Radiation-Resistant Thin LGADs for Enhanced 4D Tracking

A. R. Altamura, L. Anderlini, R. Arcidiacono, G. Borghi, M. Boscardin, N. Cartiglia, M. Centis Vignali, T. Croci, F. Davolio, M. Durando, M. Ferrero, A. Fondacci, S. Galletto, L. Lanteri, L. Menzio, A. Morozzi, F. Moscatelli, D. Passeri, N. Pastrone, G. Paternoster, F. Siviero, R. White, V. Sola

EXFLU1 R&D – The Goals

➤Improve LGADs temporal resolution

➤Improve LGADs radiation tolerance

RADIATION DAMAGE IN SILICON - The Challenge

- **Defects in the silicon lattice structure**

$$\Delta I_{leak} = \alpha V \Phi$$

In sensors with internal gain :

$$\Delta I_{leak} = G \alpha V \Phi$$

LEAKAGE CURRENT INCREASE

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- **Trapping of the carriers**

Signal reduced by trapping due to irradiation :

$$I(t) = I_0 e^{-\frac{t}{\tau_{tr}}}$$

With:

$$\frac{1}{\tau_{tr}} = \beta \Phi$$

DECREASE OF CHARGE COLLECTION EFFICIENCY

RADIATION DAMAGE IN SILICON - The Challenge

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$$\Delta I_{leak} = G \alpha V \Phi$$

LEAKAGE CURRENT INCREASE

- **Change in bulk effective doping**

Acceptor density [n/cm^3] scales with fluence:

$$p(\phi) = \underbrace{g_{eff}\Phi}_{\substack{\text{ACCEPTOR} \\ \text{CREATION}}} + \underbrace{p(0)e^{-c_A\Phi}}_{\substack{\text{ACCEPTOR} \\ \text{REMOVAL}}}$$

ACCEPTOR   ACCEPTOR
CREATION   REMOVAL

Depletion voltage affected by radiation as linearly dependent on $p(\Phi)$

IMPOSSIBLE TO FULLY DEPLETE THE SENSOR
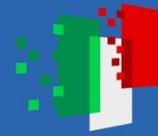
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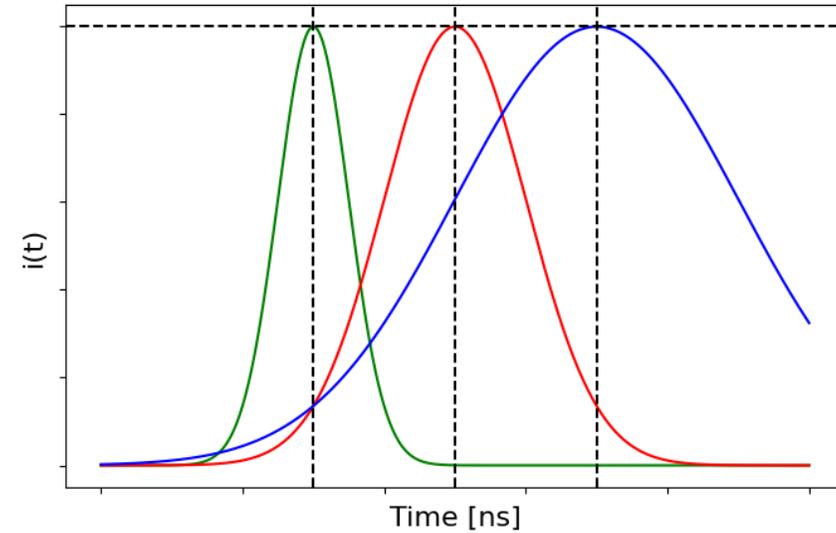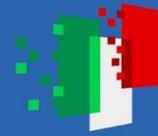DECREASE OF CHARGE COLLECTION EFFICIENCY

Thin LGADs - A solution?

- **IMPROVEMENT OF TEMPORAL RESOLUTION**

$$\frac{dI_{Gain}}{dt} \sim \frac{dV}{dt} \propto \frac{G}{d}$$

Thin sensors means better resolution due to a faster charge collection

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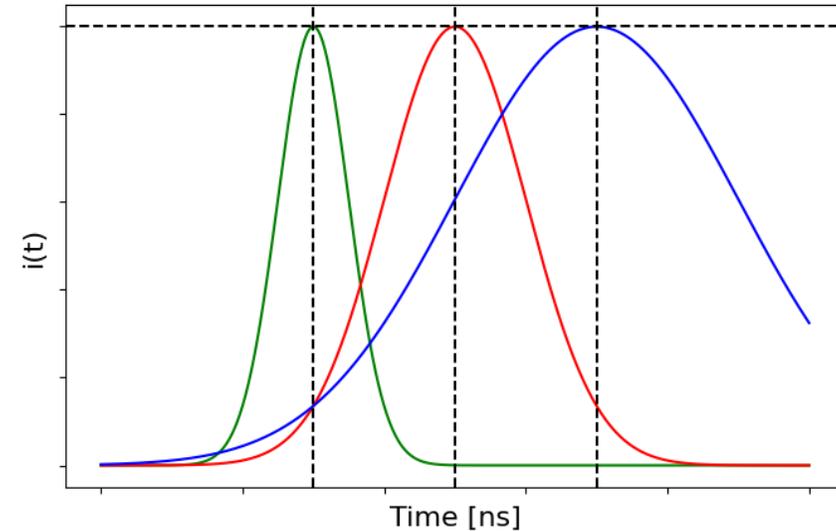
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$$\frac{dI_{Gain}}{dt} \sim \frac{dV}{dt} \propto \frac{G}{d}$$

Thin sensors means better resolution due to a faster charge collection

- **IMPROVEMENT OF RADIATION TOLERANCE**

$$V_{FD} = \frac{qN_{eff}}{2\epsilon} d^2$$

Lower increase of the depletion voltage with fluence, allowing LGADs to operate at voltages well above full depletion while maintaining good efficiency even after heavy irradiation.

At high fluences:

➤ $V_{FD}^{Thin} < V_{BD}^{Thin}$ Sensor **still** efficient !!

EXFLU1 – The Batch

The EXFLU1 thin LGAD batch was released by FBK in 2023

GOAL:

To improve the radiation tolerance in LGADs up to 25×10^{14} n_{eq}/cm^2

MAIN FEATURES:

- New guard ring design
- Thin substrates ($15 - 45$ μm)
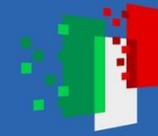- Decrease of the acceptor removal – gain layer design

SIMULATION

FABRICATION

CHARACTERISATION

EXFLU1 – Specifications

Wafer index	Thickness / µm	p⁺ dose /	C dose /	Diffusion	Bulk
1	45	1.14	1.0	CBL	very high ρ
5	30	1.12	1.0	CBL	high ρ
16	20	0.80	1.0	CHBL	low ρ
17	20	0.96	1.0	CBL	low ρ
18	15	0.94	1.0	CBL	low ρ

CHBL : Carbon High Boron Low diffusion
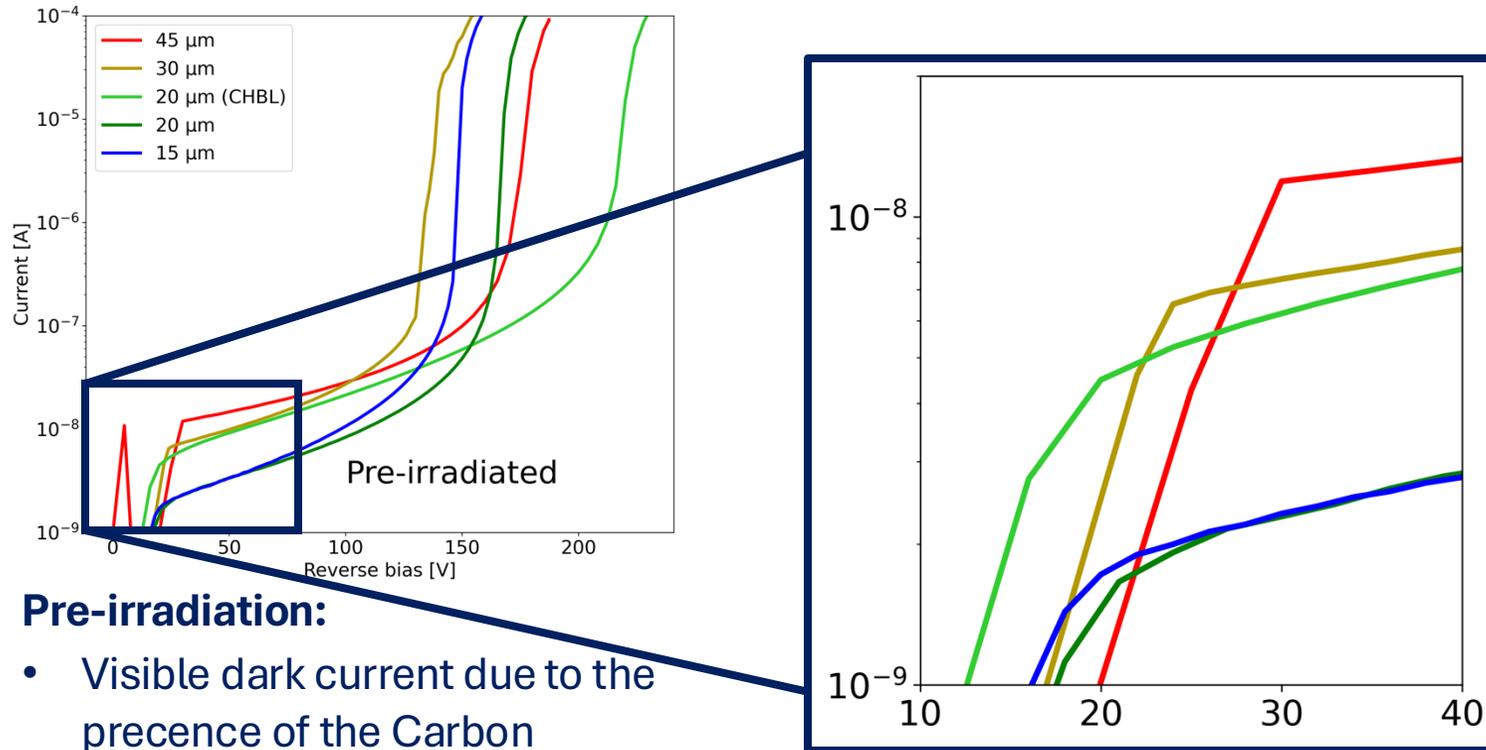CBL : Carbon Boron Low diffusion

