

IMB-CNM Activities for the CMS High Luminosity Upgrade and ECFA DRDs

CMSUPG2 Project, 2026 Project Meeting
(PID2023-148418NB-C42, 01/09/2024-31/12/2027)

Zoom SIFCA. 30 July 2026

S. Hidalgo, J. Bravo, F. Dougados, R. Durá, P. Fernández, D. Flores, C. Fleta,
M. Manna, X. Mas, A. Merlos, A. Moreno, J. Pallarés, J. Villegas

- Subproject Objectives and Tasks

- WP2. Sensor production, Module assembly, and Hybrid testing of the CMS ETL
 - Objective WP2.O1. *Manufacturing and QC of LGAD sensors for the ETL detector*
 - ✓ WP2.T1: Pre-production and production of LGAD sensors
- WP3. R&D on solid state detectors for 4D tracking and extreme radiation environments inside the DRD3 collaboration
 - Objective WP3.O1. *Development of 4D tracking detectors for precise timing and tracking based on the LGAD and 3D sensor architectures*
 - Objective WP3.O2. *Development of detectors for extreme fluence environments based on radiation hardened LGADs, 3D and SiC*
 - ✓ WP3.T1.a: Silicon. New Technologies for 4D Tracking and Extreme Fluence Environments
 - ✓ WP3.T1.b: SiC. New Technologies for 4D Tracking and Extreme Fluence Environments
 - ✓ WP3.T2: Si and SiC Detectors Characterization and POC Validation

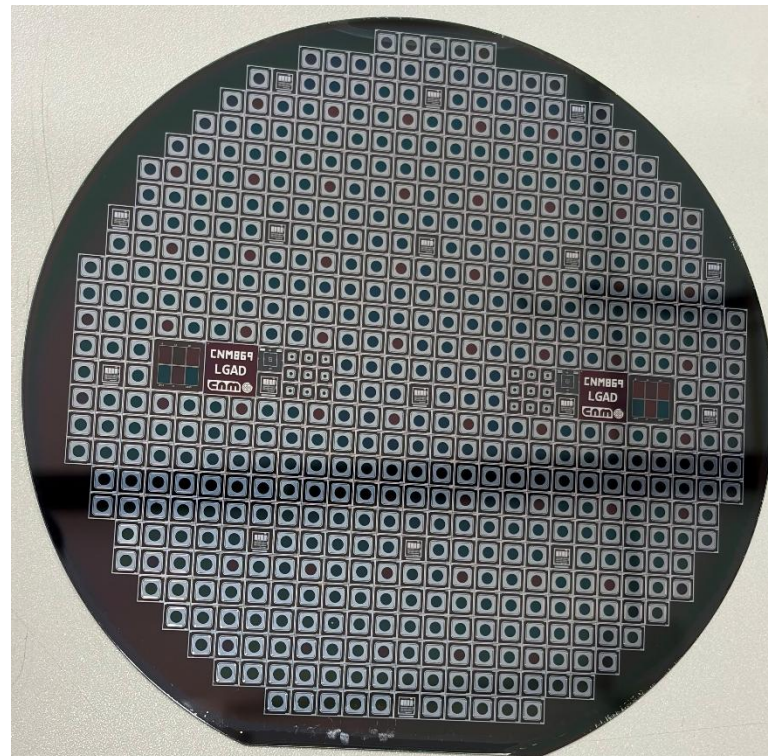
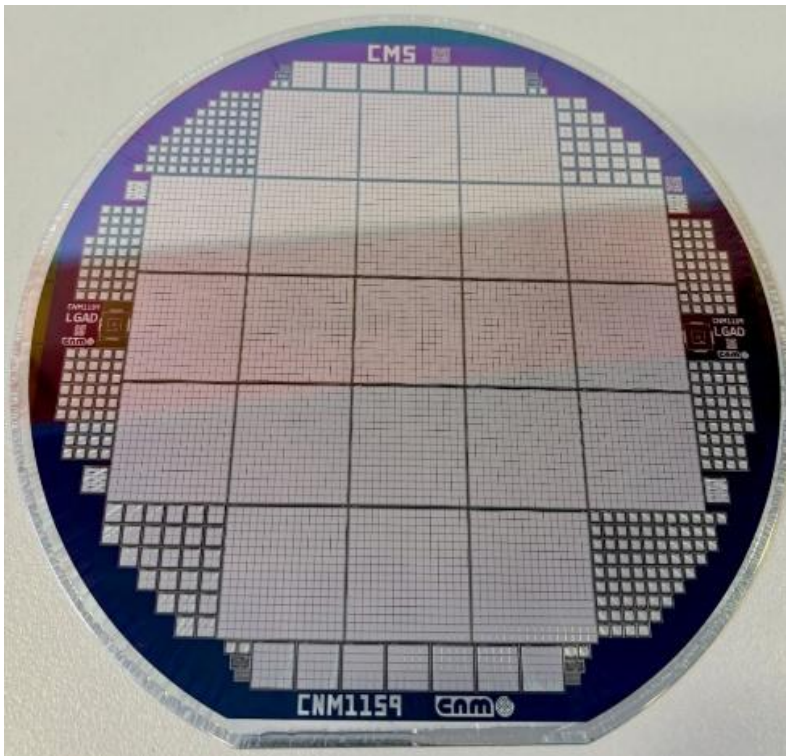
- Technologies Developed

- LGAD. 6DLG2v1, 6LG2v2, 6DLG2v2, 6DLG3v1, 6LG1v1, 6LG3v3
- iLGAD. 4TILG2v2, 4TILG3v2
- nLGAD. 4NLG1v2, 6NLG1v1
- 3D. 43D1v2, 43D1v3, 43D1v4
- PiN. 6PN1v1, 6PN1v2, 6PN1v3, 6PN1v4
- SiC. 3 μ m & 50 μ m N-Type Diodes



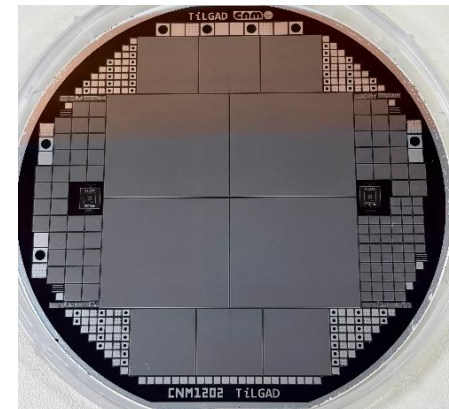
Subproject Objectives

- WP2. Sensor production, Module assembly, and Hybrid testing of the CMS ETL
 - Objective WP2.O1. *Manufacturing and QC of LGAD sensors for the ETL detector*
 - WP2.T1: Pre-production and production of LGAD sensors
 - ✓ LGADs fabrication compliant with the technical specifications established for the ETL sub-detector
 - ✓ Quality control process to ensure they meet the required specifications

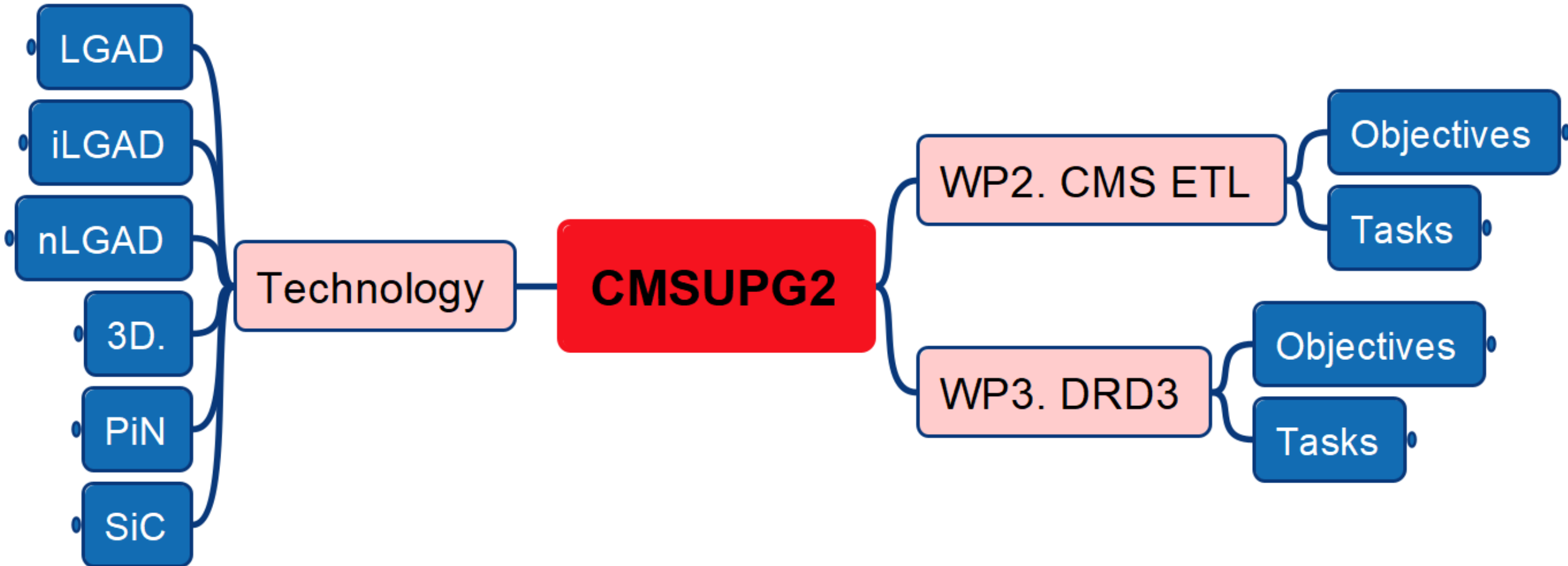


Subproject Objectives

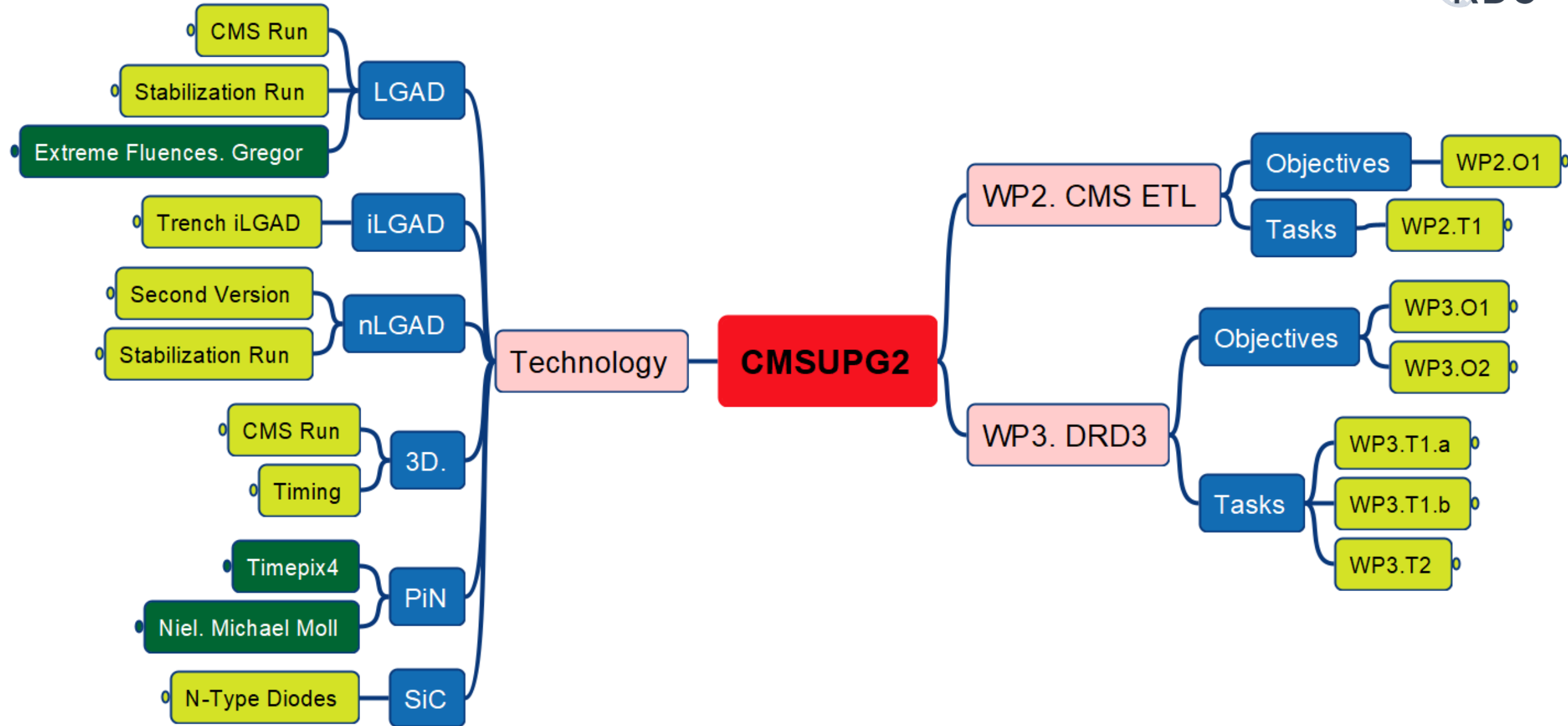
- WP3. R&D on solid state detectors for 4D tracking and extreme radiation environments inside the DRD3 collaboration
 - **Objective WP3.O1.** *Development of 4D tracking detectors for precise timing and tracking based on the LGAD and 3D sensor architectures*
 - **Objective WP3.O2.** *Development of detectors for extreme fluence environments based on radiation hardened LGADs, 3D and SiC*
 - WP3.T1.a: New Technologies for 4D Tracking and Extreme Fluence Environments (Si Based)
 - WP3.T1.b: New Technologies for 4D Tracking and Extreme Fluence Environments (SiC Based)
 - ✓ Understand the limit of precision timing in sensors with and without internal multiplication
 - ✓ Develop pixel sensors with internal multiplication with 100% fill factor (iLGAD, Trench iLGAD)
 - ✓ Exploring the timing possibilities of pixelated sensors with higher radiation resistance (3D)
 - WP3.T2: Si and SiC Detectors Characterization and Proof of Concept Validation
 - ✓ Extend the capabilities of solid-state detector technologies (LGAD and 3D) to operate at extreme fluences (from 1×10^{16} to $5 \times 10^{18} \text{ n}_{\text{eq}} \text{ cm}^{-2}$) and evolve their design to cope with the highest possible fluence
 - ✓ Upgrading the simulation strategies for the extreme radiation damage
 - ✓ Use of wide bandgap semiconductors (SiC in particular) as radiation detectors



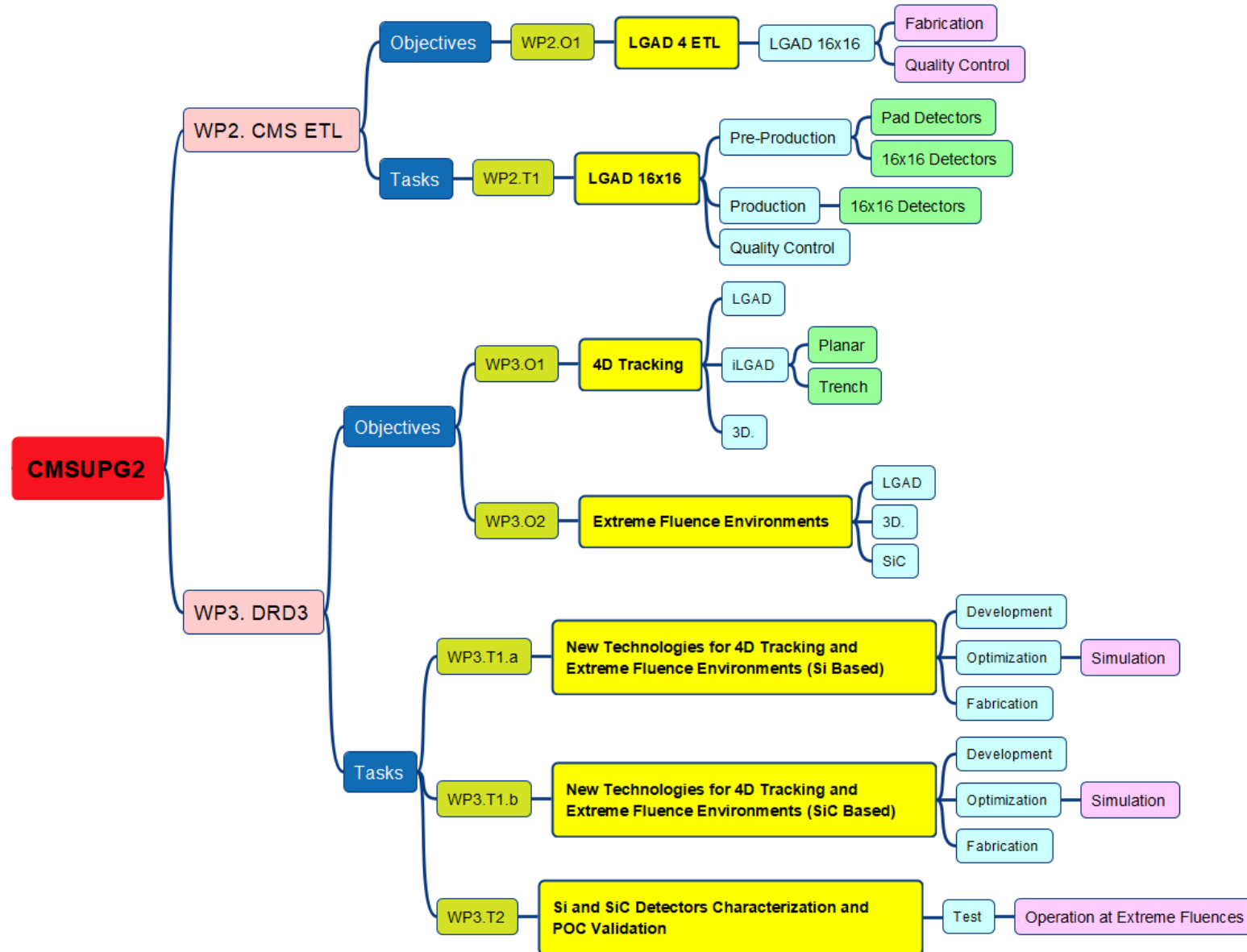
Subproject Objectives



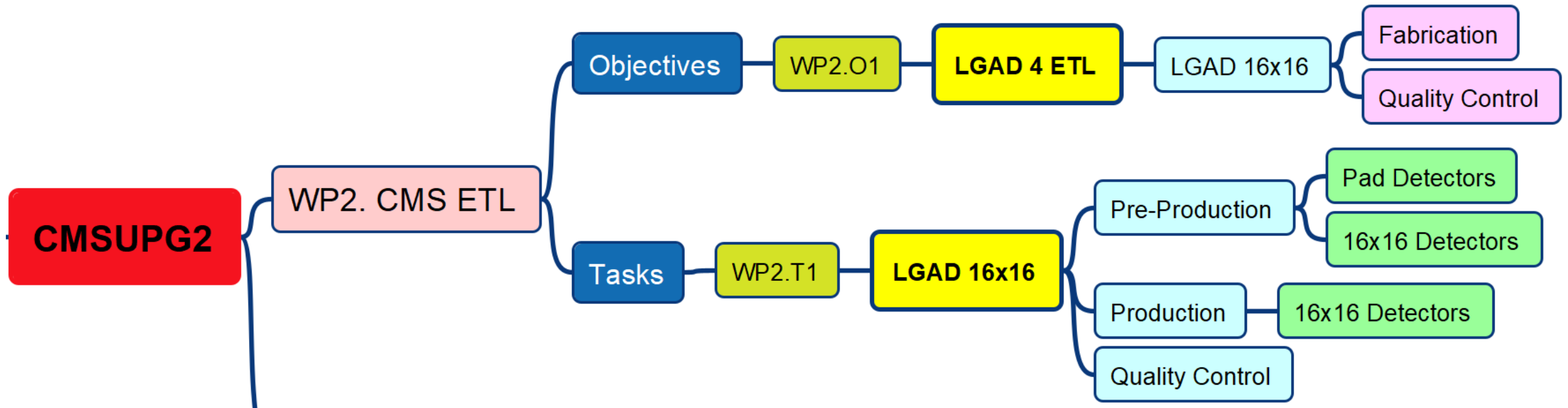
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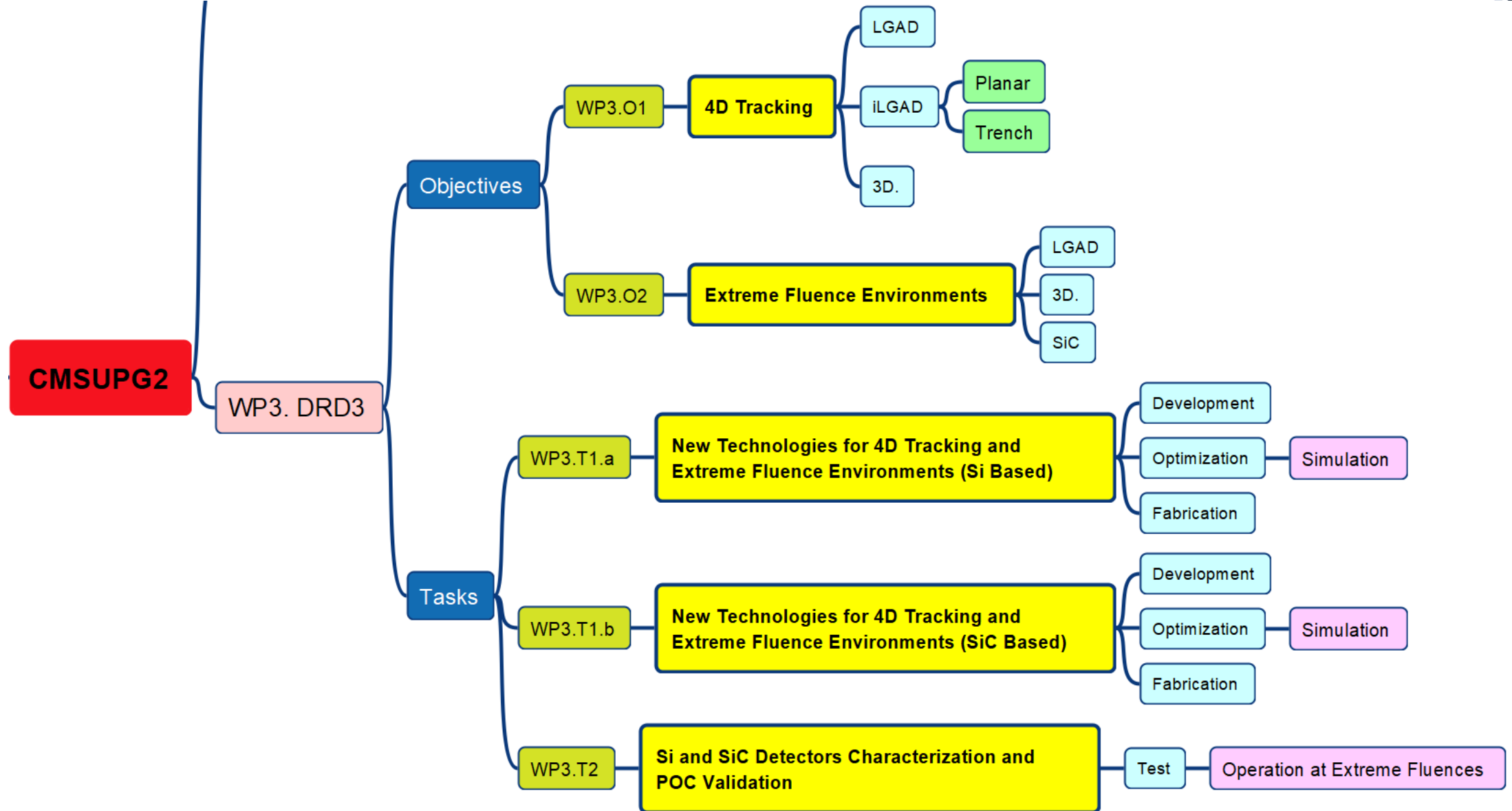
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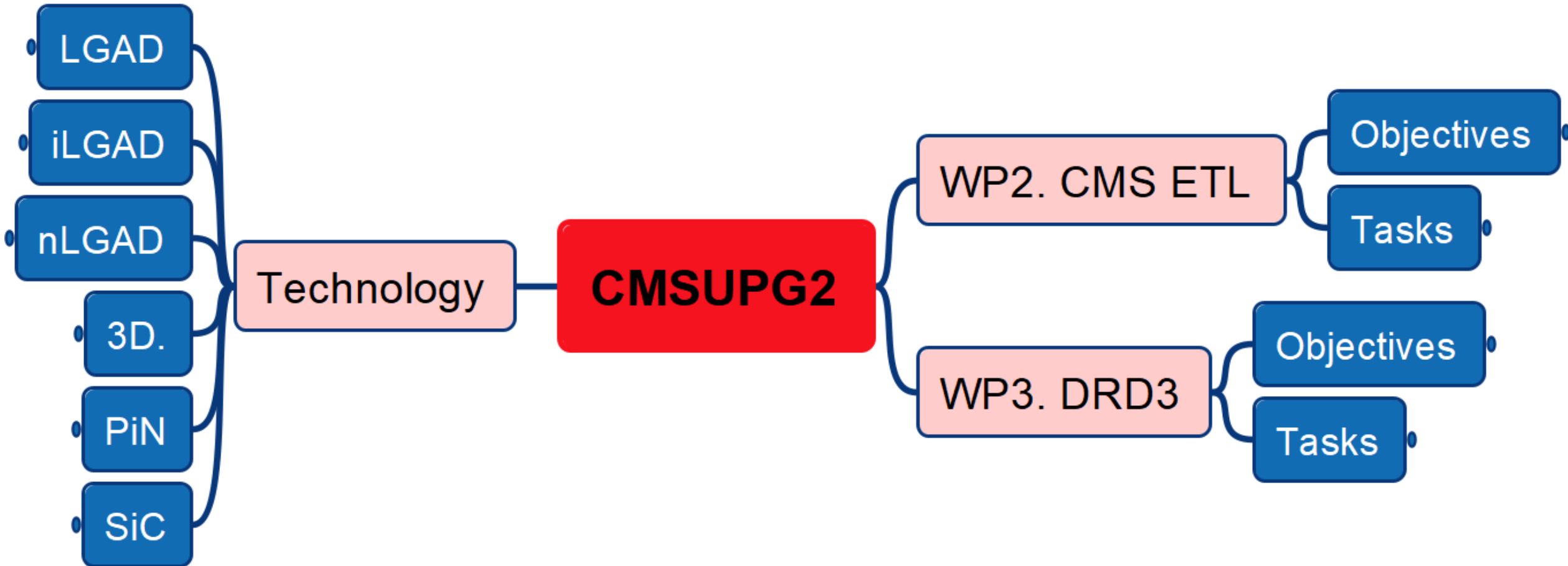
Subproject Objectives. WP2



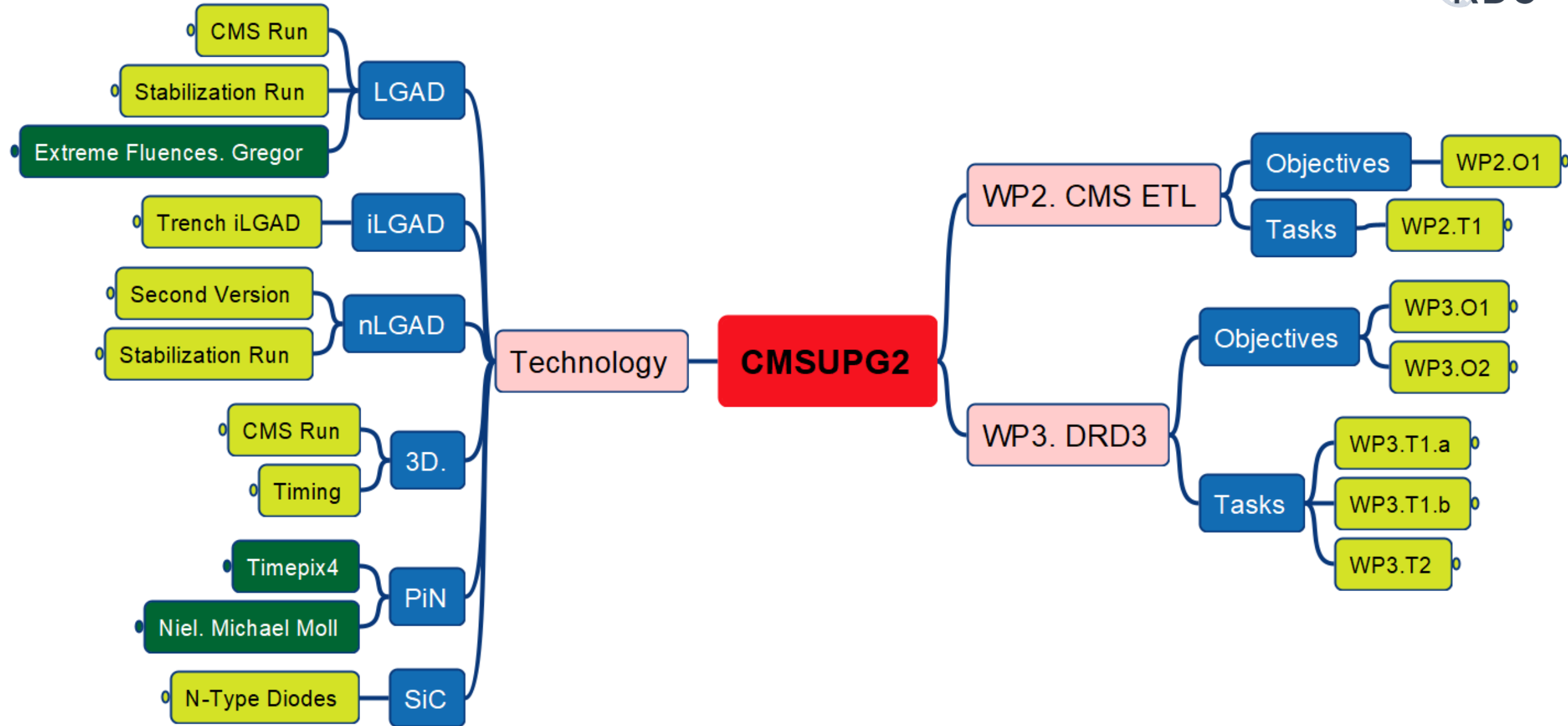
Subproject Objectives. WP3



Subproject Objectives



Subproject Objectives

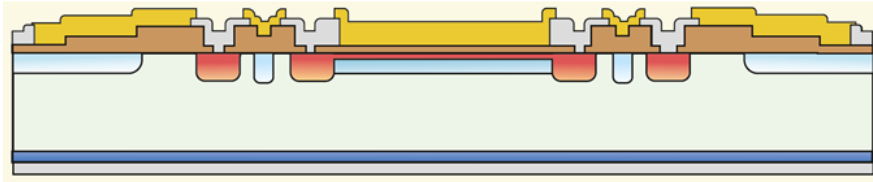
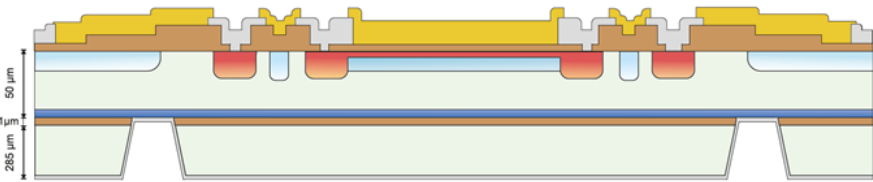
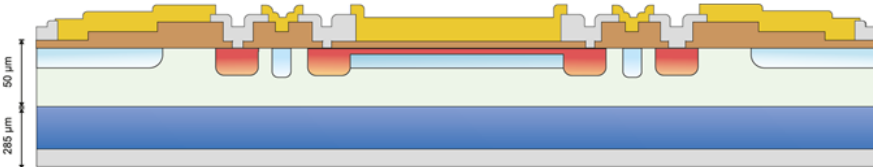
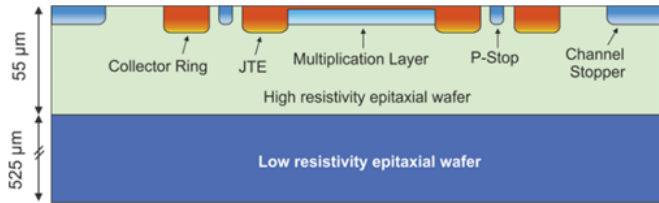


Technological Processes Developed

Acronyms for IMB-CNM Runs							
Run	PID	Acronym	Project(s)	Year	Description	Mask	Notes
13002	CMSUPG	6LG3-v1	ATLAS and CMS experiments phase-II upgrade	2021	First version of carbonated LGAD on Epitaxial(3) wafers of 6 inches (150 mm) diameter and 50 μ m active thickness.	CNM869	
14002 15037	CMSUPG	4NLG1-v1	AIDAINNOVA	2022	First version of nLGAD on FZ(1) wafers of 4 inches (100 mm) diameter and 300 μ m thickness.	CNM652	LGADs for Low Penetration Particules Detection
15246	CMSUPG TOMULGAD	6LG3-v2	ATLAS and CMS experiments phase-II upgrade	2022	Second version of carbonated LGAD on Epitaxial(3) wafers of 6 inches (150 mm) diameter and 50 μ m active thickness.	CNM1023	
16421	CMSUPG	4TILG2-v1	AIDAINNOVA	2023	First version Trench inverse LGAD on Si-Si(2) wafers of 4 inches (100 mm) diameter and 50 μ m active thickness.	CNM1086	
16421	CMSUPG	4TILG3-v1	AIDAINNOVA	2023	First version of Trench inverse LGAD on Epitaxial(3) wafers of 4 inches (100 mm) diameter.	CNM1086	
15973	CMSUPG TOMULGAD	6LG2-v1	ATLAS experiment phase-II upgrade	2023	First version of carbonated LGAD on Si-Si(2) wafers of 6 inches (150 mm) diameter and 50 μ m active thickness.	CNM1139	Phosphorous
16602	CMSUPG CMSUPG2	6DLG2-v1	CMS experiment phase-II upgrade	2024	First version of Deep profile carbonated LGAD on Si-Si(2) wafers of 6 inches (150 mm) diameter and 50 μ m active thickness.	CNM1159	Phosphorous W1,W2,W3 High Phosphorous Diffusion STD Profile
16602	CMSUPG TOMULGAD PROTECT CMSUPG2	6LG2-v2	CMS experiment phase-II upgrade	2024	Second version of carbonated LGAD on Si-Si(2) wafers of 6 inches (150 mm) diameter and 50 μ m active thickness.	CNM1159	Phosphorous W1,W2,W3
16375	CMSUPG CMSUPG2	4NLG1-v2	AIDAINNOVA	2024	Second version of nLGAD on FZ(1) wafers of 4 inches (100 mm) diameter and 300 μ m thickness.	CNM873	LGADs for Low Penetration Particules Detection
17941 18236	CMSUPG CMSUPG2	4TILG2-v2	AIDAINNOVA	2024	Second version of Trench inverse LGAD on Si-Si(2) wafers of 4 inches (100 mm) diameter and 50 μ m active thickness.	CNM1202	
17941 18236	CMSUPG CMSUPG2	4TILG3-v2	AIDAINNOVA	2024	Second version of Trench inverse LGAD on Epitaxial(3) wafers of 4 inches (100 mm) diameter.	CNM1202	
16602 17591	CMSUPG CMSUPG2	6DLG2-v2	CMS experiment phase-II upgrade	2024	Second version of Deep profile carbonated LGAD on Si-Si(2) wafers of 6 inches (150 mm) diameter and 50 μ m active thickness.	CNM1159	Arsenic W7,W8,W9 Spikes
16069	CMSUPG2	43D1-v3	3D Timing, Altiroc1, Medipix3	2024	First version of 3D Radiation Hard Timing Detectors	CNM987	3D-DS Timing
15534	RD50	6PN1-v1	Pin Timepix4, Timepix3	2024	First version of Pin Timepix3 Timepix4 on Thick(1) wafers of 6 inches (150 mm) diameter and 300 μ m active thickness	CNM1084	Pin. Timepix4. Abraham
17958	CMSUPG PROTECT CMSUPG2	6DLG3-v1	CMS experiment phase-II upgrade	2025	First version of Deep profile carbonated LGAD on Epitaxial(3) wafers of 6 inches (150 mm) diameter and 50 μ m active thickness.	CNM1159	Arsenic 16X16 Modules waiting for USTC IV Measurements
18399	CMSUPG2	6LG3-v3	CMS experiment phase-II upgrade	2025	Third version of carbonated LGAD on Epitaxial(3) wafers of 6 inches (150 mm) diameter and 50 μ m active thickness	CNM869	Phosphorous
16827 18111	CMSUPG CMSUPG2	43D1-v2	CMS experiment phase-II upgrade	2025	Second version of 3D on Thick(1) wafers of 4 inches (100 mm) diameter and 300 μ m active thickness	CNM1125	3D CMS Preproduction
16069	CMSUPG2	43D1-v3	CMS experiment phase-II upgrade	2025	First version of 3D Timing on Thick(1) wafers of 4 inches (100 mm) diameter and 300 μ m active thickness	CNM987	3D Tiiming
18245	CMSUPG2	43D1-v4	CMS experiment phase-II upgrade	2025	Second version of 3D Timing on Thick(1) wafers of 4 inches (100 mm) diameter and 300 μ m active thickness	CNM1247	3D Tiiming
18111	CMSUPG2	43D1-v2	3D CMS	2025	First 3D run fabricated using "new" equipment (DRIE Sentech, Poly and the B/P doping process in Tempres Fournaces)	CNM1125	3D-SS 4 CROC
18245	CMSUPG2	43D1-v4	3D Timing, Timepix3	2025	Second version of 3D Radiation Hard Timing Detectors	CNM1247	3D-DS Timing
18177	RD50	6PN1-v2	Pin Timepix4, Timepix3	2025	Second version of Pin Timepix3 Timepix4 on Thick(1) wafers of 6 inches (150 mm) diameter and 300 μ m active thickness	CNM1084	Pin. Timepix4. Abraham
18182	RD50	6PN1-v3	PIN 4 NIEL M. Moll	2025	First version of PIN for NIEL on Thick(1) wafers of 6 inches (150 mm) diameter and 300 μ m active thickness	CNM869	+R16827 PIN. NIEL. Michael Moll
18399	CMSUPG2	6LG1-v1	CMS experiment phase-II upgrade	2026	First version of carbonated LGAD on Thick(1) wafers of 6 inches (150 mm) diameter and 300 μ m active thickness	CNM869	Phosphorous
18550	CMSUPG2	6NLG1-v1	LGADs for Low Penetration Particules Detection	2026	Third version of nLGAD on Thick(1) wafers of 6 inches (150 mm) diameter and 300 μ m active thickness	CNM869	

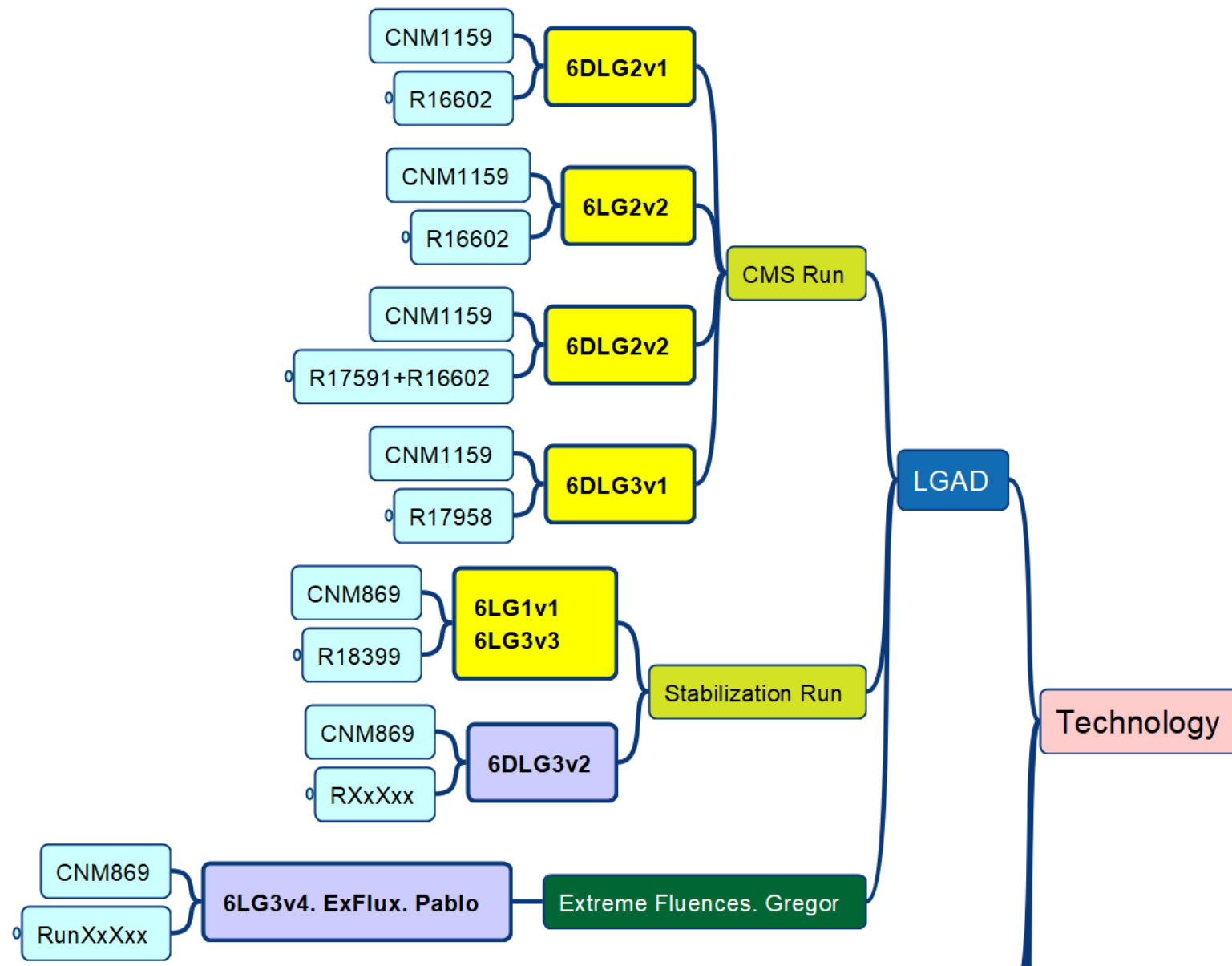
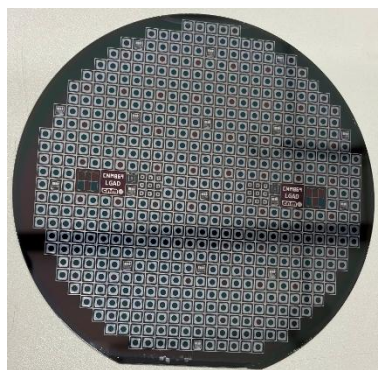
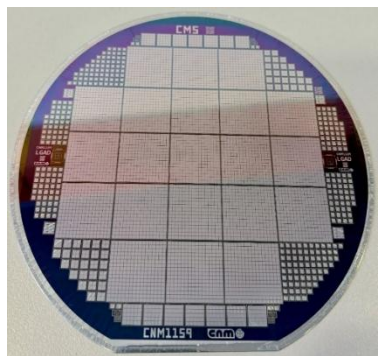


Technological Processes Developed

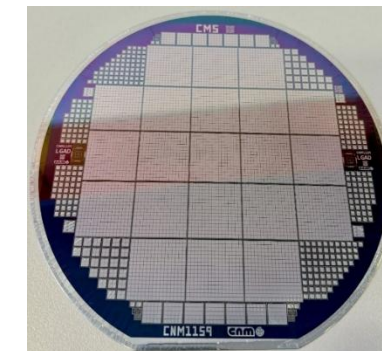
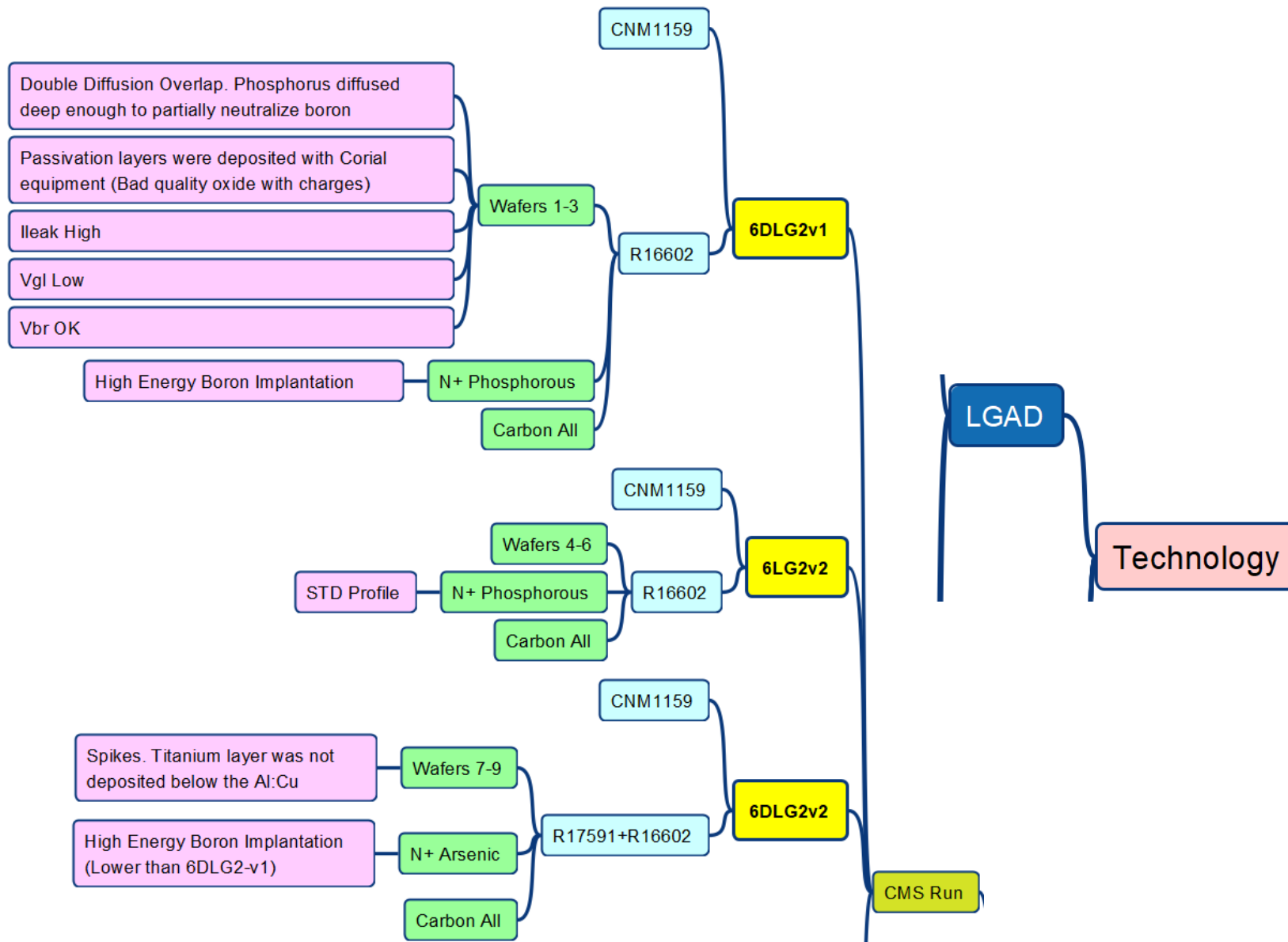
LGAD Generation	Wafer type	
6LG1	300 μm thick	
6LG4	50 μm SOI	
6LG2	50 μm Si-Si	
6LG3	55 μm epitaxial	



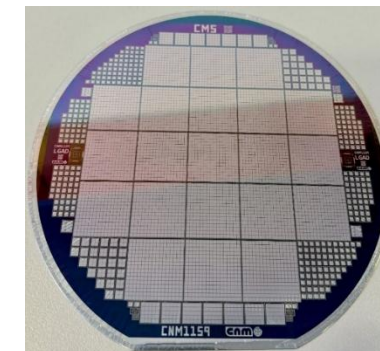
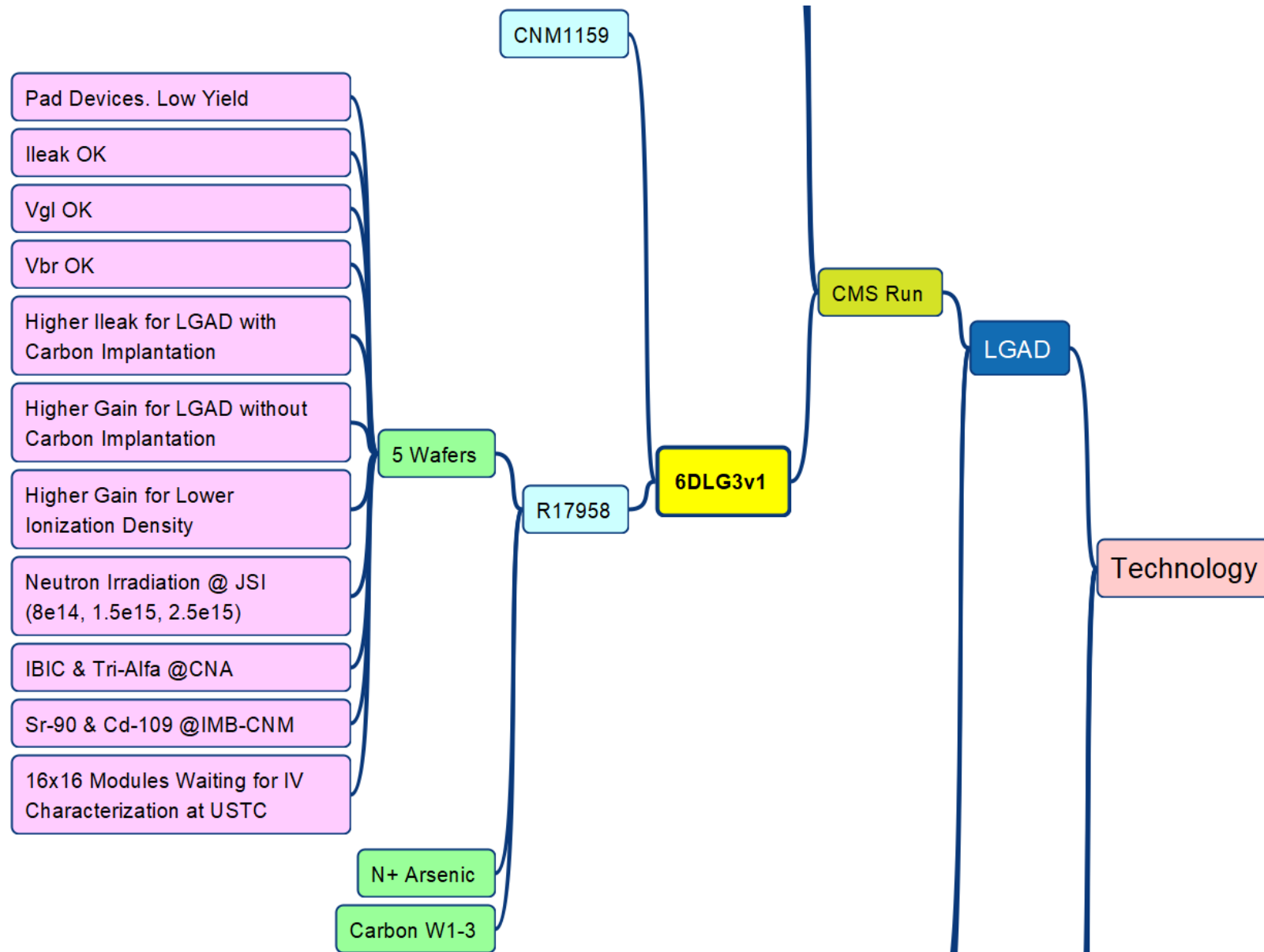
Subproject Objectives. Technologies. LGAD



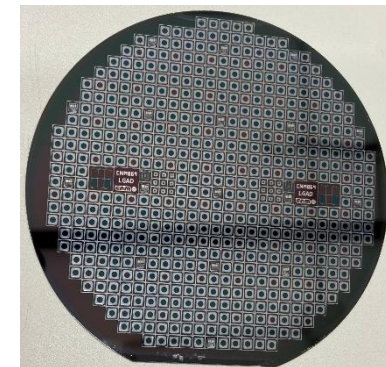
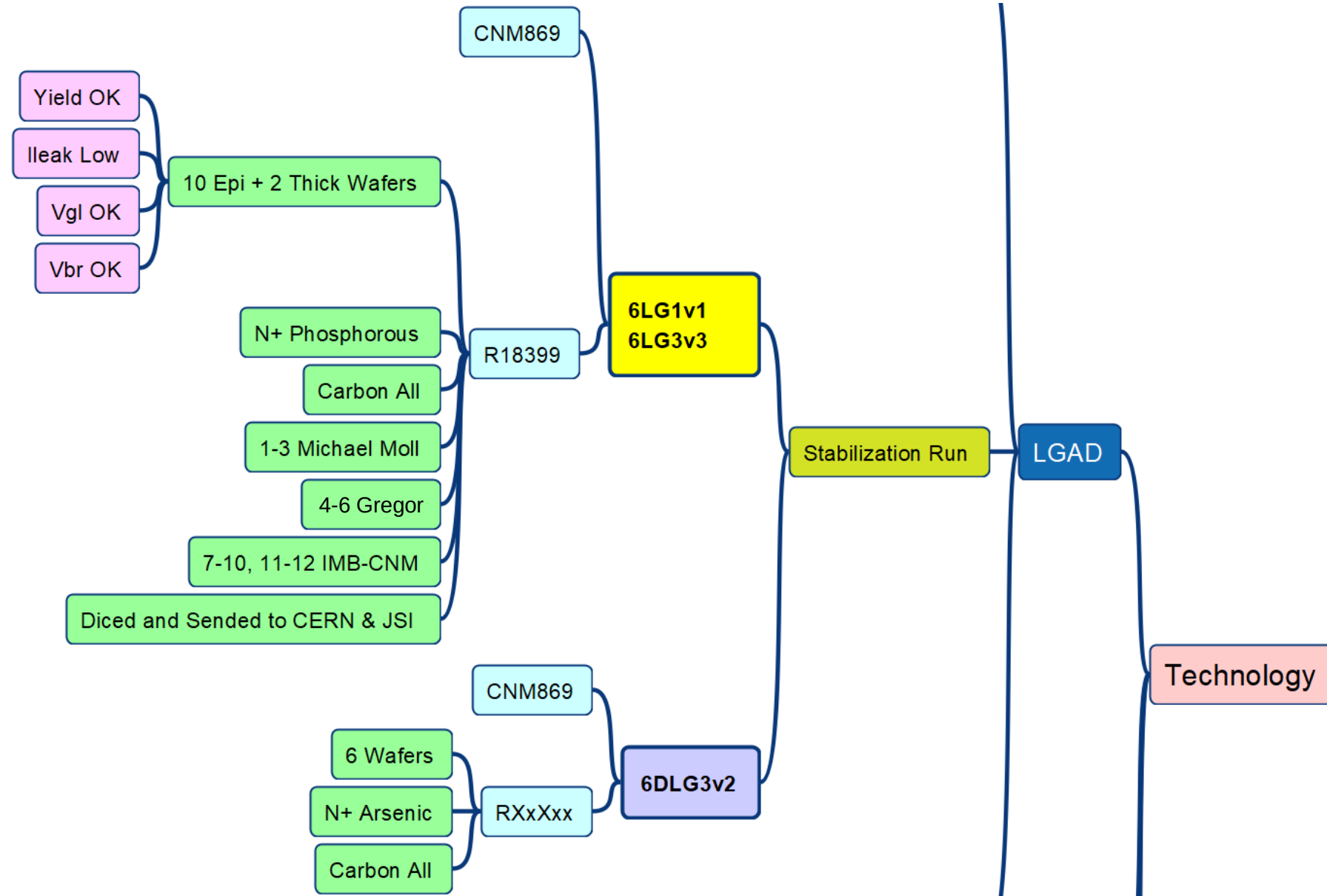
Subproject Objectives. Technologies. LGAD



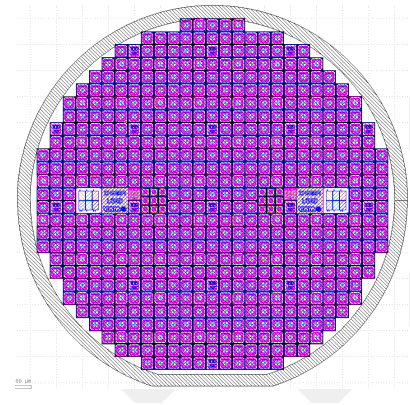
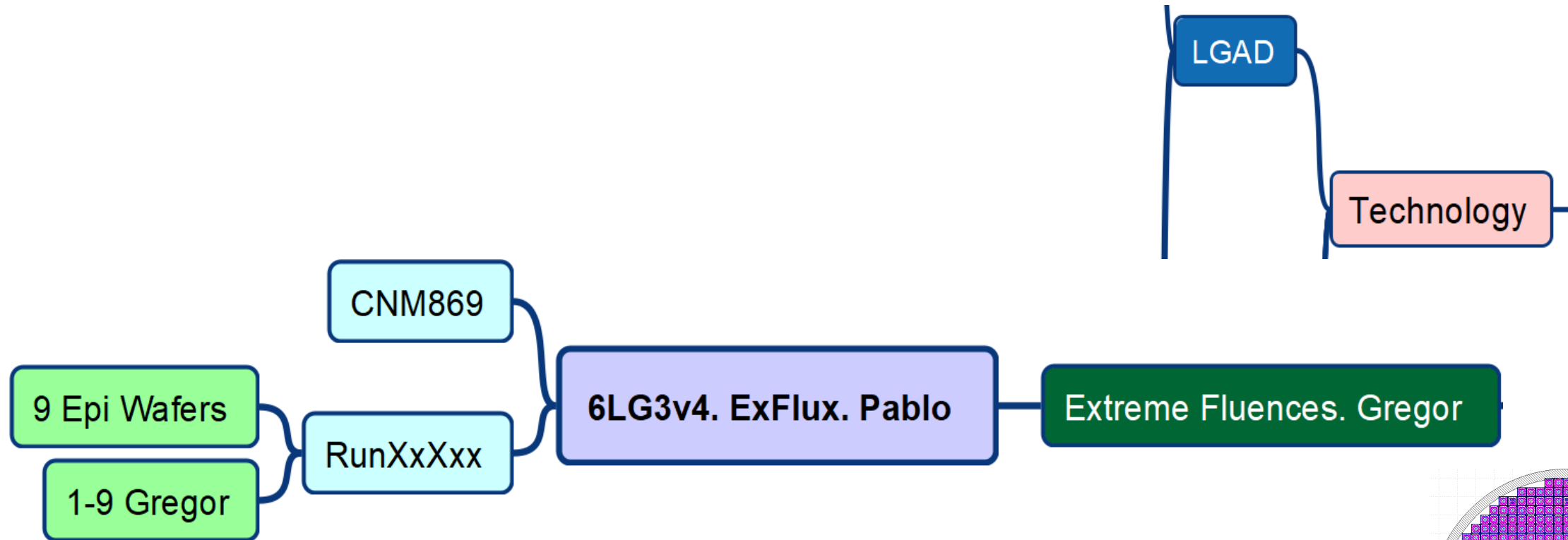
Subproject Objectives. Technologies. LGAD



