Characterisation of the FBK EXFLU1 thin sensors with gain at high fluence

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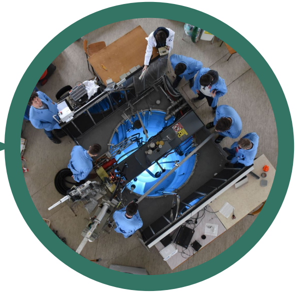
Timeline of the FBK EXFLU1 thin sensors

Perugia simulate thin sensor designs for the **EXFLU1** production with a gain layer implant (LGAD)

Sensors synthesised with implant according to **sensor thickness**, doping profile, pad design

Torino perform measurements (IV, CV, Cf) on the sensors prior to irradiation



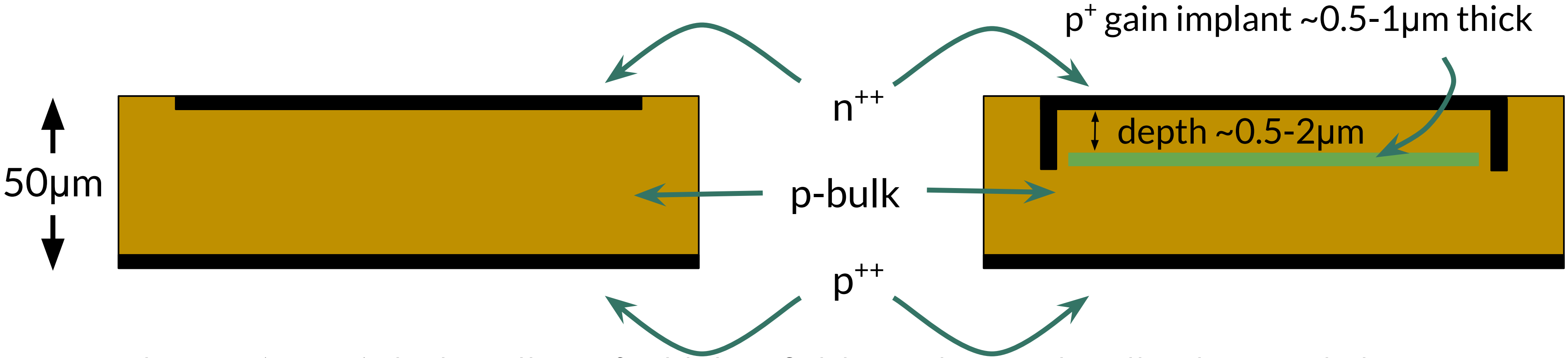
Sent to Ljubljana for irradiation at various fluences in their research reactor

Timeline of the FBK EXFLU1 thin sensors

Measurements repeated on the now-irradiated sensors to:

- Study the effects of irradiation on thin sensor **IV profiles**
- Study the **gain degradation** in LGADs

PIN vs LGAD design



Low-Gain APD (LGAD) design allows for high E-field ~300kV/cm localised to a gain layer

- p^+-doped implant (B, Ga) near *pn* junction depleted before bulk
  - On depletion, avalanche activated
  - High E-field region confined away from periphery
- Implant acceptor density ~10^{16} atoms/cm^3

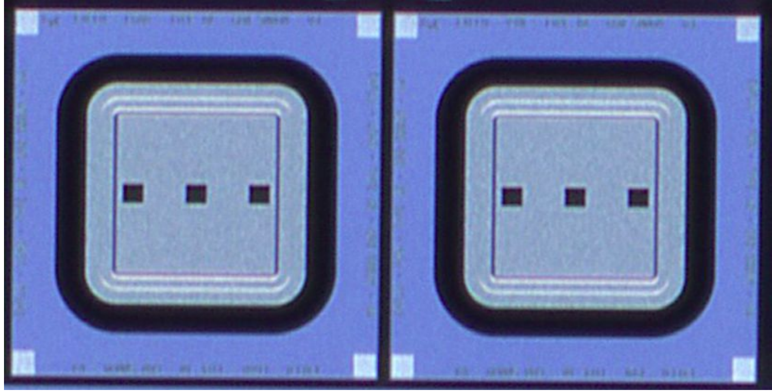
LGAD design offers segmented low-noise, low-leakage gain ~10-30

Standard EXFLU1 LGAD specifications

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

Wafers irradiated between $\Phi = 1 \times 10^{14}$ and $5 \times 10^{15}\ n_{eq}cm^{-2}$

Studies to perform

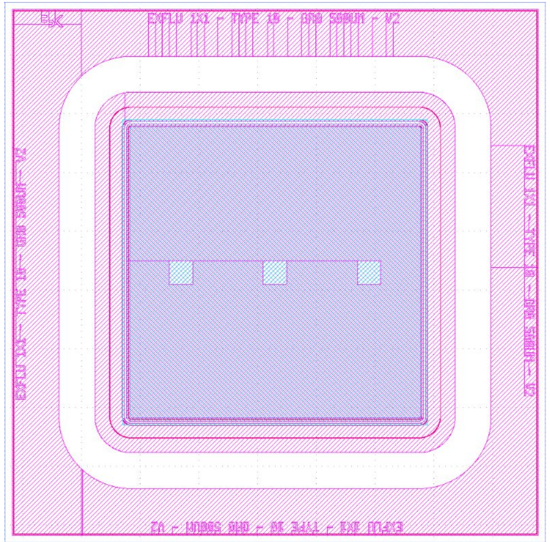


IV characteristics

- Perform scans up to depletion for various temperatures

CV characteristics

- Determine the **depletion voltage** of the gain layer, V_{gl}
    - Bulk breakdown point also calculable
- Infer the **rate of degradation** in V_{gl} due to irradiation



Gain profile

- Obtain **gain profile** of the sensor to compare at various fluences
    - Compare LGAD to PIN characteristics
    - Compare across the various LGAD designs

