Electrical characterization and attenuation factor determination of AC-LGAD run at CNM

The 42nd RD50 Workshop

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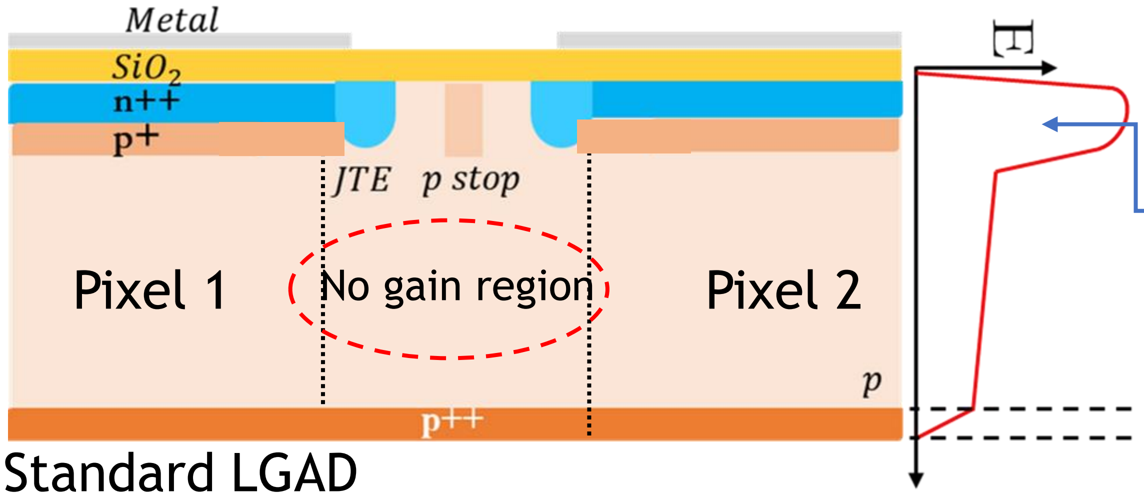
Centro Nacional de Microelectrónica IMB

CSIC Consejo Superior de Investigaciones Científicas

LGAD Technology



Standard LGAD

Impact ionization mechanism → Charge is multiplied **Gain 10-20** → DC signal readout

55 µm pitch
- Excellent spatial resolution
- Compatible with ASICs Timepix4 & Medipix4

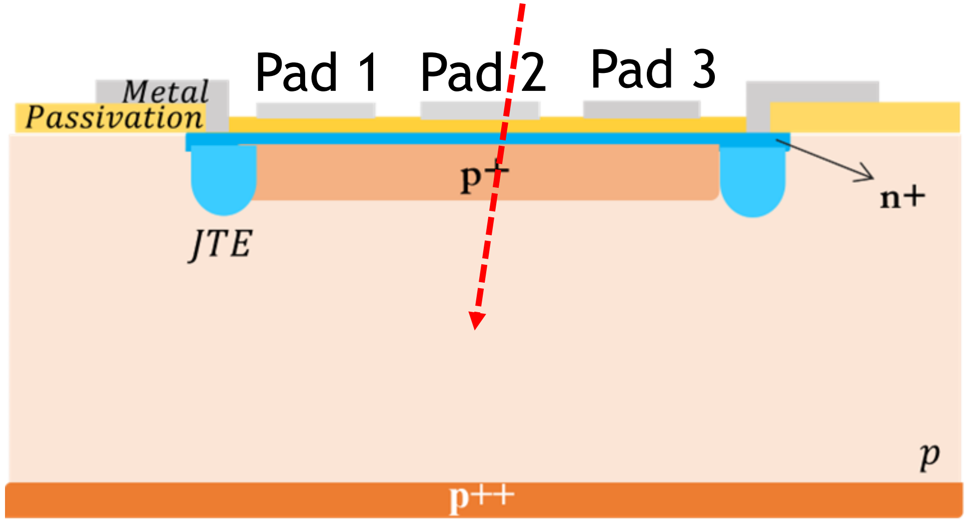
Edge termination
- Electric field lines bending – gain is annulled
- FF (fill factor) = A_G/A_{total} is limited

How to overcome these drawbacks?

AC-LGAD

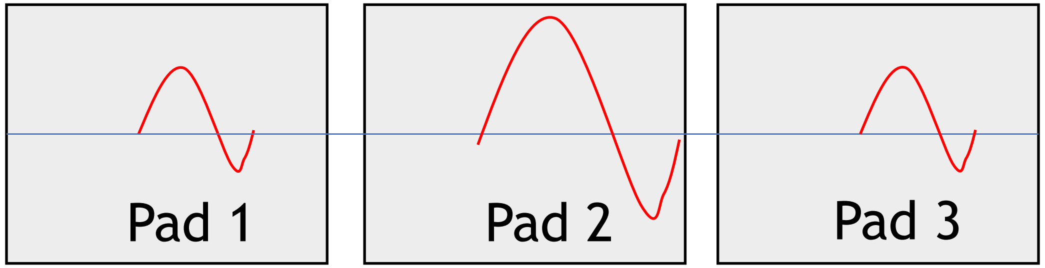
Confirmed by TCAD simulation

AC-LGAD Technology



AC-LGAD

Signal exhibits sharing between pads



- n^{++} layer is replaced with a less doped continous n^{+}
- Gain layer is continous so fill factor is is maximized
- Metal pads are separated by a thin continous dielectric from the n^{+}
- Signal is capacitevely induced od the metal plates connected to redout

- F_i – fraction of total signal amplitude in pad *i*
- d_i – distance from the hit point to ith metal edge
- α_i – solid angle under which the charge "sees" the pad

$$F_i(\alpha_i, d_i) = \frac{\frac{\alpha_i}{ln(d_i/d_0)}}{\sum_1^n \frac{\alpha_i}{ln(d_i/d_0)}}$$ [1]

[1] Tornago, M. *et al.* (2021) 'Resistive AC-coupled silicon detectors: Principles of operation and first results from a combined analysis of beam test and laser data', *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 1003, p. 165319. **doi:10.1016/j.nima.2021.165319.**

Further readings & past work:

AC-LGAD measurement 2017, M. Carulla
https://indico.cern.ch/event/577879/contributions/2740418/attachments/1575077/2487327/HSTD1--HFWS1.pdf

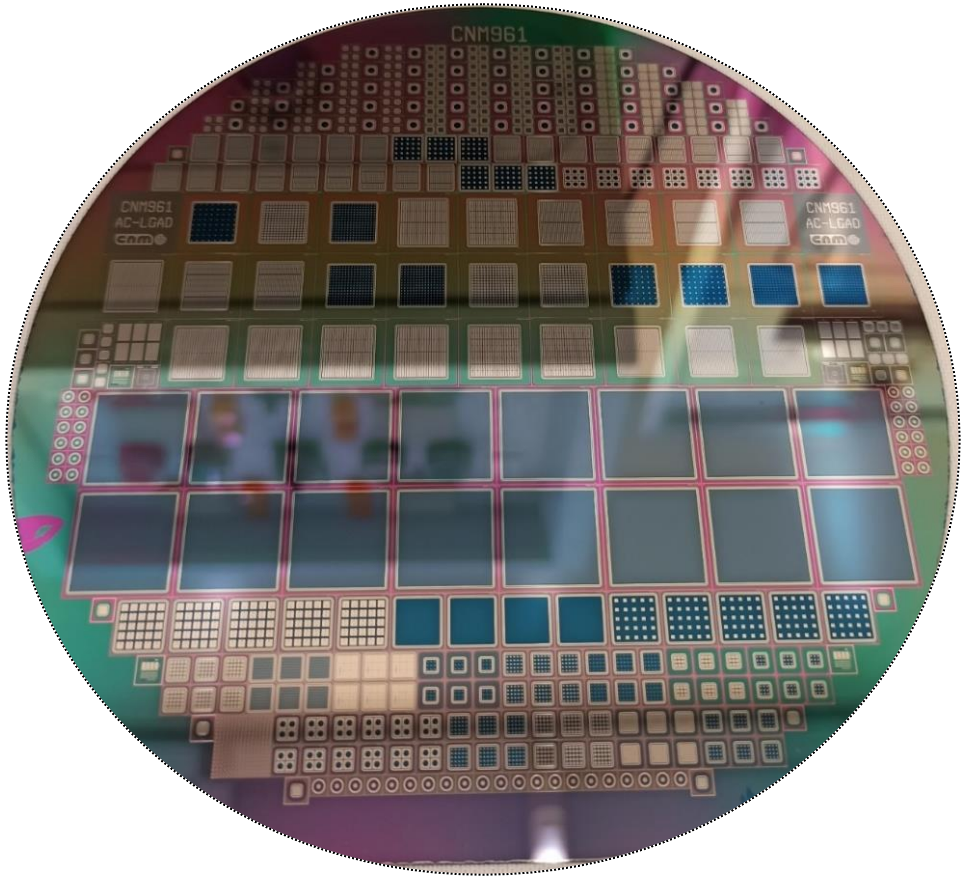
Thin LGAD Timing Detectors for The Atlas Experiment, M. Carulla, PhD Thesis, 2019
2019 Thesis_MarCarulla_ThinLGADtiming.pdf - Files - CERNBox

AC-LGAD (6LG4)

Wafer consists of:

- 443 Integrated structures
  - 42 Strip detectors
  - 16 Timepix3
    - 1 Timepix3 without gain
  - 5 HGTD, Pad size 0.5 mm
  - 5 HGTD, Pad size 1 mm
  - 61 DC-Pad diodes
  - 6 AC-Pad diodes
  - 12 DC-Arrays
  - 296 AC-Arrays
- Three different multi doses
  - Low - 2.0 e12/cm^3
  - Medium - 2.1 e12/cm^3
  - High - 2.2 e12/cm^3

$$\text{Yield}_{\text{Wafer}} = 13/15$$



Run 16020

Wafer	Multi dose	Thickness
1	Low	Silicon 300 μm
2	Low	Silicon 300 μm
3	Medium	Silicon 300 μm
4	Medium	Silicon 300 μm
5	High	Silicon 300 μm
6	High	Silicon 300 μm
7	Low	Silicon 300 μm
8	Low	Silicon 300 μm
9	Low	SiSi 50 μm
10	Low	SiSi 50 μm
11	Medium	SiSi 50 μm
12	Medium	SiSi 50 μm
13	High	SiSi 50 μm
14	High	SiSi 50 μm
15	NA	Silicon 300 μm

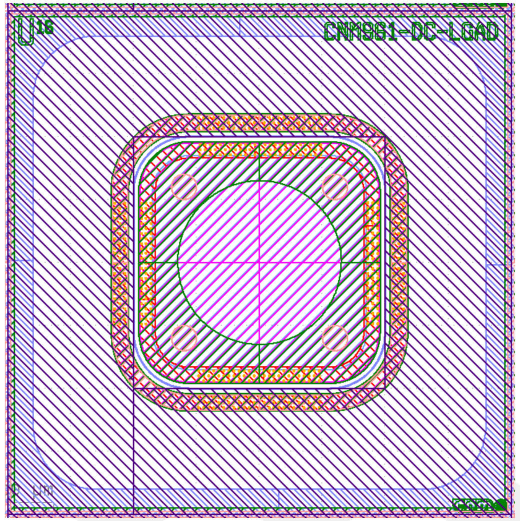
Broken (red)

Reprocessed and soon to finish (yellow)

I Part - Electrical Characterization

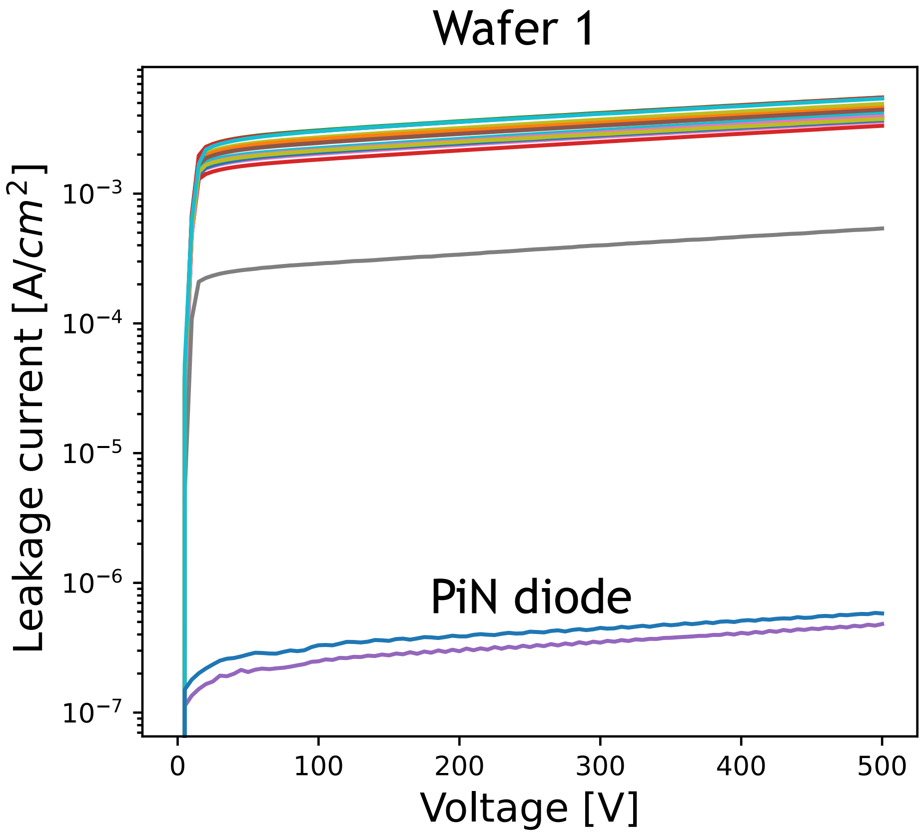
Electrical Characterization

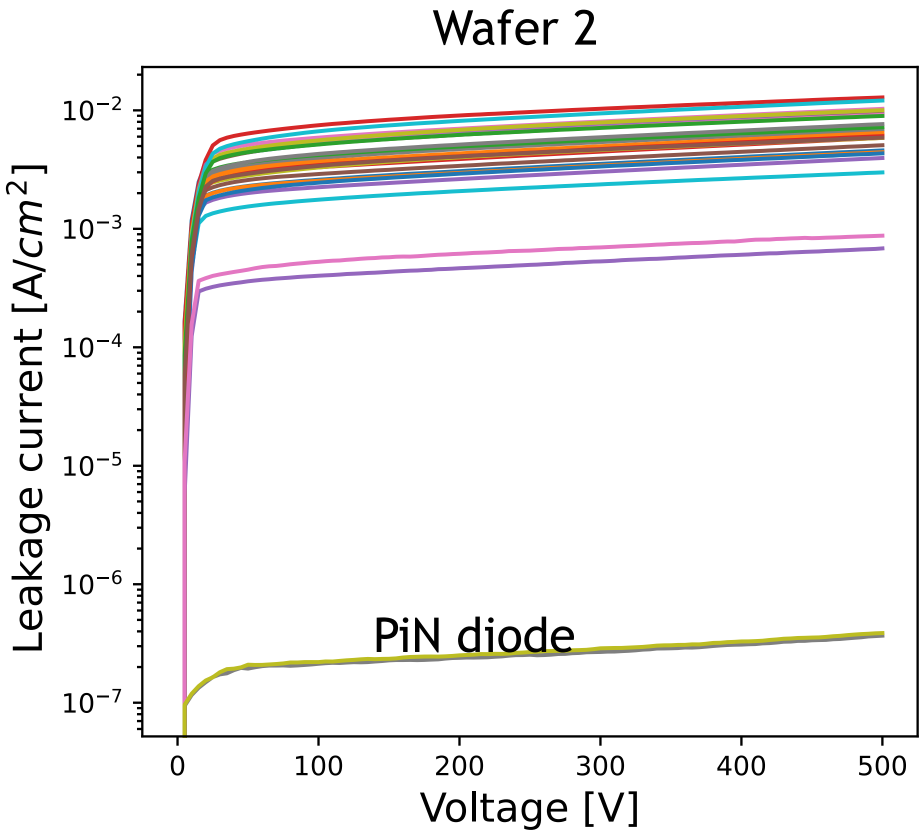
- Targeted devices mostly U and V (LGAD and the correspondind PIN diode)
- Active area (measured from p-stop to p-stop) of 2 mm^2
- Gain of these device was preaviously measured [2]
  - Depending on the multi layer dose gain slightly varies
  - However gain is very low (1.2)
    - Due to TCAD Simulation thermal step mistake made before fabrication