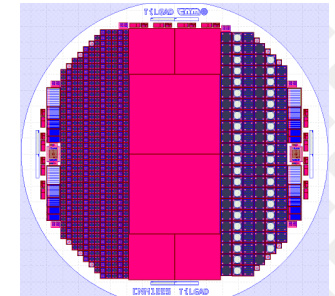
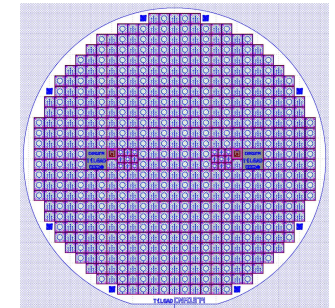
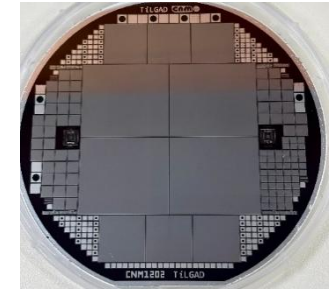
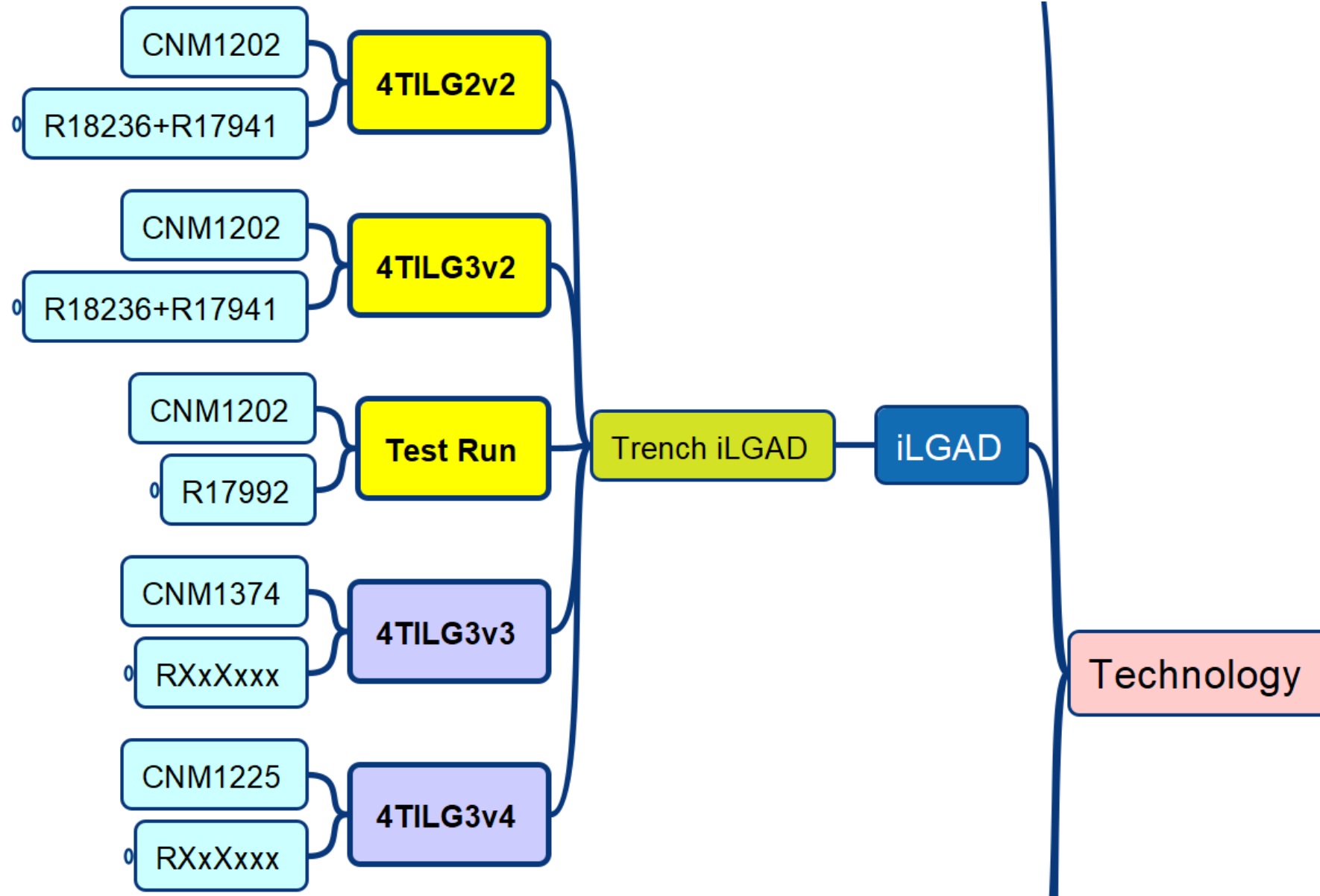
Subproject Objectives. Technologies. LGAD



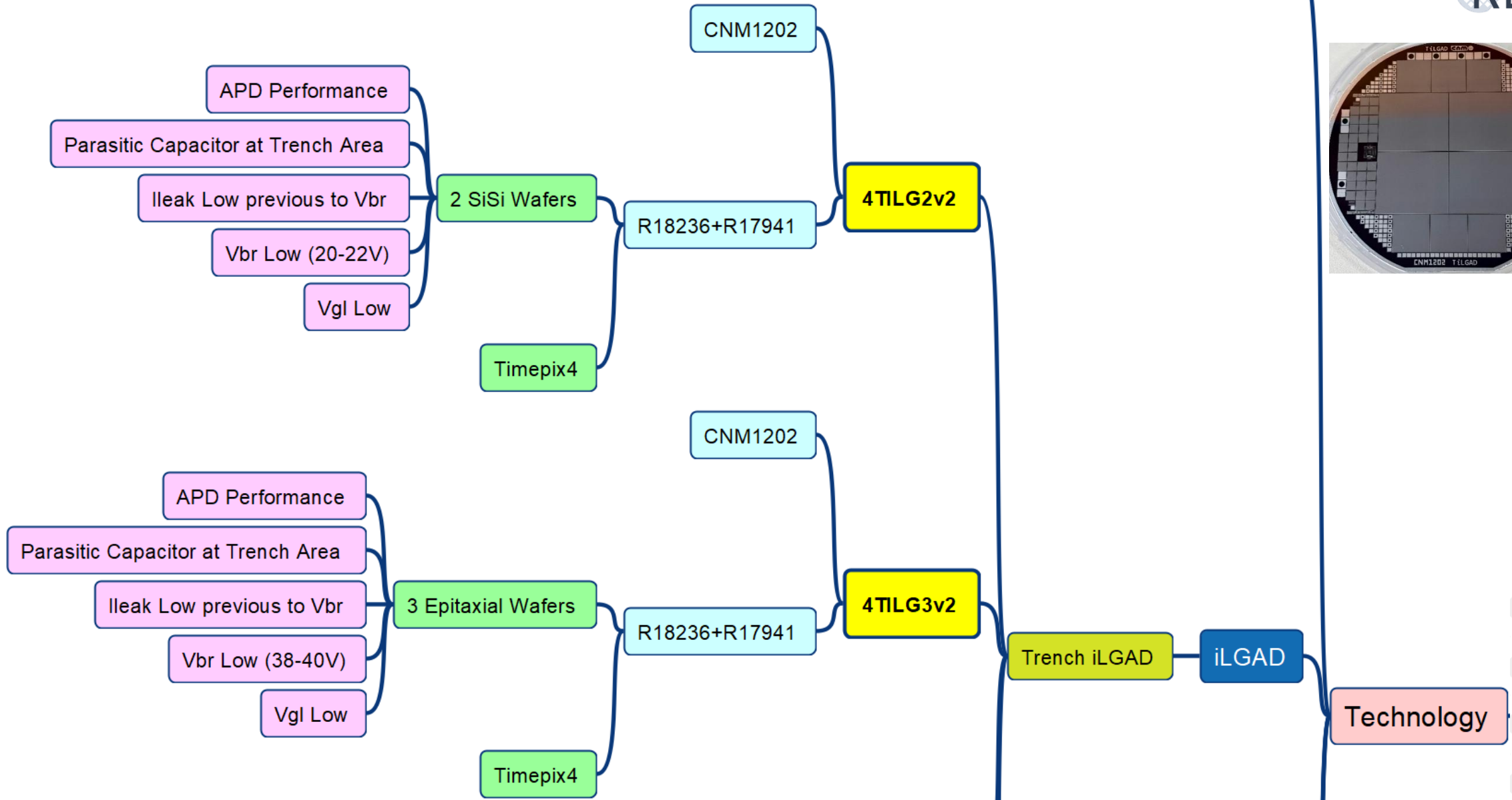
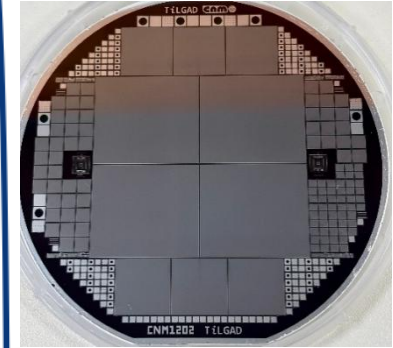
Subproject Objectives. Technologies. LGAD



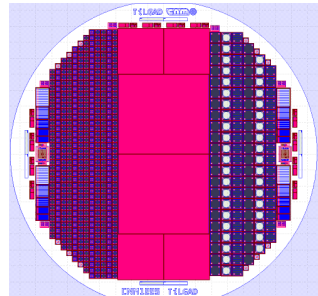
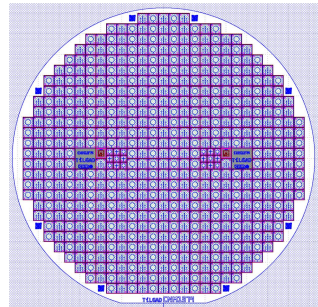
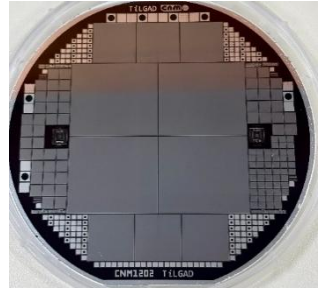
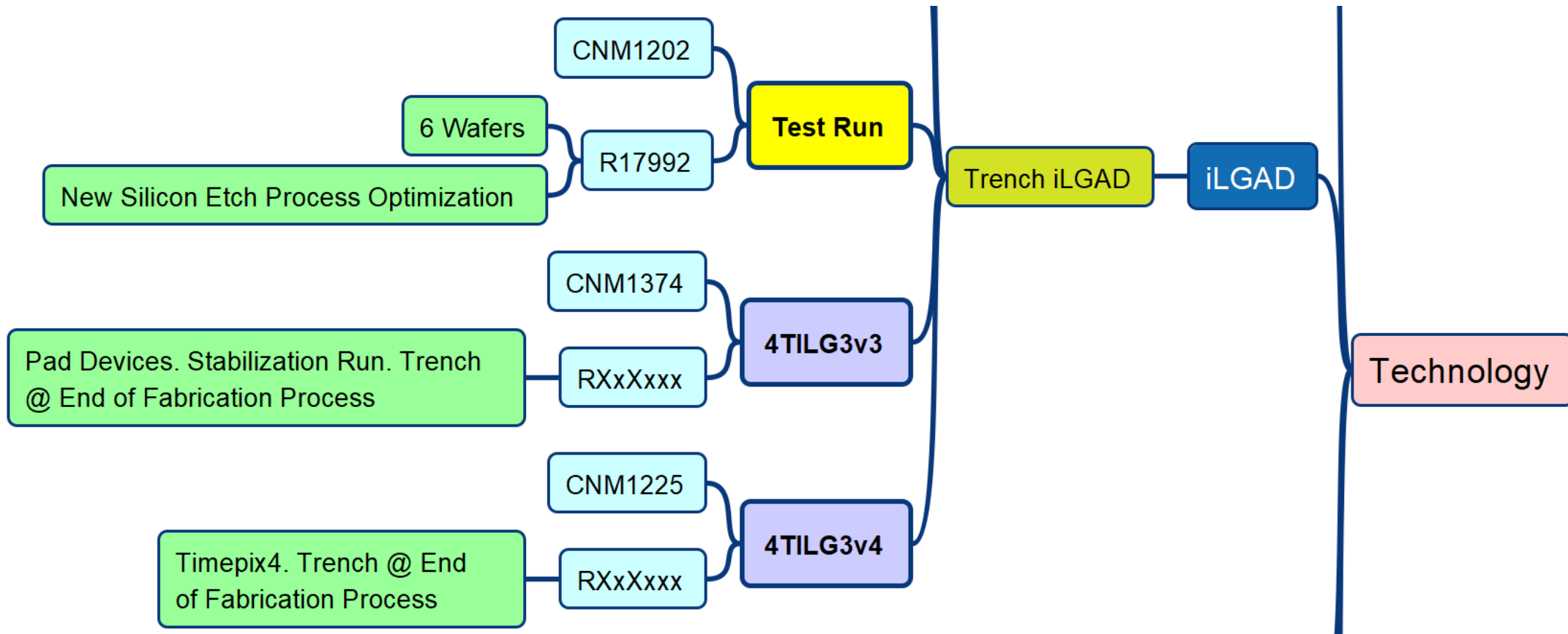
Subproject Objectives. Technologies. iLGAD



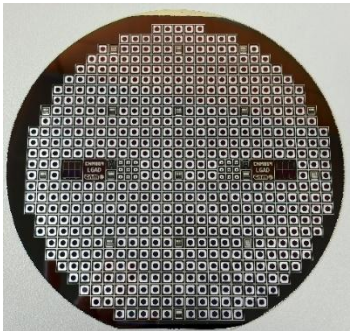
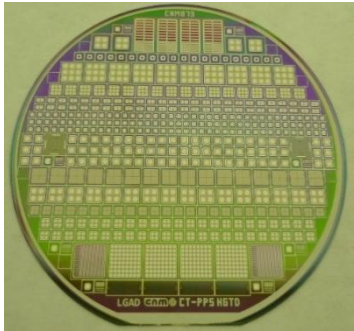
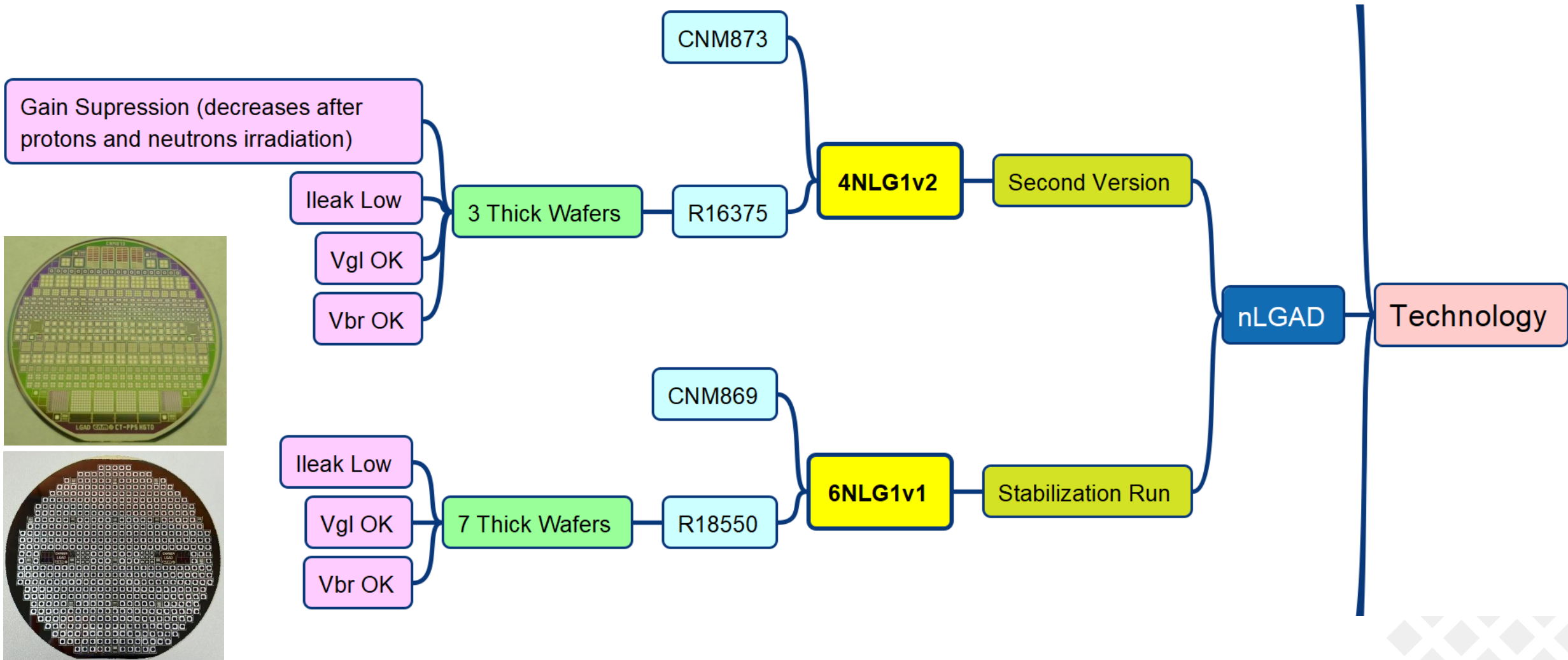
Subproject Objectives. iLGAD



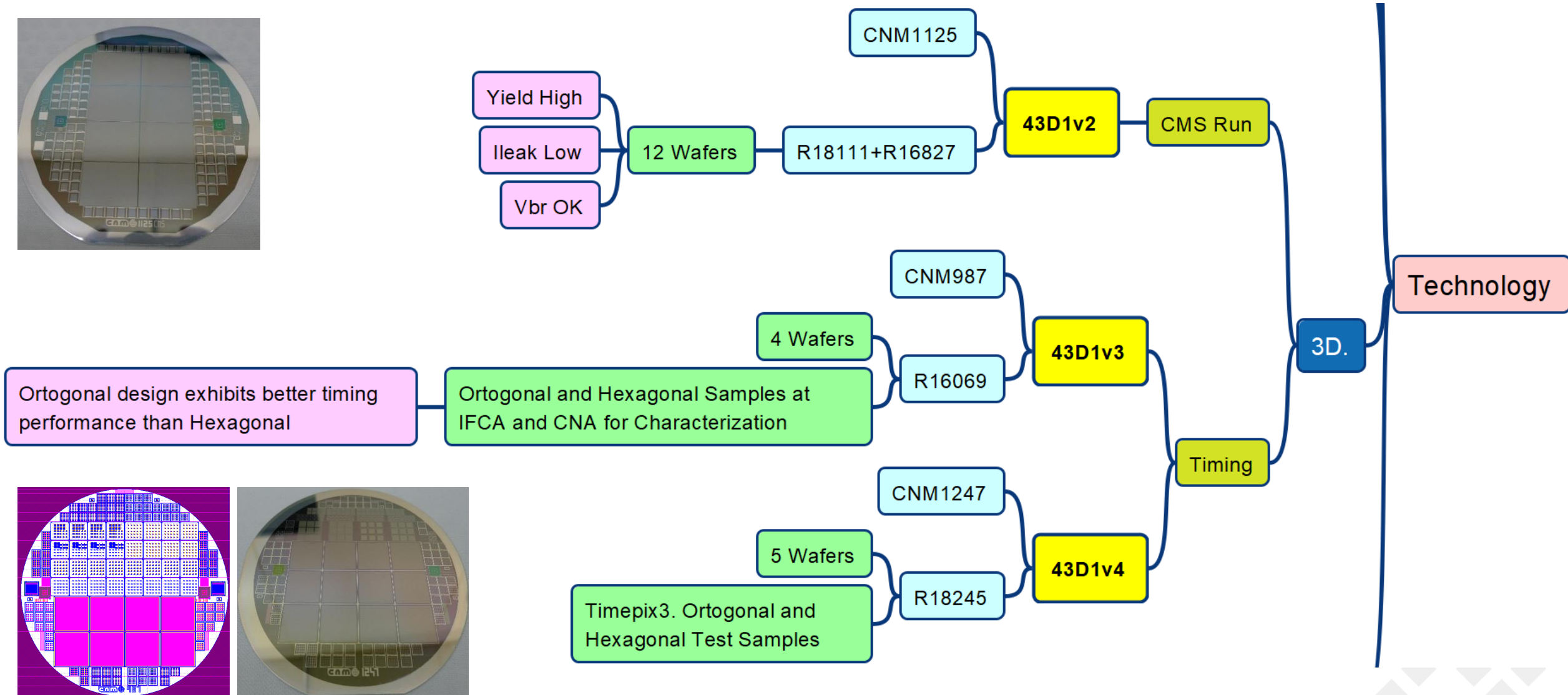
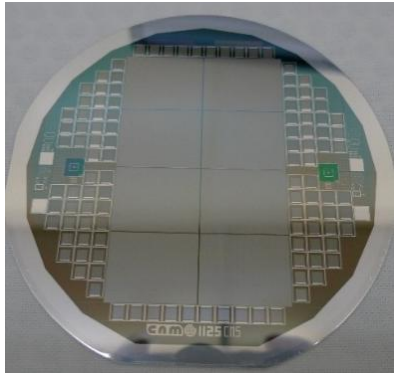
Subproject Objectives. Technologies. iLGAD



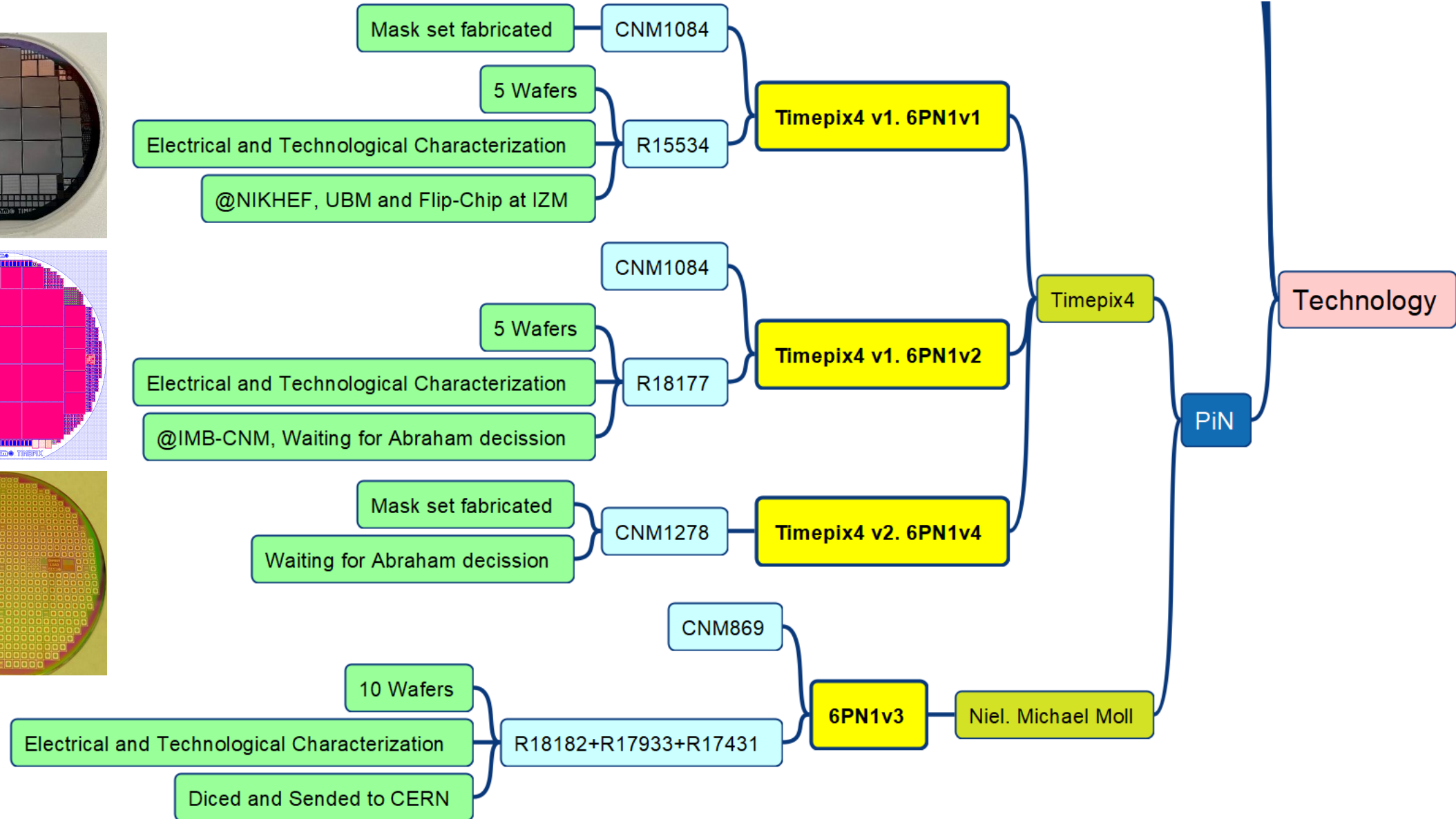
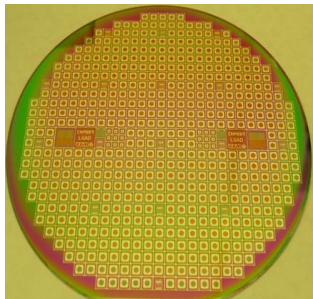
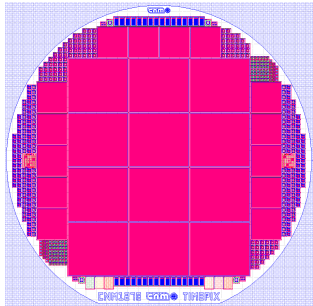
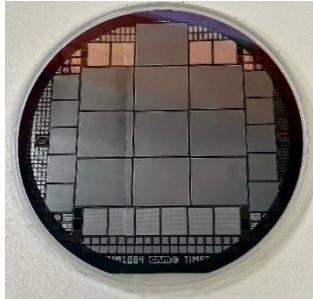
Subproject Objectives. nLGAD



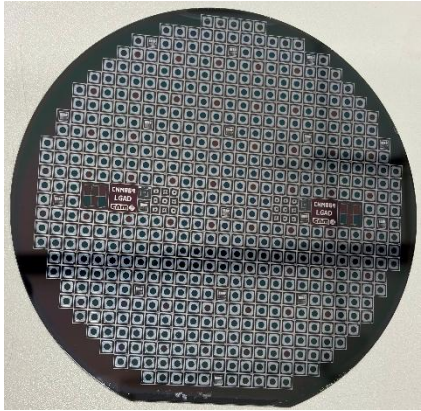
Subproject Objectives. 3D



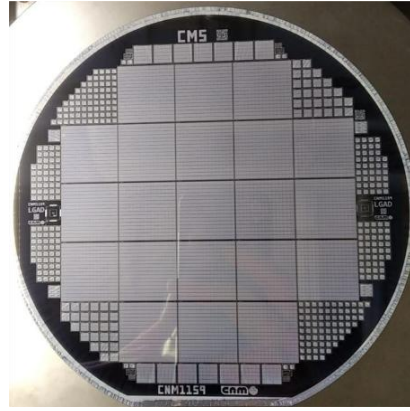
Subproject Objectives. PiN



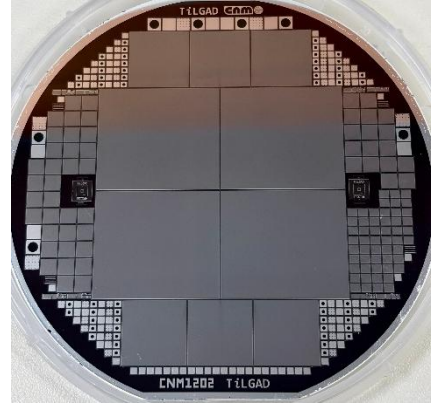
CMSUPG2 Technological Processes Developed



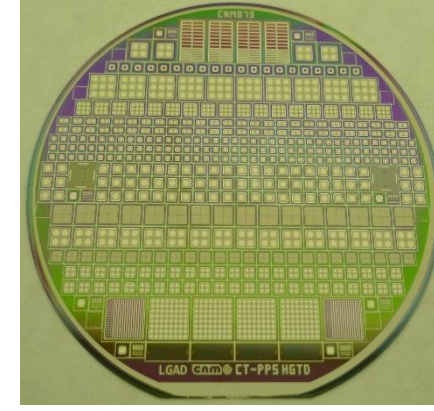
Oblea de 150 mm en la que se integran prototipos de detectores **LGAD** sobre sustratos epitaxiales. Dispositivos Pad con perfil original. Tecnología **6LG3v3**



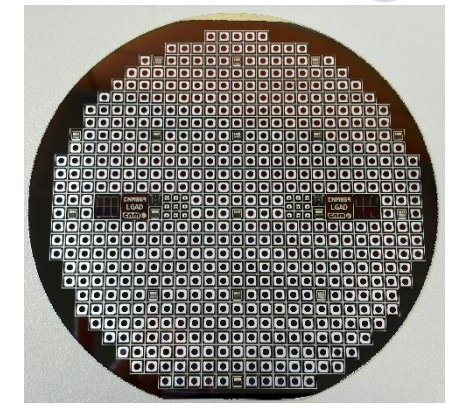
Oblea de 150 mm en la que se integran prototipos de detectores **LGAD** sobre sustratos epitaxiales. Módulos 16x16 con perfil profundo. Tecnología **6DLG3v1**



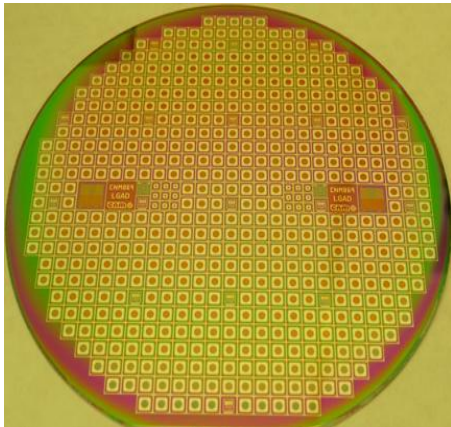
Oblea de 100 mm en la que se integran prototipos de detectores **Trench iLGAD** con diseño **Timepix4**. Primera Generación. Tecnologías **4TILG2v2** y **4TILG3v2**



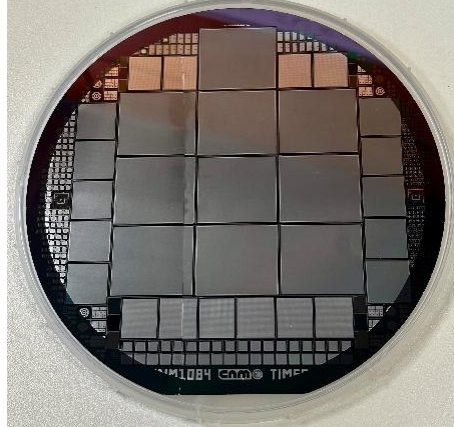
Oblea de 100 mm en la que se integran prototipos de detectores **nLGAD**. Segunda Generación. Tecnología **4NLG1v2**



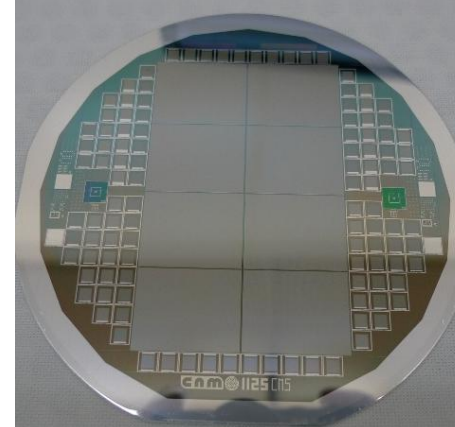
Oblea de 150 mm en la que se integran prototipos de detectores **nLGAD**. Tercera Generación. Tecnología **6NLG1v1**



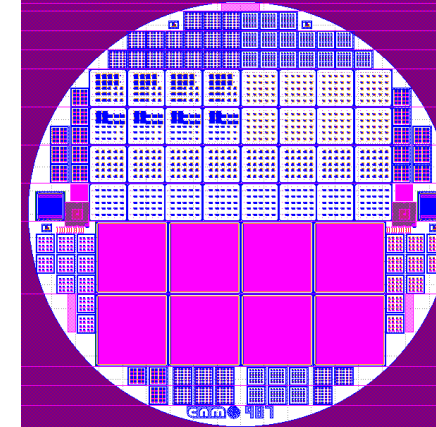
Oblea de 150 mm en la que se integran prototipos de detectores **PiN** para **RD50**. Tecnología **6PN1v3**



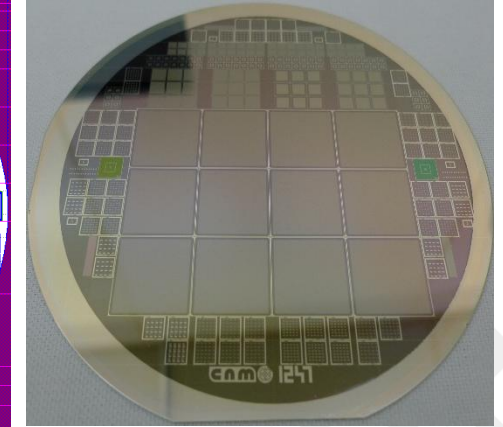
Oblea de 150 mm en la que se integran prototipos de detectores **PiN** con diseño **Timepix4**. Primera y Segunda Generación. Tecnologías **6PN1v1** y **6PN1v2**



Oblea de 100 mm en la que se integran prototipos de detectores **3D Single Side** compatibles con **CMSROC**. Tecnología **43D1v2**

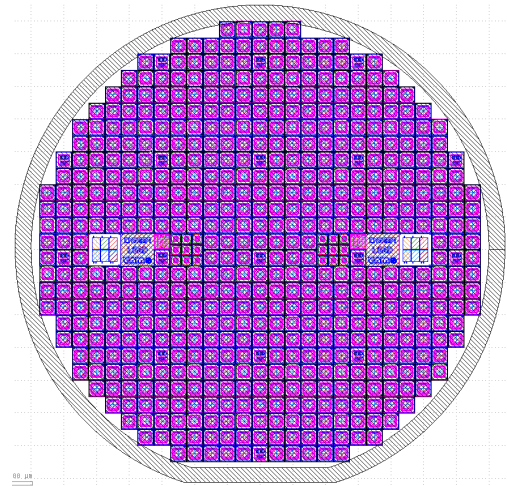


Oblea de 100 mm en la que se integran la primera generación de detectores **3D Single Side** para aplicaciones de **Timing**. Tecnología **43D1v3**

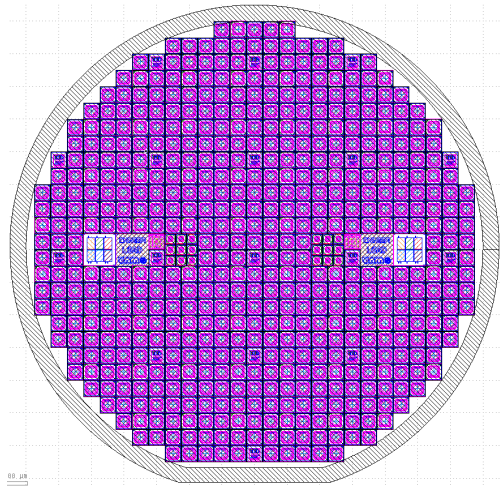


Oblea de 100 mm en la que se integran la segunda generación de detectores **3D Single Side** para aplicaciones de **Timing**. Tecnología **43D1v4**

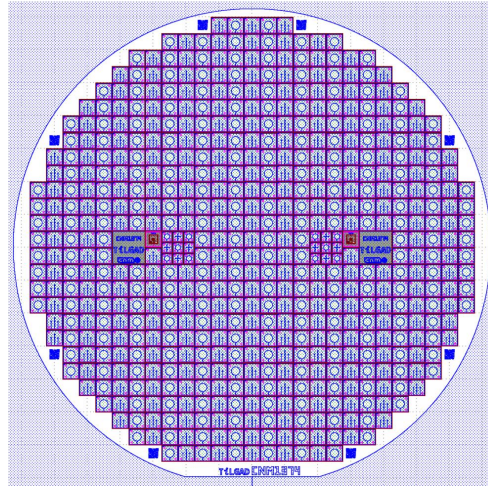
CMSUPG2 Technological Processes Developed



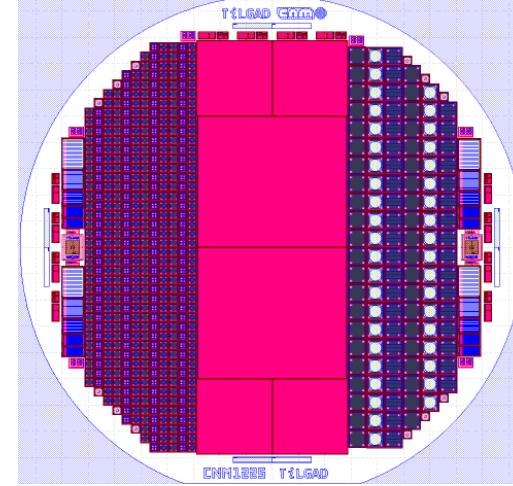
Oblea de 150 mm en la que se integraran prototipos de detectores **LGAD** para **RD50 ExFlux**. Tecnología **6LG3v4**



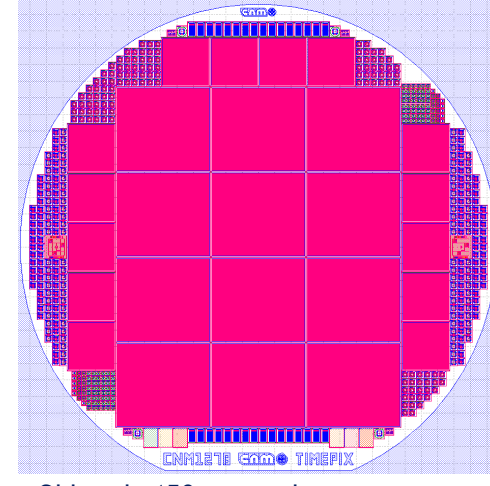
Oblea de 150 mm en la que se integraran prototipos de detectores **LGAD** sobre sustratos epitaxiales. Dispositivos **Pad** con **perfil profundo**. Tecnología **6DLG3v2**



Oblea de 100 mm en la que se integraran prototipos de detectores **Trench iLGAD** con diseño **Single Pad**. **Segunda Generación**. Tecnología **4TILG3v3**

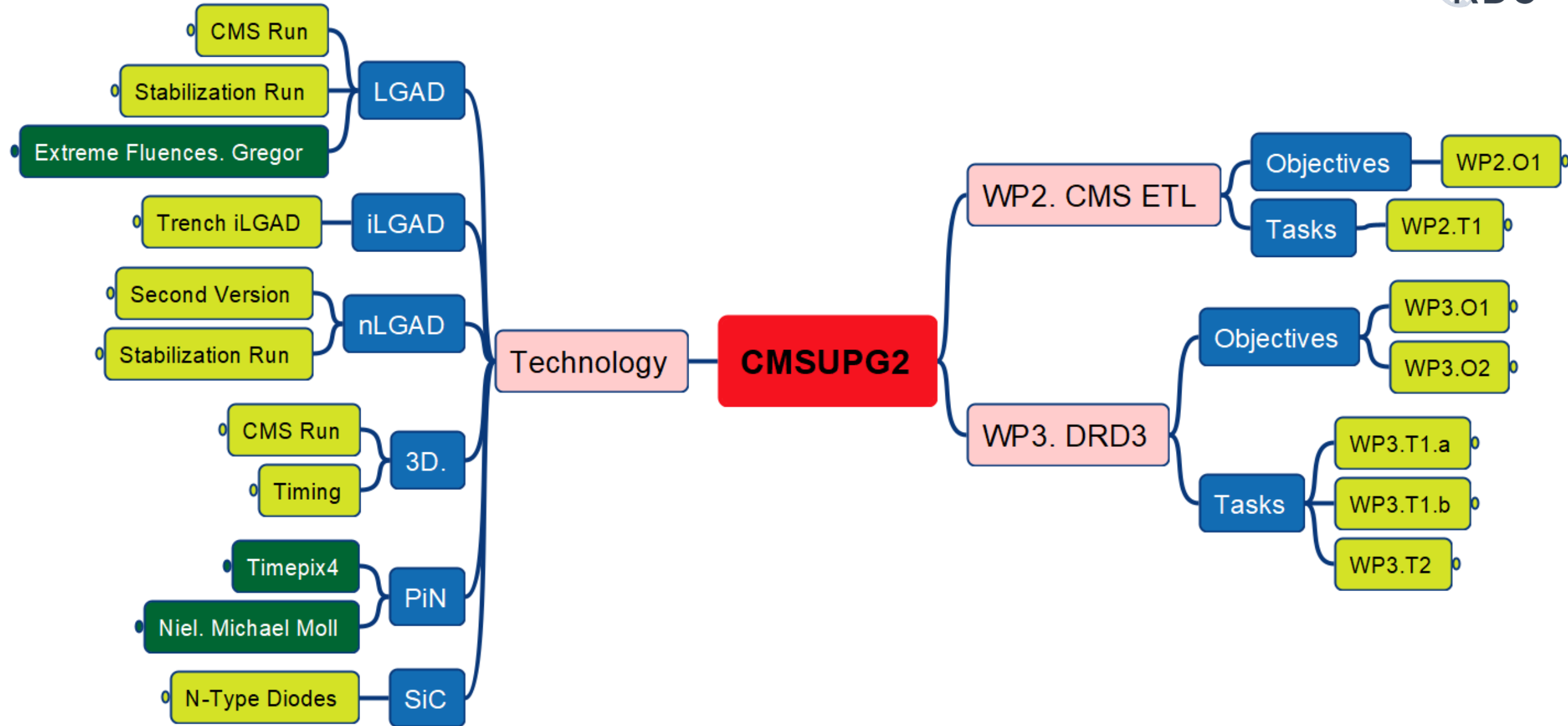


Oblea de 100 mm en la que se integraran prototipos de detectores **Trench iLGAD** con diseño **Timepix4**. **Segunda Generación**. Tecnología **4TILG3v4**

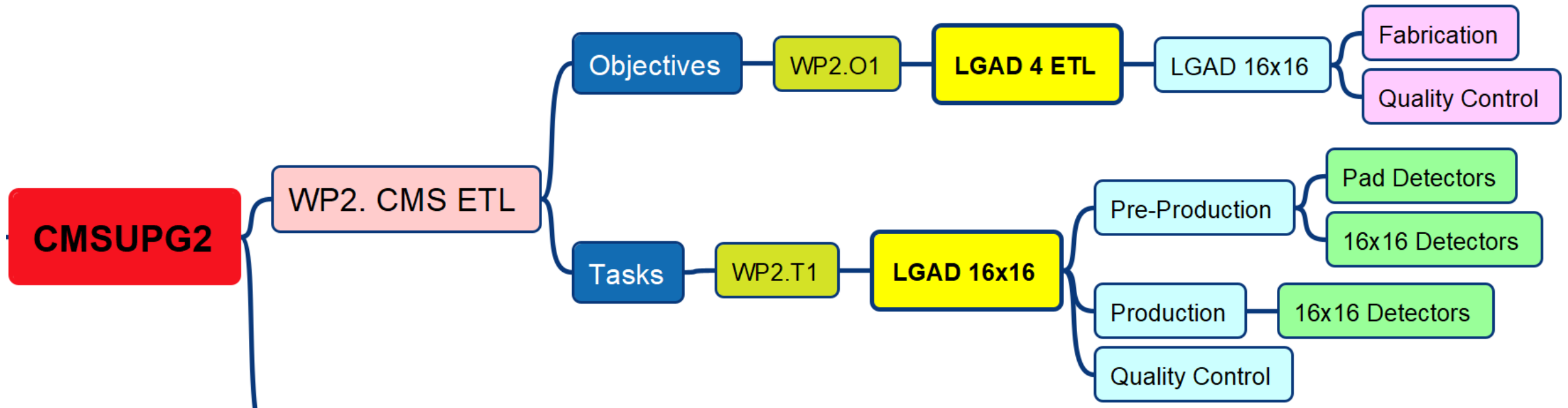


Oblea de 150 mm en la que se integraran prototipos de detectores **PiN** con diseño **Timepix4**. **Tercera Generación**. Tecnología **6PN1v4**

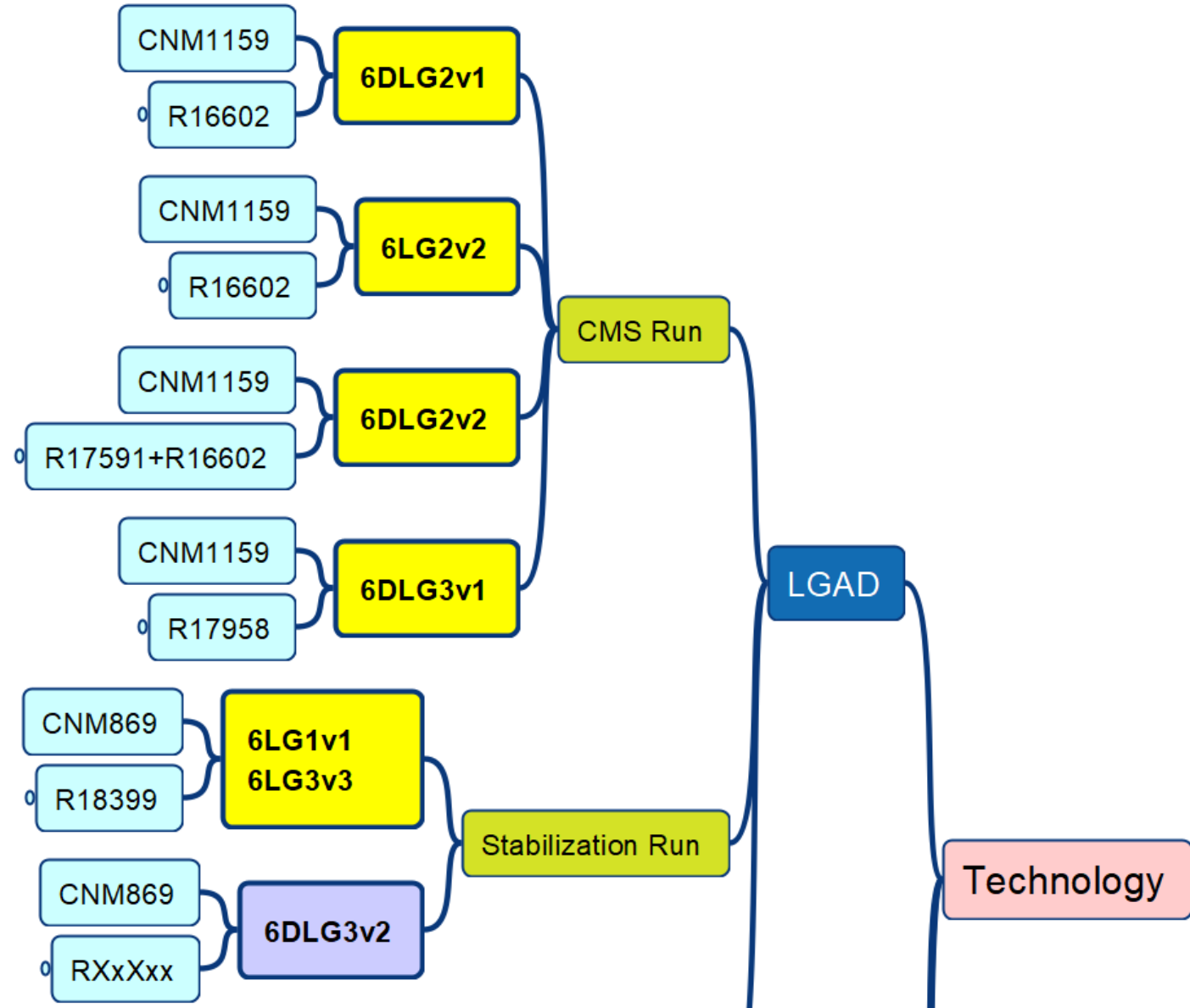
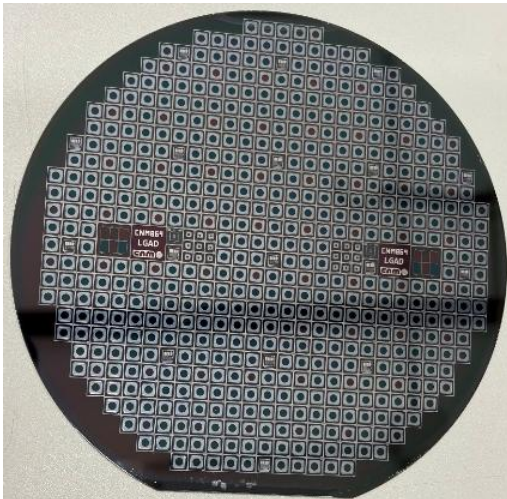
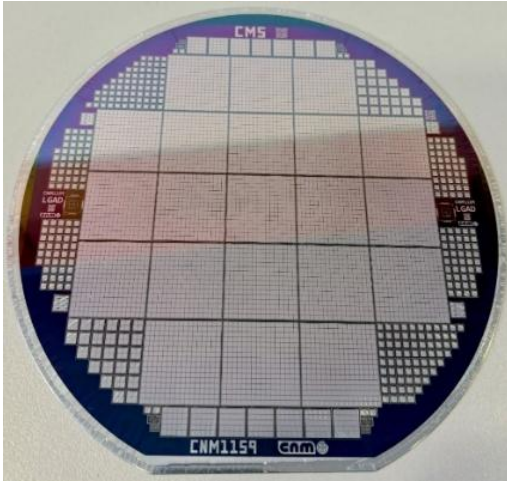
Subproject Objectives



Subproject Objectives. WP2

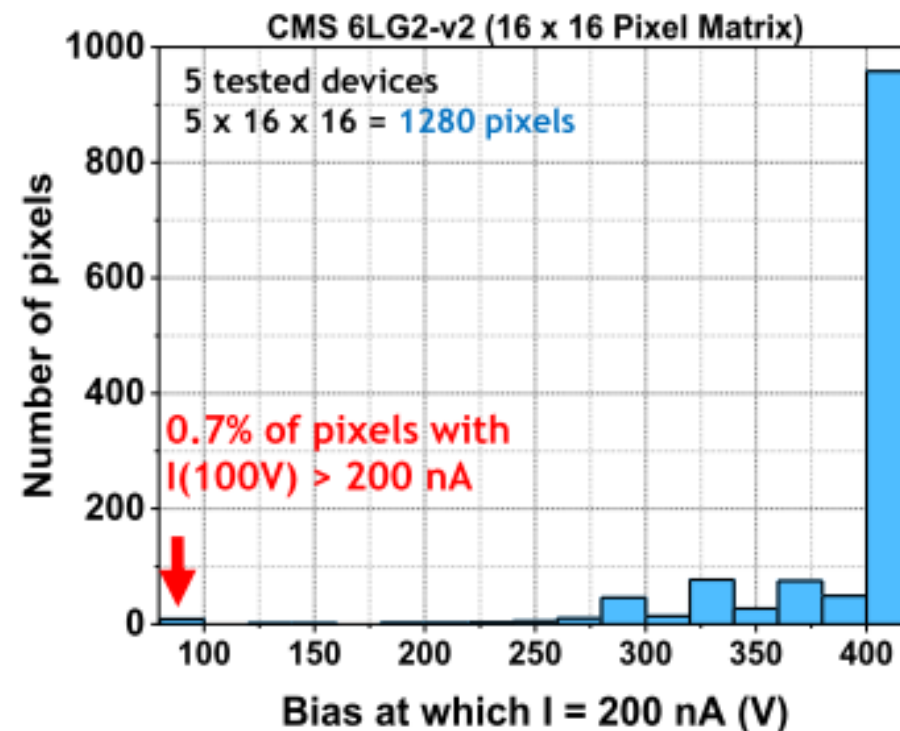
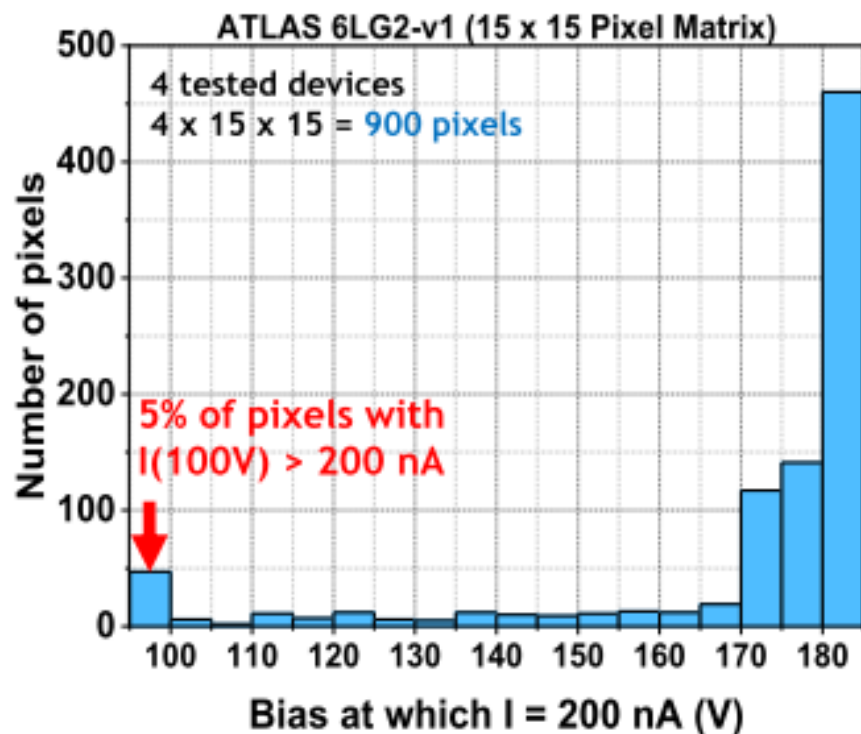


WP2. Technologies Developed. LGAD



Pixel yield on standard CNM LGADs

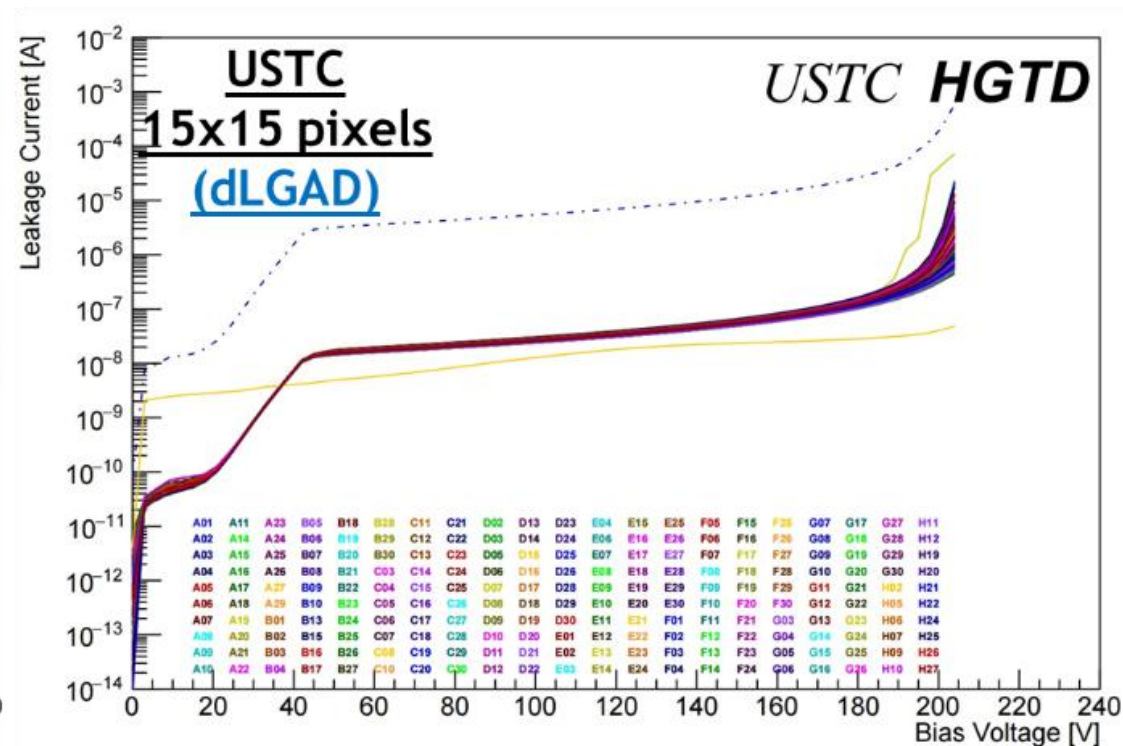
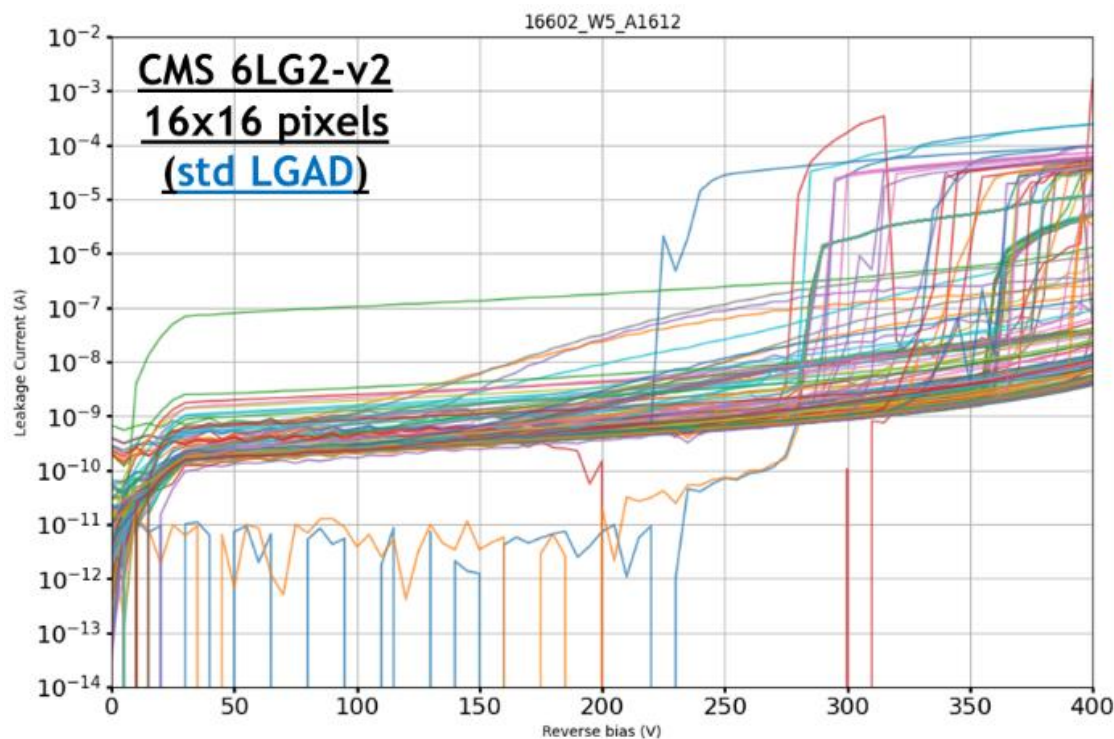
- Even if the current levels and the pixel yield was overall good, there was a dispersion in V_{BD} higher than desirable for large area pixelated devices
- In addition, even one pixel with high current is enough to spoil the full matrix performance

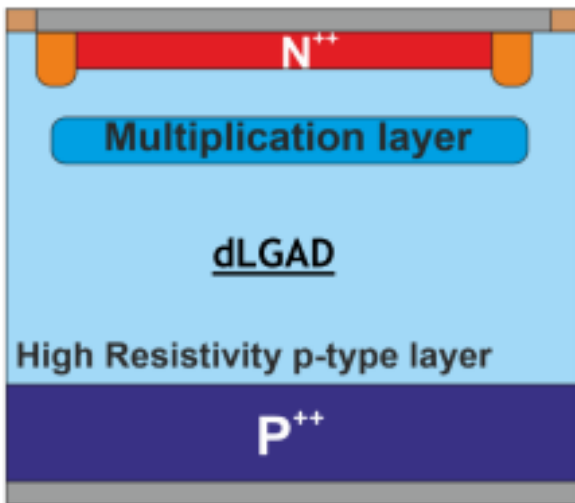
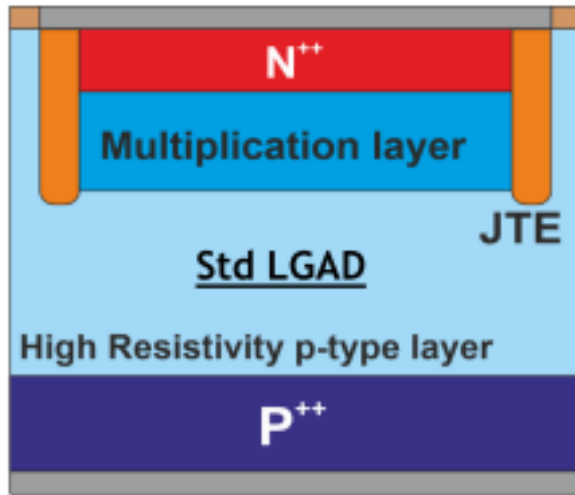


J. Villegas: PhD Thesis

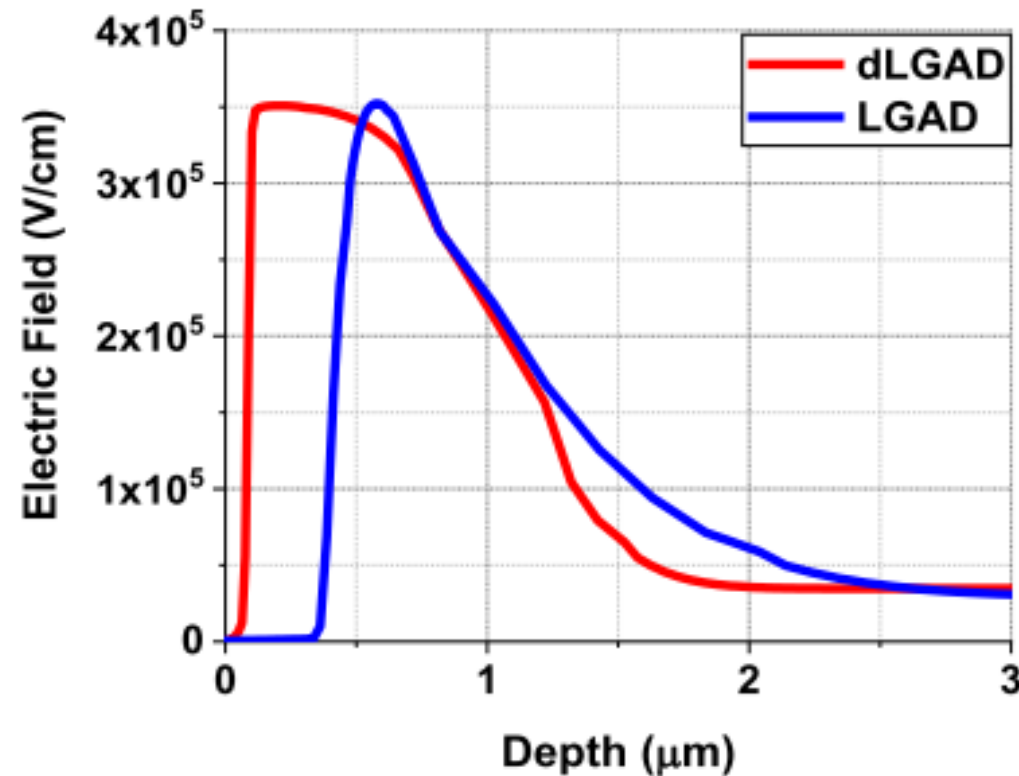
- Large-size Modules. IV characteristics comparison:

- 16x16 6LG2v2. Manufactured at the IMB-CNM during the PID2020-113705RB-C32 project with the **original profile**,
- 15x15. Manufactured by the Institute of Microelectronics of the Chinese Academy of Sciences (IMECAS) and designed at USTC, with a **deep-well profile**.