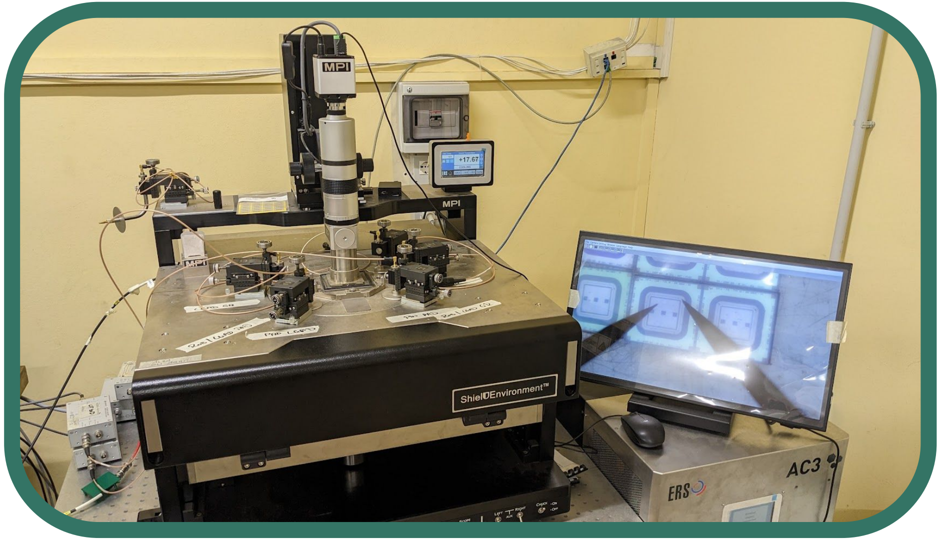
Cold probe station

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

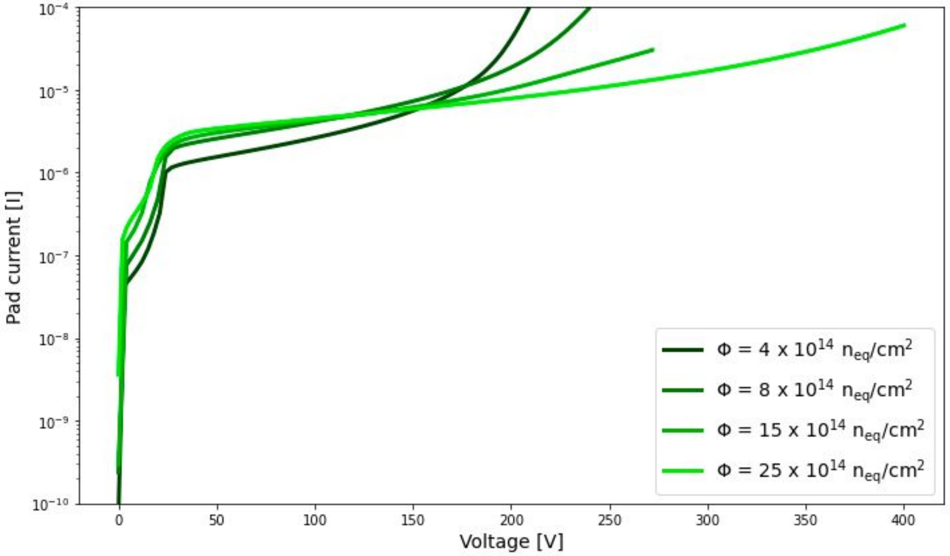
Thermal chuck -40/+300°C

IV | W5 (CBL) LGAD

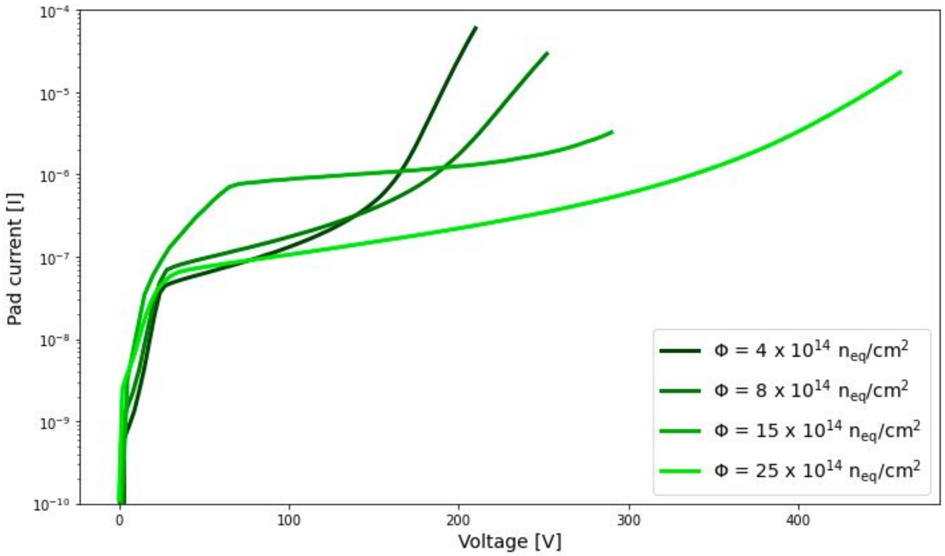
Wafer index	Thickness / μm	p^{+} dose /
1	45	1.14
5	30	1.12
16	20	0.80
17	20	0.96
18	15	0.94

Log-scale IV characteristics for LGAD sensors at 20˚C and -20˚C

T = 20°C



T = -20°C

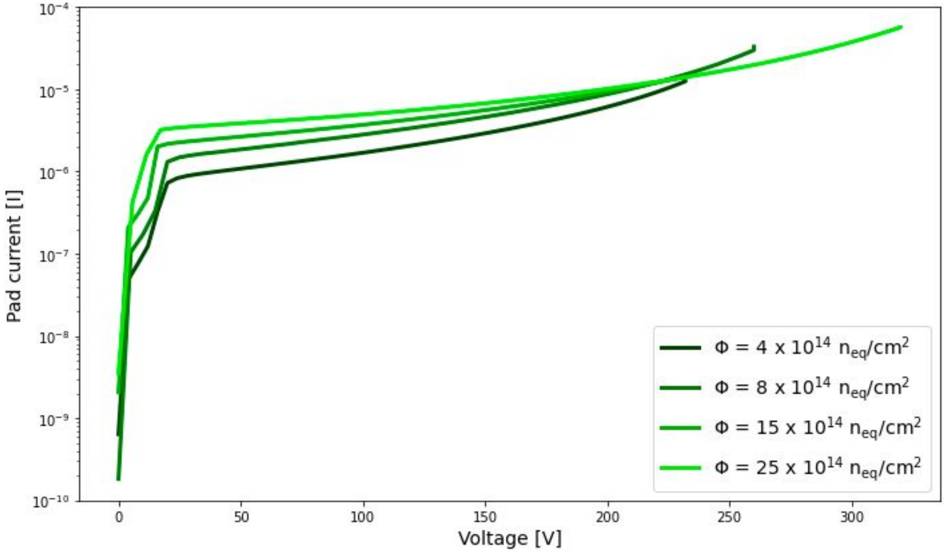


IV | W16 (CHBL) LGAD

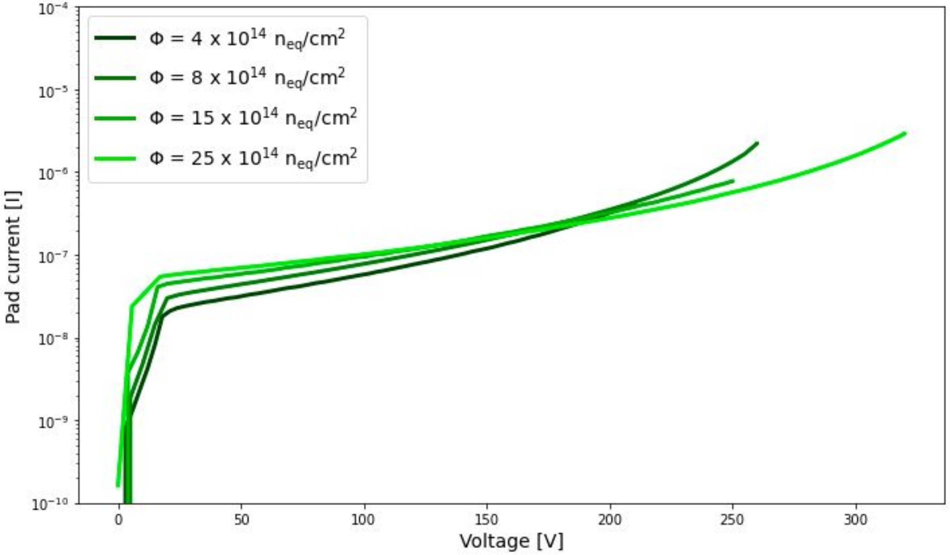
Wafer index	Thickness / µm	p⁺ dose /
1	45	1.14
5	30	1.12
16	20	0.80
17	20	0.96
18	15	0.94

Log-scale IV characteristics for LGAD sensors at 20˚C and -20˚C

T = 20°C



T = -20°C

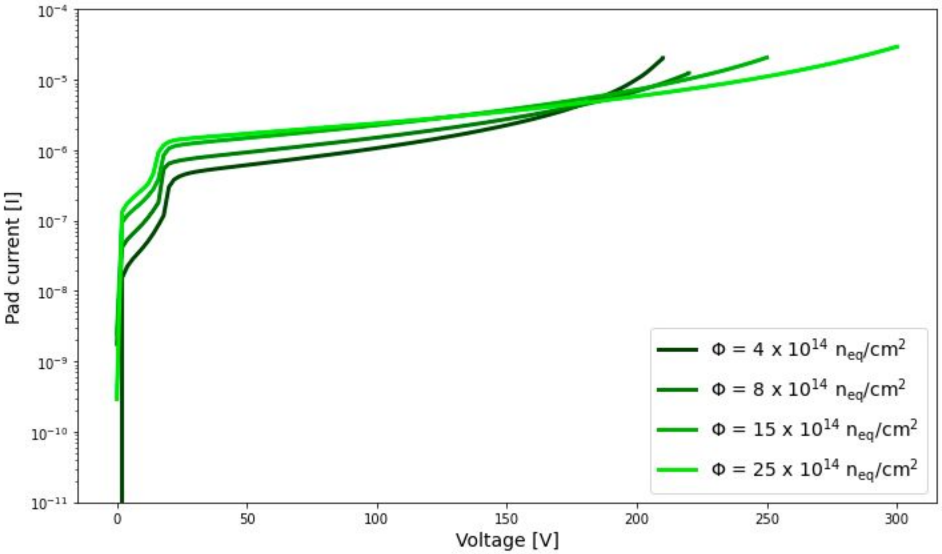


IV | W17 (CBL) LGAD

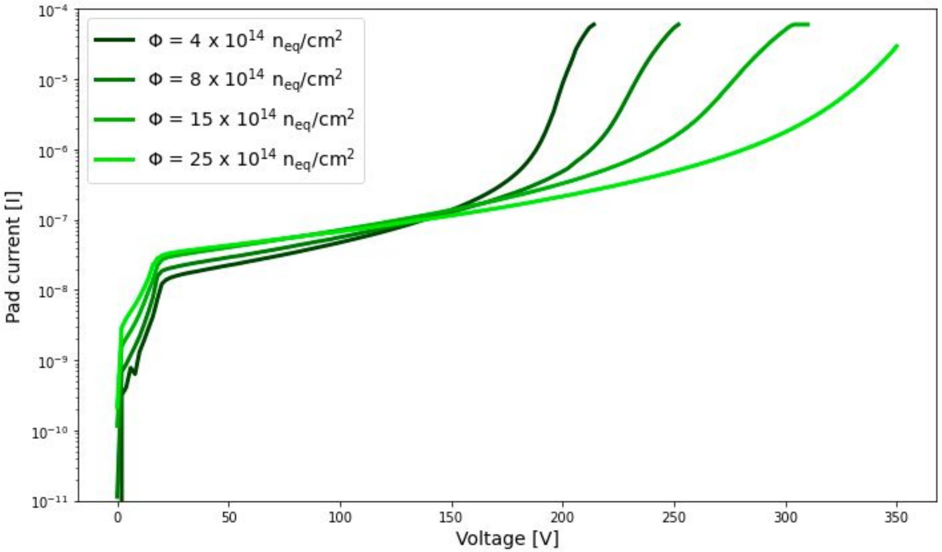
Wafer index	Thickness / µm	p^+ dose /
1	45	1.14
5	30	1.12
16	20	0.80
17	20	0.96
18	15	0.94

