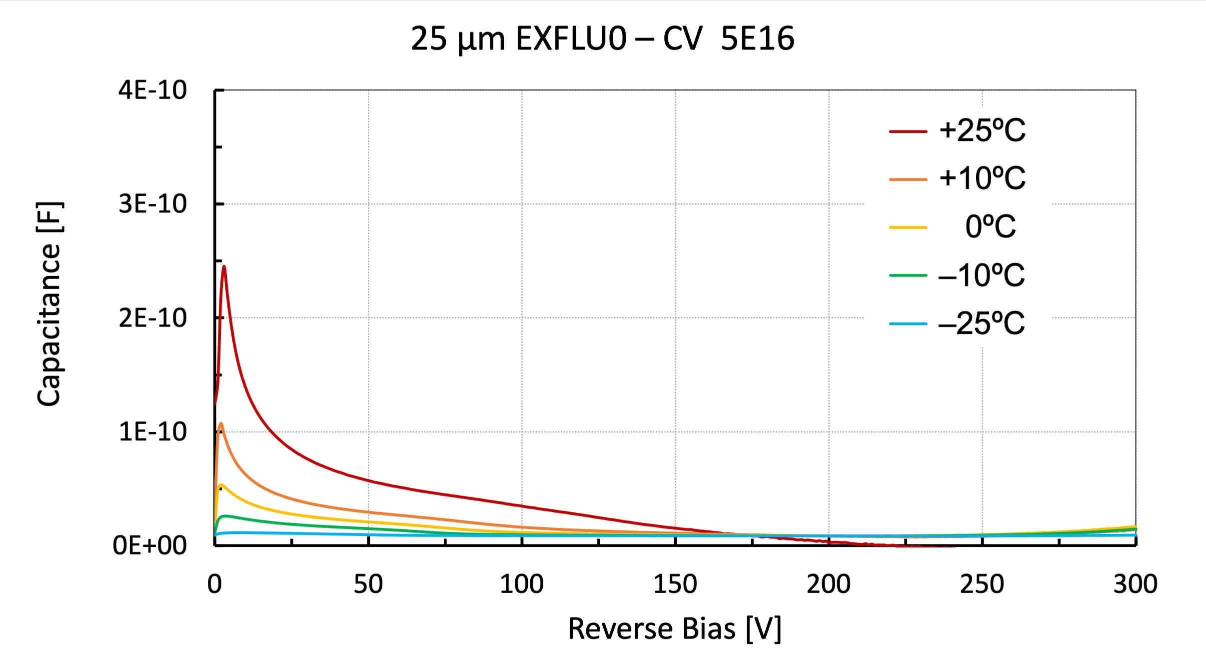
HF-CV with Keysight B1505A – f = 1 kHz

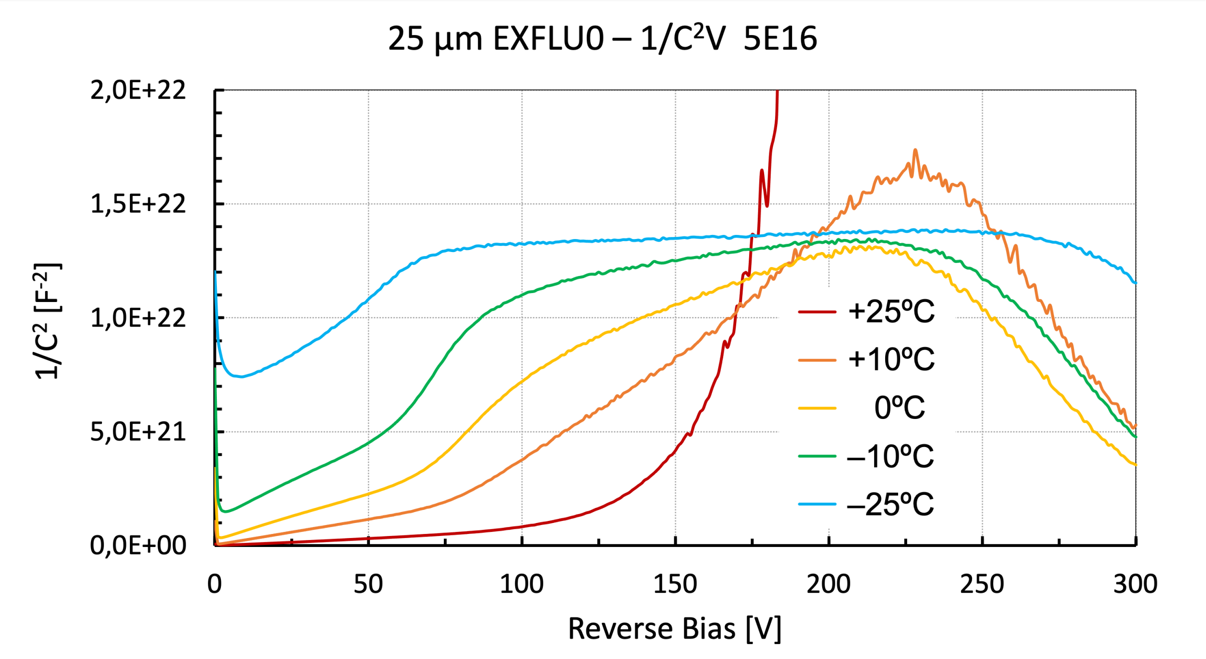




CV on 25 μm LGAD – Φ = 5E16 n_{eq}/cm^2

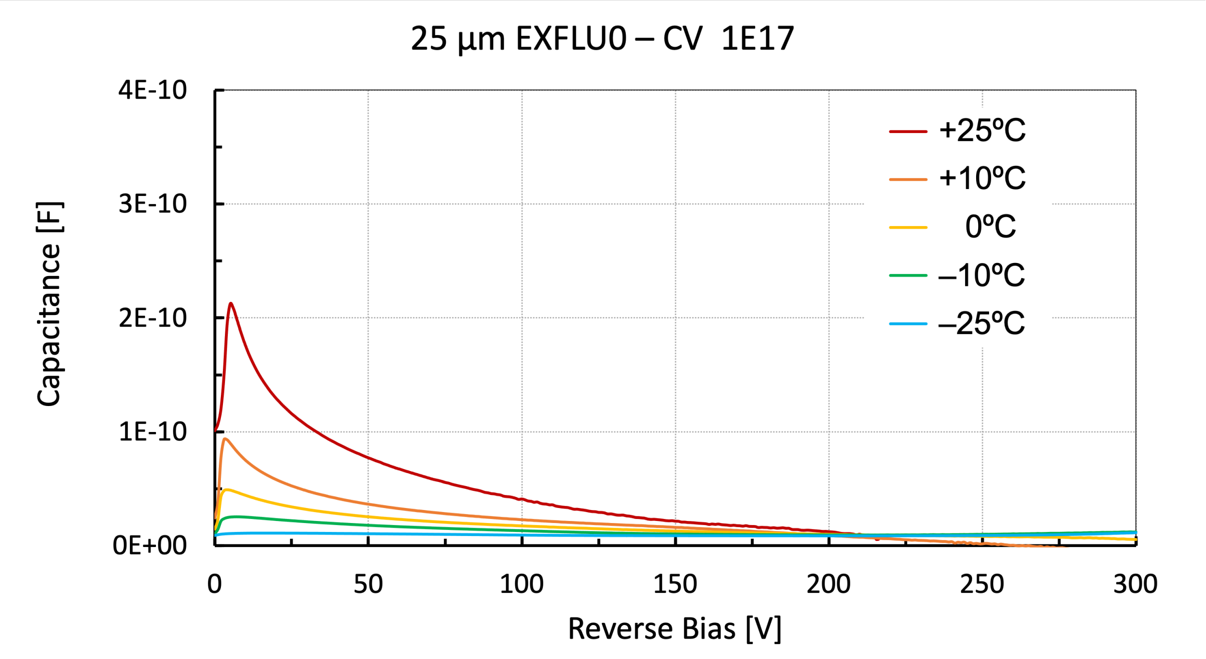
HF-CV with Keysight B1505A – f = 1 kHz

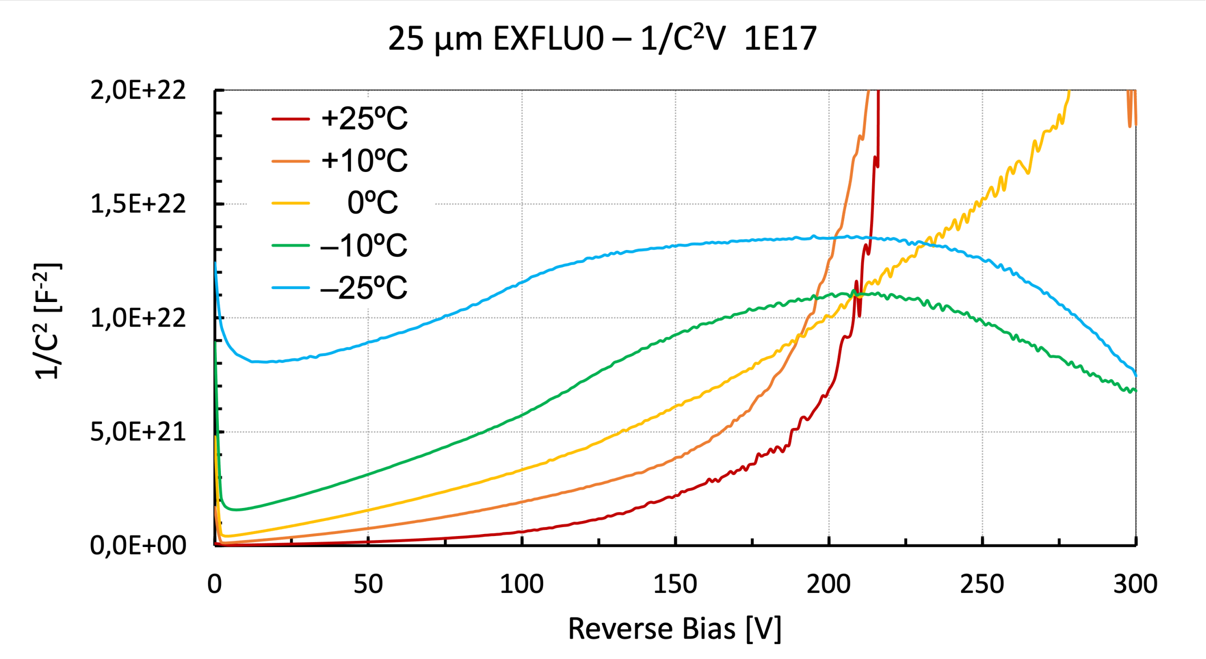




CV on 25 µm LGAD – Φ = 1E17 n_{eq}/cm^2

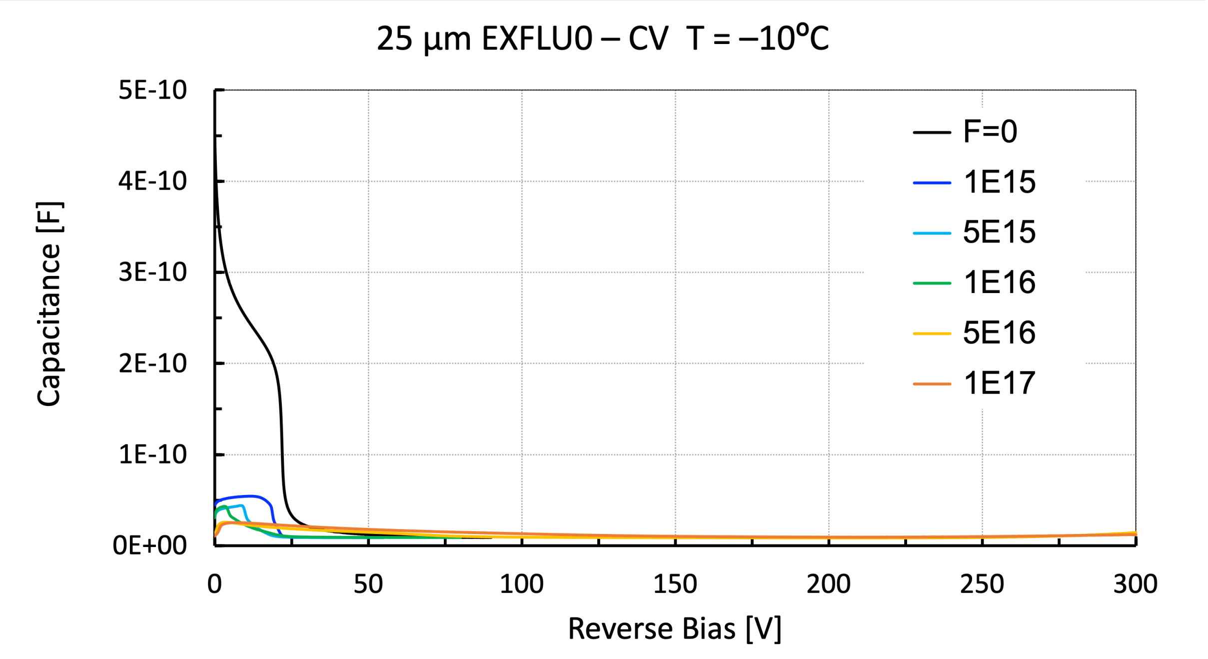
HF-CV with Keysight B1505A – f = 1 kHz