[2] N. Moffat, M. Manojlovic, J. Villegas, S. Hidalgo, G. Pellegrin, Update of AC-LGAD at CNM, The 41th RD50 Workshop, https://indico.cern.ch/event/1132520/contributions/5149452/attachments/2558030/4408416/RD50-Sevilla-2022-AC-LGAD.pptx

Electrical Characterization - IV





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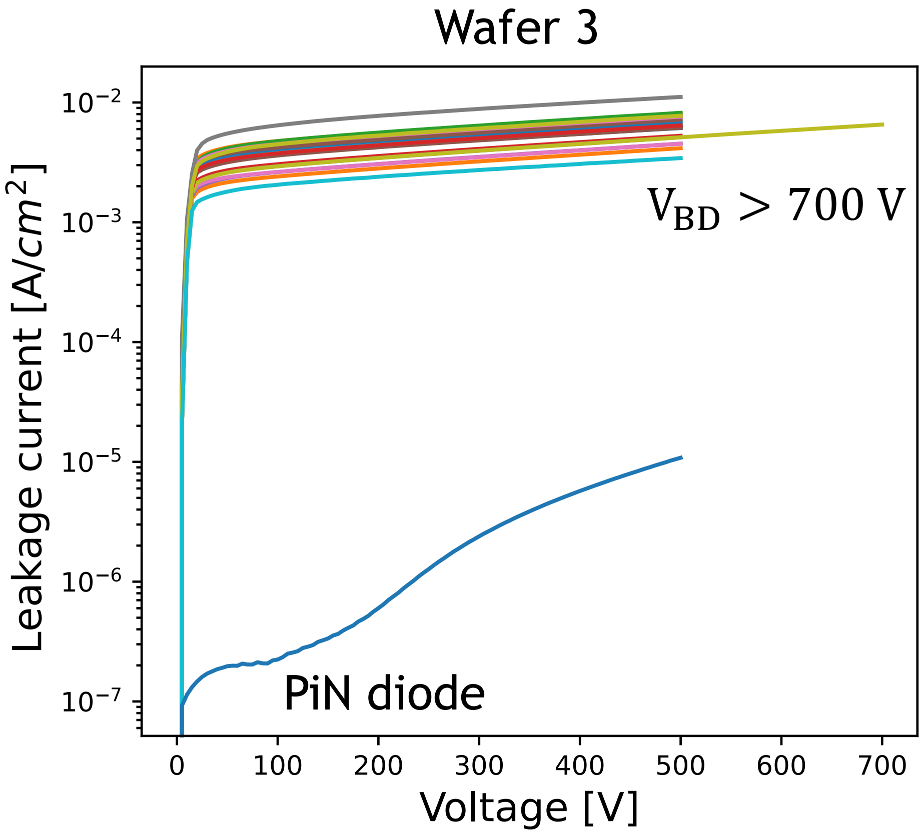

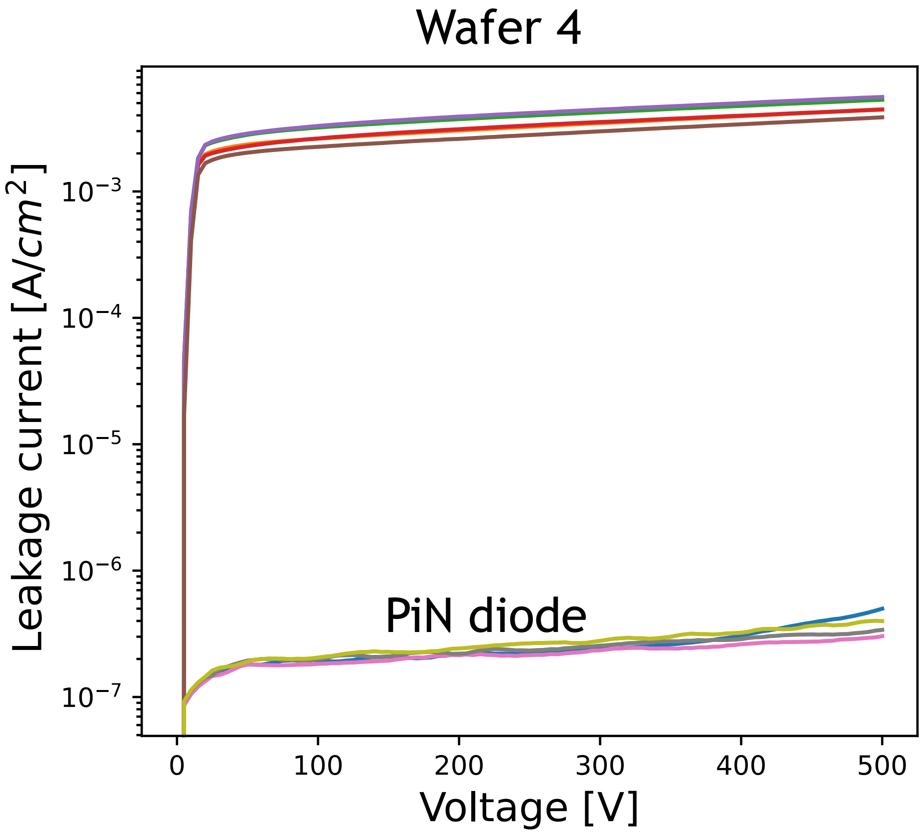

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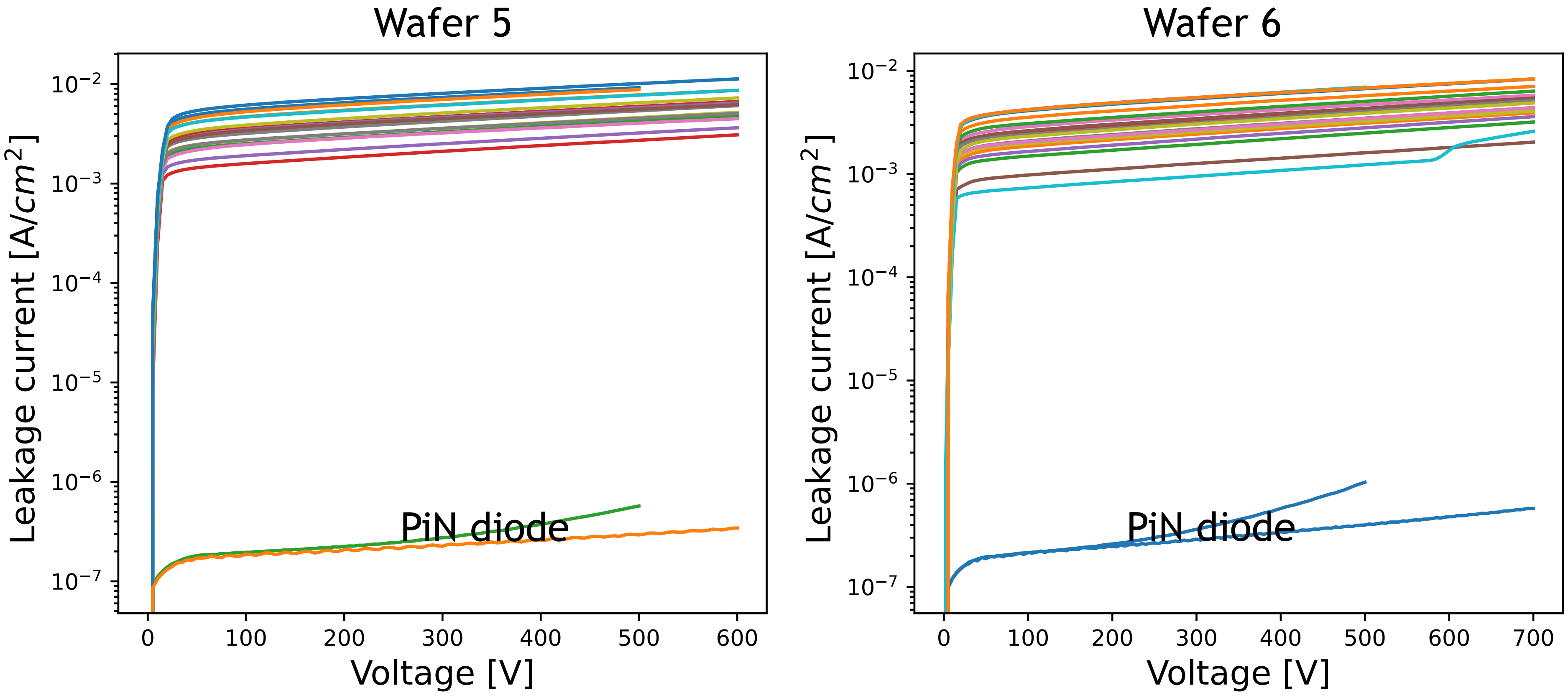

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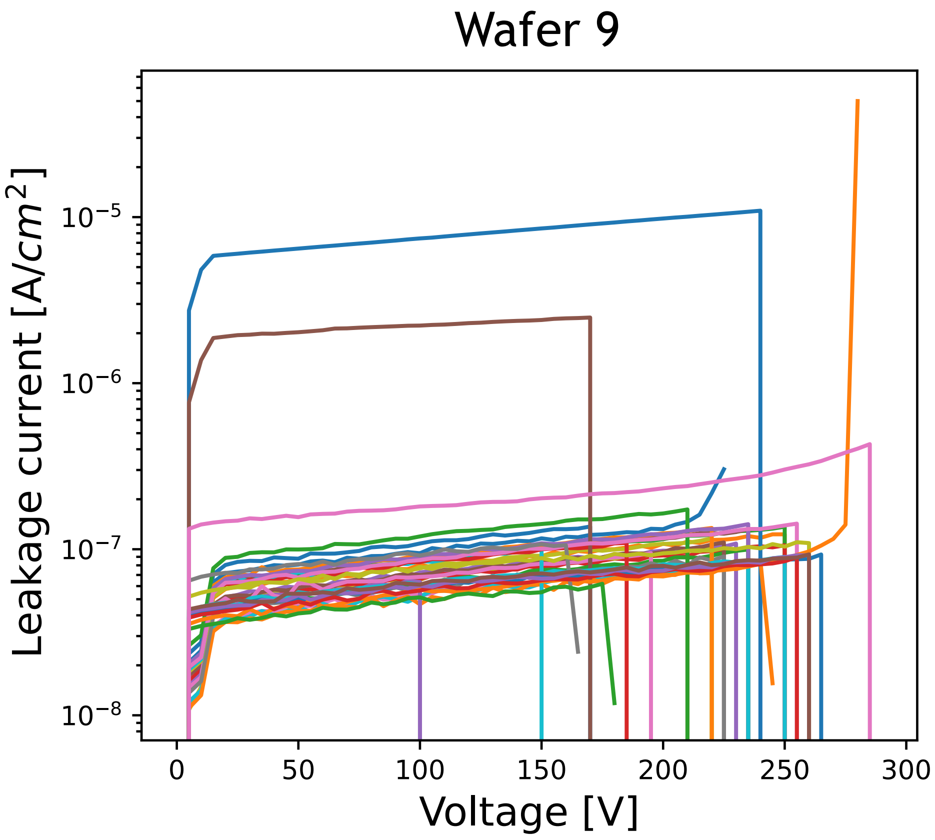

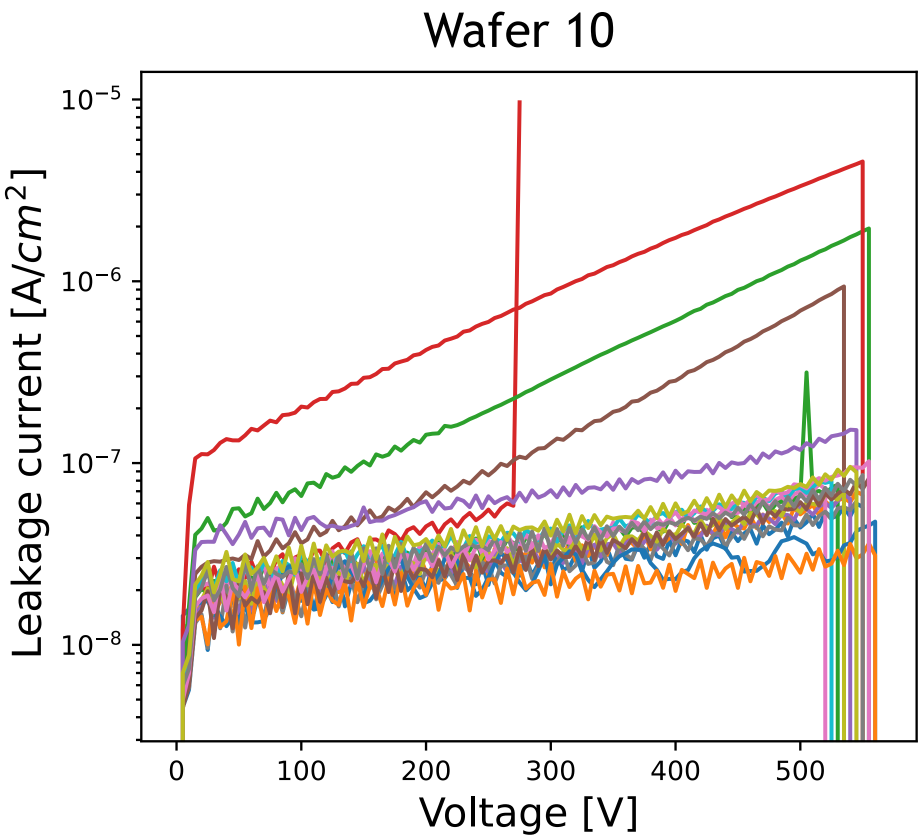

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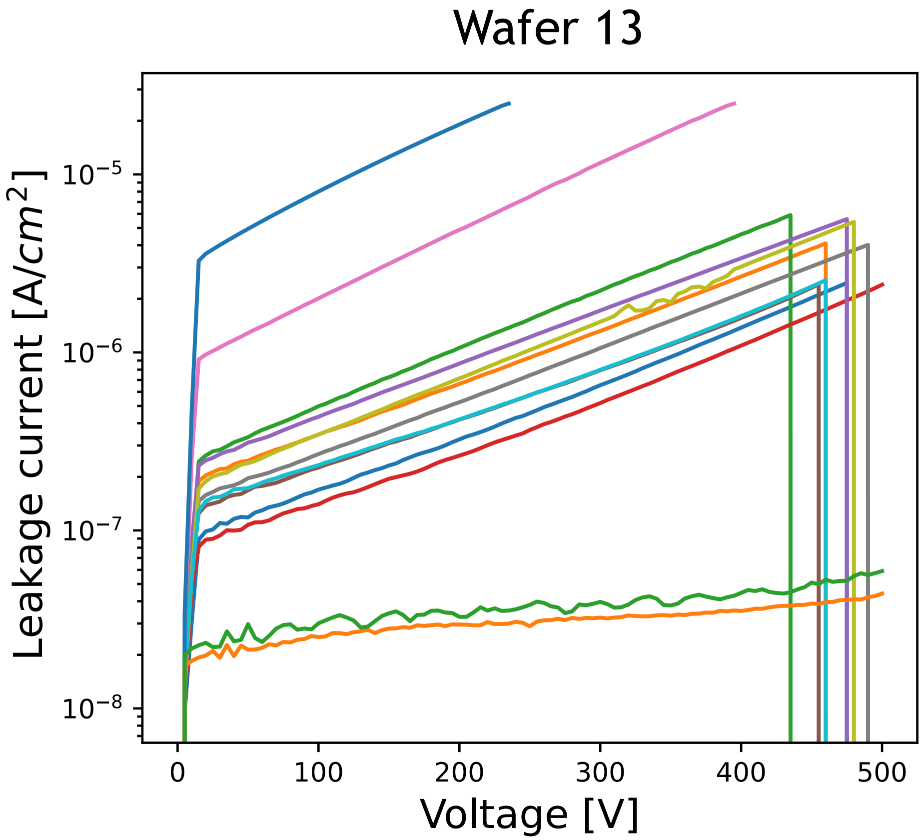