Log-scale IV characteristics for LGAD sensors at 20˚C and -20˚C

T = 20°C



T = -20°C

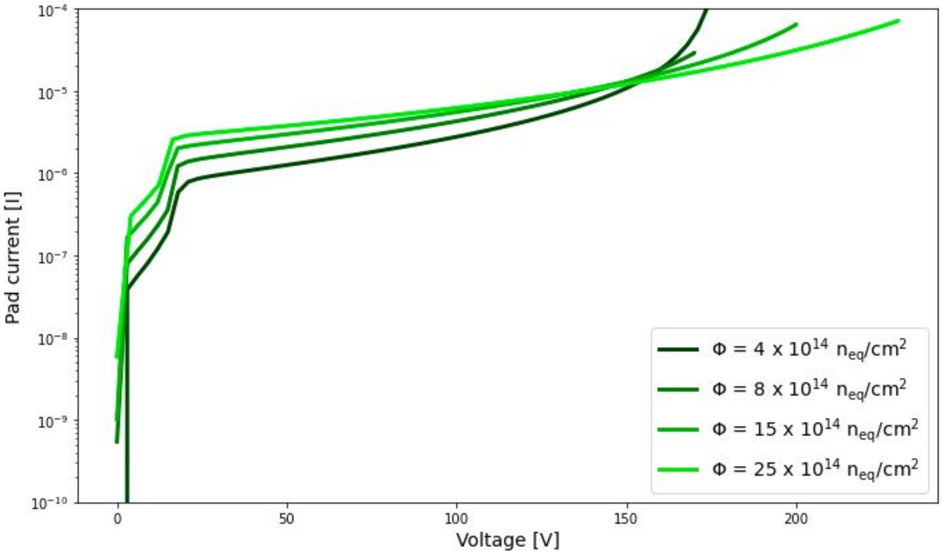


IV | W18 (CBL) LGAD

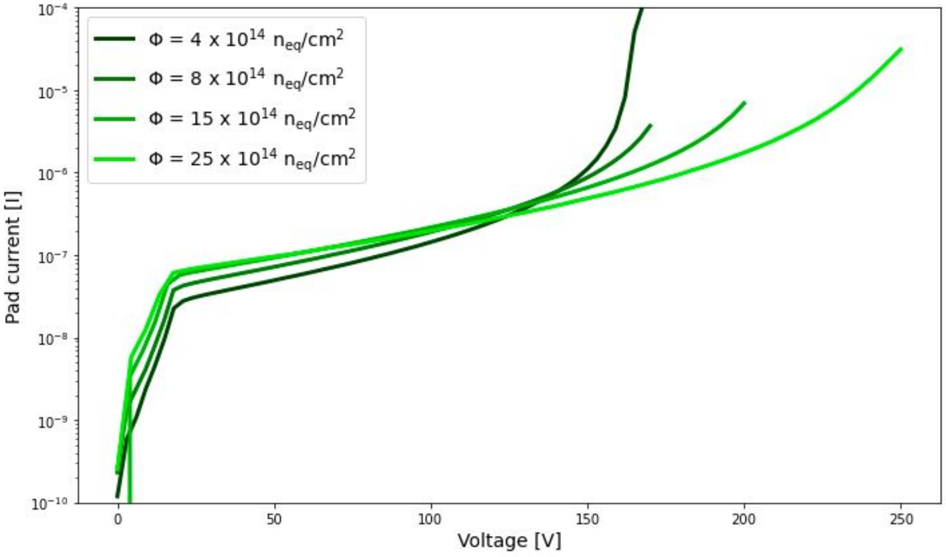
Wafer index	Thickness / µm	p^{+} dose /
1	45	1.14
5	30	1.12
16	20	0.80
17	20	0.96
18	15	0.94