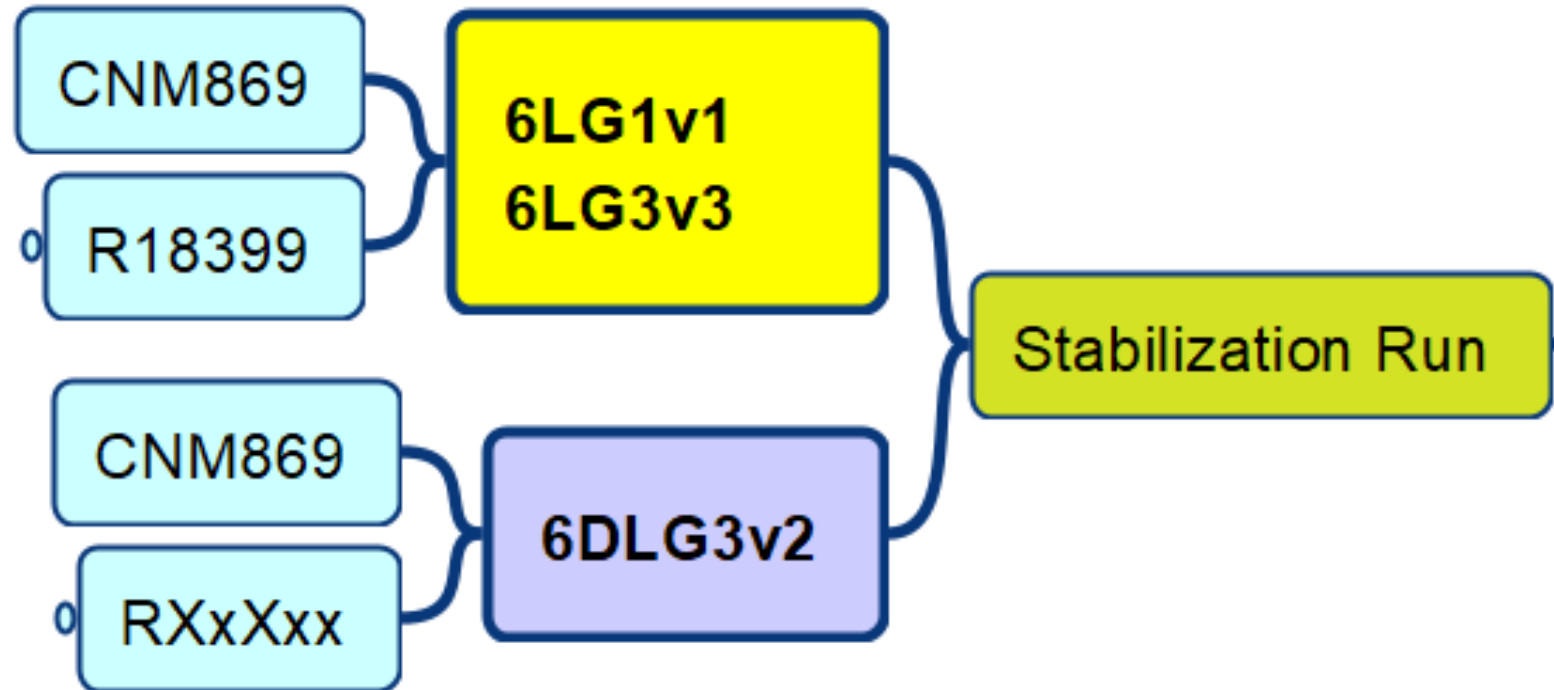
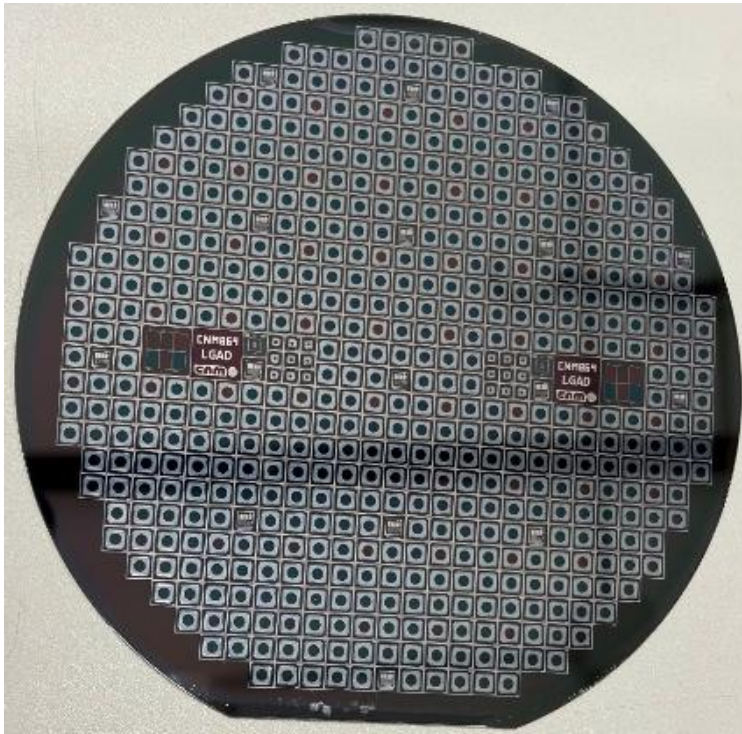
- Standard CNM LGAD: the N^{++} overlaps the Multiplication layer, and the **electric field peaks at the PN junction**
- dLGAD: the N^{++} and the Multiplication layer are **physically separated**, and the **electric field is nearly flat within this gap**



WP2.01. Manufacturing and QC of LGAD sensors for the ETL detector

Run	Description	Mask	Carbonated	IMB-CNM equipment	N ⁺⁺ dopant	Status
6DLG2v1	Si-Si wafers. CMS 16x16	CNM1159	Yes	New	Phosphorus	Finished
6DLG2v2	Si-Si wafers. CMS 16x16	CNM1159	Yes	New	Arsenic	Finished
6DLG3v1	Epitaxial wafers. CMS 16x16	CNM1159	Yes	New	Arsenic	Finished
6DLG3v2	Epitaxial wafers. Pad Devices	CNM869	Yes	New	Arsenic	Planned

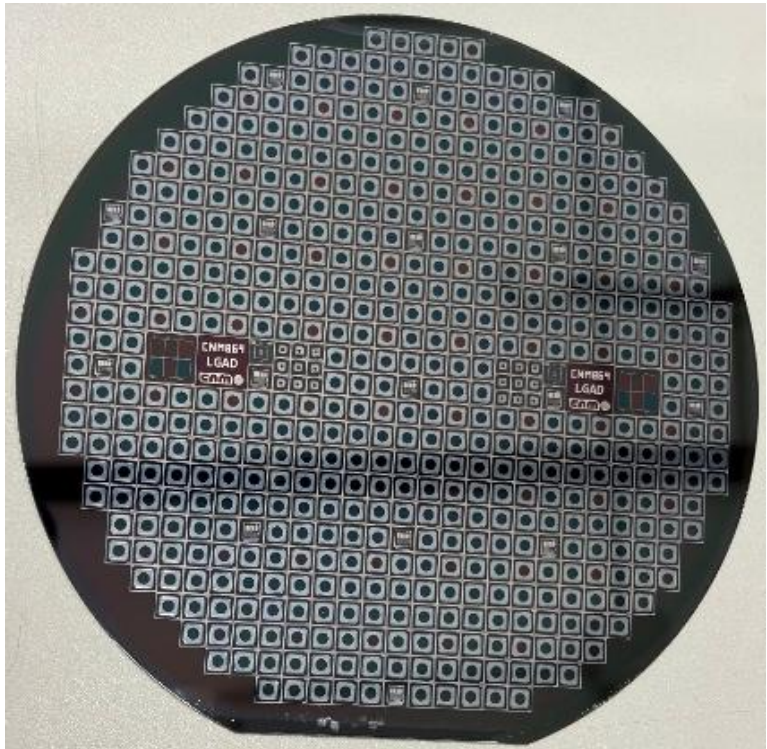
Run	Description	Mask	Carbonated	IMB-CNM equipment	N ⁺⁺ dopant	Status
6LG2v2	Si-Si wafers. CMS 16x16	CNM1159	Yes	New	Phosphorus	Finished
6LG1v1	Si thick wafers. Pad Devices	CNM869	Yes	New	Phosphorus	Finished
6LG3v3	Epitaxial wafers. Pad Devices	CNM869	Yes	New	Phosphorus	Finished



CMS 6LG3v3. R18399

- 10 Wafers
- Mask CNM869 → Single-pads only
- 586 LGADs of 3.3 mm and 16 LGADs of 1.3 mm
- 64 PiNs of 3.3 mm and 2 PiNs of 1.3 mm
- ATLAS IP Parameters

- Yield condition: $V_{BD} > 90\text{ V}$
- On samples of $3.3 \times 3.3\text{ mm}^2$



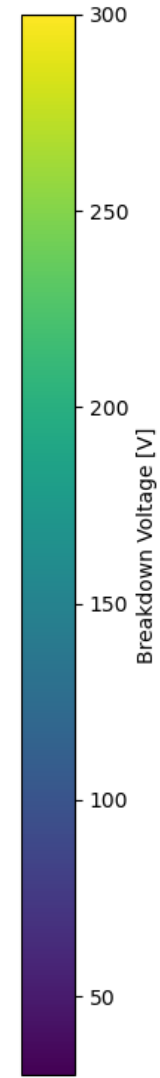
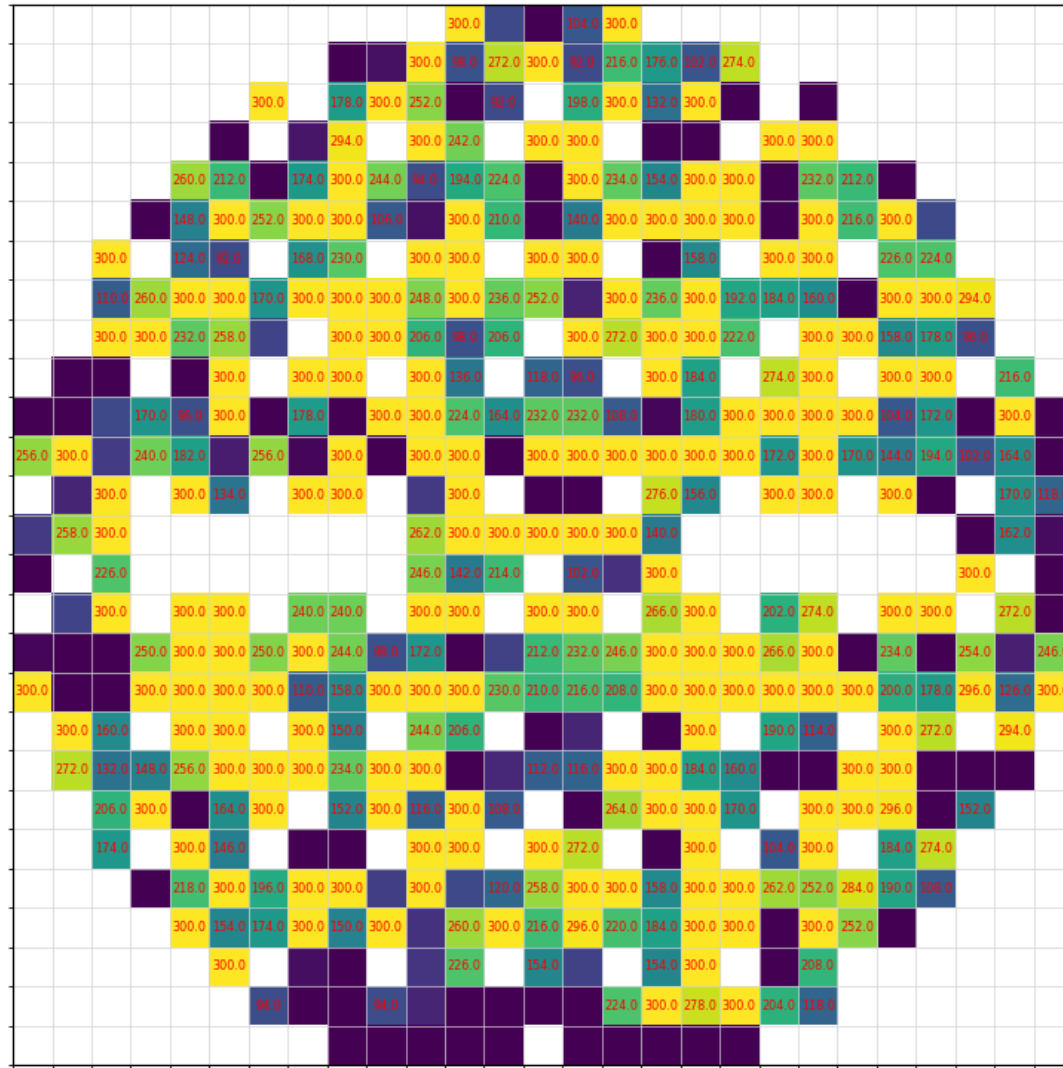
Wafer	Features	Type
1	<u>Std LGAD</u>	150 mm Epitaxial wafers 55 μm active thickness 525 μm low-resistivity p-type handle wafer
2	$E_{\text{Boron}} = 100\text{ keV}$	
3	$D_{\text{Boron}} = 1.9\text{e}13\text{ at/cm}^2$	
4	$E_{\text{Phosp}} = 70 \text{ \& } 150\text{ keV}$	
5	$D_{\text{Phosp}} = 1\text{e}15 \text{ \& } 5\text{e}14\text{ at/cm}^2$	
6		
7	$E_{\text{Carbon}} = 150\text{ keV}$	
8	$D_{\text{Carbon}} = 4\text{e}14\text{ at/cm}^2$	
9	1100°C 180 min	
10	Same as W4 CMS Run16602	

Wafer	Yield [%]
W1	77
W2	73
W3	81
W4	74
W5	81
W6	63
W7	82
W8	85
W9	81

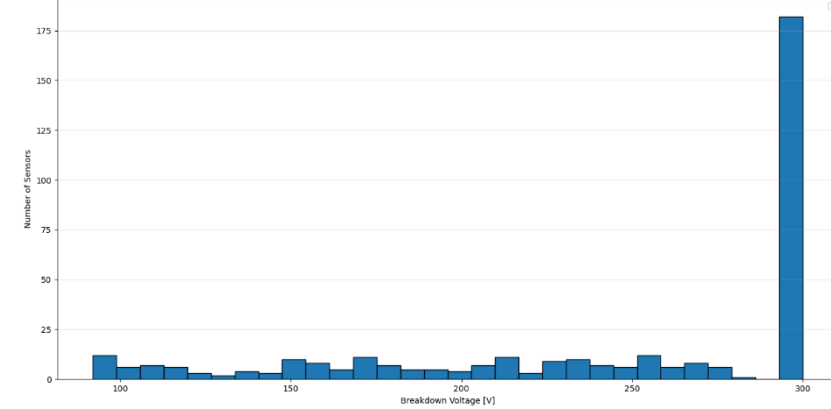
Wafer	Features	Laboratory	Type	T_{ML} (Å)	T_N (Å)
1	Std LGAD $E_{Boron} = 100$ keV $D_{Boron} = 1.9e13$ at/cm² $E_{Phosp} = 70$ & 150 keV $D_{Phosp} = 1e15$ & $5e14$ at/cm² $E_{Carbon} = 150$ keV $D_{Carbon} = 4e14$ at/cm² 1100°C 180 min Same as W4 CMS Run16602	RD50 (Gregor)	150 mm Epitaxial wafers	Regular screen oxide annealing (expected ≈ 200 Å)	NEW screen oxide annealing (expected ≈ 600 Å)
2					
3					
4					
5					
6					
7					
8					
9					
10		IMB-CNM (W10-W12)	150 mm FZ wafers 300 μ m active thickness No handle wafer	Regular screen oxide annealing (expected ≈ 200 Å)	Regular (≈ 100 Å)
11					NEW (≈ 600 Å)
12					Regular (≈ 100 Å)



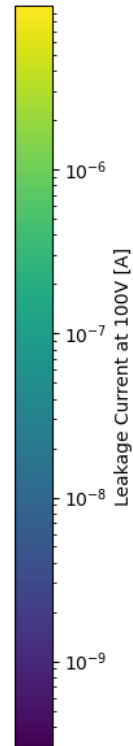
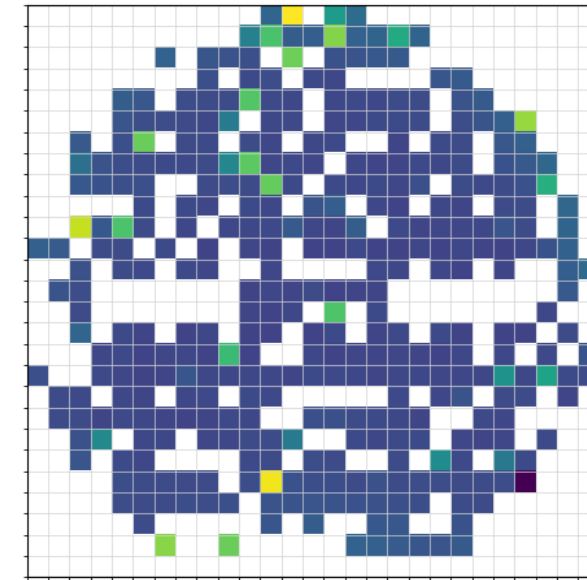
Breakdown Voltage Map of W1



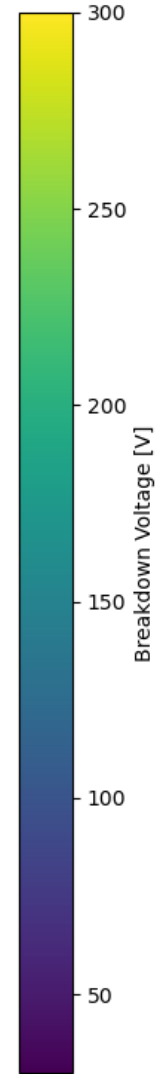
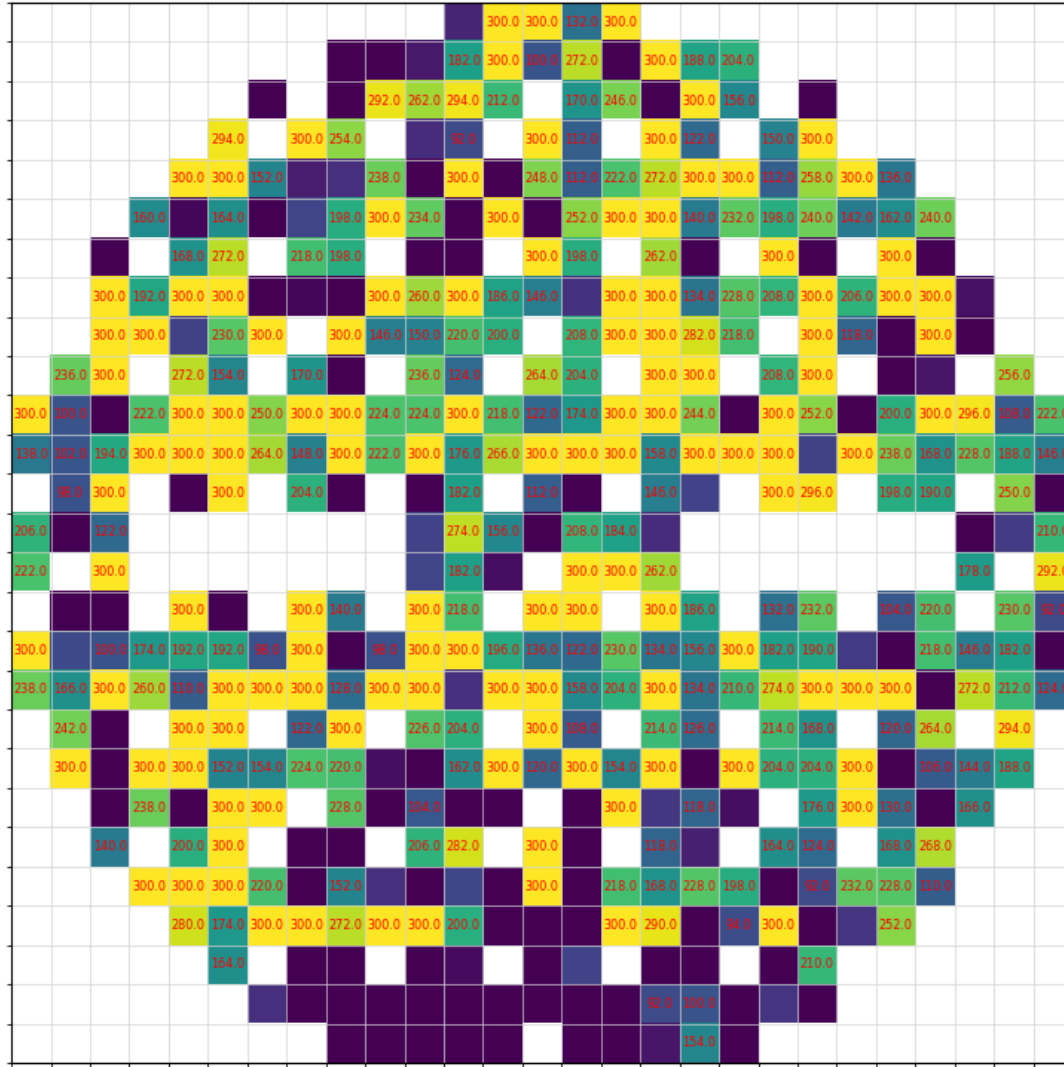
LGAD W1 Breakdown Voltage Distribution



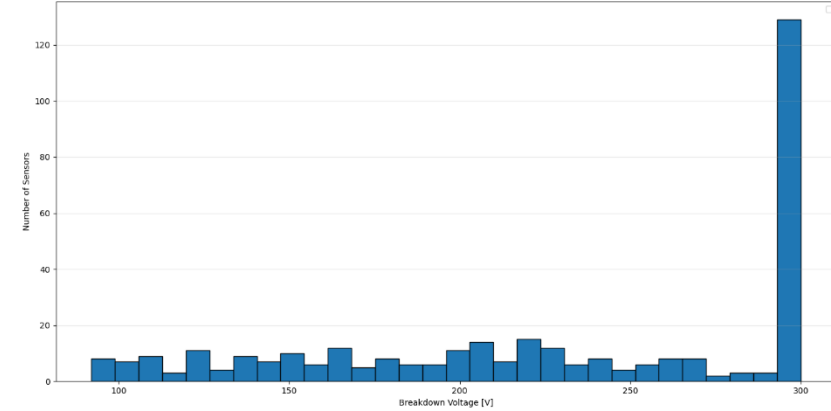
Leakage Current at 100V of W1



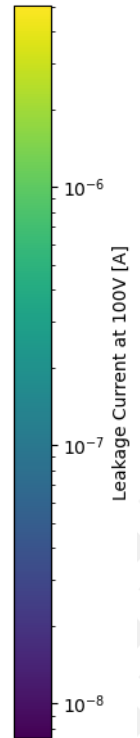
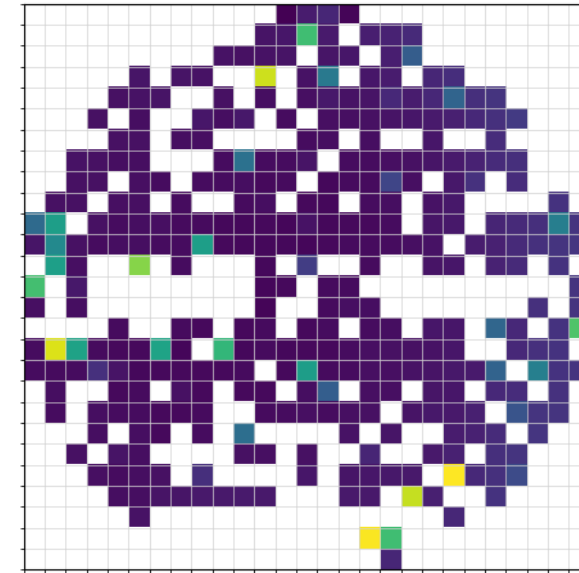
Breakdown Voltage Map of W2



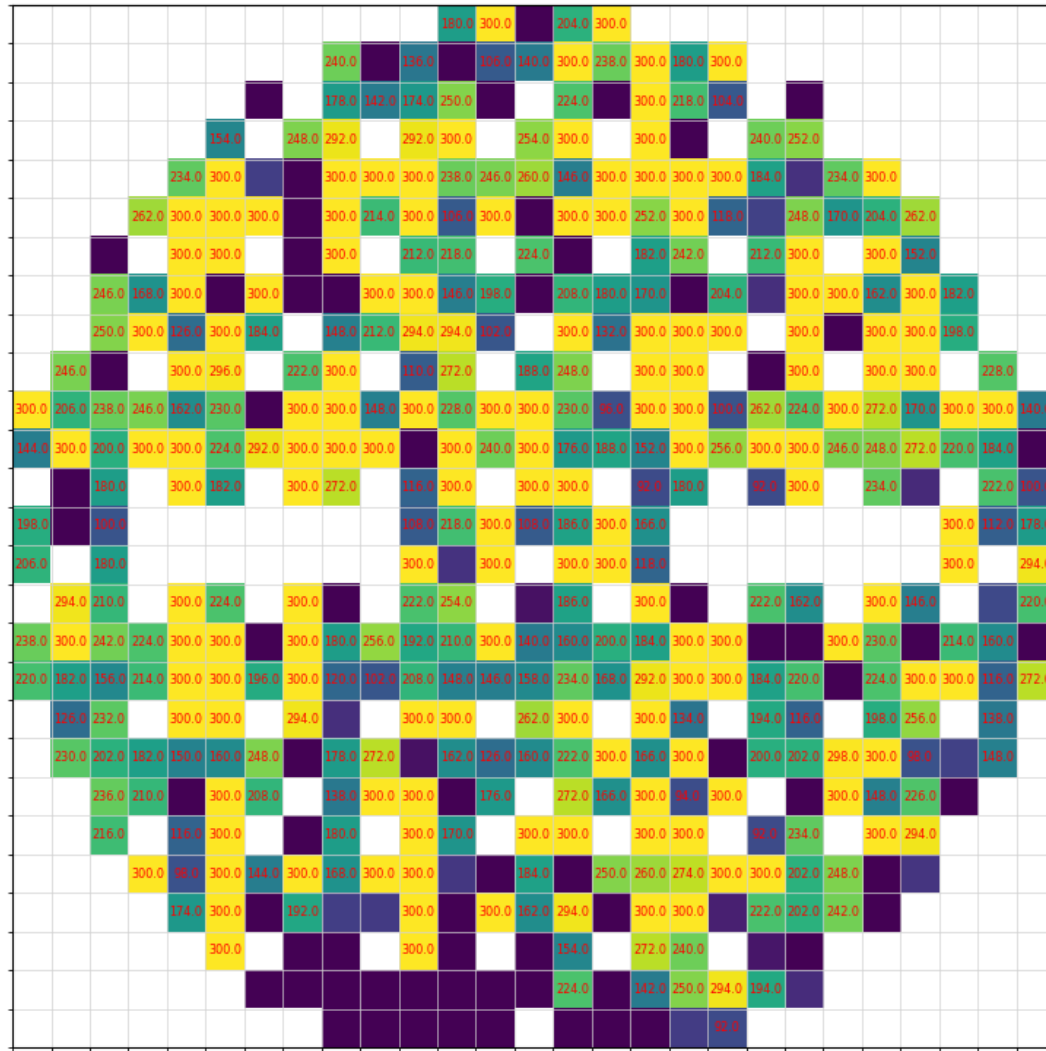
LGAD W2 Breakdown Voltage Distribution



Leakage Current at 100V of W2

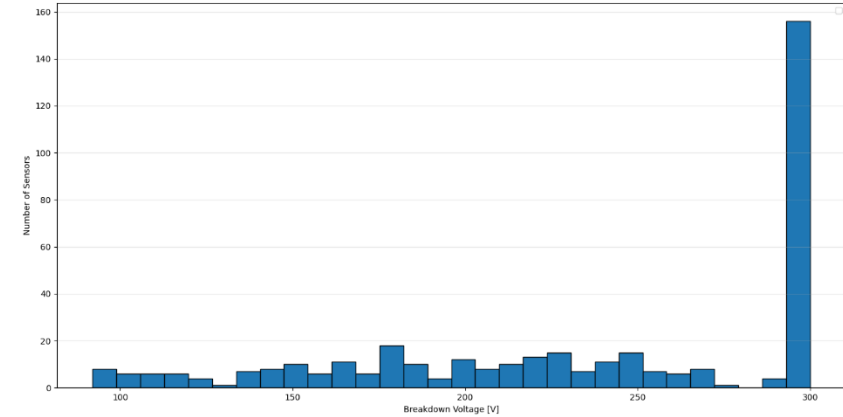


Breakdown Voltage Map of W3

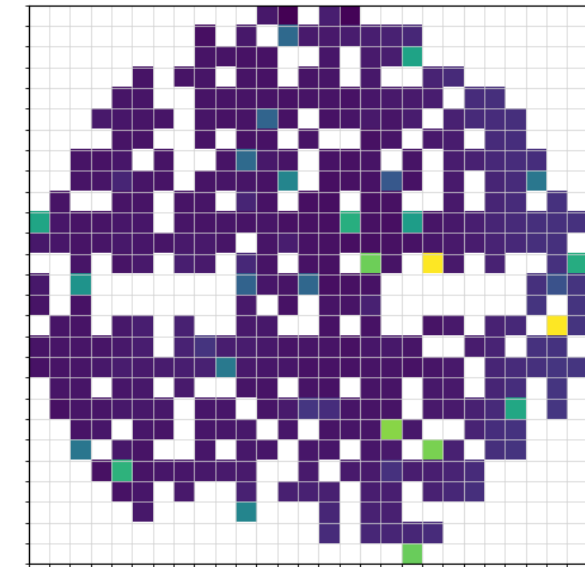


Breakdown Voltage [V]

LGAD W3 Breakdown Voltage Distribution



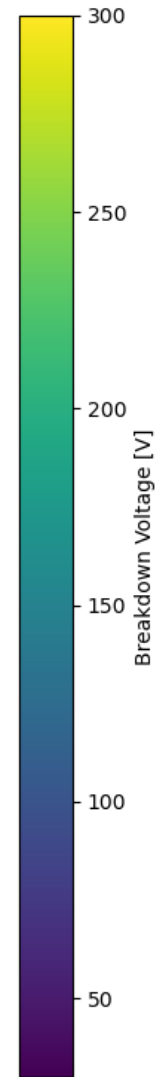
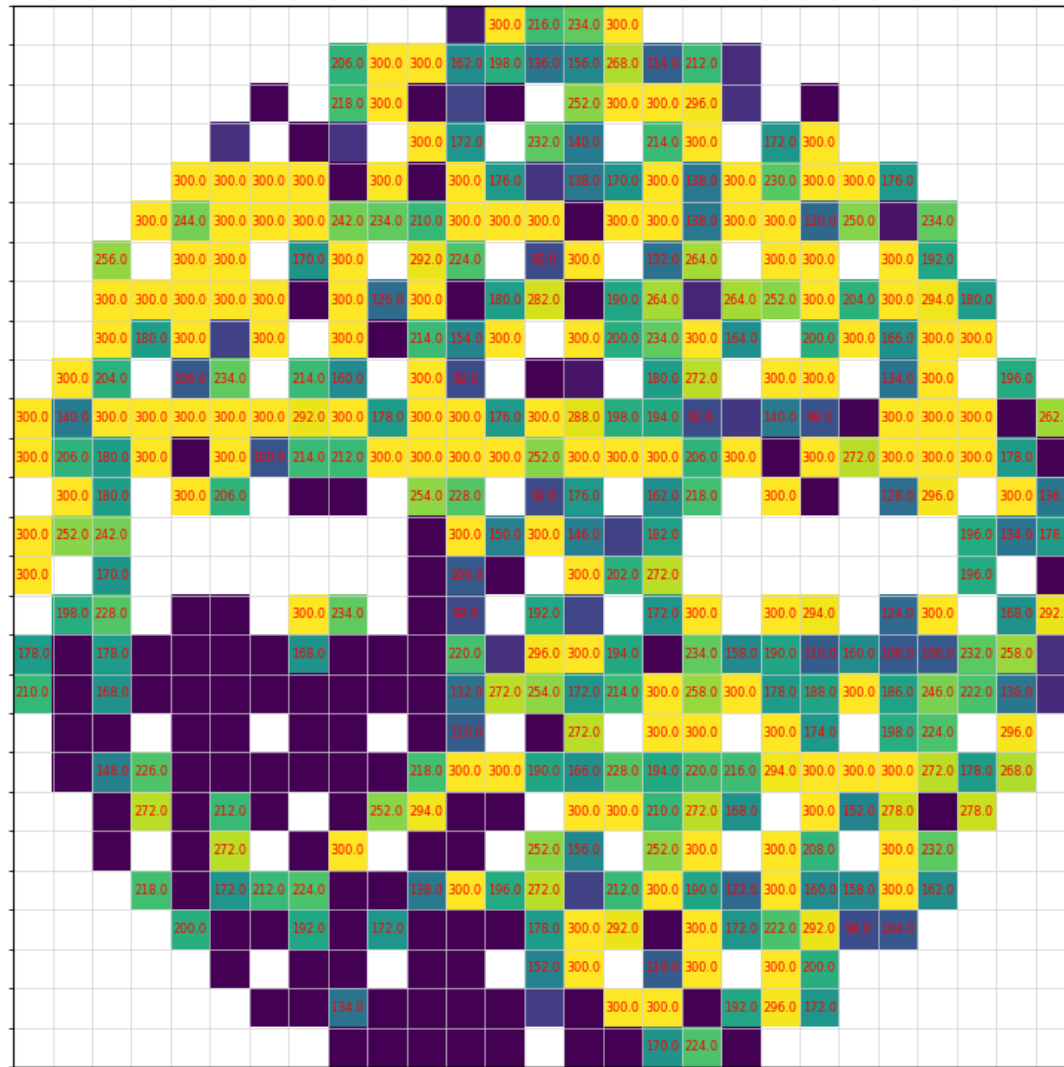
Leakage Current at 100V of W3



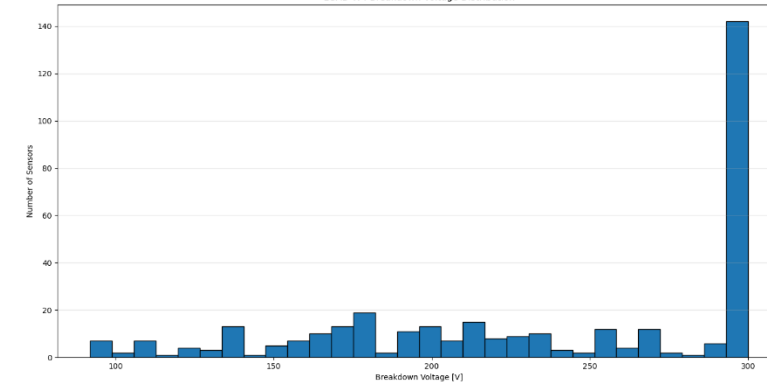
Leakage Current at 100V [A]



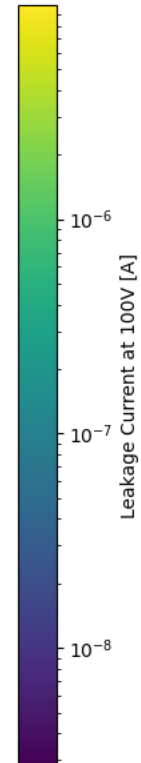
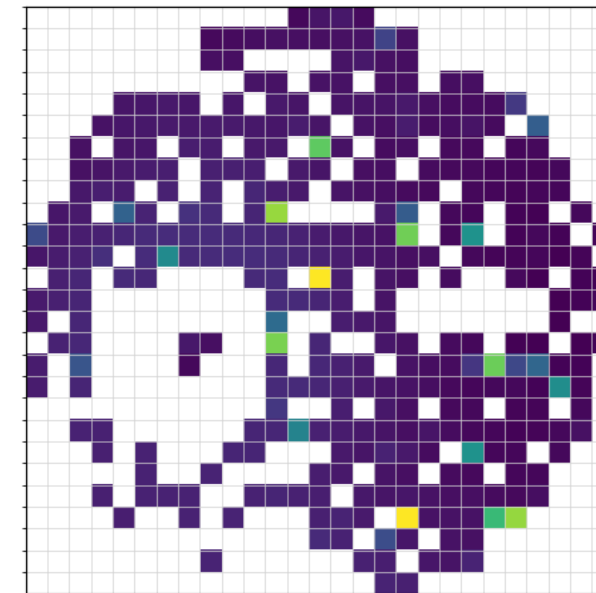
Breakdown Voltage Map of W4



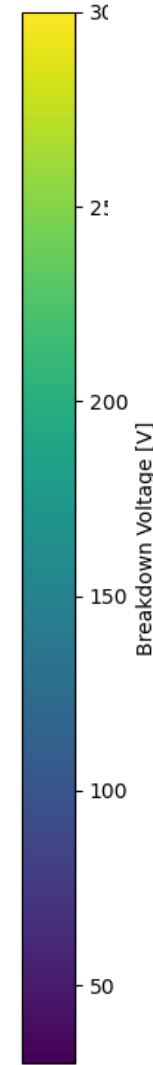
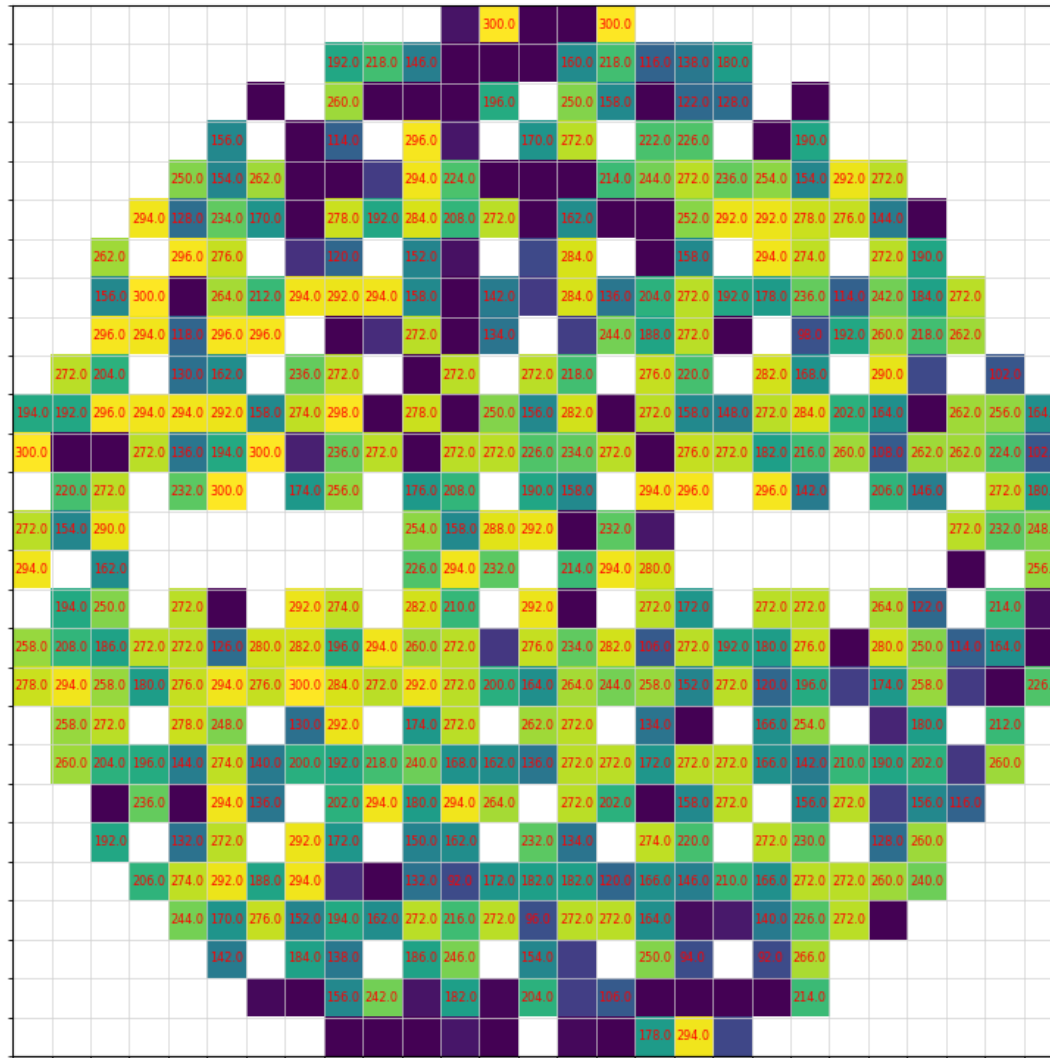
LGAD W4 Breakdown Voltage Distribution



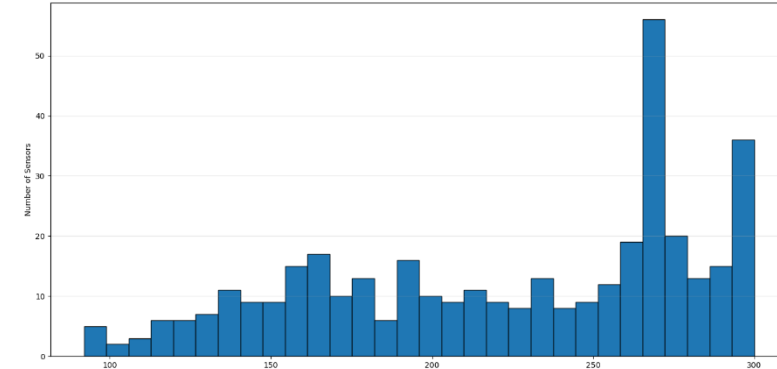
Leakage Current at 100V of W4



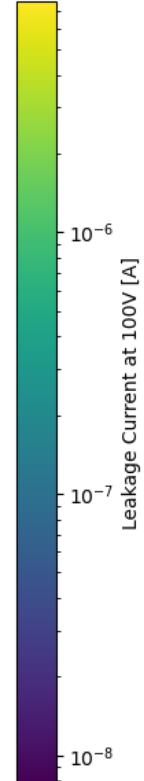
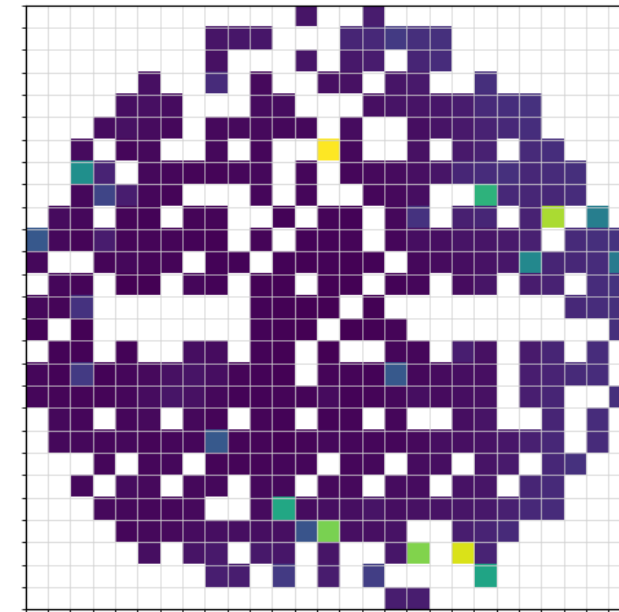
Breakdown Voltage Map of W5



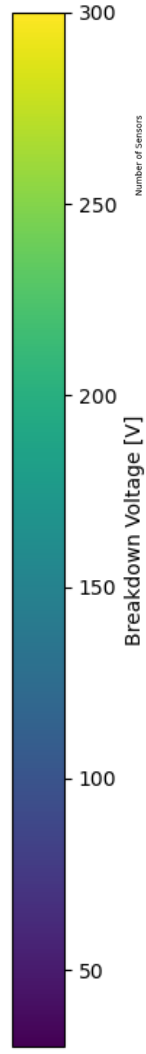
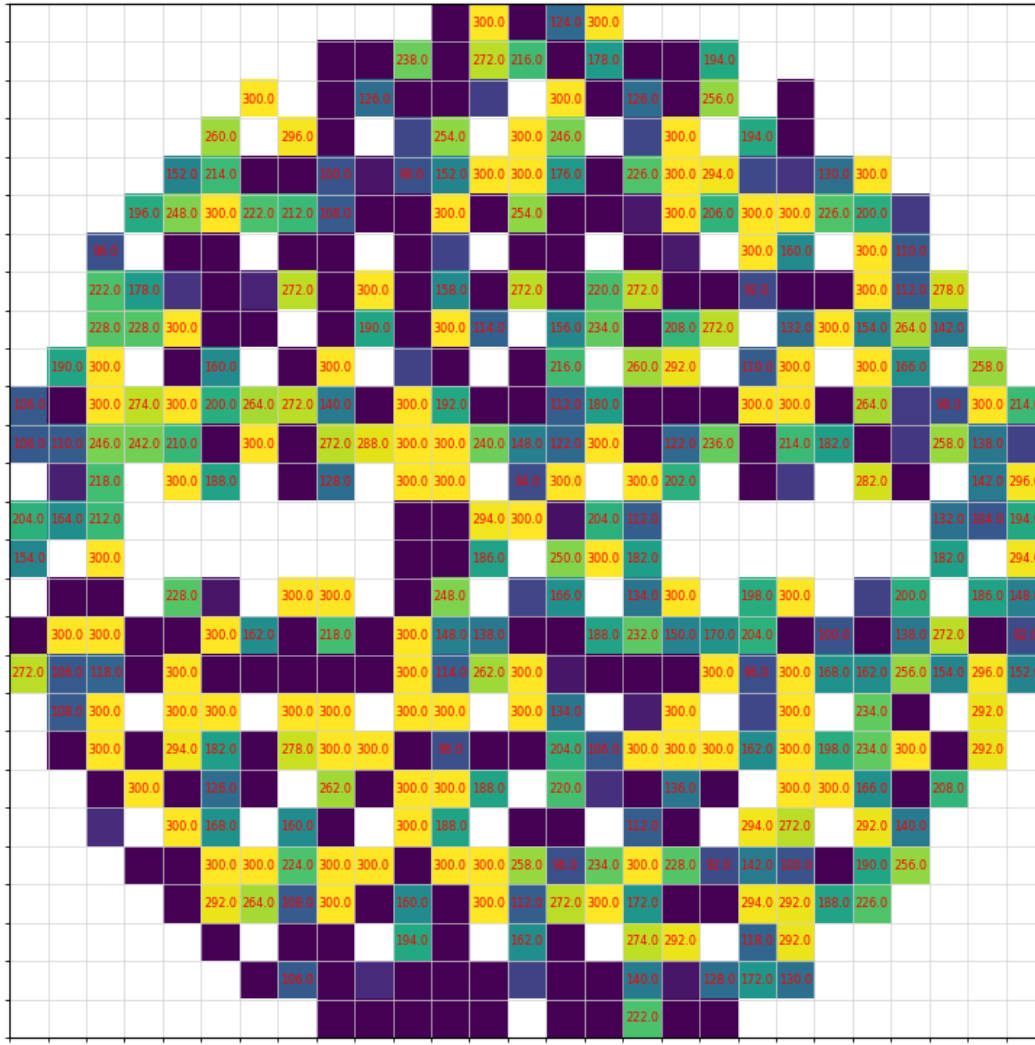
LGAD W5 Breakdown Voltage Distribution



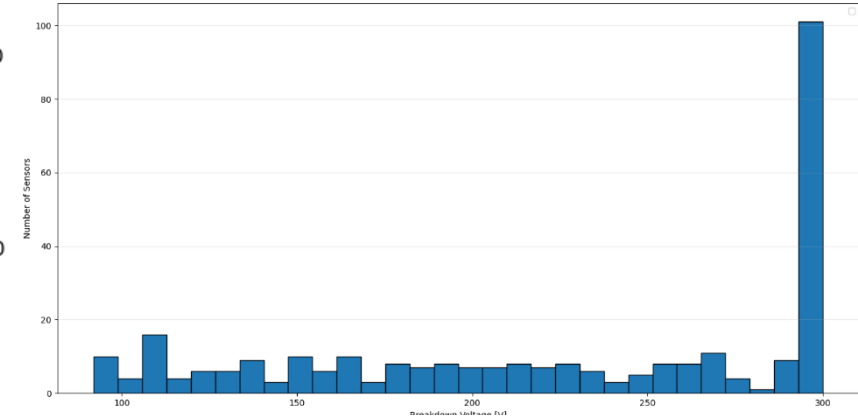
Leakage Current at 100V of W5



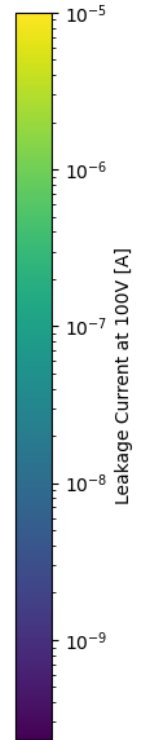
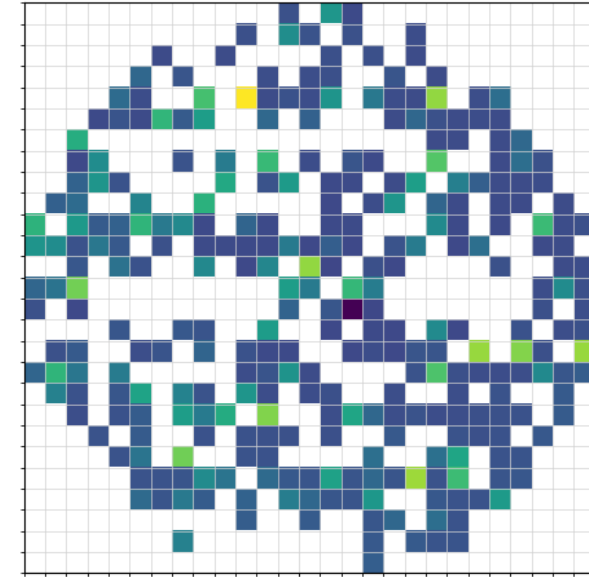
Breakdown Voltage Map of W6