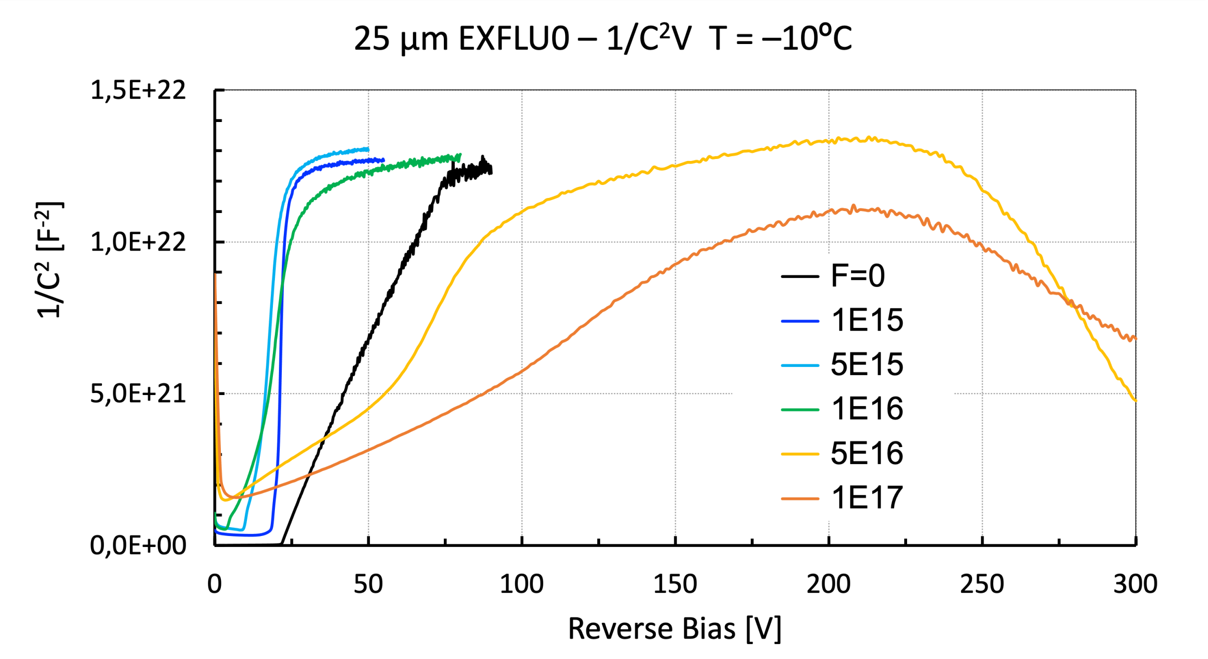




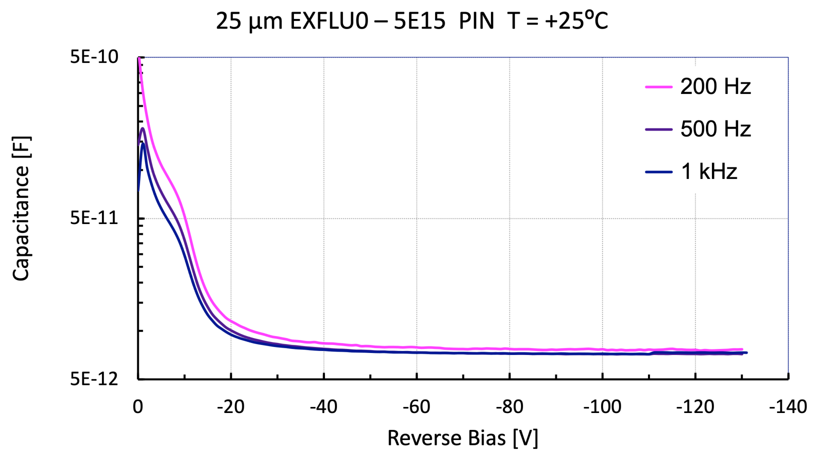
CV on 25 µm LGAD – T = -10°C

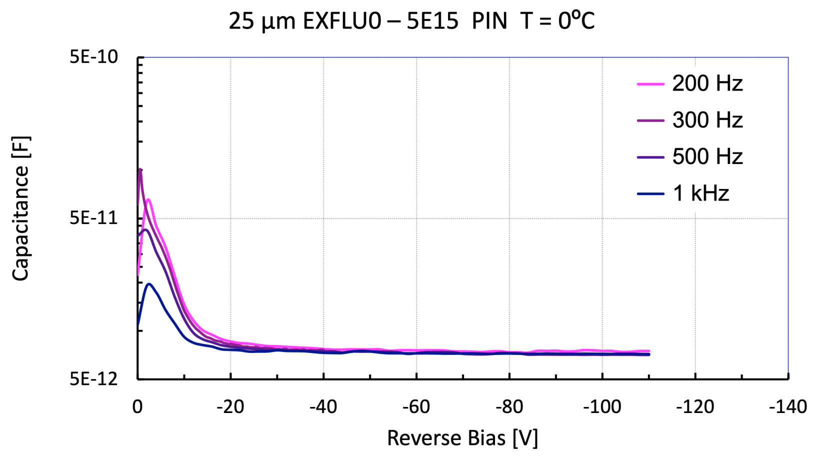
HF-CV with Keysight B1505A

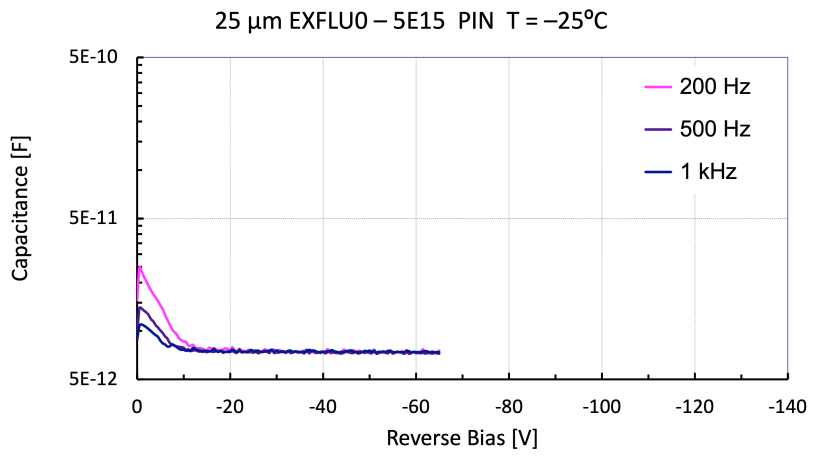


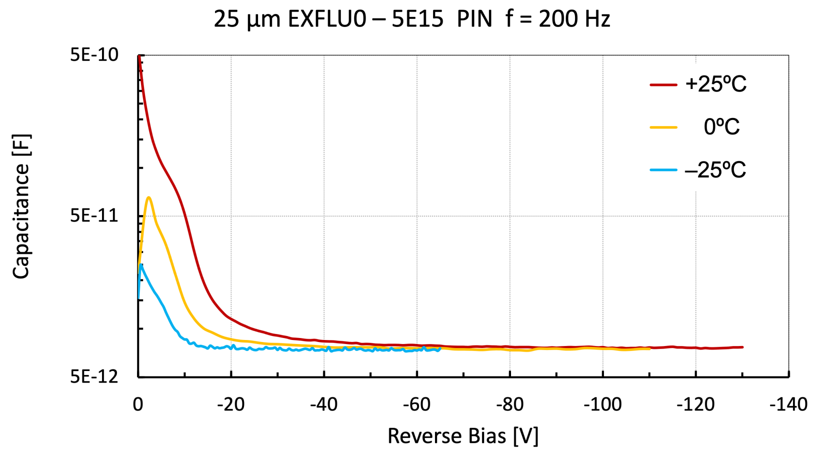


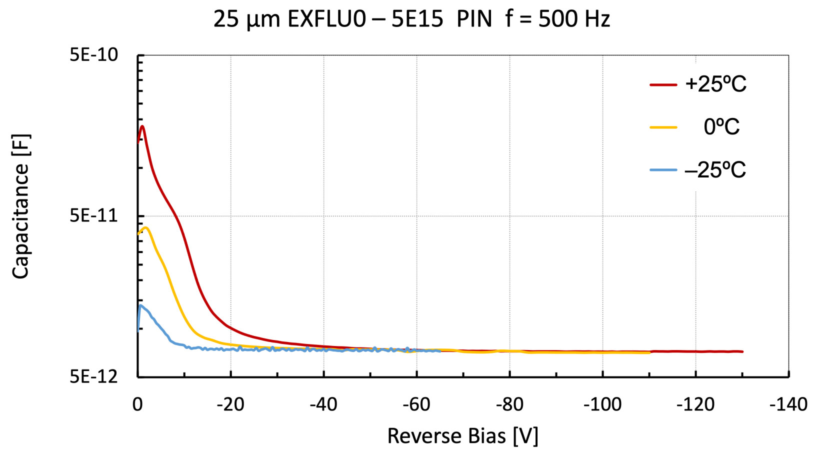
CV on PiN @ different T & f – 5E15 n_{eq}/cm^2

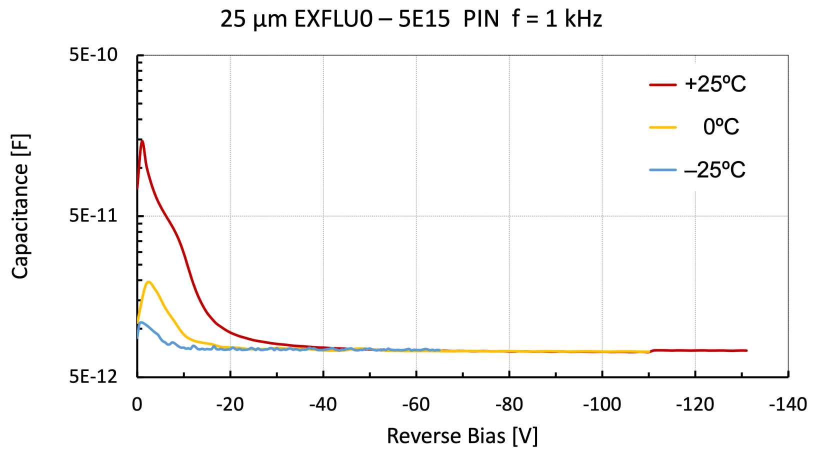

25 µm EXFLU0 – 5E15 PIN T = +25ºC