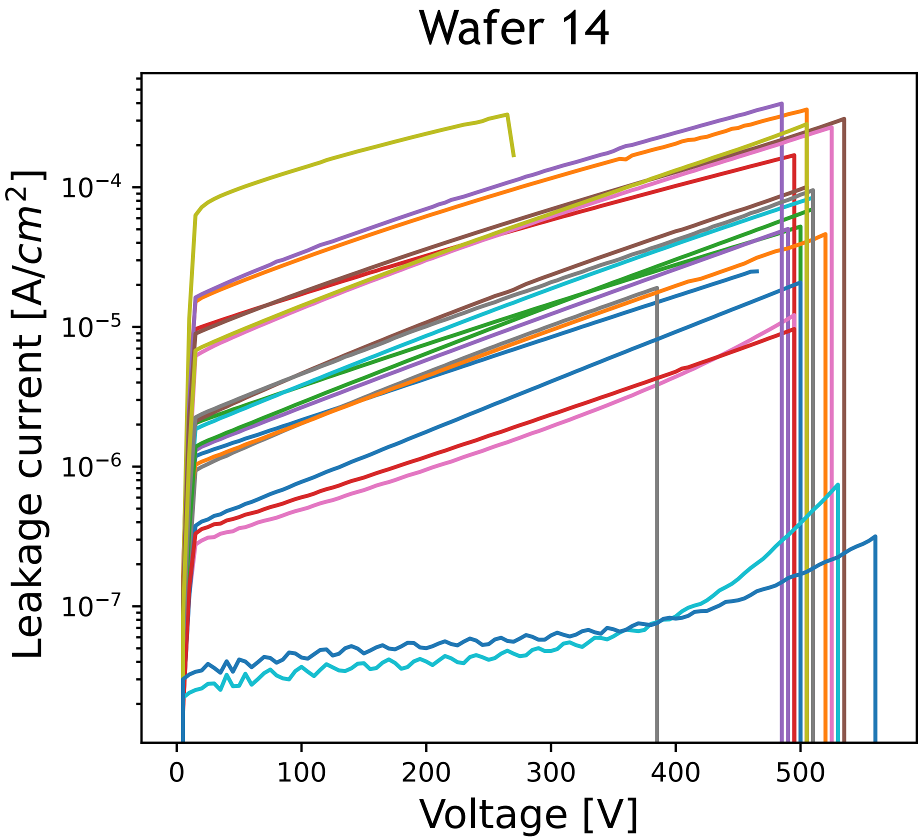

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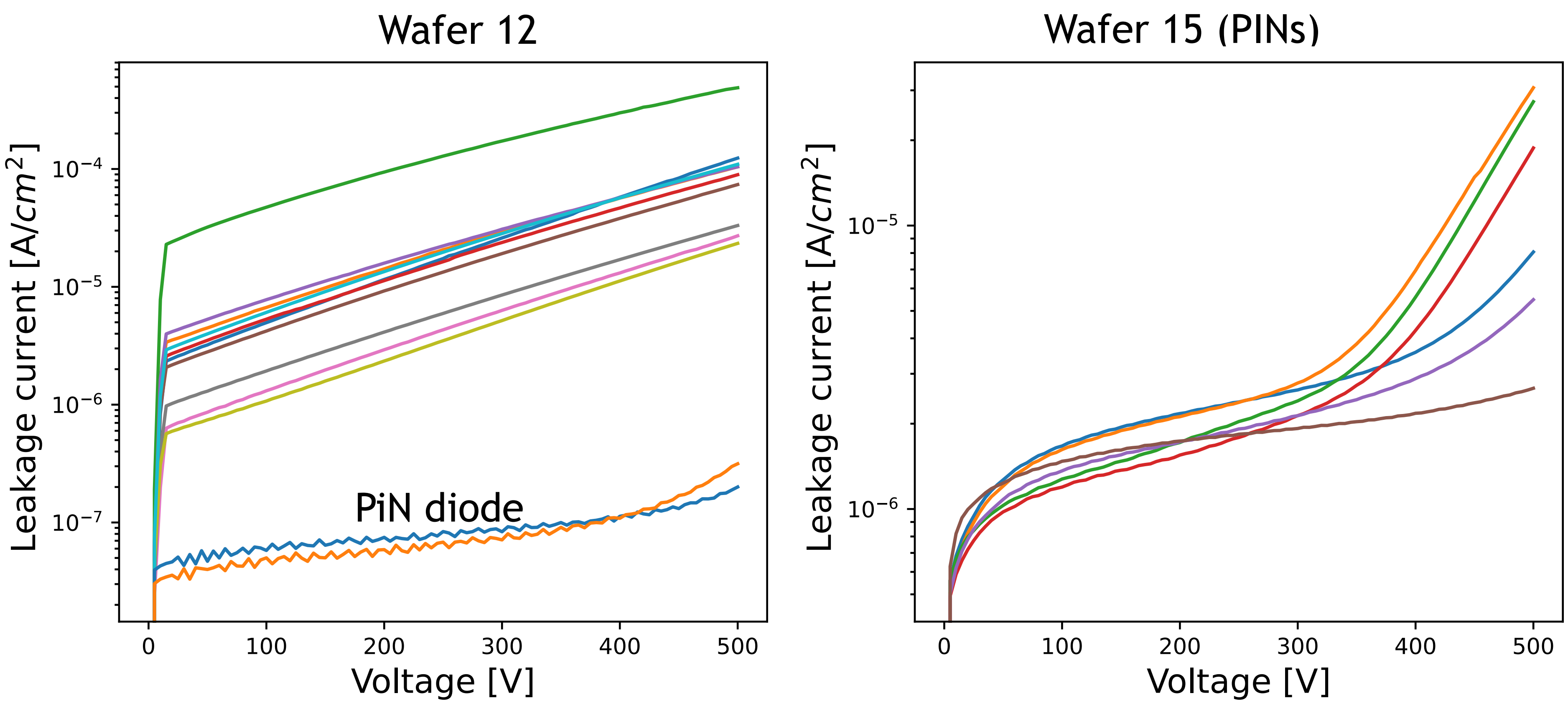

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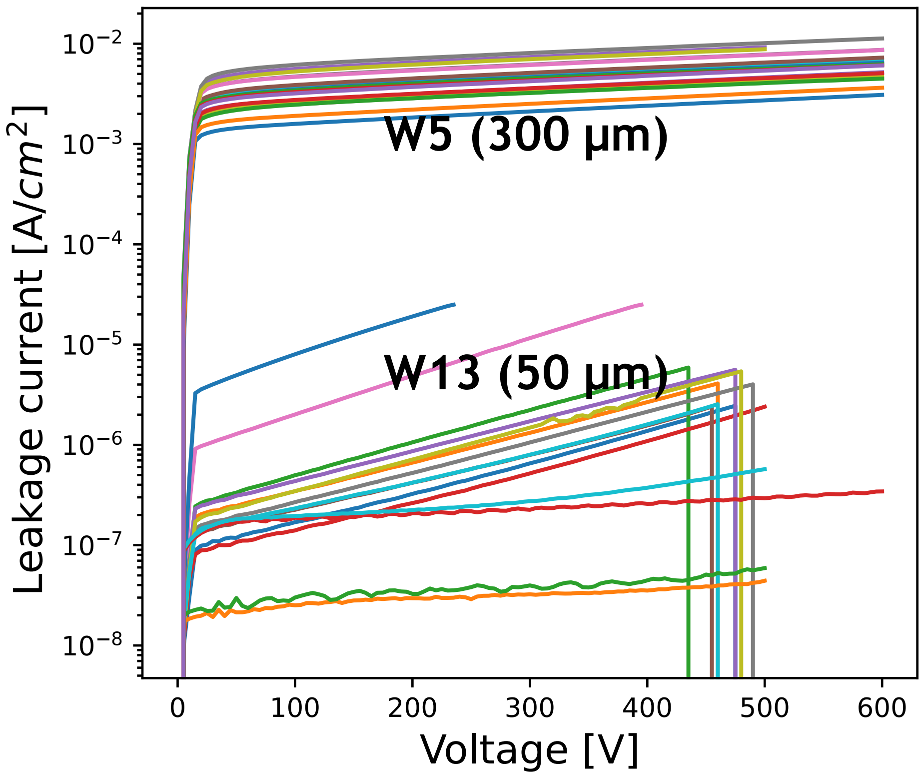
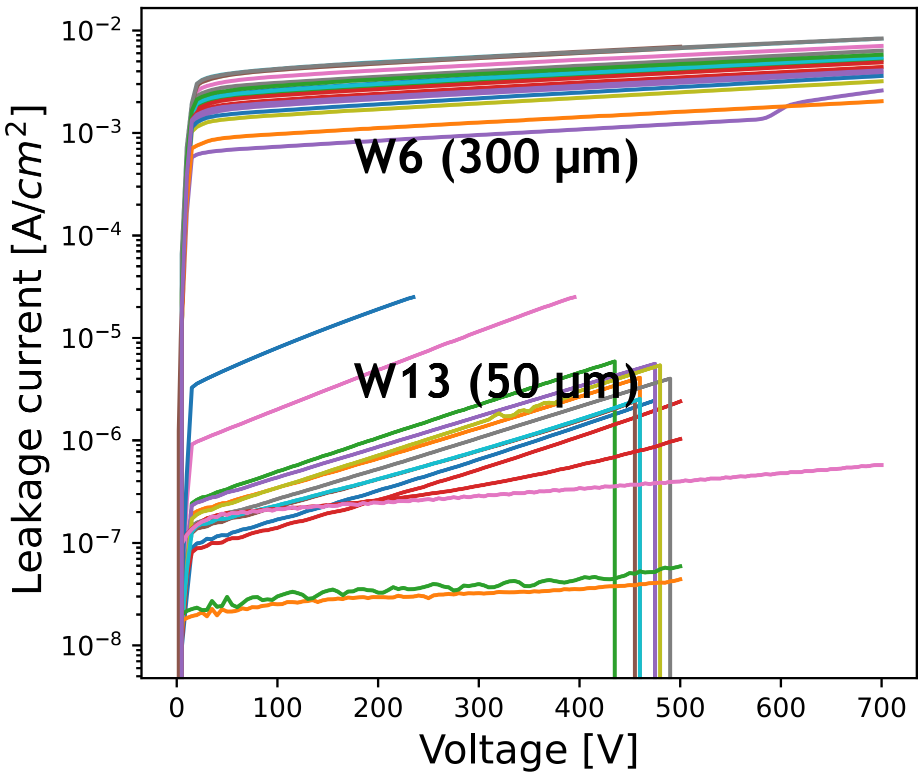
9	Low	SiSi 50 μm
10	Low	SiSi 50 μm
11	Medium	SiSi 50 μm
12	Medium	SiSi 50 μm
13	High	SiSi 50 μm
14	High	SiSi 50 μm
15	NA	Silicon 300 μm

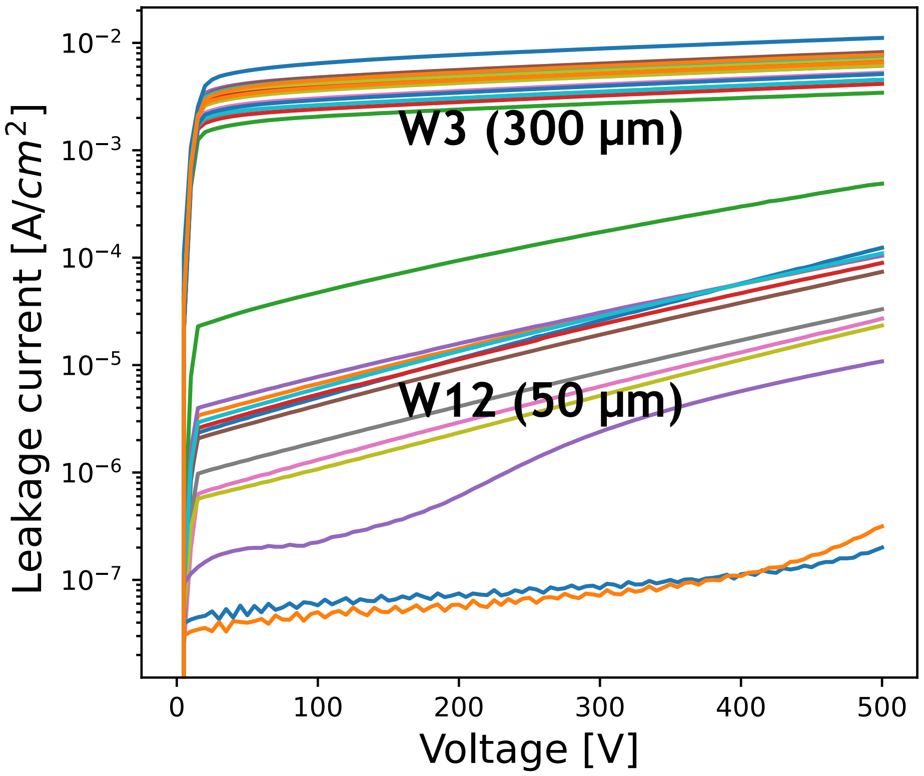
IV - High dose - Thick VS Thin Wafer Comparison