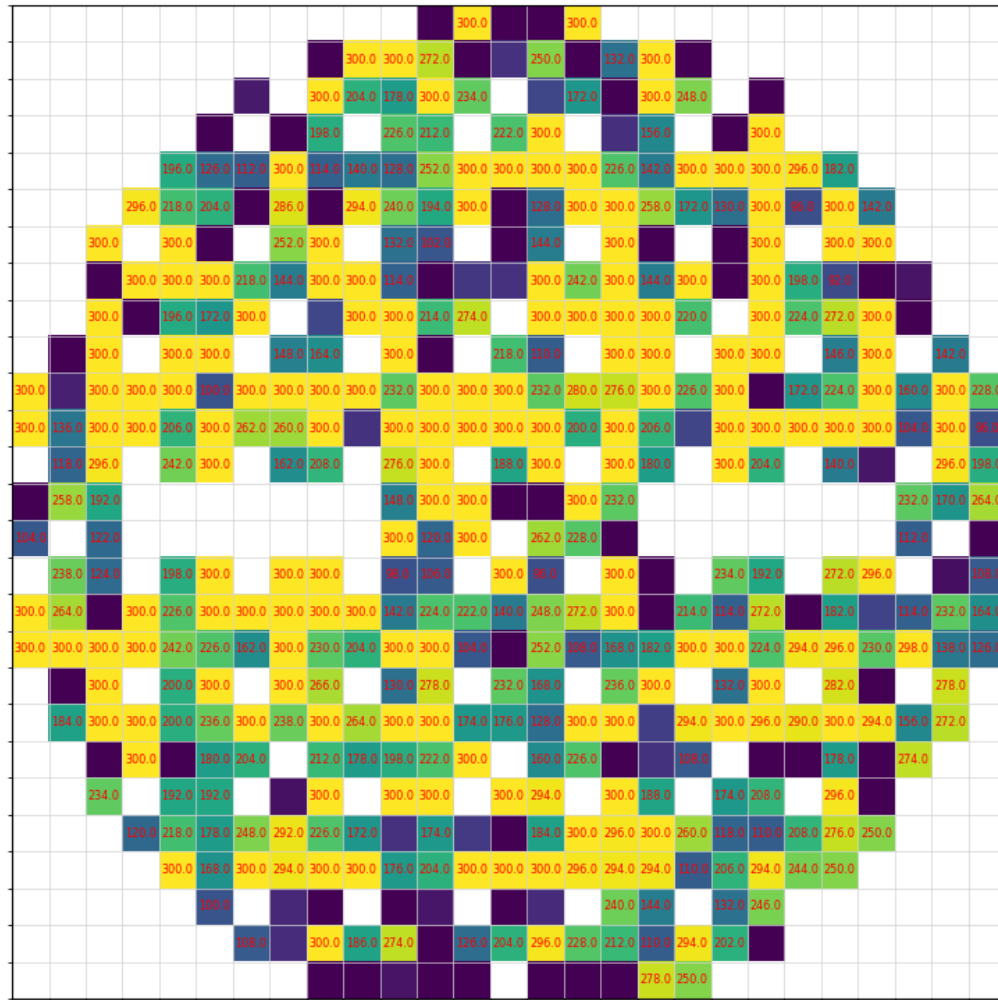
LGAD W6 Breakdown Voltage Distribution



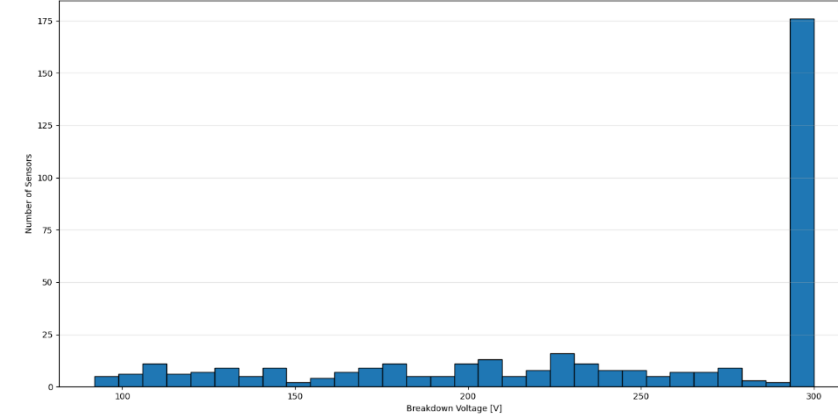
Leakage Current at 100V of W6



Breakdown Voltage Map of W7

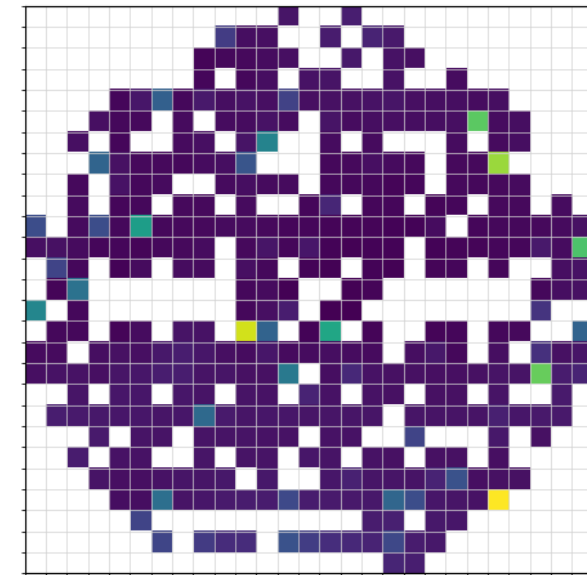


LGAD W7 Breakdown Voltage Distribution



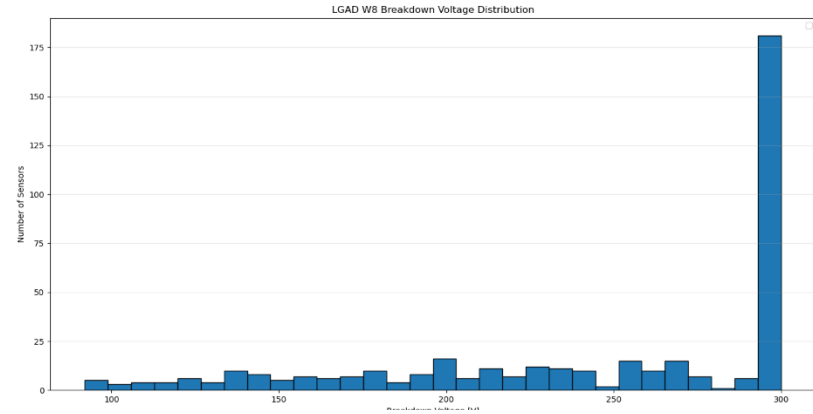
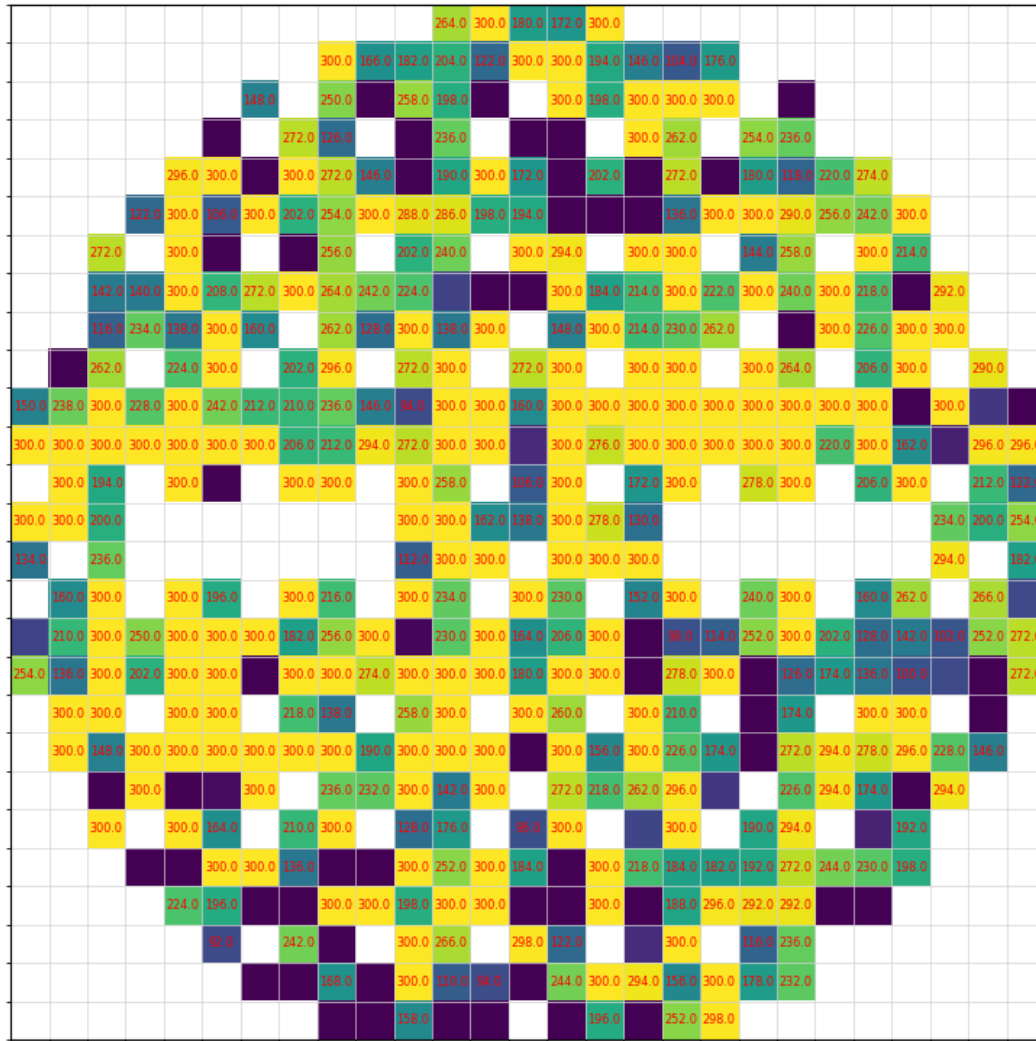
Breakdown Voltage [V]

Leakage Current at 100V of W7

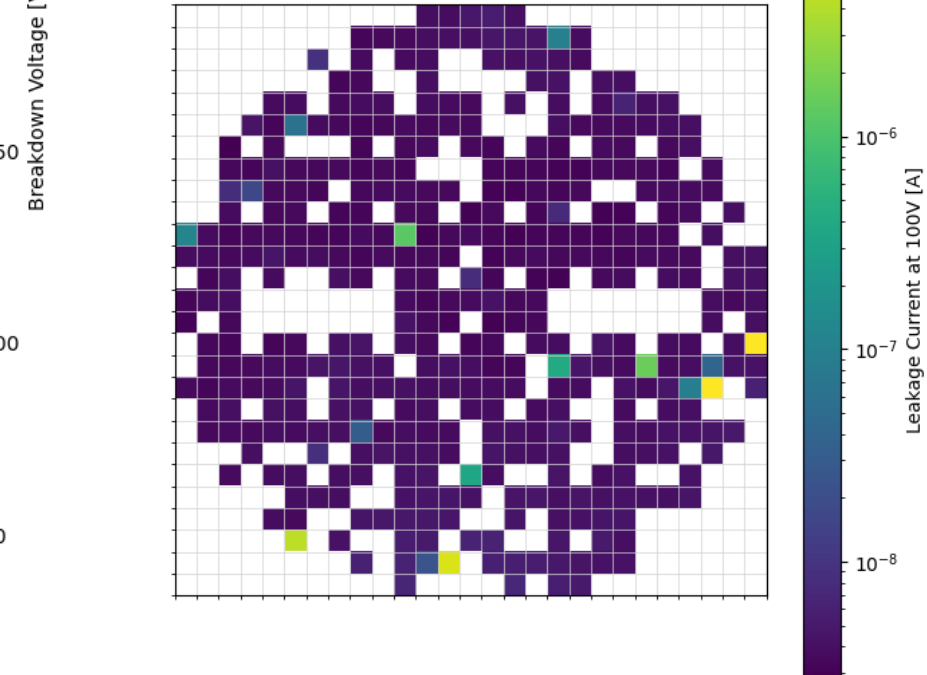


Leakage Current at 100V [A]

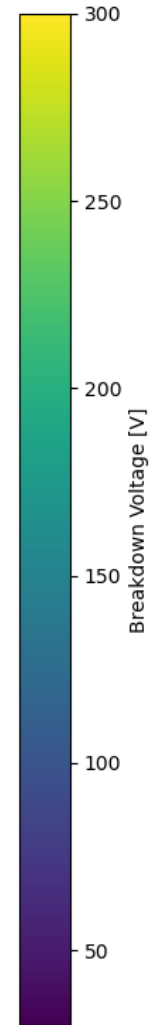
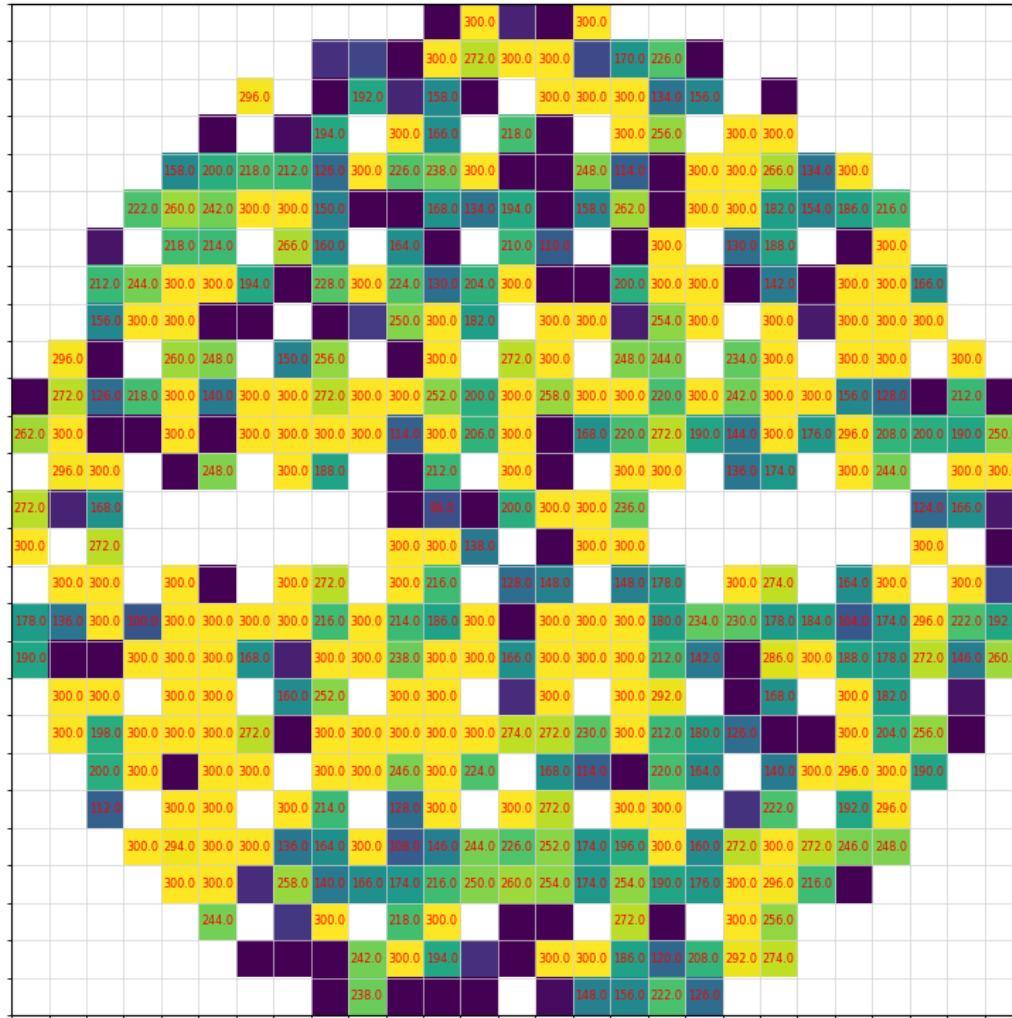
Breakdown Voltage Map of W8



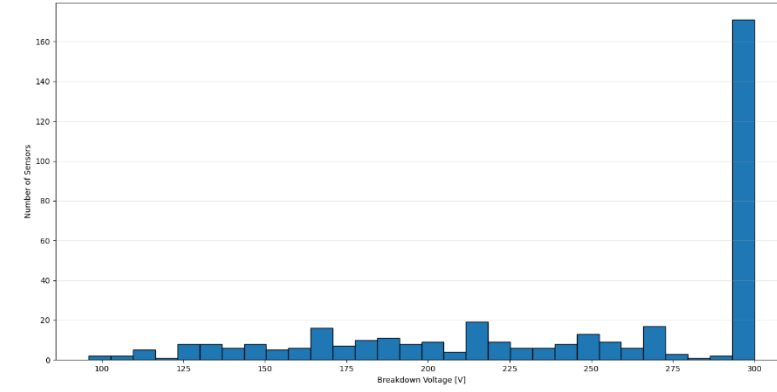
Leakage Current at 100V of W8



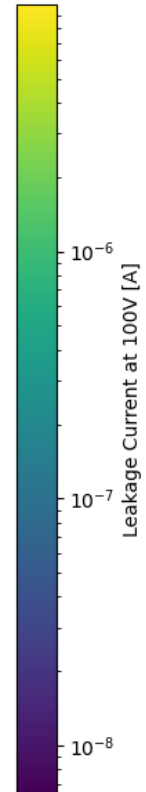
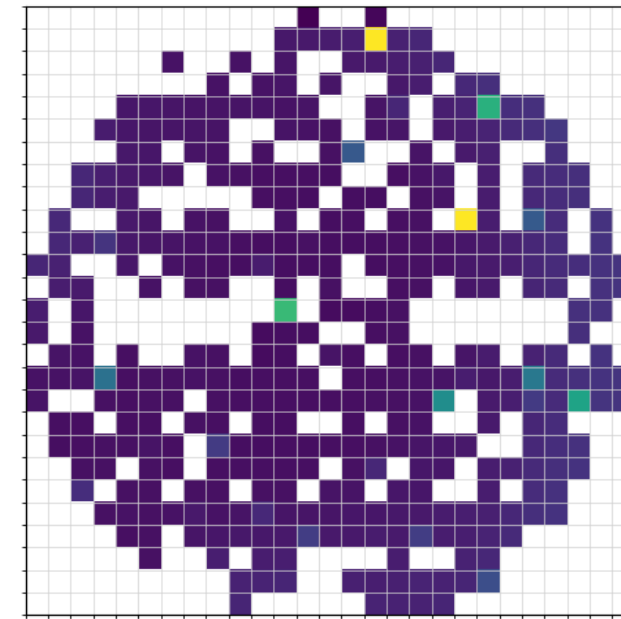
Breakdown Voltage Map of W9



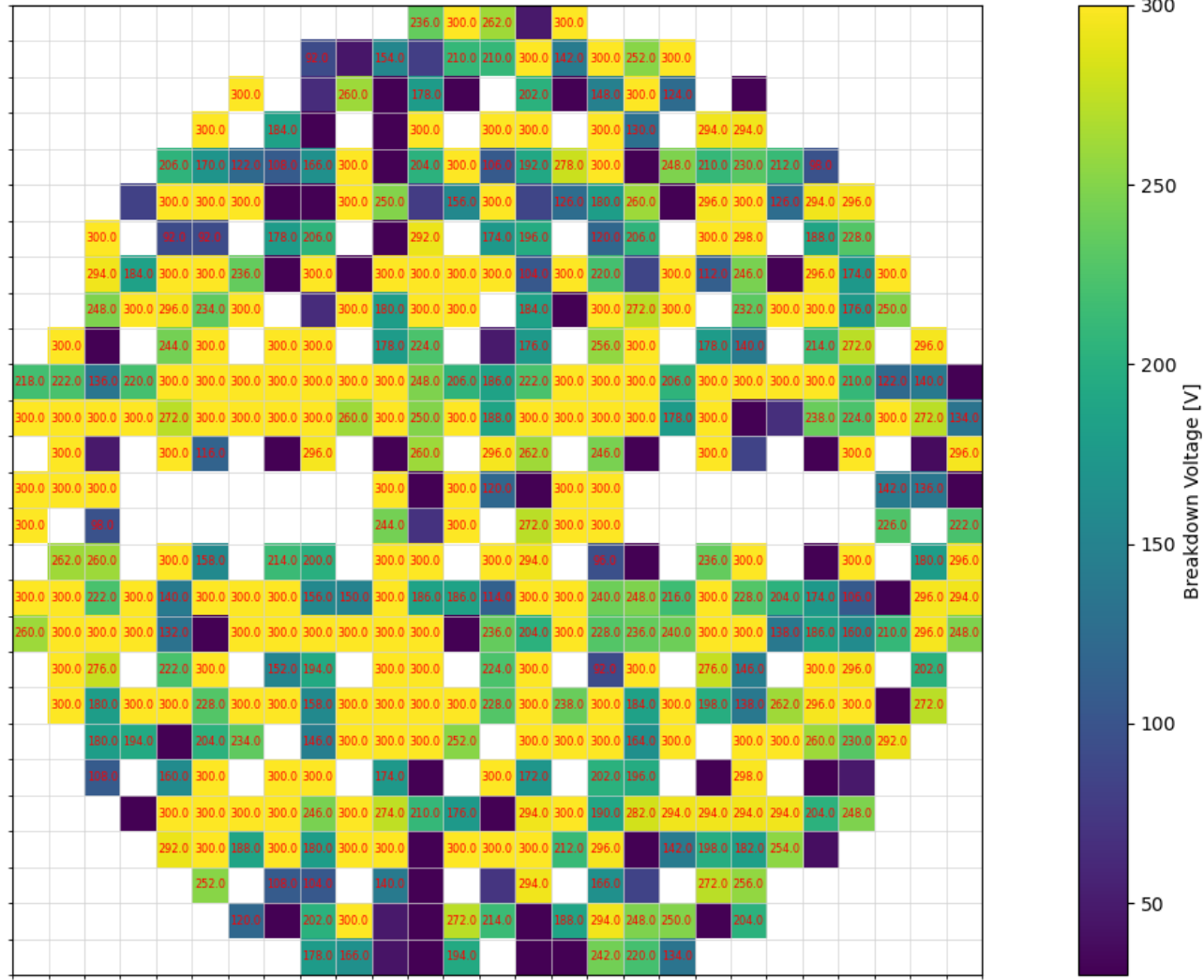
LGAD W9 Breakdown Voltage Distribution



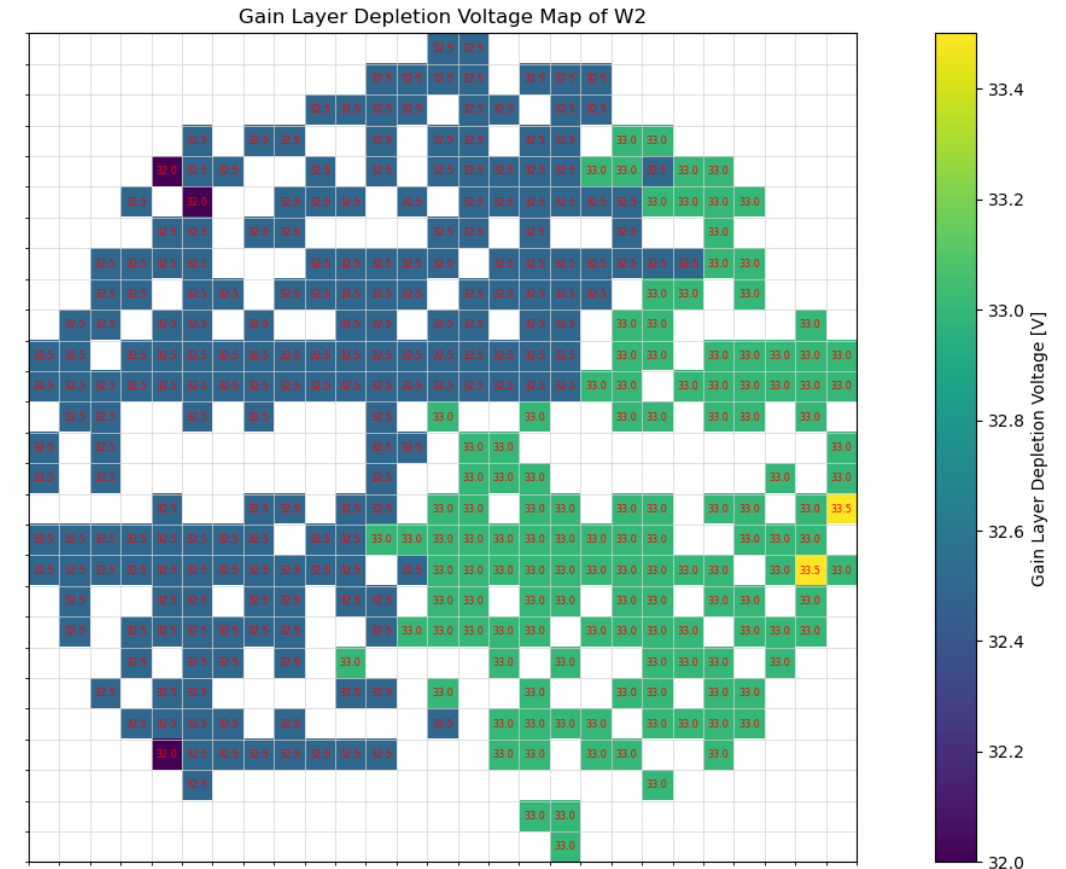
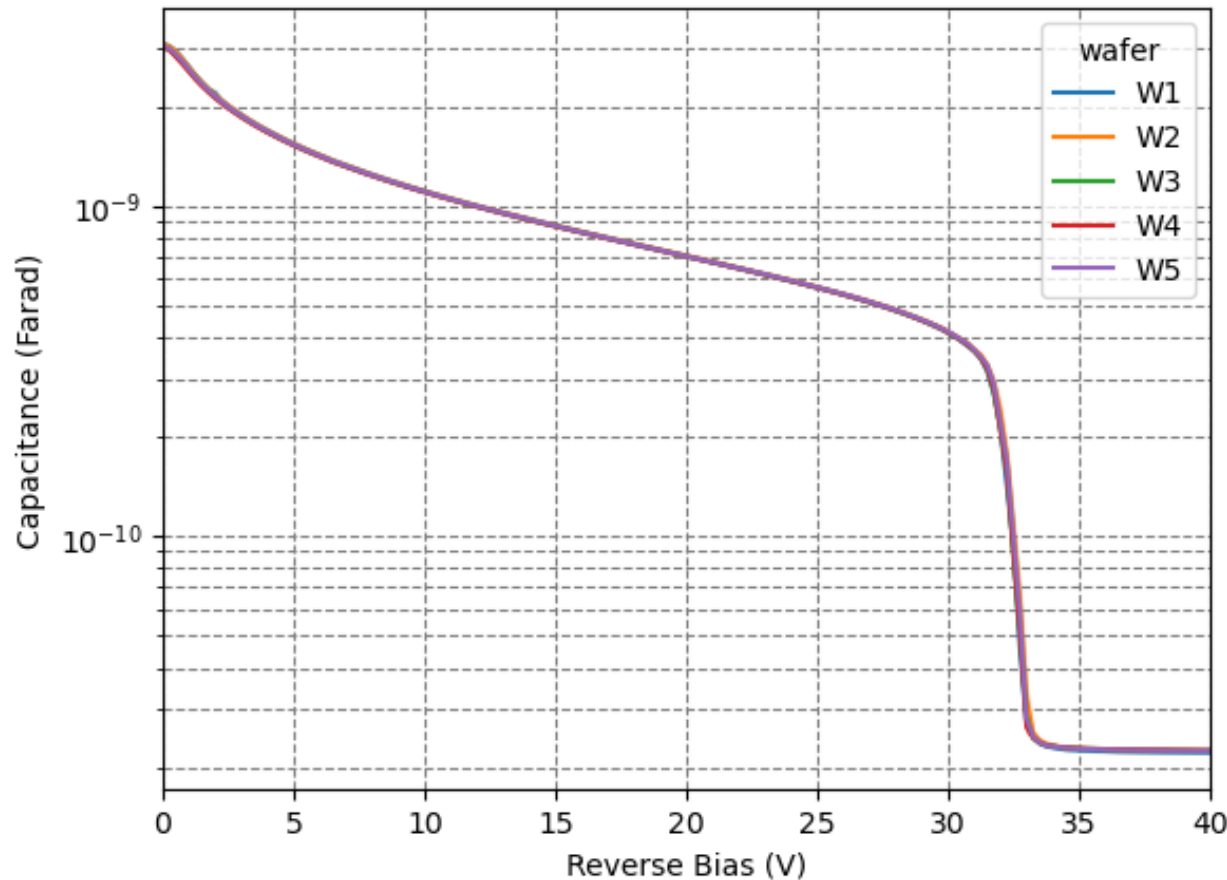
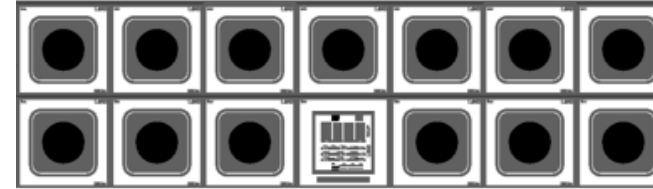
Leakage Current at 100V of W9



Breakdown Voltage Map of W10



- 13 sensors measured in the center of the wafer
- Same Vgl for all the wafers measured up to now

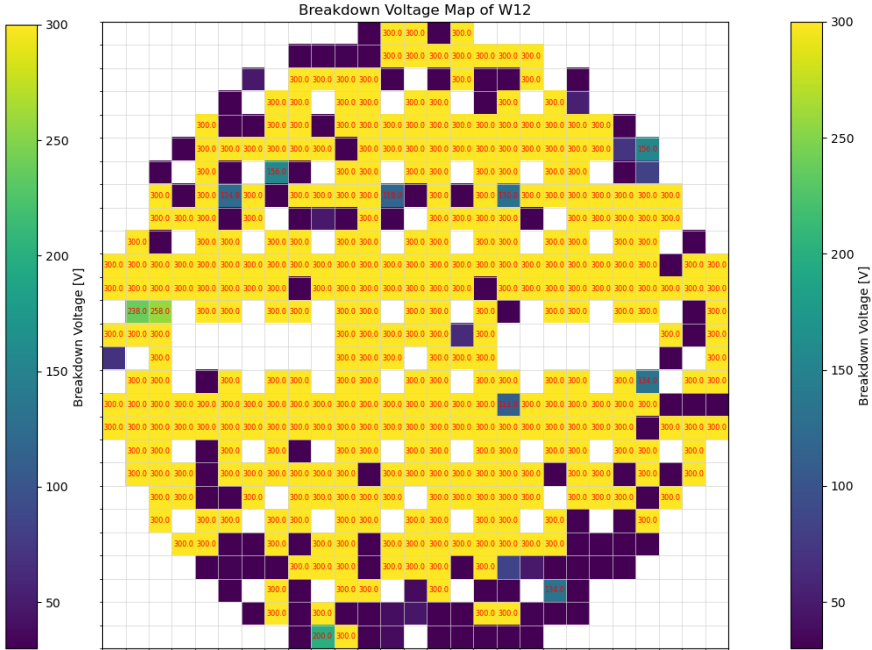
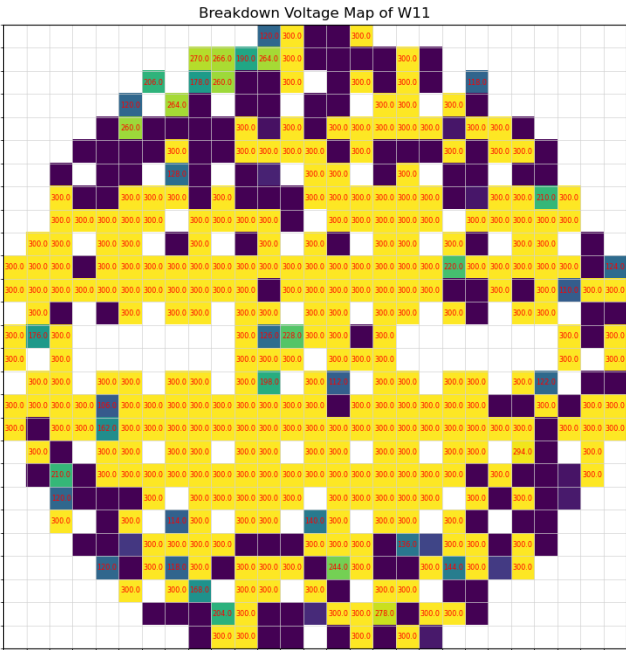
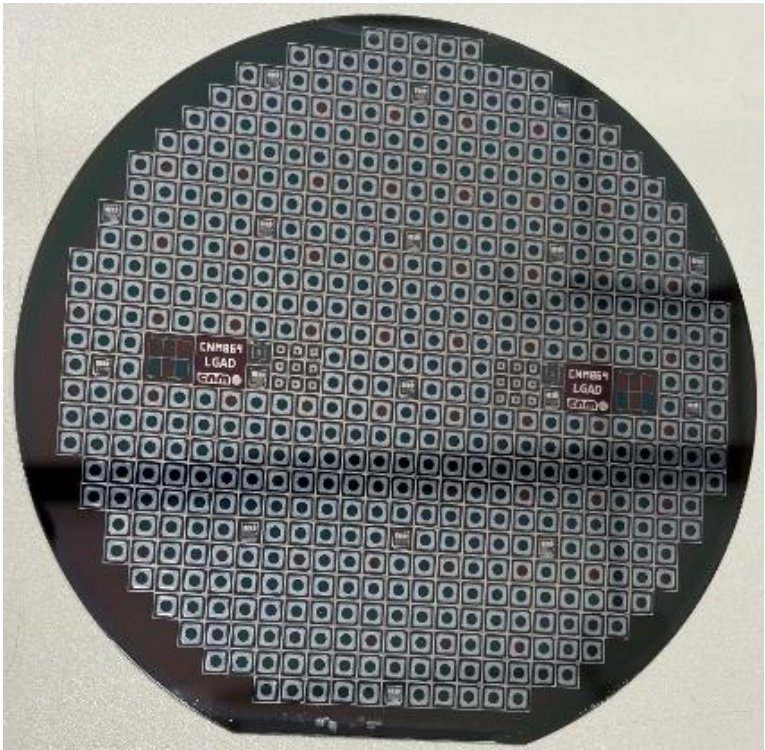


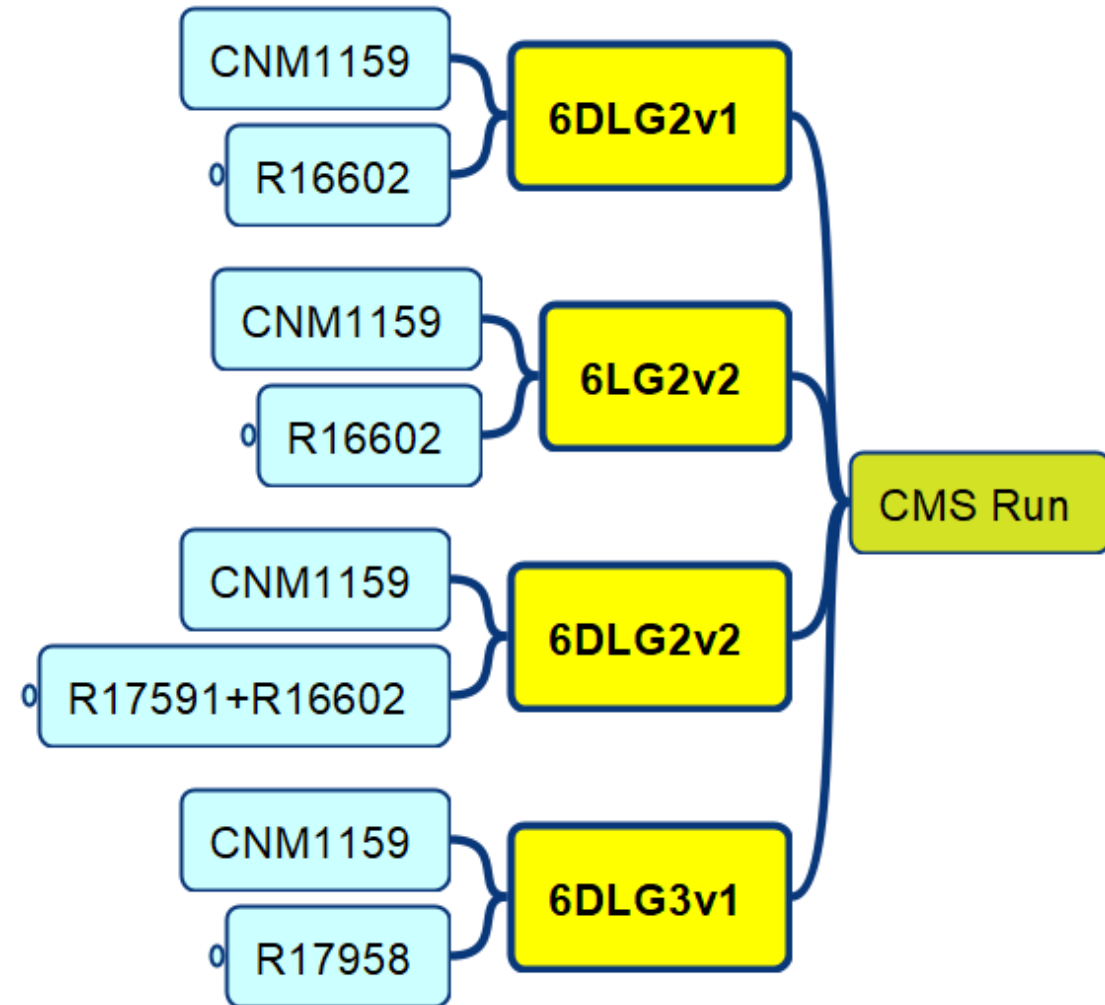
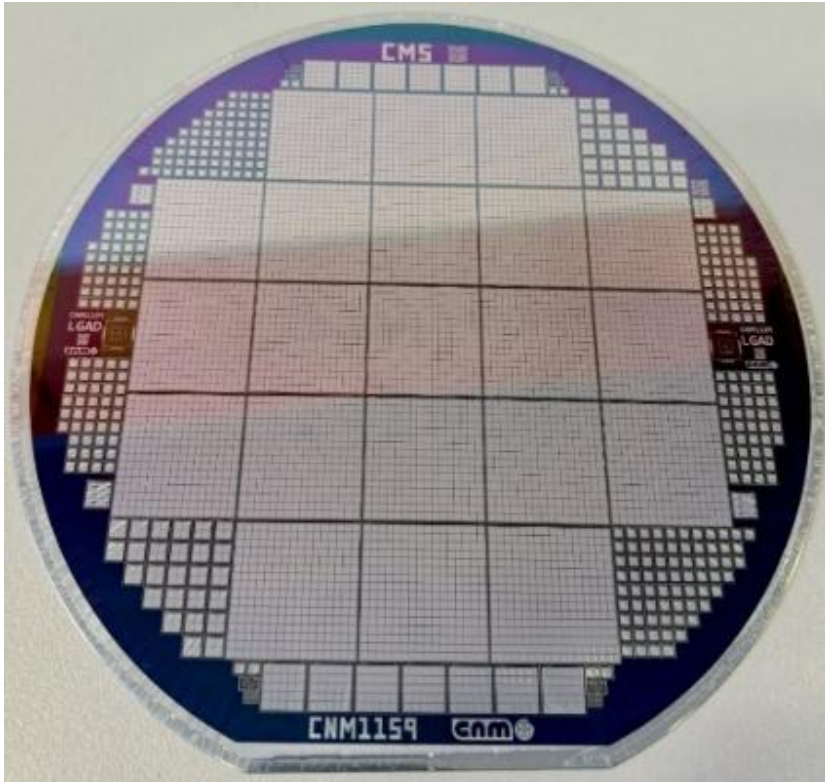
CMS 6LG1v1. R18399

- 2 Wafers, 300 μm Thick
- Mask CNM869 $\rightarrow$ Single-pads only
- > 400 LGADs of 3.3 mm and 16 LGADs of 1.3 mm
- 64 PiNs of 3.3 mm and 2 PiNs of 1.3 mm
- ATLAS IP Parameters
- No Passivation for W11

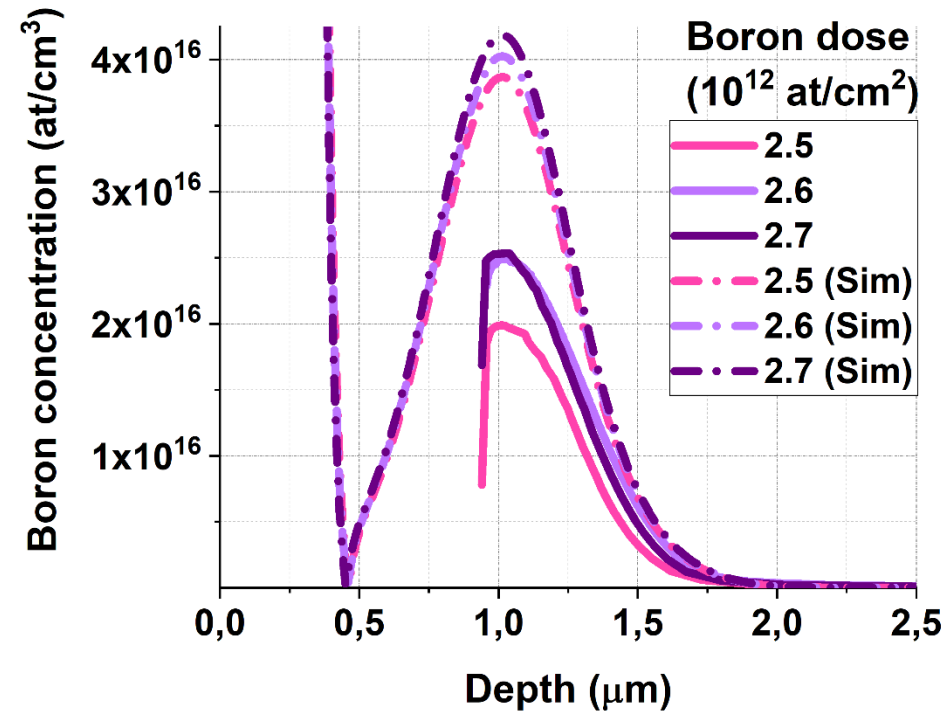
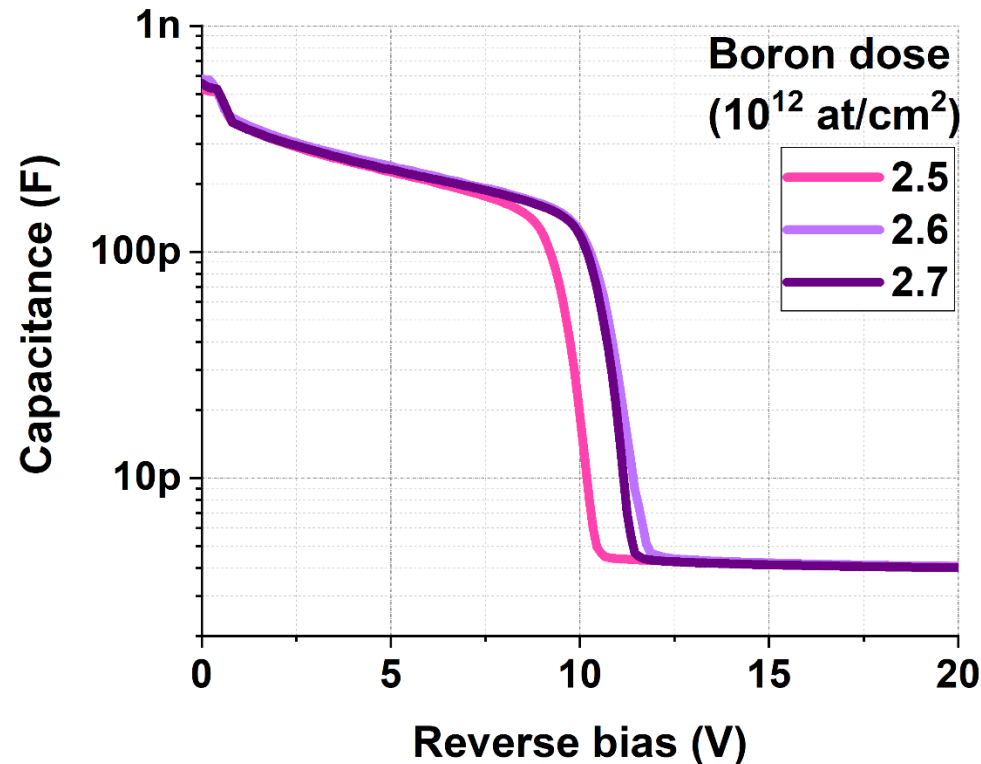
- Yield condition: $V_{\text{BD}} > 90 \text{ V}$
- On samples of $3.3 \times 3.3 \text{ mm}^2$

Wafer	Type	T_{ML} (Å)	T_{N} (Å)
11	6" FZ wafers 300 μm active thickness No handle wafer	Regular screen oxide annealing (expected $\approx 200 \text{ Å}$)	NEW ($\approx 600 \text{ Å}$)
12			Regular ($\approx 100 \text{ Å}$)



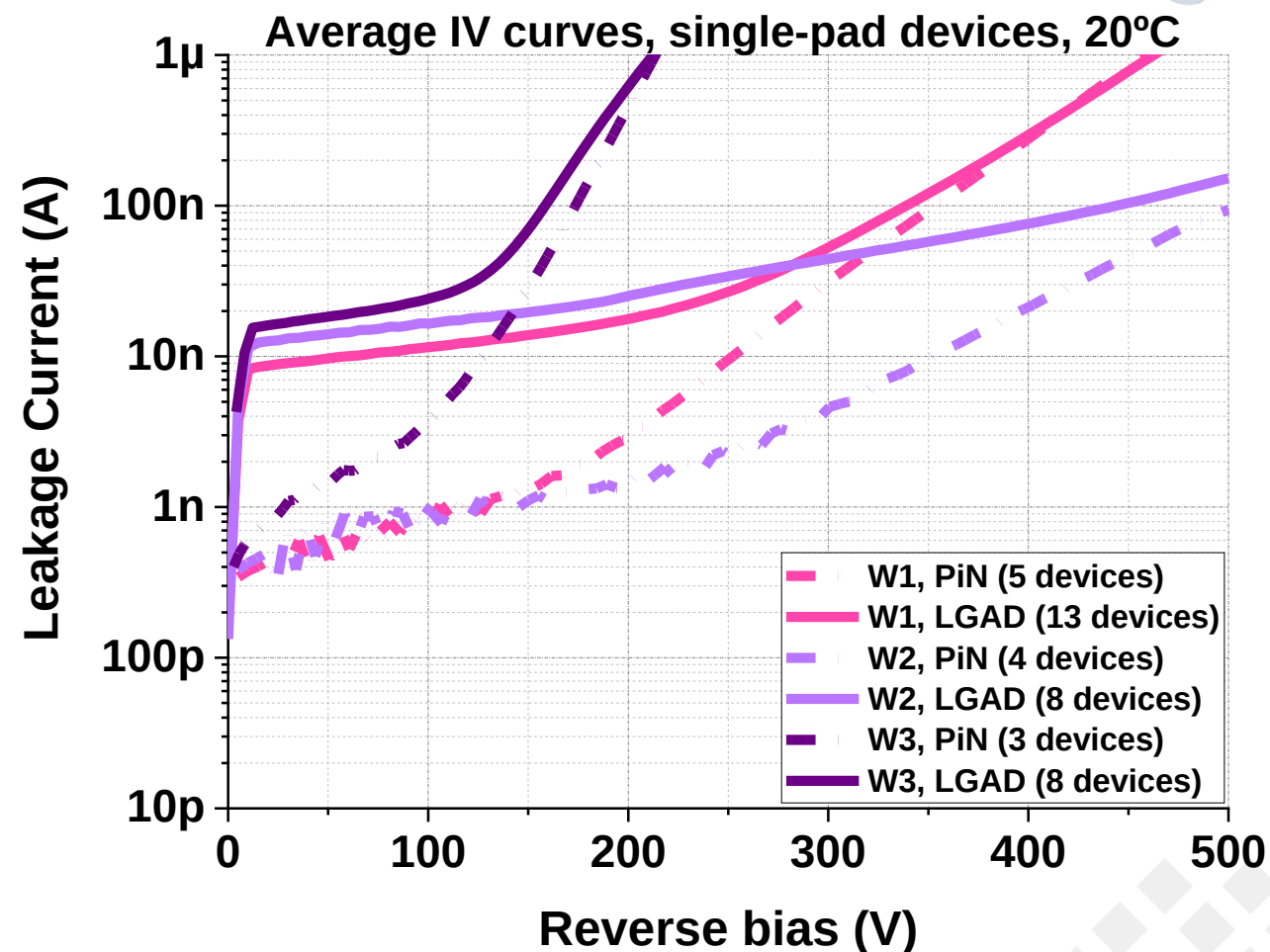


Run	Mask	Carbonated	N ⁺⁺ dopant	Boron implantation (mult layer)	RTA
6DLG2v1	CNM1159	Yes 480 keV & 5e13 at/cm ²	Phosphorus 30 keV & 1e15 at/cm	480 keV & 2.5 e12 at/cm ²	1100°C 30 s + 1050°C 30 s
				480 keV & 2.6 e12 at/cm ²	
				480 keV & 2.7 e12 at/cm ²	



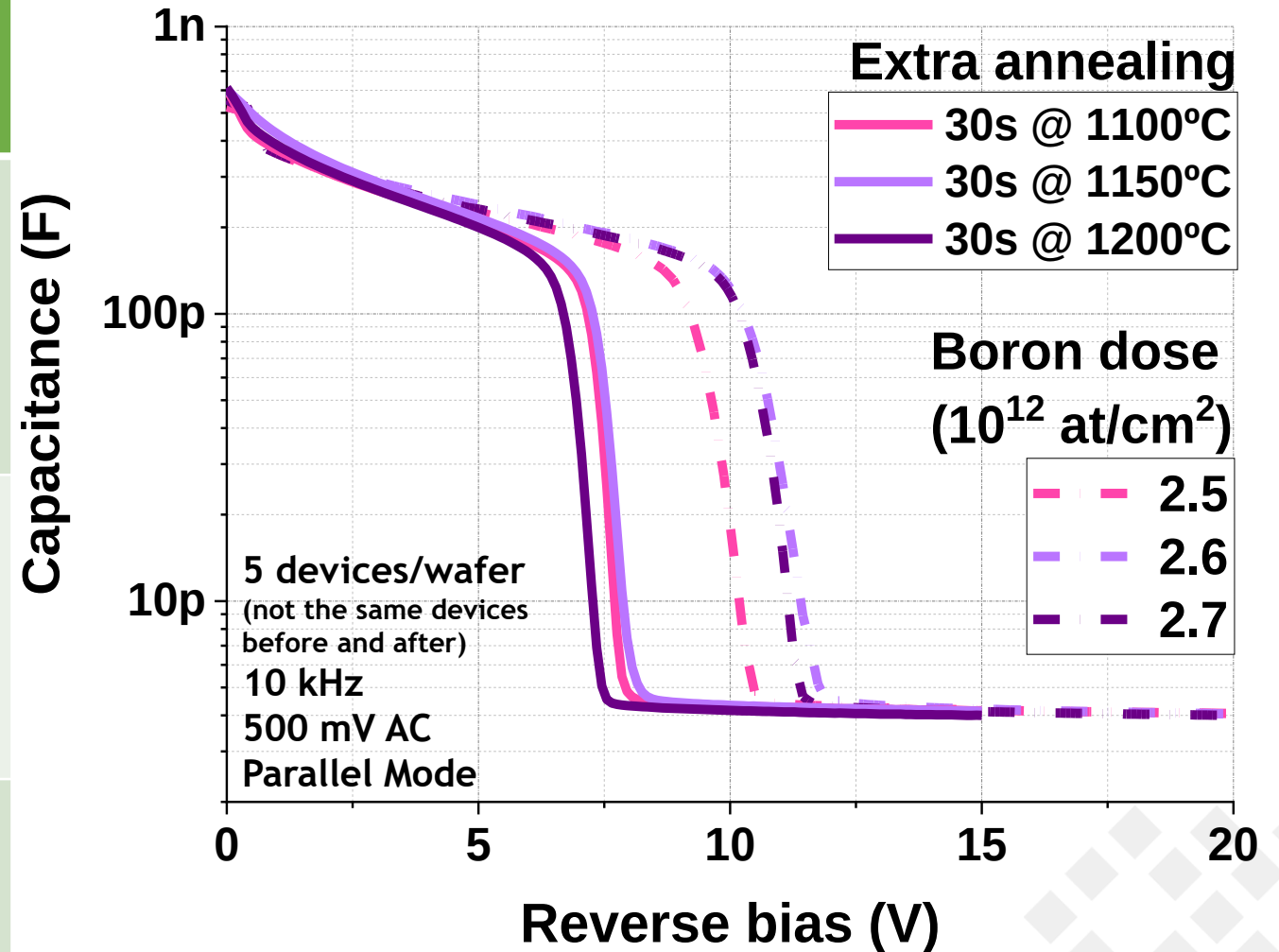
- VBD (20°C) > 500 V (PiN behavior)
- Phosphorus diffused deep enough to partially neutralize boron
- SRP ongoing!