25 µm EXFLU0 – 5E15 PIN T = 0ºC

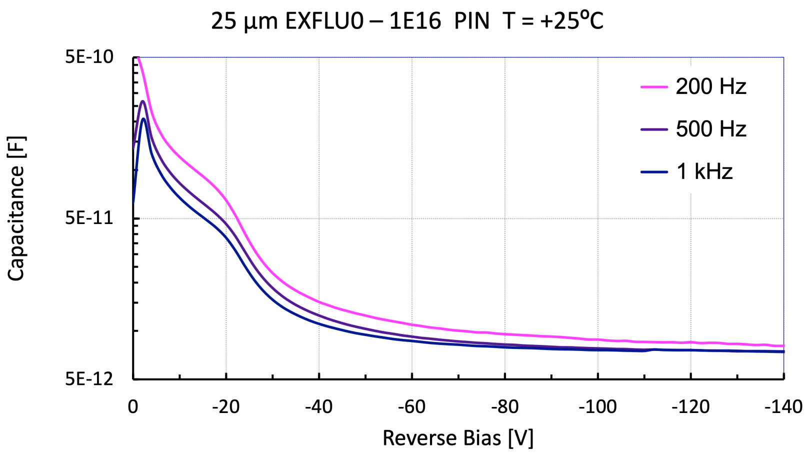

25 µm EXFLU0 – 5E15 PIN T = –25ºC

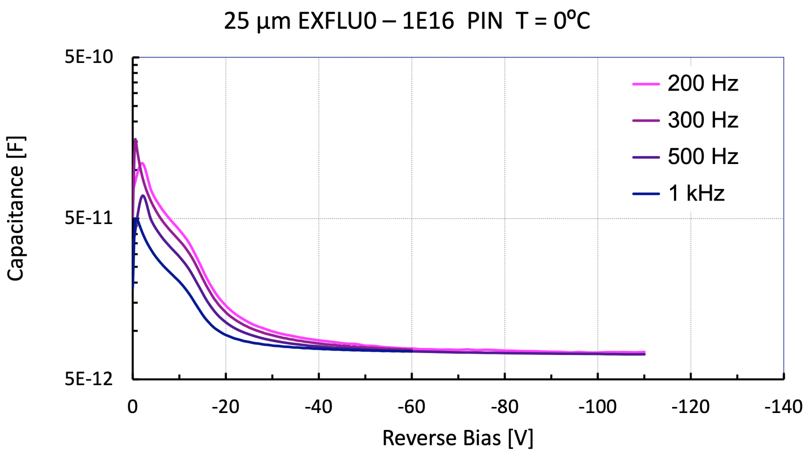

25 µm EXFLU0 – 5E15 PIN f = 200 Hz

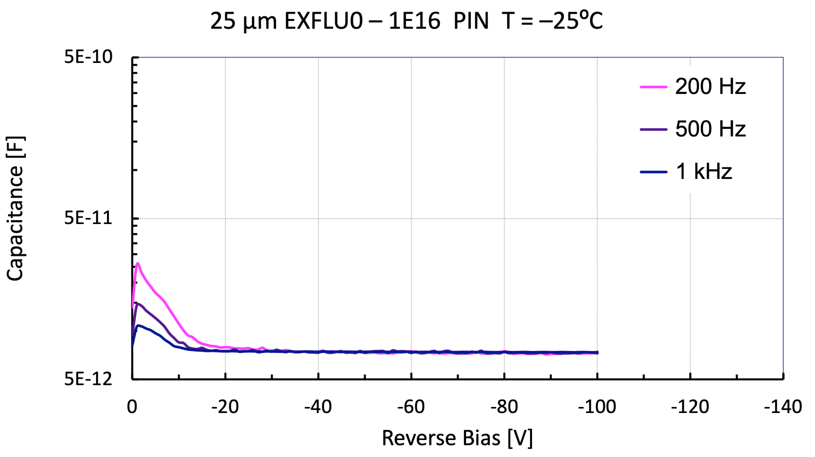

25 µm EXFLU0 – 5E15 PIN f = 500 Hz

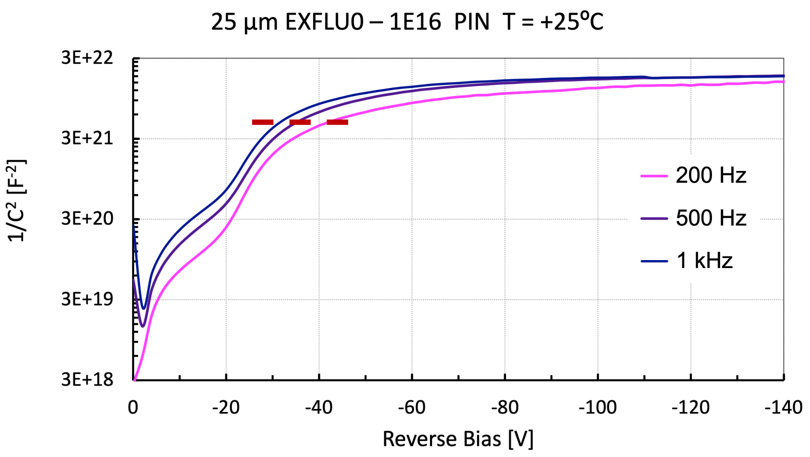

25 µm EXFLU0 – 5E15 PIN f = 1 kHz

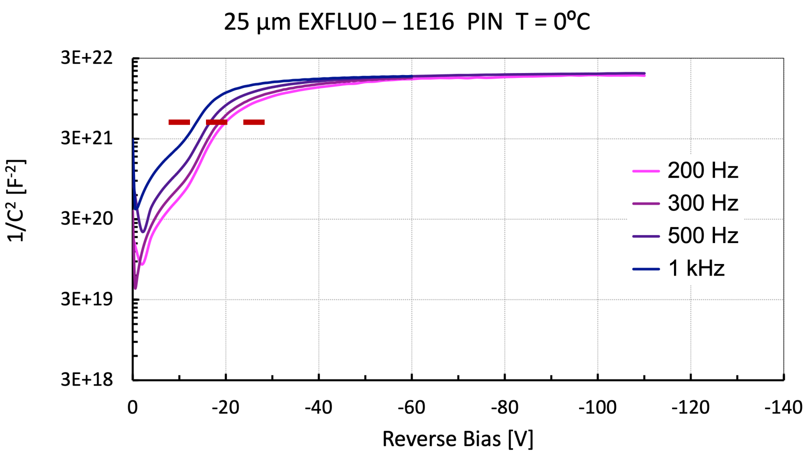
CV on PiN @ different T & f – 1E16 n_{eq}/cm^2