Log-scale IV characteristics for LGAD sensors at 20˚C and -20˚C

T = 20°C

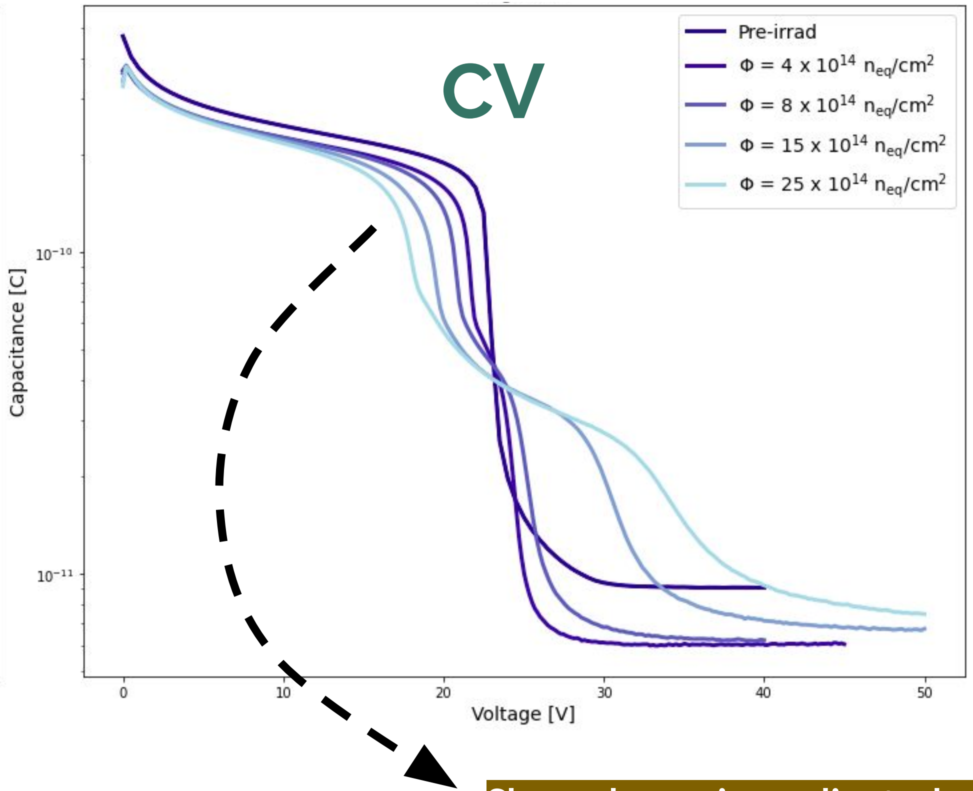


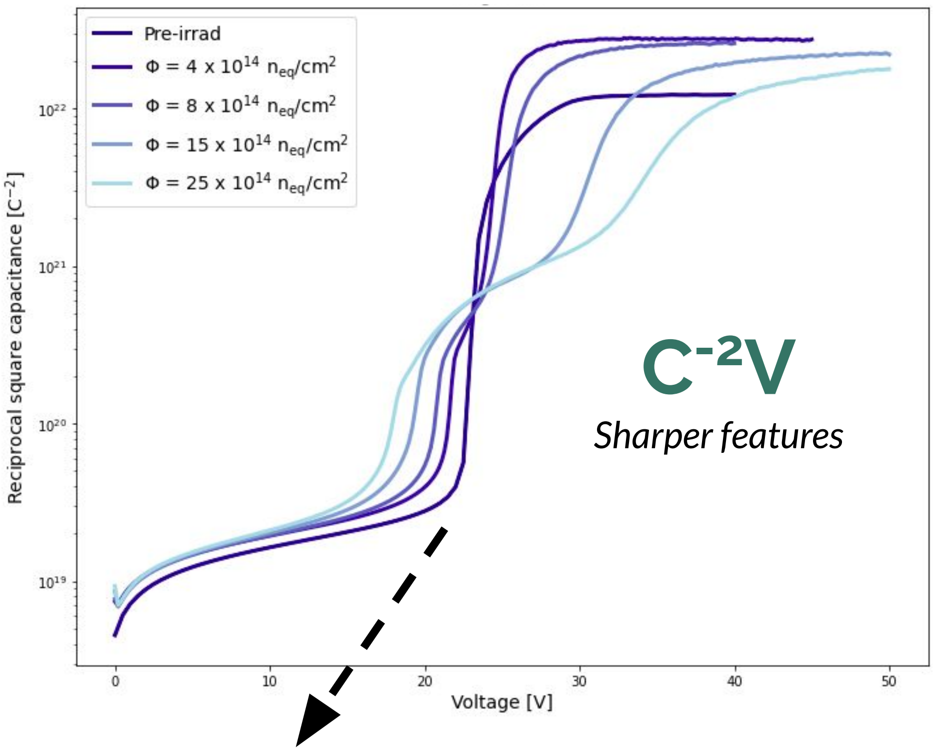
T = -20°C



CV, C^{-2}V curves | W5

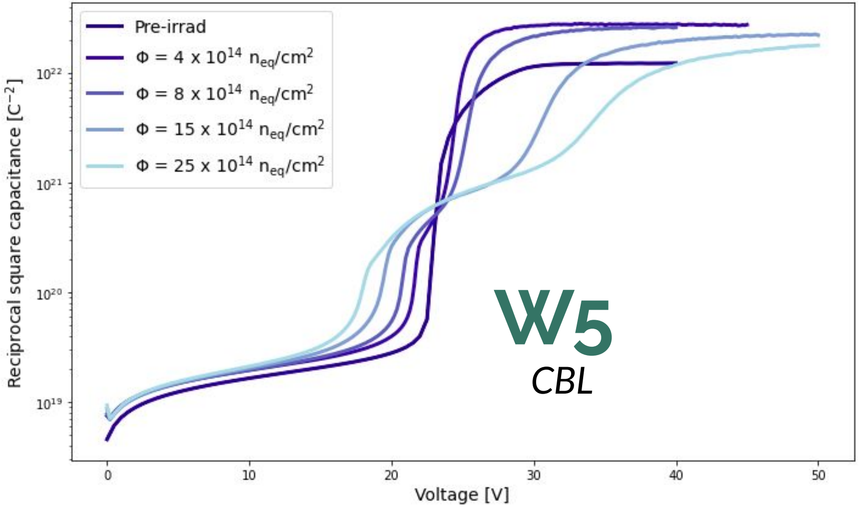
1-2kHz @ 20°C

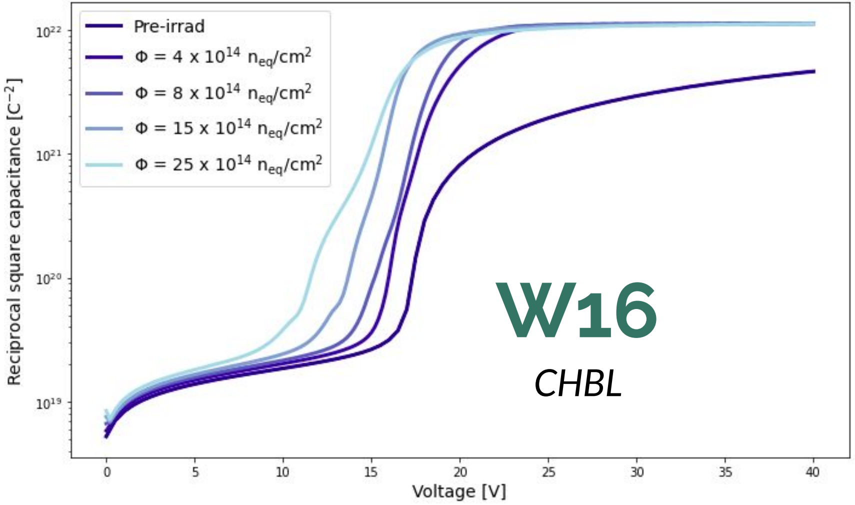


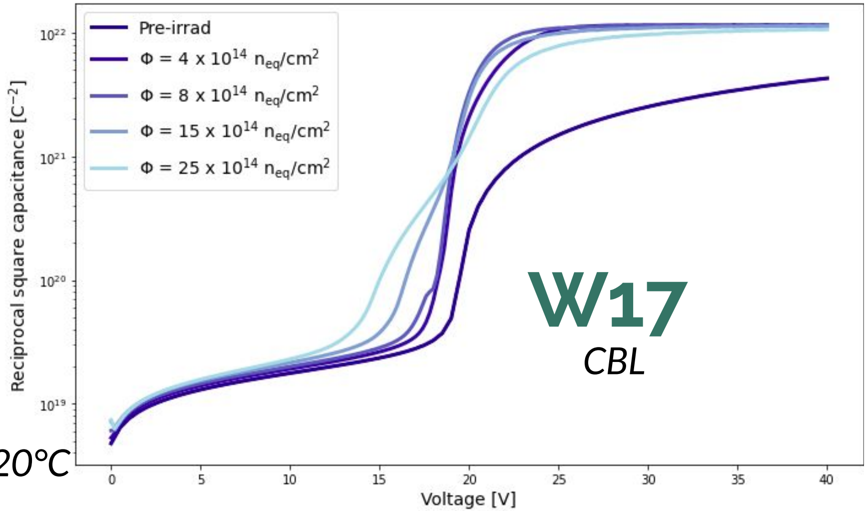


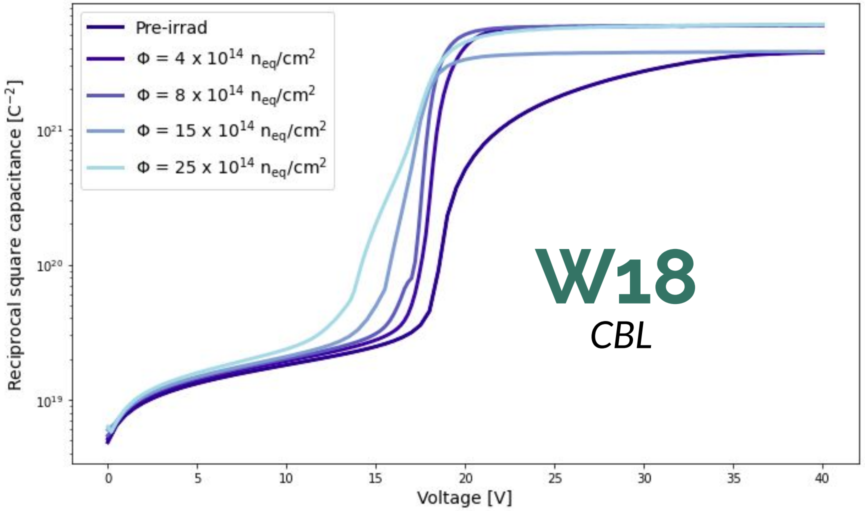
Sharp change in gradient ≈ breakdown of gain layer