Wafer	Common parameters and comments	D_{Boron} (at/cm ²)
1	<u>Carbon is implanted prior to Boron</u> ($E_{\text{Carbon}} = 480$ keV, $D_{\text{Carbon}} = 5e13$ at/cm²) <u>Boron for the multiplication layer</u> ($E_{\text{Boron}} = 480$ keV, D_{Boron} is swept) <u>is activated with three annealings</u>: 104 min @ 800°C (wet) ➤ 850 Å of oxide that prevents subsequent phosphorus implantation from forming a floating PN junction near the cutlines ➤ Annealing of carbon implantation damage	2.5e12
2	84 min at 950°C (dry) ➤ Screen oxide prior to phosphorus implantation for N⁺⁺ ➤ Annealing of carbon implantation damage	2.6e12
3	30 s @ 1100°C + 30 s @ 1050°C (RTA) ➤ To fully activate boron in the multiplication layer ➤ To activate phosphorus in the N⁺⁺ <u>N⁺⁺ is implanted with Phosphorus</u>: $E_{\text{Ph}} = 30$ keV, $D_{\text{Pho}} = 1e15$ at/cm²	2.7e12



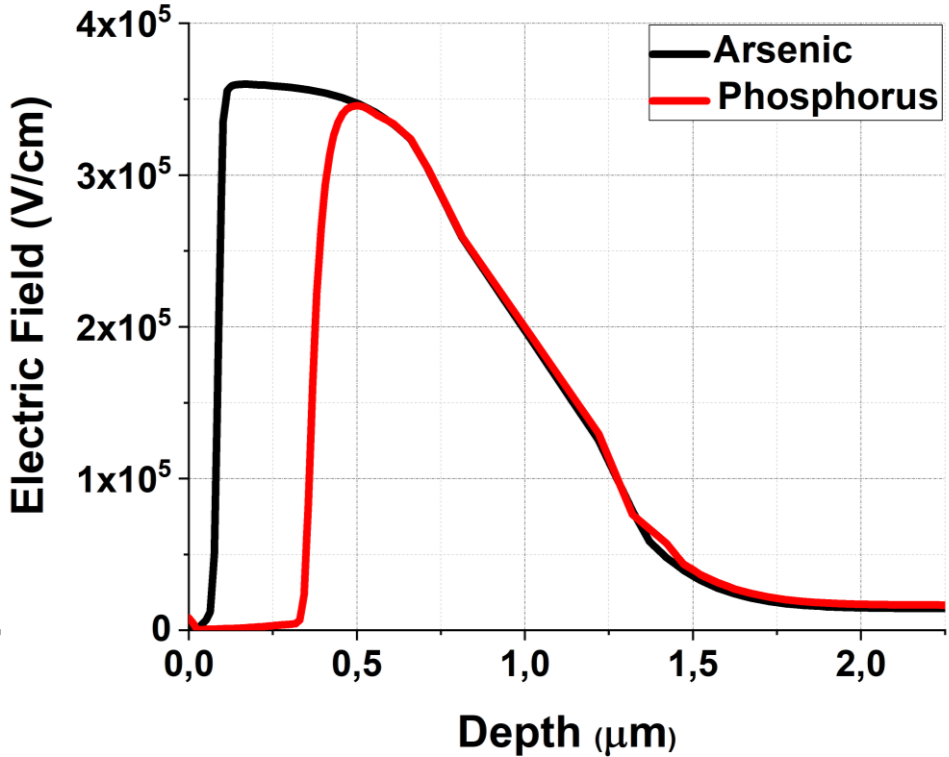
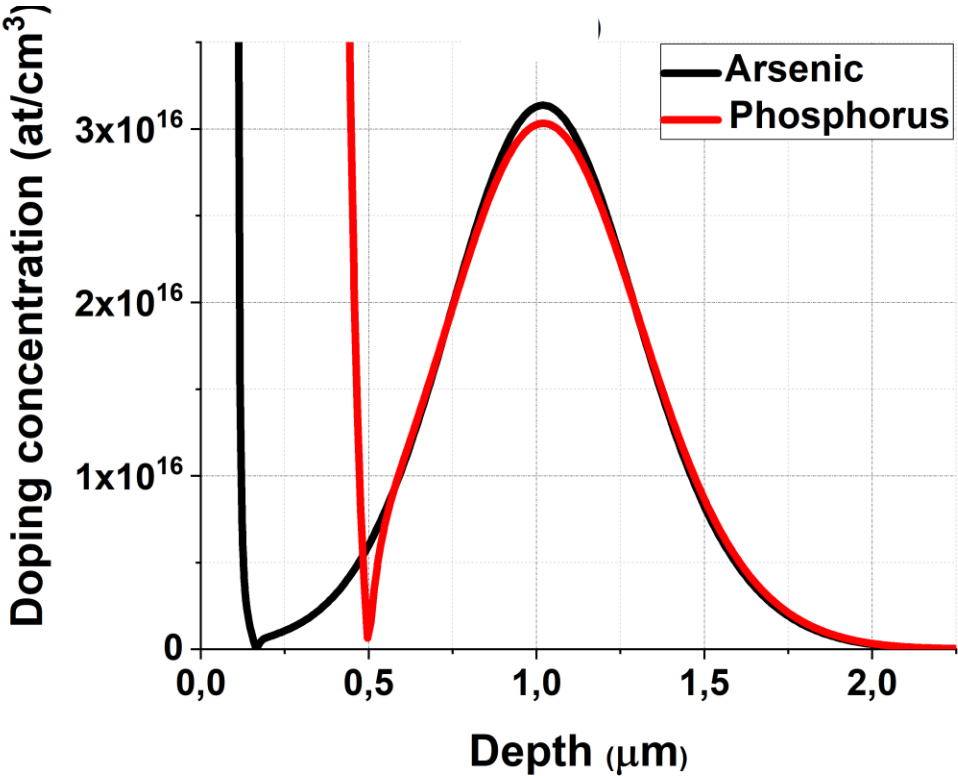
- Passivation layers were deposited with Corial equipment (bad quality oxide with charges)
- This affected both LGAD and PiN detectors
- Breakdown voltage could not be extracted from IVs

Wafer	Common parameters and comments	D_{Boron} (at/cm ²)
1	<u>Carbon is implanted prior to Boron</u> ($E_{\text{Carbon}} = 480$ keV, $D_{\text{Carbon}} = 5e13$ at/cm²) <u>Boron for the multiplication layer</u> ($E_{\text{Boron}} = 480$ keV, D_{Boron} is swept) <u>is activated with three annealings</u>: 104 min @ 800°C (wet) ➤ 850 Å of oxide that prevents subsequent phosphorus implantation from forming a floating PN junction near the cutlines ➤ Annealing of carbon implantation damage	2.5e12
2	84 min at 950°C (dry) ➤ Screen oxide prior to phosphorus implantation for N⁺⁺ ➤ Annealing of carbon implantation damage	2.6e12
3	30 s @ 1100°C + 30 s @ 1050°C (RTA) ➤ To fully activate boron in the multiplication layer ➤ To activate phosphorus in the N⁺⁺ <u>N⁺⁺ is implanted with Phosphorus</u>: $E_{\text{Ph}} = 30$ keV, $D_{\text{Pho}} = 1e15$ at/cm²	2.7e12



- The partial activation hypothesis was discarded, as V_{gl} dropped after additional RTA processes

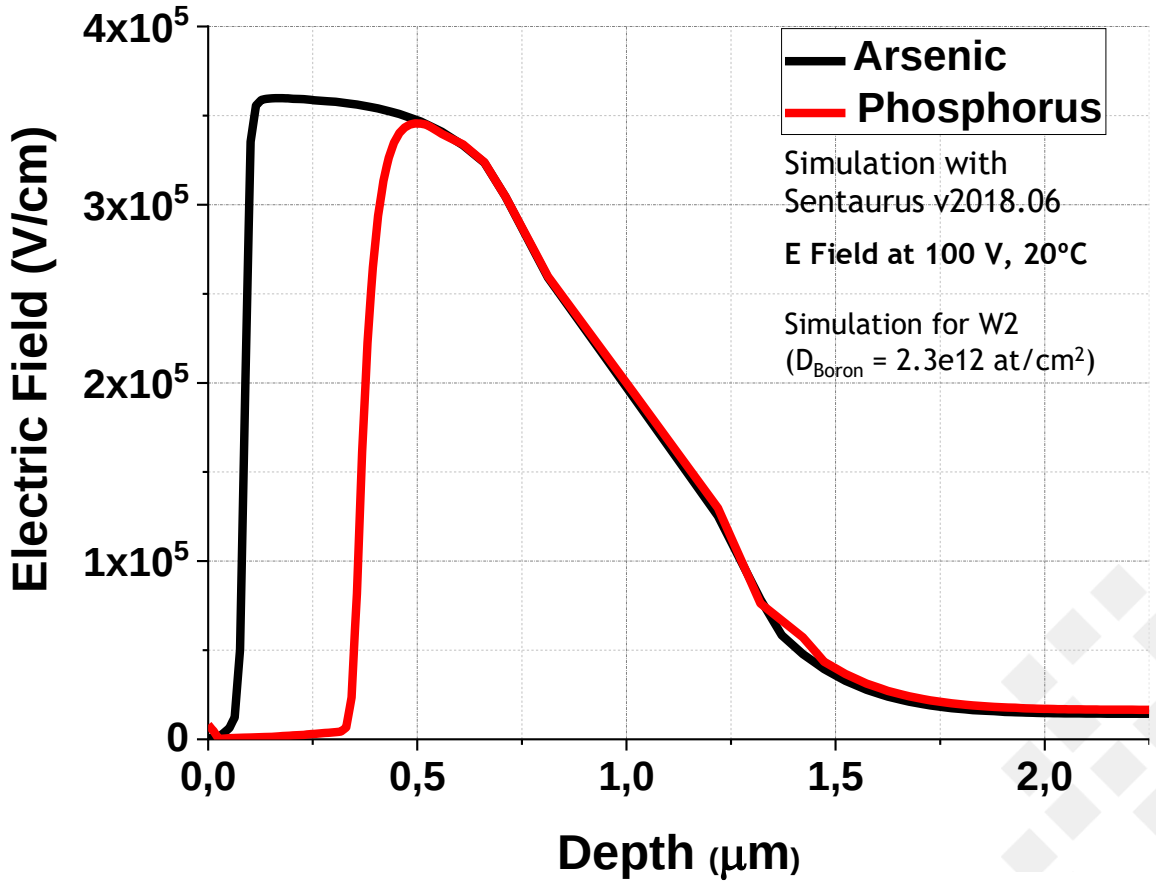
Run	Mask	Carbonated	N ⁺⁺ dopant	Boron implantation (mult layer)	RTA
6DLG2-v2	CNM1159	Yes 480 keV & 5e13 at/cm ²	Arsenic 30 keV & 1e15 at/cm	480 keV & 2.3e12 at/cm ²	1100°C 30 s + 1050°C 30 s
				480 keV & 2.5e12 at/cm ²	
				480 keV & 2.7e12 at/cm ²	



- Arsenic has a lower diffusion in silicon than phosphorus
- TCAD Simulation suggested that the high electric field would extended wider for As than for P

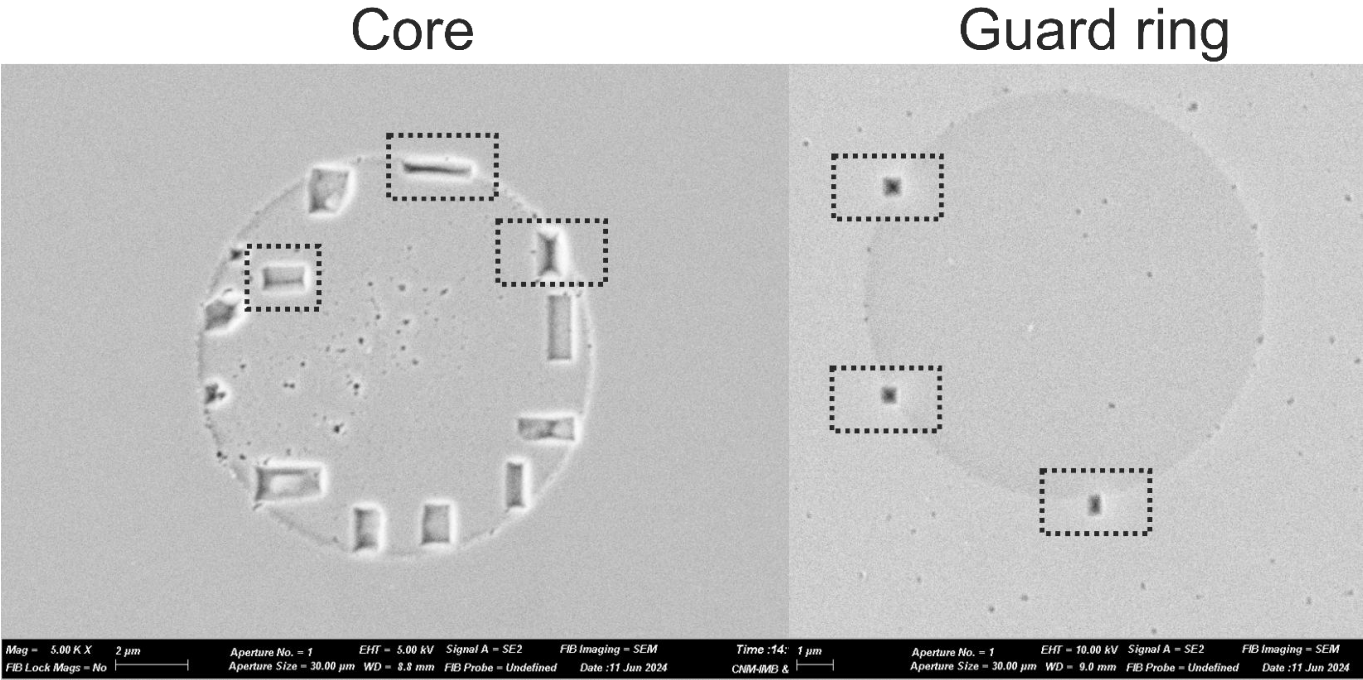
Wafer	Common parameters and comments	D_{Boron} (at/cm ²)
1	<u>Carbon is implanted prior to Boron</u> ($E_{\text{Carbon}} = 480$ keV, $D_{\text{Carbon}} = 5e13$ at/cm ²) <u>Boron for the multiplication layer</u> ($E_{\text{Boron}} = 480$ keV, D_{Boron} is swept) <u>is activated with three annealings:</u> 104 min @ 800°C (wet) ➤ 850 Å of oxide that prevents subsequent arsenic implantation from forming a floating PN junction near the cutlines ➤ Annealing of carbon implantation damage 84 min at 950°C (dry) ➤ Screen oxide prior to arsenic implantation for N⁺⁺ ➤ Annealing of carbon implantation damage 30 s @ 1100°C + 30 s @ 1050°C (RTA) ➤ To fully activate boron in the multiplication layer ➤ To activate arsenic in the N⁺⁺	2.1e12
2		2.3e12
3	<u>N⁺⁺ is implanted with Arsenic:</u> $E_{\text{Ars}} = 30$ keV, $D_{\text{Ars}} = 1e15$ at/cm ²	2.5e12

- Changes with respect to CMS Run16602 (2023)
 - Arsenic instead of phosphorus for the N⁺⁺
 - Boron dose in multiplication layer was reduced, to avoid having a large charge integral in the multiplication layer potentially leading to early breakdown (e.g. APD)



Wafer	Common parameters and comments	D _{Boron} (at/cm ²)
1	<u>Carbon is implanted prior to Boron</u> ($E_{\text{Carbon}} = 480$ keV, $D_{\text{Carbon}} = 5e13$ at/cm²) <u>Boron for the multiplication layer</u> ($E_{\text{Boron}} = 480$ keV, D_{Boron} is swept) <u>is activated with three annealings:</u> 104 min @ 800°C (wet) ➤ 850 Å of oxide that prevents subsequent arsenic implantation from forming a floating PN junction near the cutlines ➤ Annealing of carbon implantation damage	2.1e12
2	84 min at 950°C (dry) ➤ Screen oxide prior to arsenic implantation for N⁺⁺ ➤ Annealing of carbon implantation damage	2.3e12
3	30 s @ 1100°C + 30 s @ 1050°C (RTA) ➤ To fully activate boron in the multiplication layer ➤ To activate arsenic in the N⁺⁺ <u>N⁺⁺ is implanted with Arsenic:</u> $E_{\text{Ars}} = 30$ keV, $D_{\text{Ars}} = 1e15$ at/cm²	2.5e12

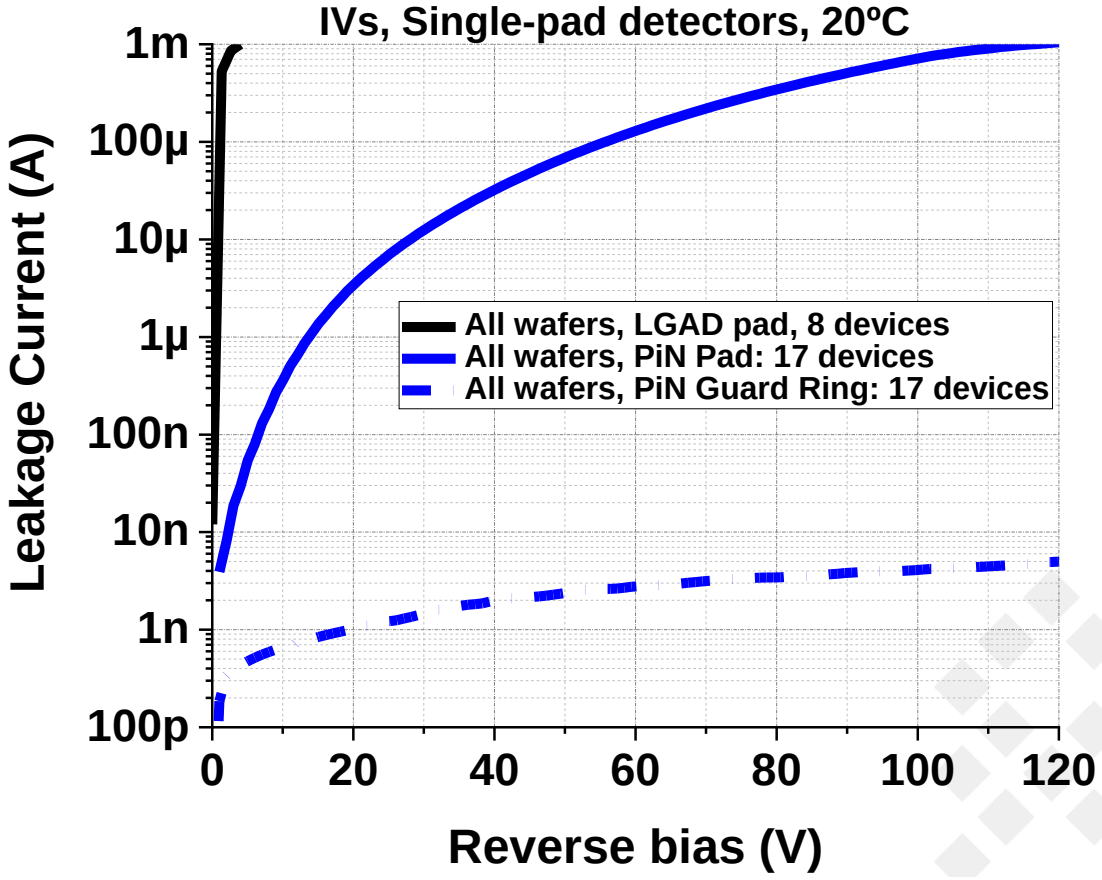
- A Titanium layer was not deposited below the Al:Cu, so spikes were formed. Devices, either PiN or LGAD, were NOT functional



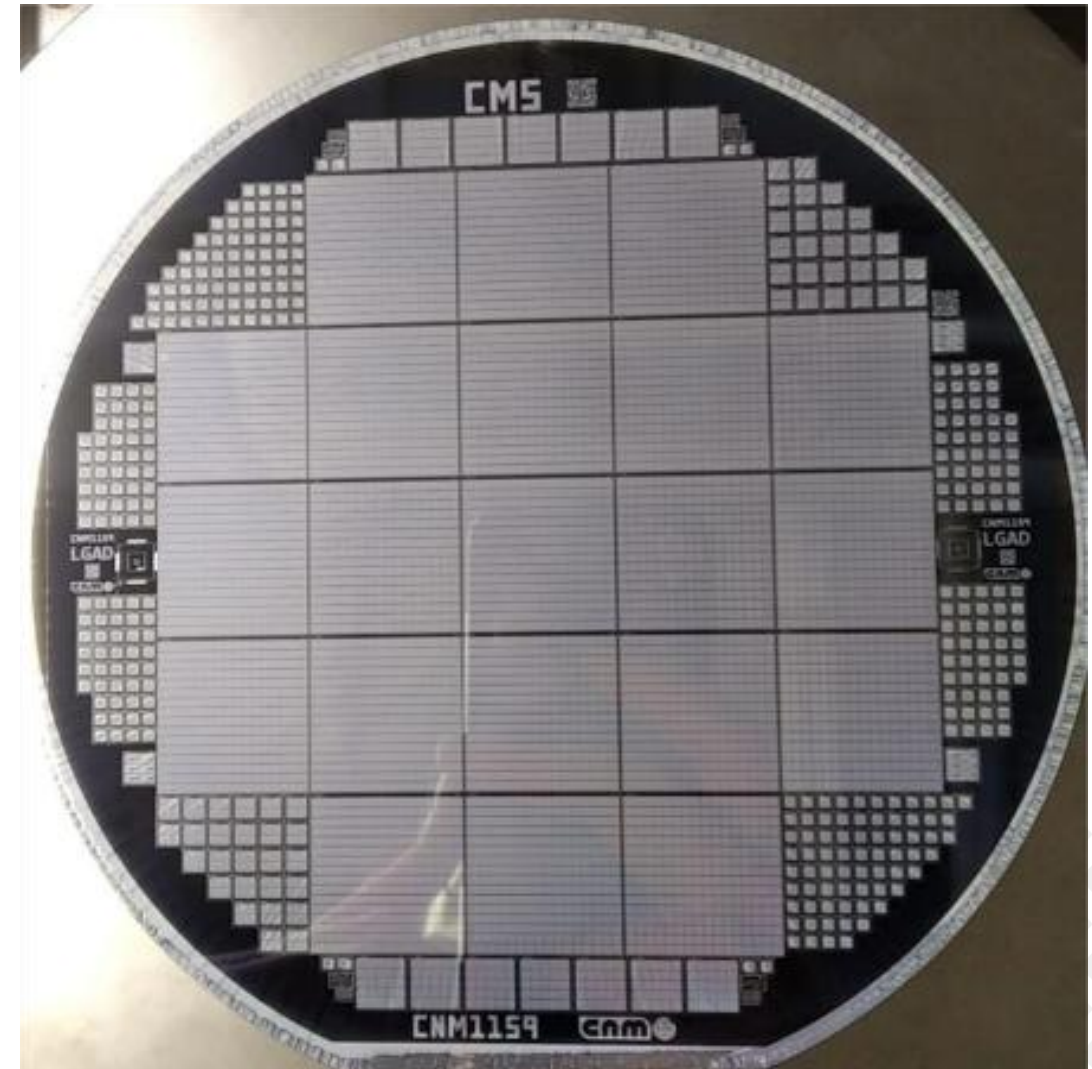
- Spikes were formed during the Al:Cu layer annealing both in the dLGAD core and guard ring

Wafer	Common parameters and comments	D_{Boron} (at/cm ²)
1	<u>Carbon is implanted prior to Boron</u> ($E_{\text{Carbon}} = 480$ keV, $D_{\text{Carbon}} = 5e13$ at/cm ²) <u>Boron for the multiplication layer</u> ($E_{\text{Boron}} = 480$ keV, D_{Boron} is swept) <u>is activated with three annealings:</u> 104 min @ 800°C (wet) ➤ 850 Å of oxide that prevents subsequent arsenic implantation from forming a floating PN junction near the cutlines ➤ Annealing of carbon implantation damage	2.1e12
2	84 min at 950°C (dry) ➤ Screen oxide prior to arsenic implantation for N⁺⁺ ➤ Annealing of carbon implantation damage	2.3e12
3	30 s @ 1100°C + 30 s @ 1050°C (RTA) ➤ To fully activate boron in the multiplication layer ➤ To activate arsenic in the N⁺⁺ <u>N⁺⁺ is implanted with Arsenic:</u> $E_{\text{Ars}} = 30$ keV, $D_{\text{Ars}} = 1e15$ at/cm ²	2.5e12

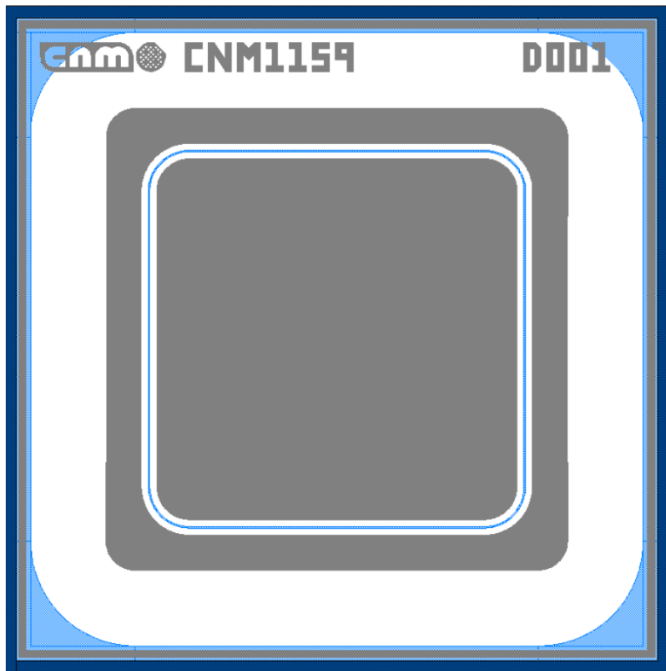
- A Titanium layer was not deposited below the Al:Cu, so spikes were formed. Devices, either PiN or LGAD, were NOT functional
- Only guard rings were functional: JTE diffusion prevented shortcut from spikes



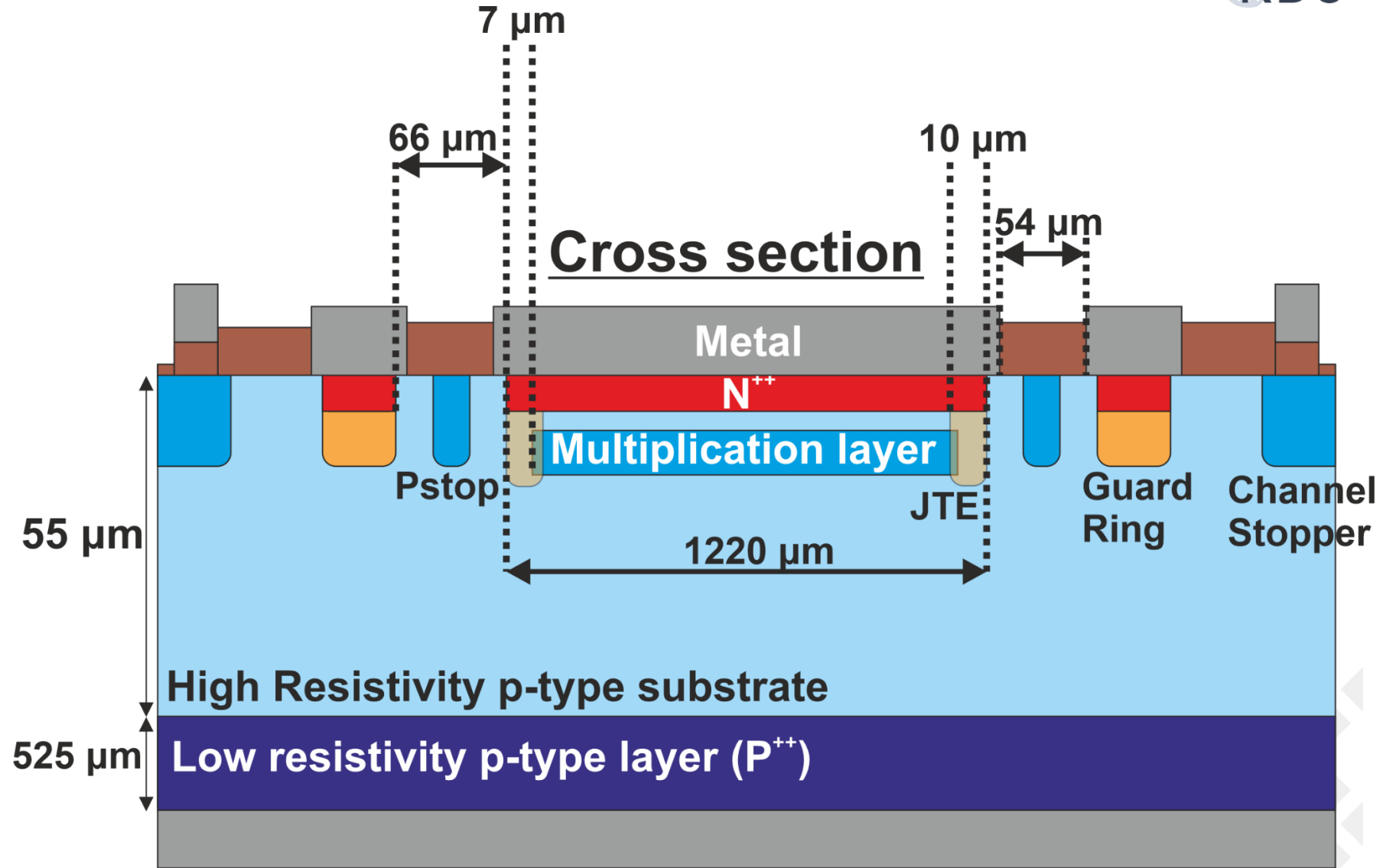
- Mask **CNM1159** (All runs discussed are fabricated with these set of masks)
- **Epitaxial** wafers (**55 μm** active thickness on 585 μm P++ handle wafer)
- Pixel size (enclosed by p-stop) : **1.3x1.3 mm^2**
- Pixel size (enclosed by multiplication layer): **1.22x1.22 mm^2**
- Interpad distance (**IP**) = **80 μm**
- Pstop width = 5 μm
- Guard/Extraction ring width = 113.5 μm
- JTE width = 10 μm
- JTE/Multiplication layer overlap = 3 μm
- Devices:
 - **16x16 pixels : 21 LGAD devices**
 - 5x5 pixels: 10 LGAD and 4 PiN devices
 - 2x2 pixels: 44 LGAD and 8 PiN devices
 - Single-pad: 272 LGAD + 36 PiN devices



Front view



Cross section



TARGETS

- Stabilization of dLGAD technology
- Study of carbon impact on device performance
- Study of IV uniformity in big pixelated detectors (in contrast to std CNM LGAD technology)
- Study of radiation tolerance, with and without a carbon layer

MANUFACTURING CONDITIONS

- Highest boron dose in multiplication layer (highest expected gain)
- Wafer3 is carbonated, Wafer5 is not
- Wafer3 is comparable to Wafer1 of R16602 (6DLG2v1), using Phosphorus instead of Arsenic to construct the N⁺⁺
- Only W4 is passivated. W1, W2, W3 and W5 are metalized but no annealing was carried out

Wafer	Common parameters and comments	D _{Boron} (at/cm ²)	D _{Carbon} (at/cm ²)
1	Carbon is implanted prior to Boron ($E_{\text{Carbon}} = 480 \text{ keV}$, D_{Carbon} is swept)	2.00e12	5e13
2	Boron for the multiplication layer ($E_{\text{Boron}} = 480 \text{ keV}$, D_{Boron} is swept) is activated with three annealings: 104 min @ 800°C (wet) ➤ 500 Å of oxide that prevents subsequent arsenic implantation from forming a floating PN junction near the cutlines	2.25e12	5e13
3	- Annealing of carbon implantation damage 84 min at 950°C (dry) ➤ Screen oxide prior to arsenic implantation for N⁺⁺ ➤ Annealing of carbon implantation damage 30 s @ 1100°C + 30 s @ 1050°C (RTA) ➤ To fully activate boron in the multiplication layer ➤ To activate arsenic in the N⁺⁺	2.50e12	5e13
4	N⁺⁺ is implanted with Arsenic: $E_{\text{Ars}} = 30 \text{ keV}$, $D_{\text{Ars}} = 1\text{e}15 \text{ at/cm}^2$ Same implantation parameters used in CMS Run16602, where Phosphorus was used instead of Arsenic	2.00e12	-
5	A layer of 300 Å of Titanium is deposited below 1.5 µm of Al:Cu, to avoid the spikes problem observed in CMS Run17591, where Arsenic was used for the N⁺⁺	2.50e12	-

Run	Mask	Carbonated	N ⁺⁺ dopant	Boron implantation (mult layer)	RTA
6DLG3-v1	CNM1159	Yes 480 keV & 5e13 at/cm ²	Arsenic 30 keV & 1e15 at/cm	480 keV & 2e12 at/cm ²	1100°C 30 s + 1050°C 30 s
				480 keV & 2.25e12 at/cm ²	
				<u>480 keV & 2.5e12 at/cm²</u>	
				480 keV & 2e12 at/cm ²	
				480 keV & 2.5e12 at/cm ²	

Table 1. Main fabrication parameters of the original and current IMB-CNM LGADs.

	Original LGAD	Current LGAD
Carbon dose (at/cm ²)	10^{14} – 9×10^{14}	5×10^{13}
Carbon energy (keV)	150	480
Boron dose (at/cm ²)	1.9×10^{13}	2.5×10^{12}
Boron energy (keV)	100	480
Carbon and multiplication layer annealing	180 min @ 1100 °C + 84 min @ 950 °C	104 min @ 800 °C + 84 min @ 950 °C
Phosphorus dose (at/cm ²)	5×10^{14} & 10^{15}	-
Phosphorus energy (keV)	70 & 150	-
Arsenic dose (at/cm ²)	-	10^{15}
Arsenic energy (keV)	-	30
N ⁺⁺ layer annealing	30 min @ 1000 °C	RTA: 30 s @ 1100 °C + 30 s @ 1050 °C

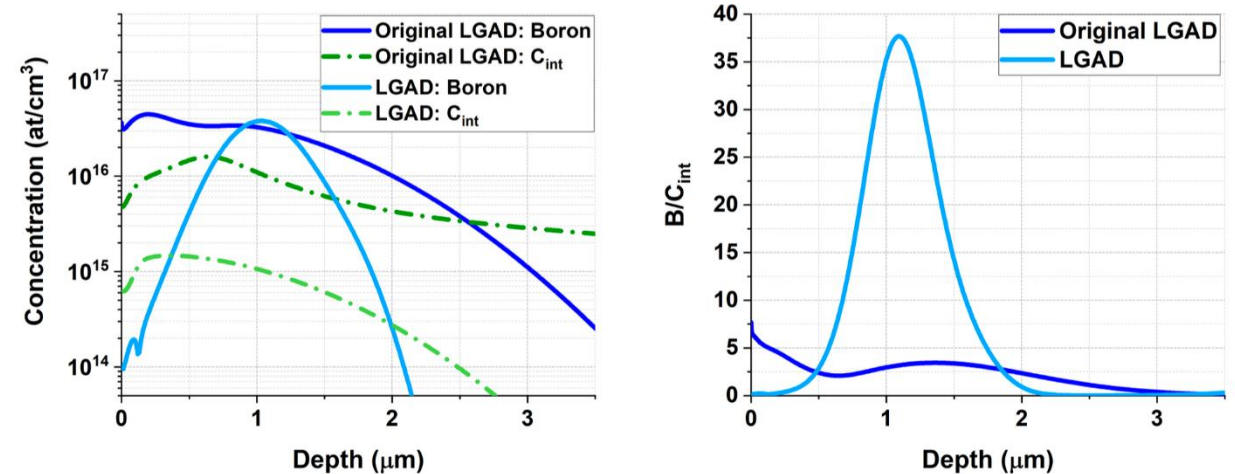
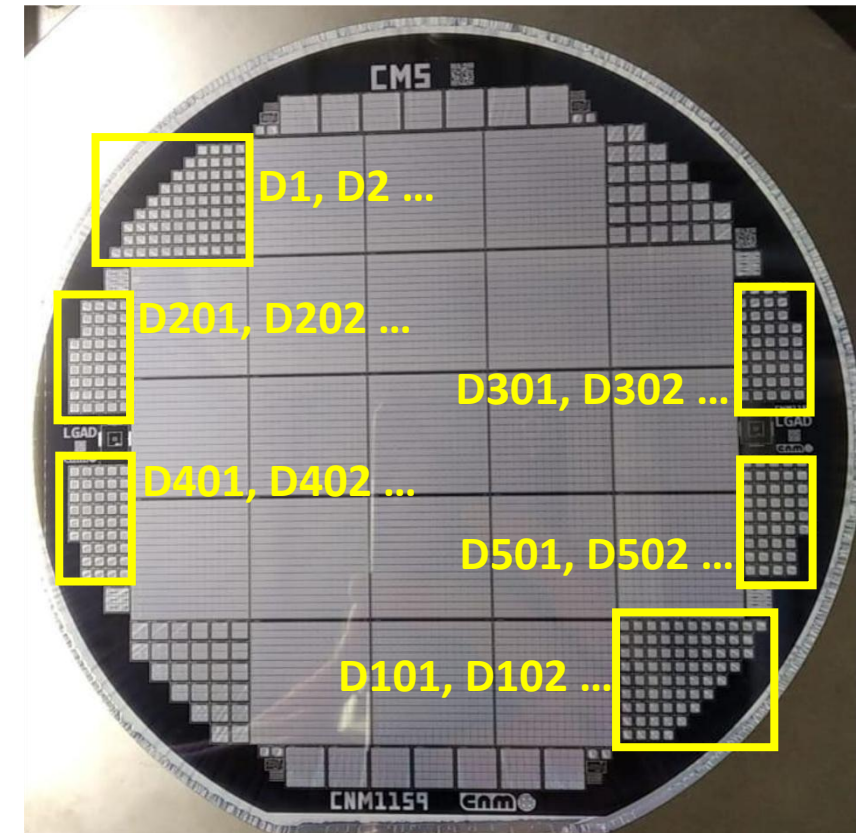


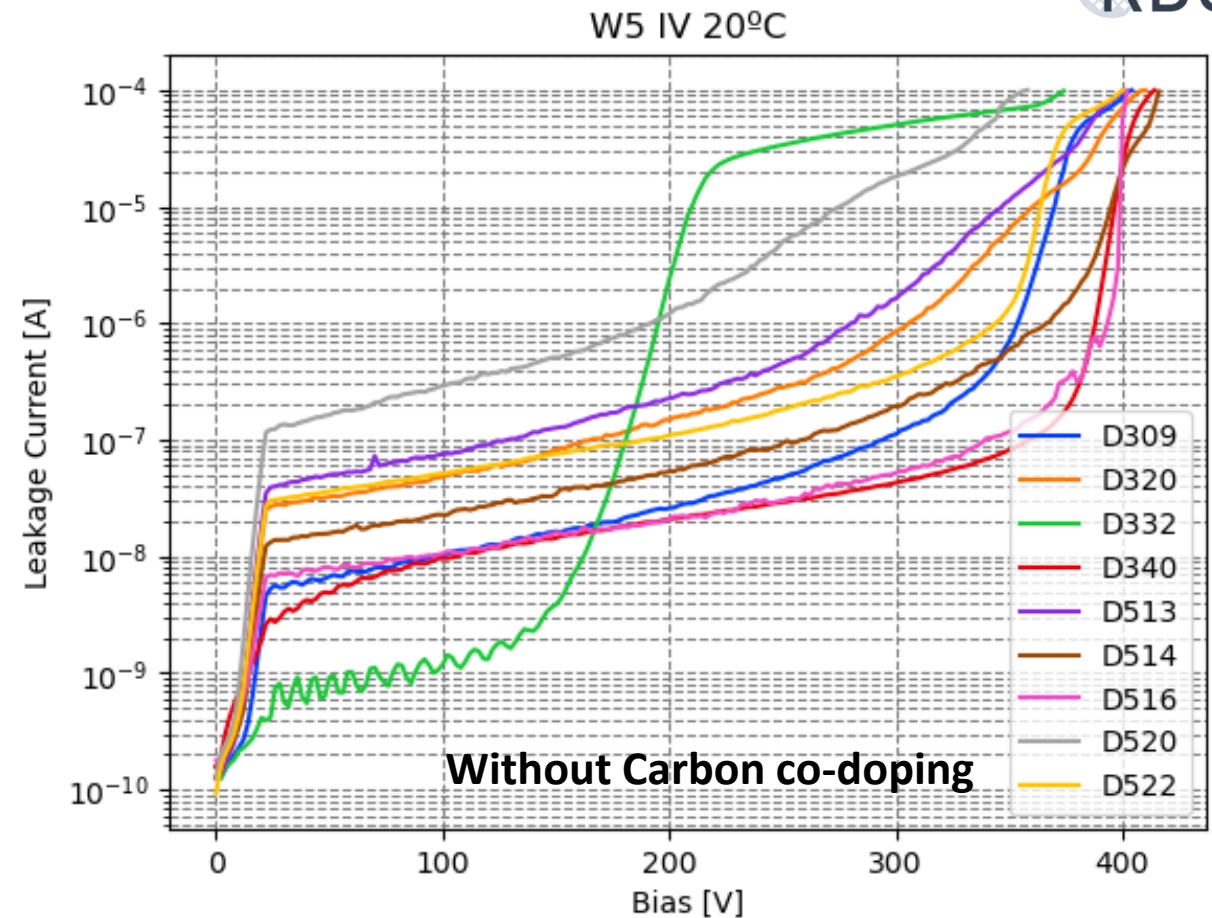
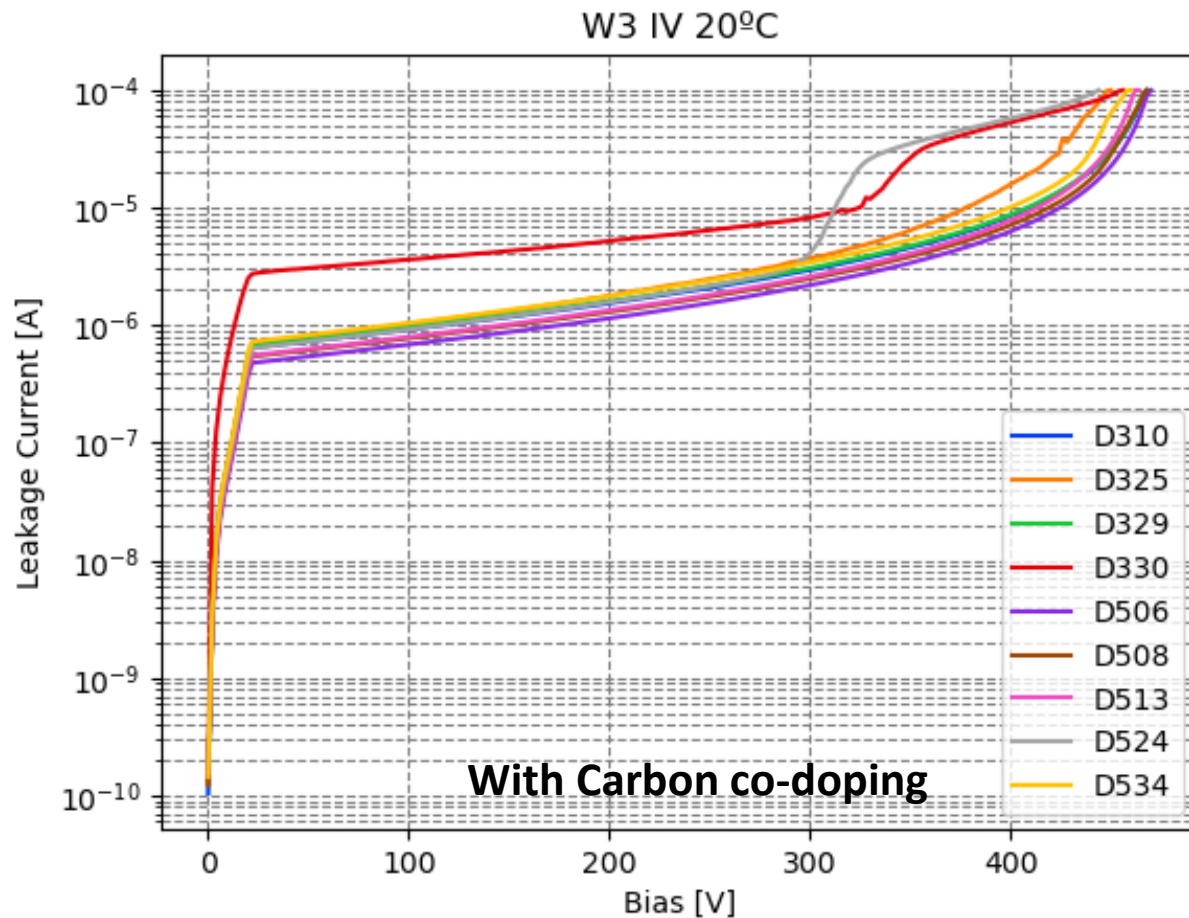
Figure 3. TCAD Sentaurus simulations of the boron and interstitial carbon (C_{int}) concentrations (left) for the original and current IMB-CNM LGAD structures, along with the B/C_{int} ratios (right) for these devices.

CMS 6DLG3v1. R17958. I-V @ LabRad. Overview

- All single-pad devices (272 samples) are tested
- I-V and C-V measurements at -25 °C (CMS experiment temperature) and after at 20 °C
- Yield condition = **Leakage Current** < 200 nA @ -25 °C for $V = 30$ V (Full Depletion)
- For most of the single-pad devices, the leakage current at -25 °C is **higher than 10 μ A @ 30 V**
- **Wafer 3** → Just 31 devices, 11 % of the total, have a reasonable leakage current for the CMS requirements, < 200 nA @ -25 °C for a wide voltage range
- **Wafer 5** → Just 19 devices, 7 % of the total have a reasonable leakage current

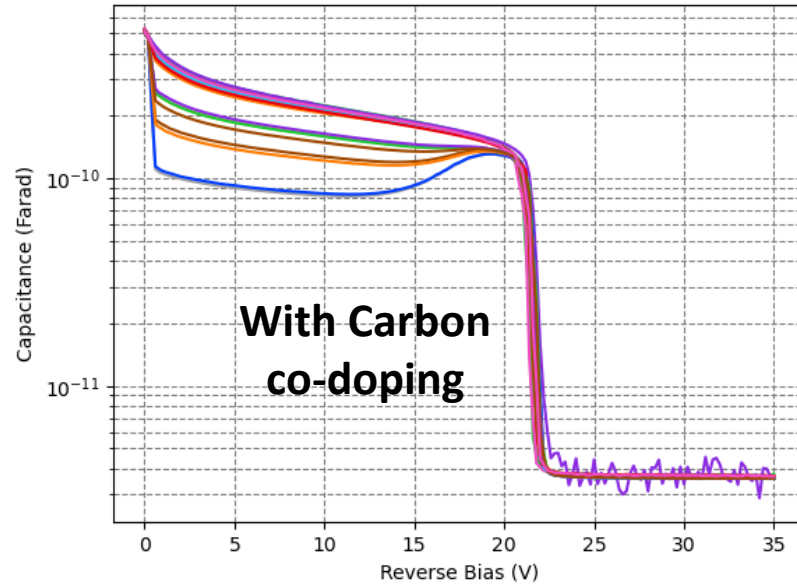
Single-pad label arrangement



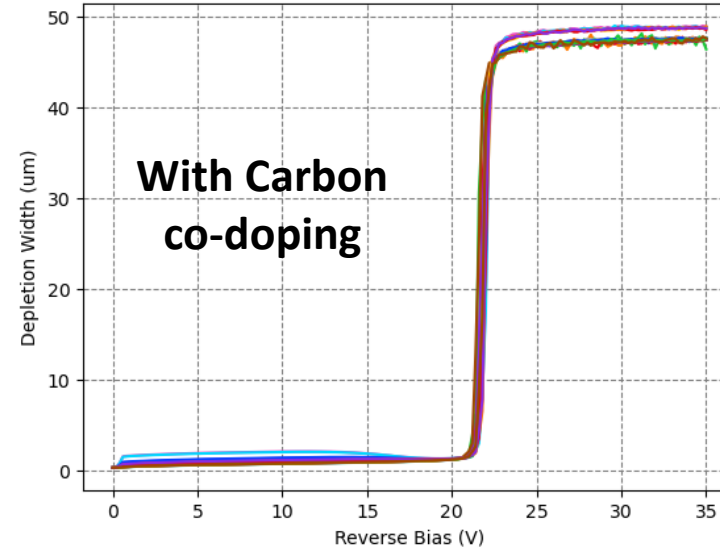


- Breakdown voltage > 300V
- Higher Leakage current for devices with carbon co-doping
- Better uniformity of the breakdown voltage for devices with carbon co-doping

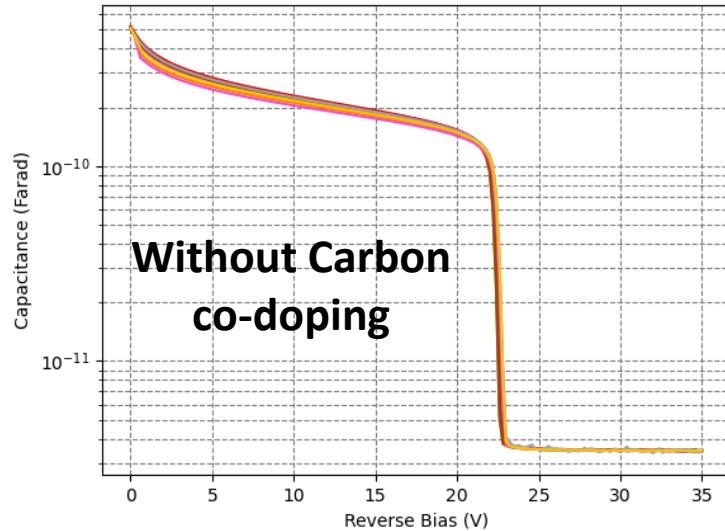
W3 CV Parallel Mode 200mV 1kHz



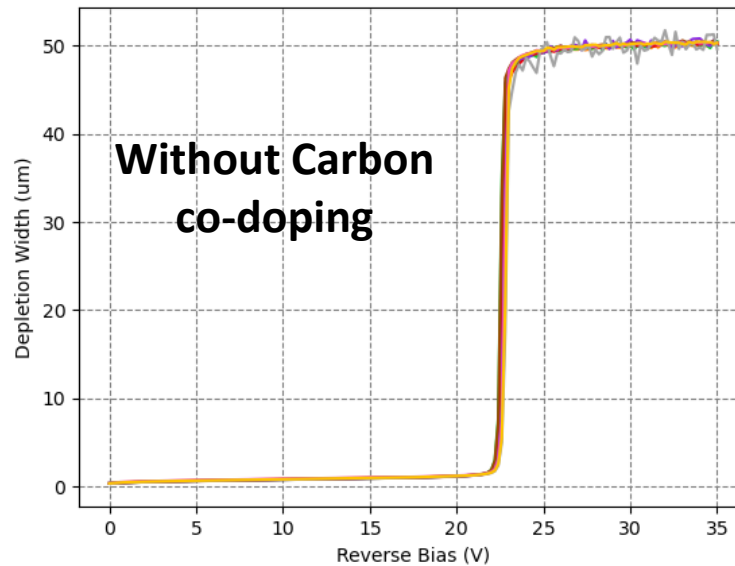
W3 CV Parallel Mode 200mV 1kHz



W5 CV Parallel Mode 200mV 1kHz



W5 CV Parallel Mode 200mV 1kHz



- Discrepancy of the capacitance during the depletion of the gain layer, being studied
- Good uniformity of the V_{gl} among the various sensors ~22-23 V



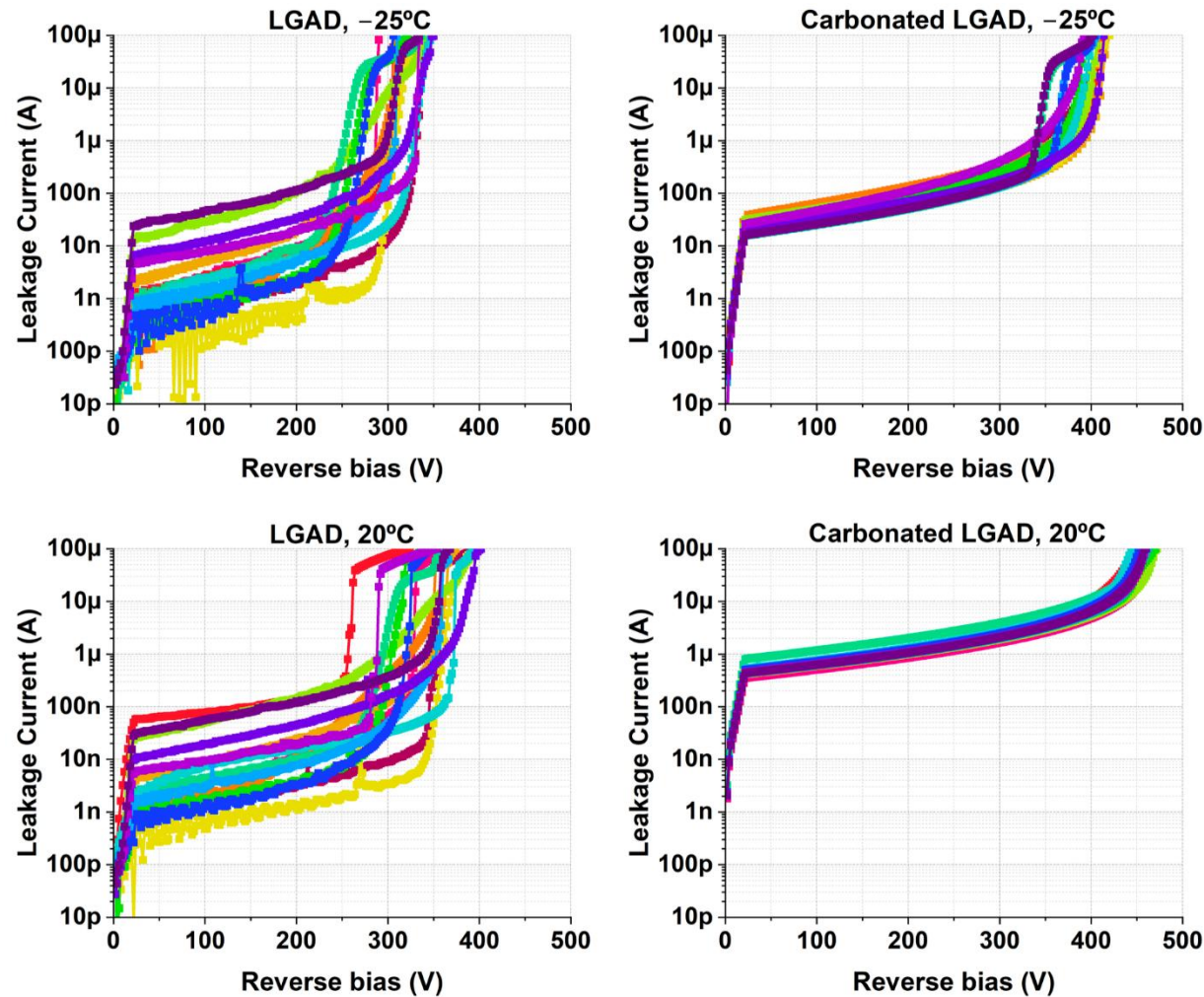


Figure 6. IV curves at -25 °C and 20 °C for 15 LGAD samples and 15 c.LGAD samples.

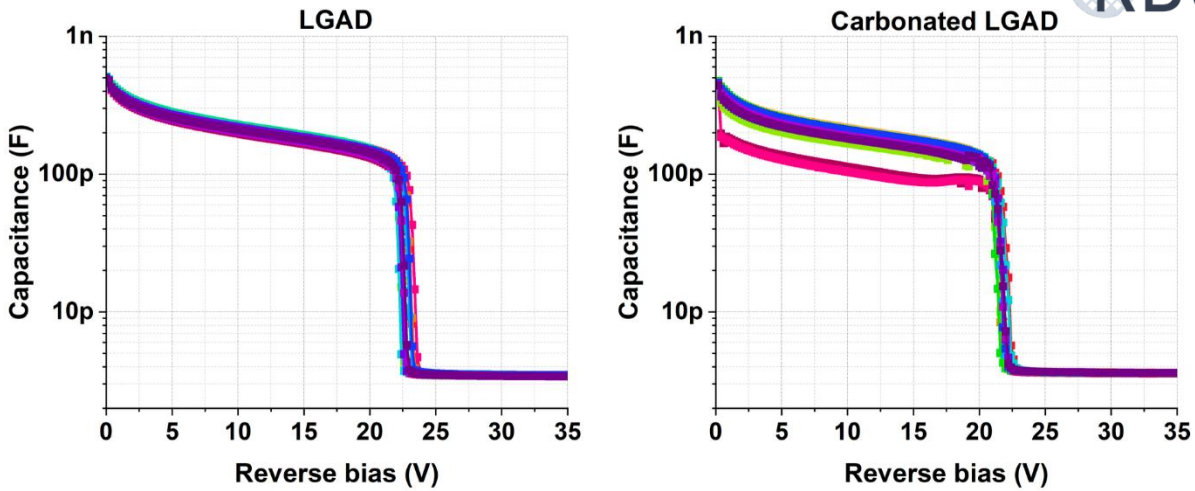


Figure 4. CV curves, at 20 °C, 10 kHz, 200 mV AC and series mode, for 15 LGAD and 15 c.LGAD samples.

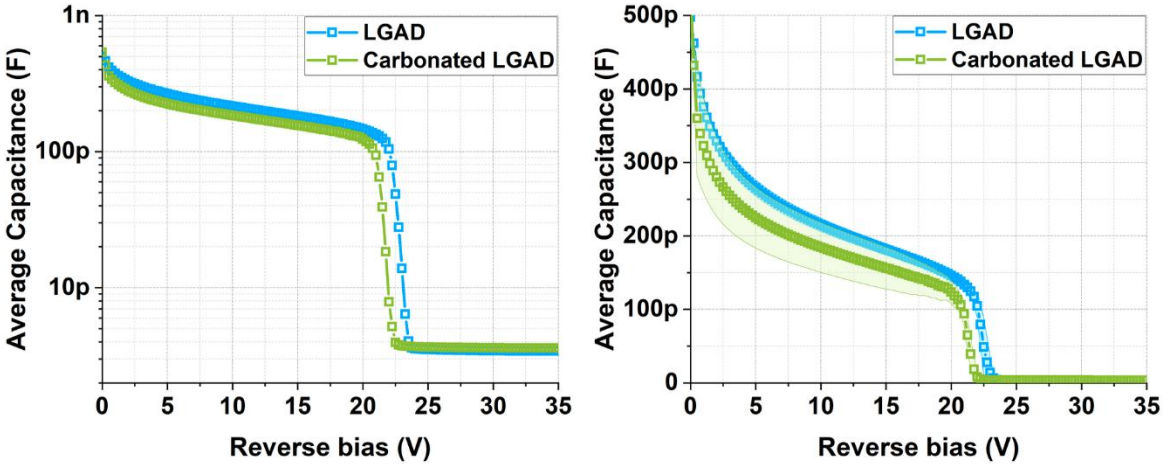


Figure 5. Average capacitance at 20 °C, 10 kHz, 200 mV AC, series mode, and with standard deviation bands for the studied samples. Both images show the same data using different scales: logarithmic on the left and linear with standard deviation bands on the right.

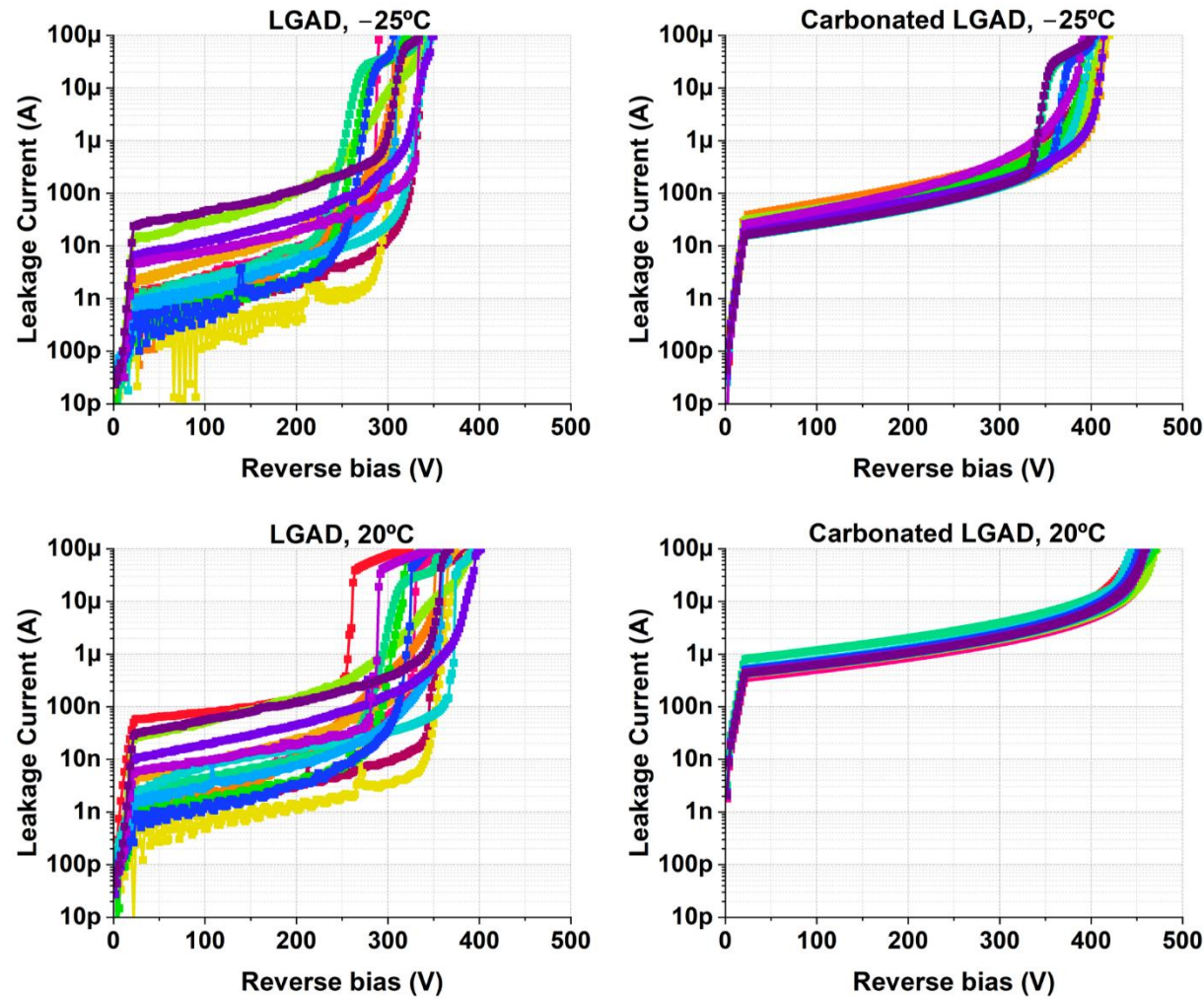


Figure 6. IV curves at -25 °C and 20 °C for 15 LGAD samples and 15 c.LGAD samples.

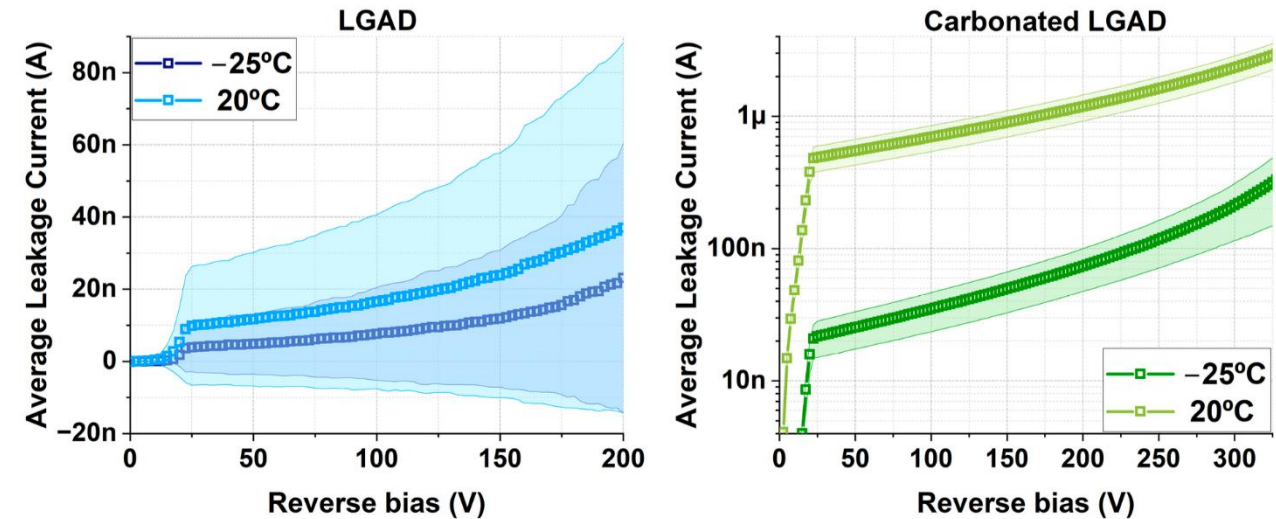


Figure 7. Average leakage current with standard deviation bands for the studied samples (LGAD on the left, c.LGADs on the right). For the c.LGADs, the results are shown on a logarithmic scale to better distinguish the curves at -25 °C and 20 °C.