Wafers irradiated between $\Phi = 4 \times 10^{14}$ and 25×10^{14} $n_{eq}cm^{-2}$ at Jožef Stefan Institute (JSI) in Ljubljana.
Annealing: 80 minutes at 60°C

EXFLU1 – IV characteristics (pre – irradiation)

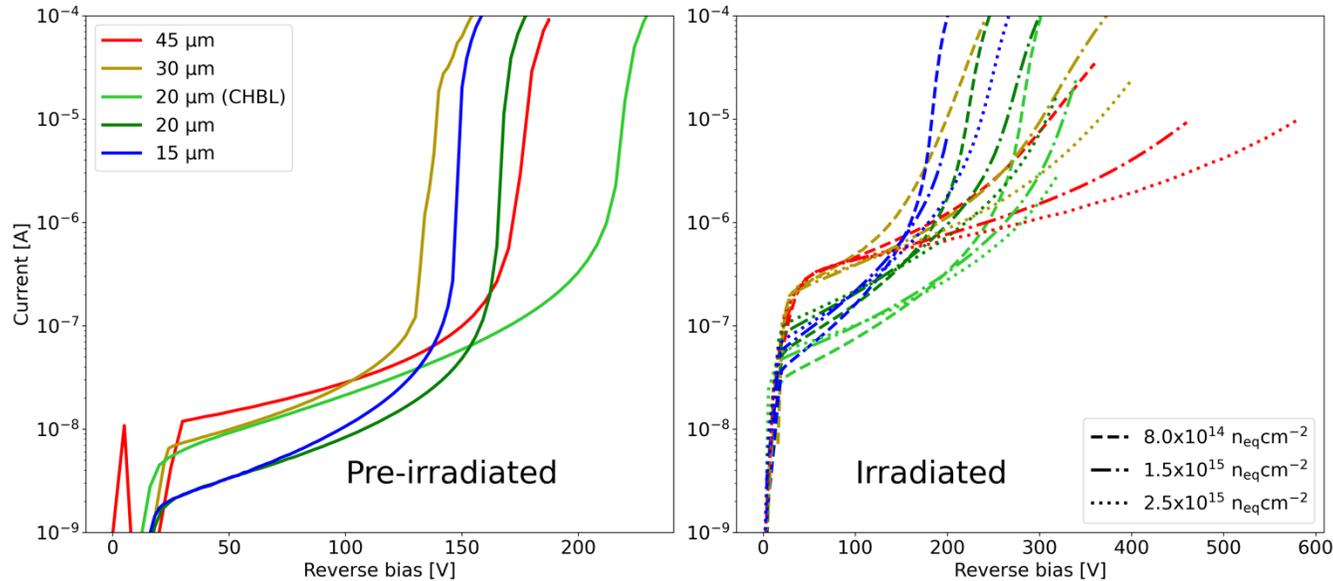

Pre-irradiated: +20°C

Irradiated: -20°C

○ Bias scan at -2V intervals up to breakdown

Pre-irradiation:

- Visible dark current due to the precence of the Carbon
- Small range of V_{gl} by design
- V_{BD} between 100 – 200 by gain layer design

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Irradiated:

- Decrease of the gain

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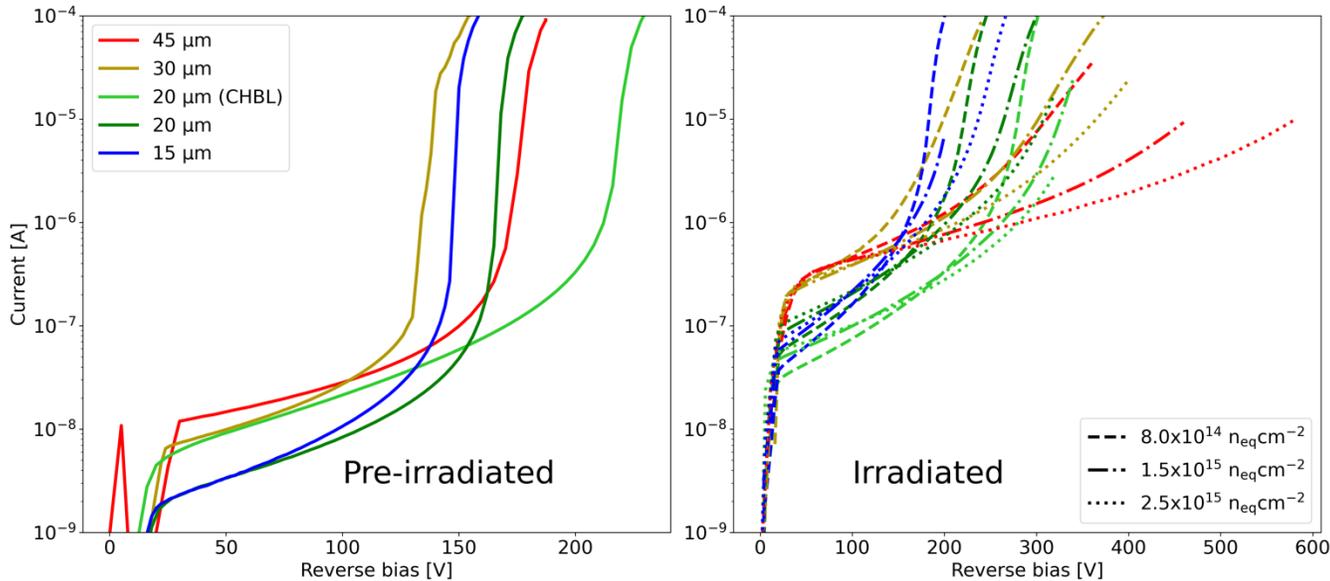- Bias scan at -2V intervals up to breakdown

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- Decrease of the gain
- Increase of V_{BD}