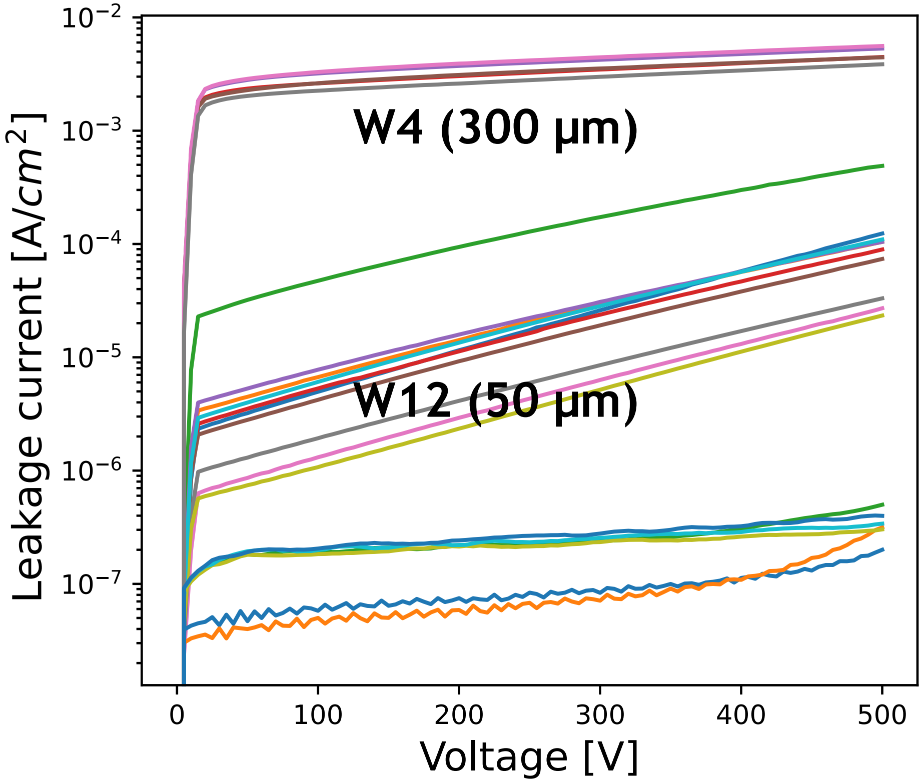




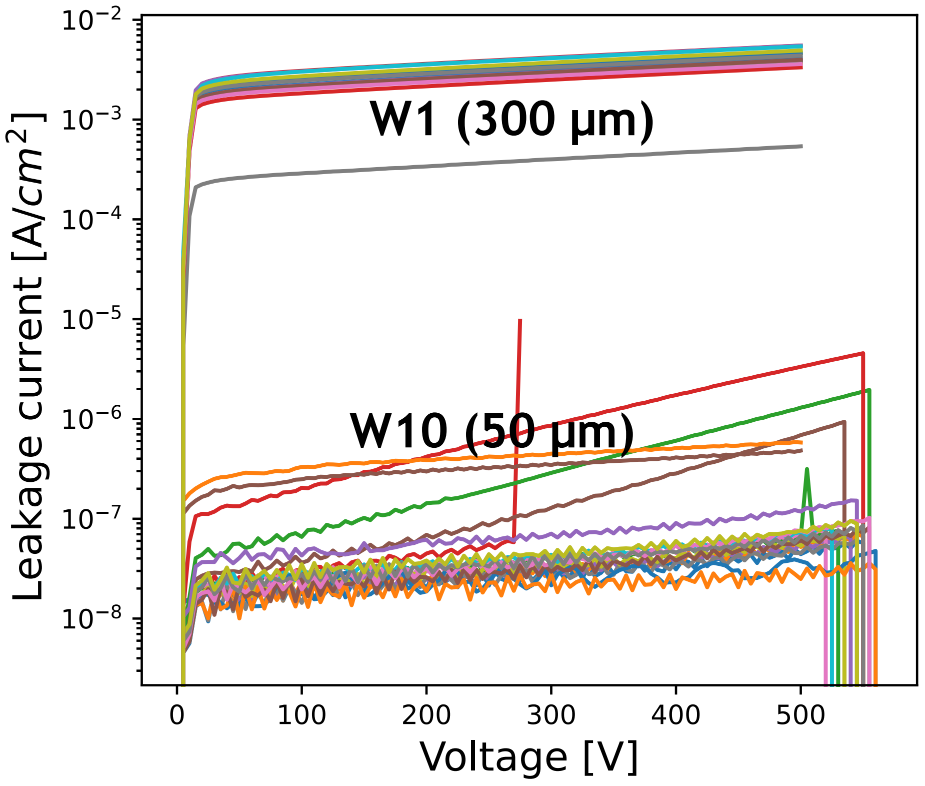
Leakage current difference of more than 1000 times!

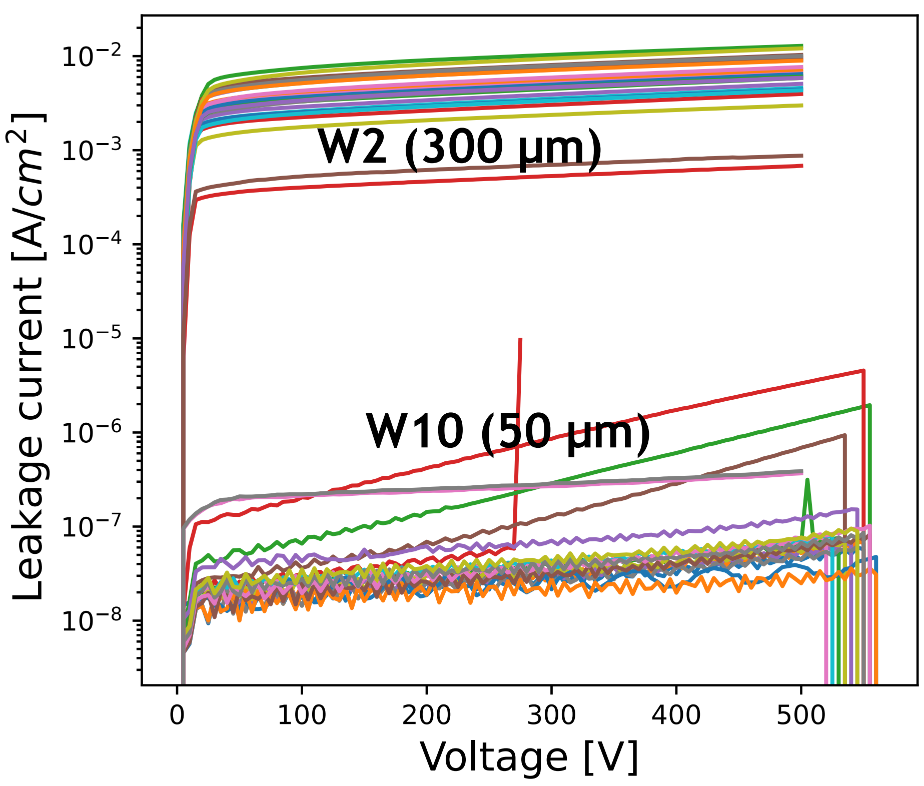
IV - Medium dose - Thick VS Thin Wafer Comparison





IV - Low dose - Thick VS Thin Wafer Comparison





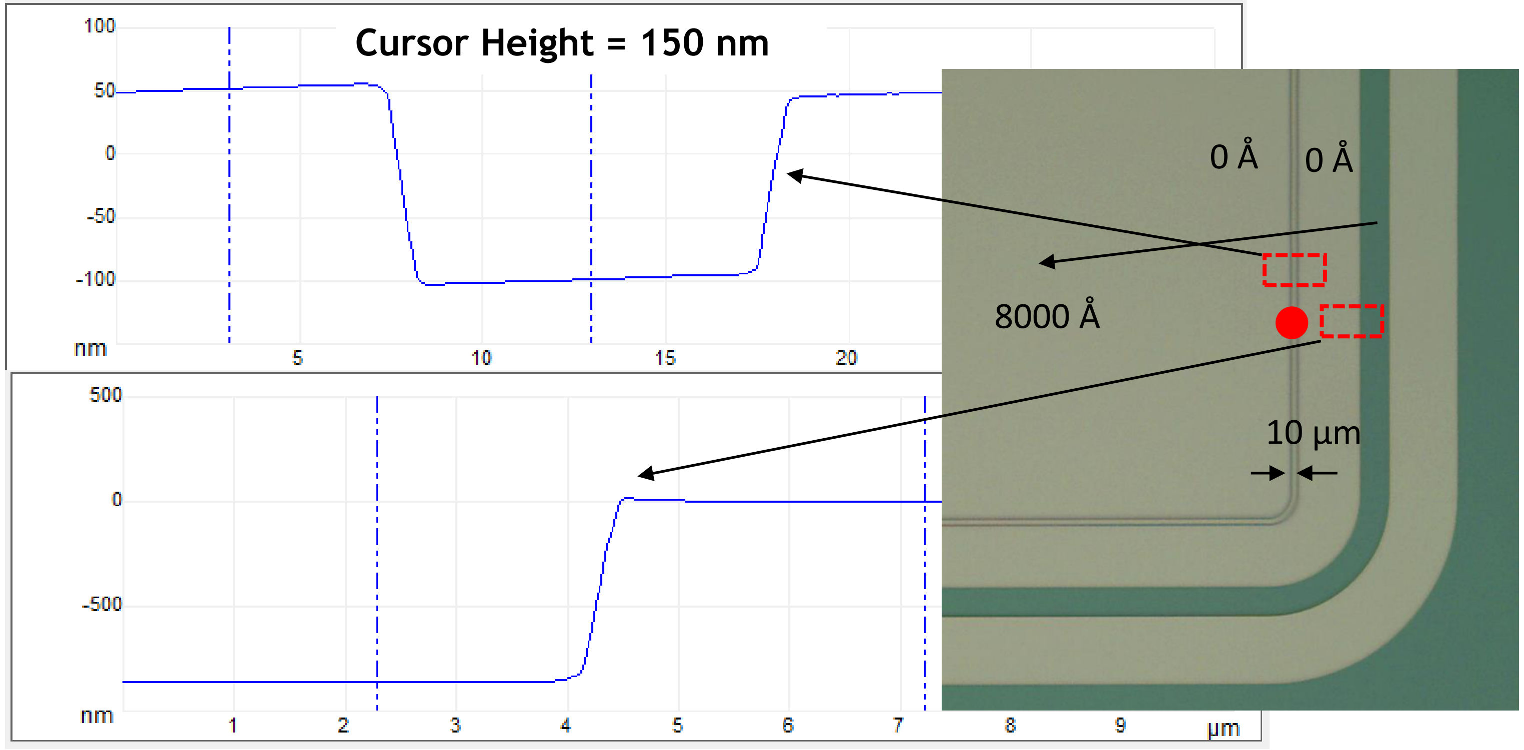
Summary of the IV results

- 300 µm thick wafers have high currents and show no breakdown up to 700 V
  - By exception PIN diodes have low current
  - Independent of the implantation dose

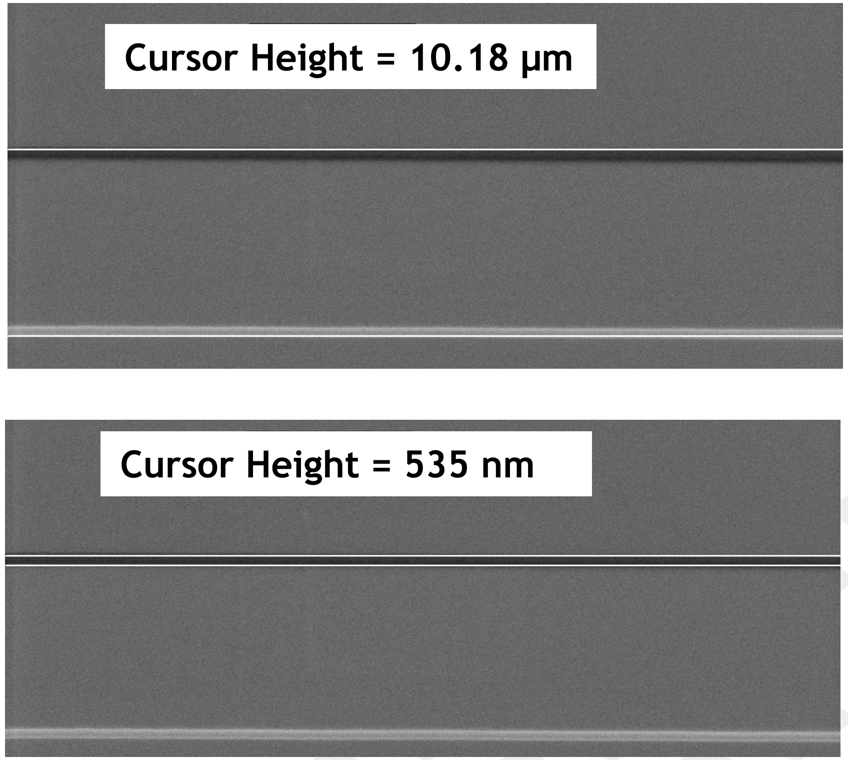
- 50 µm thick wafers have low currents and show a breakdown around 500+V

- Difference in leakage current between thin and thick wafers around 1000 times
- All the wafers have been processed and fabricated the same way
  - Possibely a bad backside contact (implantation dose low)

- In a newly run 16273 of the pLGAD device a *possible reason* for such high current has been noted
- Mask design has an overlap of multiplication layer and JTE which results in an unexpected trench