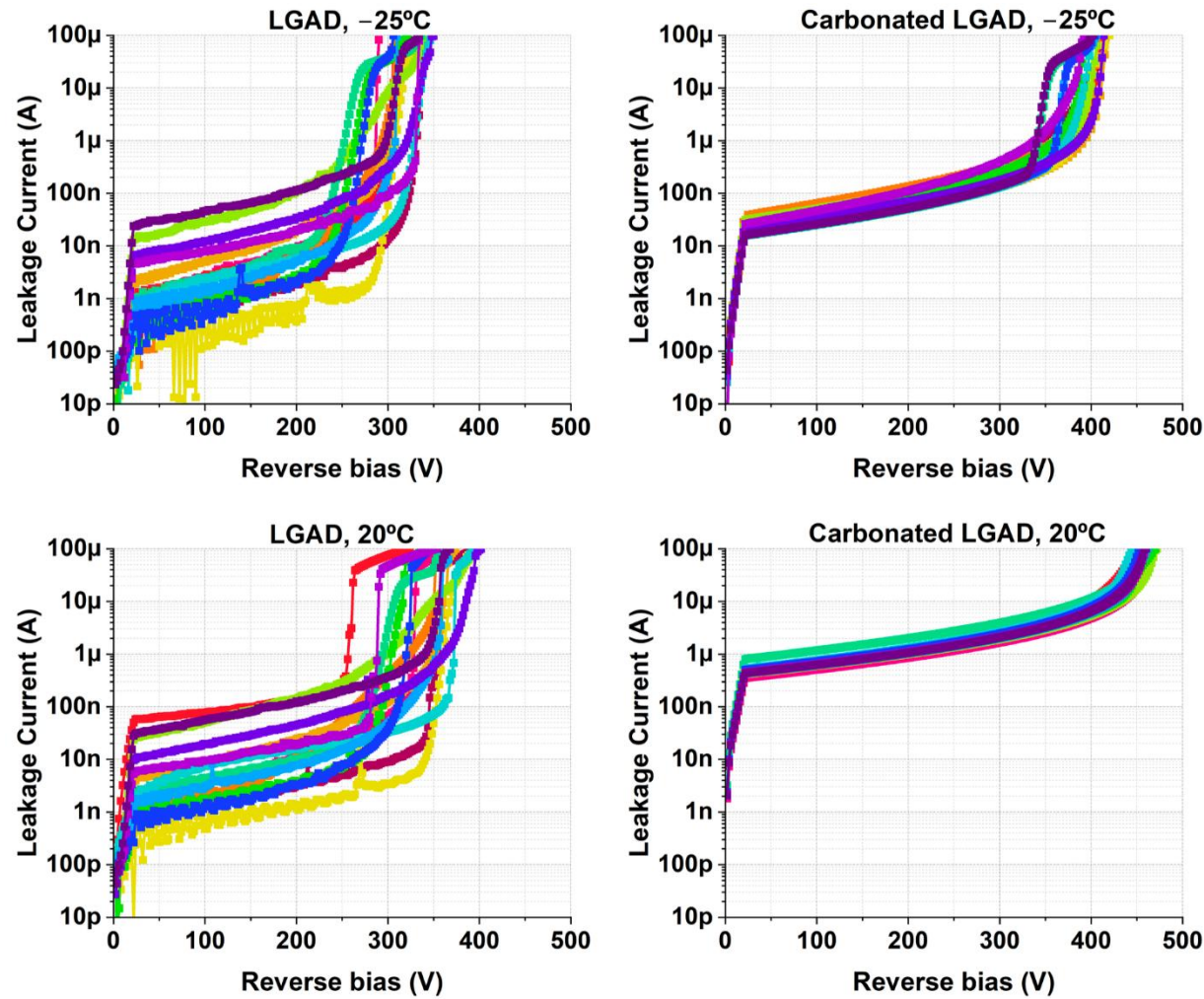


Figure 6. IV curves at -25 °C and 20 °C for 15 LGAD samples and 15 c.LGAD samples.

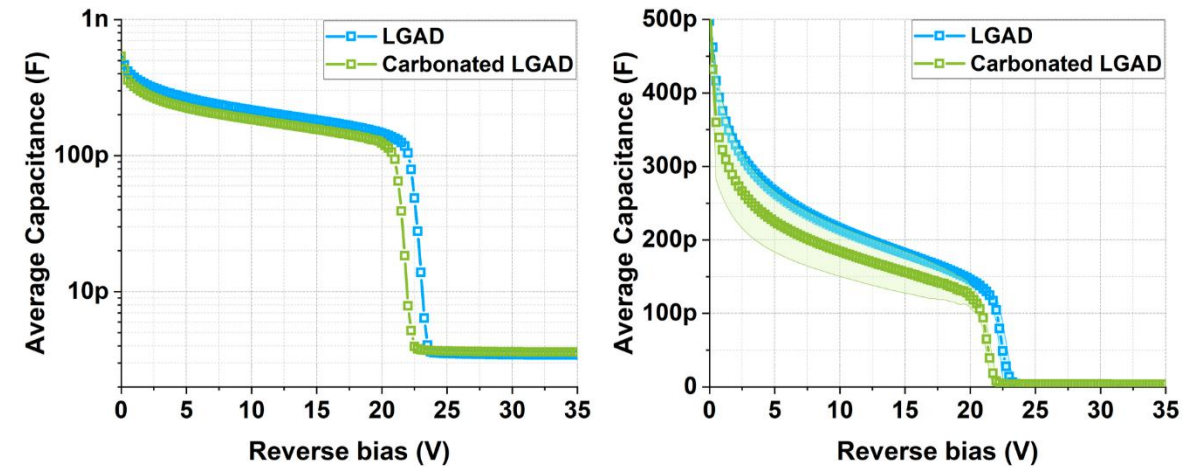


Figure 5. Average capacitance at 20 °C, 10 kHz, 200 mV AC, series mode, and with standard deviation bands for the studied samples. Both images show the same data using different scales: logarithmic on the left and linear with standard deviation bands on the right.

With carbon co-doping

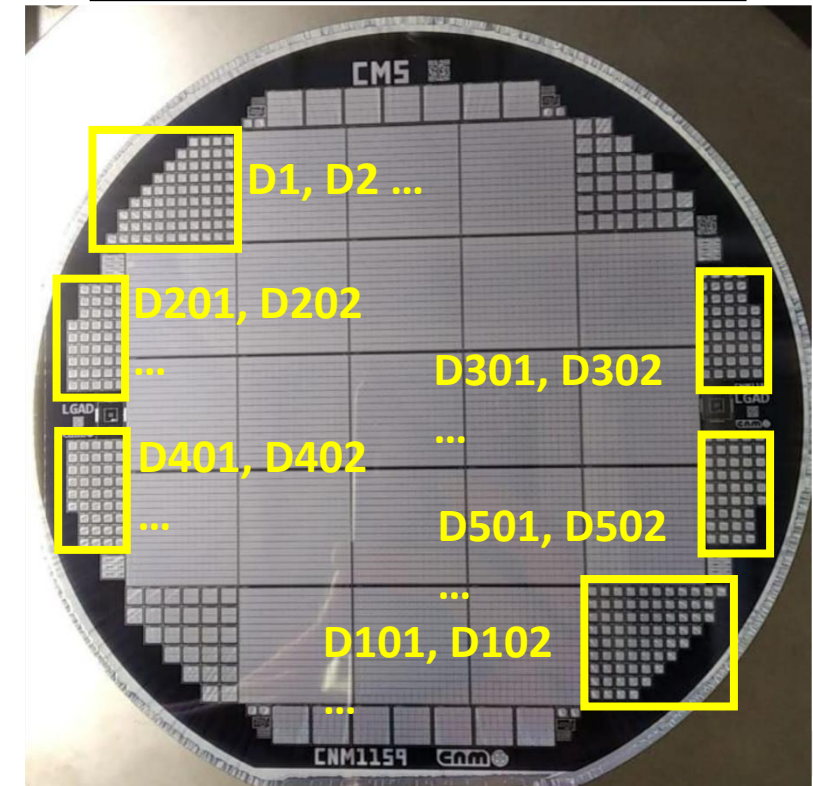
Higher leakage current

Higher breakdown voltage

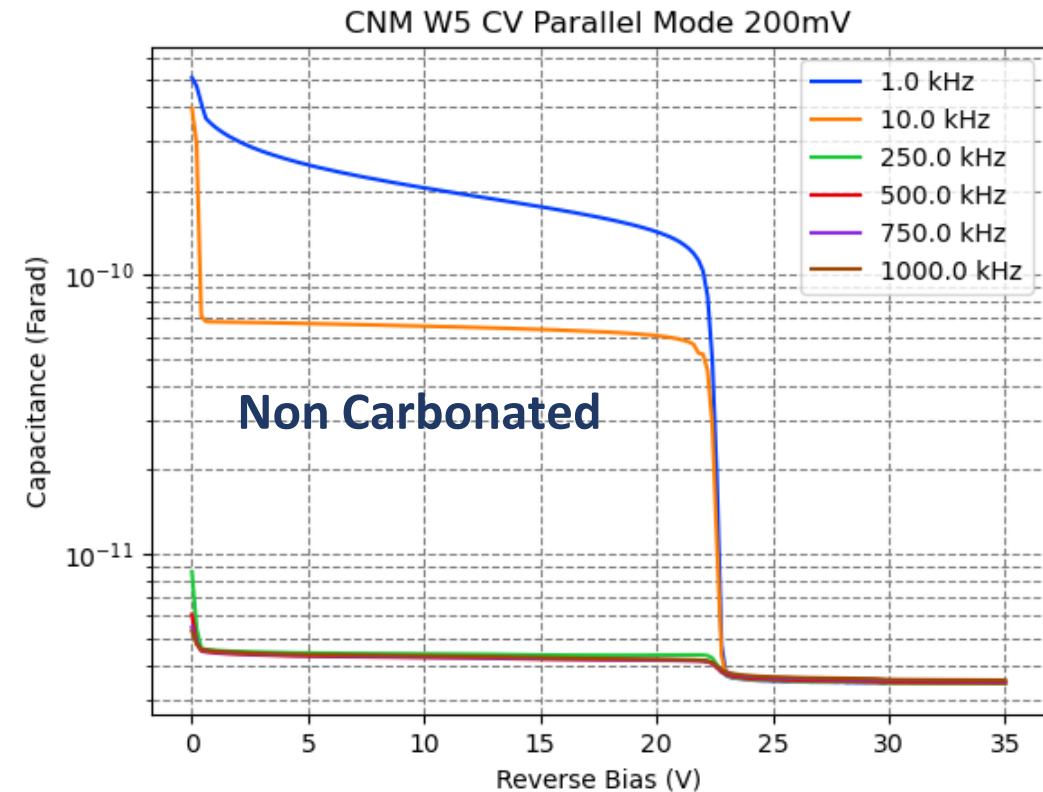
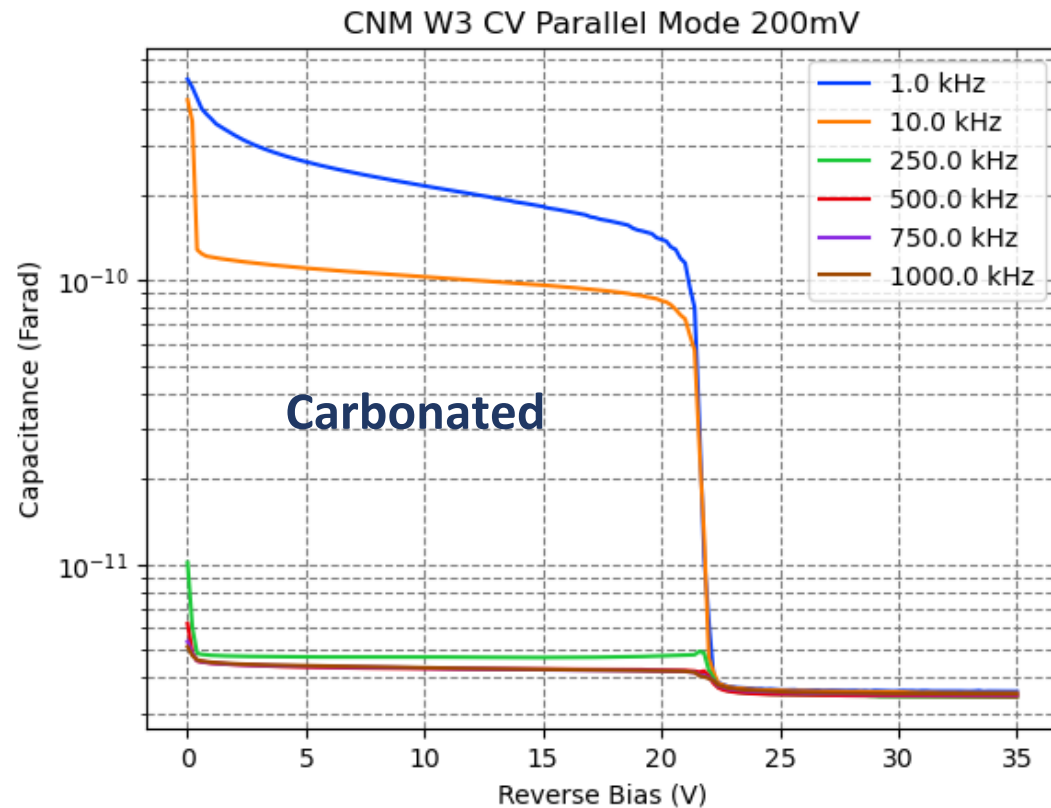
Lower depletion voltage of the multiplication layer

- All single-pad devices (272 samples) are tested
- IV and CV measurements at -25°C (CMS experiment temperature) and after at 20°C
- Yield condition = Leakage Current $< 200\text{ nA}$ @ -25°C for $V = 30\text{ V}$ (Full Depletion)
- For most of the single-pad devices, the leakage current at -25°C is higher than $10\text{ }\mu\text{A}$ @ 30 V
- Wafer3 $\rightarrow$ Just 31 devices, 11% of the total, have a reasonable leakage current for the CMS requirements, $< 200\text{ nA}$ @ -25°C for a wide voltage range
- Wafer5 $\rightarrow$ Just 19 devices, 7% of the total have a reasonable leakage current
- High dispersion of capacitance was seen with measurements at 10 kHz $\rightarrow$ Possible presence of traps in the gain layer
- After that, all measurements were done at 1 kHz , 200 mV , in parallel mode

Single-pad label arrangement

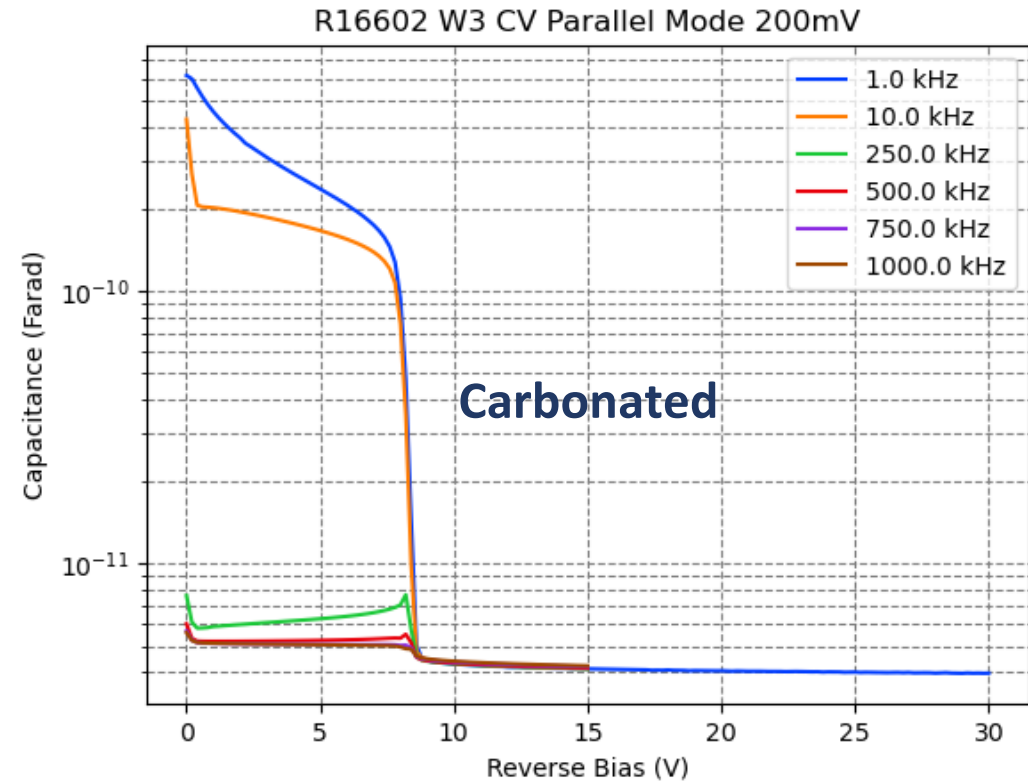
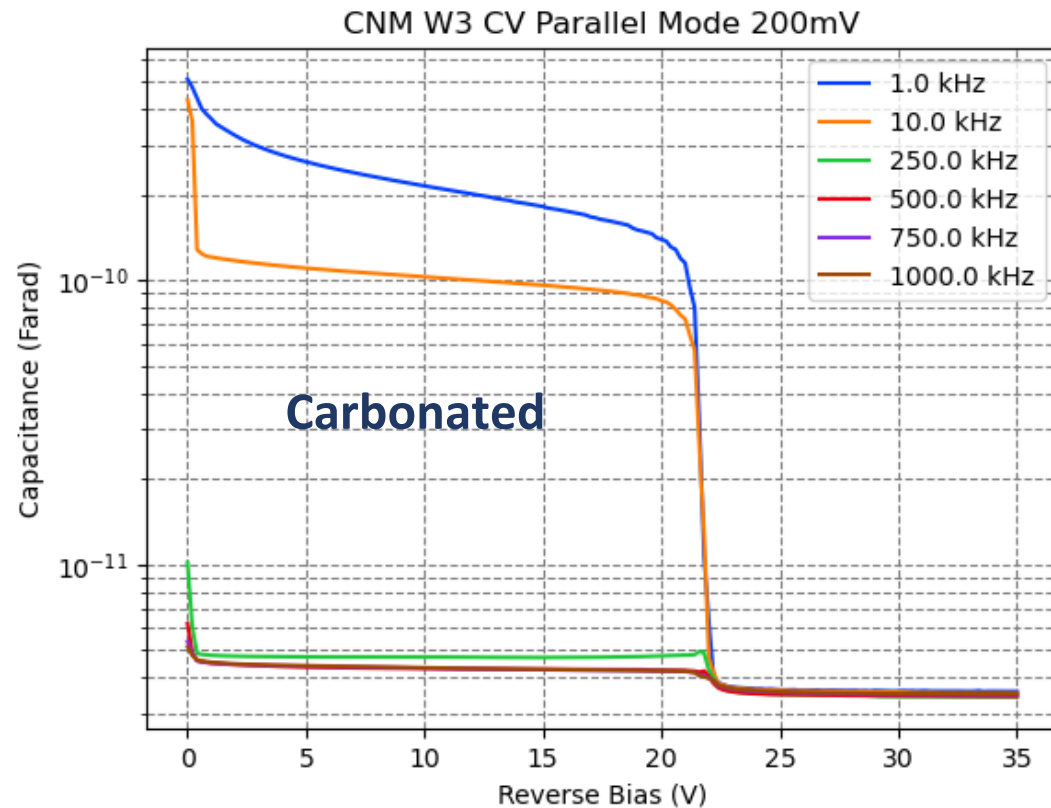


○ Capacitance changes with frequency



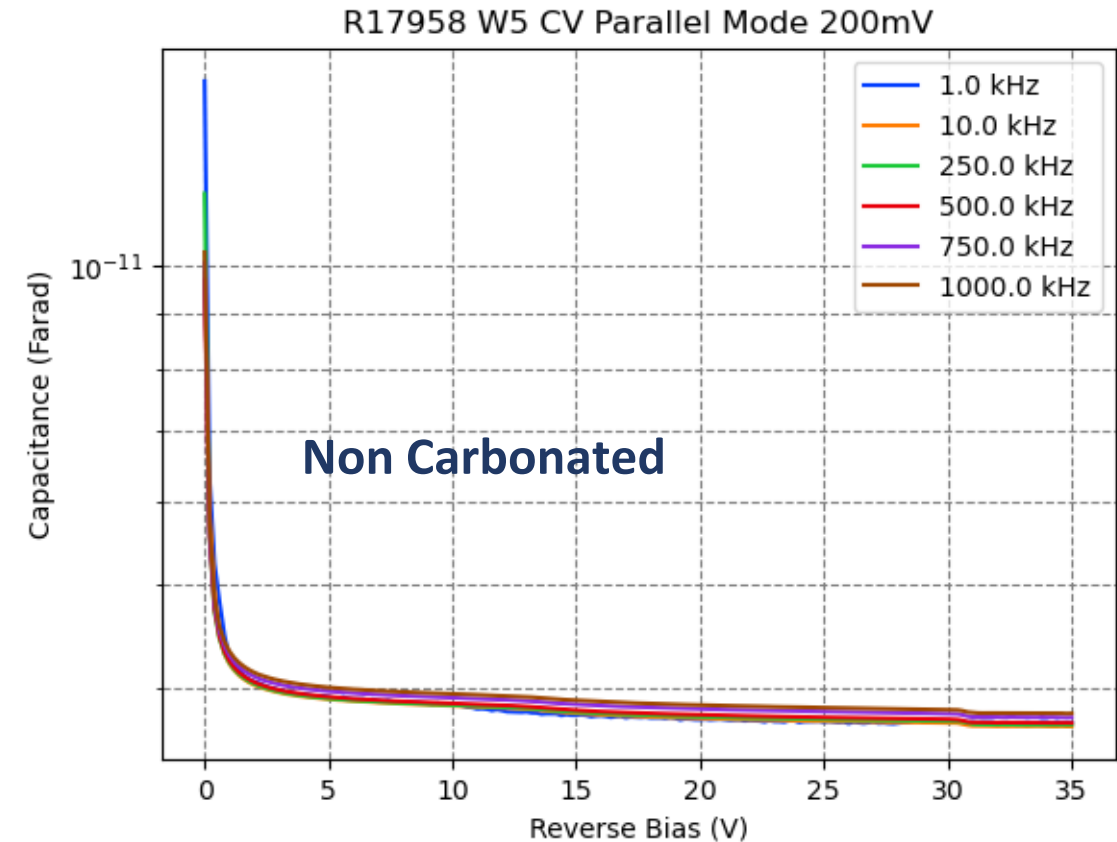
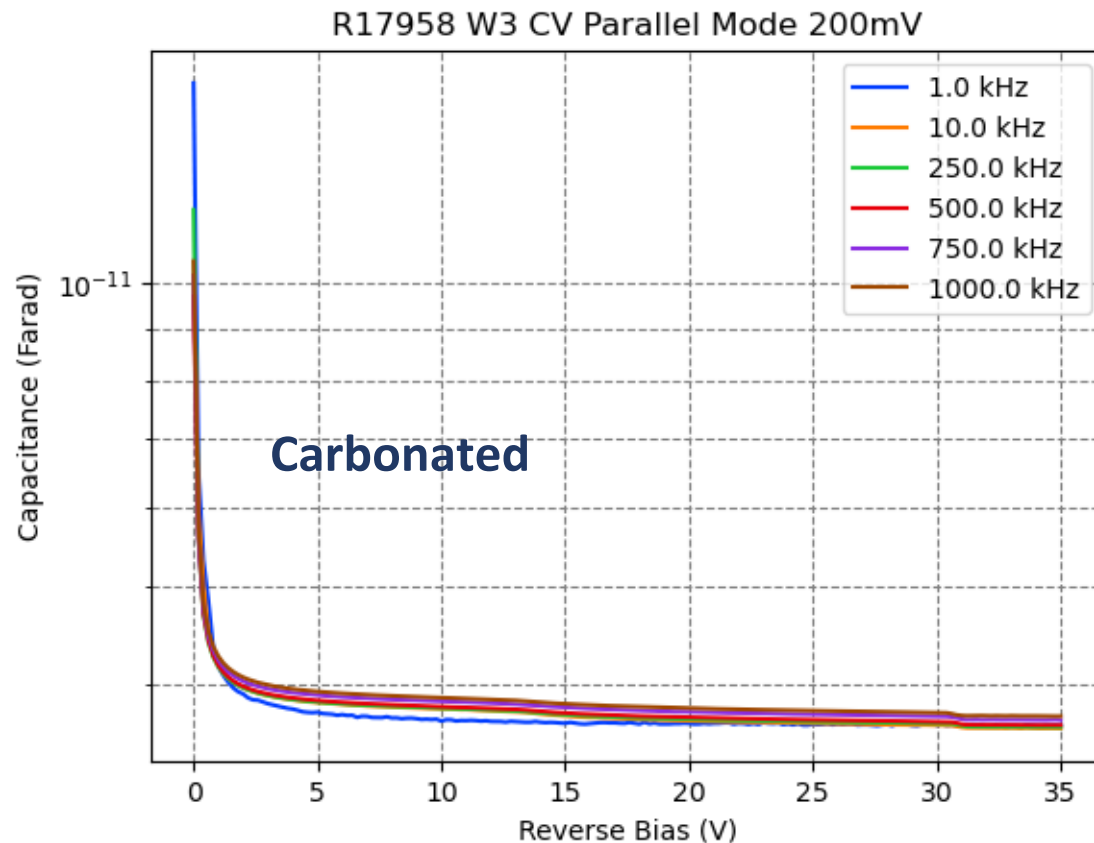
- Capacitance is dropping when increasing the frequency -> **Deep-level traps?**
- **Carbon Implantation does not seem to be responsible of the defects**

○ Capacitance changes with frequency



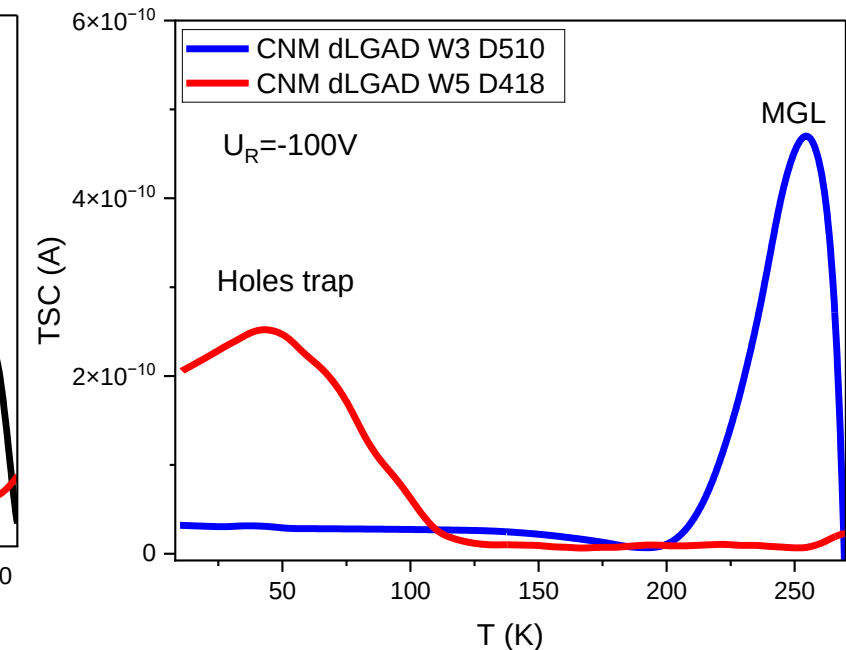
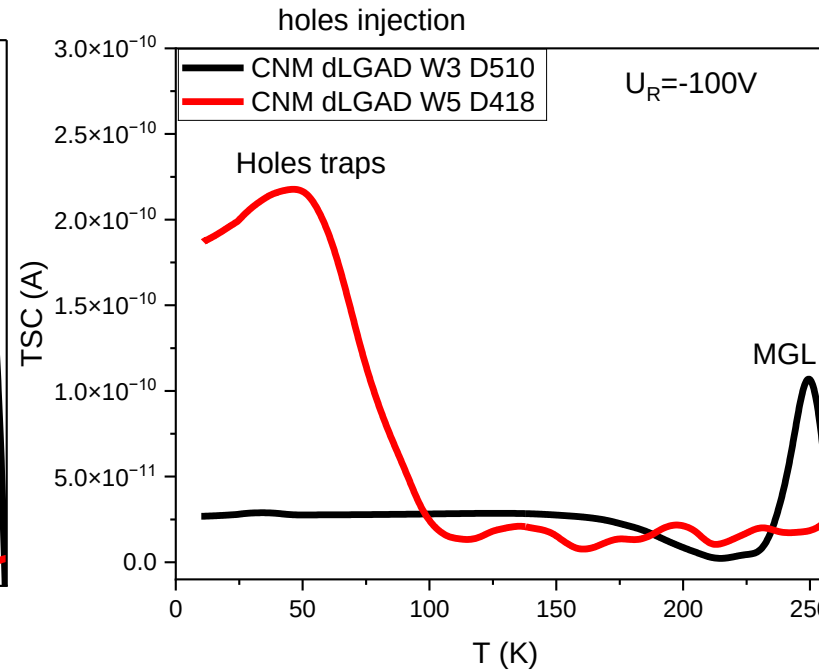
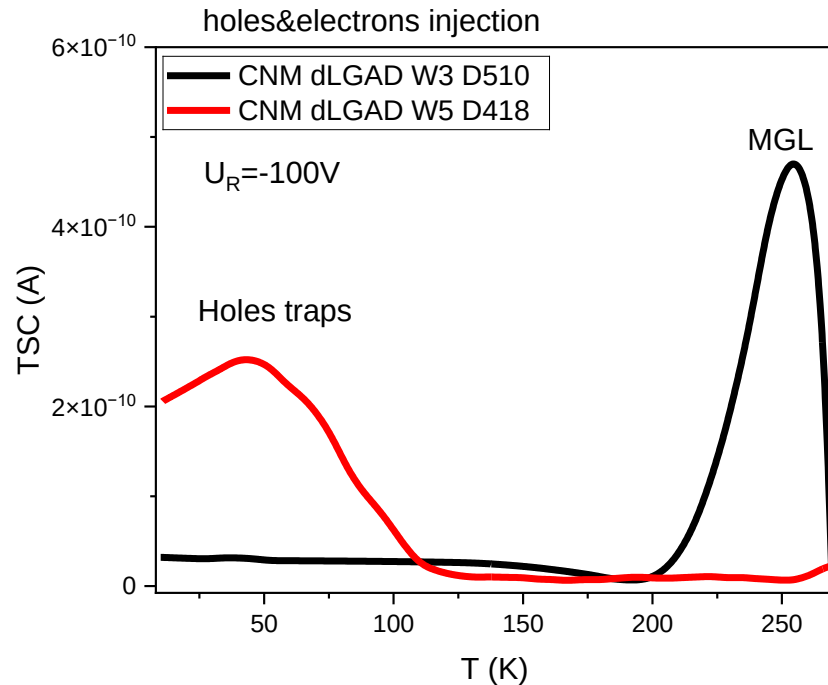
- 1st run of dLGAD R16602: Boron Dose = 2.7×10^{12} at/cm², P instead of As
- Defects are not coming from As implantation

○ Capacitance changes with frequency



- Phenomenon is **not observed with PiN**
- **Defects are not coming from the substrate** but from the gain layer

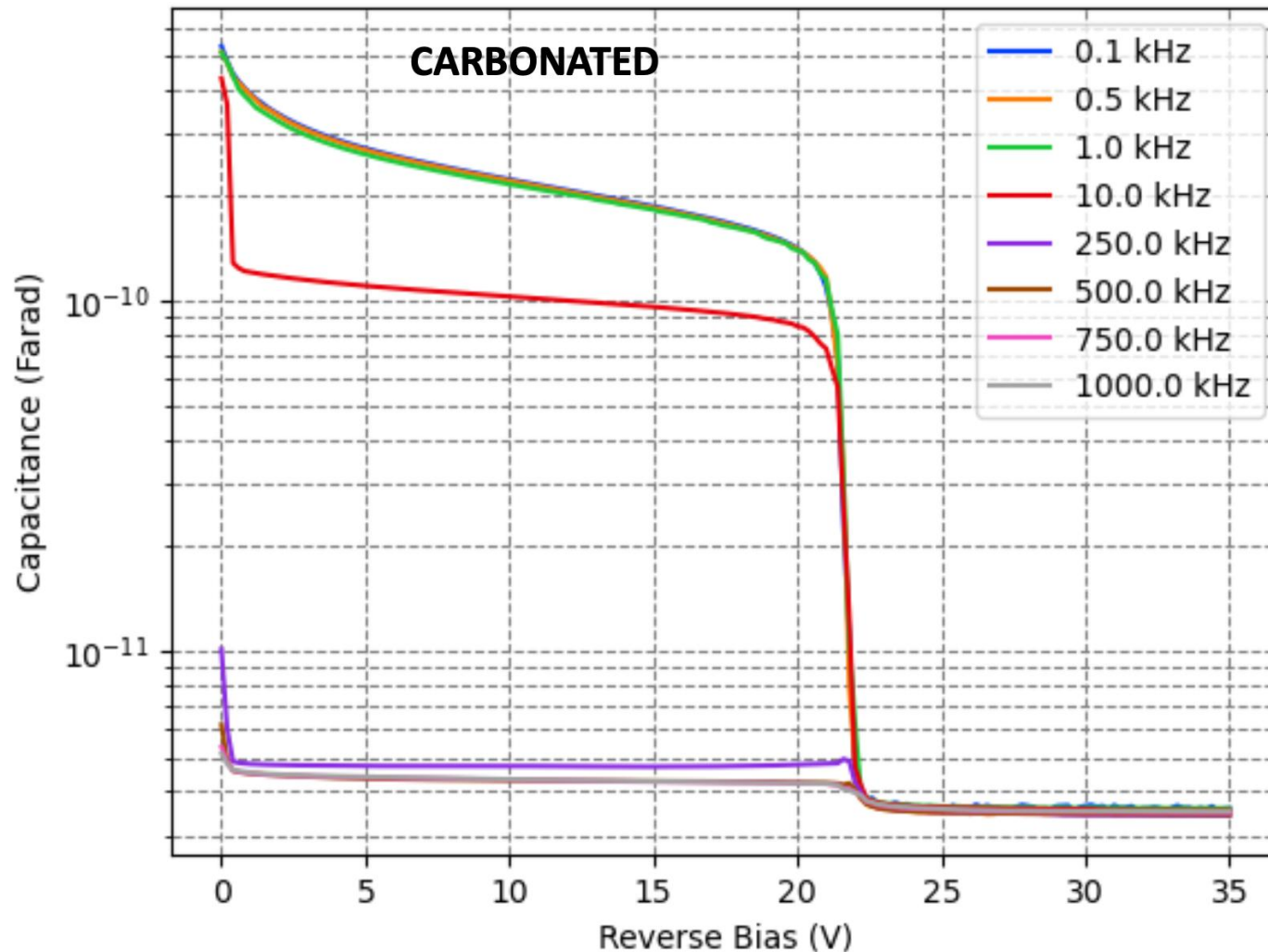
- Samples were sent to Romania to the National Institute of Materials for defects measurements with TSC (Thermally Stimulated Current)



- In W3 sample a **close to mid-gap level (MGL) is detected**. Such center exchange charge with both valence and conduction bands and **generates leakage current**. It can also contribute to N_{eff} , depending on its charge state and occupancy at a certain temperature.
- In W5 sample **MGL vanish and several holes traps are formed**. These ones exchange carriers only with valence band and **cannot generate leakage current**.

CV measurements at various frequencies on sensor D510

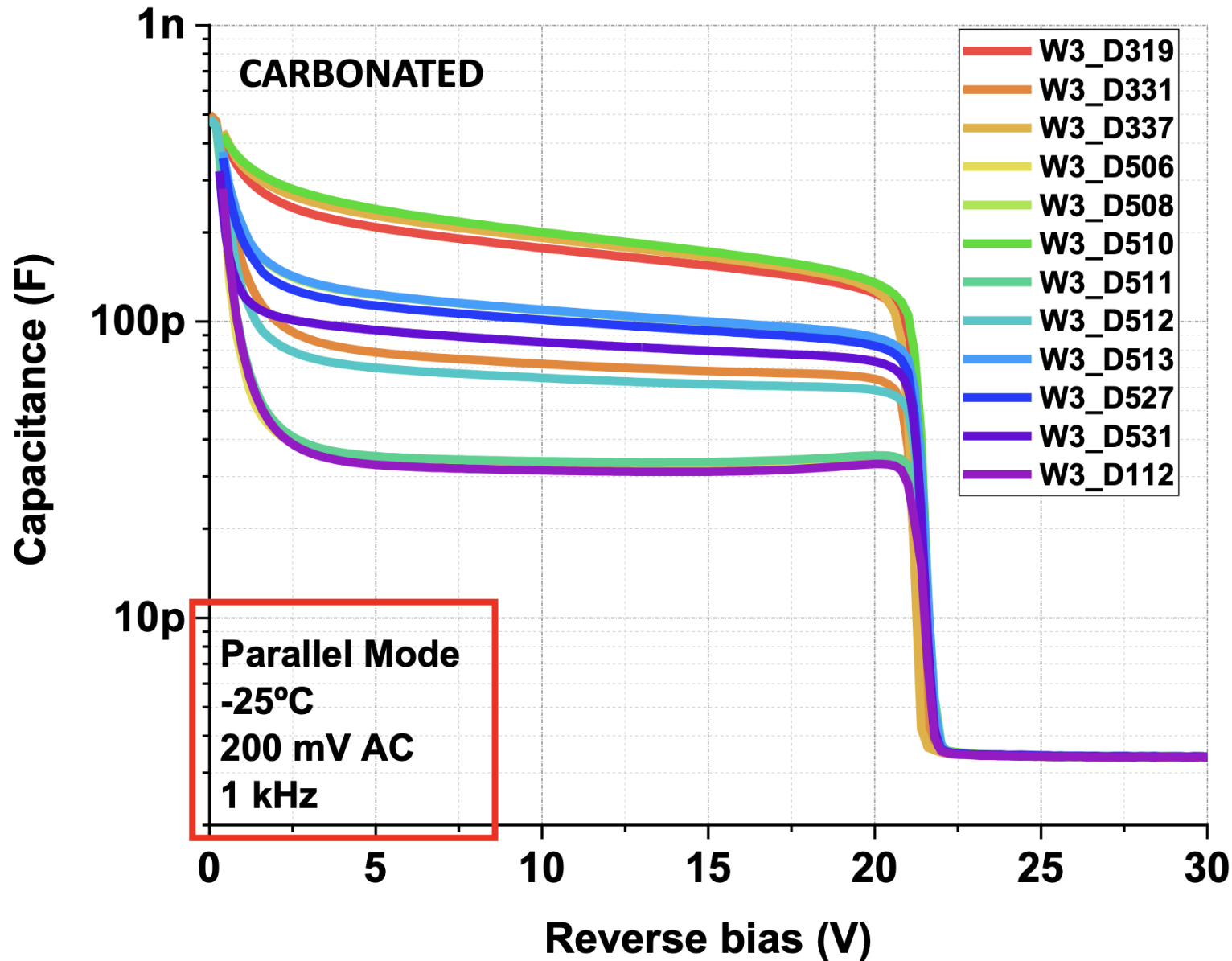
W3 D510 CV Parallel Mode 200mV



- Possible presence of deep level traps
- CV measurements similar at 0.1, 0.5, 1 kHz

➡ **CV Measurement done at 1kHz** to extract information on doping profile and depletion width

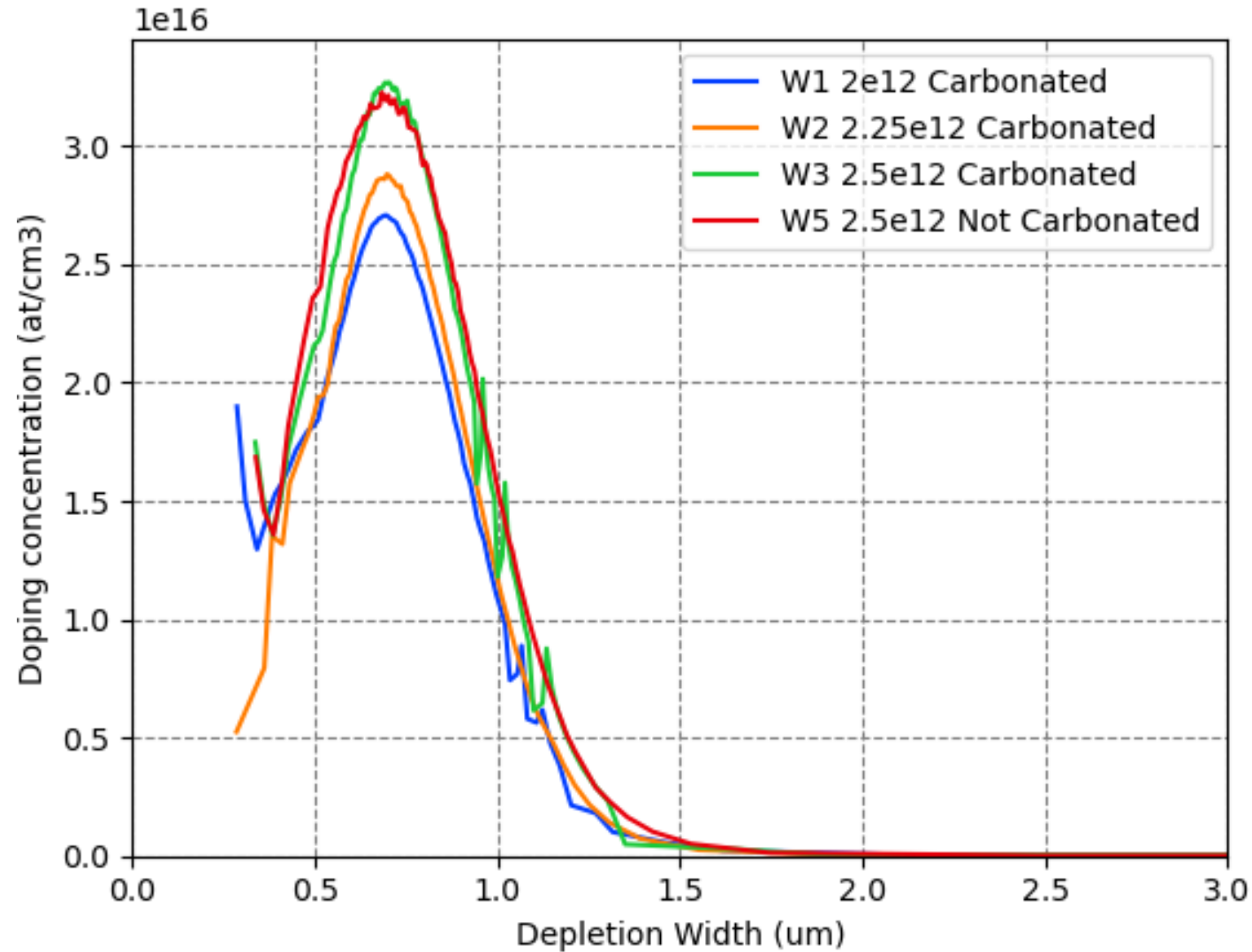




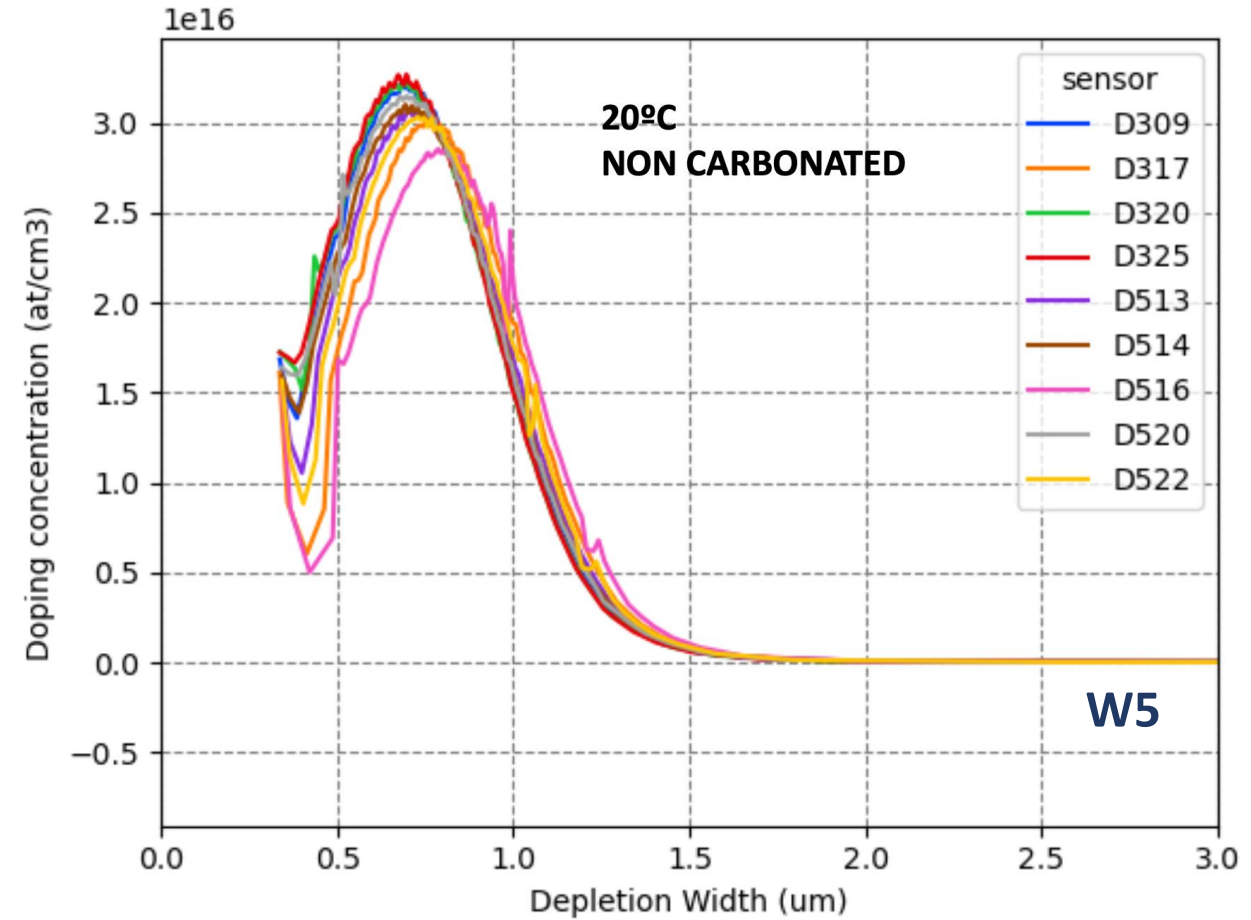
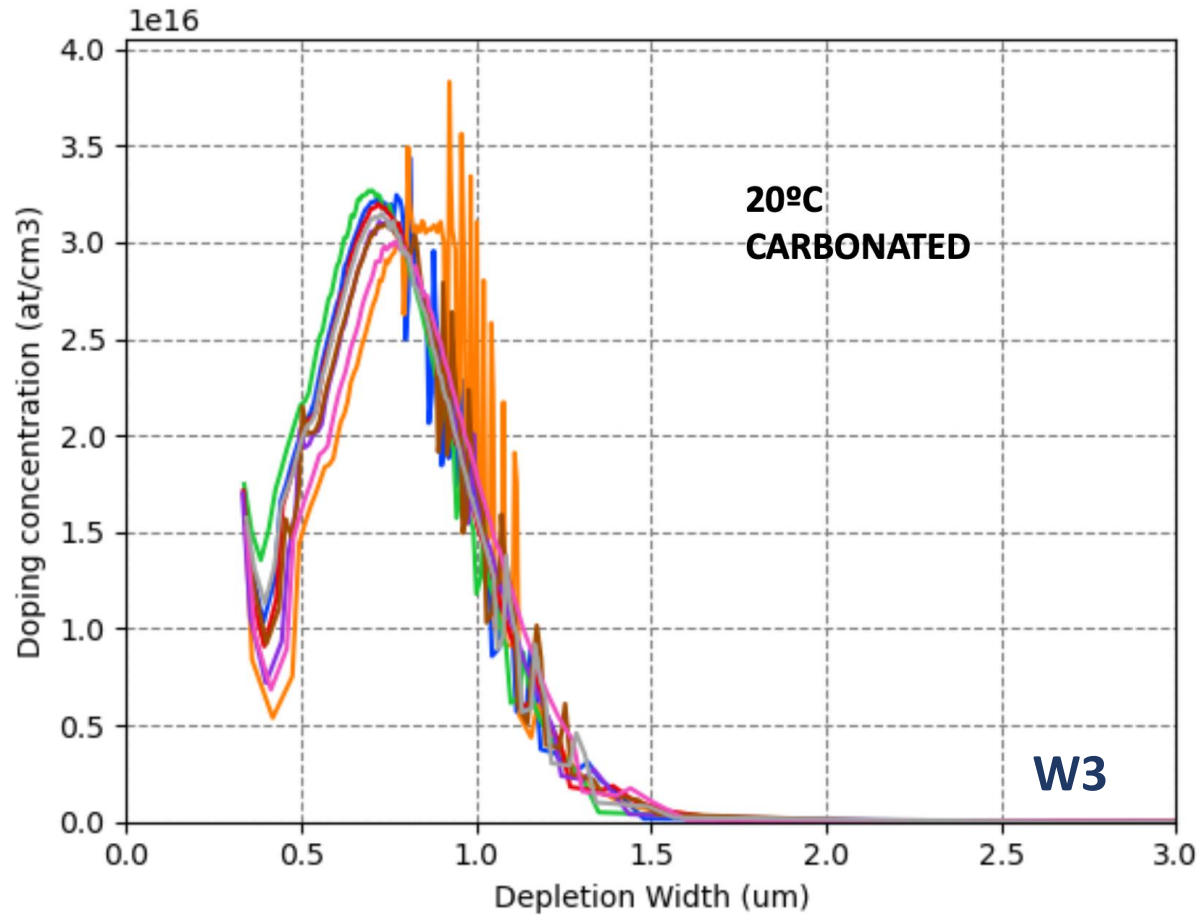
- The very best 12 devices
- $I < 200$ nA for $V < 300$ V
- All of them are located at the right side of the wafer (D100, D300 & D500 side)
- High dispersion on capacitance before depletion
- $V_{gl} \approx 21$ V
- $V_{FD} \approx 25-30$ V



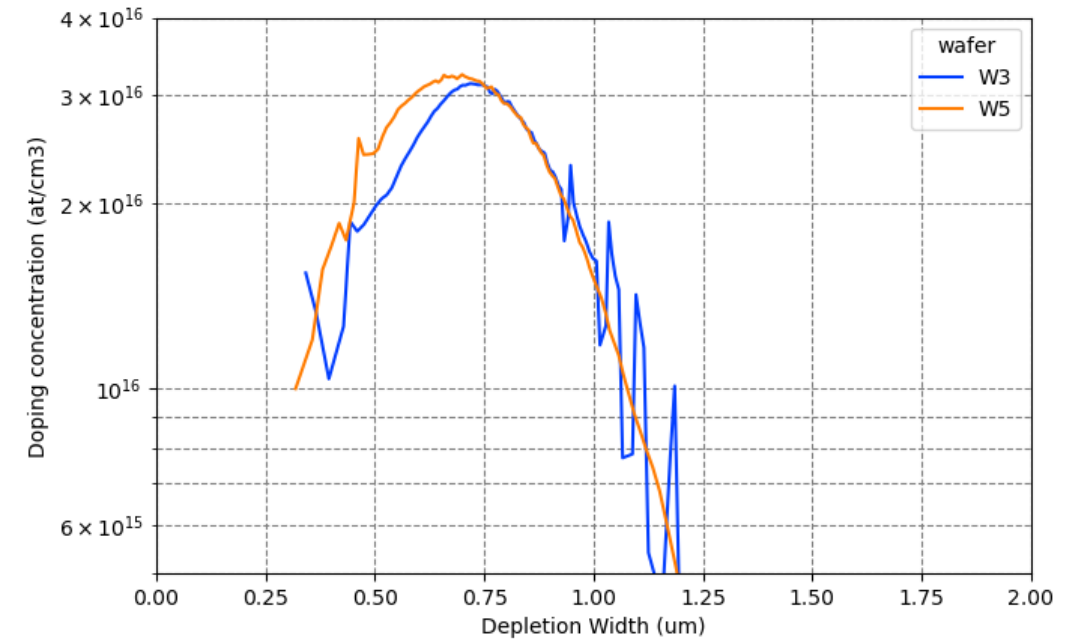
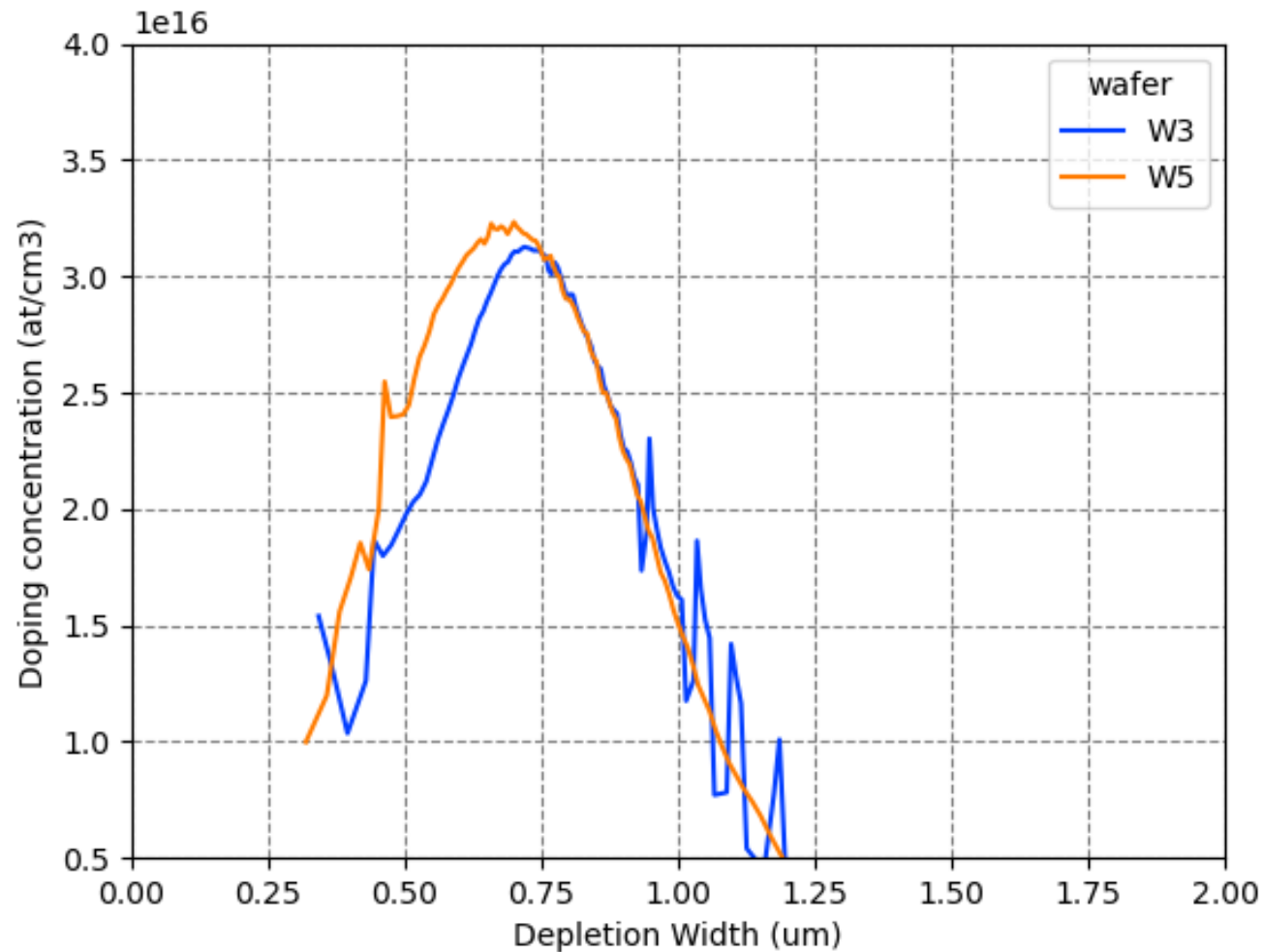
C-V Extracted Impurity Profile



C-V Extracted Impurity Profile

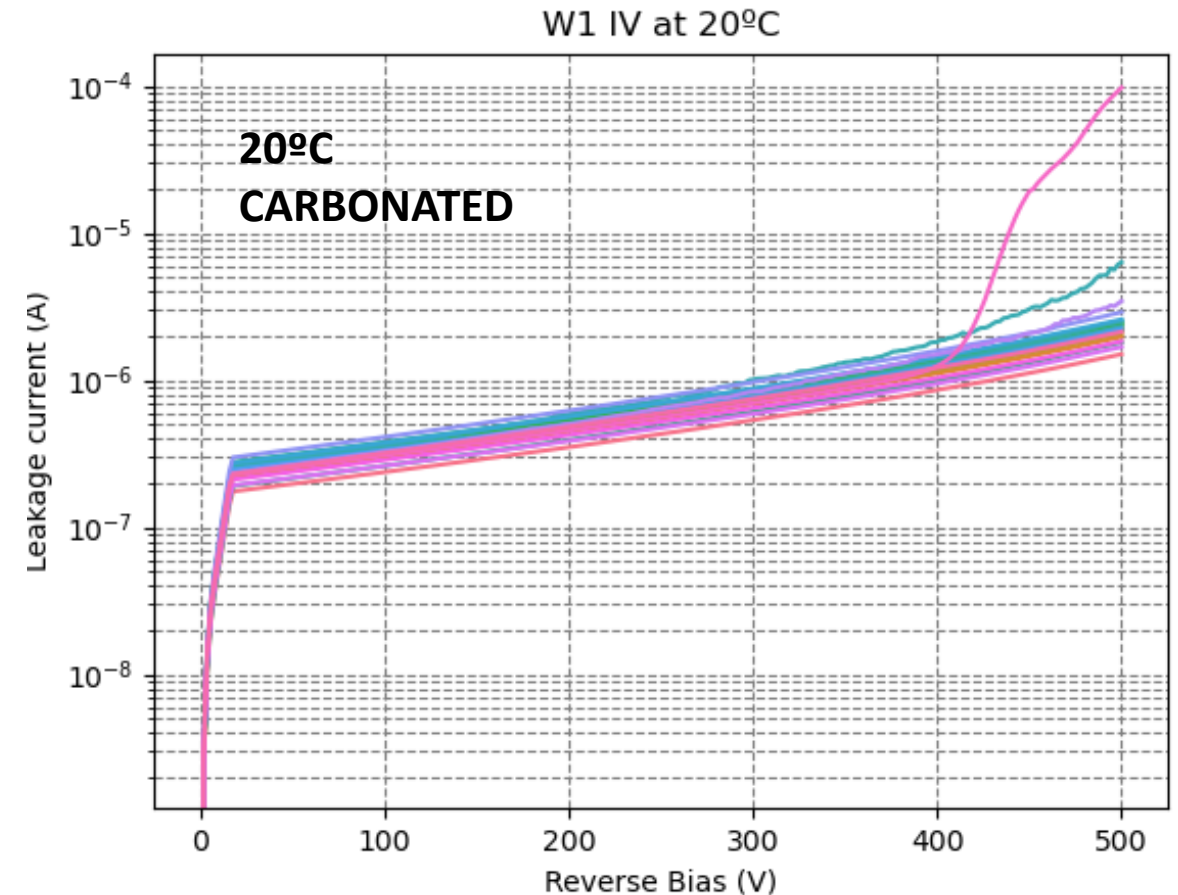
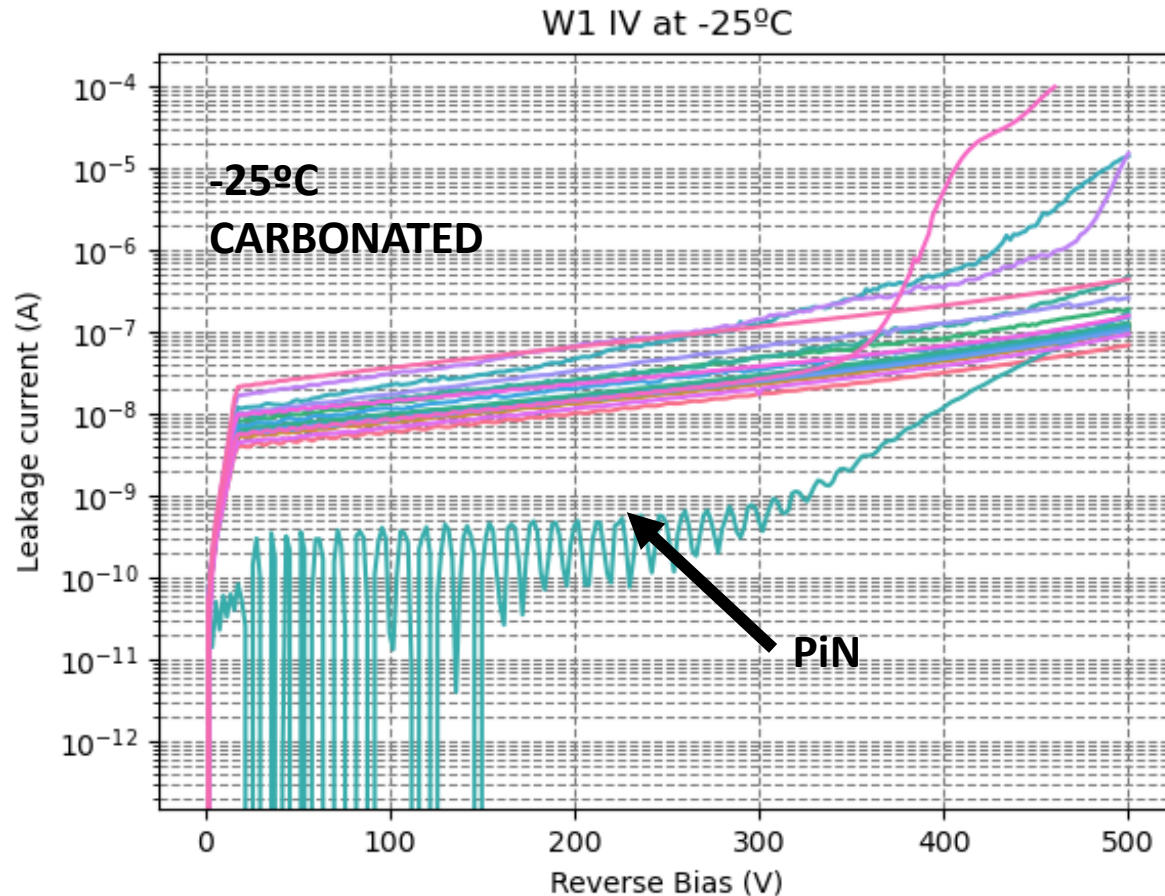