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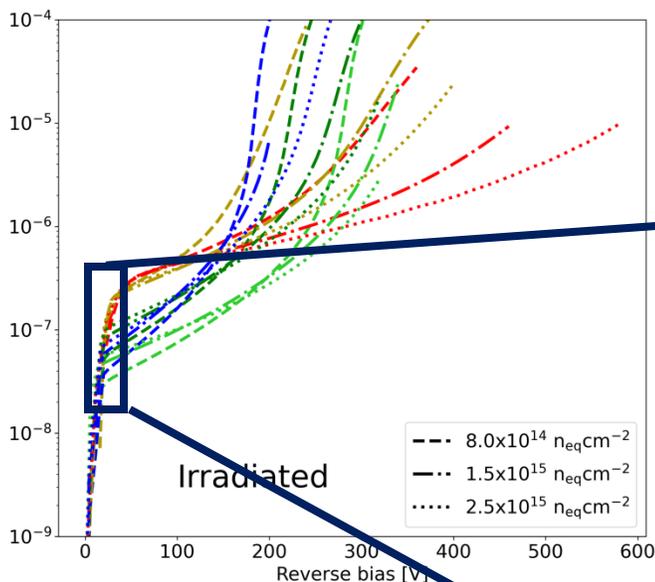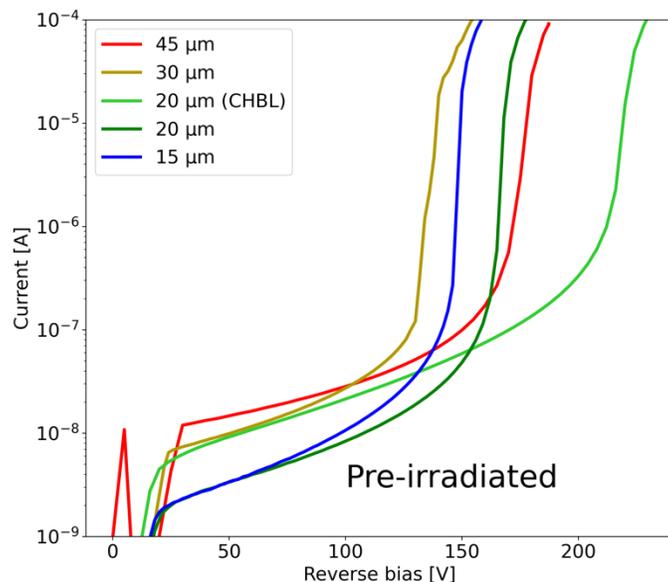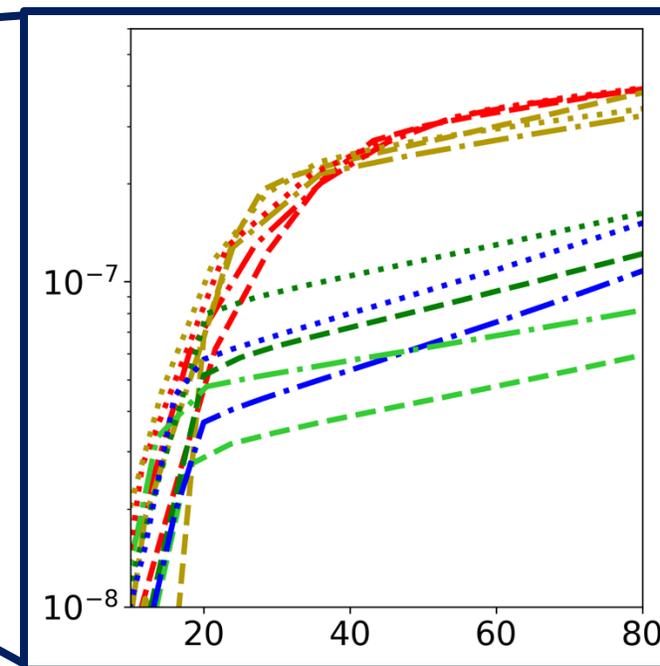- Bias scan at -2V intervals up to breakdown

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Irradiated:

- Decrease of the gain
- Increase of V_{BD}
- Dark current increasing with fluence according to
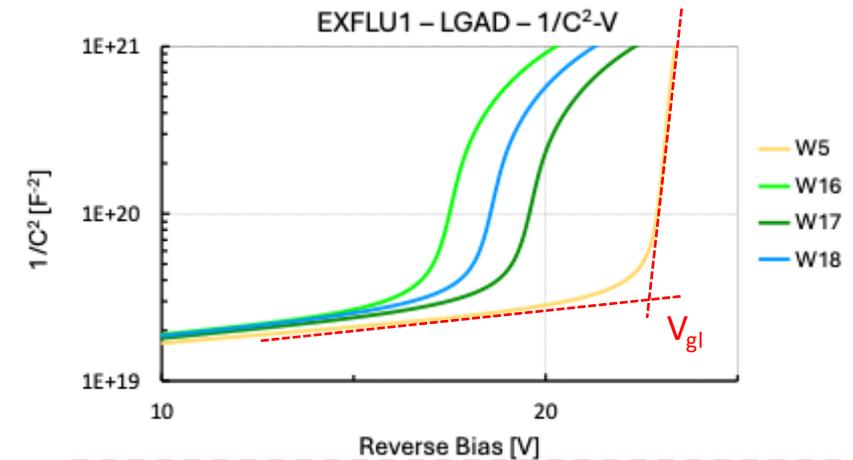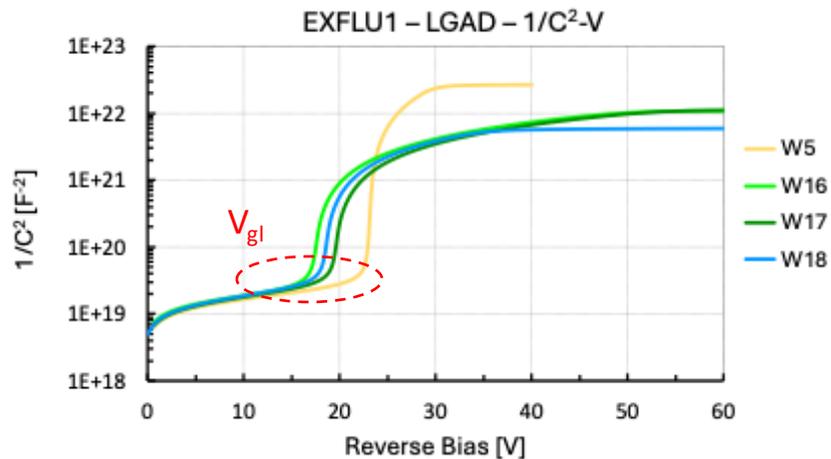
$$\alpha = \alpha_{Si_{nogain}}$$

EXFLU1 – CV characteristics (pre – irradiation)

(1-2kHz @ 20°C)

Wafer index	Thickness / µm	p+ dose /	C dose /	Diffusion	Bulk
1	45	1.14	1.0	CBL	very high ρ
5	30	1.12	1.0	CBL	high ρ
16	20	0.80	1.0	CHBL	low ρ
17	20	0.96	1.0	CBL	low ρ
18	15	0.94	1.0	CBL	low ρ

Three tasks:

1. Determine the depletion voltage V_{gl} of the sensor
2. Extract the doping profile
3. Infer the rate of degradation in V_{gl} due to irradiation

- Easier interpretation of the data by plotting C^{-2} vs V
- V_{gl} can be extracted with four different methods
  - **Earlier V_{gl} in CHBL than CBL**

(More on the V_{gl} extraction methods in *Radiation resistant LGAD design*, M. Ferrero et al.)

Example of V_{gl} excractred as x-value of intercept of two linear fits of the curve
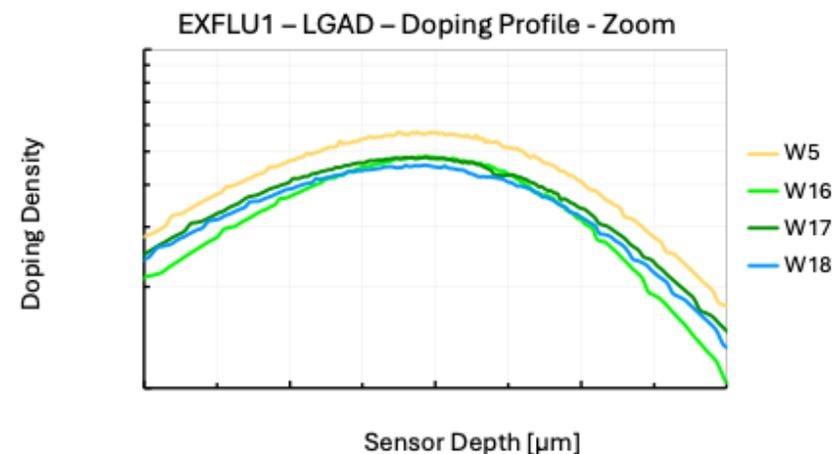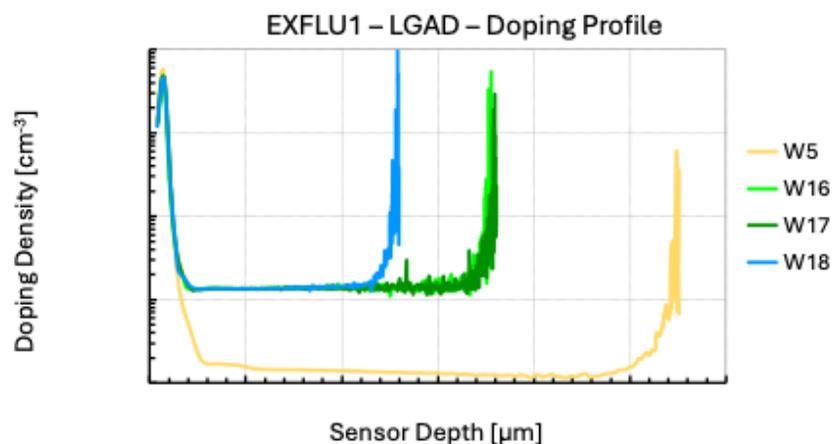
EXFLU1 – CV characteristics (pre – irradiation)

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EXFLU1 – LGAD – Doping Profile

