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55 µm thick NLGAD sensors from FBK

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Motivation and the transition from p- to n-LGAD technology

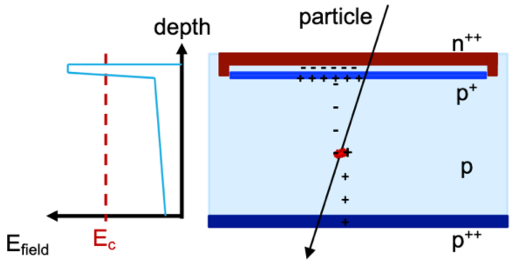
Motivation

- To detect low-penetrating particles, e.g., photons
- To investigate the design of the n-type gain implant, useful in the design of compensated LGAD
- To directly investigate donor removal at the donor concentration used in compensated LGAD

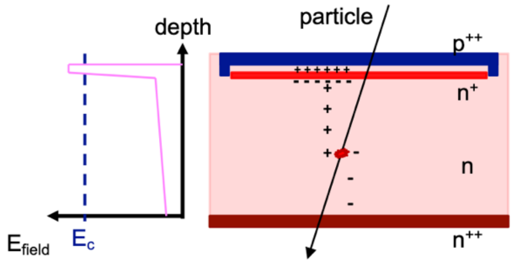
Two n-type LGAD (NLGAD) batches already produced by CNM on 300 μm thick substrates
[J. A. Villegas Dominguez et al., 41st RD50 Workshop]
[J. A. Villegas Dominguez et al., TREDI 2024]

Transition from p- to n-LGAD technology

- Swap of the type of the implants
- Tuning of implants concentration, based on their shape, through TCAD simulation



p-type LGAD
n-in-p
readout e



n-type LGAD
p-in-n
readout h

Motivation and the transition from p- to n-LGAD technology

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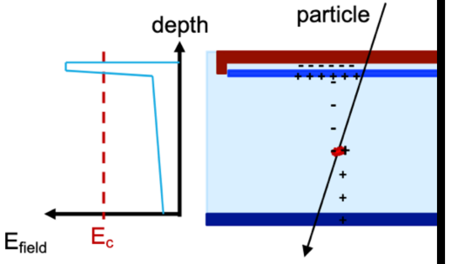

p-type LGAD
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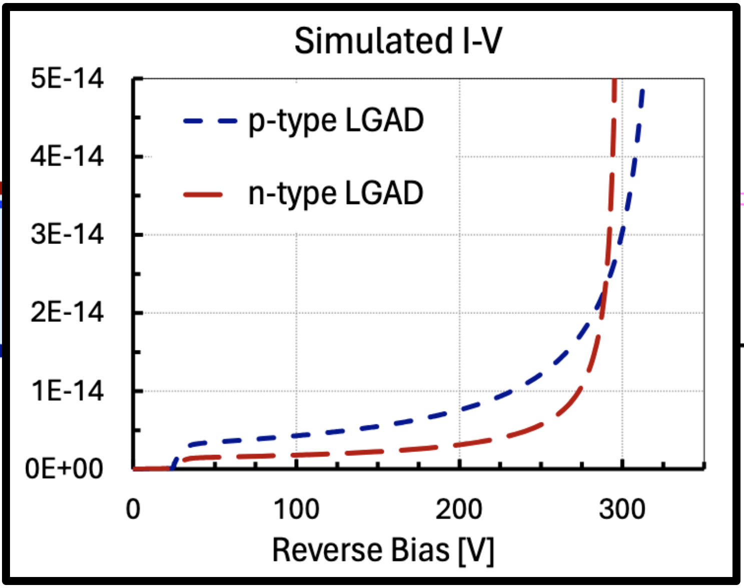
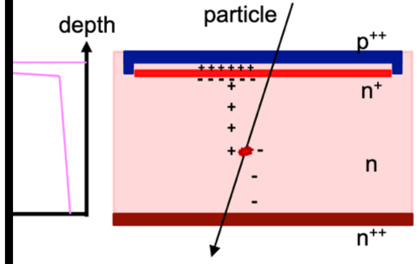
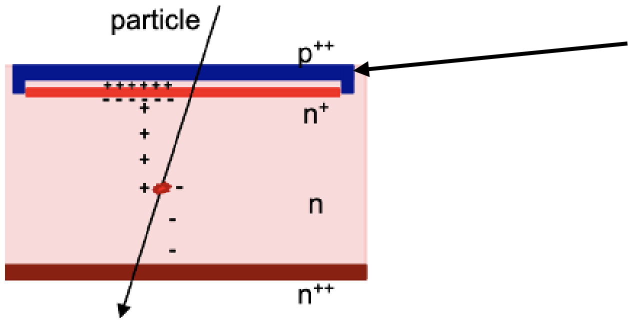




n-type LGAD
p-in-n
readout h

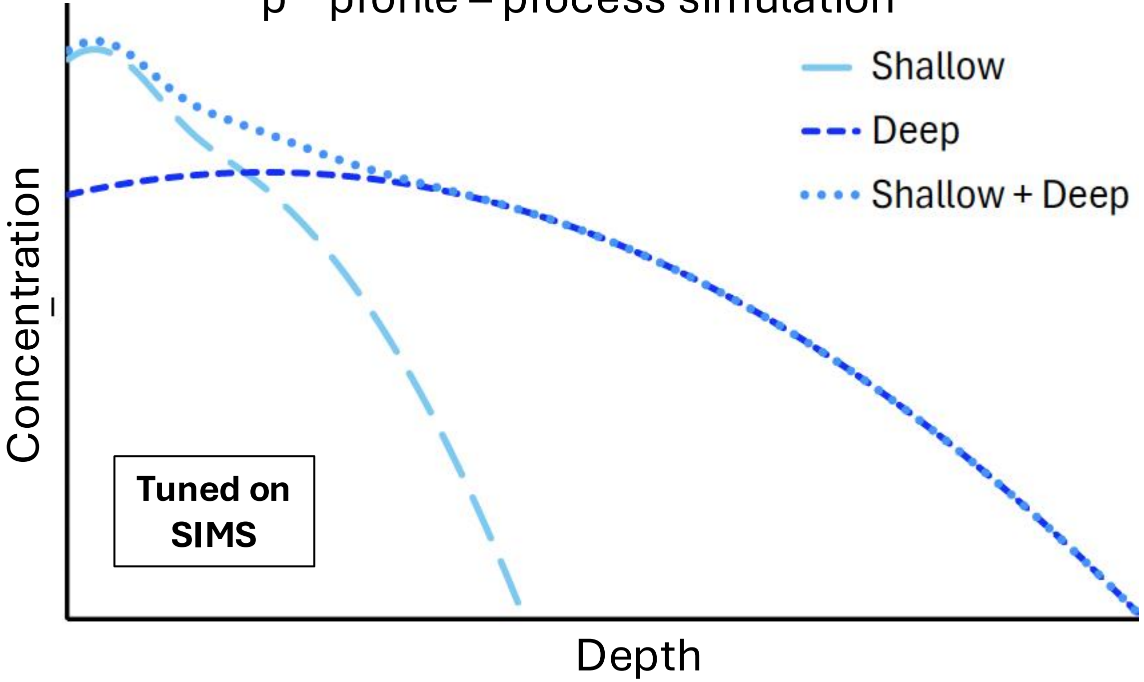
Design of the p^{++} electrode



Boron has a different penetration range and diffusivity in silicon, compared with n-elements

→ the p^{++} implant was designed explicitly for n-LGAD sensors

p^{++} profile – process simulation

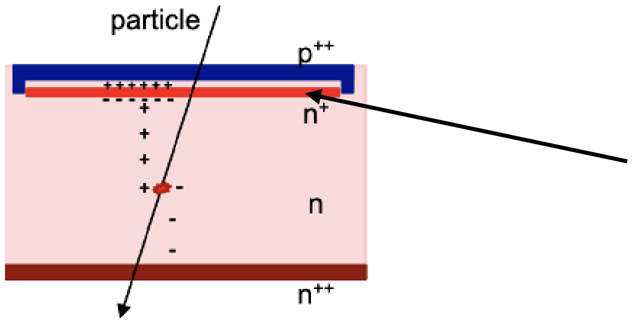


A lot of simulation have been performed to optimize the design of the p^{++}

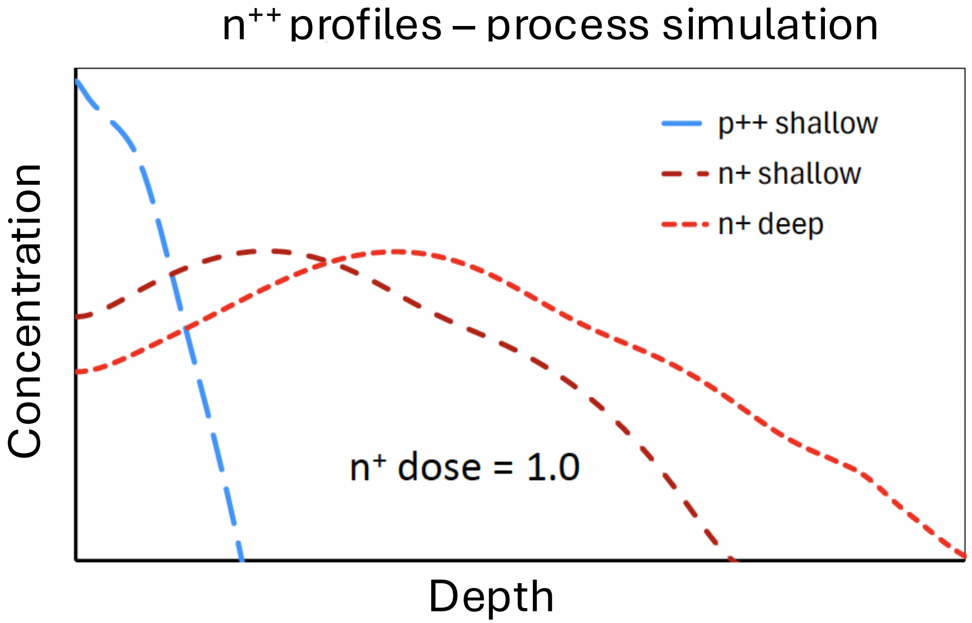
Three different design of the p^{++}:

- Shallow
- Deep
- Shallow-Deep

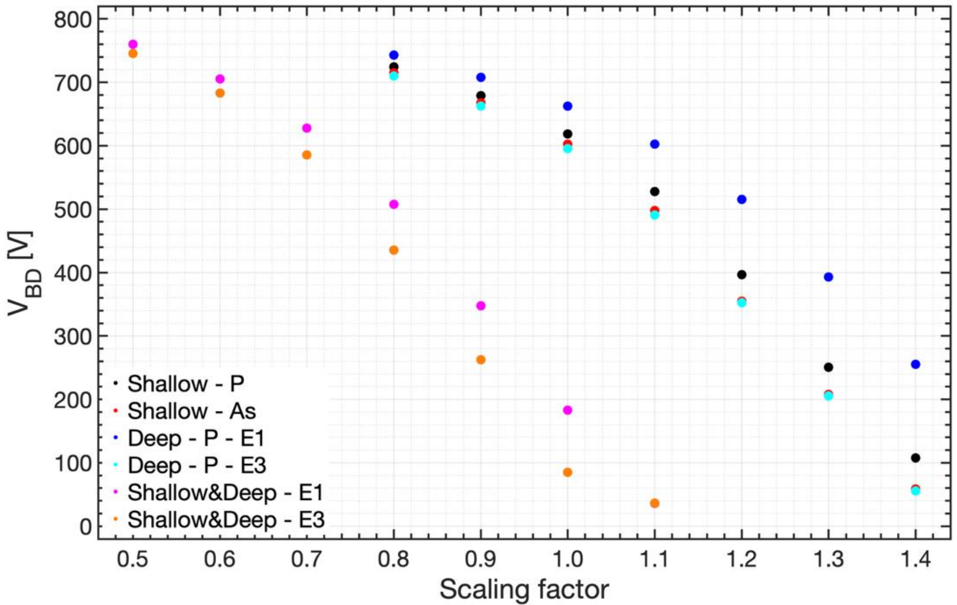
Design of the n$^+$ gain implant



- Two different depth of the n$^+$-implant have been investigated
- Different n$^+$ doses have been investigated
- Two n-type elements are used: Phosphorus and Arsenic



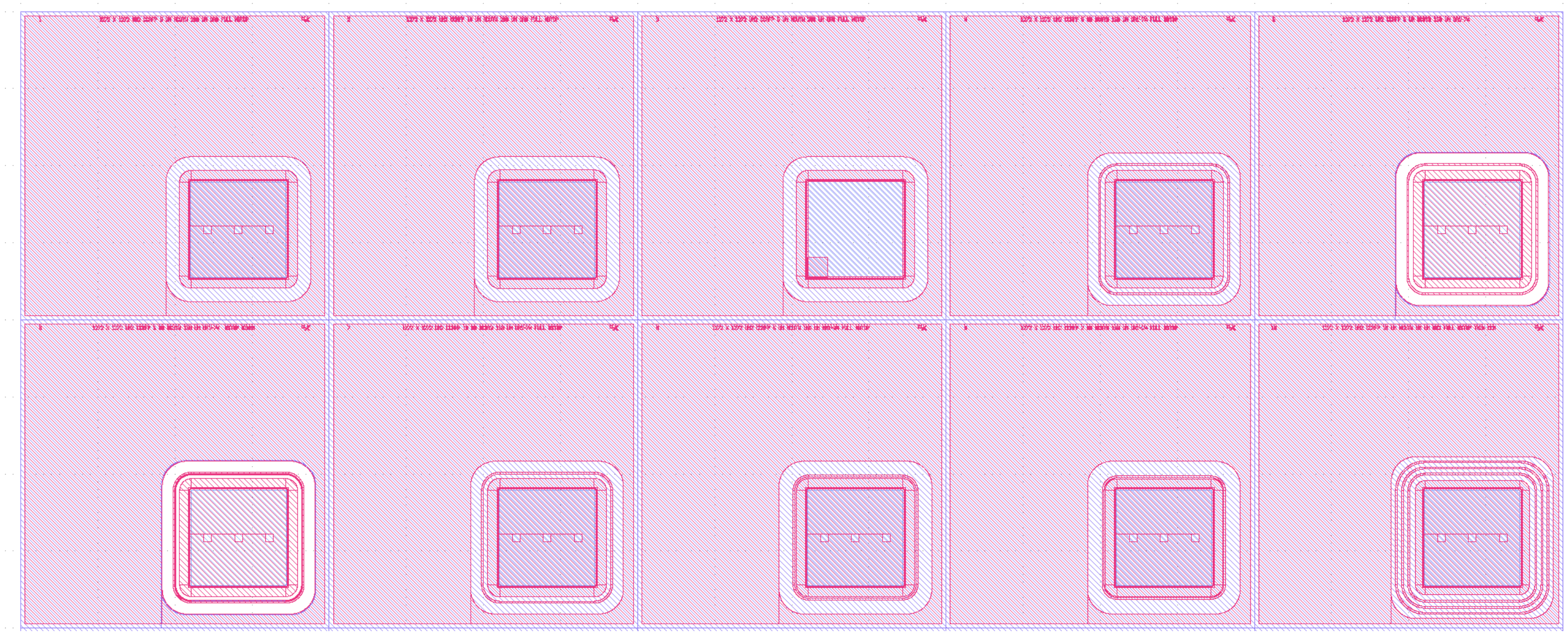
Several process simulation to assess the n$^+$ implantation energy



Several electrical simulation to select the optimal n$^+$ concentration

Design of the pixel periphery

The sensor periphery was designed to take into account the active thickness of **55 µm** and the very **high resistivity (> 10k Ω/cm)** of the **epitaxial substrates** of the NLGAD batch



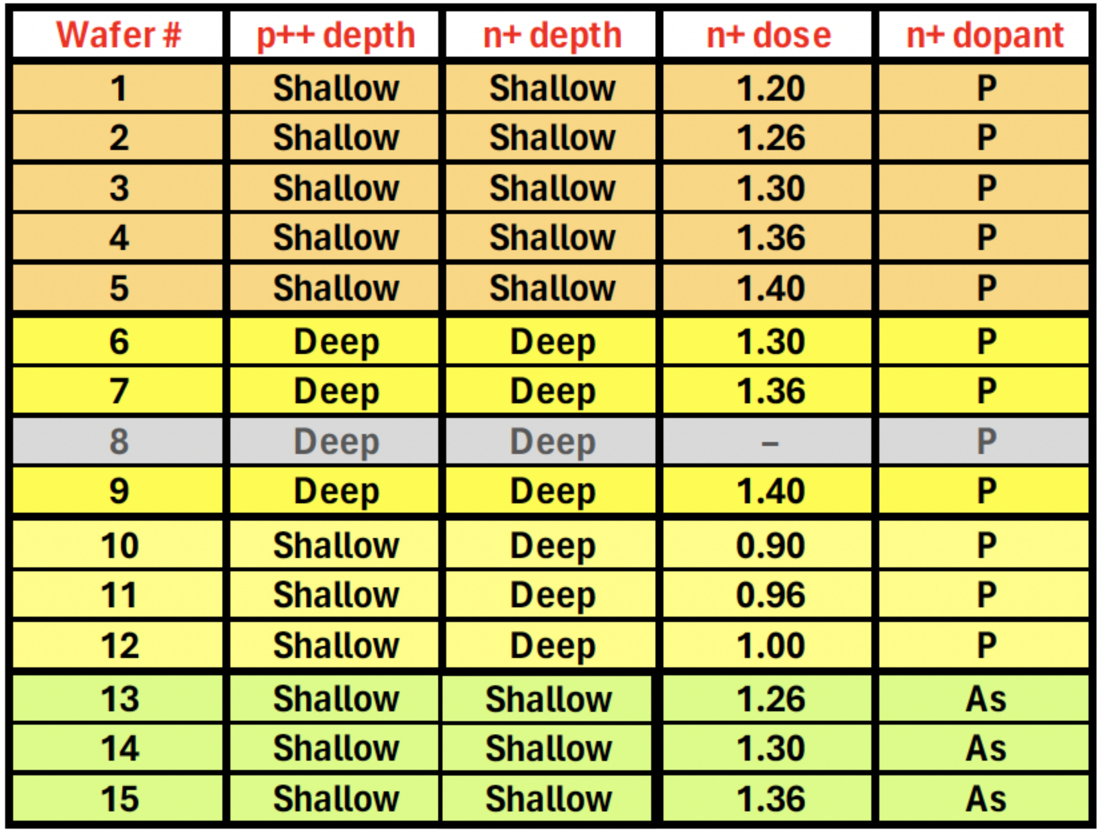
- **Edge width of 500 µm**

- **Three floating guardring options**
  - GR0 (zero floating GR)
  - GR1 (one floating GR)
  - GR3 (three floating GR)