C-V Extracted Impurity Profile Comparison

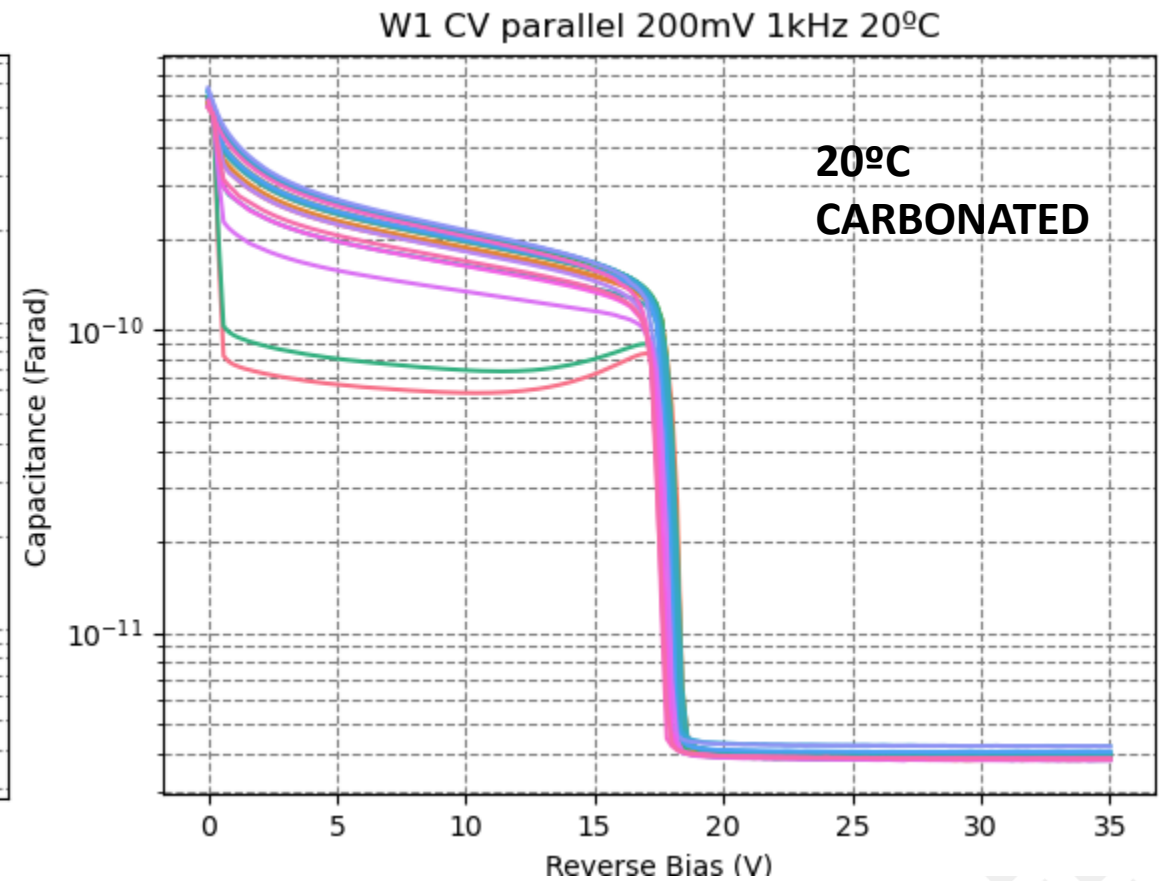
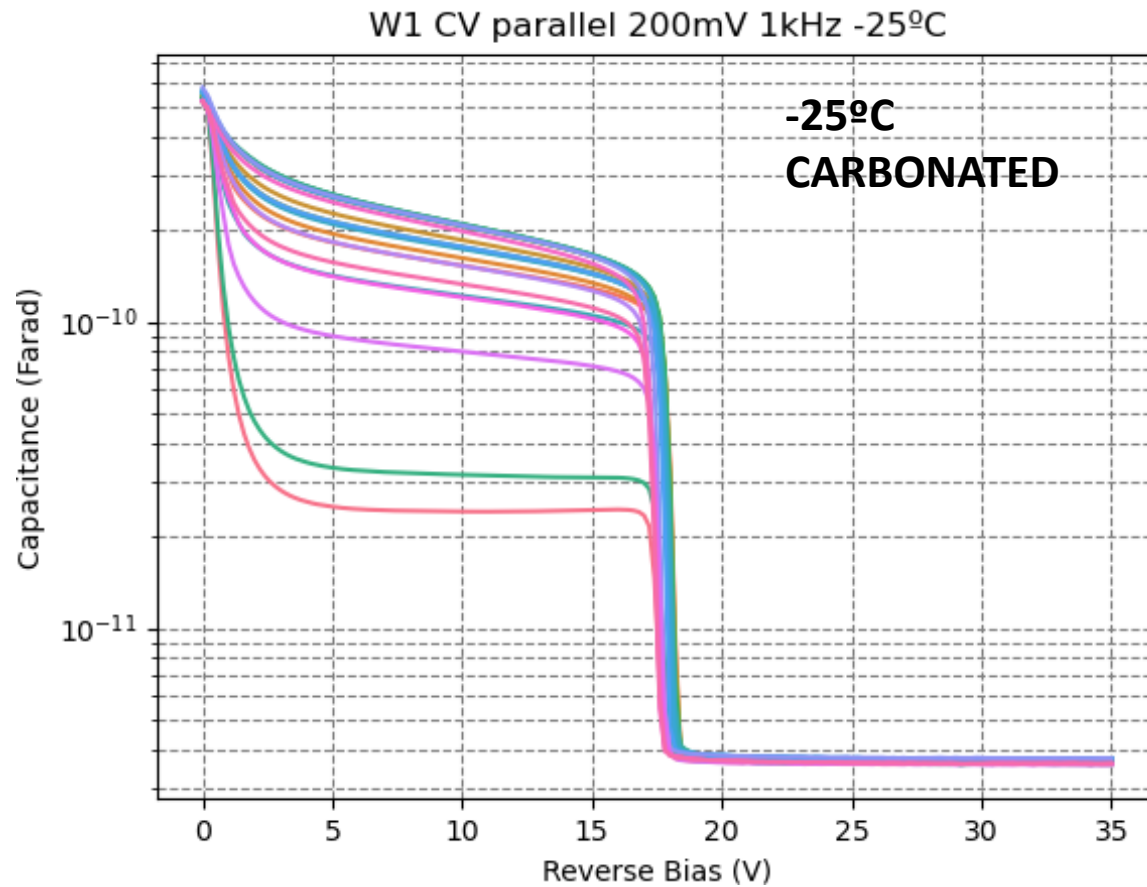


SRP measurement ongoing

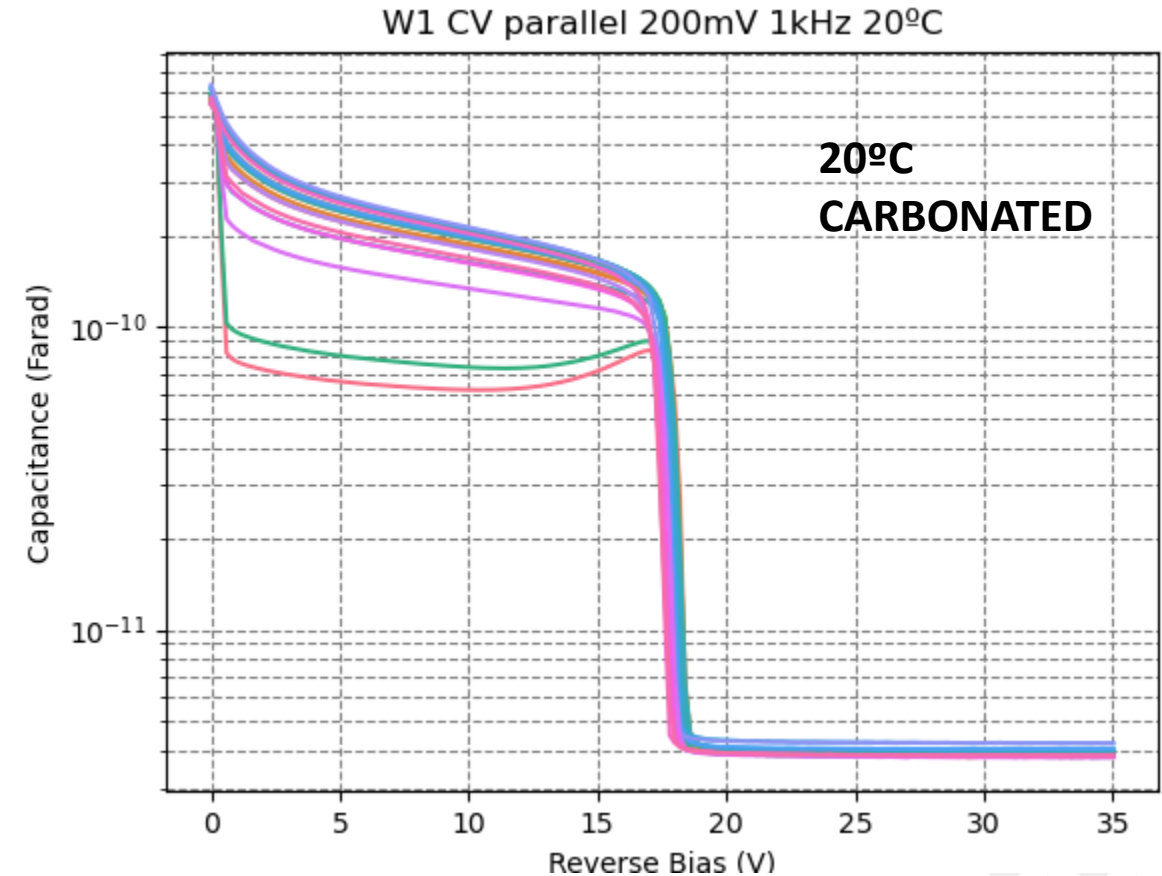
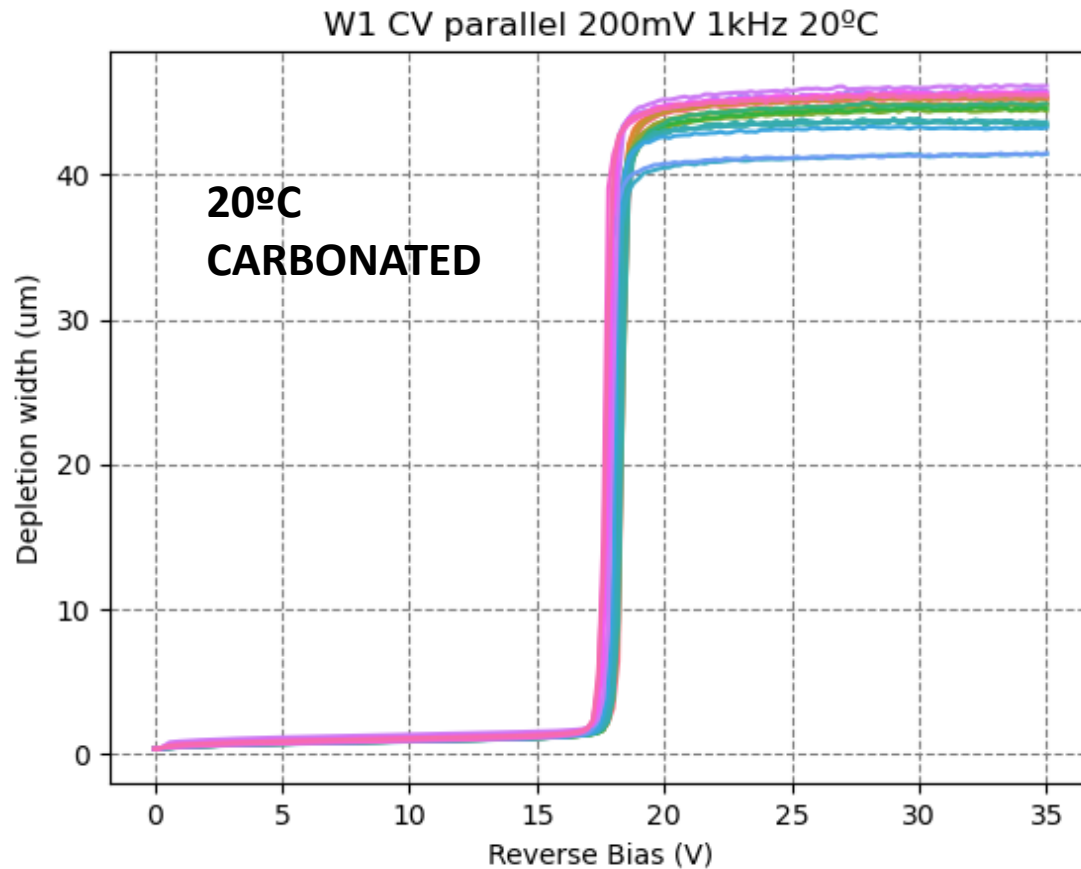
- Yield of W1 = 15% ($I < 200$ nA at 30V, for $T = -25^\circ\text{C}$)
- 22 sensors with $I < 200$ nA at 300 V, for $T = -25^\circ\text{C}$



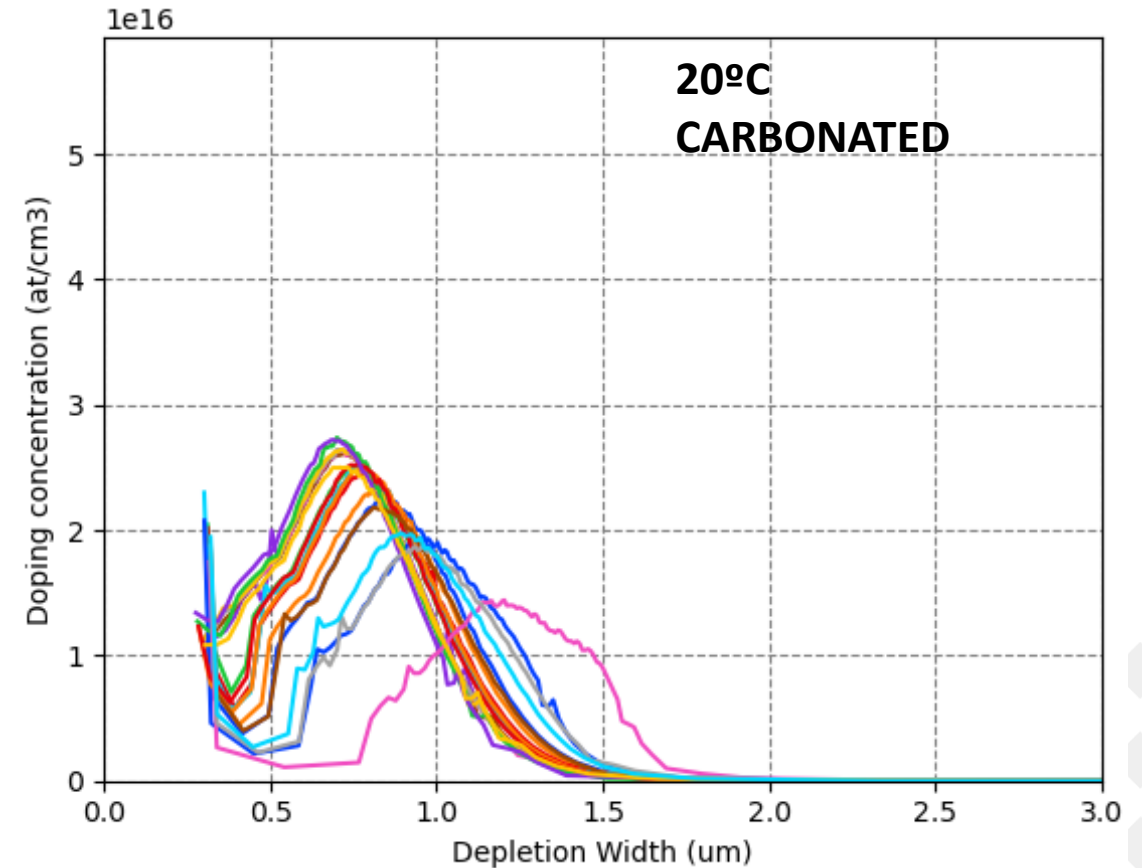
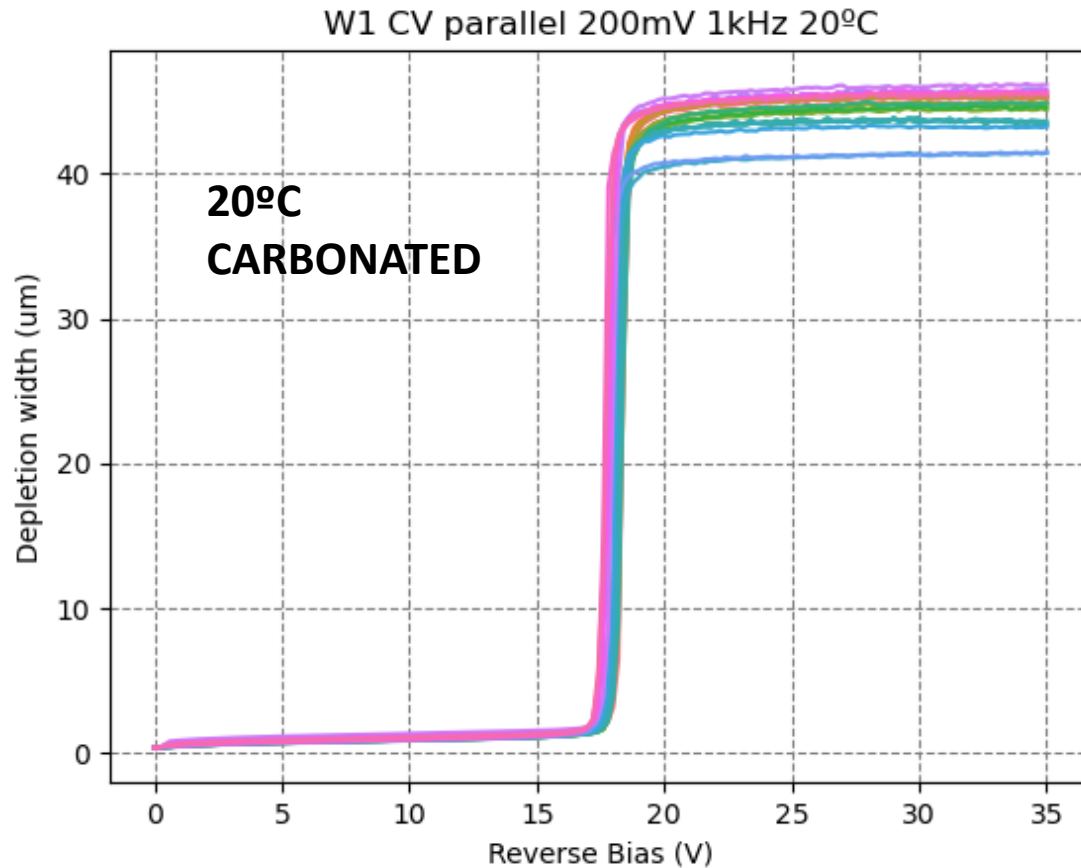
- 22 sensors with $I < 200$ nA at 300 V, for $T = -25^{\circ}\text{C}$ (Guard ring was not connected)



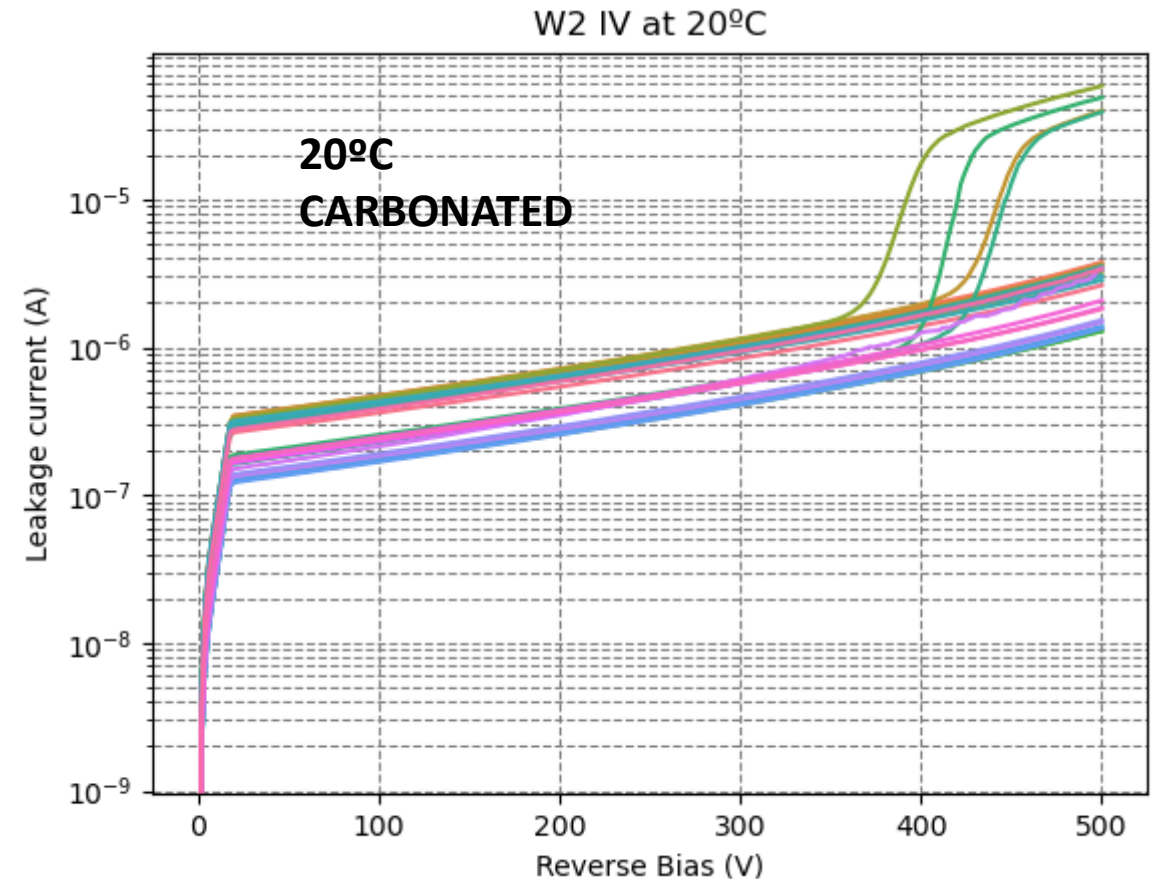
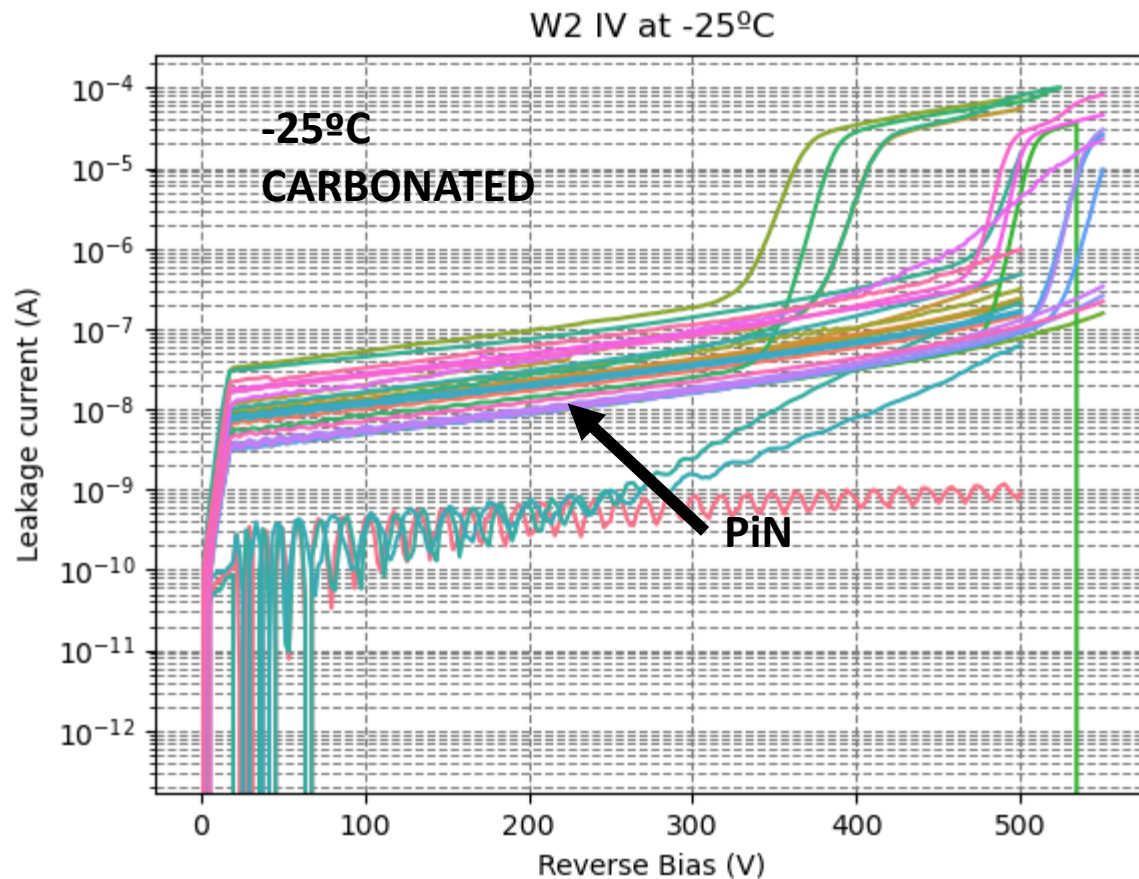
- 22 sensors with $I < 200$ nA at 300 V, for $T = -25^{\circ}\text{C}$



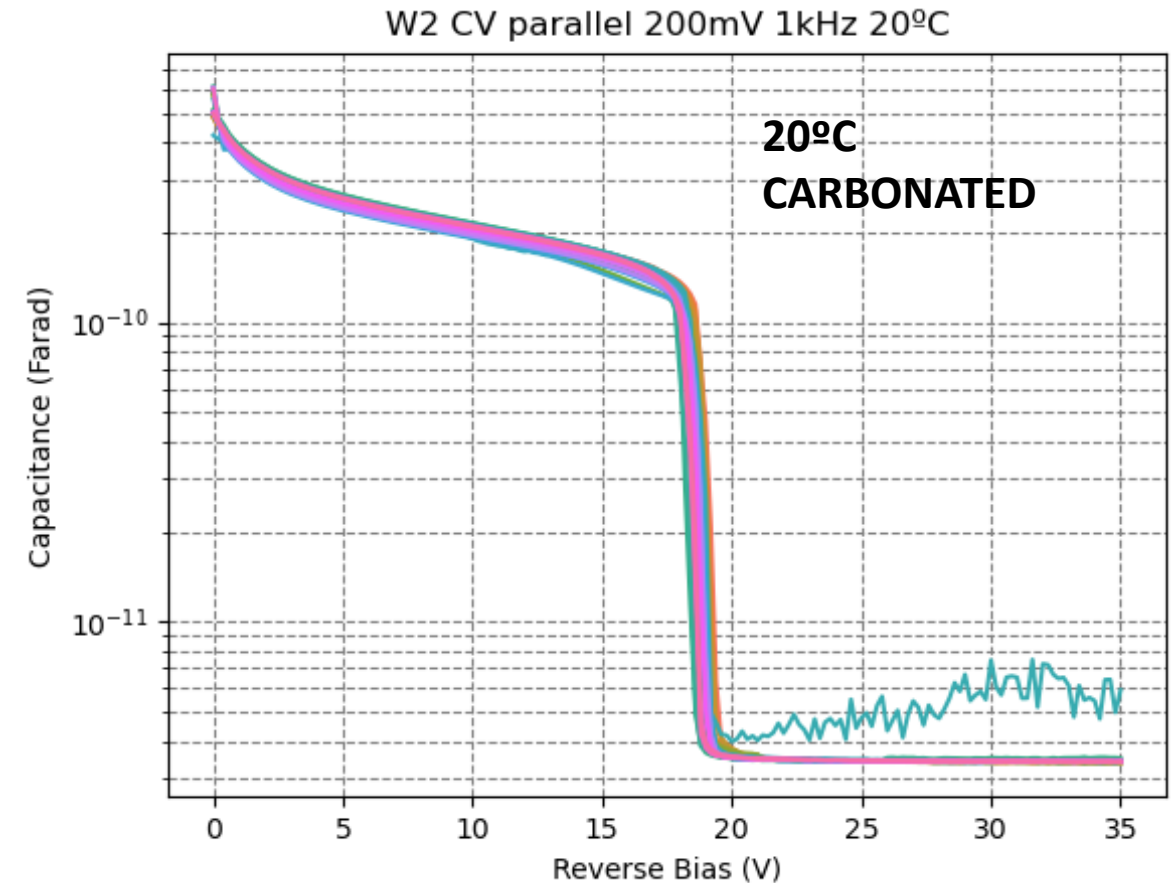
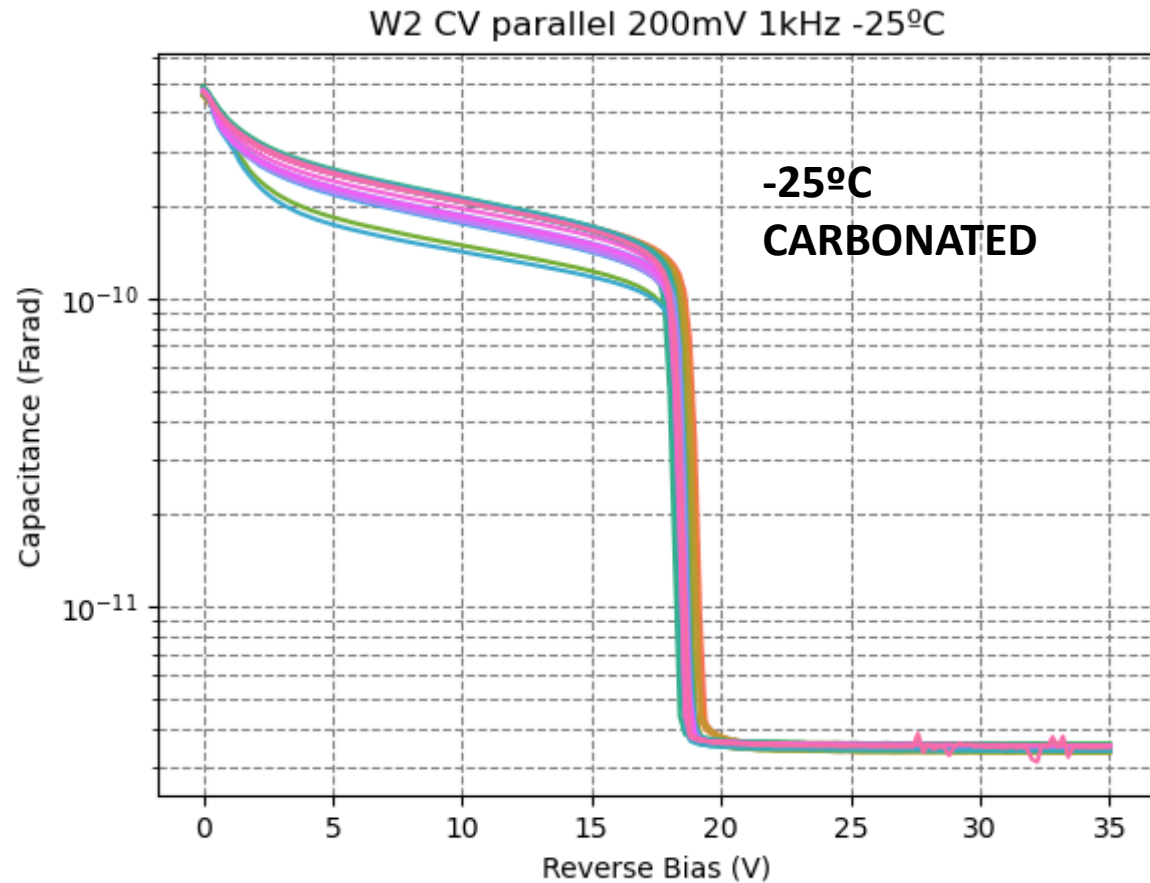
- 22 sensors with $I < 200$ nA at 300 V, for $T = -25^{\circ}\text{C}$



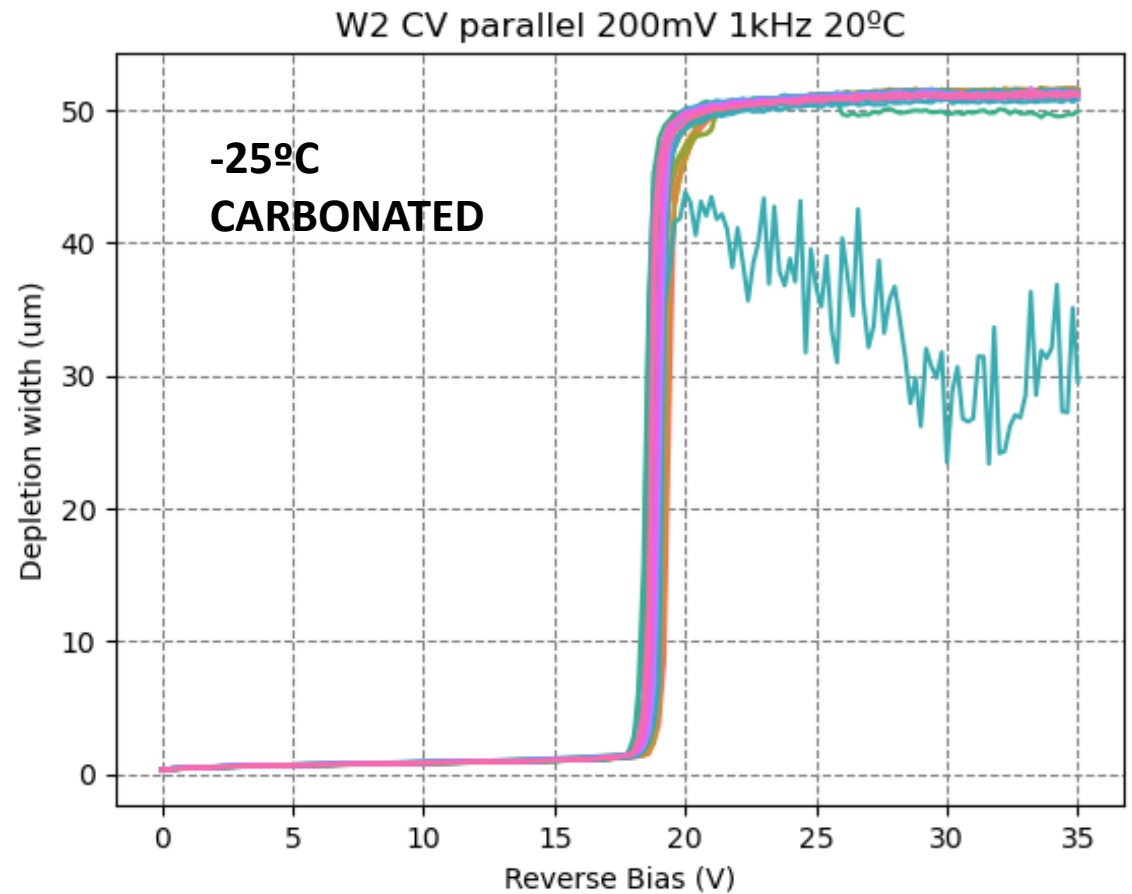
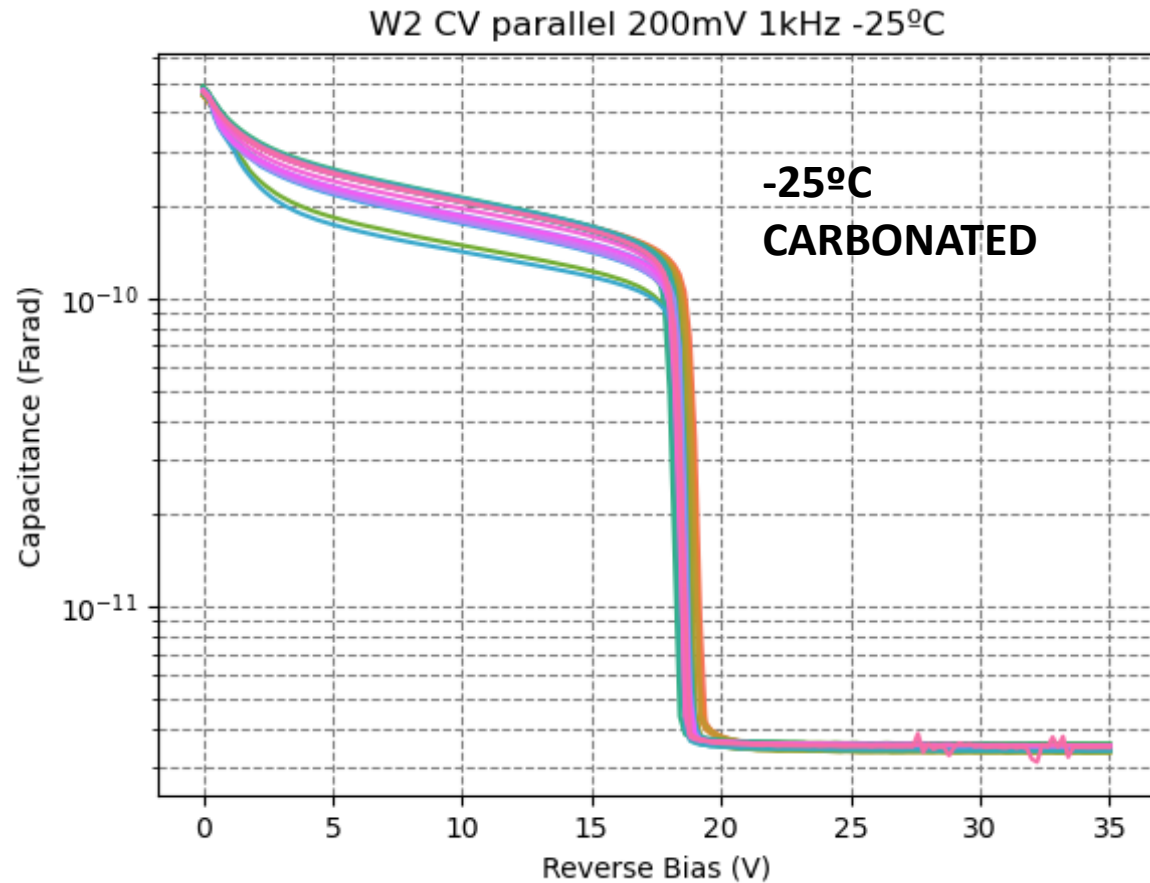
- Yield of W2 = 15% ($I < 200$ nA at 30V, for $T = -25^{\circ}\text{C}$)
- 26 sensors with $I < 200$ nA at 300 V, for $T = -25^{\circ}\text{C}$



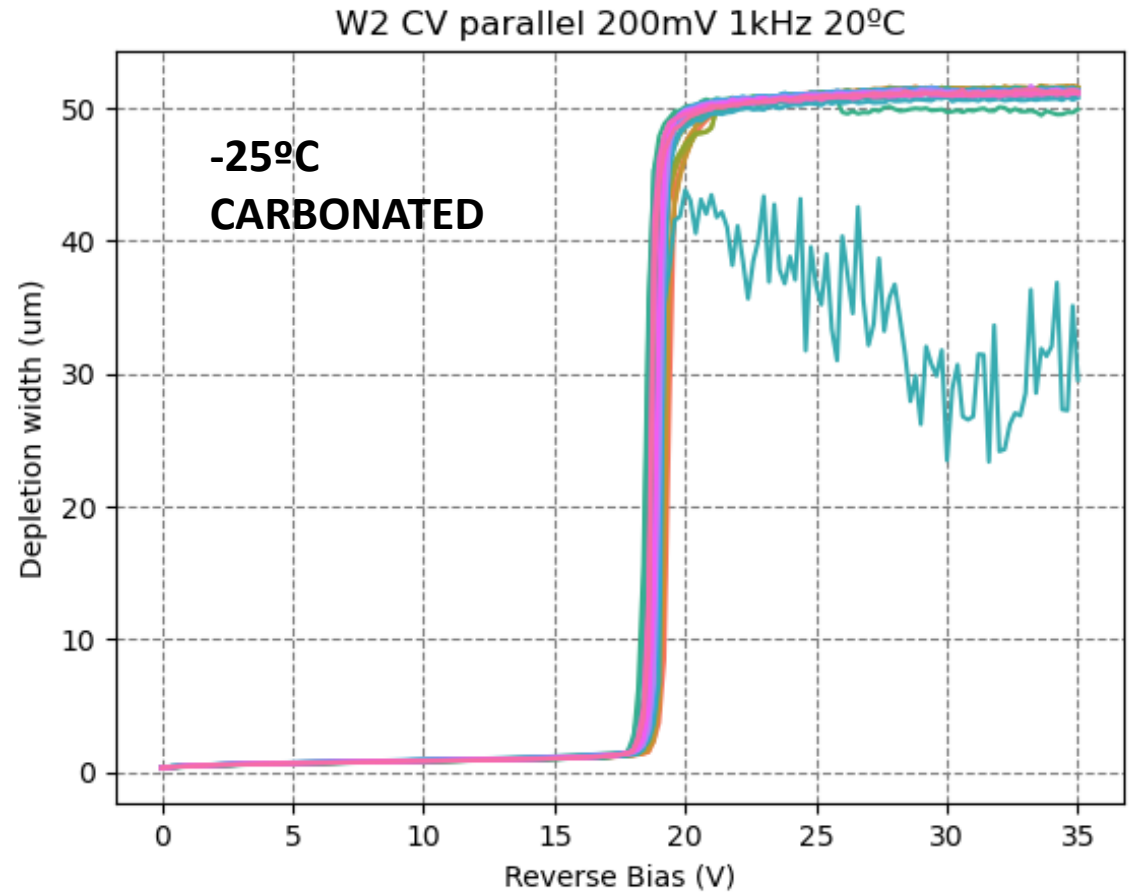
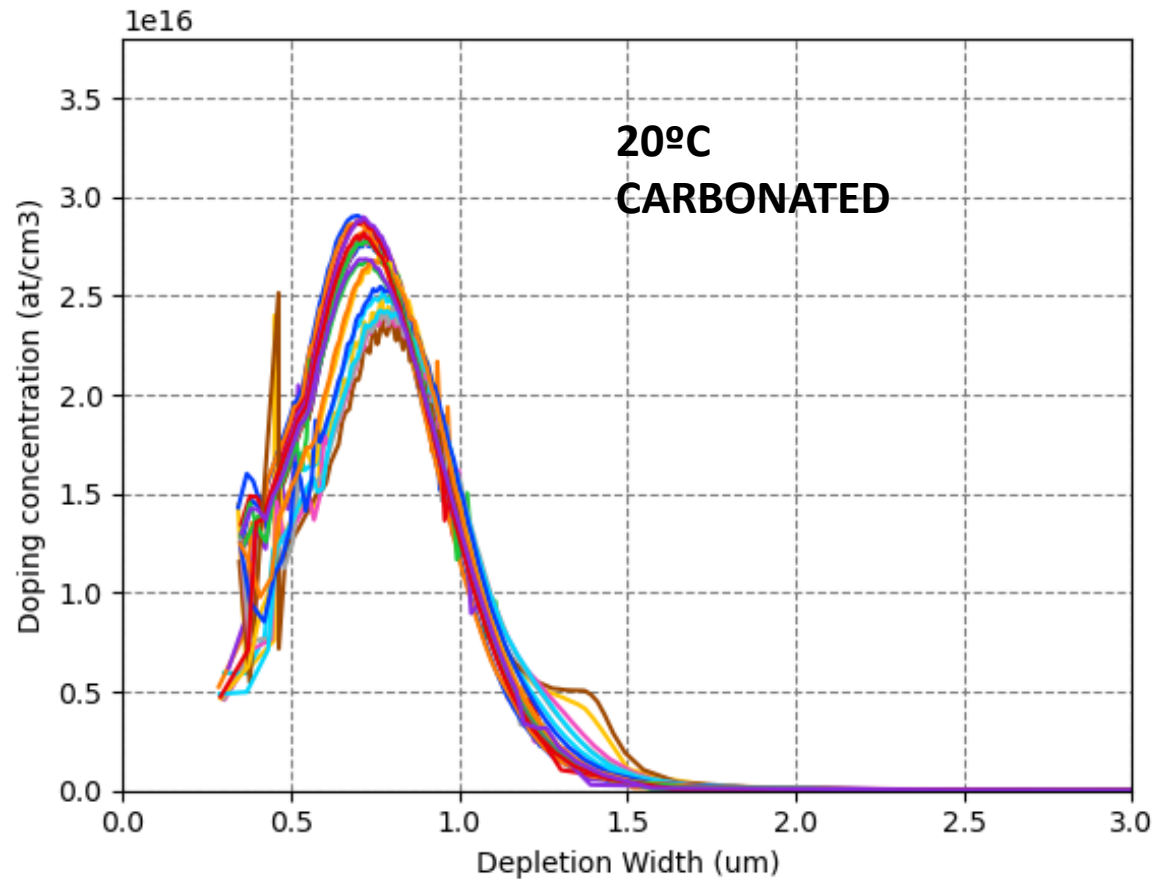
- 26 sensors with $I < 200$ nA at 300 V, for $T = -25^{\circ}\text{C}$



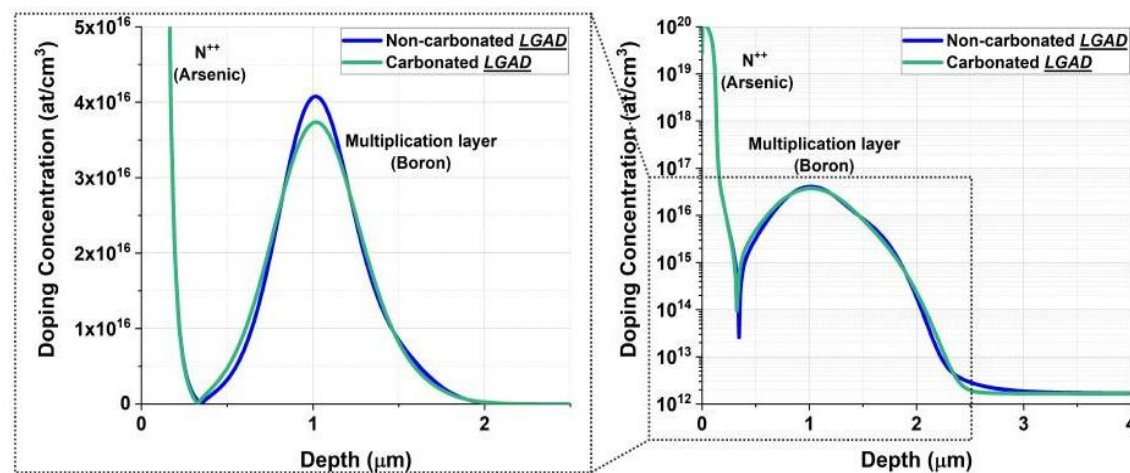
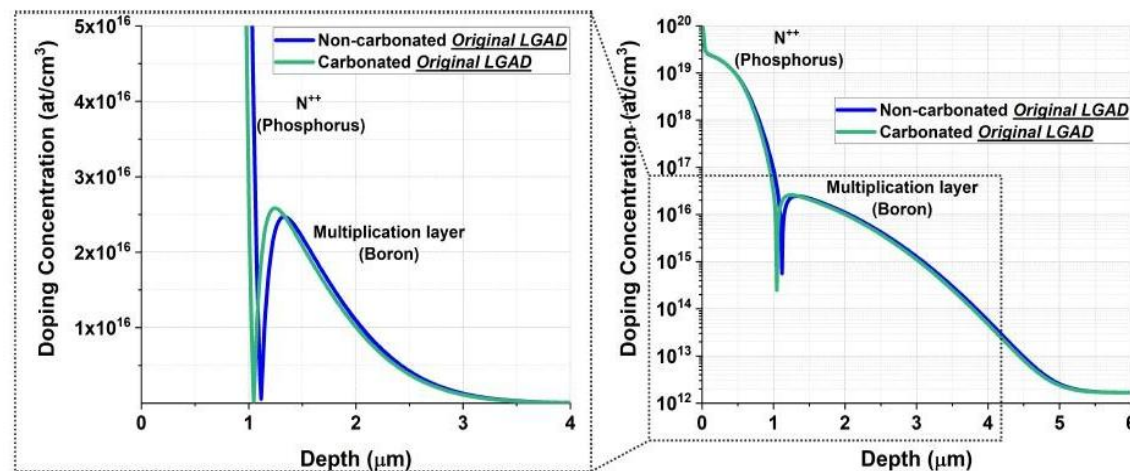
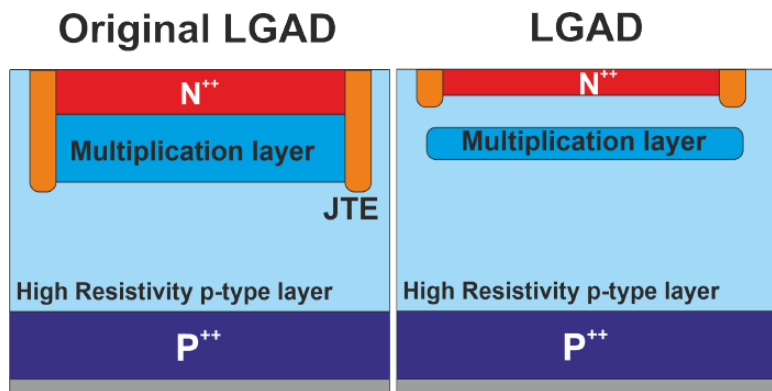
- 26 sensors with $I < 200$ nA at 300 V, for $T = -25^{\circ}\text{C}$



- 26 sensors with $I < 200$ nA at 300 V, for $T = -25^{\circ}\text{C}$



CMS 6DLG3v1. Effects of carbon co-implantation



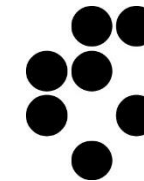
Shallow Gain Layer with carbon co-doping	Deep Gain Layer with carbon co-doping
Slower diffusion of Boron	Faster diffusion of Boron
Carbon atoms blocking excess interstitial paths	Higher lattice damage from the high-energy implantation
Higher doping peak than devices without carbon co-doping	Lower doping peak than devices without carbon co-doping

Previous paper:

The effects in fabrication and performance of carbon doping on IMB-CNM manufactured LGADs
J. Villegas et al [10.1016/j.nima.2024.169424](https://doi.org/10.1016/j.nima.2024.169424)

CMS 6DLG3v1. R17958. Gain Measurements

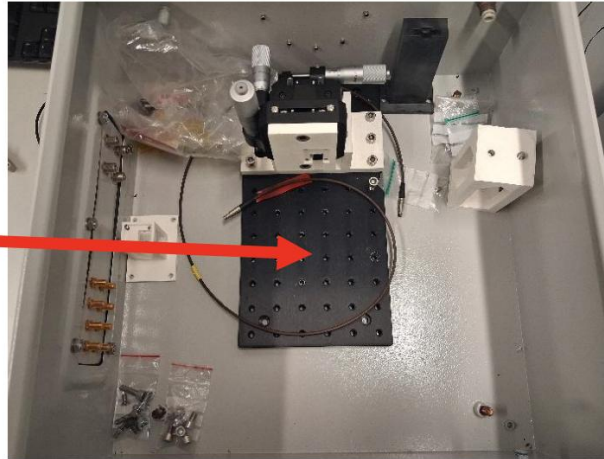
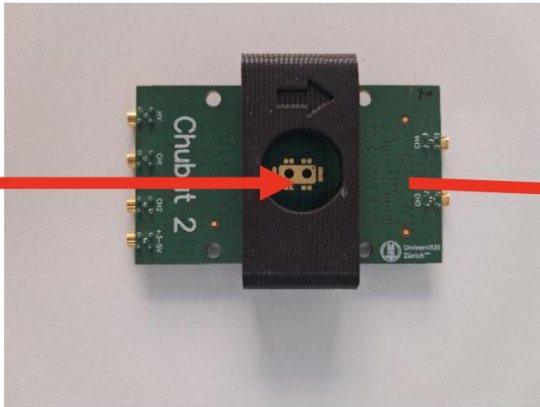
- **Sr-90** at CNM
 - **Electrons of 546 keV**
 - First approximation made with source placed on top of the sensor
 - Ongoing measurements with source and detector in coincidence
- **Cd-109** at CNM
 - **X-rays of 22.1 keV**
 - Source placed on top of the sensor
- **IBIC** at CNA
 - **2.3 MeV Microbeam Protons**
- **Tri-Alpha** source at CNA
 - **Alphas of 5.15, 5.48, 5.79 MeV** (239-Pu, 241-Am, 244-Cu)
- **Neutron Irradiation** at JSI TRIGA Reactor



Jožef Stefan Institute
Ljubljana, Slovenia

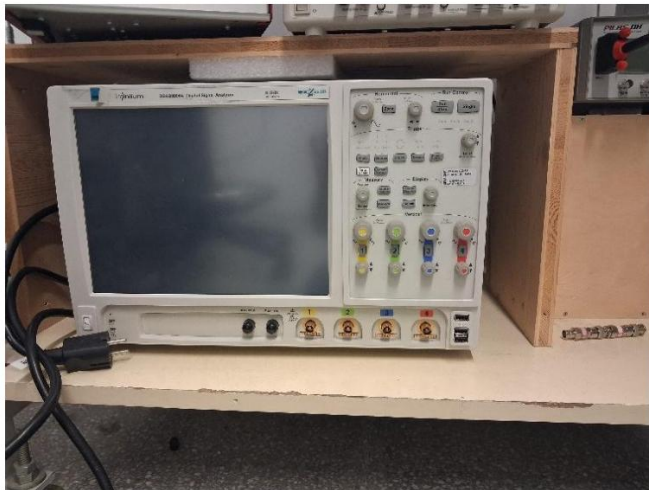


Gain Measurements. Sr90-Cd109 Set up



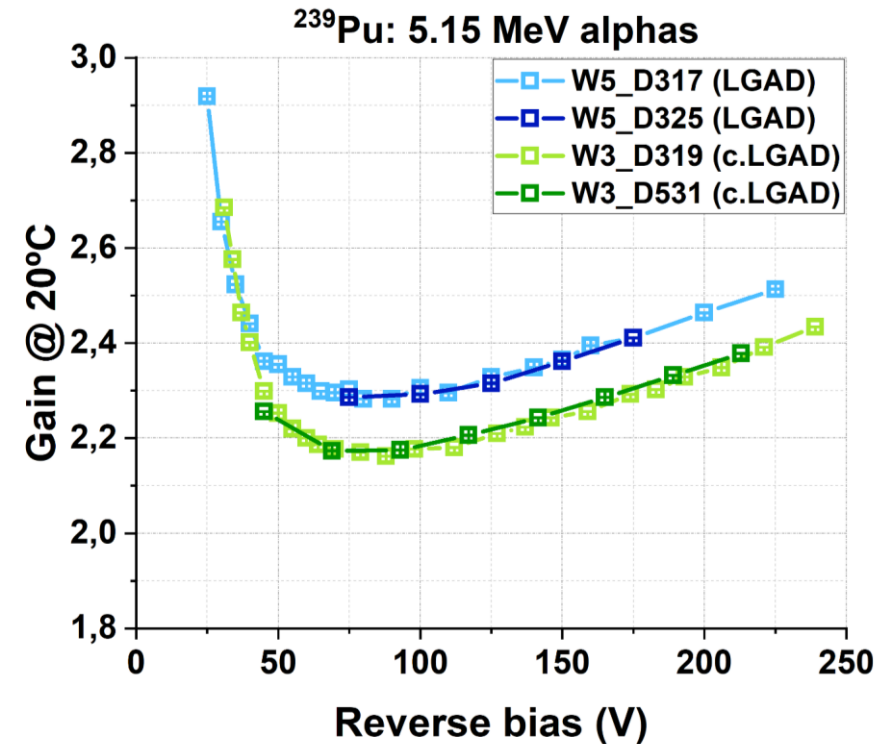
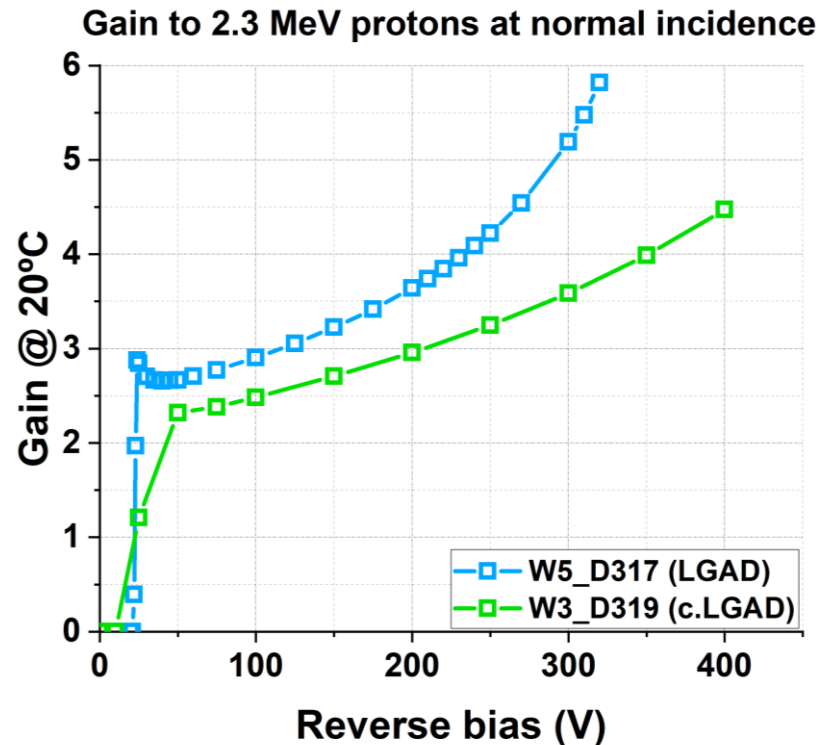
Sr-90/Cd-109 placed on top of the Chubut board inside the box