Doping Density [cm^{-3}]
Sensor Depth [µm]

- W5
- W16
- W17
- W18

EXFLU1 – LGAD – Doping Profile - Zoom

Doping Density
Sensor Depth [µm]

- W5
- W16
- W17
- W18

TO NOTE:

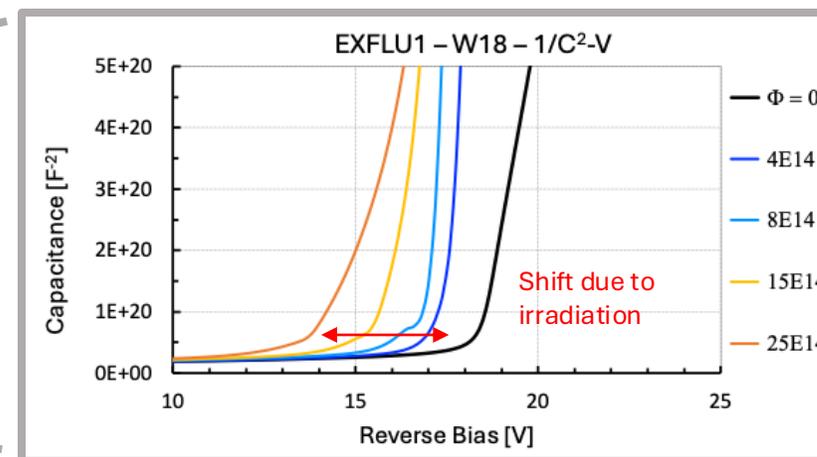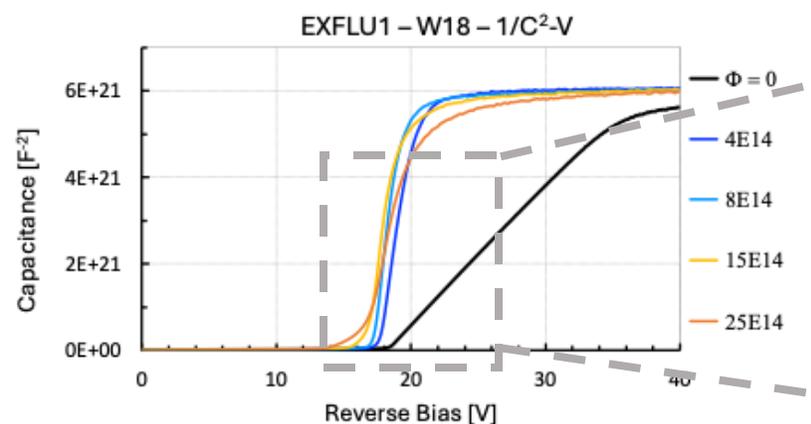Same doping density peak with different p$^+$ dose implant

EXFLU1 – CV characteristics (Irradiated)

(1-2kHz @ 20°C)

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- The slope of pre-irradiated ($\Phi=0$) sensor reflects the acceptor removal in the low-resistivity bulk
- Slight decrease of V_{gl} with fluence
  - Gain layer affected by the radiation → **Limited gain degradation (< 5V)** until $25 \times 10^{14}\ n_{eq}cm^{-2}$

EXFLU1 – Acceptor removal

Main damage mechanism - Acceptor Removal

Deactivation of the p^+-doping of the gain layer with irradiation according to

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

where c_A is the acceptor removal coefficient

c_A depends on the initial acceptor density, $p^+(0)$, and on the defect engineering of the gain layer atoms
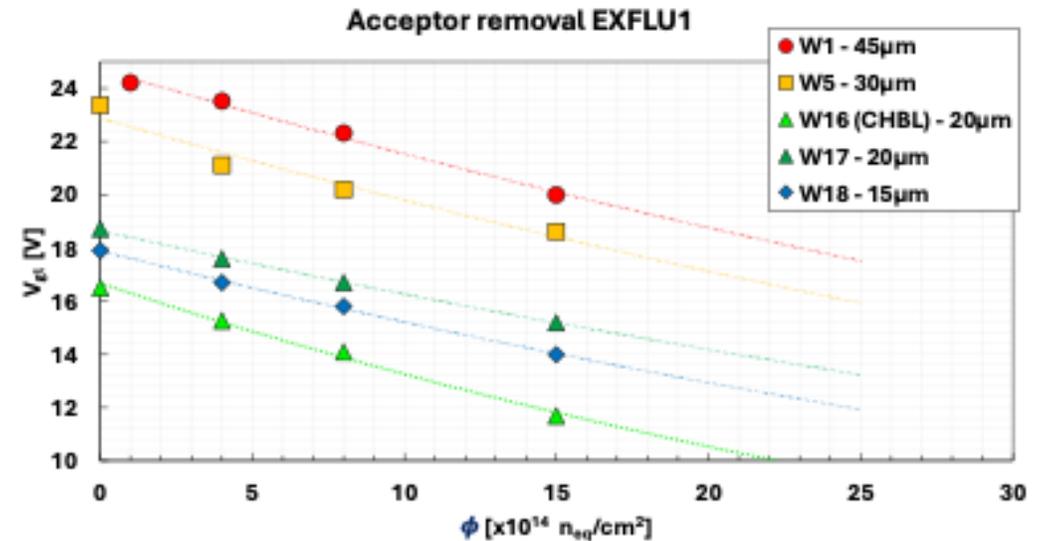[M. Ferrero et al., doi:10.1201/9781003131946]

V_{gl} linearly dependent on $p^+(\Phi)$ → c_A can be extracted from V_{gl}

$$\frac{V_{gl}(\Phi)}{V_{gl}(0)} = \frac{p^+(\Phi)}{p^+(0)} = e^{-c_A\Phi}$$

o   Exponential fit on the V_{gl} vs Φ curves

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Acceptor removal EXFLU1

- W1 - 45µm
- W5 - 30µm
- W16 (CHBL) - 20µm
- W17 - 20µm
- W18 - 15µm

EXFLU1 – Acceptor removal

Wafer [µm]	c [$\times 10^{-16}$ cm^{2}n$_{eq}^{-1}$]				Mean value	Characteristic fluence Φ_0 [$\times 10^{17}$ n$_{eq}$cm^{-2}]
	1st der	Linear fit	Fixed C	R_p		
W1* @ 45	0.95	1.04	-	1.08	1.02 ± 0.07	9.80 ± 0.67
W5 @ 30	1.36	1.20	1.12	1.21	1.22 ± 0.10	8.20 ± 0.67
W16** @ 20	2.07	2.09	2.07	2.21	2.11 ± 0.07	4.74 ± 0.16
W17 @ 20	1.24	1.21	1.37	1.34	1.29 ± 0.08	7.75 ± 0.48
W18 @ 15	1.13	1.06	1.35	1.52	1.27 ± 0.21	7.87 ± 1.30

c_A extracted values:

➢ EXFLU1 batch shows the best c_A value among all the FBK LGAD technologies produced so far
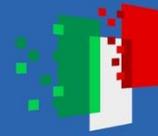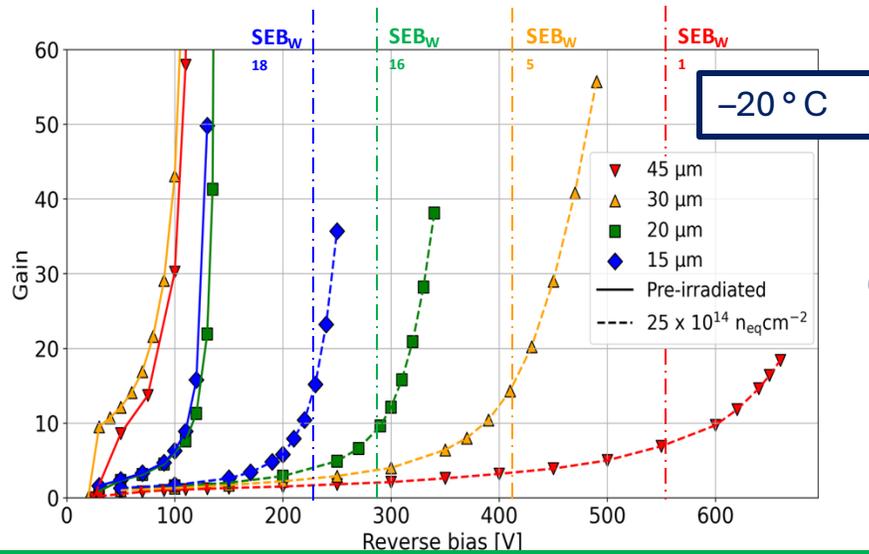➢ Gain in CBL less deactivated than in CHBL