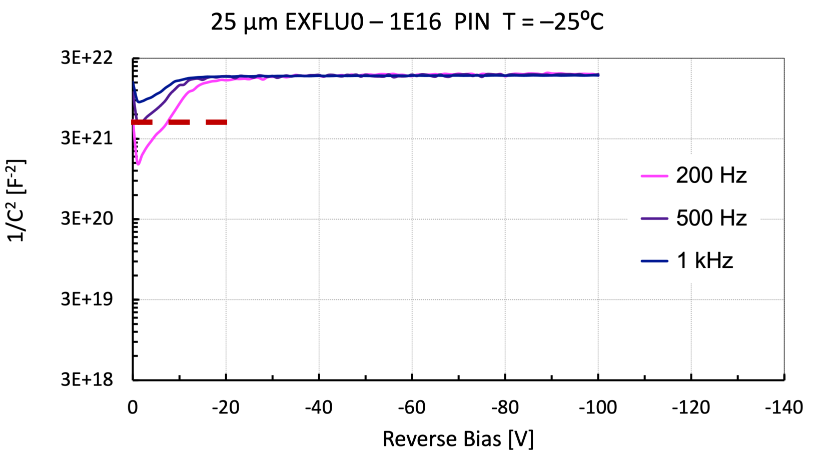




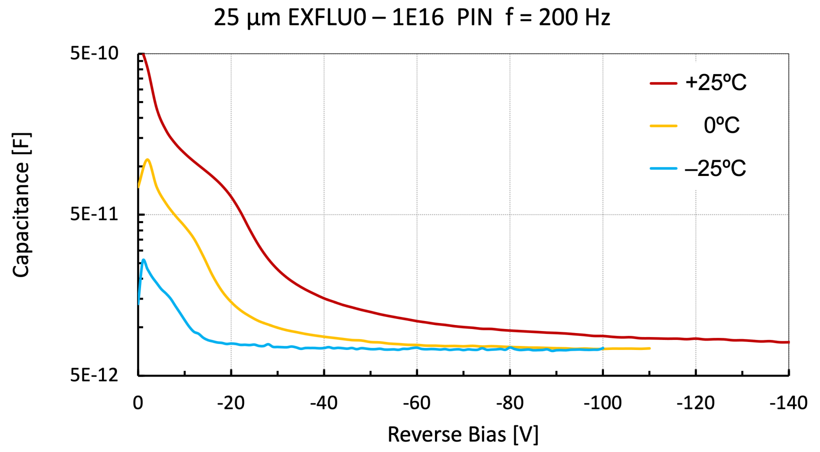


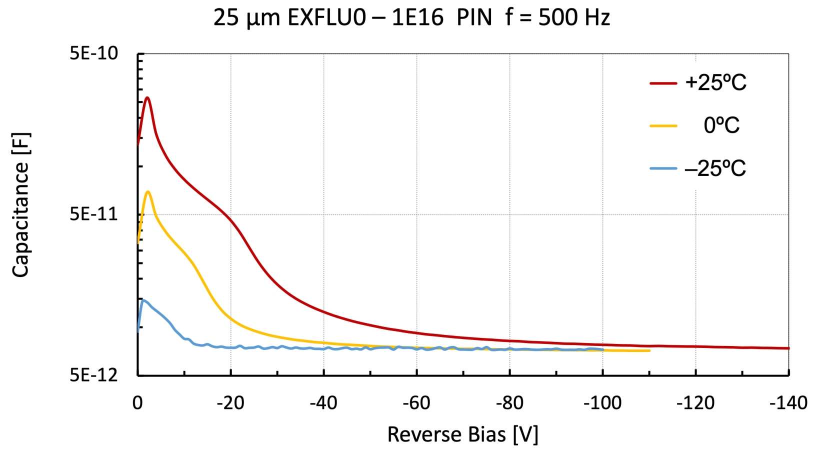


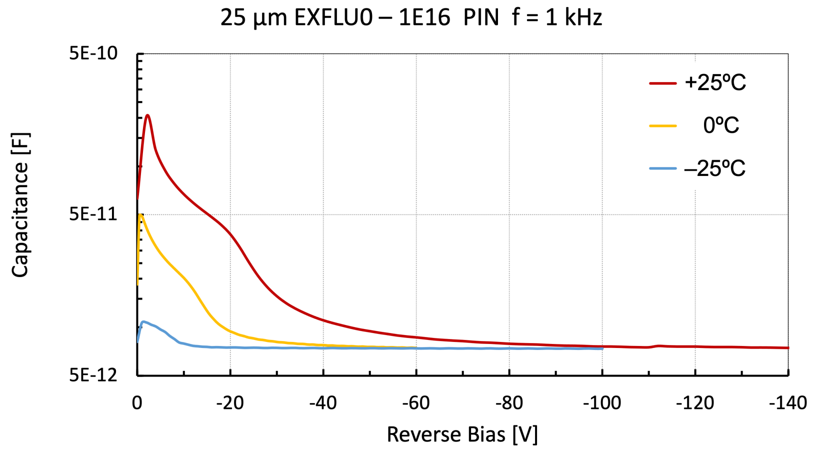


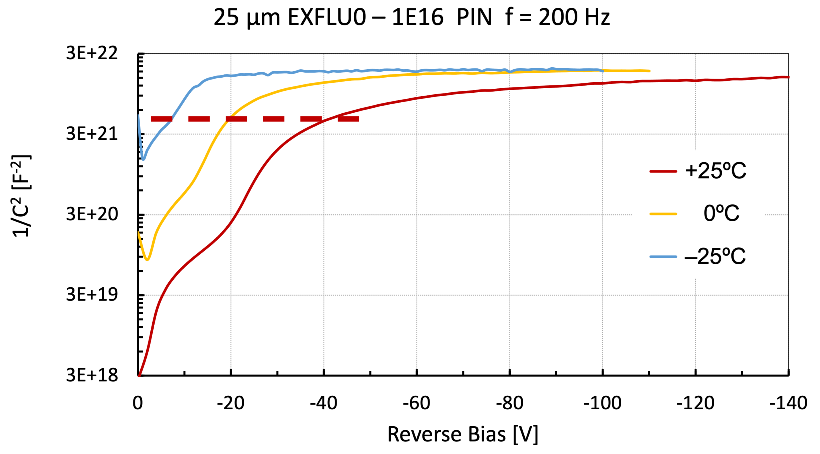


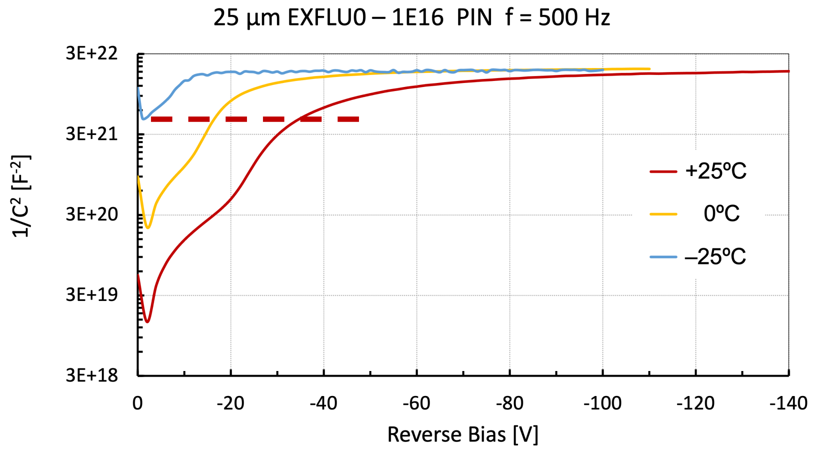
CV on PiN @ different T & f – 1E16 n_{eq}/cm^2