$C^{-2}V$



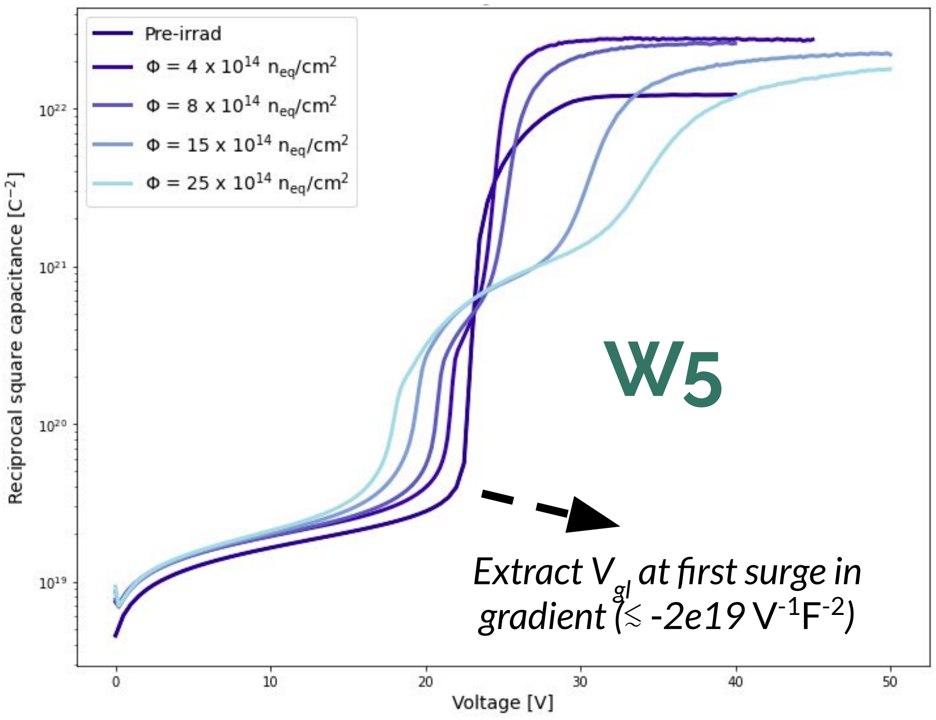






1-2kHz @ 20°C

V_{gl} extraction methods | First derivative

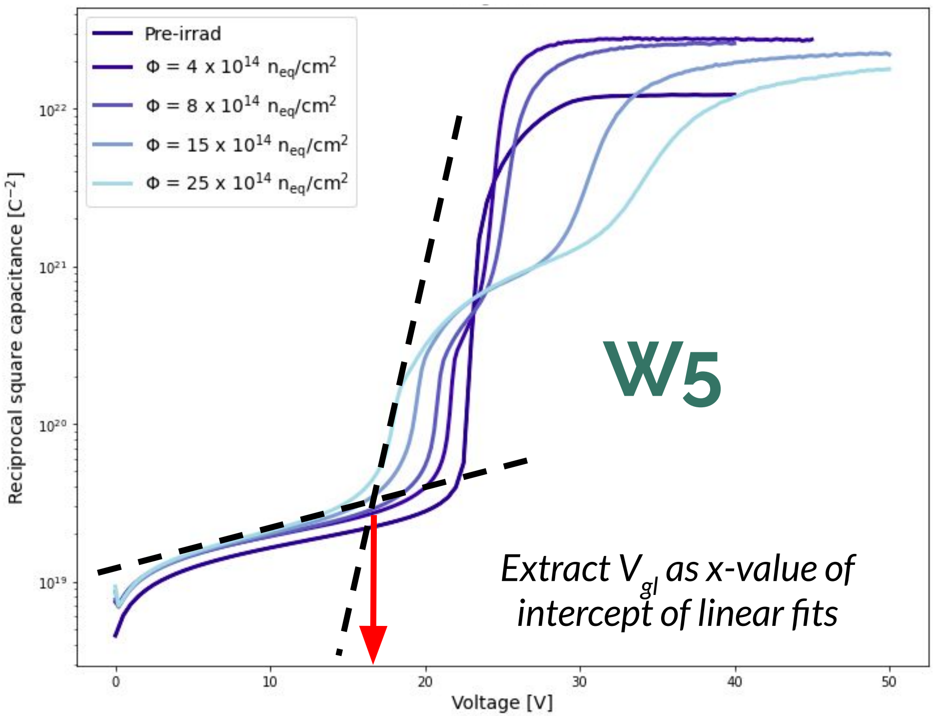


1-2kHz @ 20°C

Completely automated method

- Can tag ~98% of V_{gl} points based on gradient
  - Exceptions where gradient too shallow
- General tendency to underestimate true V_{gl}
- Also tested 2nd derivative

V_{gl} extraction methods | Linear fit

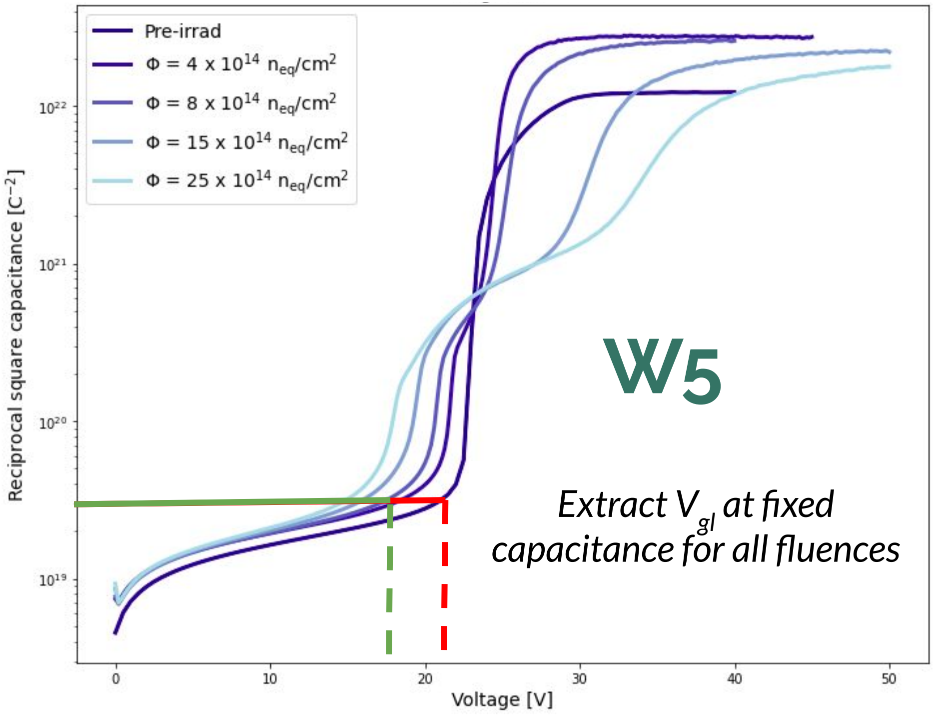


1-2kHz @ 20°C

Semi-automated method

- All $C^{-2}V$ curves have this characteristic bump, so can always find points to do linear fit
- Need to ensure sufficient number of datapoints for linear fit
  - Mainly for high fluence curves
- Does not underestimate V_{gl} necessarily

V_{gl} extraction methods | Fixed capacitance



1-2kHz @ 20°C

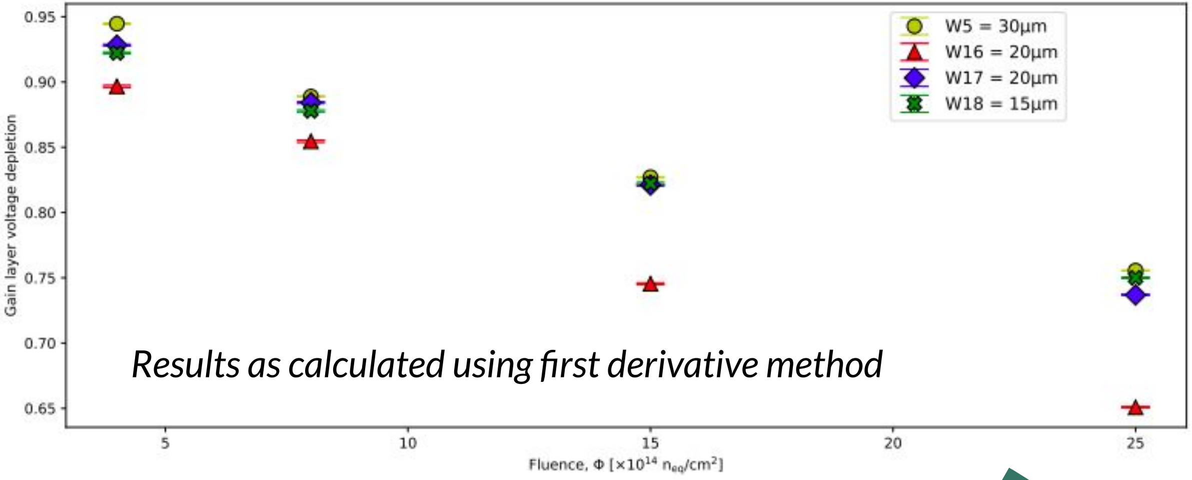
Semi-automated method

- Find points at which the capacitance increases above a threshold of ~10^{20} C^{-2}
  - This varies by wafer but constant for the fluence of each wafer
- Rise in gradient occurs at the same capacitance threshold
- Calculate the V_{gl} as the corresponding bias to the first point below that threshold
  - Subject to coarseness of bias scan

Exponential fitting to extract c coefficient

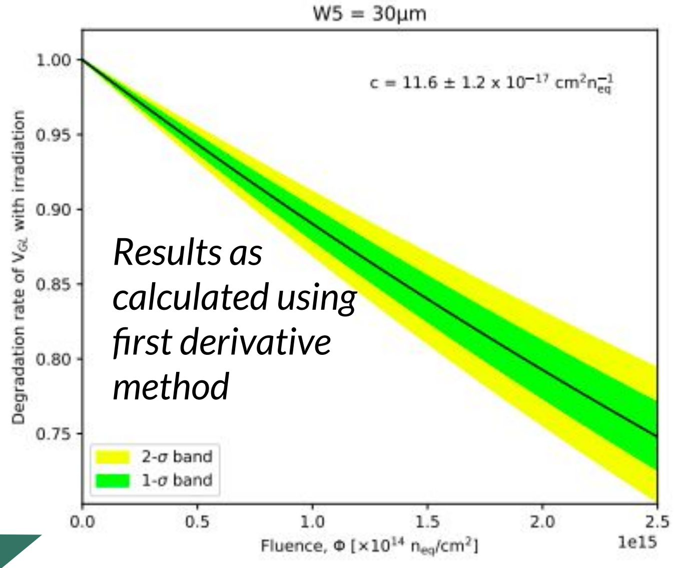
Exponential fit performed according to $\mathbf{V_N = V_{gl}(\Phi) / V_{gl,0} = e^{-c\Phi}}$

- V_N is the V_{gl} at fluence Φ normalised by the true V_{gl} from the pre-irradiated sensor
- Fluences > 2 x 10^{15} $n_{eq}cm^{-2}$ excluded from the fit