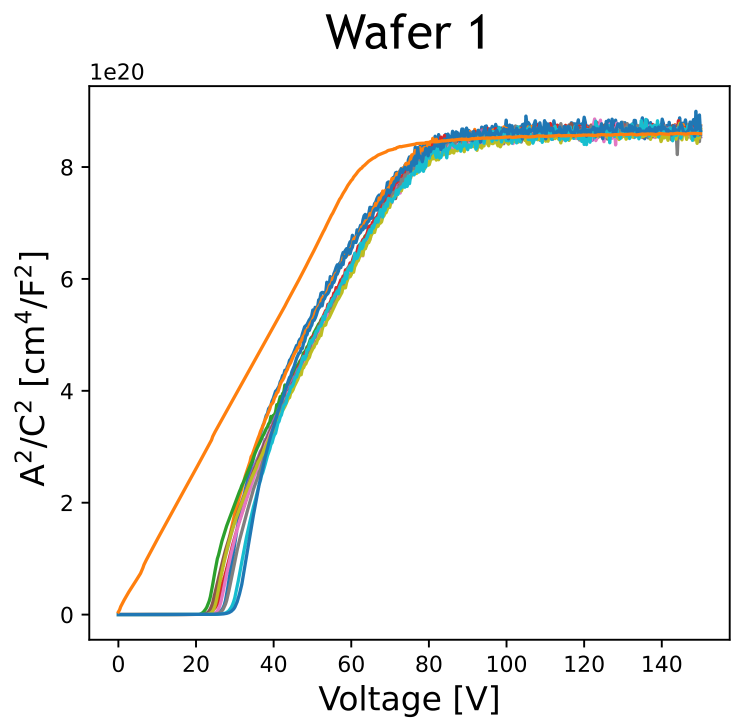


Atomic Force Microscope

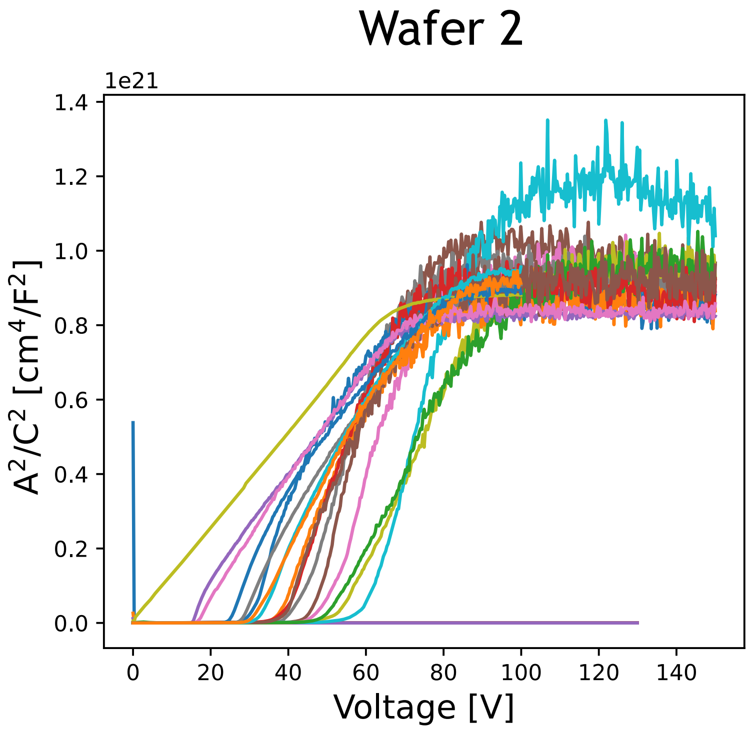


Scanning Electron Microscope

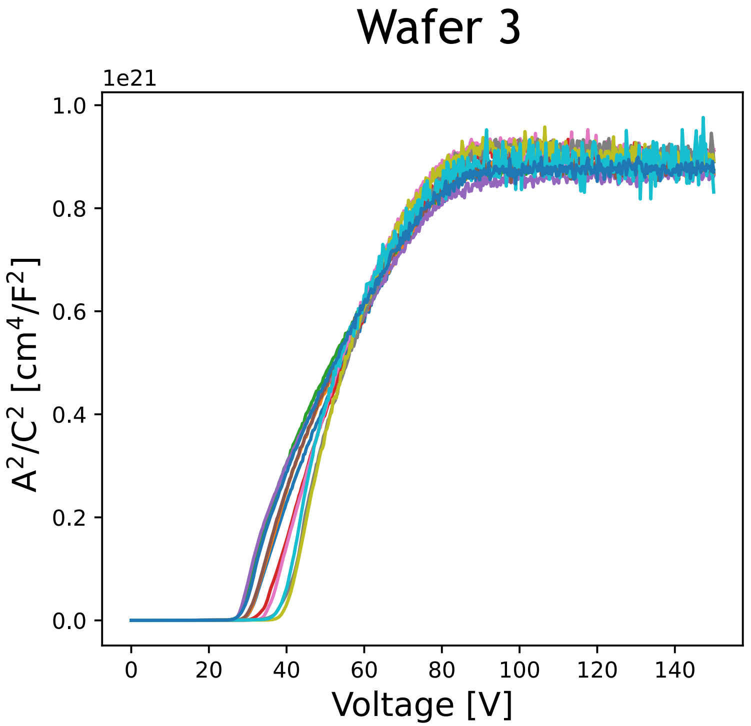
Electrical Characterization - CV



$V_{gl} = (22 - 30)\ V$

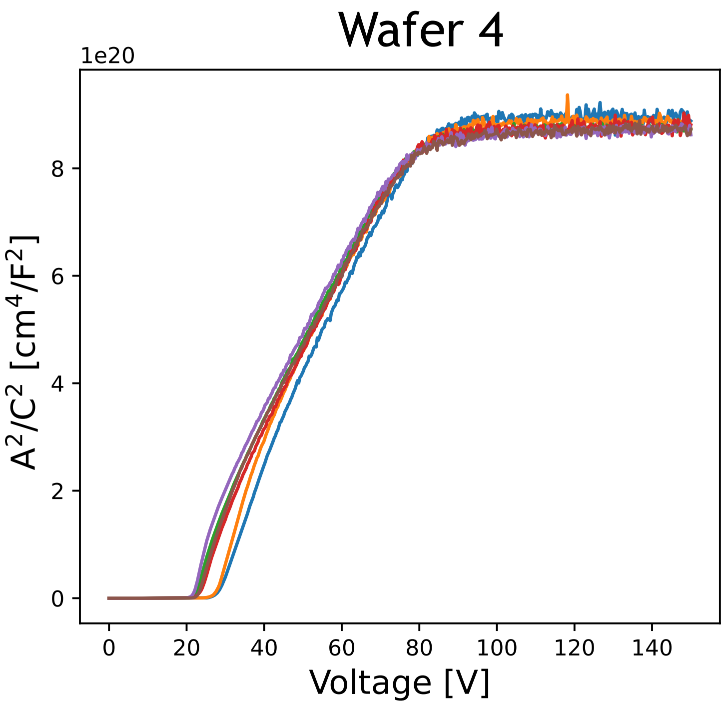


$V_{gl} = (15 - 62)\ V$

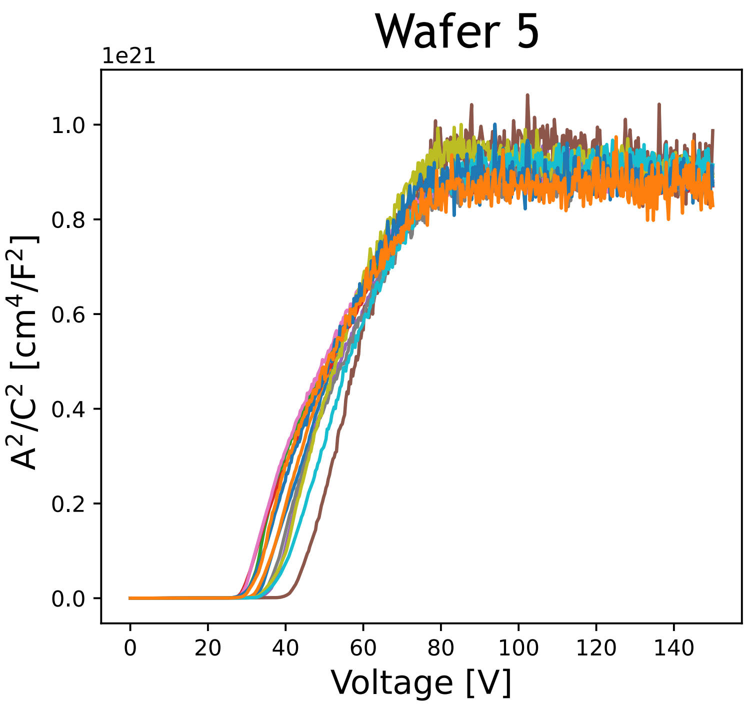


$V_{gl} = (27 - 42)\ V$

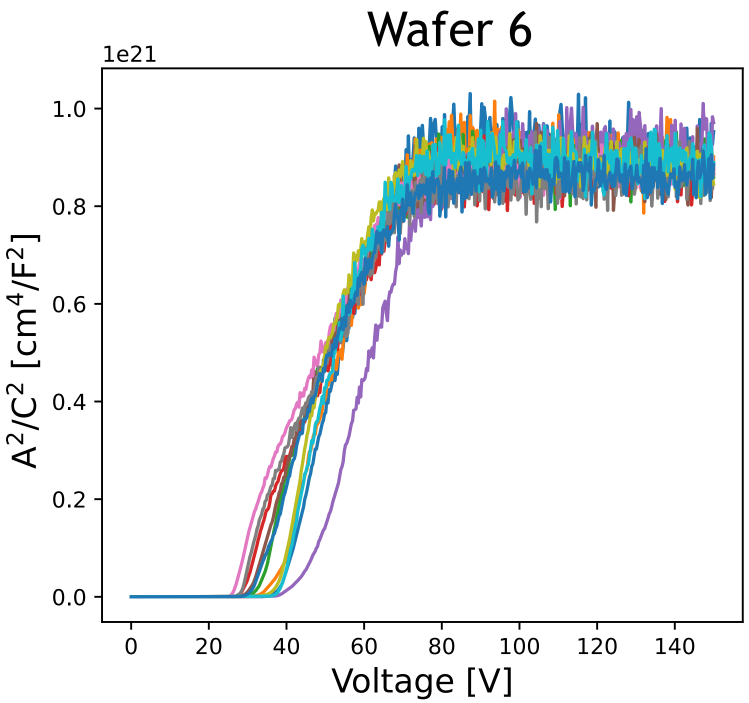
Electrical Characterization - CV



$$V_{gl} = (21 - 28)\ V$$

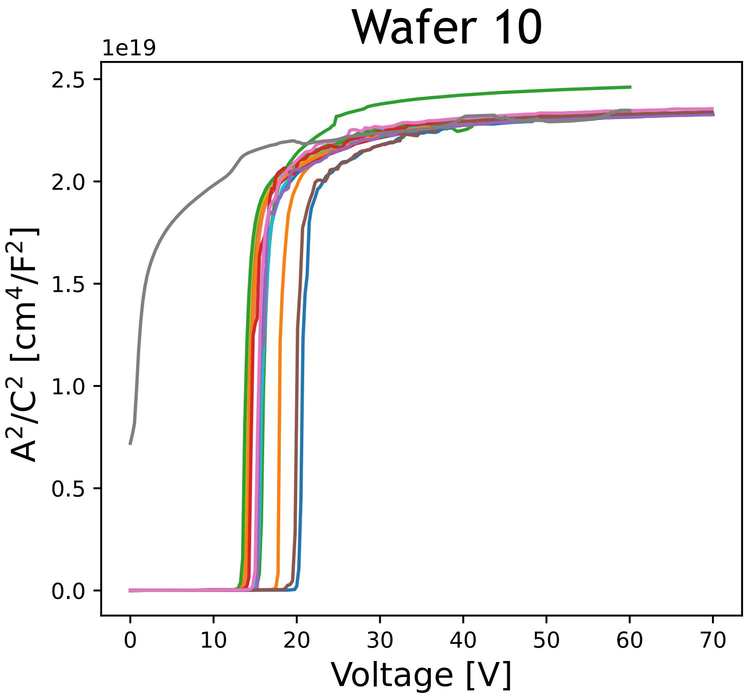


$$V_{gl} = (27 - 41)\ V$$

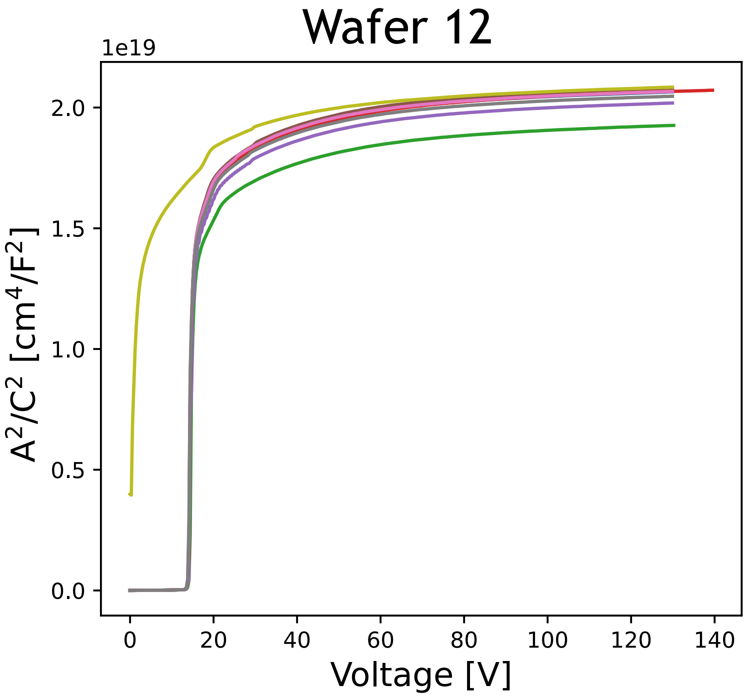


$$V_{gl} = (25 - 40)\ V$$

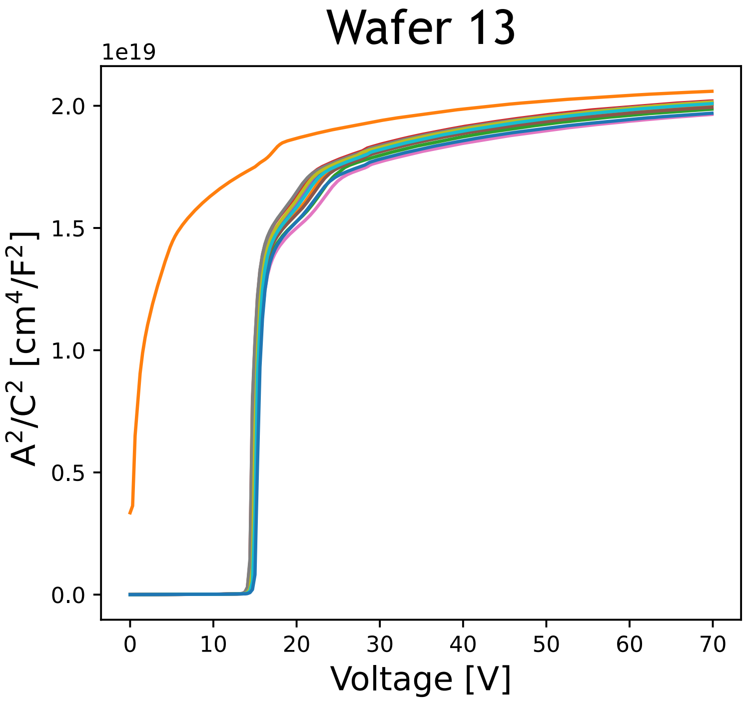
Electrical Characterization - CV



$$V_{gl} = (13 - 21)\ V$$



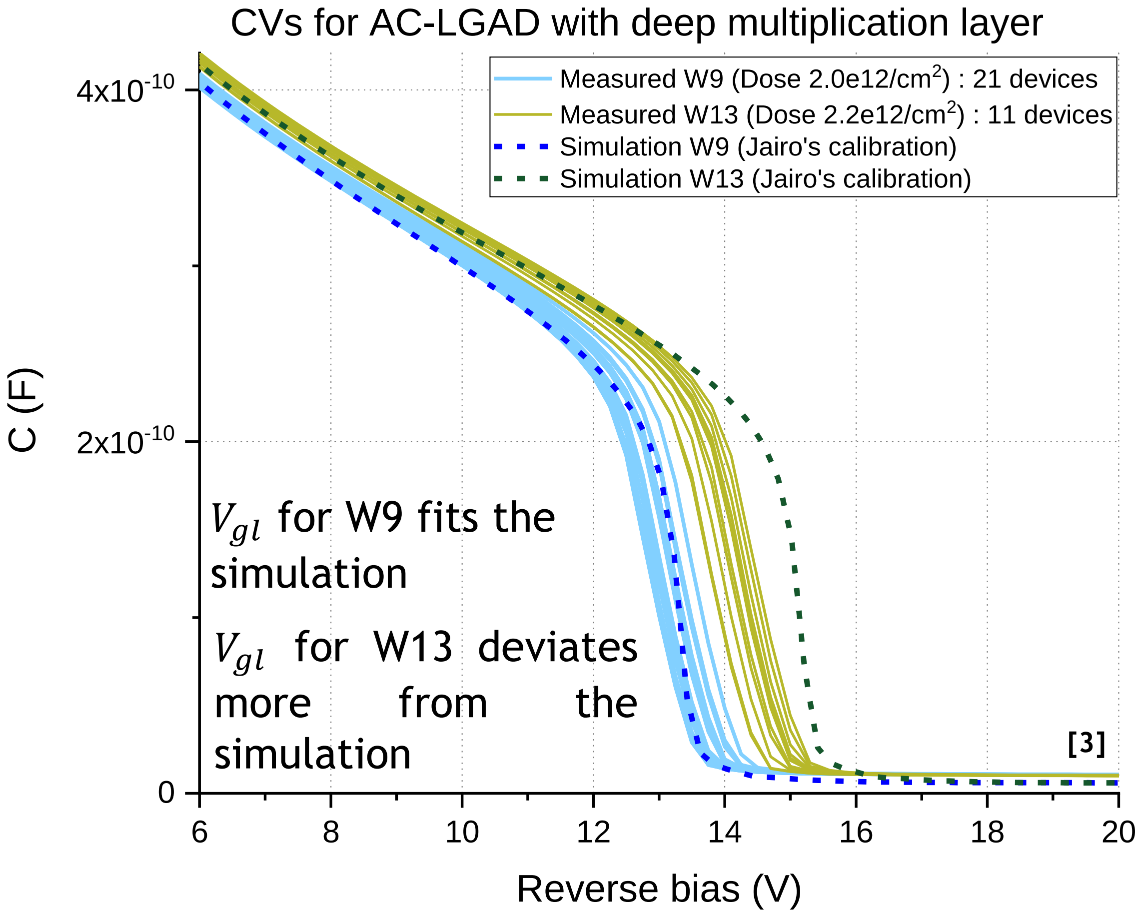
$$V_{gl} \approx 14\ V$$



$$V_{gl} \approx (14 - 15)\ V$$

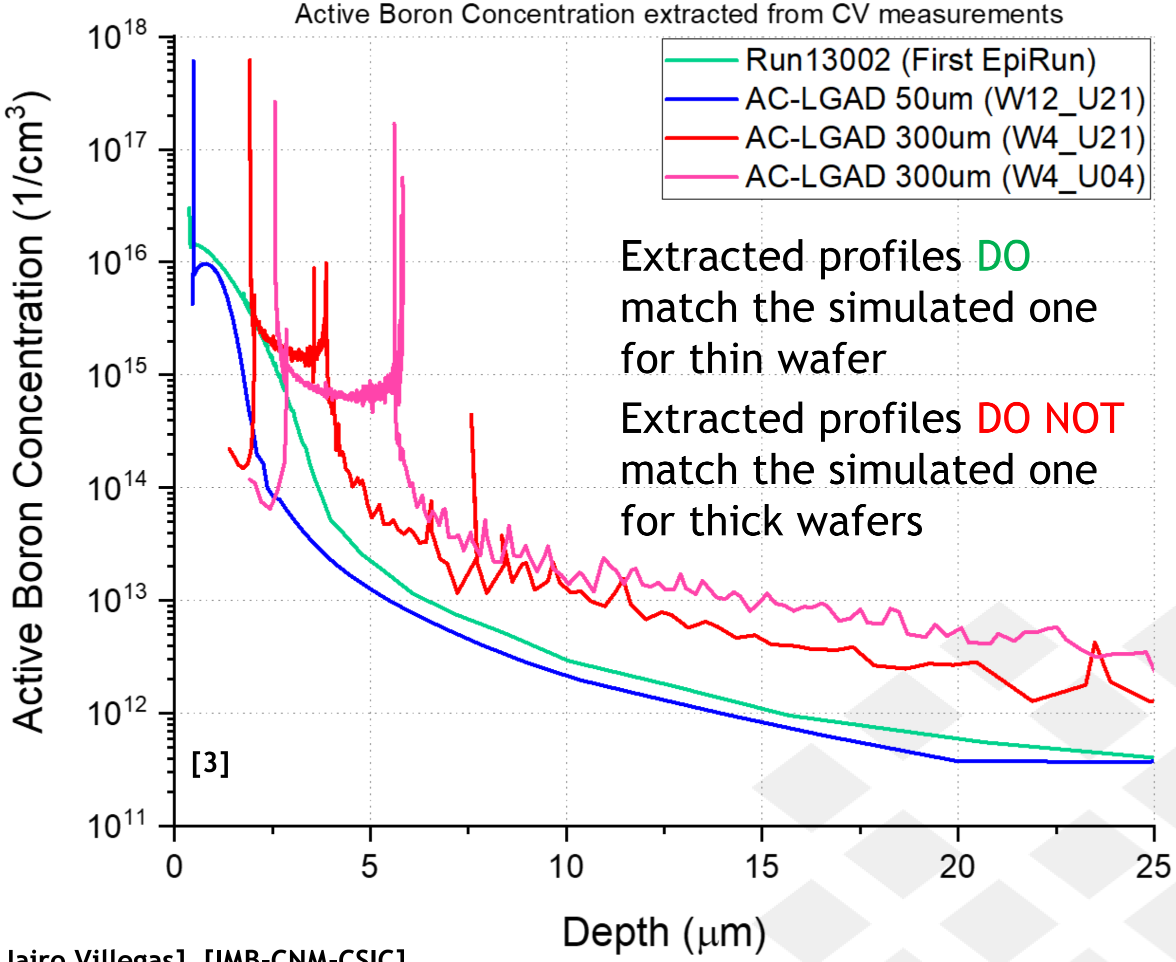
Simulation of the CV

50 um thick



V_{gl} for W9 fits the simulation

V_{gl} for W13 deviates more from the simulation

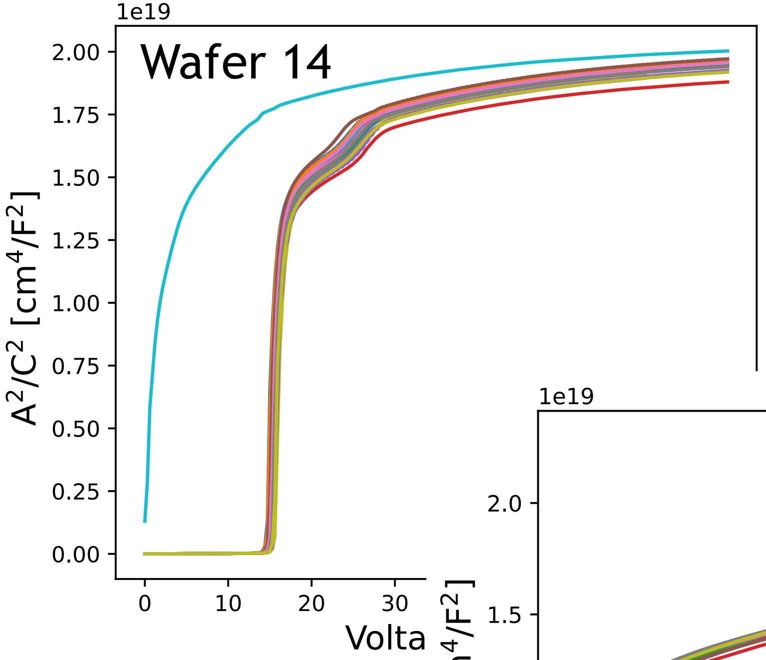


Extracted profiles DO match the simulated one for thin wafer

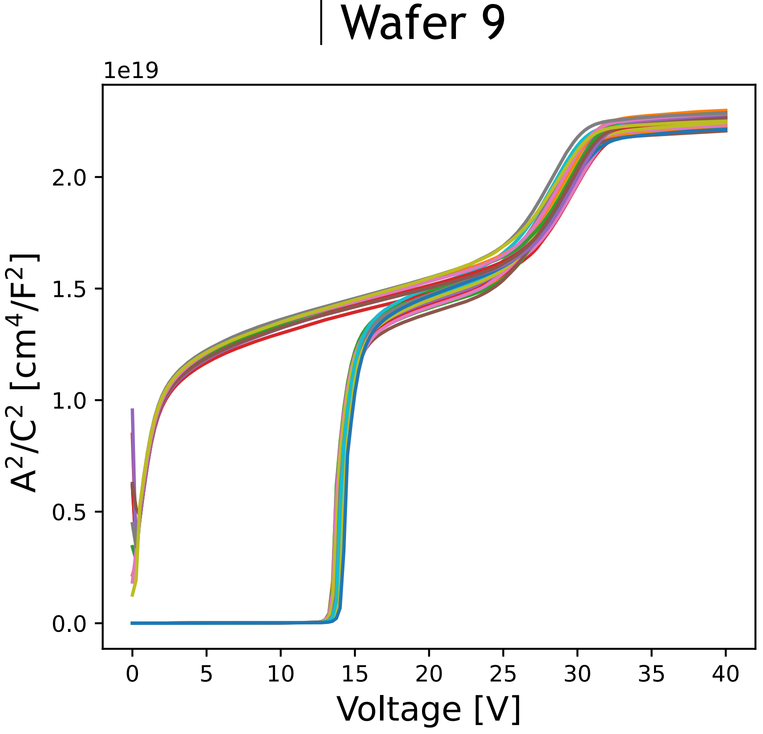
Extracted profiles DO NOT match the simulated one for thick wafers