- **Two n-type isolation strategy**
  - n-stop
  - n-spray
    - High dose
    - Low dose

NLGAD batch at FBK

15 epitaxial wafers with active thickness of 55 µm



Wafer #	p++ depth	n+ depth	n+ dose	n+ dopant
1	Shallow	Shallow	1.20	P
2	Shallow	Shallow	1.26	P
3	Shallow	Shallow	1.30	P
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5	Shallow	Shallow	1.40	P
6	Deep	Deep	1.30	P
7	Deep	Deep	1.36	P
8	Deep	Deep	–	P
9	Deep	Deep	1.40	P
10	Shallow	Deep	0.90	P
11	Shallow	Deep	0.96	P
12	Shallow	Deep	1.00	P
13	Shallow	Shallow	1.26	As
14	Shallow	Shallow	1.30	As
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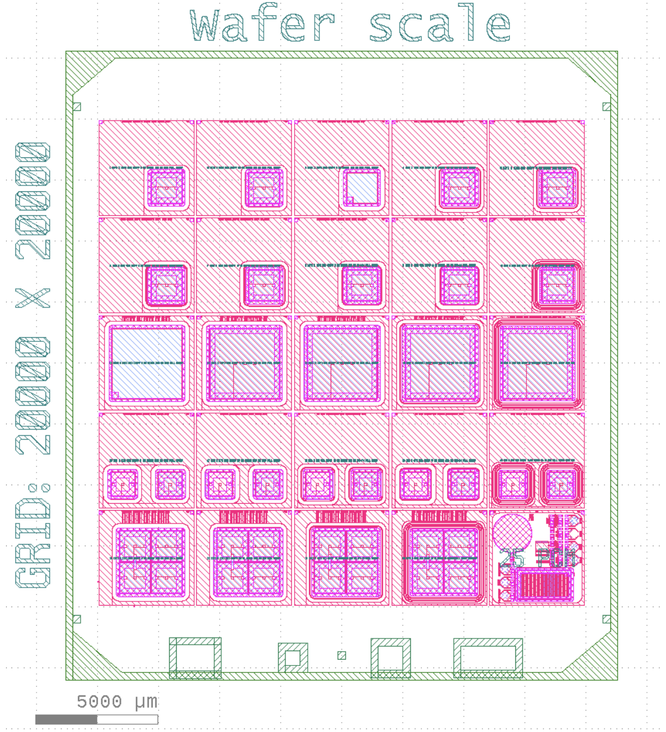
Reticle layout



Device geometries:

- Single pad
- PiN-LGAD couples
- 2x2 array
- Test structure

NLGAD batch at FBK

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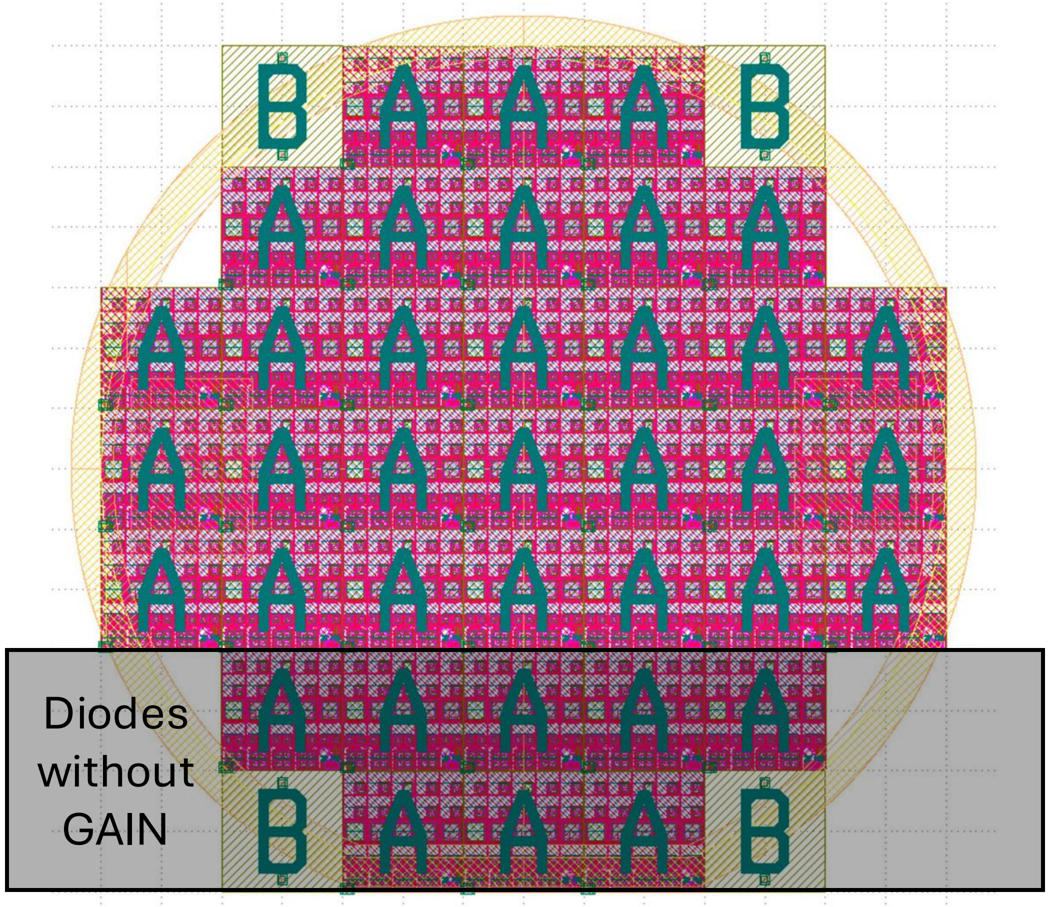
15	Shallow	Shallow	1.36	As

Two row without n^+ gain implant to test the working condition of the periphery



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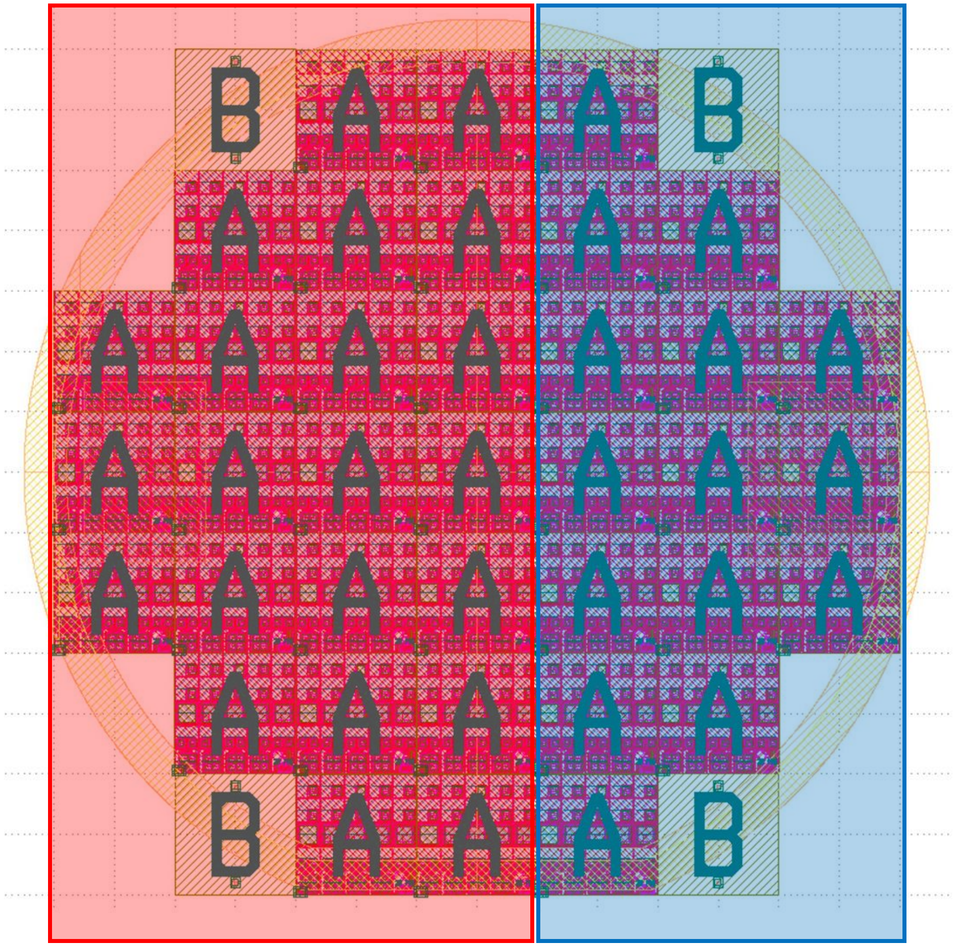
13	Shallow	Shallow	1.26	As
14	Shallow	Shallow	1.30	As
15	Shallow	Shallow	1.36	As