Results as calculated using first derivative method

CHBL diffusion



Results as calculated using first derivative method

Comparison of the methods

Compute acceptor removal coefficient from exponential fit

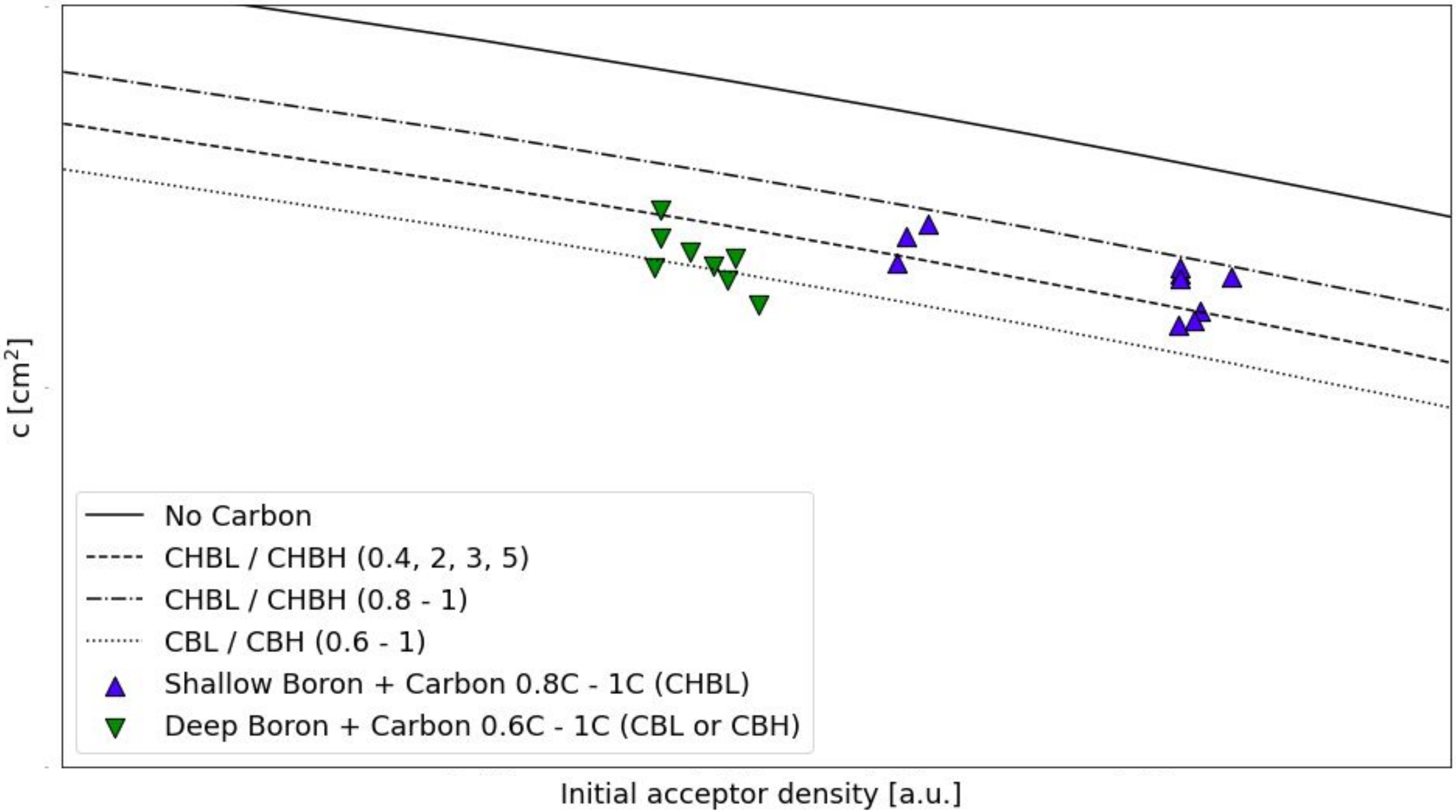
- $N_A(\Phi) = N_{A,0}e^{-c\Phi} = N_{A,0}e^{-\Phi/\Phi_0}$, where $\Phi_0 = 1/c$ is the characteristic fluence at which gain layer doping concentration reduces by ≈37%

Wafer [μm]	c [x 10^{-16} $cm^2 n_{eq}^{-1}$]				Characteristic fluence Φ_0 [x 10^{17} $n_{eq} cm^{-2}$]
	1st der	**Linear fit**	**Fixed C**	**Mean value**	
W1* @ 45	—	1.36	—	1.36	7.4
W5 @ 30	1.16 ± 0.12	1.34	1.26 ± 0.03	1.25 ± 0.04	8.0 ± 0.3
W16** @ 20	1.74 ± 0.16	1.78	2.14 ± 0.13	1.89 ± 0.07	5.3 ± 0.2
W17 @ 20	1.10 ± 0.04	1.37	1.38 ± 0.07	1.28 ± 0.02	7.8 ± 0.1
W18 @ 15	1.05 ± 0.11	1.37	1.11 ± 0.05	1.17 ± 0.04	8.5 ± 0.3