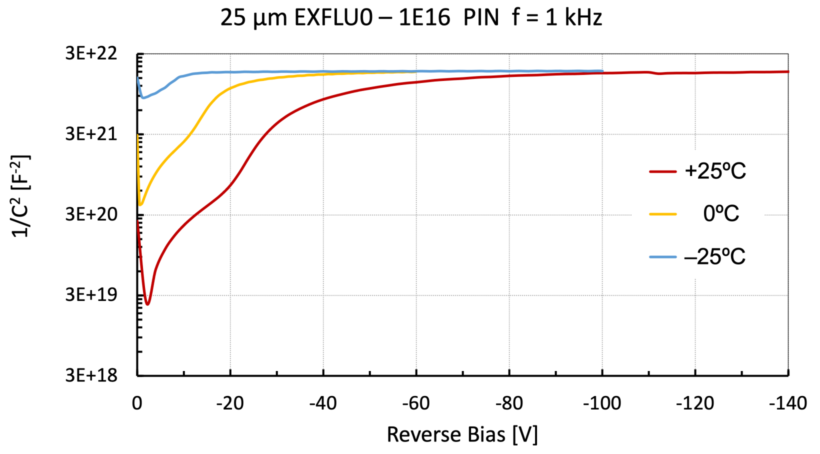

25 µm EXFLU0 – 1E16 PIN f = 200 Hz


25 µm EXFLU0 – 1E16 PIN f = 500 Hz


25 µm EXFLU0 – 1E16 PIN f = 1 kHz

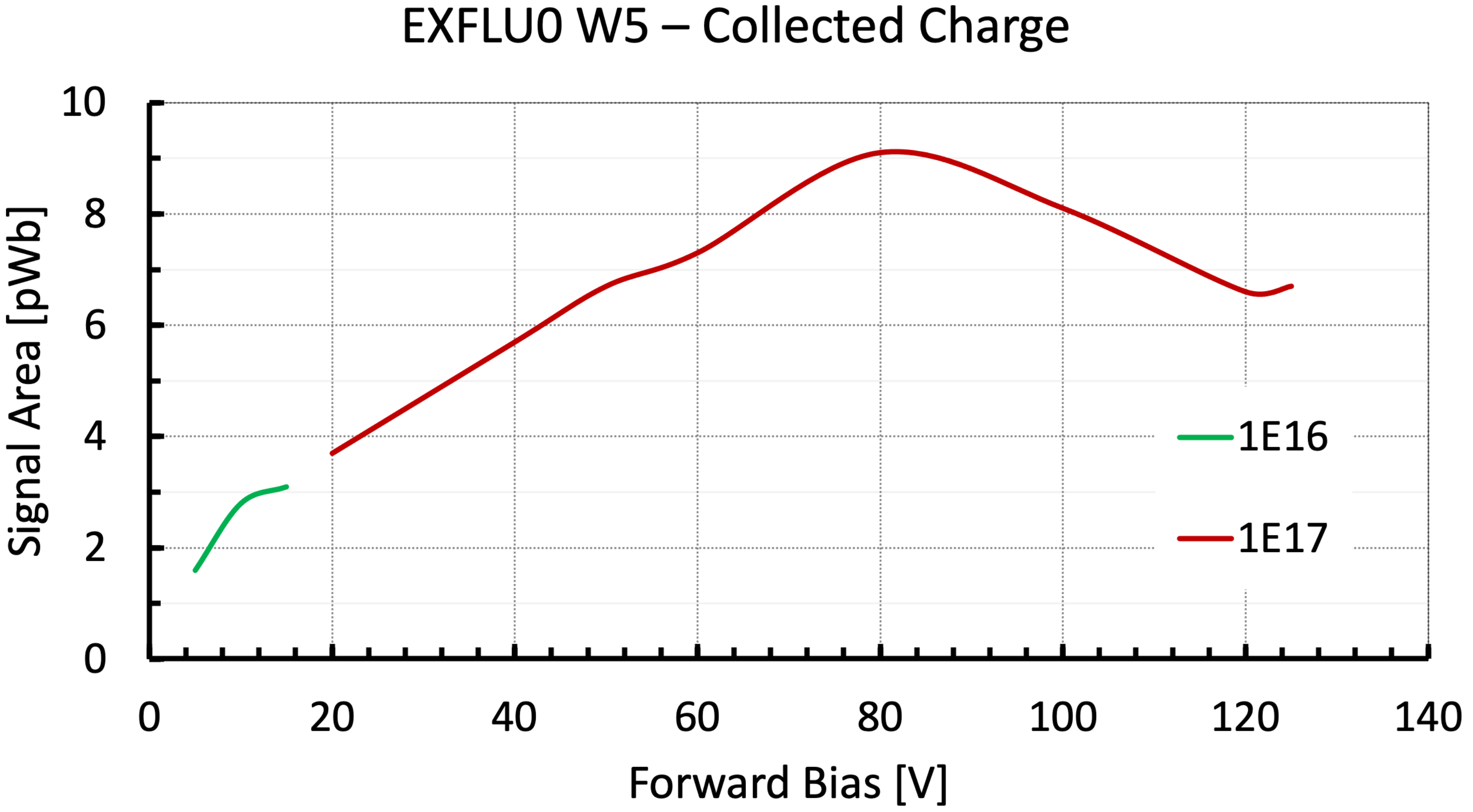

25 µm EXFLU0 – 1E16 PIN f = 200 Hz


25 µm EXFLU0 – 1E16 PIN f = 500 Hz

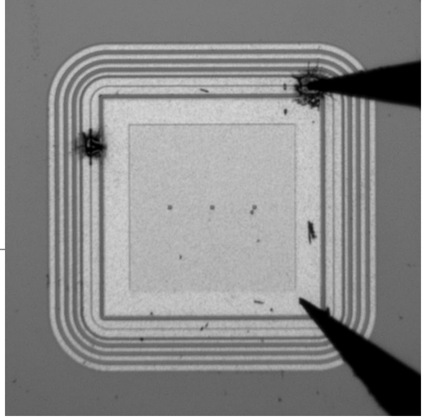

25 µm EXFLU0 – 1E16 PIN f = 1 kHz

CCE in Forward Bias – TCT

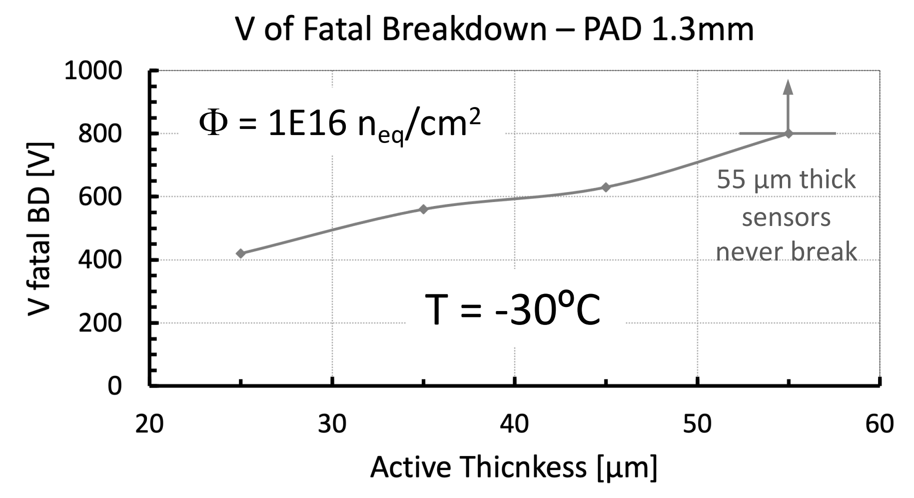
Laser intensity ~ few MIPs

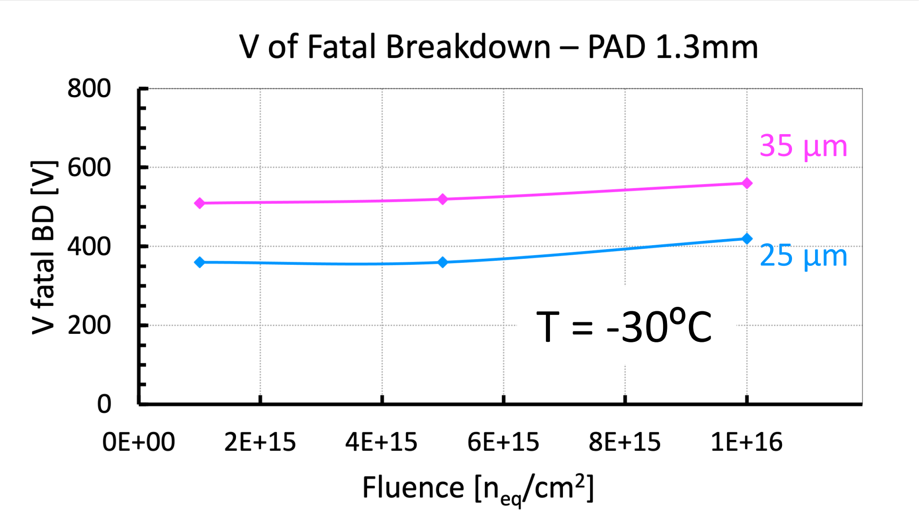


Breakdown on Thin LGAD



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





→ 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**

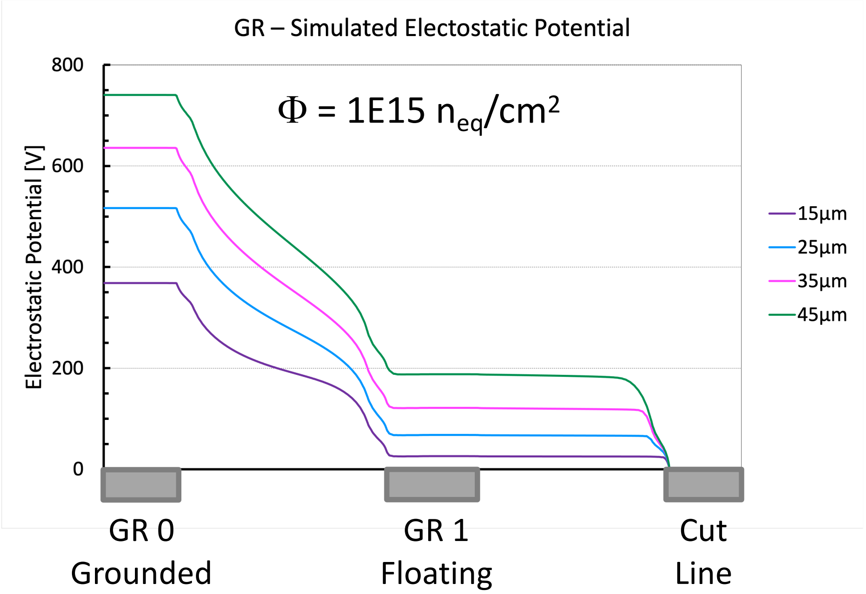
⟹ R&D on the guard-ring structures optimised for thin substrates is needed
and will be pursued towards the EXFLU1 sensor production