Two different doses of n-spray are implanted

High n-spay dose **Low n-spay dose**



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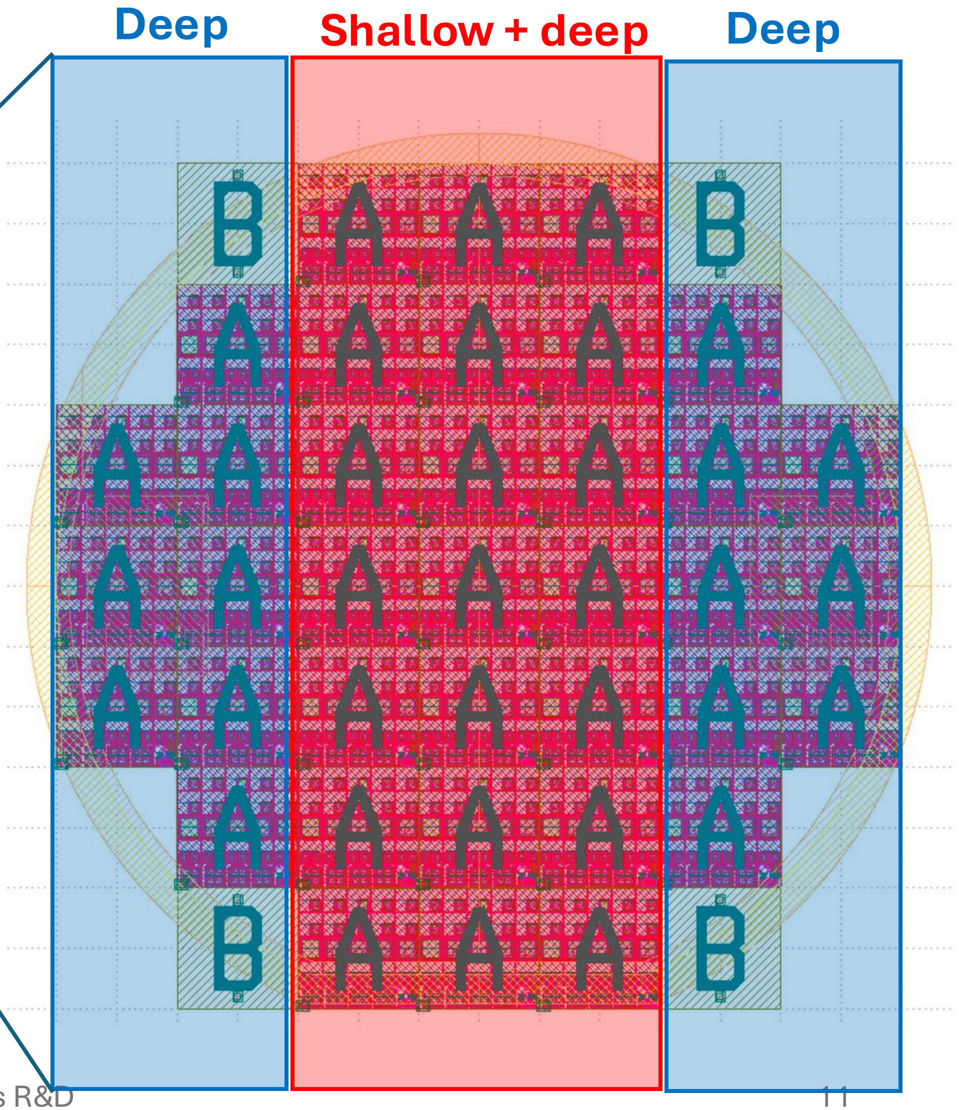
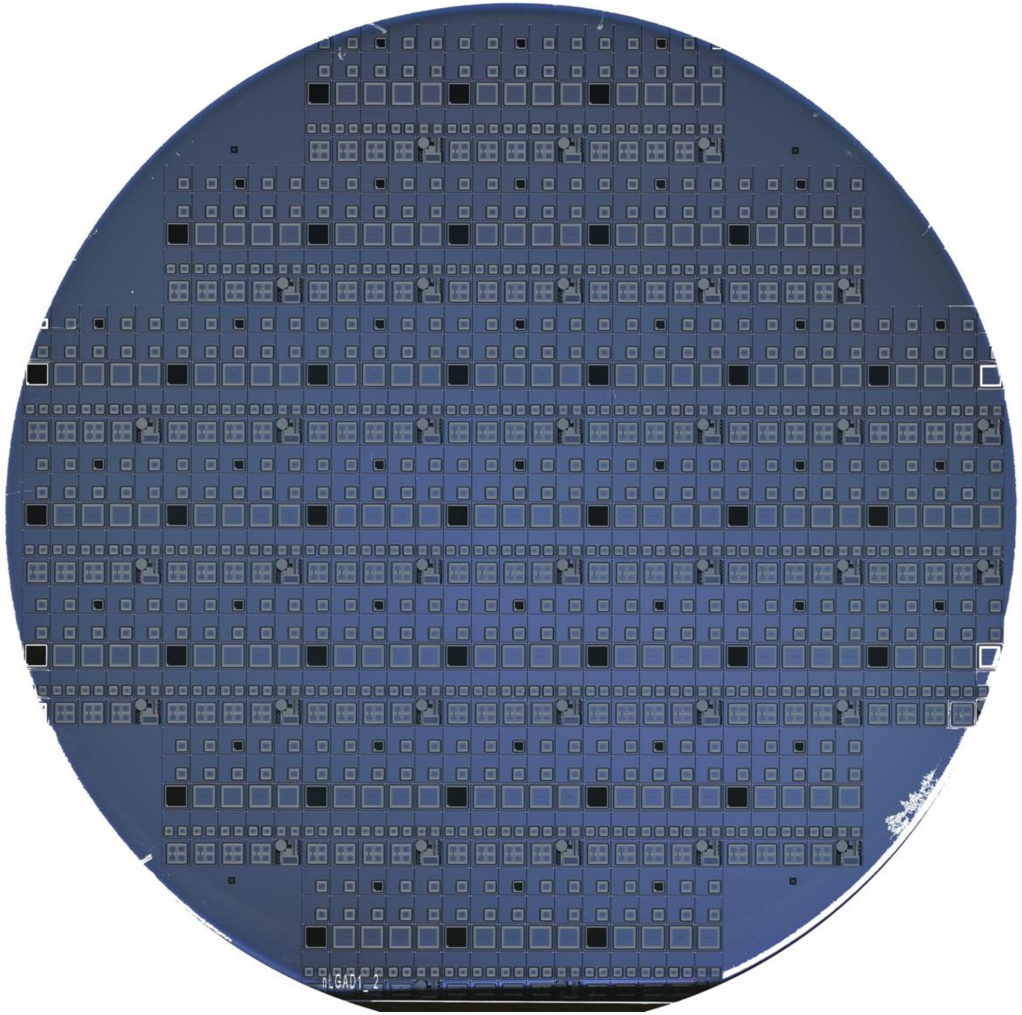
13	Shallow	Shallow	1.26	As
14	Shallow	Shallow	1.30	As
15	Shallow	Shallow	1.36	As

For deep p^{++}, also Shallow + Deep is investigated



Measurements on NLGAD batch

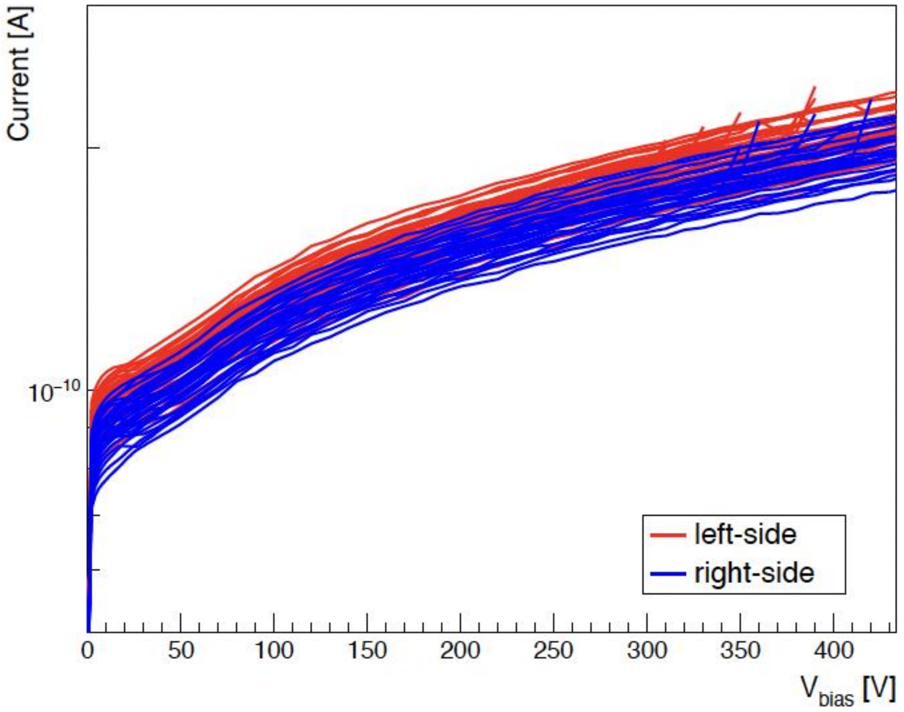


The NLGAD batch was released by the FBK clean room in mid September

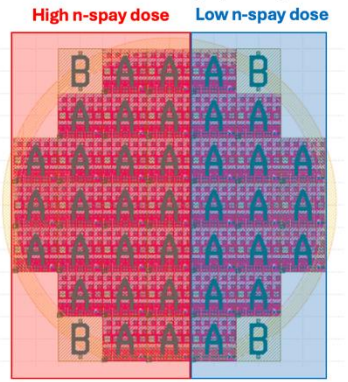
On-wafer measurements are on-going
- IV
- CV
- PCM
- Gain with Red & blue led