**No pre-irradiated CV for W1, additional amplitude parameter to fit*

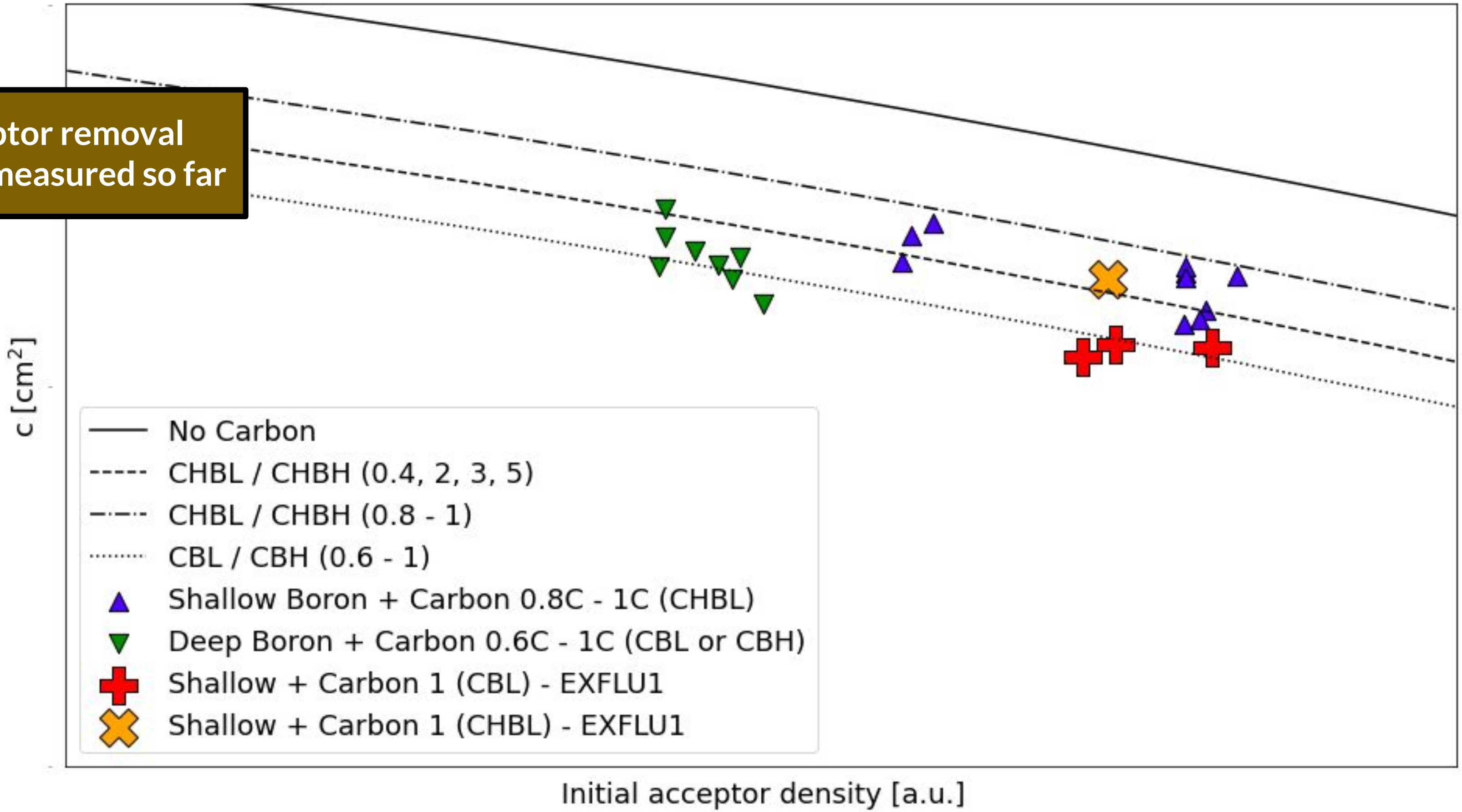
***CHBL diffusion*

Acceptor removal in EXFLU1 sensors



Acceptor removal in EXFLU1 sensors

Best acceptor removal coefficients measured so far



Signal-Bias Measurements using TCT setup

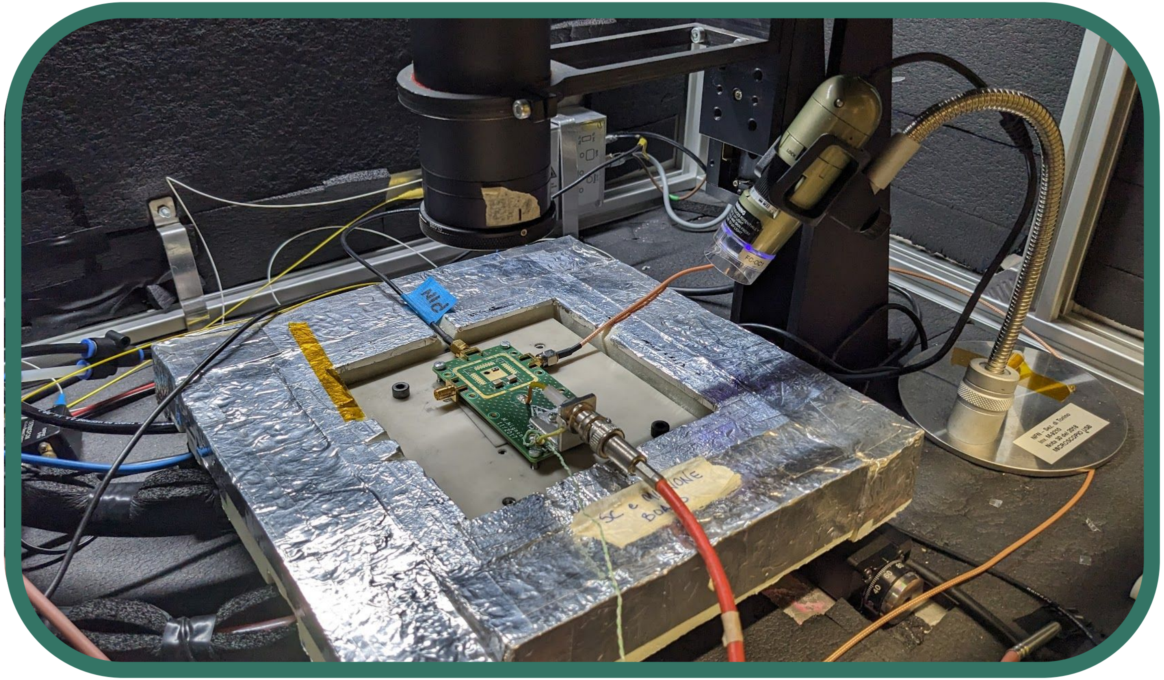
Using LGAD-PIN as measured for different fluences

- 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}

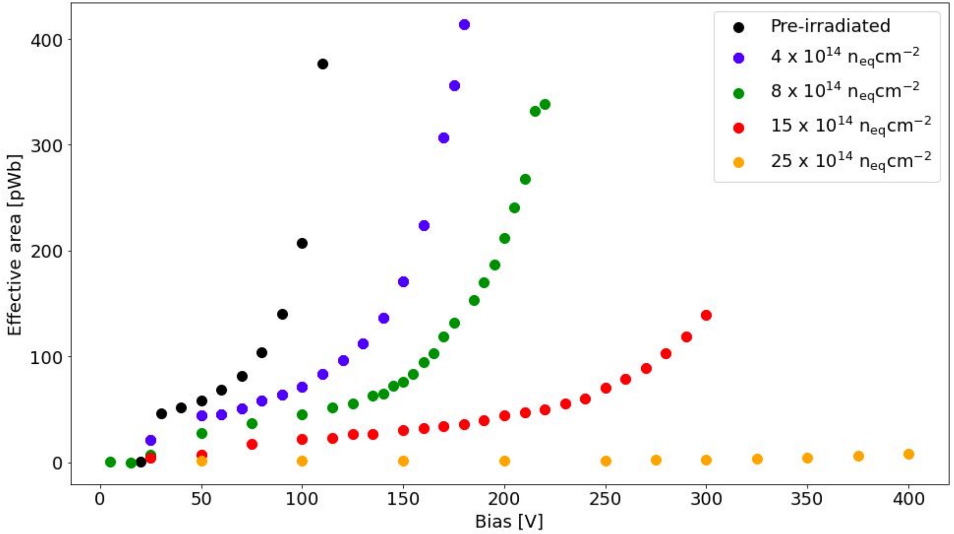


Time-intensive measurement

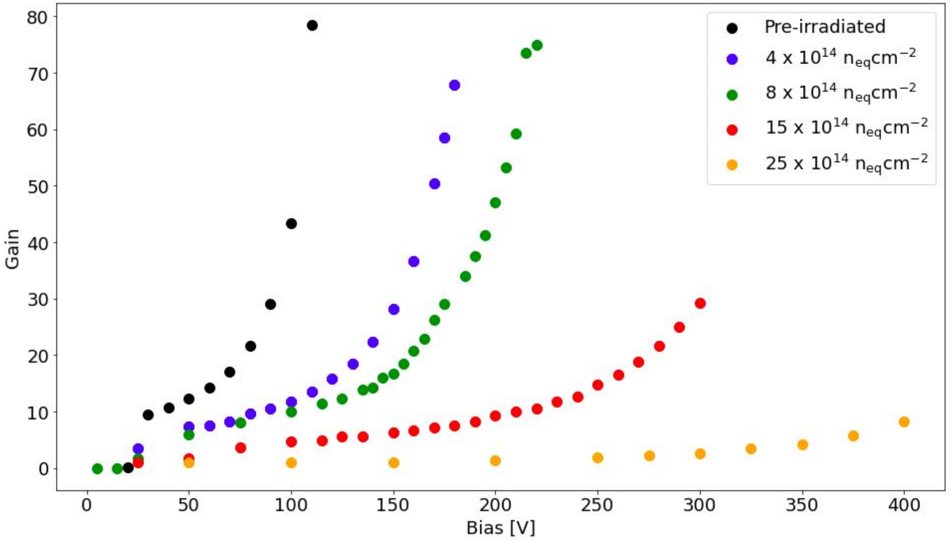
W5 effective signal area and gain

Results recorded for 3.5-4.2 MIPs @ -10˚C

$A_{eff, LGAD} = A_{signal\ area} - A_{no\ signal\ area}$



$G_{LGAD} = A_{eff, LGAD} / <A_{eff, PIN}>$



Summary

Substantial progress in the irradiated FBK EXFLU1 sensor campaign

- IV and CV measurements performed at various fluences in cold probe station
- Signal-bias measurements performed at various fluences in the TCT setup

Extracted gain information from EXFLU1 sensors

- **Best series of acceptor removal coefficients reported for standard LGAD wafers**
- Gain profile from TCT to corroborate the results for these wafers

Ringraziamenti

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Ministero della Ricerca, Italia, PRIN 2022, progetto 2022RK39RF – ComonSens

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BACKUP

Wafer reference

WAFER LIST

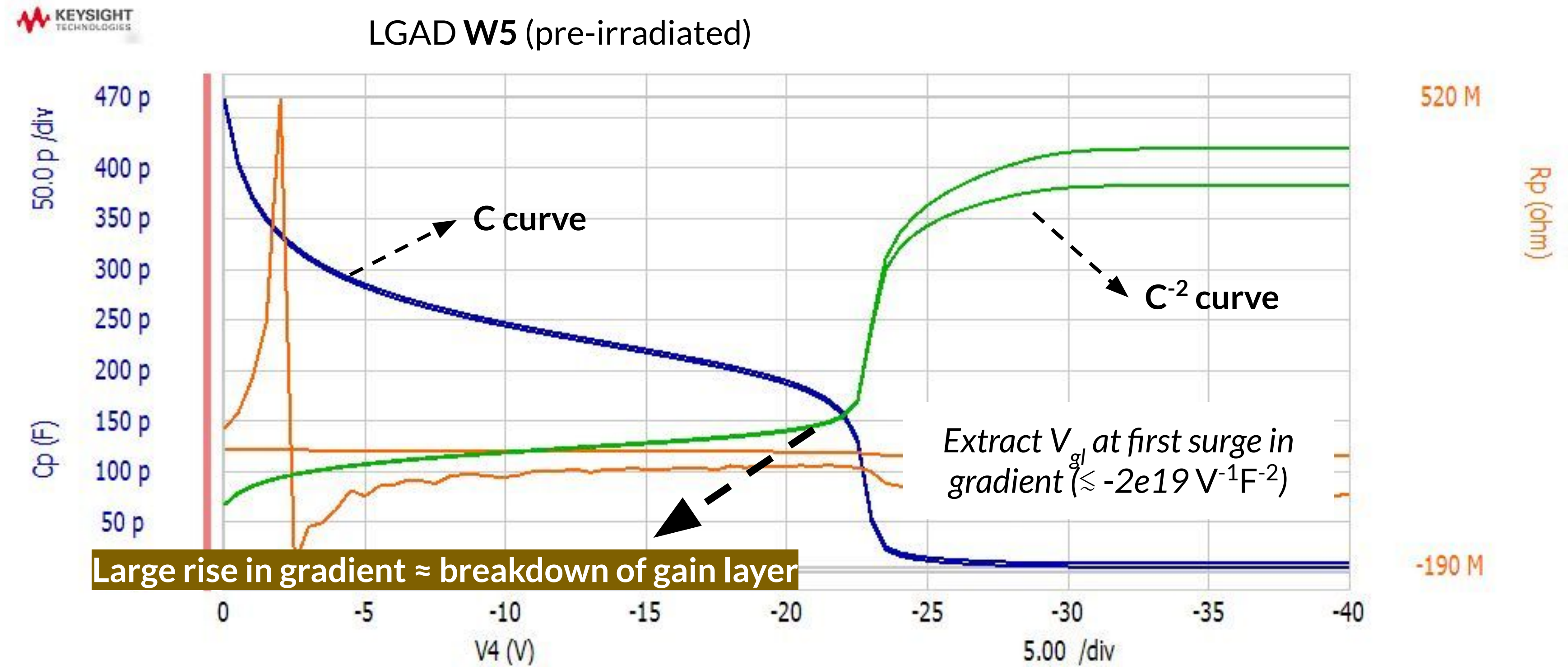
Standard LGAD

Wafer #	Thickness	p+ dose	C dose	C shield	Diffusion	Bulk
1	45	1.14	1.0		CBL	n-type
2	45	1.00		0.6	CBL	
3	45	1.16	1.0	0.6	CBL	
4	45	1.16	1.0	1.0	CBL	
5	30	1.12	1.0		CBL	high rho
16	20	0.80	1.0		CHBL	low rho
17	20	0.96	1.0		CBL	
18	15	0.94	1.0		CBL	