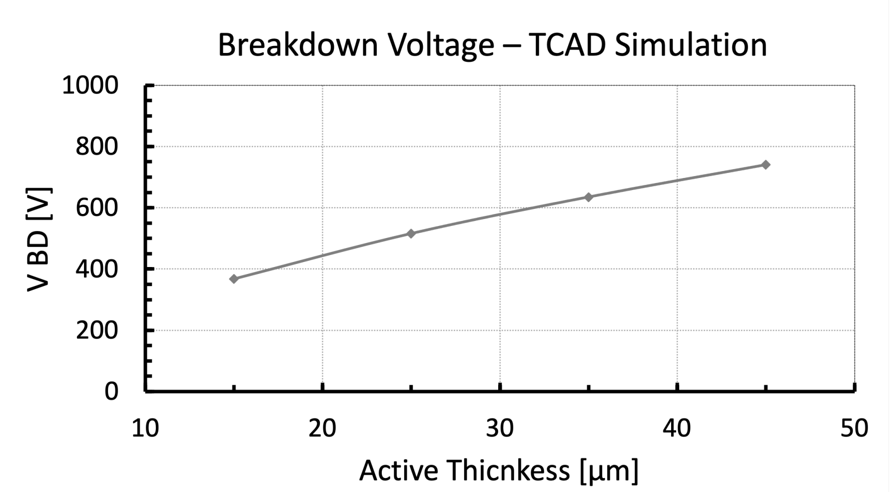
Simulated Breakdown

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



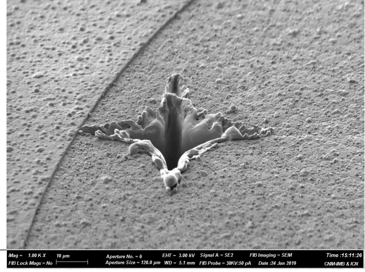


→ The simulated breakdown voltage has a trend similar to data

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

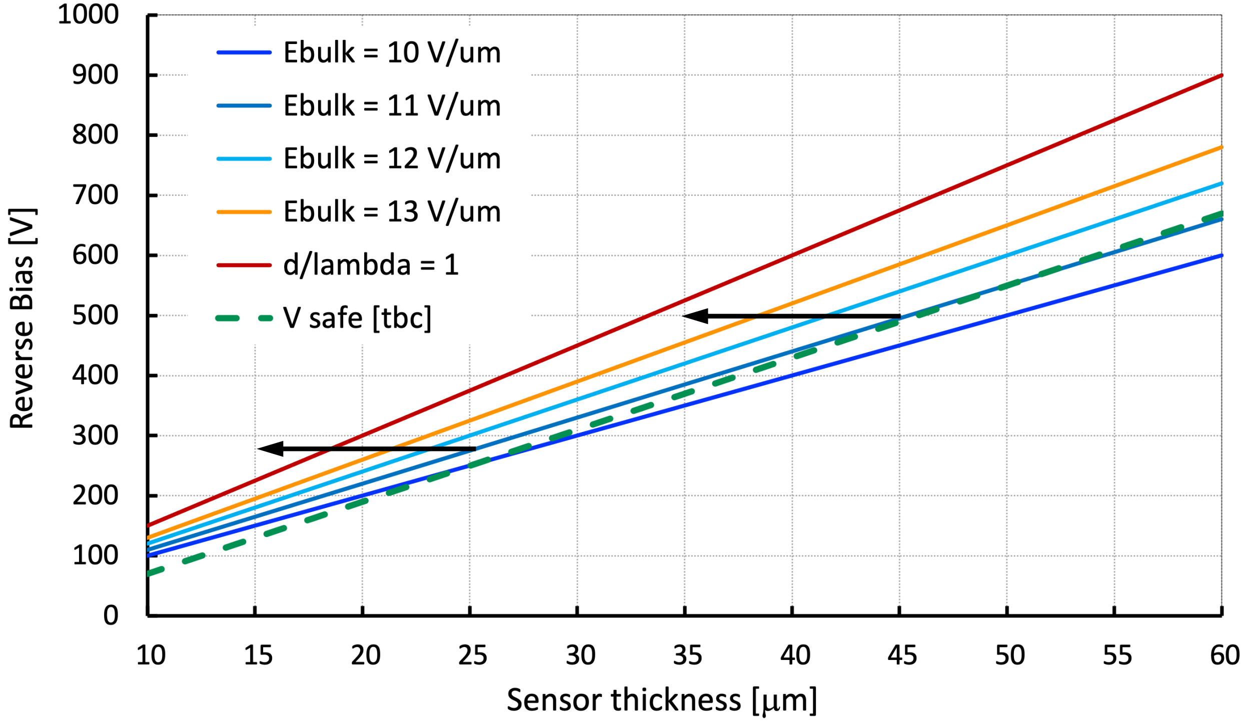
⟹ Different guard-ring designs will be simulated and tested in the EXFLU1 production

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**



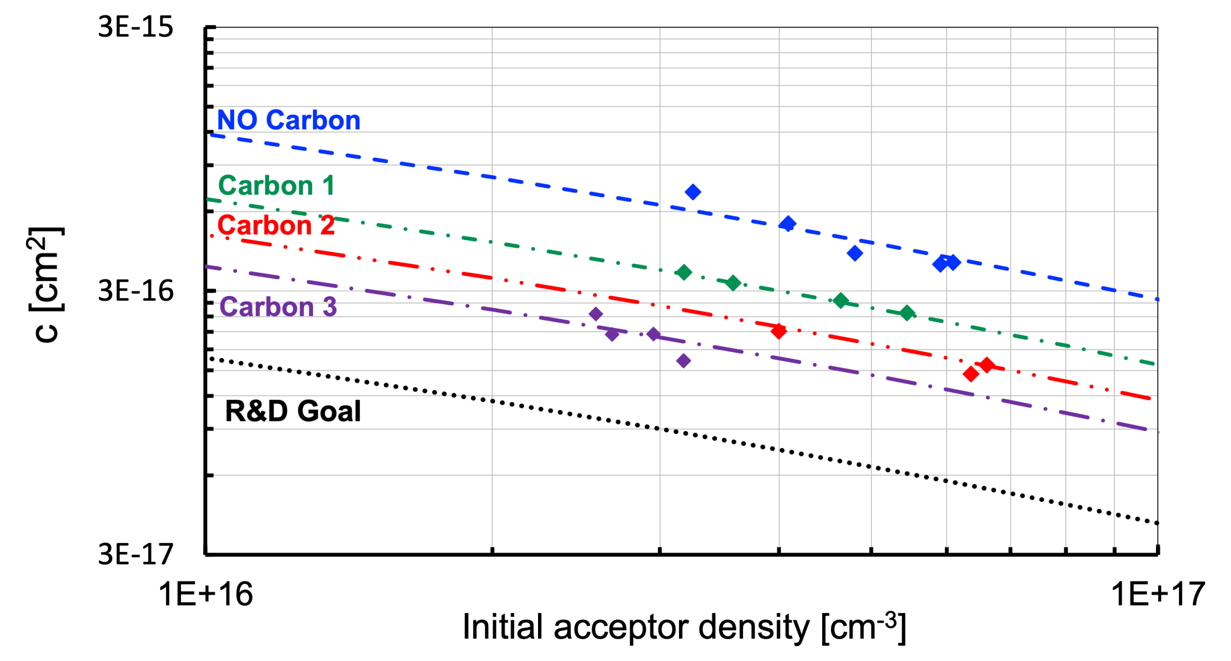
A local sensor thickness reduction can have more impact on thin sensors

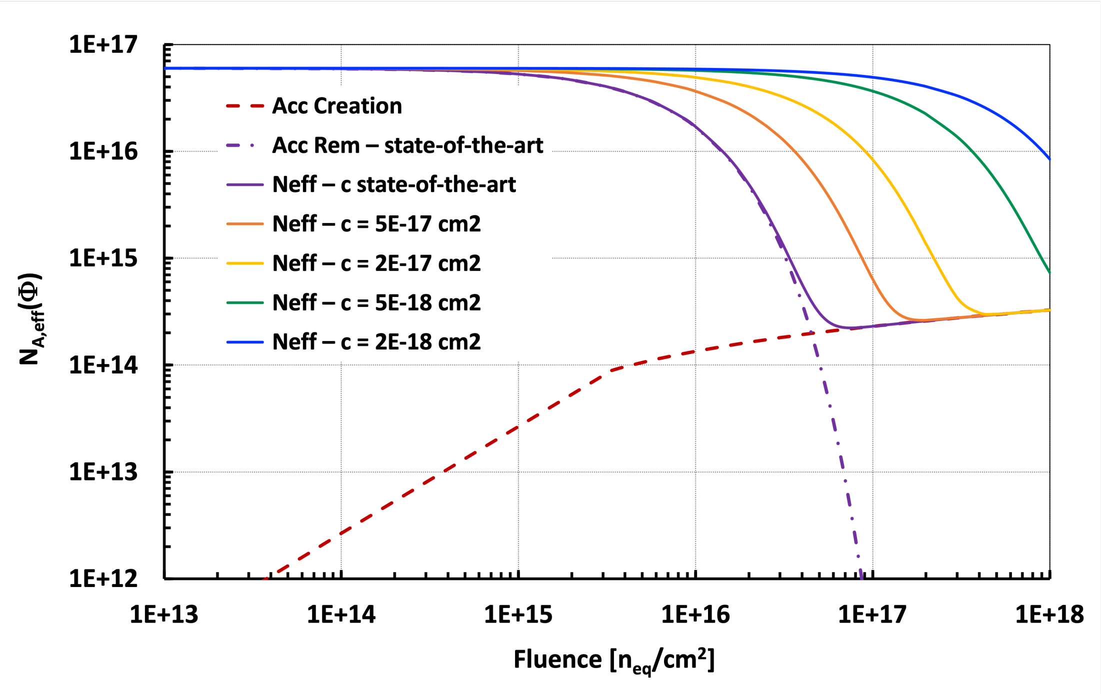
Beam tests on EXFLU0 are necessary to understand the effect of highly ionising particles on thin sensors