IV from PiN diode

IV curves from LGAD-PIN structures on W12

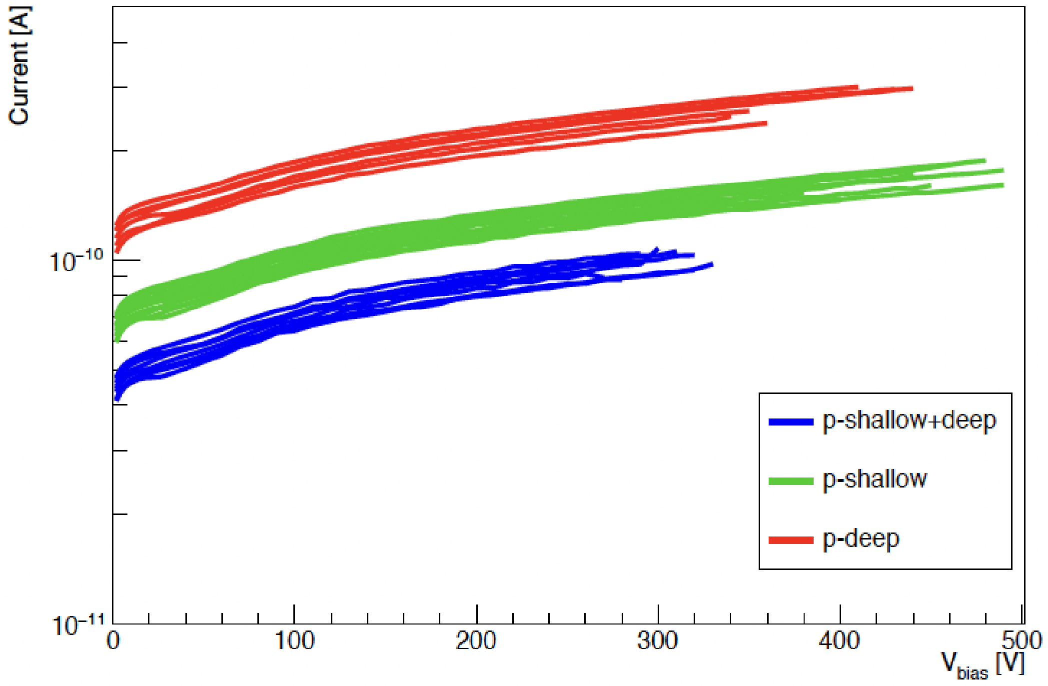


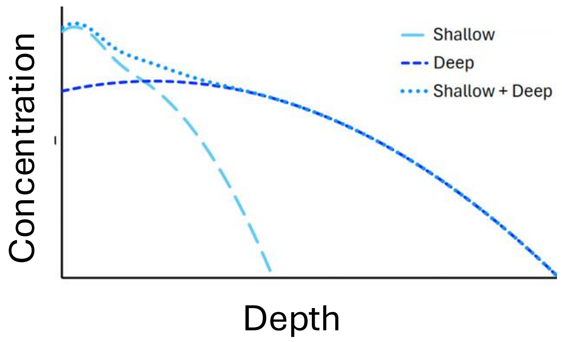
- Excellent quality of the substrate, very low and uniform leakage current (~ 10^{-10} A)
- Stable behaviour up to 400V
- No effect on the leakage current due to the n-spray dose



IV From PiN diode – p^{++} design

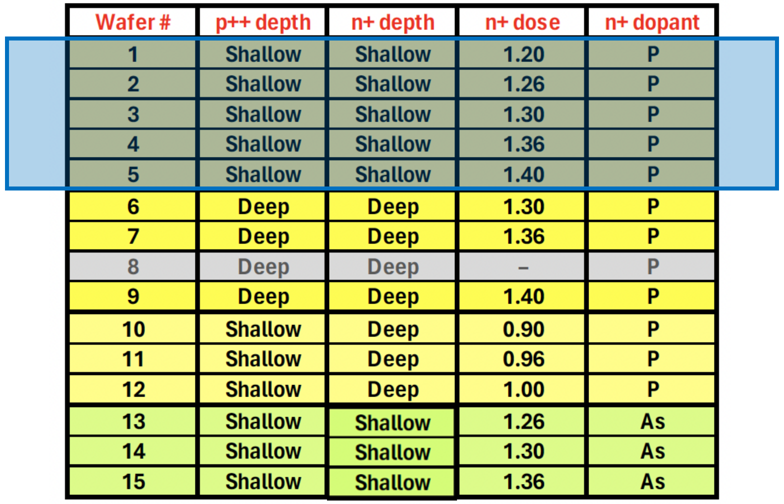
The design of the p^{++} contact has an impact on the leakage current





The higher p^{++} concentration at the surface, the lower leakage current

IV on wafer - LGAD



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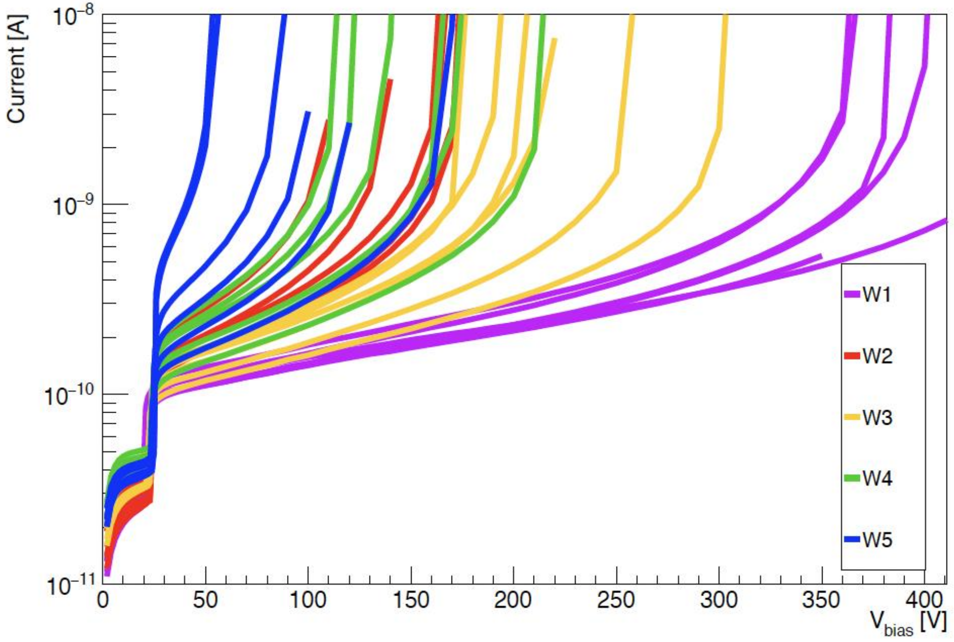


IV - shallow p^{++} and n^{+} implants

- IV characteristics similar to standard LGAD

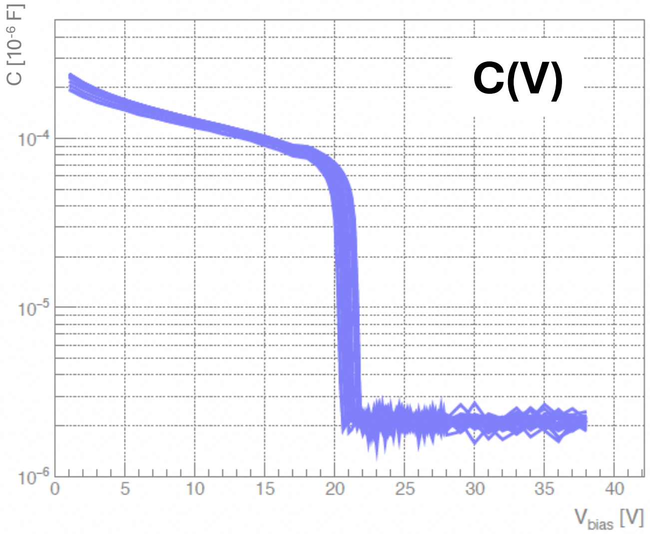
- Big spread of the breakdown on sensors from the same wafer
  - → to understand whether this effect is due to the uniformity of the n^{++} implant or to the multiplication mechanism of holes