EXFLU1 – Acceptor removal

No pre-irradiated CV for W1
**CHBL diffusion*

Wafer [μm]	Mean value	Characteristic fluence Φ_0 [x 10^{17} $n_{eq}cm^{-2}$]
W1* @ 45	1.02 ± 0.07	9.80 ± 0.67
W5 @ 30	1.22 ± 0.10	8.20 ± 0.67
W16** @ 20	2.11 ± 0.07	4.74 ± 0.16
W17 @ 20	1.29 ± 0.08	7.75 ± 0.48
W18 @ 15	1.27 ± 0.21	7.87 ± 1.30

Plot legend:
- No Carbon
- CHBL / CHBH (0.4, 2, 3, 5)
- CHBL / CHBH (0.8 - 1)
- CBL / CBH (0.6 - 1)
- ▲ Shallow Boron + Carbon 0.8C - 1C (CHBL)
- ▼ Deep Boron + Carbon 0.6C - 1C (CBL/CBH)
- ◇ Shallow + Carbon 1 (CBL) - EXFLU1
- ■ Shallow + Carbon 1 (CHBL) - EXFLU1
- ◆ 45 μm
- ◆ 30 μm
- ■ 20 μm (CHBL)
- ◆ 20 μm
- ◆ 15 μm

Axes: c_A [cm^2] vs Initial acceptor density [a.u.]

c_A extracted values:
➢ EXFLU1 batch shows the best c_A value among all the FBK LGAD technologies produced so far
➢ Gain in CBL less deactivated than in CHBL
  o Good agreement with parametrisations from previous FBK R&D

EXFLU1 – Gain profile (TCT)

Gain profile using a **Transient Current Technique (TCT)**

- ❑ TCT performed inside a black box at -10°C
- ❑ NIR laser at ~4 MIPs incident on LGAD-PIN
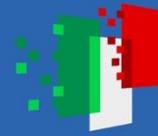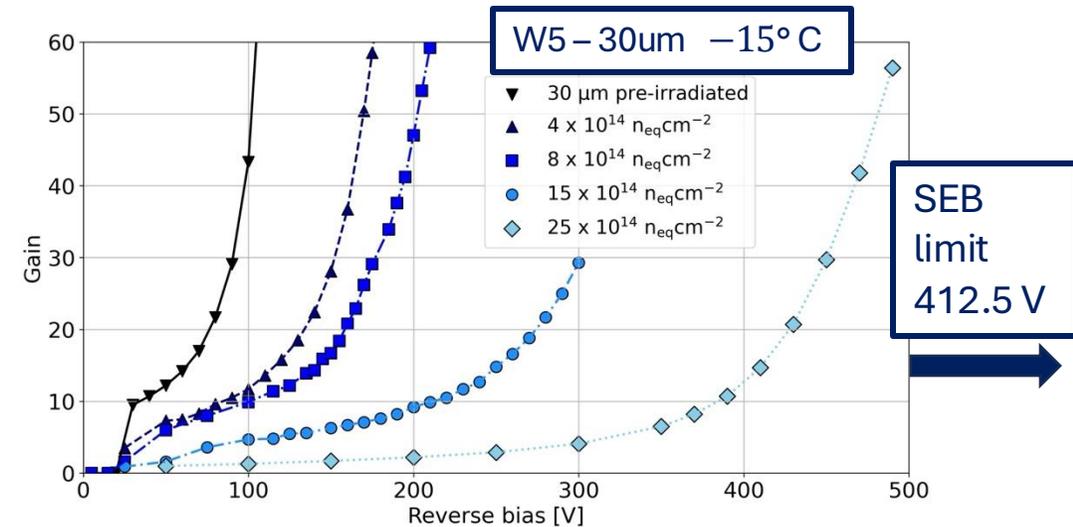- ❑ Measure signal area for increasing bias

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$$Gain = \frac{A_{LGAD}}{<A_{PIN}>_{No\ gain}}$$

Key point:
Still gain until a fluence of 25x10^{14} n$_{eq}$/cm^2

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$$Gain = \frac{A_{LGAD}}{<A_{PIN}>_{No\ gain}}$$

W5 – 30um –15° C

SEB limit 412.5 V

(More about SEB in the interesting M. Ferrero's talk at 43rd RD50)

Key point:
Still gain until a fluence of 25x10^{14} n$_{eq}$/cm^2

EXFLU1 – Guard ring design

(For further information, have a look to the amazing poster by T. Croci et al.)

An optimized guard ring design is essential to control the electric field and reduce the noise impact in LGAD sensors.
16 different guard rings on PIN sensors , **optimised for thin substrates and extreme fluences**
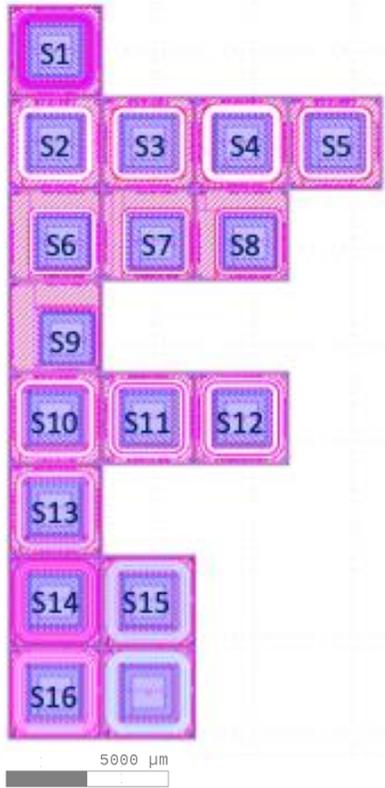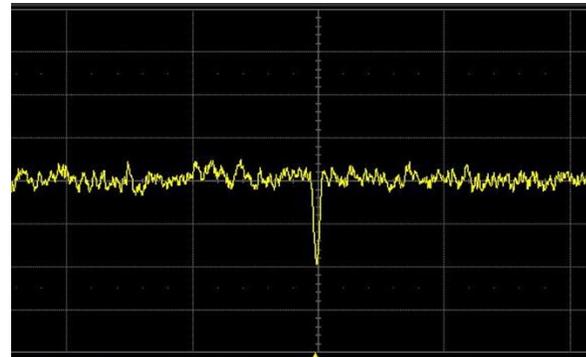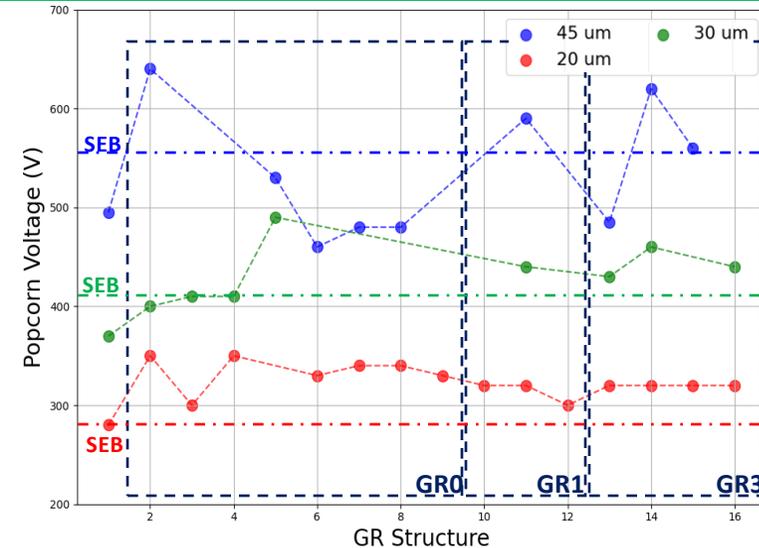

➢ **standard design** used in previous UFSD batches

➢ **0 GR floating**, different edge size
   o different size of the 'empty' region
   o different size of the edge region: 500, 300 & 200 μm

➢ **1 GR floating**, different GR positions

➢ **3 GR floating** with different design

EXFLU1 – Guard ring design

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An optimized guard ring design is essential to control the electric field and reduce the noise impact in LGAD sensors.
16 different guard rings on PIN sensors , **optimised for thin substrates and extreme fluences**

PN characterised by **sudden peaks** in the output signal which can exhibit **significant amplitude** in absence of external stimuli

Not all structures under investigation show popcorn noise
❑ S1 (standard design) worst GR design, so far

Popcorn noise: current spikes that degrade signal stability and timing resolution.

❑ Almost all the GR structures in 20-30 um show popcorn noise close to the breakdown voltage and beyond the SEB limit, before and after irradiation.