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

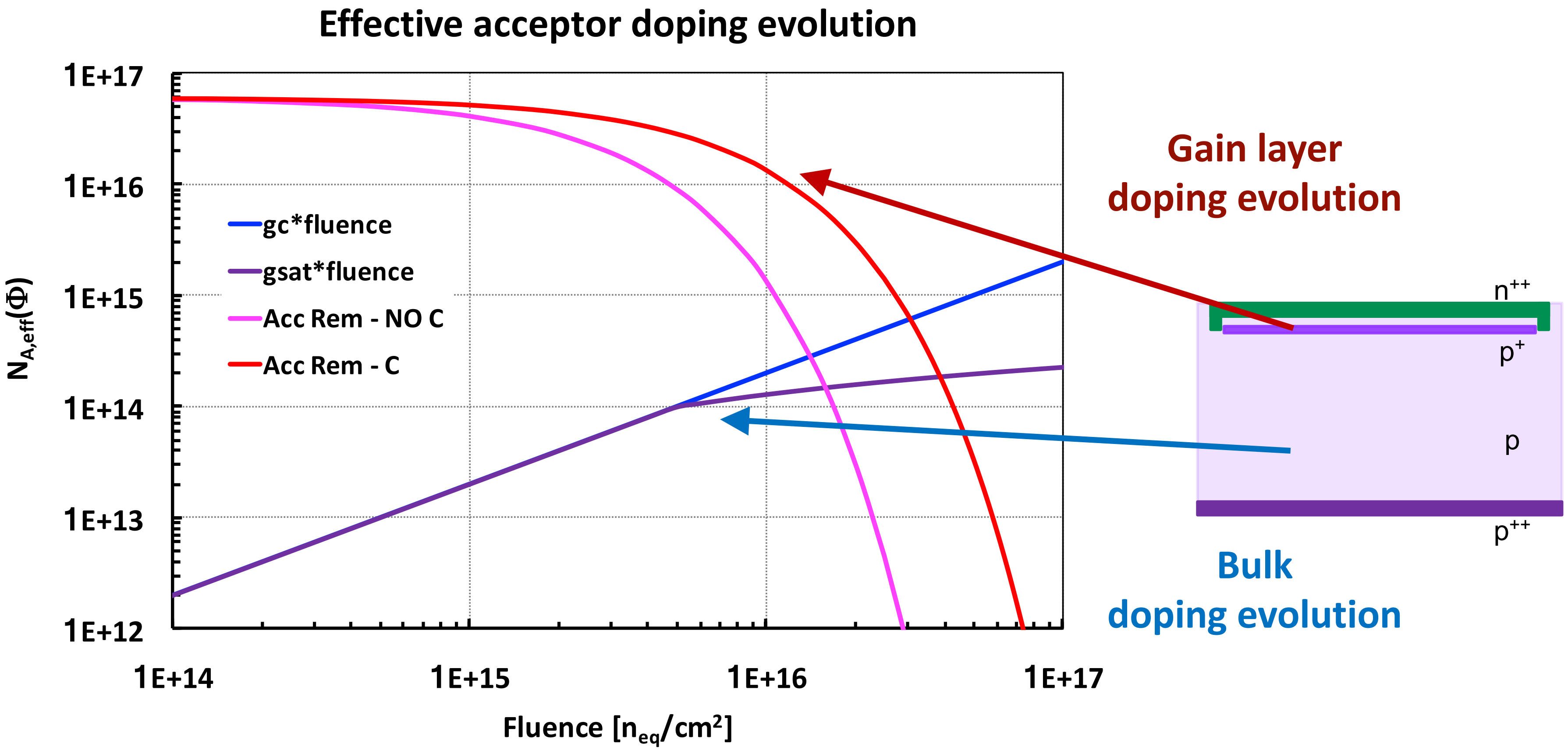




$$N_{A,eff}(\Phi) = N_A(0)\cdot e^{-c\Phi} + g_c\Phi$$

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 LAYER RADIATION TOLERANCE

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

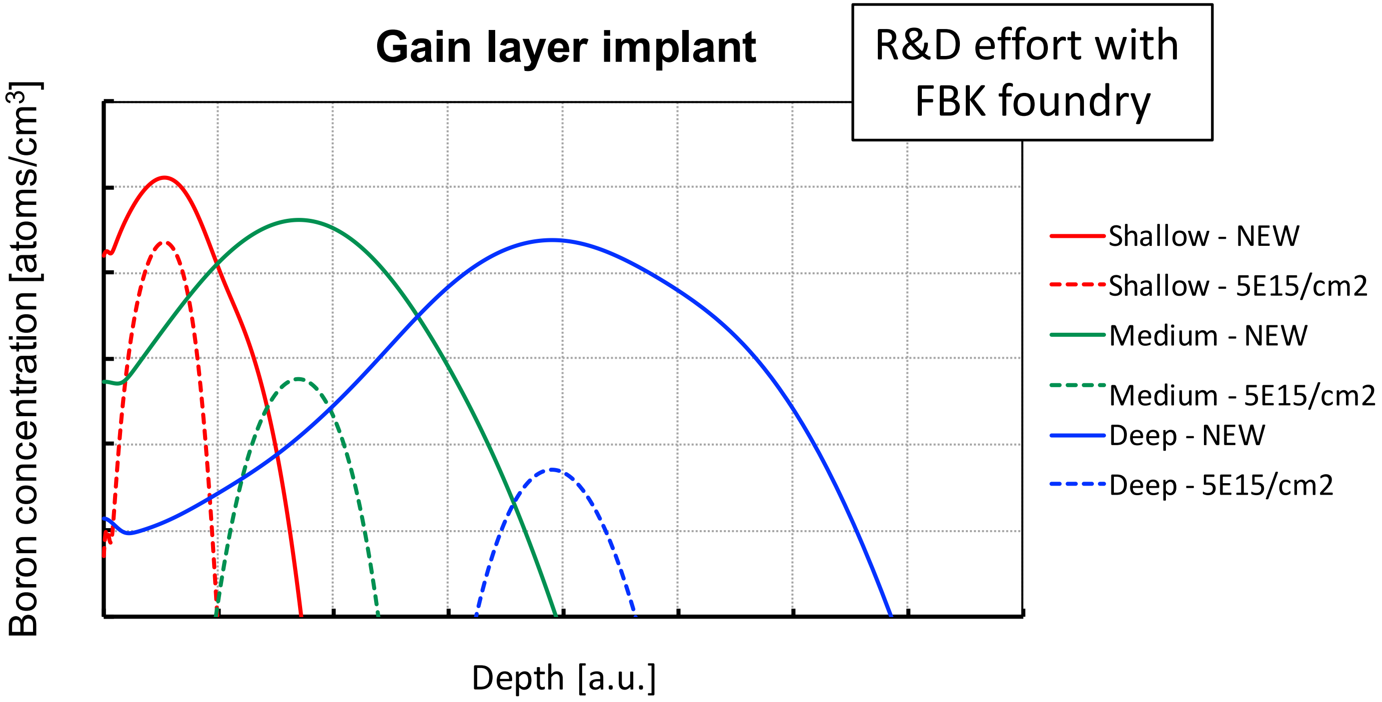
Acceptor removal:

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

Defect engineering and different gain layer implantation strategies will be investigated

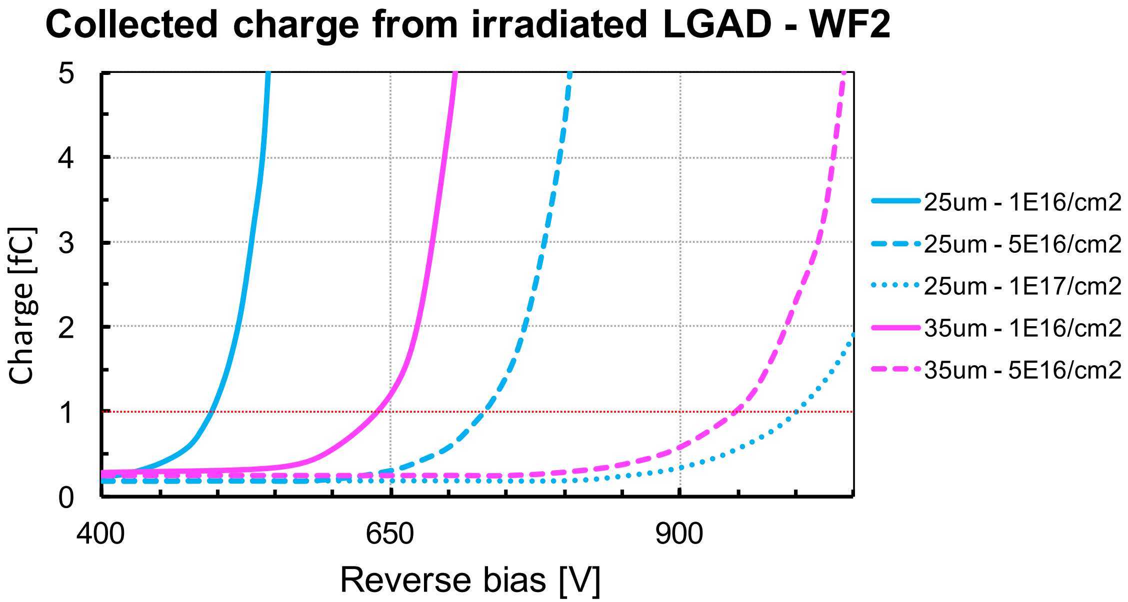
$$\mathbf{c \cdot N_{A,0} = 60\ cm^{-1} \rightarrow\ < 10\ cm^{-1}}$$