[3] Plot created by [Jairo Villegas], [IMB-CNM-CSIC]

Electrical Characterization - CV



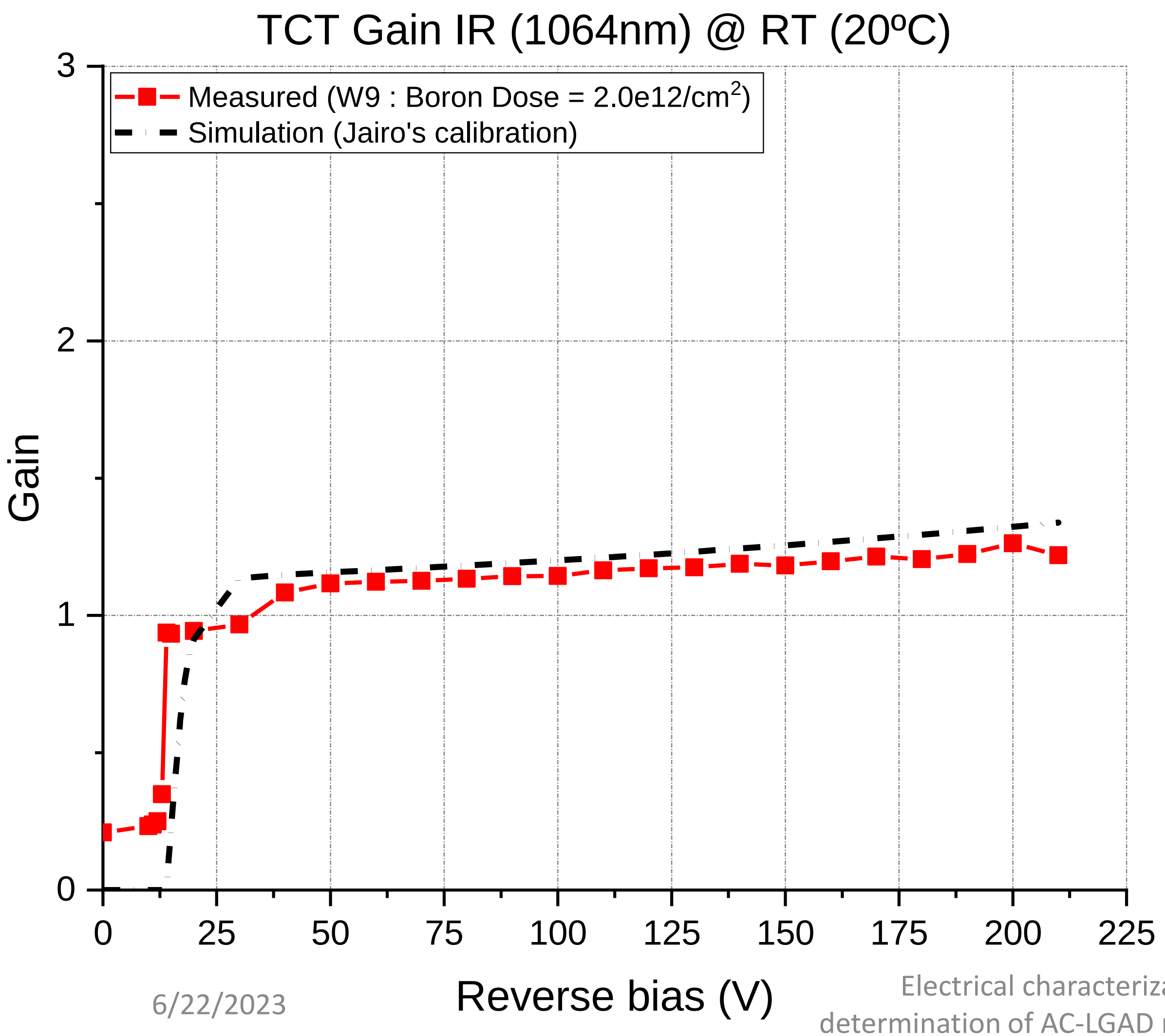
$V_{gl} \approx (14 - 15)\ V$



Summary of the CV results

- **Thick wafers have high spread in V_{gl}**
- **Thin wafers have much narrower V_{gl}**
- **V_{FD} is not precisely determined as for the higher voltages the current is unstable**
  - Estimated range (60-80 V)
- **The device is instantly depleted with exception of wafer 9**
- Extracting the doping profile from the CV curves for thin wafers gives a good agreemeng with the simulation results wheares no agreement was found with thick wafer

Gain Simulation

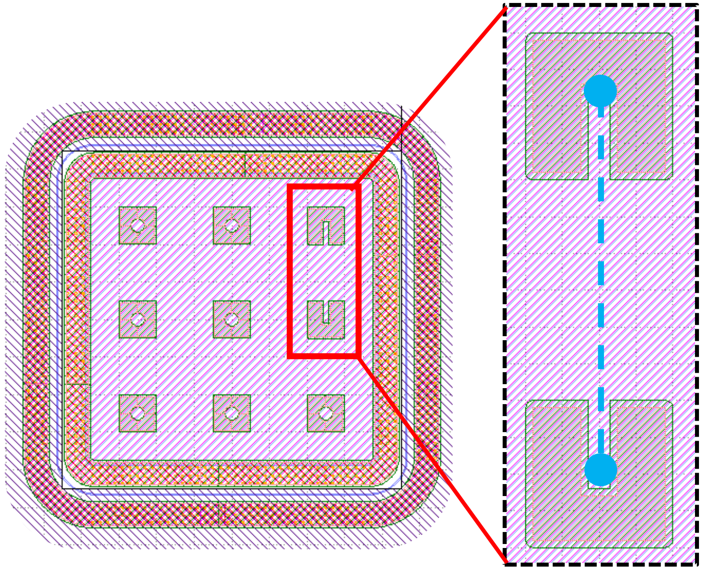


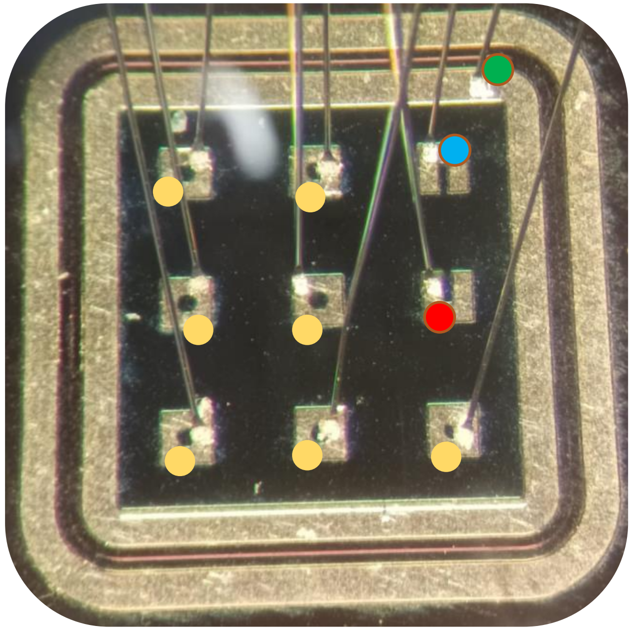
- The simulation matches the measurement well
- Reprocessed W7 is expected to have higher gain
- New AC-LGAD run is planned and will have higher gain

II Part - TCT Measurements

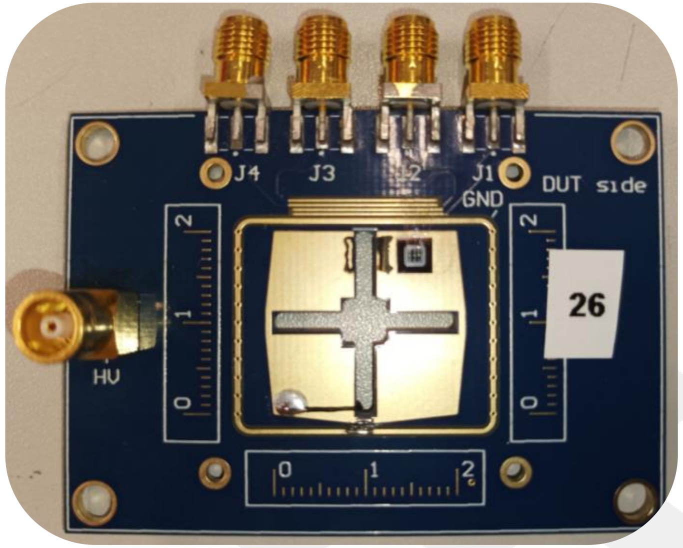
Samples & Experimental Setup

- Wafer 9 (50 µm); low dose 2.0 e12/cm^2; sample I05
- Wafer 14 (50 µm); high dose 2.2 e12/cm^2; sample I05





Channel 1
Channel 2
Channel 3
Channel 4



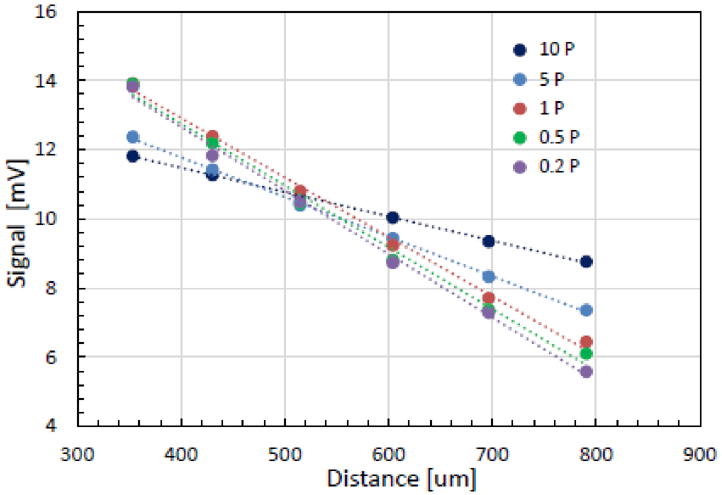
Line scan between 2 pixel openings → Signal recorded in 3 channels