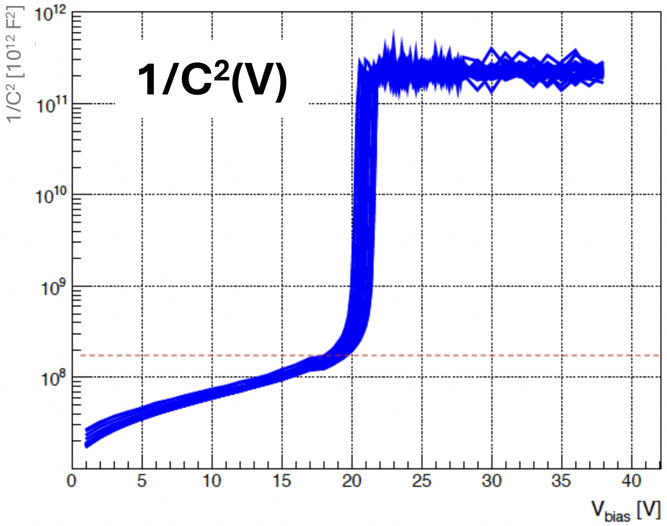
CV on wafer – LGAD from W1

Wafer #	p++ depth	n+ depth	n+ dose	n+ dopant
1	Shallow	Shallow	1.20	P

CV curve like Standard LGAD with a clear transition from gain implant and bulk region

CV performed with fine binning between 18V and 28V to precisely spot V_{GL}

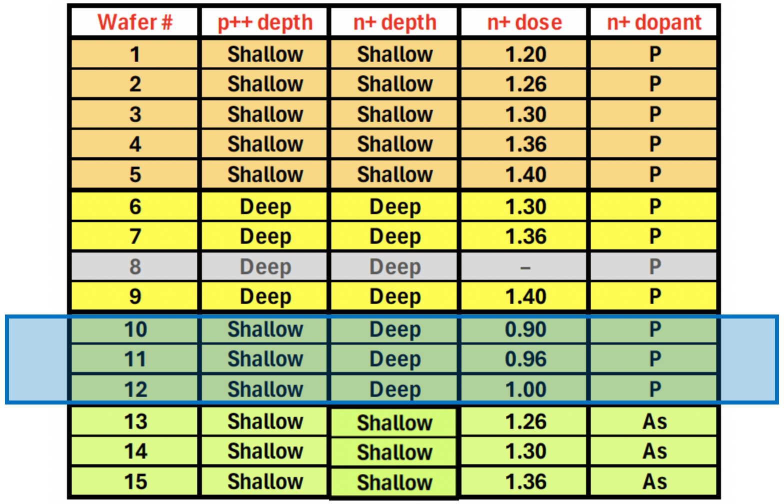




For W1
V_{GL} = 20.2 V
with 2.1% spread

Uniformity of the n^+ gain implant at ~ 2% level, as in standard LGAD productions

IV on wafer - LGAD



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13	Shallow	Shallow	1.26	As
14	Shallow	Shallow	1.30	As
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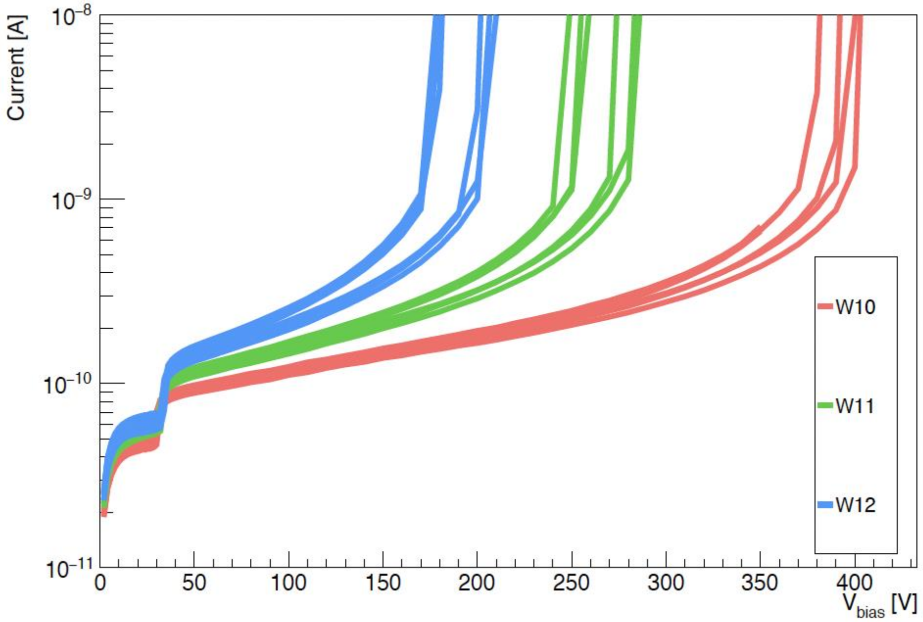
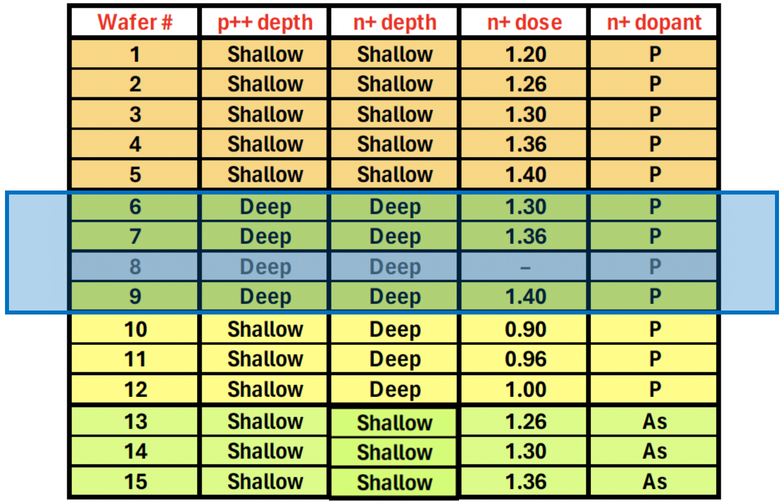
IV - shallow p^{++} and deep n^{+} implants



Nice I-V behaviour of NLGAD sensors with shallow p++ and deep n+ implants

IV on wafer - LGAD



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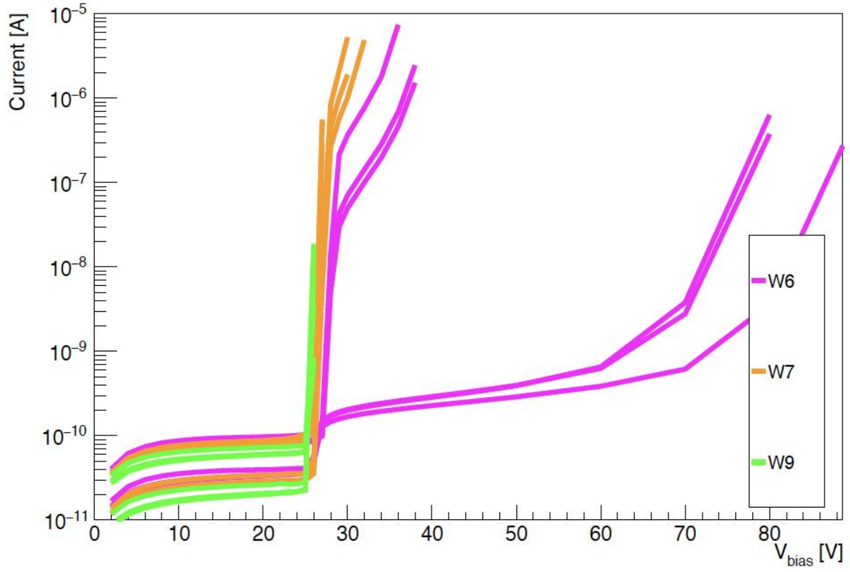
10	Shallow	Deep	0.90	P
11	Shallow	Deep	0.96	P
12	Shallow	Deep	1.00	P
13	Shallow	Shallow	1.26	As
14	Shallow	Shallow	1.30	As
15	Shallow	Shallow	1.36	As

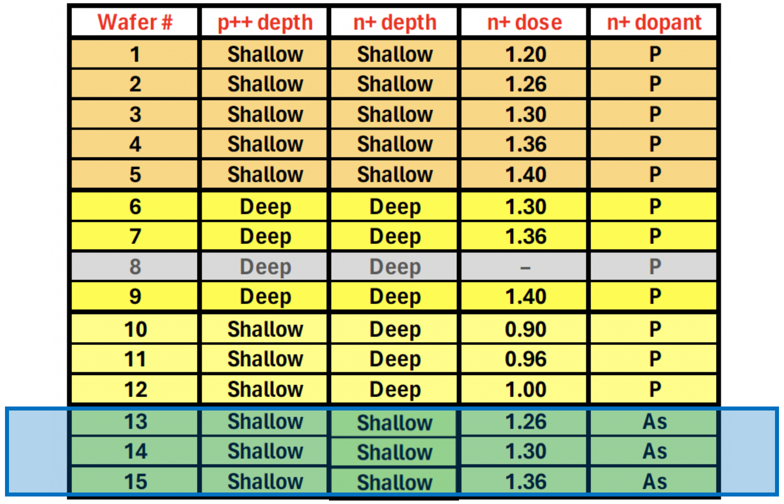
IV – deep and shallow + deep p^{++} - deep n^{+} implants



NLGAD sensors with deep and deep + shallow p^{++} implants combined with n^{+} gain implant show premature breakdown in all wafer produces

W6 shows a large difference in the breakdown voltage between deep and shallow + deep p^{++} implant