EXFLU1 – Beam test at DESY

(More in the wonderful M. Ferrero's talk at 20th TREDI)

Setup:

➢ Electron beam: **E = 4 GeV**

➢ DAQ based on Lecroy oscilloscope (**2GHz - 10 GSa/s**)

➢ Time reference: Photonis MCP whit **t_{res} ~5 ps**

➢ Trigger: LGAD sensor (thickness 45µm; surface: 13 mm^2)

➢ Read-out chain: single channel Santa Cruz Board + 20dB amplifier 97% geometric efficiency between trigger and MCP
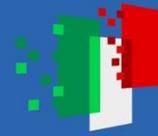
Cold Box for Irradiated samples:

➢ Cooling by dry ice

➢ Monitoring of Temperature with Arduino

    o Temperature range between -50 and -35°C (not controlled temperature)

Production	Wafer	Thickness [µm]	Gain implant Diffusion	p$^+$ Dose	C Dose	Sensor capacitance [pF]
EXFLU1	W3	45	CBL	1.14	1	3.9
EXFLU0	W6	35	CHBL	0.94	1	5
EXFLU1	W5	30	CBL	1.12	1	2.2
EXFLU0	W5	25	CHBL	0.94	1	4.1
EXFLU1	W16	20	CHBL	0.80	1	3.3
EXFLU1	W17	20	CBL	0.96	1	3.3

FOCUS

30 µm-thick (0.6 mm^2) sensors tested post-irradiation (4, 8, 15, and 25x10^{14} n_{eq}/cm^2)

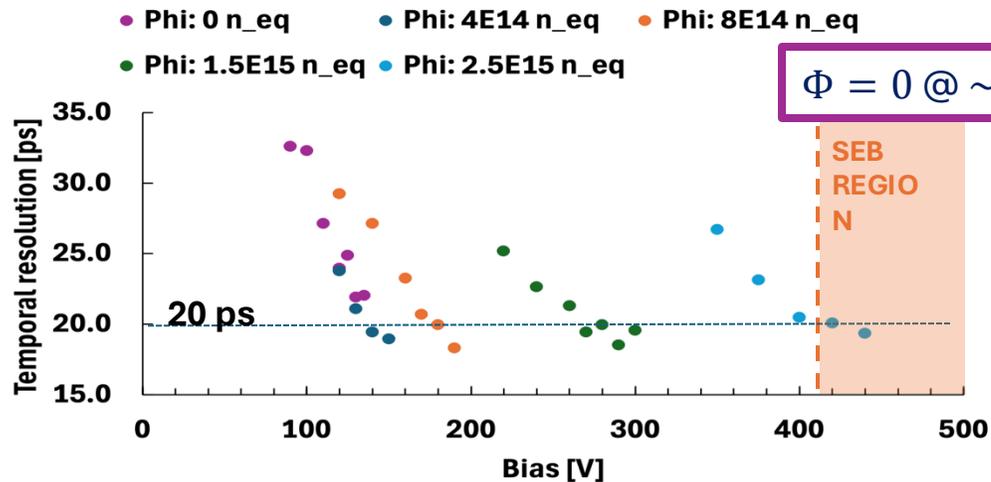# EXFLU1 – Timing resolution of irradiated 30 µm LGADs

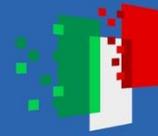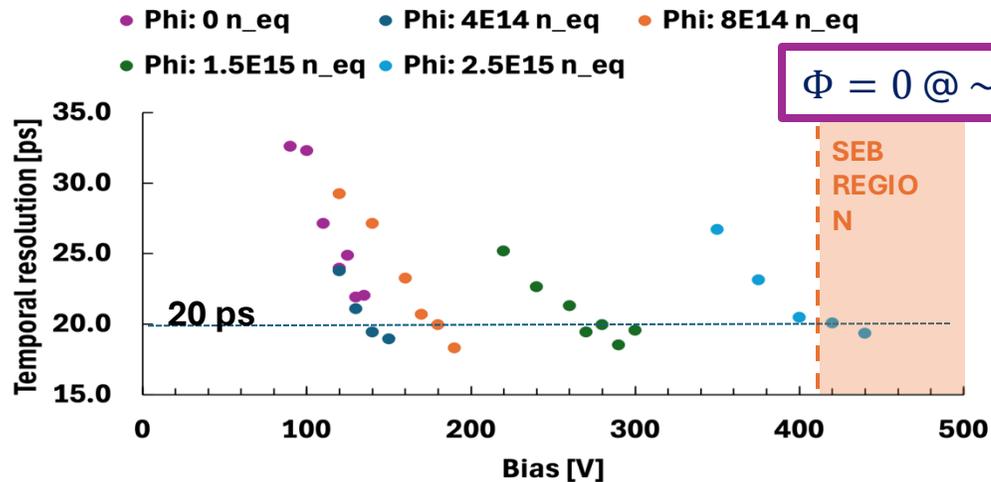The sensors have been measured in a range of temperatures between -35°C and -50°C.

The wide temperature range affects the relationship between gain and timing resolution with bias

Analysis:

➤ Constant Fraction Discriminator method

➤ CFD$_{th}$ of 30% is used for DUTs and MCP

➤ MCP contribution: **5 ps**

$$\sigma_t(DUT) = \sqrt{\sigma_t^2(MCP; DUT) - \sigma_t^2(MCP)}$$

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$$\sigma_t(DUT) = \sqrt{\sigma_t^2(MCP; DUT) - \sigma_t^2(MCP)}$$

- Phi: 0 n_eq
- Phi: 4E14 n_eq
- Phi: 8E14 n_eq
- Phi: 1.5E15 n_eq
- Phi: 2.5E15 n_eq

$\Phi = 0$ @ ~18 °C

SEB REGION

20 ps

ϕ [n_{eq}/cm^2]	σ_t [ps]
4E14	19.0
8E14	18.3
15E14	18.5
25E14	20.5

Irradiated 30 µm-thick LGADs

➢ 20 ps of resolution before the SEB ($E_{th-30µm}$~ **13.5 V/µm**), up to a fluence of 25×10^{14} n_{eq}/cm^2

max σ_t before SEB

EXFLU1 – Take-away points

➢ **EXFLU1 batch** designed to improve timing resolution and radiation tolerance
  - o Different thickness explored
  - o CHBL diffusion for 20 um sensor to compare with CBL
  - o 16 different guard ring design
➢ Characterization
  - o I-V
    - ▪ Decrease of the gain and iIncrease of V_{BD}
  - o C-V
    - ▪ Peak of doping density at the same depth with different p+ dose implants
    - ▪ Slight decrease of V_{gl} with fluence and earlier V_{gl} in CHBL than CBL
  - o Acceptor removal
    - ▪ **Best c_A value** among all the FBK LGAD technologies produced so far
    - ▪ Gain in CBL less deactivated than in CHBL
  - o TCT
    - ▪ After 25×10^{14} n_{eq}/cm^2, **Gain ~ 10 achieved**
➢ Beam test at DESY
  - o Sensors with different technology and thickness tested
  - o **20 ps of resolution** before the SEB up to a fluence of **25×10^{14} n_{eq}/cm^2** on 30um thick LGADs

EXFLU1 – Take-away points

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   - Different thickness explored
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     - **Best c_A value** among all the FBK LGAD technologies produced so far
     - Gain in CBL less deactivated than in CHBL
   - TCT
     - After $25 \times 10^{14}\, n_{eq}/cm^2$, **Gain $\sim$ 10 achieved**
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   - Sensors with different technology and thickness tested
   - **20 ps of resolution** before the SEB up to a fluence of **$25 \times 10^{14}\, n_{eq}/cm^2$** on 30um thick LGADs

EXFLU1 – Take-away points

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ACKNOWLEDGEMENTS

BACKUP

EXFLU1 – CV characteristics (Irradiated)

Three tasks from the capacitance measurements:

1. Extract the doping profile
2. Determine the depletion voltage V_{gl} of the sensor
3. Infer the rate of degradation in V_{gl} due to irradiation

Wafer index	Thickness / μm	p⁺ dose /	C dose /	Diffusion	Bulk
1	45	1.14	1.0	CBL	very high ρ
5	30	1.12	1.0	CBL	high ρ
16	20	0.80	1.0	CHBL	low ρ
17	20	0.96	1.0	CBL	low ρ
18	15	0.94	1.0	CBL	low ρ

EXFLU1 – W18 – C-V

EXFLU1 – W18 – C-V - Zoom

- Slight decrease of V_{gl} with fluence
  - Gain layer affected by the radiation → **Gain degradation**

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EXFLU1 – SEB

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

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

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

SEB consequence:
→ Impossible to operate irradiated thin sensors above the critical electric field (E_{SEB})
→ The E_{SEB} value is higher for thinner sensors

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

Minimum quantity of charge to reach 25 ps and 30 ps of resolution vs sensors thickness

Localized melt and vaporization of silicon

SEM picture   [SSP group,UniTO]