Compensated LGAD

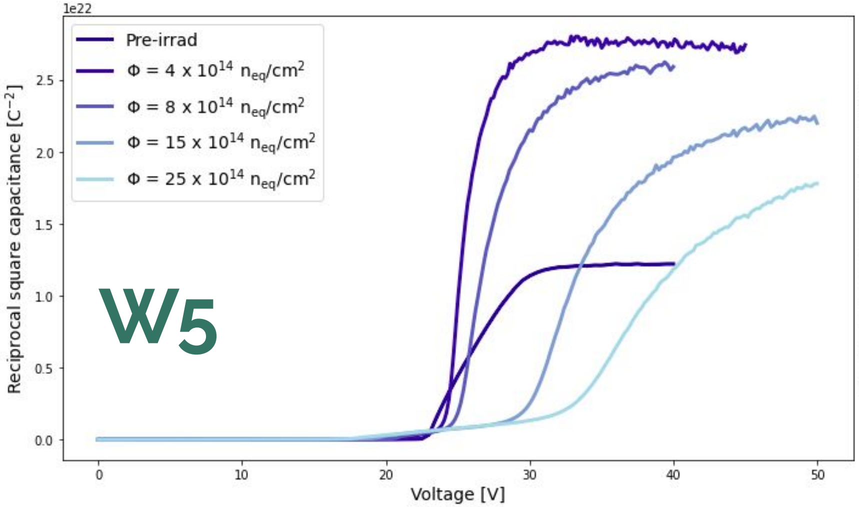
Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
7	30	2 b	1	
8	30	2 b	1	
9	30	2 c	1	
10	30	3 a	2	
11	30	3 b	2	
12	30	3 b	2	
13	30	3 b	2	1.0
14	30	3 c	2	
15	30	5 a	4	

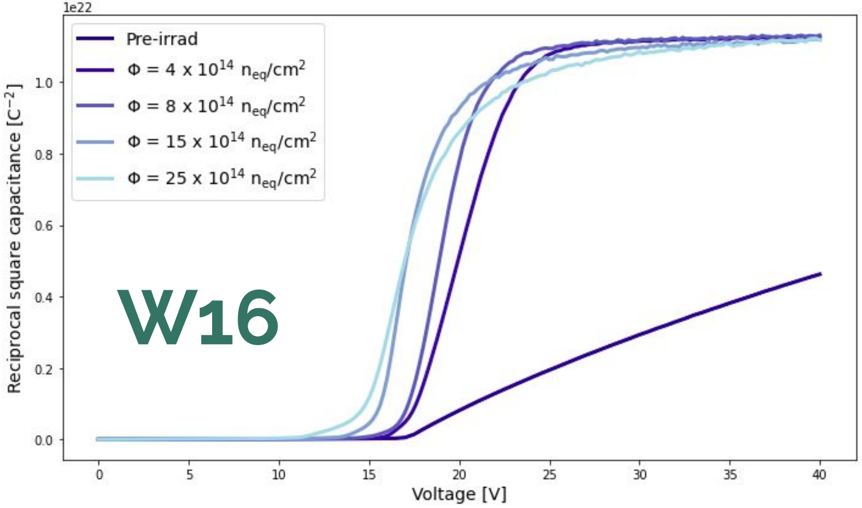
V_{gl} extraction method: first derivative (POV CPS)

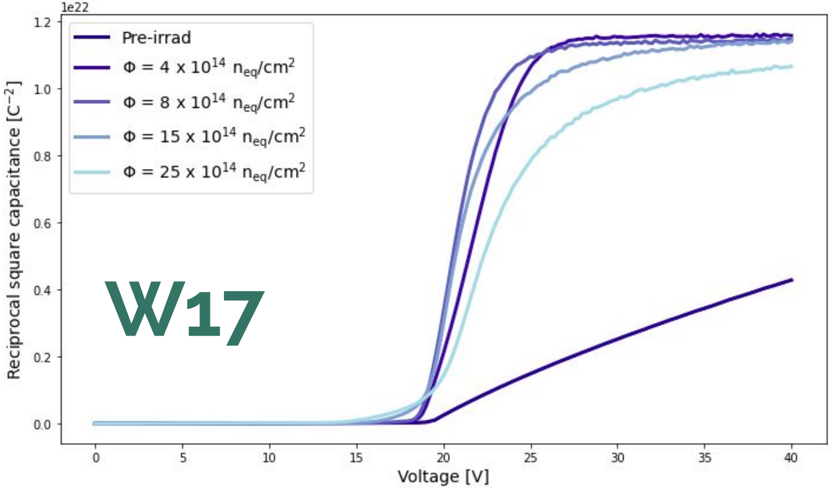


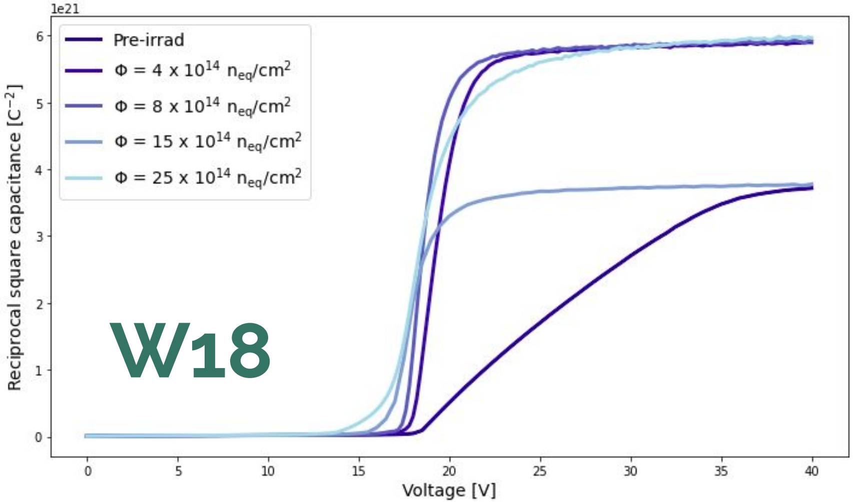
C^{-2}V

Linear y-axis

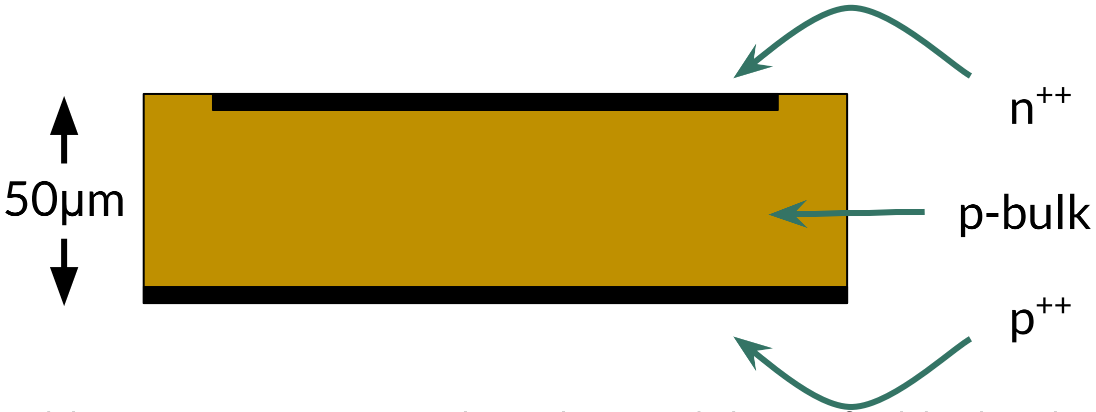








PIN design



Thin sensors measure location and time of a hit simultaneously and accurately

- Temporal resolution ~30ps, spatial ~10μm
- Requires intrinsic gain ~20 excess *eh* pairs and fine sensor segmentation

Standard PIN requires a high E-field from high external bias voltage

- Tendency for device breakdown due to high field at periphery