Linear attenuation

- **The signal decreases with increasing the distance of the laser from the AC pad**
  - **The signal decrease between adjacent pads shows linear attenuation behavior**
  - **Linear attenuation is described by the linear attenuation factor A [mV/µm]**

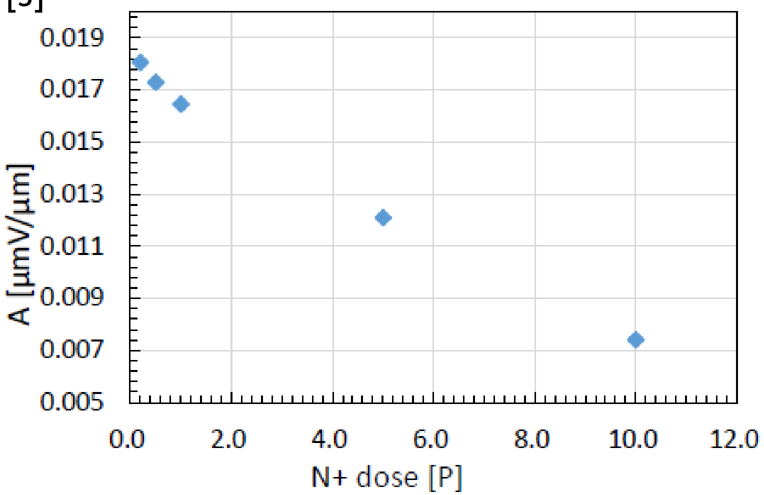
- **The attenuation factor is dependant on the n+ dose**
  - **0.0074 mV/µm - 0.018 mV/µm for 10P and 0.2P dose respectively [3]**

[3]



(a)

[3]

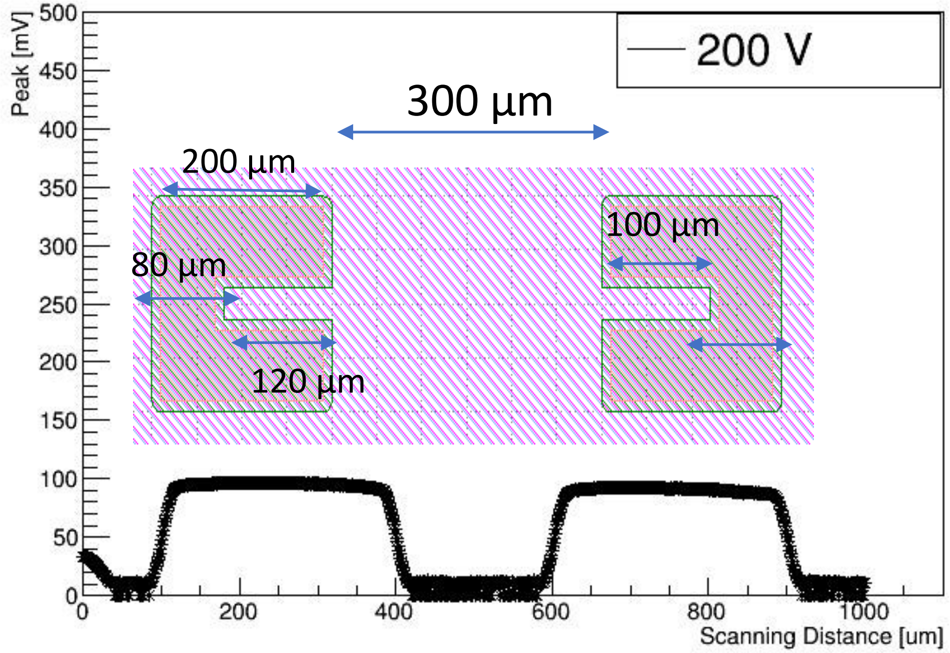


(b)

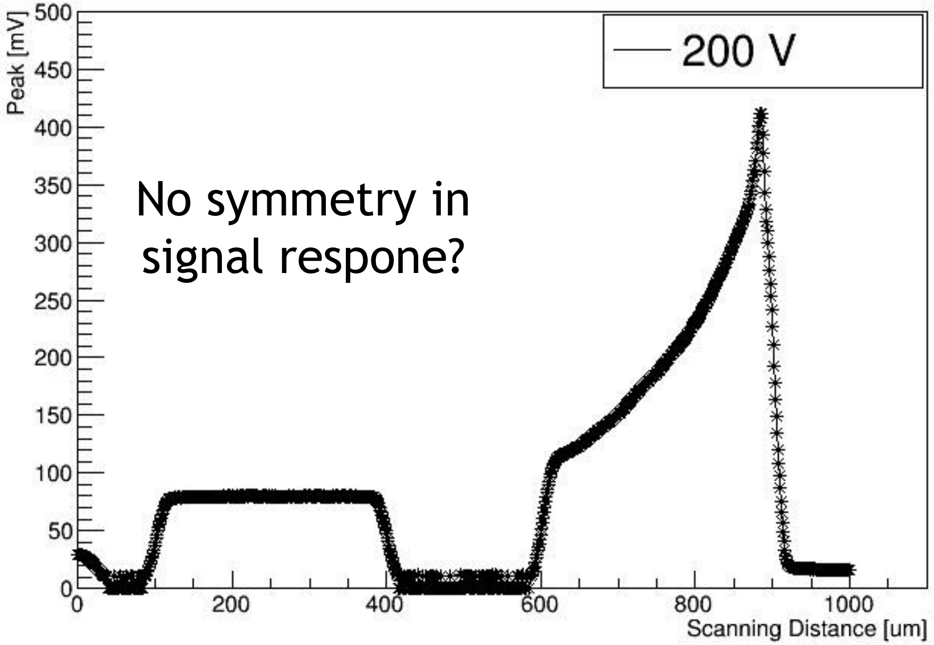
[3] Li, M. (2022, December 7). *The performance of large-pitch AC-LGAD with different N+ dose*. arXiv.org. https://arxiv.org/abs/2212.03754

Wafer 9 (50 µm); low dose 2.0 e12/cm^2; **sample I05**

Channel 1



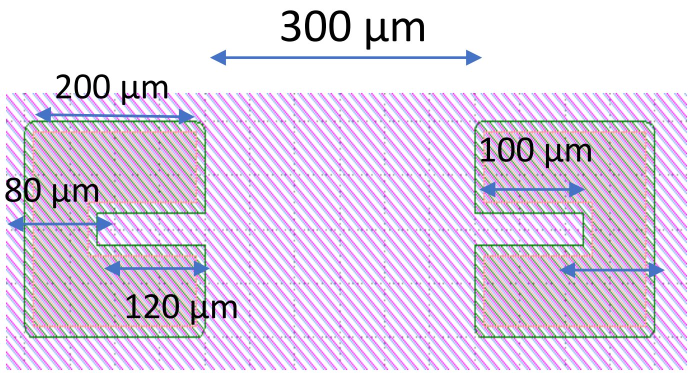
Channel 2



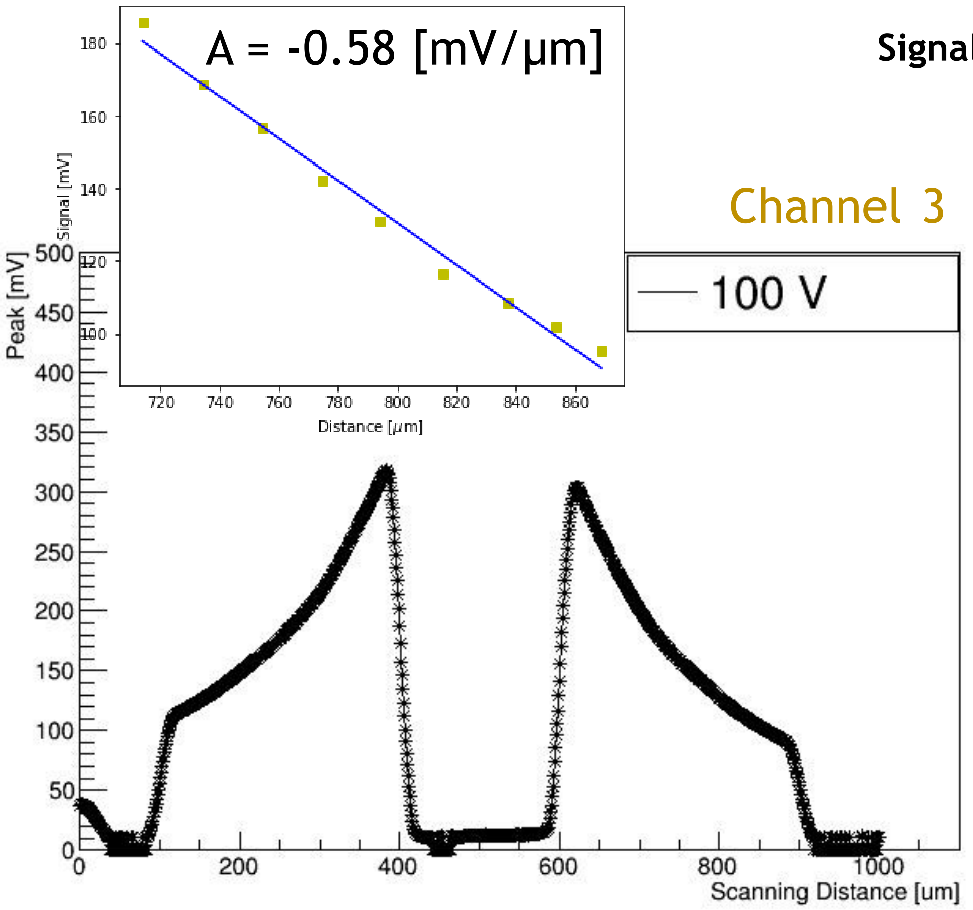
No symmetry in signal respone?