EXFLU1 – Cold probe station

Measure bias voltage across the sensor

- Pad probe to backplate voltage measured
- Probe to guard ring grounded

Perform IV and CV in the probe station

- IV performed at 20°C, 0°C, -20°C
    - Bias scan at -2V intervals up to breakdown
- CV performed at 20°C
    - Determine optimal bias frequency from peak in Cf profile for each sensor
    - Typically between 1-2kHz with bias between 2-25V
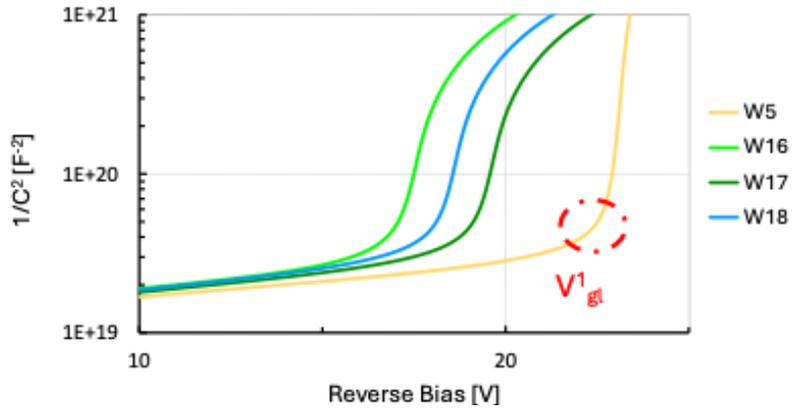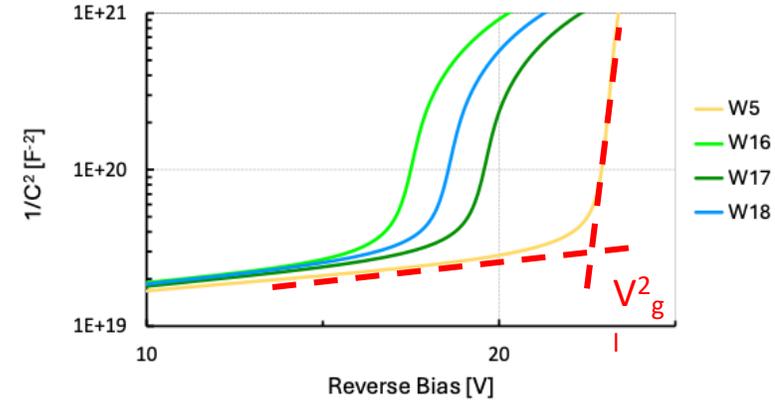   - Bias scan at -0.2V intervals

MPI TS200-SE
Thermal chuck -40/+300°C

EXFLU1 – Extraction methods of V_{gl}

1. First surge in gradient (1st derivative)

2. Linear fit

3. Fixed Capacitance threshold

4. Sharp decrease of R_p

Radiation resistant LGAD design, M. Ferrero et al.)
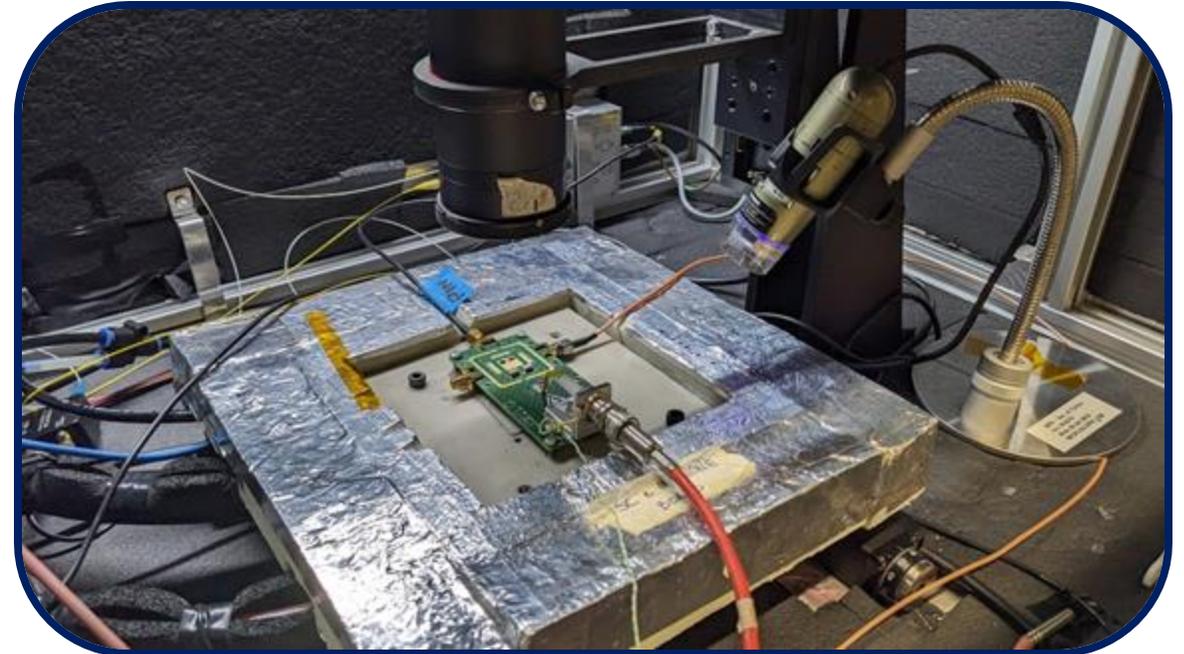
EXFLU1 – TCT Setup
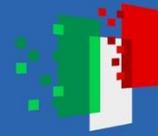
Using LGAD-PIN as measured for different fluences
- **PIN measured at 25 V intervals**
- **LGAD measured at 5-10 V intervals near breakdown**

Use Transient Current Technique setup at INFN Torino
- **Scan PIN and LGAD at -10°C**
- **Pulsed laser incident on optical window @ ~4 MIPs**
  - **Set intensity, increment V**

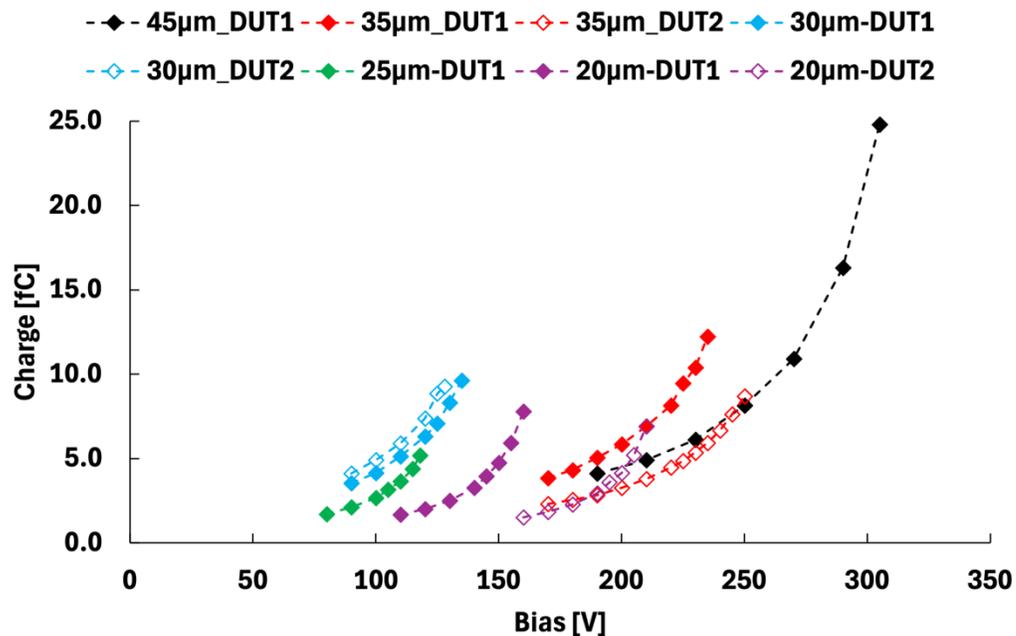**Measure effective signal area and gain as functions of V$_{bias}$**
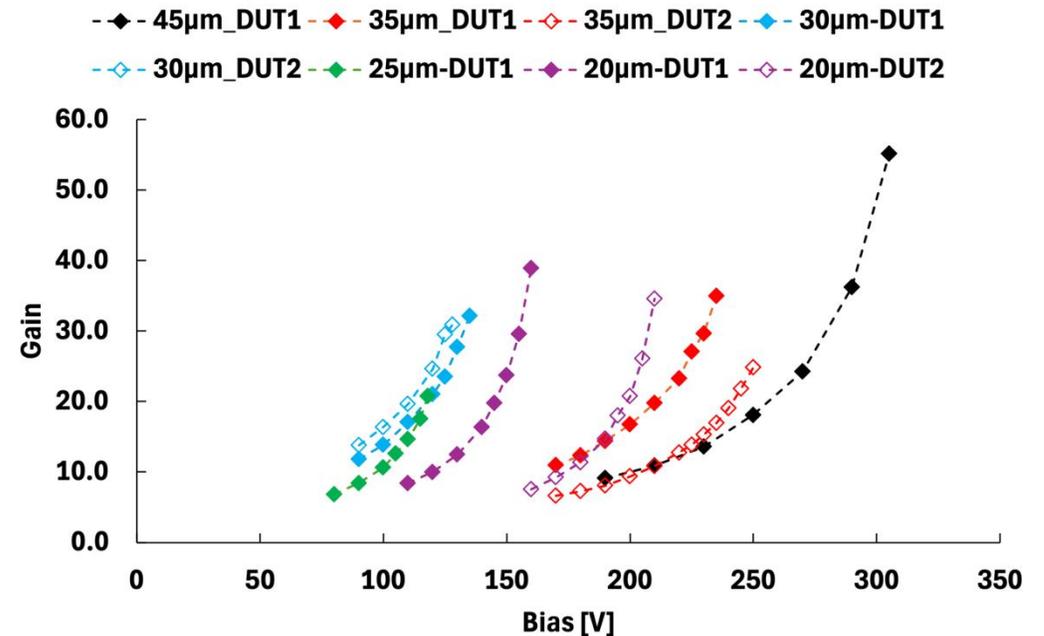
EXFLU1 – Collected charge and gain