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



R&D effort with FBK foundry

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]`

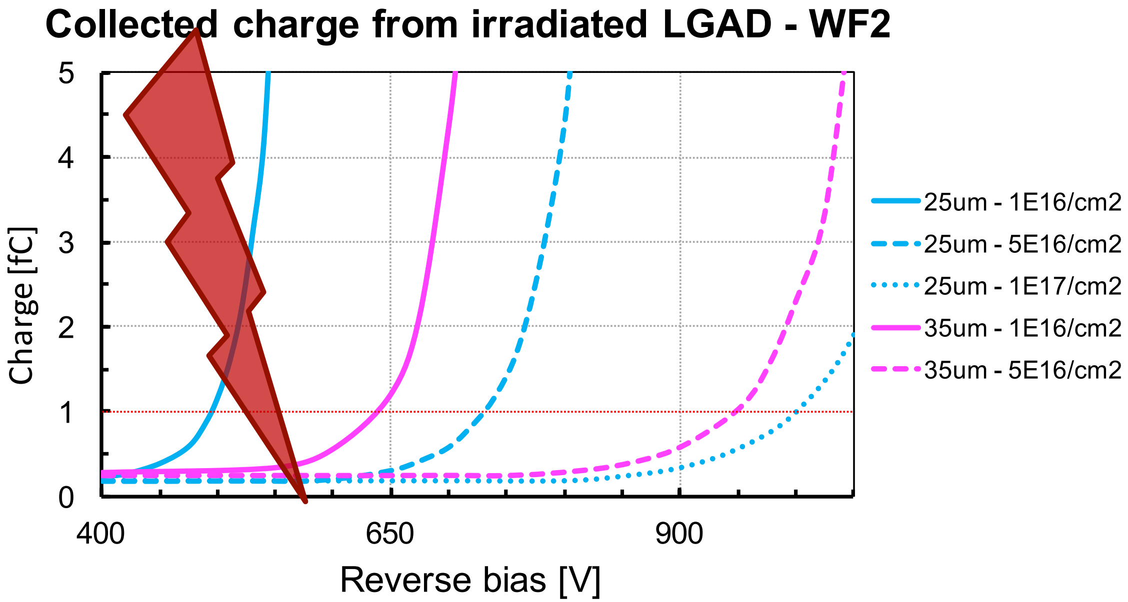
Simulation in progress with the Perugia group to find the optimal sensor design for the next production on thin wafers – EXFLU1

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

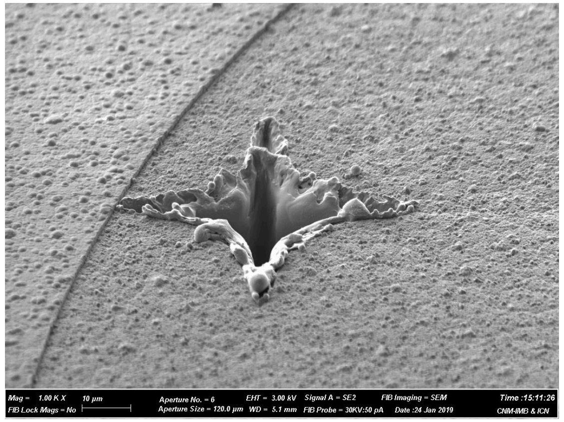
`[A. Morozzi et al., doi:10.22323/1.373.0050]`

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

HIGHLY IONISING EVENTS ON THIN SENSORS


Collected charge from irradiated LGAD - WF2

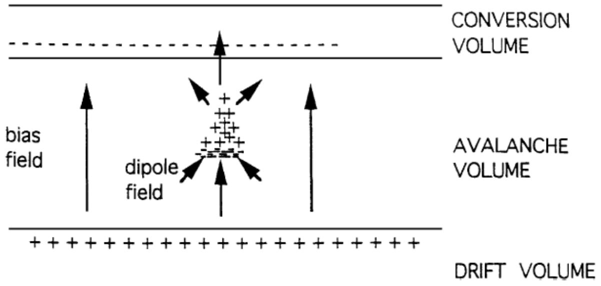
What happens if the sensor experiences a fatal highly ionising particle at a bias lower to the one necessary to collect 1fC?



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

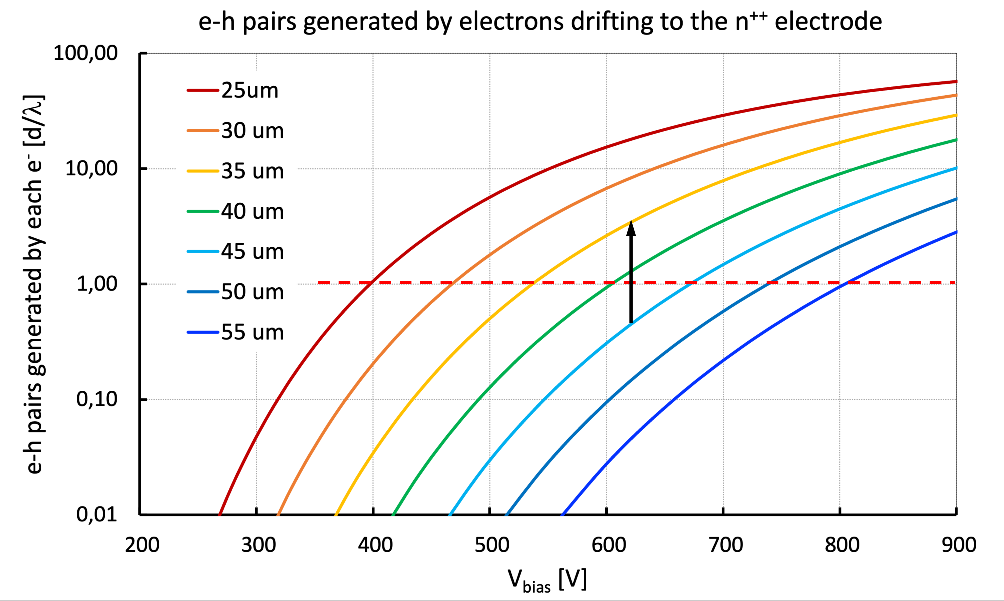


Same effect was observed in APD
`[G. Anzivino et al. NIM A 430 (1999) 100]`

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

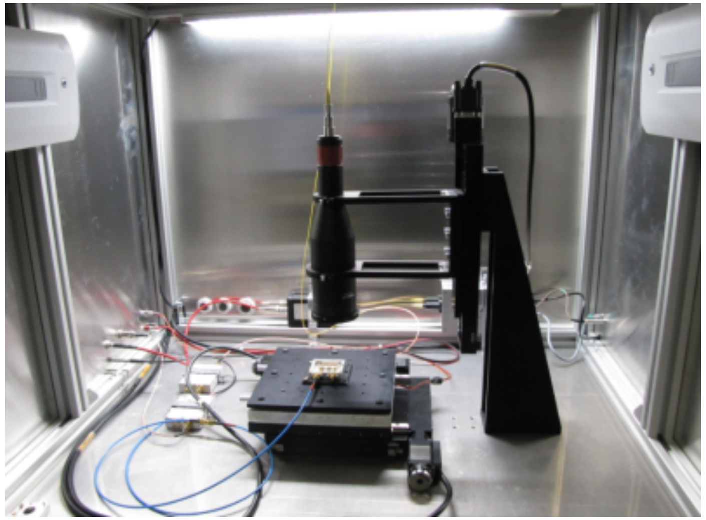
COOL SYSTEMS

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

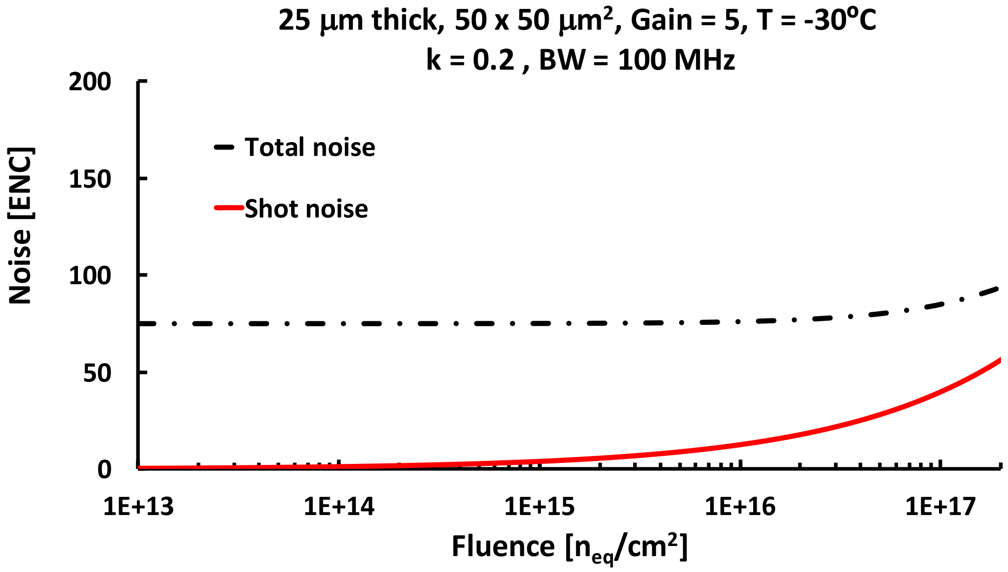
Vötsch VCL4010 Test Chamber
with temperature range from -40 to +180°C
available in Torino Laboratory



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

SHOT NOISE

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



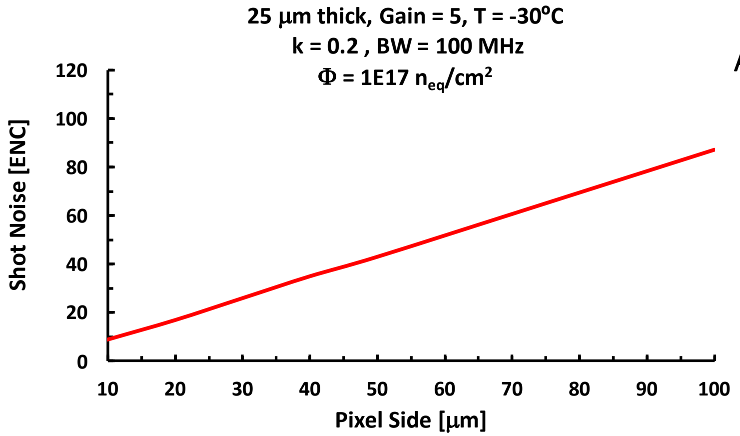
For LGAD sensors, shot noise is given by

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

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