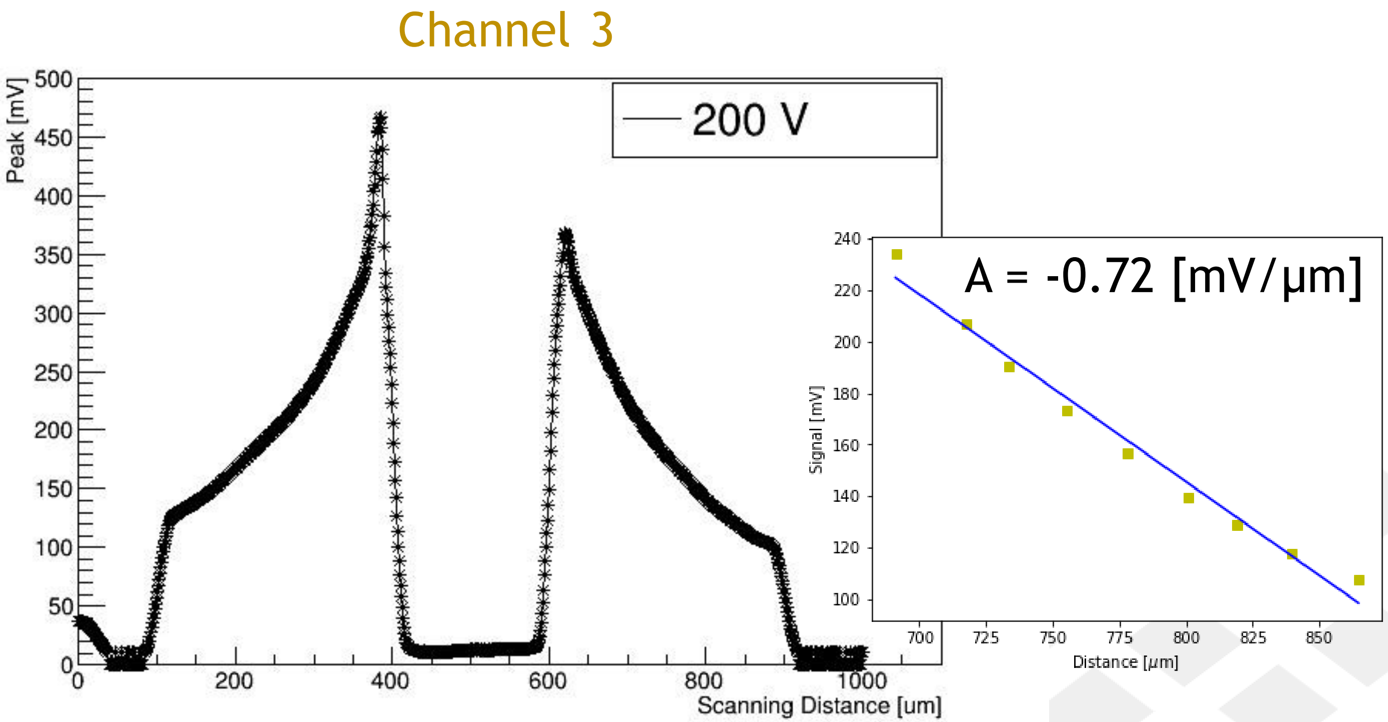
Possible misalignment

Wafer 9 (50 µm); low dose 2.0 e12/cm^2; **sample I05**

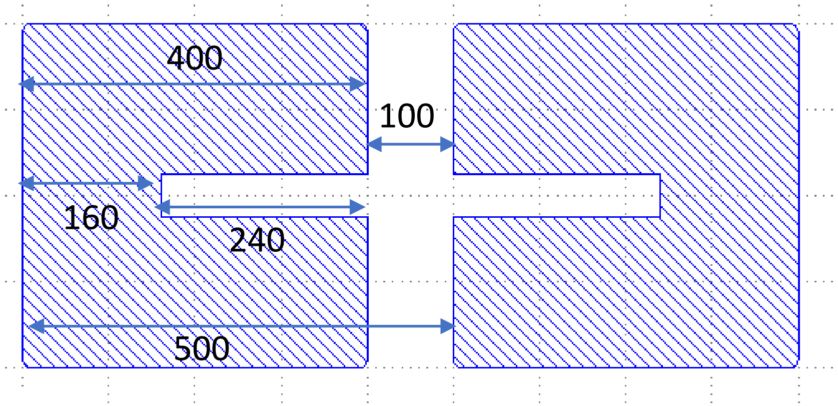


Signal symmetrical with respect to the pitch distance

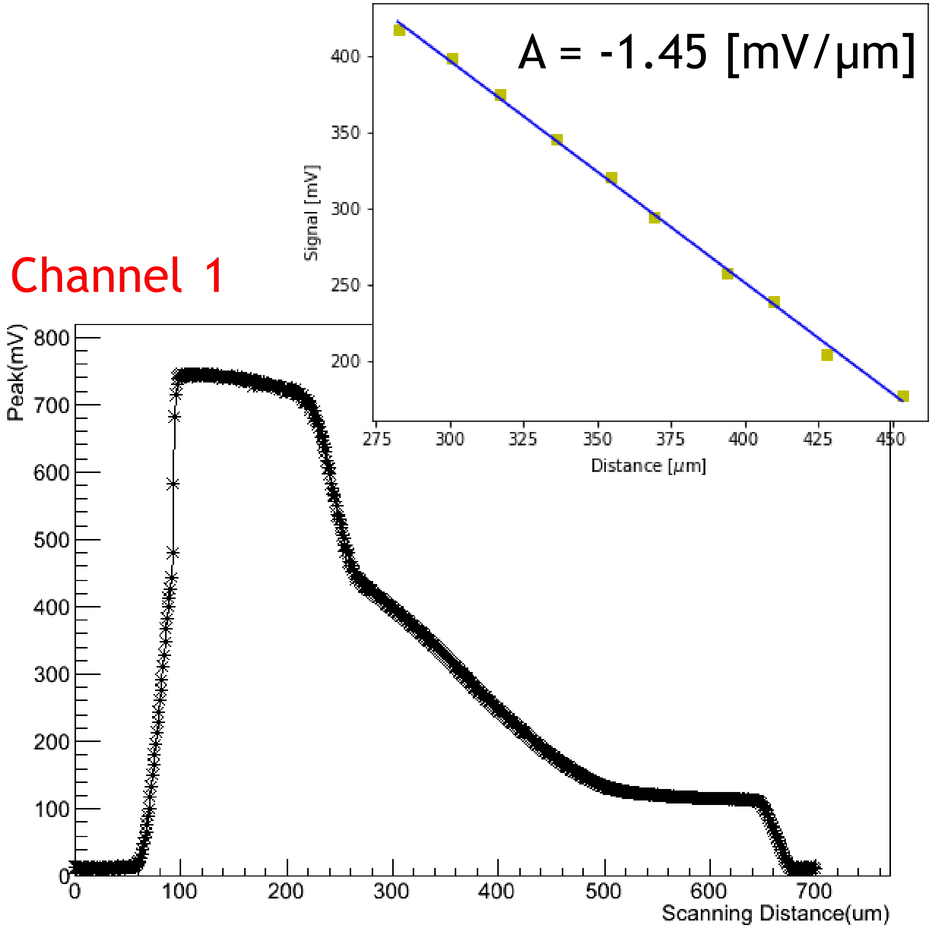




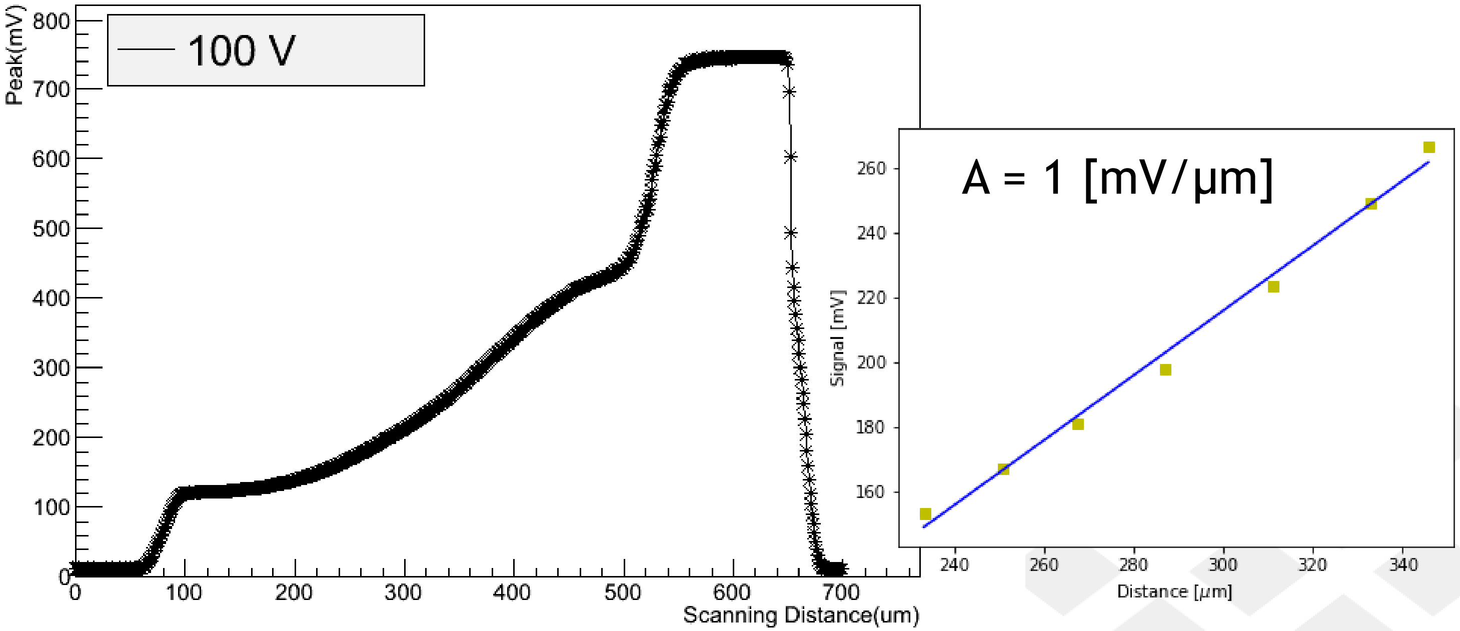
Wafer 9 (50 µm); low dose 2.0 e12/cm^2; **sample 02**



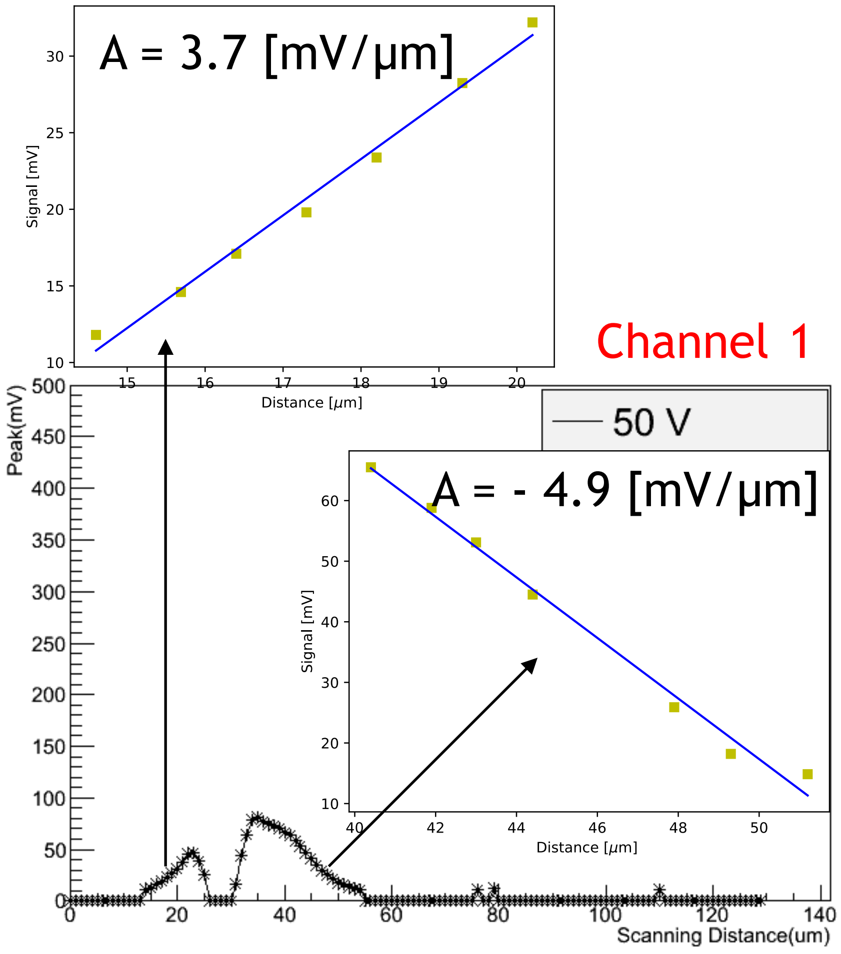
Channel 1

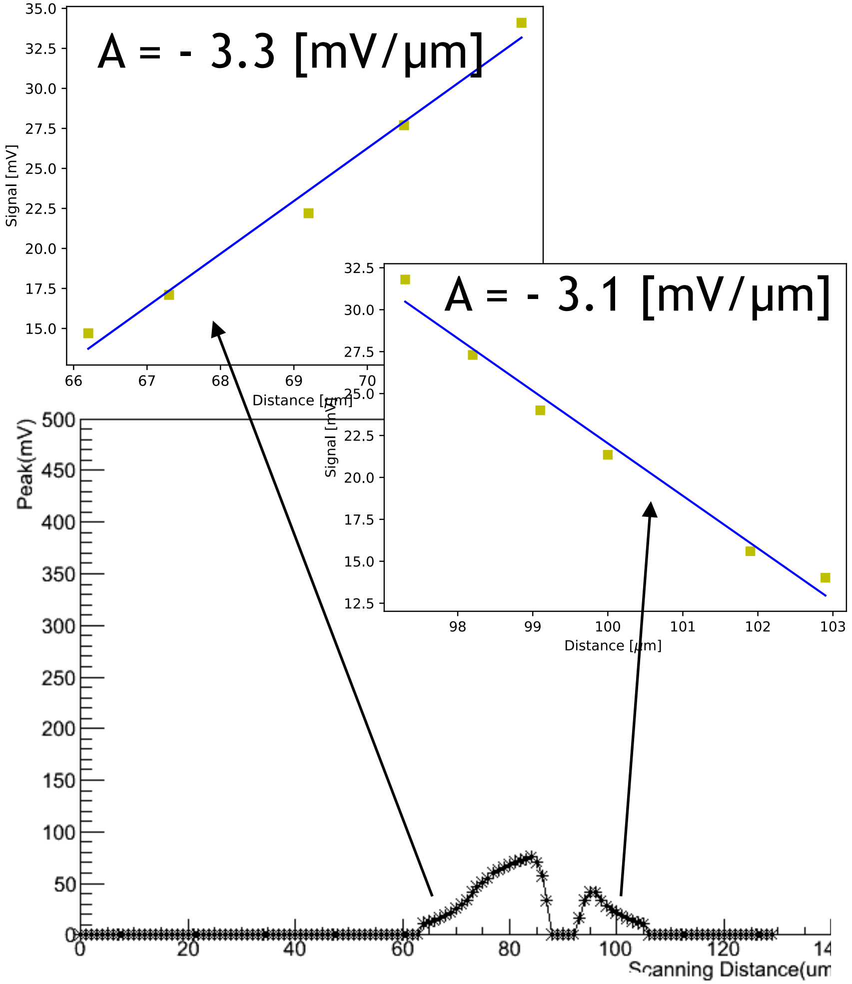


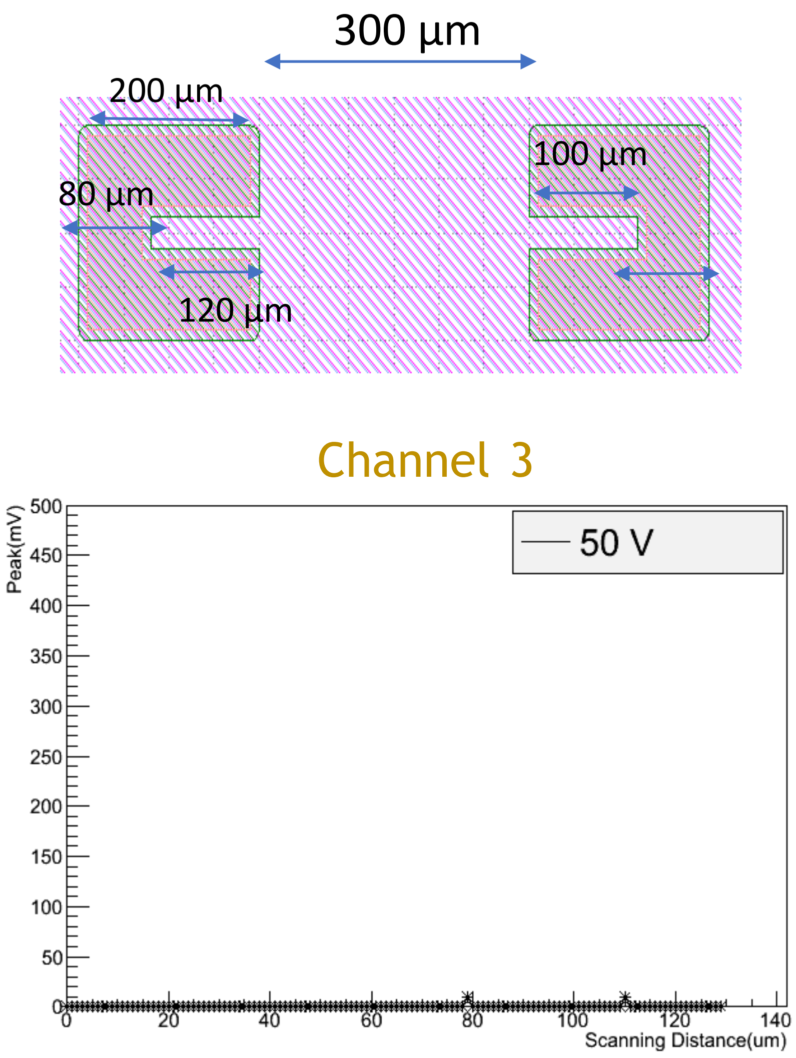
Channel 2



Wafer 14 (300 µm); high dose 2.2 e12/cm^2; **sample 02**

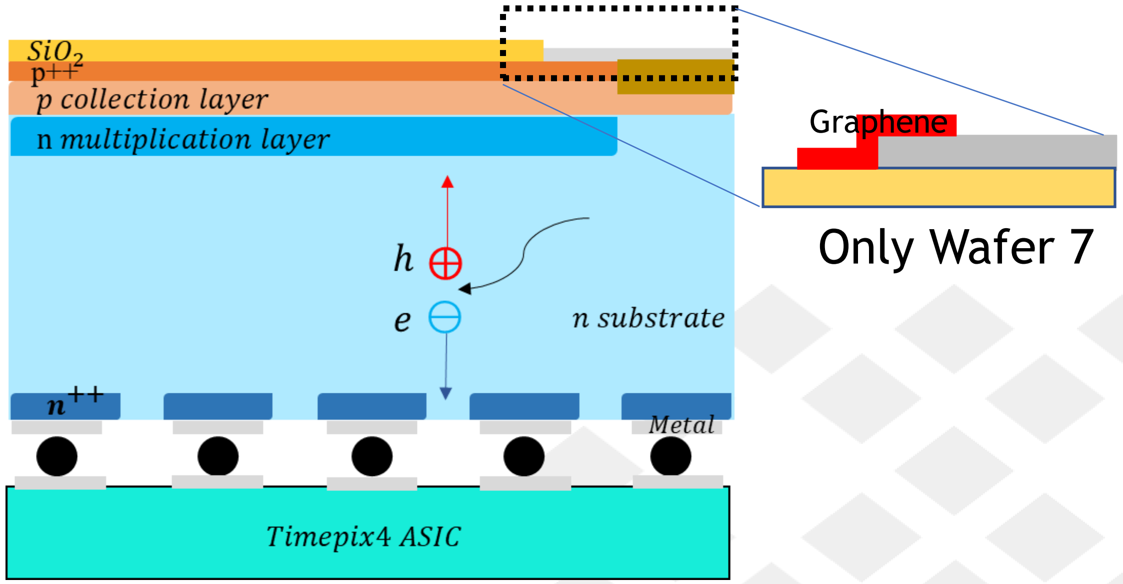






Conclucions & Future Plan

- 16020 run - 12 wafers already finished and tested
  - Thick wafers show extremely high leakage current
  - Gain is small (1.2) but new run is planned to be launched in the near future for higher gain wafers
  - Wafer 7 is reprocessed and is going to be implemented with graphene (to make contact with metal and dielectric)
  - The wafers have been sent for UBM
  - Proton irradiation planned in the future
- pLGAD run 16273 is soon to finish
  - The SoftPix project aims to produce pixel photon counting pixel sensor with high spatial resolution (55 μm) by bump-bonding a pLGAD and AC-LGAD pixel sensor to Timepix4 and Medipix3
    - Image soft objects that are transparent for X-ray photons with energy of 1 keV (to be tested)



Acknowledgements

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"Una manera de hacer Europa"

AGENCIA ESTATAL DE INVESTIGACIÓN

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Thanks for
your attention

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Backup

PIN doping conc. from 1/C2

Wafer	N [cm-3]	R [kΩ cm]
1	1.006E+12	13.183
2	7.64E+11	17.354
4	1.01E+12	13.131
5	1.006E+12	13.183
6	1.20962E+12	10.965

Should be (6-12 kΩ cm)

Wafer	N [cm-3]	R [kΩ cm]
10	4.83E+12	2.764
12	1.097E+13	1.217
13	8.95E+12	1.483
14	6.19E+12	2.144

Should be > 1 kΩ cm

PIN IVs from all wafers