Charge-Voltage characteristics

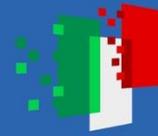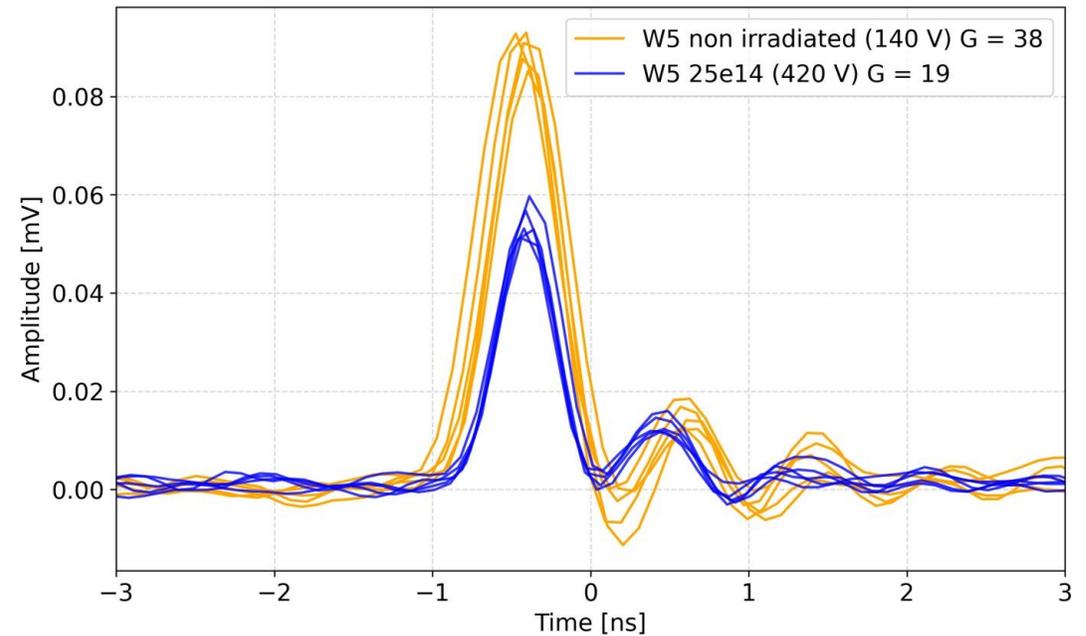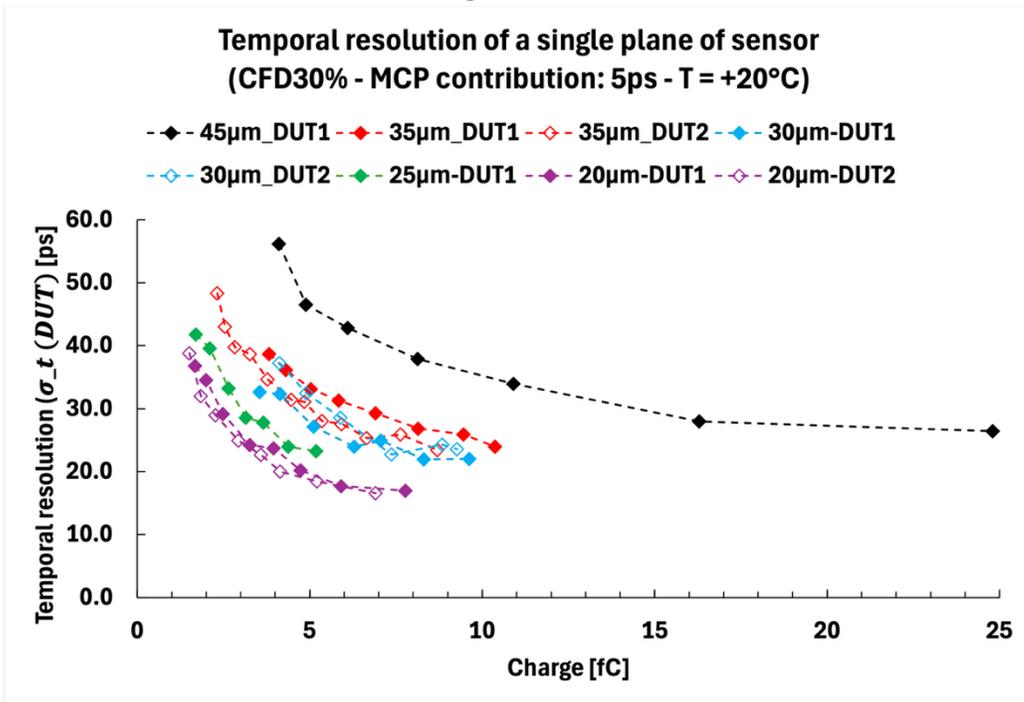**Gain-Voltage characteristics**

➢ The delivered charge in sensors with thicknesses between 20 and 35 µm varies between 2 and 15 fC
➢ The gain is in a range of 5-35 for almost all sensors
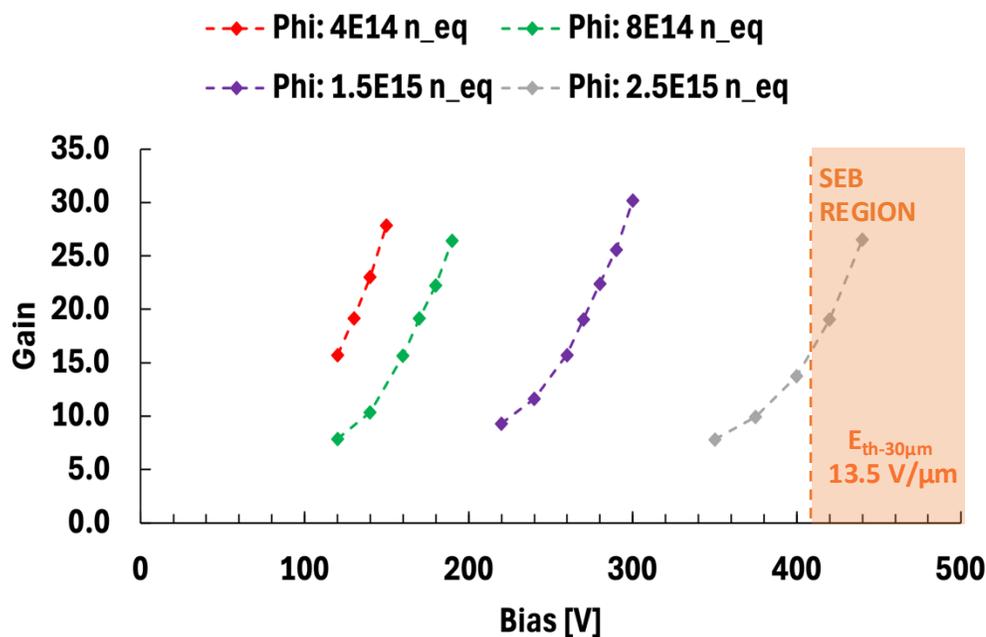
EXFLU1 – Collected charge

Analysis:

➤ Constant Fraction Discriminator method

➤ CFD_{th} of 30% is used for DUTs and MCP

➤ MCP contribution: **5 ps**

Temporal resolution of a single plane of sensor (CFD30% - MCP contribution: 5ps - T = +20°C)

EXFLU1 – Gain of irradiated 30 µm LGADs

The sensors have been measured in a range of temperatures between -35°C and -50°C, this wide range affects the relationship between gain and timing resolution with bias

Gain-V curves vs Irradiation fluence

Irradiated 30 µm-thick LGADs

➢ provide gain/charge in range [7/2fC, 30/9fC] up to an irradiation fluence of 15×10^{14} n_{eq}/cm^2

➢ provide gain/charge in range [7/2fC, 15/4.5fC] up to an irradiation fluence of 25×10^{14} n_{eq}/cm^2

$$Gain = \frac{Q}{0.3\,fC}$$