IV on wafer - LGAD



Wafer #	p++ depth	n+ depth	n+ dose	n+ dopant
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12	Shallow	Deep	1.00	P
13	Shallow	Shallow	1.26	As
14	Shallow	Shallow	1.30	As
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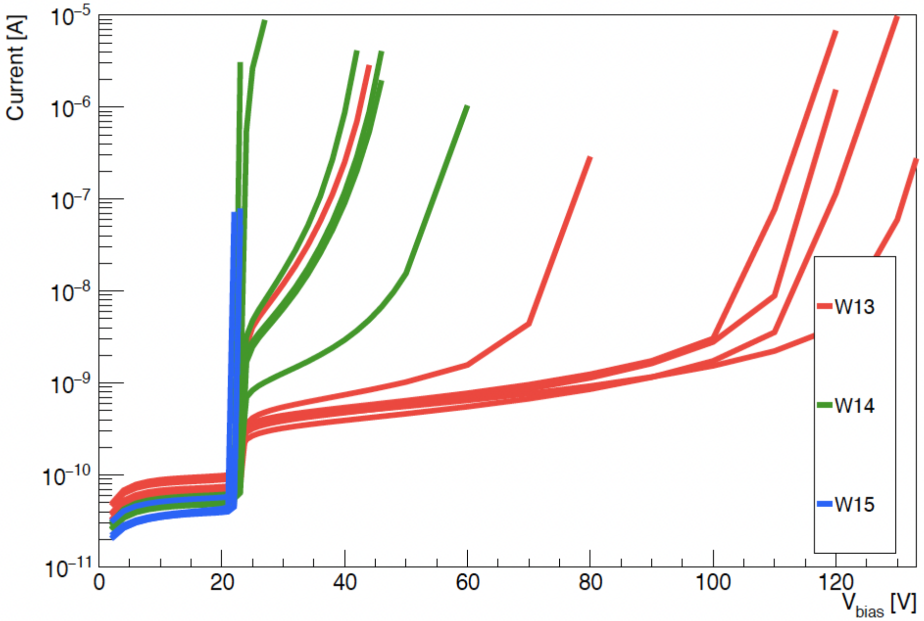
IV – Arsenic gain implant

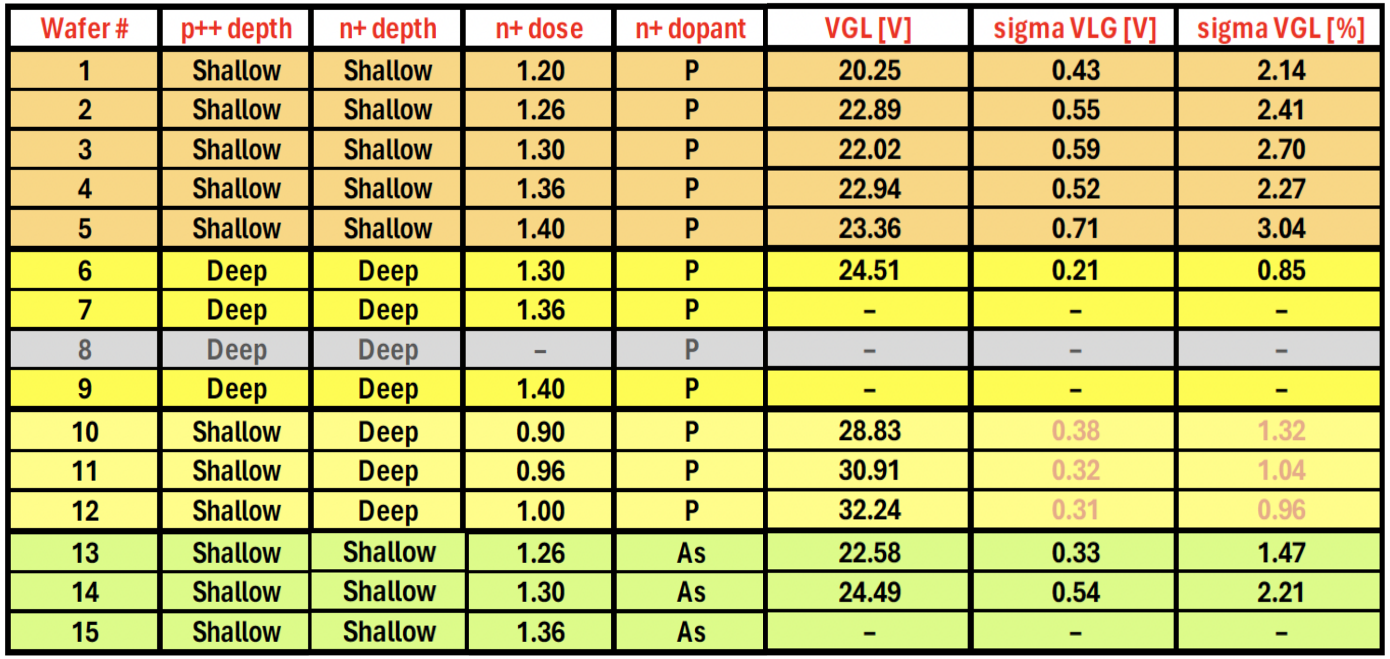


Arsenic activation and diffusion at the n^+ concentration levels need to be explored and characterised

- ➢ W13 has a reasonable behaviour in term of Breakdown
- ➢ W14 and 15 have too high multiplication

CV summary and uniformity of the n$^+$ implant

The bias of the gain implant depletion has been extracted from C-V measurements for all wafers with a good I-V behaviour



Wafer #	p++ depth	n+ depth	n+ dose	n+ dopant	VGL [V]	sigma VLG [V]	sigma VGL [%]
1	Shallow	Shallow	1.20	P	20.25	0.43	2.14
2	Shallow	Shallow	1.26	P	22.89	0.55	2.41
3	Shallow	Shallow	1.30	P	22.02	0.59	2.70
4	Shallow	Shallow	1.36	P	22.94	0.52	2.27
5	Shallow	Shallow	1.40	P	23.36	0.71	3.04
6	Deep	Deep	1.30	P	24.51	0.21	0.85
7	Deep	Deep	1.36	P	–	–	–
8	Deep	Deep	–	P	–	–	–
9	Deep	Deep	1.40	P	–	–	–
10	Shallow	Deep	0.90	P	28.83	0.38	1.32
11	Shallow	Deep	0.96	P	30.91	0.32	1.04
12	Shallow	Deep	1.00	P	32.24	0.31	0.96
13	Shallow	Shallow	1.26	As	22.58	0.33	1.47
14	Shallow	Shallow	1.30	As	24.49	0.54	2.21
15	Shallow	Shallow	1.36	As	–	–	–

Good uniformity of VGL over the wafer, between 1% and 3%

- ➢ No geometrical effects observed
- ➢ No effect correlated to P and As observed

Summary on preliminary characterization of NLGADs

- First n-type LGAD sensors designed by FBK, Perugia and Torino and produced by FBK
- A completely new design has been developed for the p^{++} contact and n^{+} gain implant
- n-spray and n-stop peripherical structure have been designed and implemented
- An extensive testing campaign on wafer have been done
  - IV measurements show a standard LGAD-like behaviour
  - CV measurements demonstrate an excellent uniformity on the n^{+} gain implant (~2%)
- Plenty of NLGAD to share

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- AIDAinnova, WP13
- Compagnia di San Paolo
- MUR, Italia, PRIN 2022, project 2022RK39RF – ComonSens

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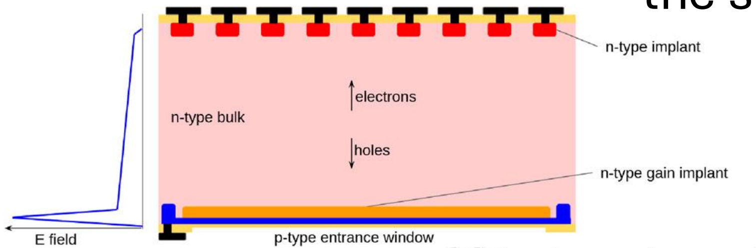
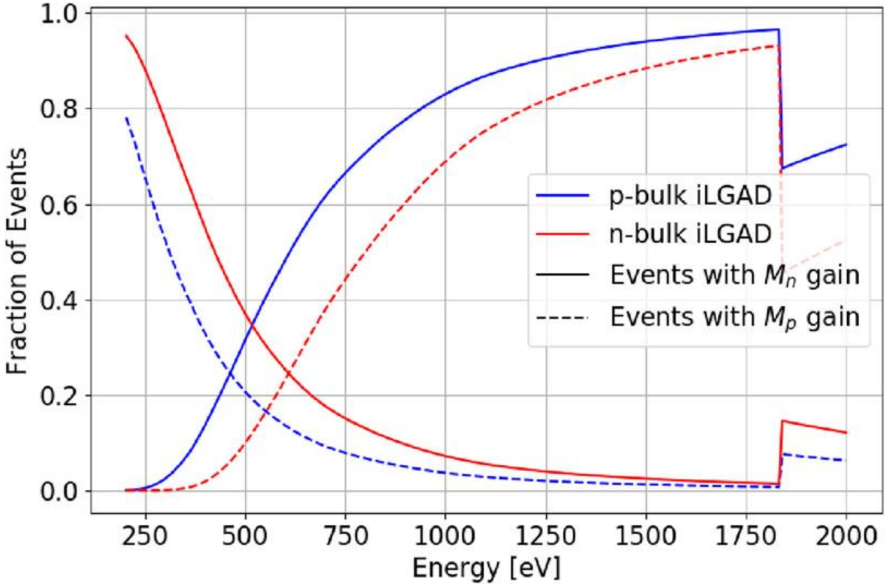
backup

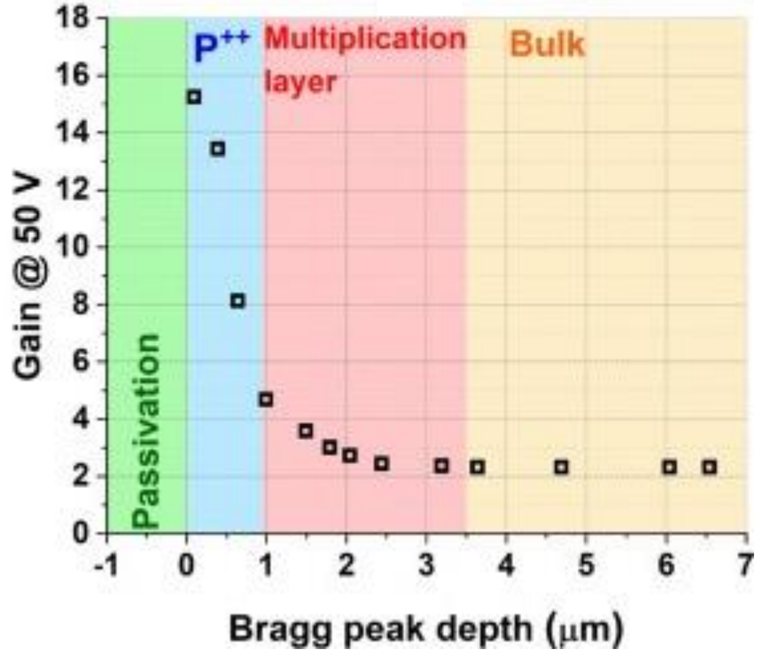
Detection of Low penetration particles

If e-h pairs are generated between a p^{++} ohmic contact and an n^{+} gain implant, the signal from low penetrating particles is enhanced





[M. Centis Vignali and G. Paternoster, doi:10.3389/fphy.2024.1359179]



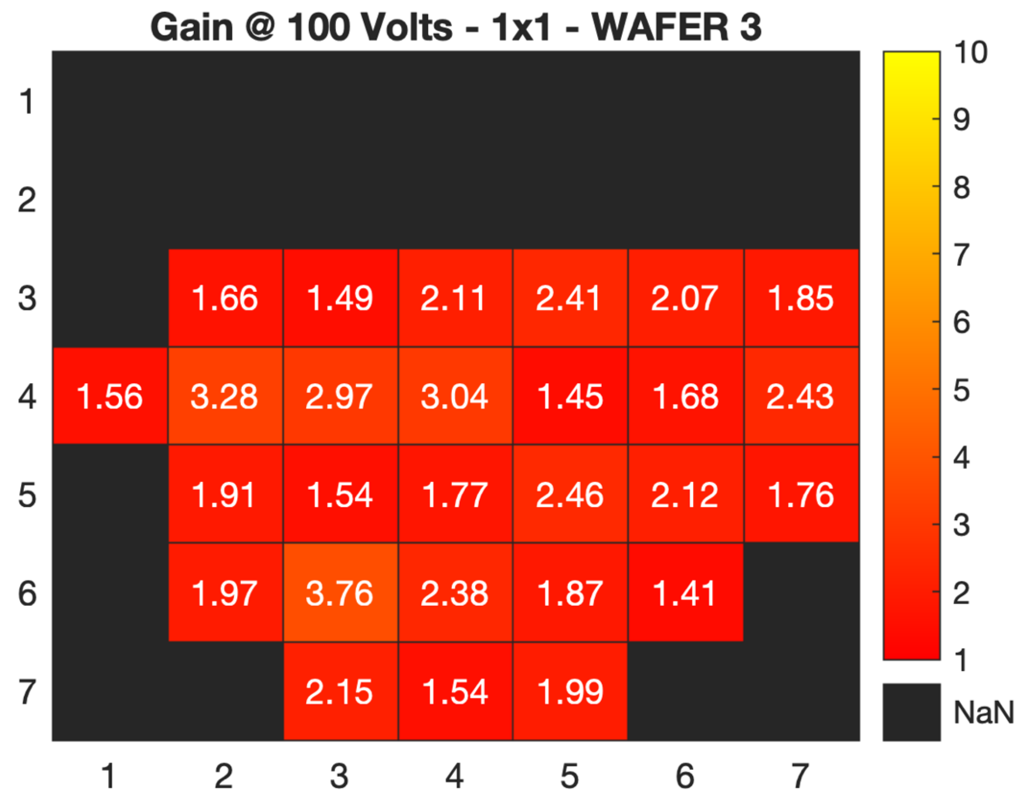
[J. Villegas et al., doi:10.1016/j.nima.2025.170208]

Gain from a red led – Wafer 3

$$\text{Gain} = \frac{I_{\text{NLGAD}}}{I_{\text{PIN}}} \text{ at fixed } V = 100 \text{ V}$$

while illuminating the sensors with a red LED ($\lambda = 950$ nm)

Wafer #	p++ depth	n+ depth	n+ dose	n+ dopant
3	Shallow	Shallow	1.30	P



Gain @ 100 Volts - 1x1 - WAFER 3

	1	2	3	4	5	6	7
1							
2							
3		1.66	1.49	2.11	2.41	2.07	1.85
4	1.56	3.28	2.97	3.04	1.45	1.68	2.43
5		1.91	1.54	1.77	2.46	2.12	1.76
6		1.97	3.76	2.38	1.87	1.41	
7			2.15	1.54	1.99		

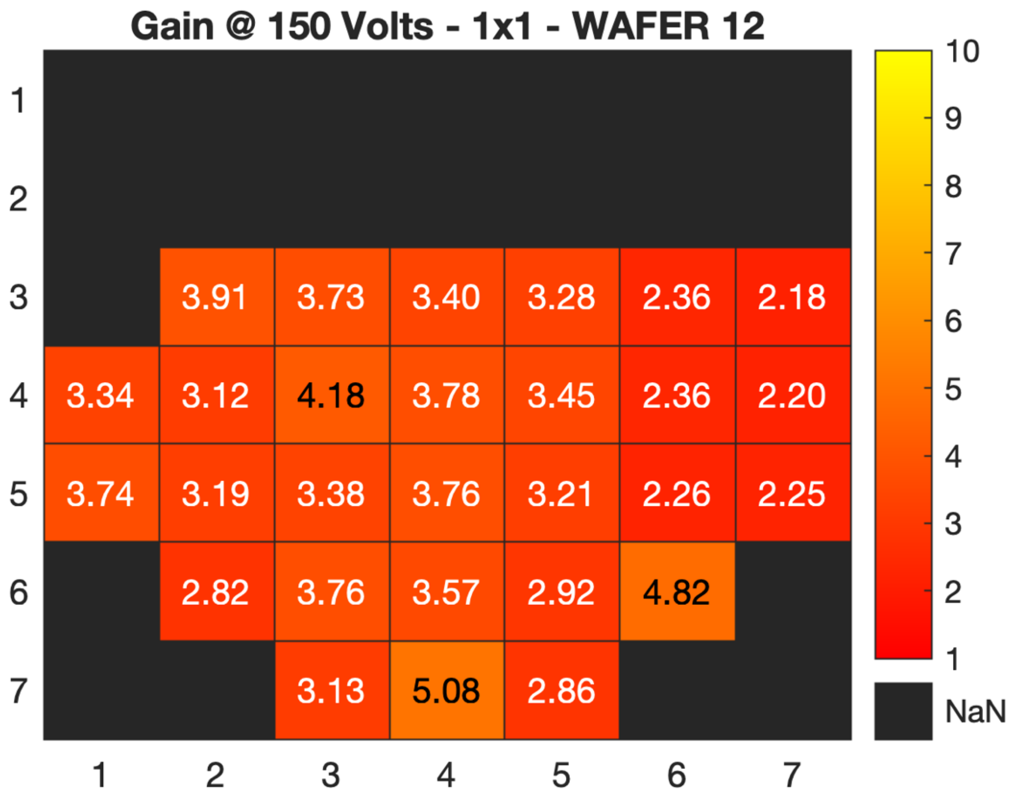
→ At V = 100 V, gain between ~ 1.5 and 3.8 when sensors are illuminated with a red LED

Gain from a red led – Wafer 12

$$\text{Gain} = \frac{I_{\text{NLGAD}}}{I_{\text{PIN}}} \quad \text{at fixed } V = 150\ \text{V}$$

while illuminating the sensors
with a red LED ($\lambda = 950$ nm)

Wafer #	p++ depth	n+ depth	n+ dose	n+ dopant
12	Shallow	Deep	1.00	P



	1	2	3	4	5	6	7
1							
2							
3		3.91	3.73	3.40	3.28	2.36	2.18
4	3.34	3.12	4.18	3.78	3.45	2.36	2.20
5	3.74	3.19	3.38	3.76	3.21	2.26	2.25
6		2.82	3.76	3.57	2.92	4.82	
7			3.13	5.08	2.86		

→ At V = 150 V, gain between ~ 2.2 and 5.1 when sensors are illuminated with a red LED