Waveforms Acquisition with **Agilent Infiniium**



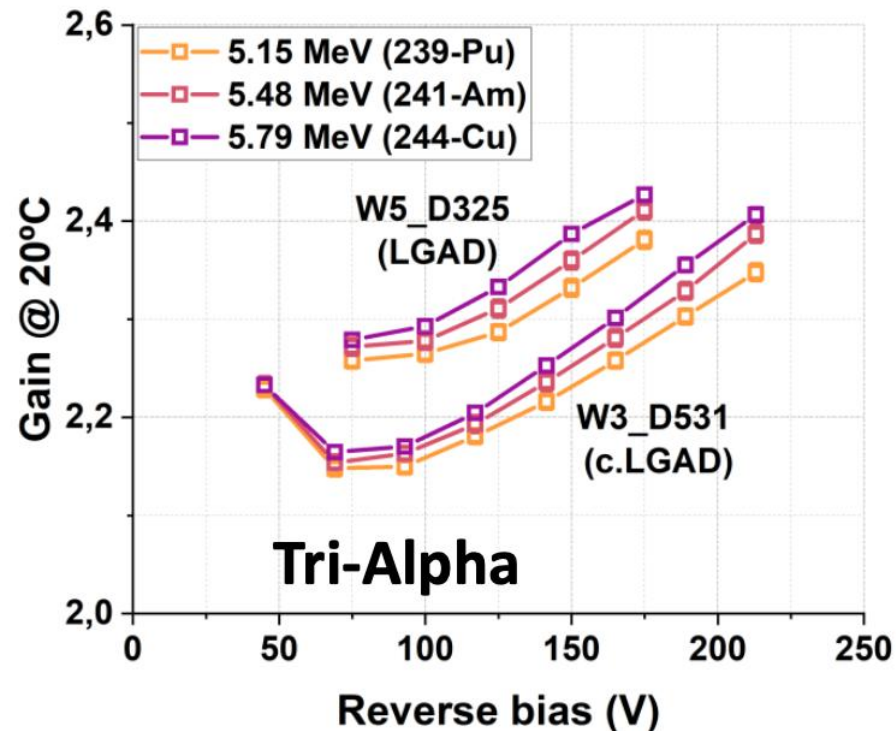
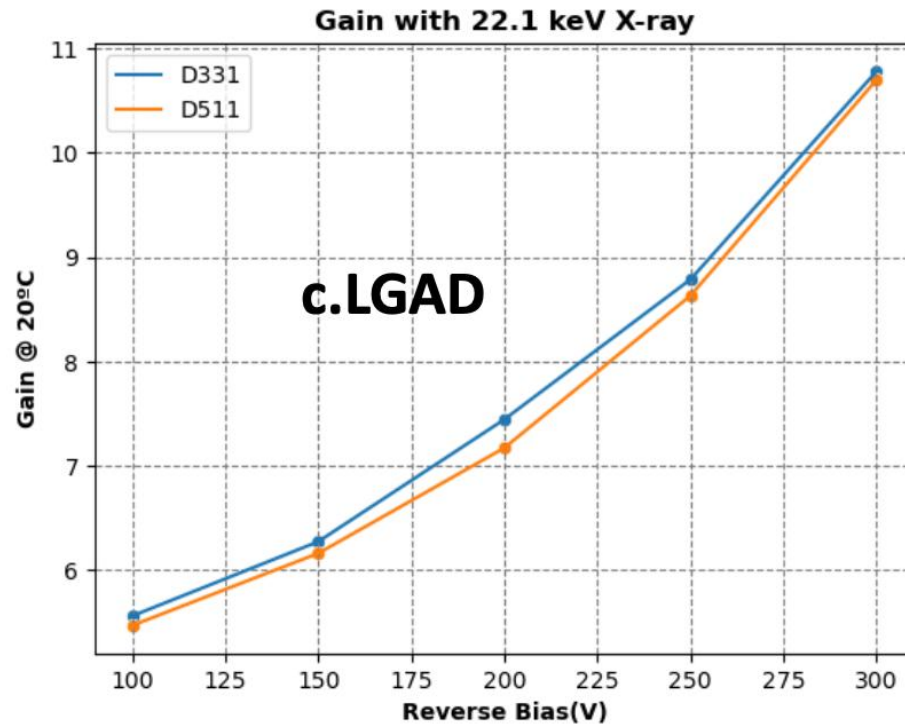
Reverse Bias applied on the **backside** of the sensor with a **Keithley 2410**

6DLG3v1. R17958. Gain measurements with Tri-alphas



- CNM Run17958 (“Deep” LGADs with arsenic implanted N^{++}) → **Single pad diodes**
- Gain measurements at the microprobe beam line (protons of 2.3 MeV) and with a Tri-Alpha source show that **carbonated “Deep” LGADs have a lower gain** when fabricated under the same conditions
- This effect is attributed to the distribution of carbon interstitials during boron diffusion during fabrication
- **Fabrication Insight and gain measurements with Tri-Alpha source are published in Sensors Journal:**
<https://doi.org/10.3390/s25175571>

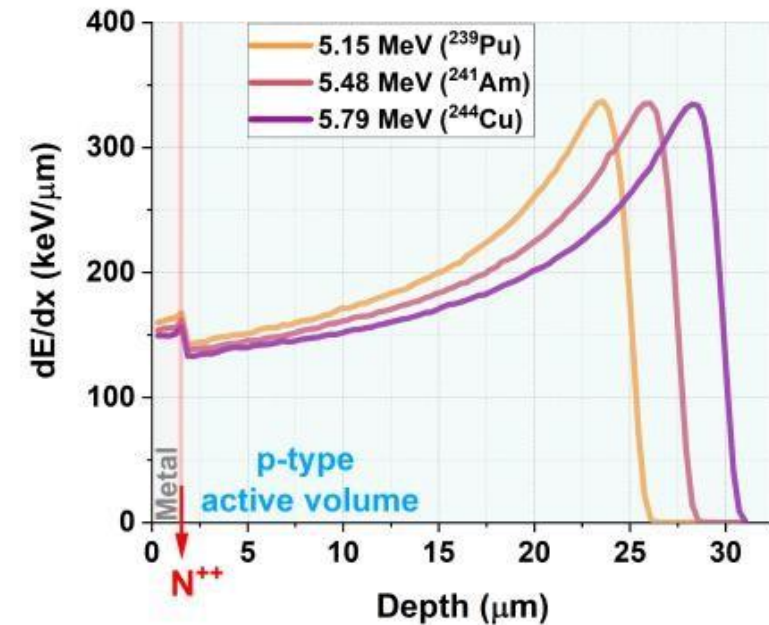
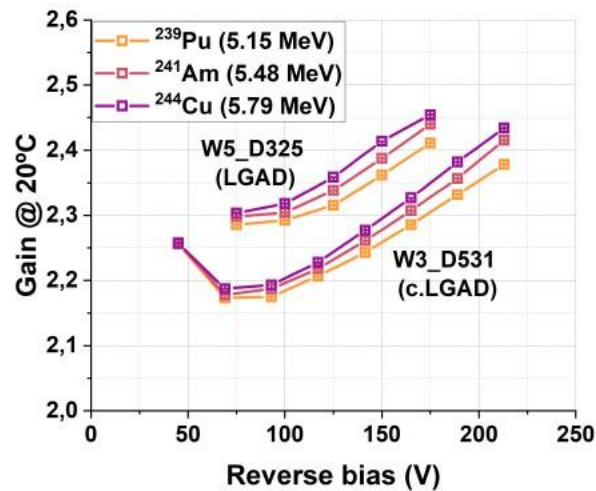
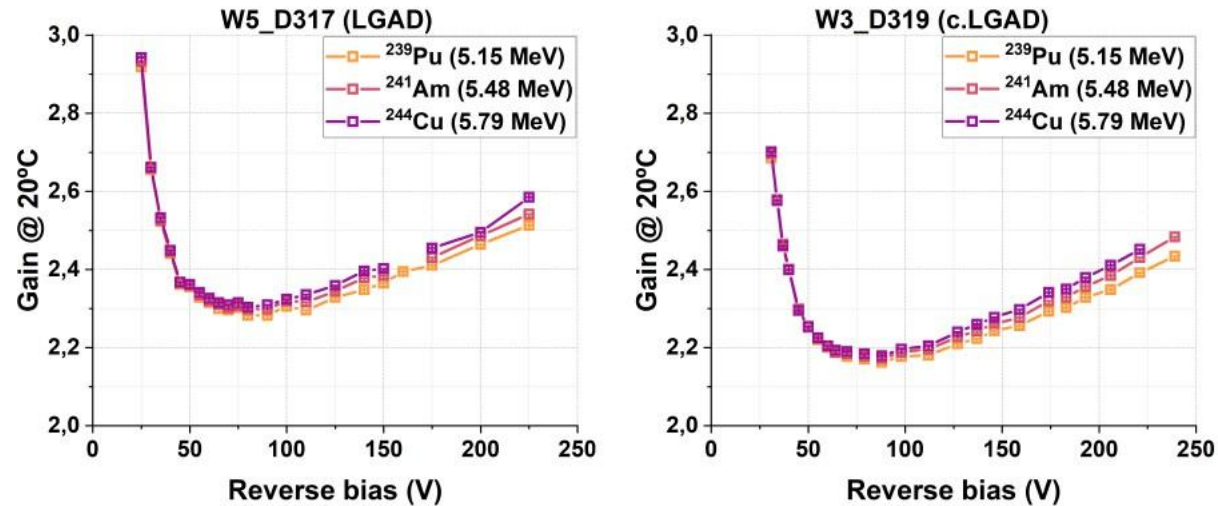
6DLG3v1. R17958. Gain measurements with Tri-alphas



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6DLG3v1. R17958. Gain measurements with tri-alphas

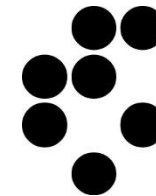
- Higher gain for devices without carbon co-doping
- Higher gain suppression the closer the Bragg Peak is to the PN Junction



- Fluences of neutron Irradiation:

- 3 sensors at $8e14 \text{ n}_{eq}/\text{cm}^2$
- 3 sensors at $1.5e15 \text{ n}_{eq}/\text{cm}^2$
- 3 sensors at $2.5e15 \text{ n}_{eq}/\text{cm}^2$

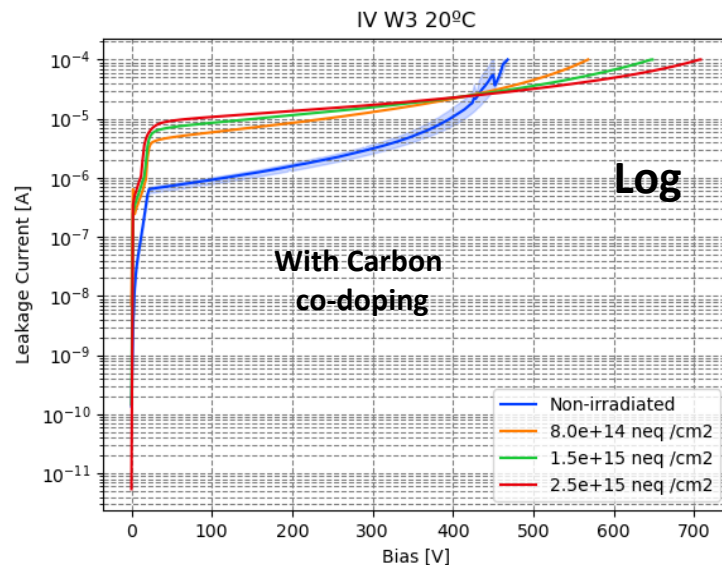
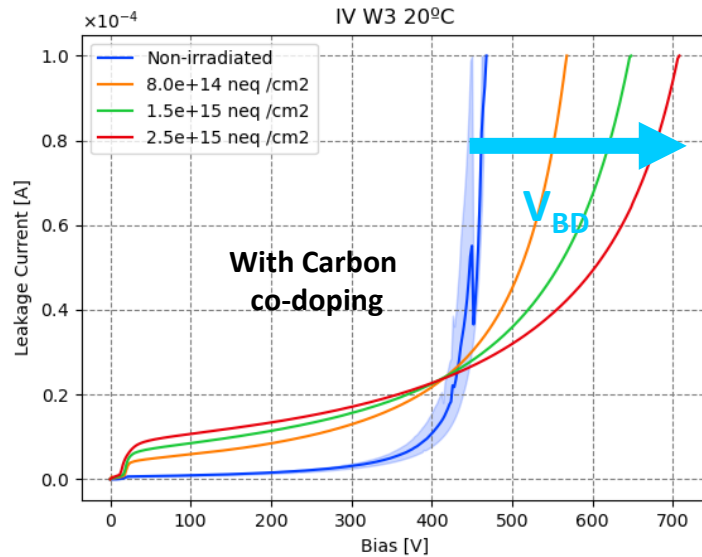
- Annealing of 60 °C and 80 minutes after irradiation



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Ljubljana, Slovenia



6DLG3v1. R17958. I-V. After Irradiation



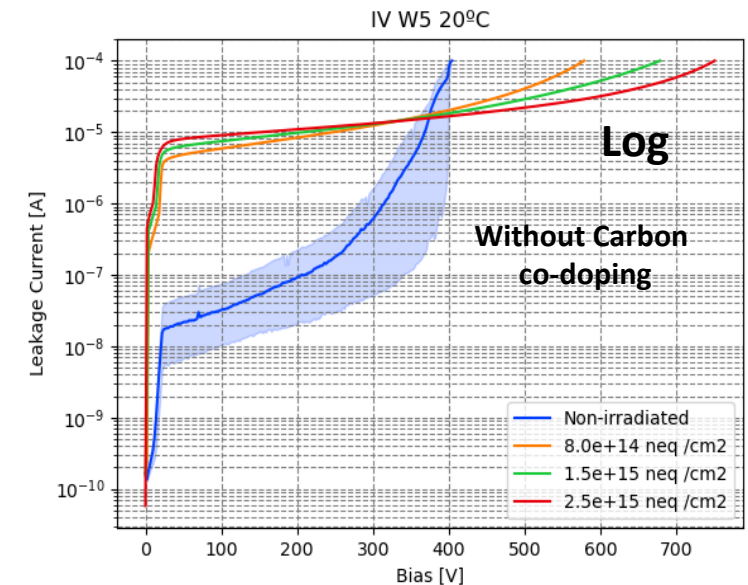
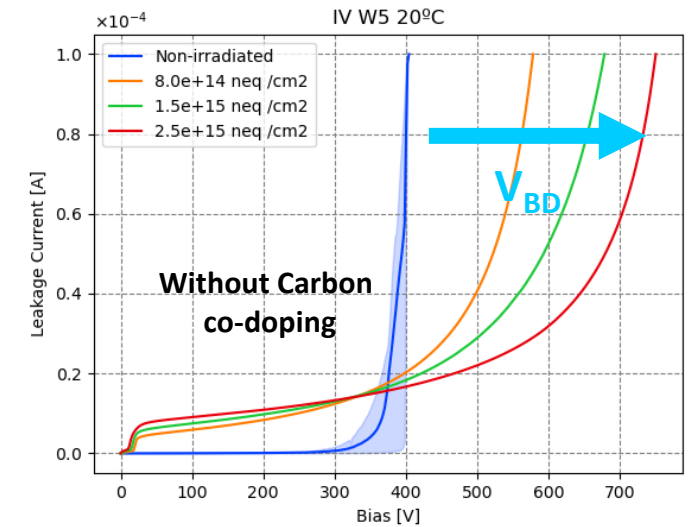
IV parameters: 0-500V, step of 2V

- Saturation of the leakage current observed
- Increase of breakdown voltage
- Same behaviour for devices with or without carbon co-doping

Results at 20 °C in concordance with the ones reported in literature:

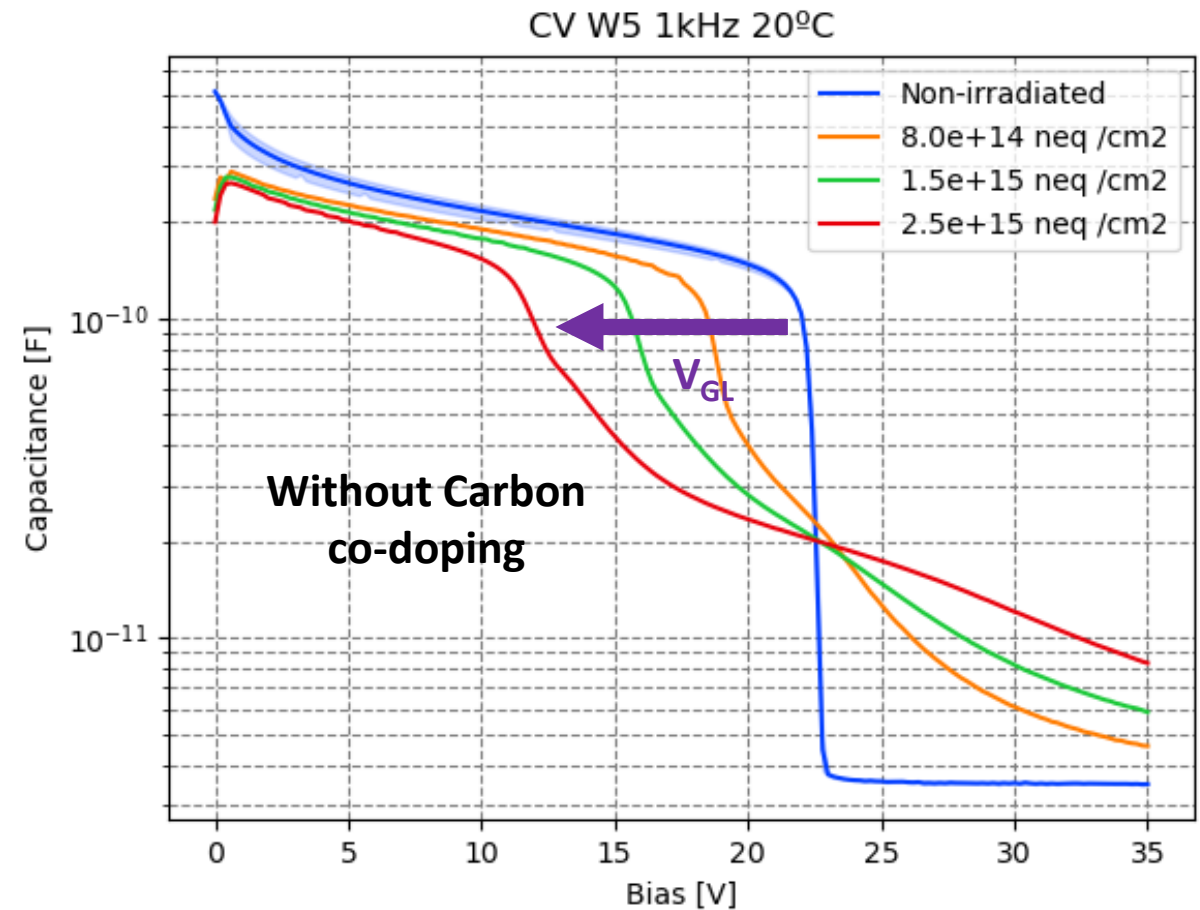
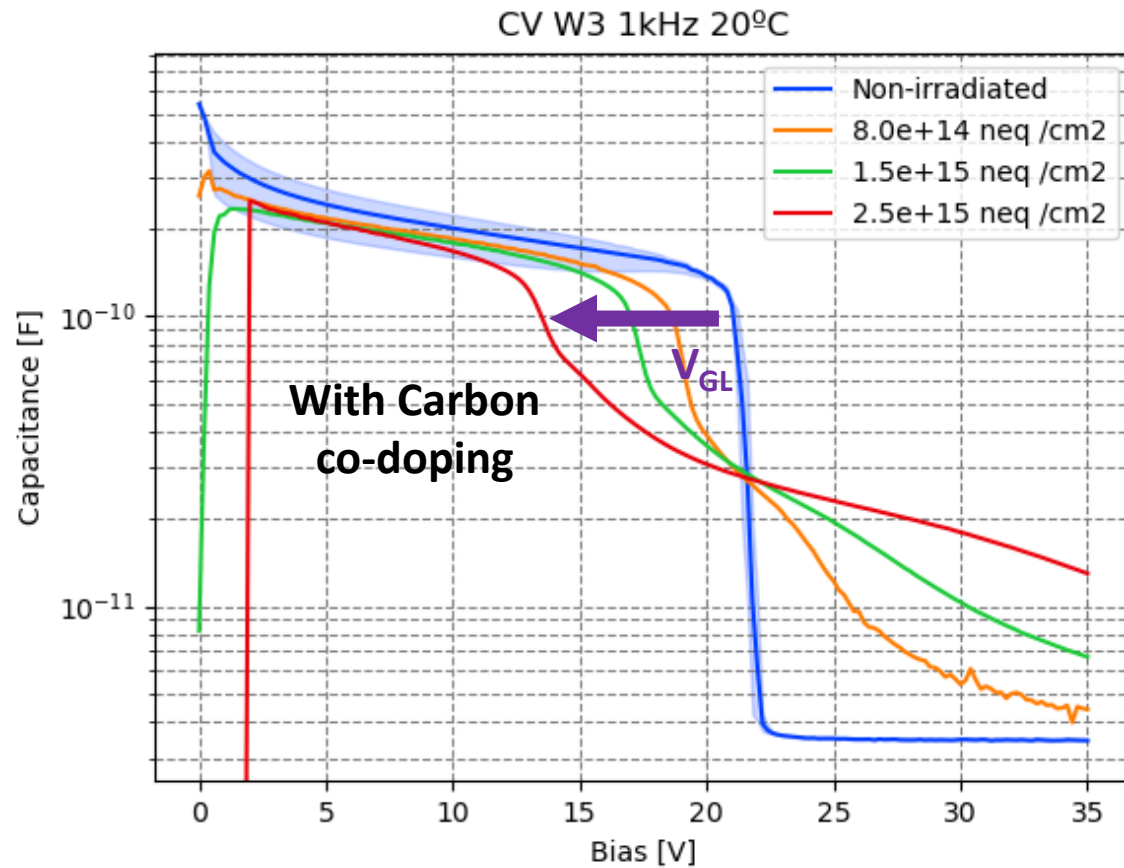
J. Sorenson et al

[10.1088/1748-0221/19/05/P05012](https://doi.org/10.1088/1748-0221/19/05/P05012)



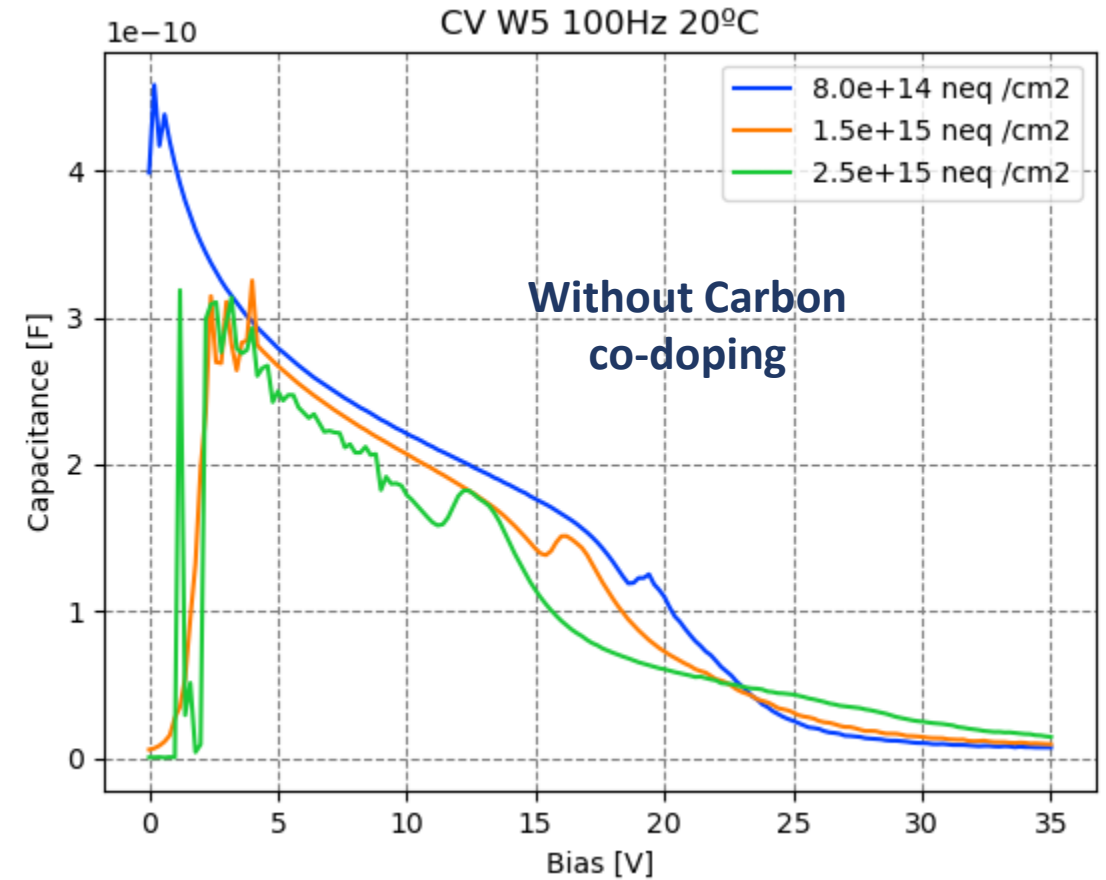
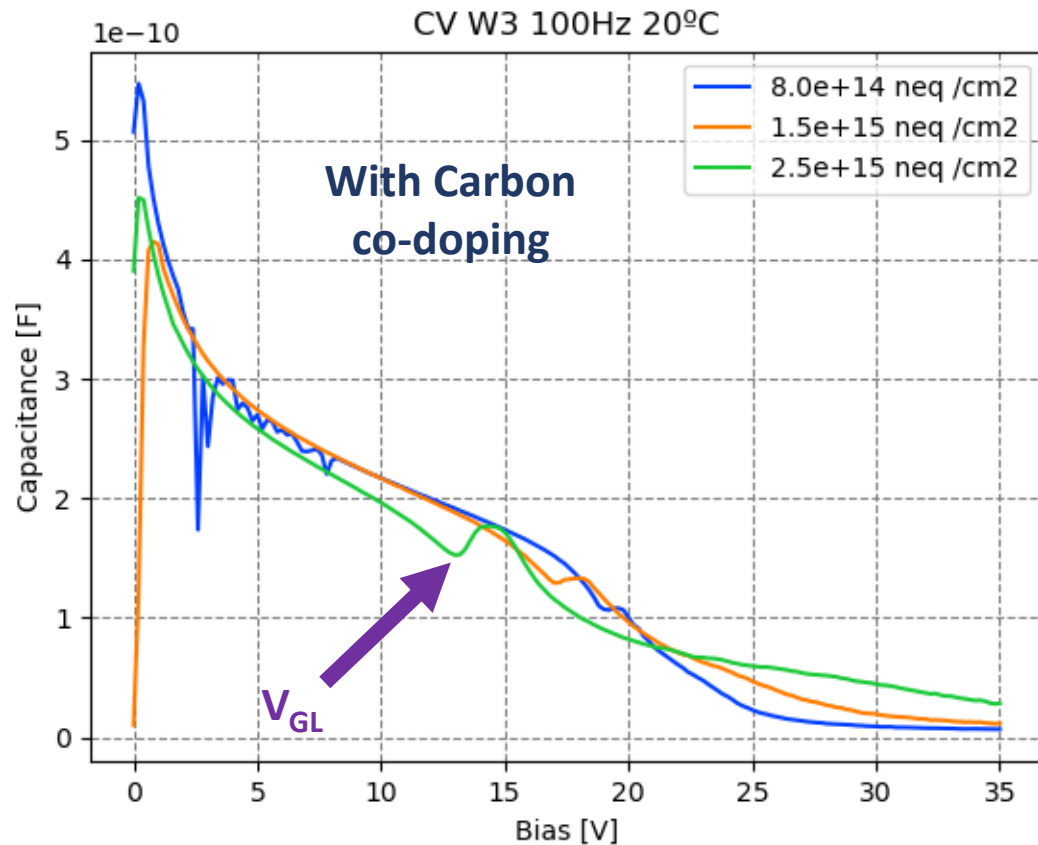
6DLG3v1. R17958. C-V. 1kHz. After Irradiation

CV parameters: 0-35V, step of 0.2V, frequency 1kHz, amplitude 200 mV



6DLG3v1. R17958. C-V. 100kHz. After Irradiation

CV parameters: 0-35V, step of 0.2V, frequency 1kHz, amplitude 200 mV



VGL determined as the voltage before the rise of capacitance, effect of the presence of the gain layer

M.Wiehe et al <https://doi.org/10.1016/j.nima.2020.164814>

6DLG3v1. R17958. Acceptor Removal Constant

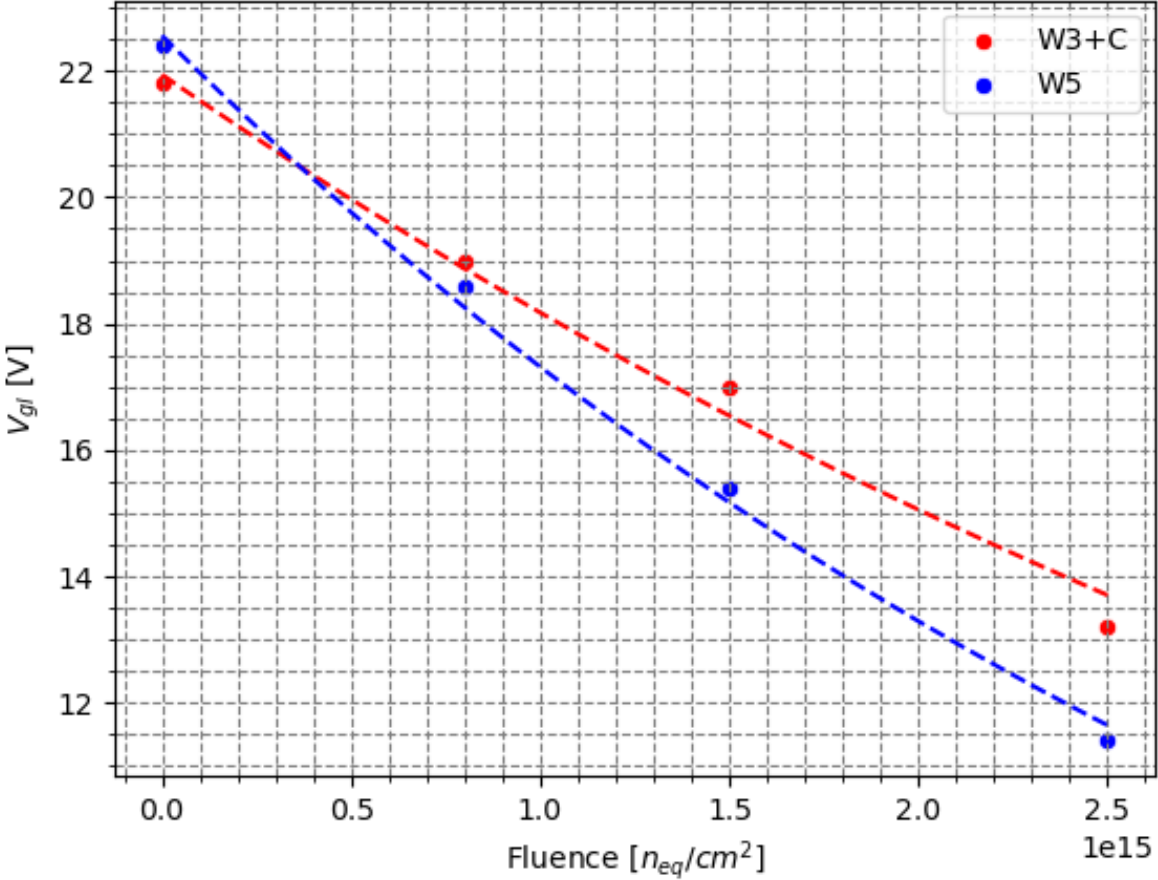
- To add uncertainties of the fluence to the calculation

Fit with $V_{gl}(\phi) = V_{gl,0} \cdot e^{-c\phi}$ to extract the acceptor removal constant c .

Wafer	$c [10^{-16}cm^2]$
W3+C	1.9
W5	2.6

Wafer	Fluence	V_{GL}
W3+C	$8e^{14}$	19
W5	$8e^{14}$	18.6
W3+C	$1.5e^{15}$	17
W5	$1.5e^{15}$	15.4
W3+C	$2.5e^{15}$	13.2
W5	$2.5e^{15}$	11.4

The fits are represented by the dashed lines



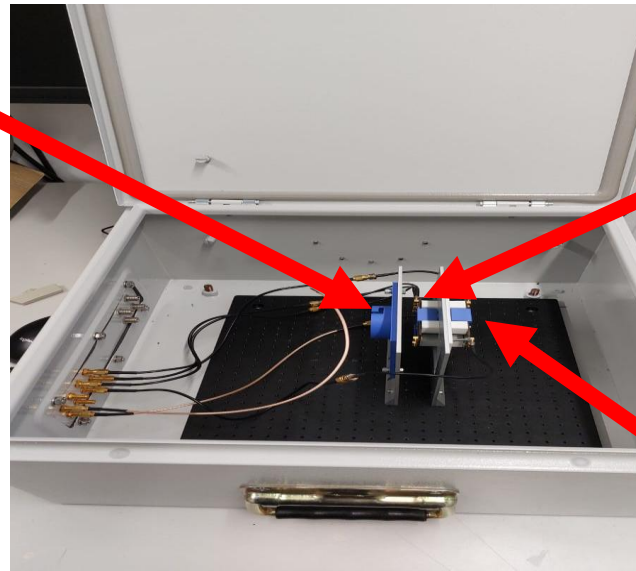
- Improvement of the radiation hardness with the carbon
- Better radiation hardness with Deep GL than IMB-CNM LGAD with shallow GL (7.9 std, 3.5 with C), E.Navarrete Ramos et al [10.1016/j.nima.2026.171305](https://doi.org/10.1016/j.nima.2026.171305)
- Similar results to other foundries, R. Padilla et al [10.1088/1748-0221/15/10/P10003](https://doi.org/10.1088/1748-0221/15/10/P10003)



6DLG3v1. R17958. Time Resolution. Sr90

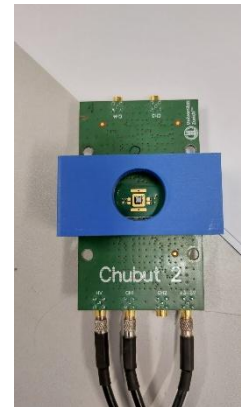
- 2000 events acquired per voltage point
- Threshold for triggers: 10 mV
- Event triggered when double coincidence
- $T = -15\text{ }^{\circ}\text{C}$
- Sample rate of 40 Gsa/s, time discretization of 25 ps
- LGAD Reference from CNM R18399, time resolution @200V = 54 ps
- CFD = 50 %

Sr90

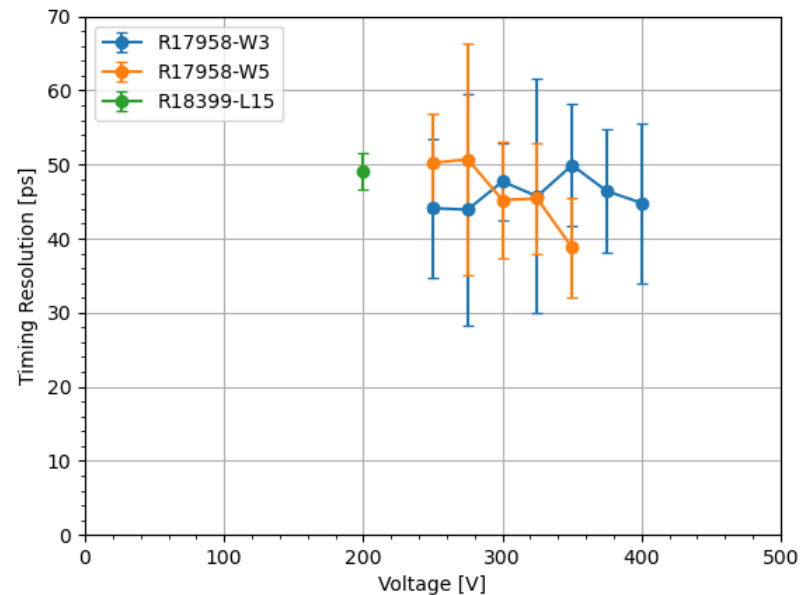
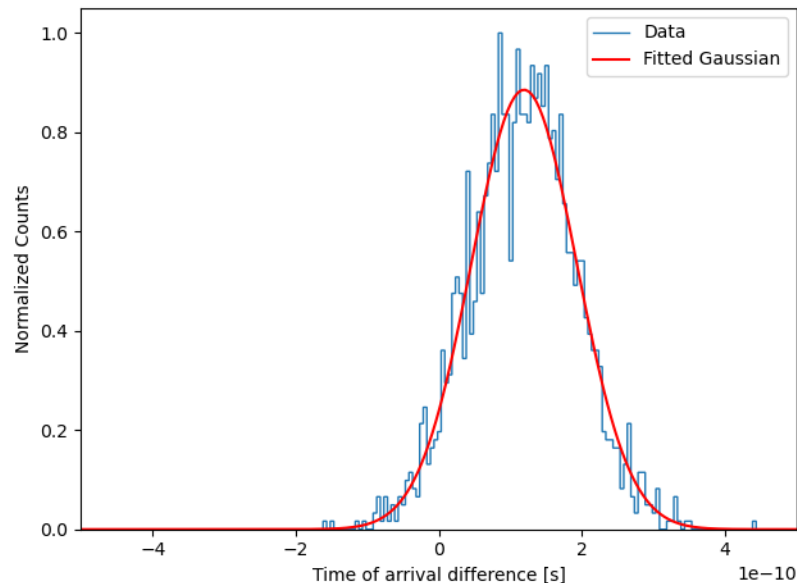


DUT

Reference
Sensor for
Trigger

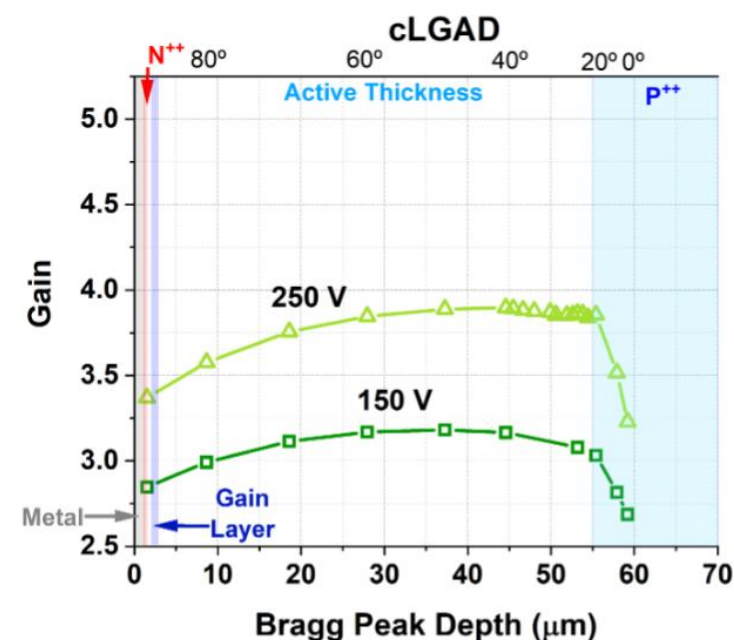
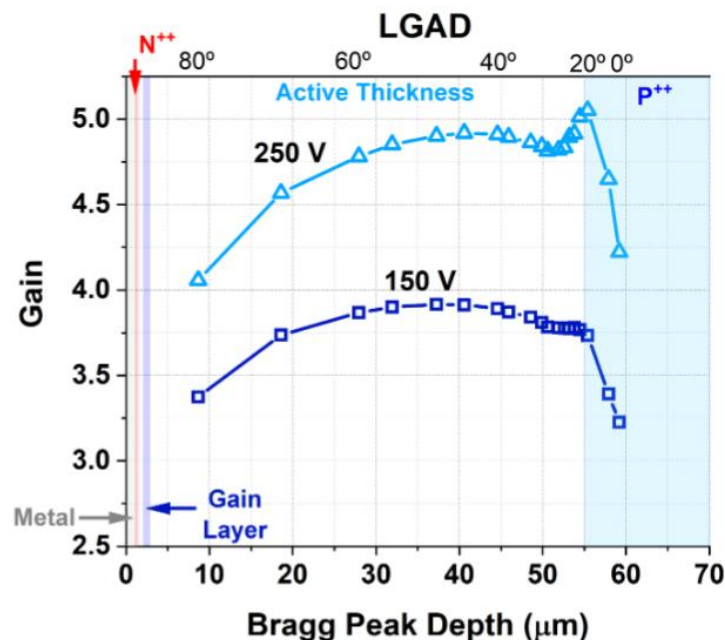
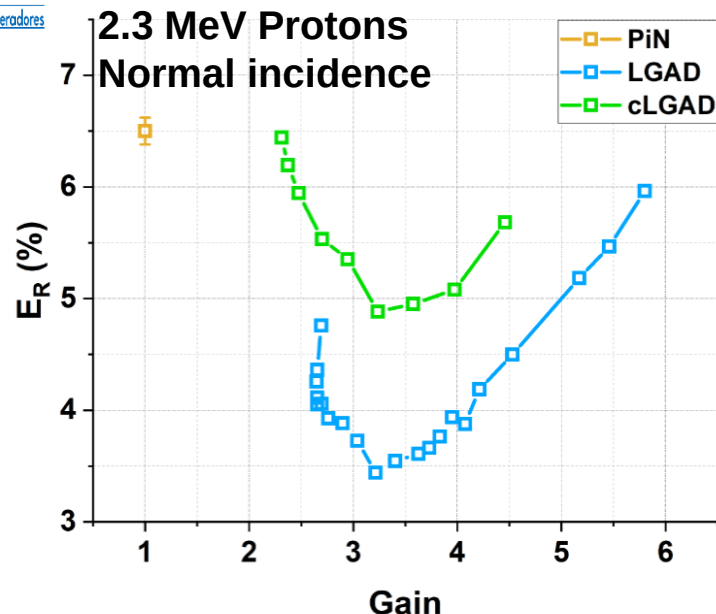


Chubut2 boards used
Transimpedance measured link below= **5050 Ω**
https://sengerm.github.io/Chubut_2/doc/testing/index.html#Transimpedance



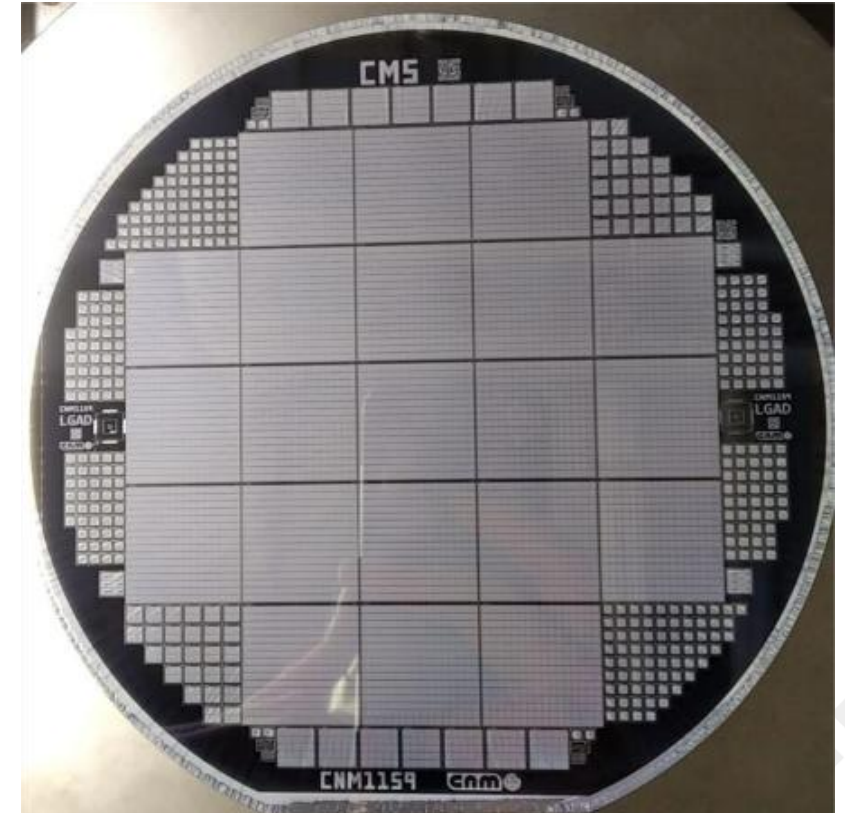
- High uncertainty on the measurement
- Time Resolution is a **bit better for sensors without carbon co-implantation**
- @350V W5 Time Resolution = **38.8 ps**

6DLG3v1. R17958. Proton Irradiation



- For 2.3 MeV protons, **gain suppression** in both “Deep” LGAD and cLGADs is **not drastic** when varying the incidence angle (higher ionization density closer to PN junction as angle increases)
- Also, the **energy resolution** at normal incidence is **better** for both “Deep” LGAD and cLGAD than for a standard **PiN detector**
- These results are about to be published in IEEE Sensors Journal: J. Villegas et al. Impact of Gain Suppression in LGADs on Energy Resolution for Charged Ion Spectrometry. IEEE Sensors Journal (2026), *Accepted for Publication in July 2026*
- Results were also presented at 4th DRD3 Workshop: <https://indico.cern.ch/event/1581713/contributions/6759972/>

- **Better radiation hardness with Deep GL than with Shallow GL for IMB-CNM LGADs.**
- Next characterization steps
 - Timing resolution and gain from MIP for unirradiated and irradiated samples
 - Characterization of pixelated samples (2x2)
- Next LGAD runs
 - Stabilize the fabrication process for high energy implantation
 - Increase gain performance
 - Implant the gain layer at higher energy > 1 MeV



6DLG3v1. R17958. Sensors Available. W3

Sensor	Measurement	Quality	State
D531	IBIC/CNA	Best	Funcioning
D319	IBIC/CNA	Best	Funcioning
D508	JSI 8e14 Neutron	Best	Funcioning
D506	JSI 8e14 Neutron	Best	Funcioning
D513	JSI 8e14 Neutron	Best	Funcioning
D310	JSI 1,5e15 Neutron	Good	Funcioning
D330	JSI 1,5e15 Neutron	Good	Funcioning
D329	JSI 1,5e15 Neutron	Good	Funcioning
D534	JSI 2,5e15 Neutron	Acceptable	Funcioning
D524	JSI 2,5e15 Neutron	Good	Funcioning
D325	JSI 2,5e15 Neutron	Acceptable	Funcioning
D331	LabRad Sr-90 CNM	Best	Funcioning
D337	LabRad Sr-90 CNM	Best	Funcioning
D527	LabRad Sr-90 CNM	Best	Funcioning
D511	LabRad Sr-90 CNM	Best	Funcioning
D301P	LabRad Sr-90 CNM	Best	Funcioning
D510	DLTS Milos Roumanie	Best	Funcioning
D512	DLTS Milos Roumanie	Best	Funcioning

Sensor	Measurement	Quality	State
D317	IBIC/CNA	Best	Funcioning
D325	IBIC/CNA	Best	Funcioning
D340	JSI 8e14 Neutron	Best	Funcioning
D309	JSI 8e14 Neutron	Good	Funcioning
D320	JSI 8e14 Neutron	Good	Funcioning
D332	JSI 1,5e15 Neutron	Good	Funcioning
D513	JSI 1,5e15 Neutron	Good	Funcioning
D514	JSI 1,5e15 Neutron	Good	Funcioning
D516	JSI 2,5e15 Neutron	Good	Funcioning
D520	JSI 2,5e15 Neutron	Good	Funcioning
D522	JSI 2,5e15 Neutron	Good	Funcioning

6DLG3v1. Sensors Irradiated @ JSI. W3, W5

Sensor	Measurement	Quality	Carbon/No Carbon	Where
D508	JSI 8e14 Neutron	Best	Carbon	
D506	JSI 8e14 Neutron	Best	Carbon	
D513	JSI 8e14 Neutron	Best	Carbon	
D310	JSI 1,5e15 Neutron	Good	Carbon	
D330	JSI 1,5e15 Neutron	Good	Carbon	
D329	JSI 1,5e15 Neutron	Good	Carbon	
D534	JSI 2,5e15 Neutron	Acceptable	Carbon	
D524	JSI 2,5e15 Neutron	Good	Carbon	
D325	JSI 2,5e15 Neutron	Acceptable	Carbon	
D340	JSI 8e14 Neutron	Best	No Carbon	
D309	JSI 8e14 Neutron	Good	No Carbon	
D320	JSI 8e14 Neutron	Good	No Carbon	
D332	JSI 1,5e15 Neutron	Good	No Carbon	
D513	JSI 1,5e15 Neutron	Good	No Carbon	
D514	JSI 1,5e15 Neutron	Good	No Carbon	
D516	JSI 2,5e15 Neutron	Good	No Carbon	
D520	JSI 2,5e15 Neutron	Good	No Carbon	
D522	JSI 2,5e15 Neutron	Good	No Carbon	

6DLG3v1. R17958. Sensors Available. W3, W5

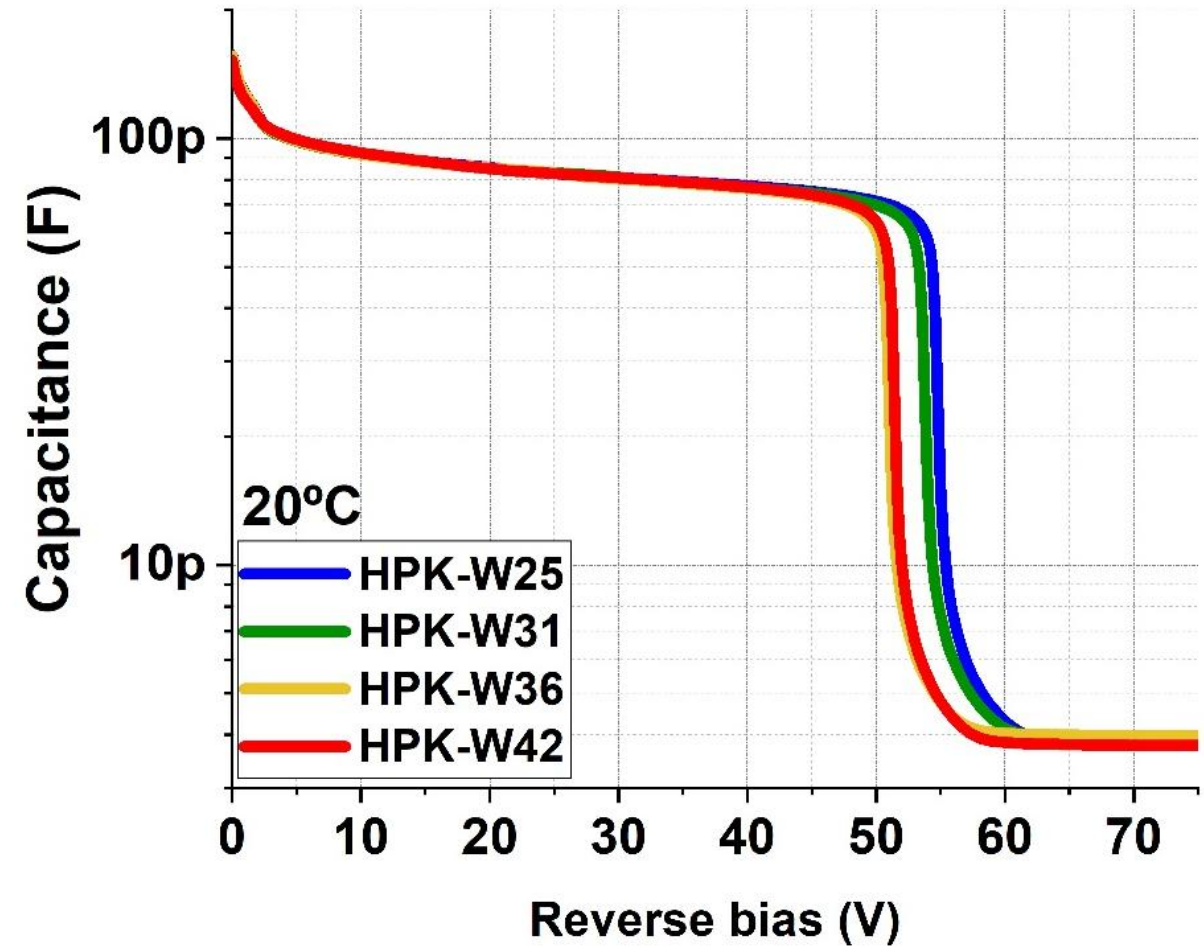
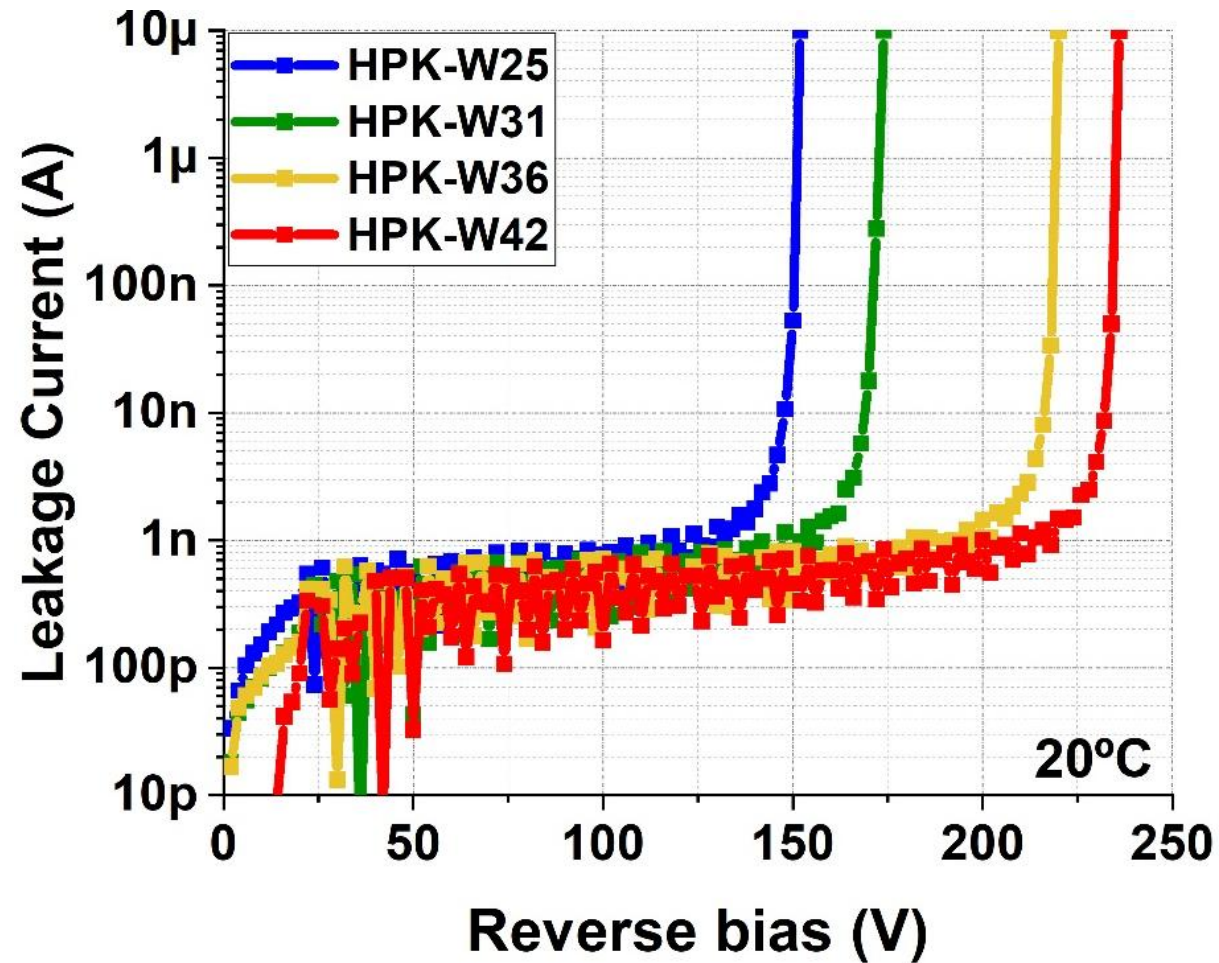
Sensor	Where	Quality	Carbon/No Carbon
D211		Best	No Carbon
D225		Best	No Carbon
D231		Best	No Carbon
D412		Best	No Carbon
D418		Best	No Carbon
D242		Acceptable	No Carbon
D206		Good	Carbon
D213		Good	Carbon
D228		Good	Carbon
D230		Good	Carbon
D415		Good	Carbon
D417		Good	Carbon
D424		Acceptable	Carbon

Evaluation of doping profiles by SRP HPK2 & R17591 CNM samples

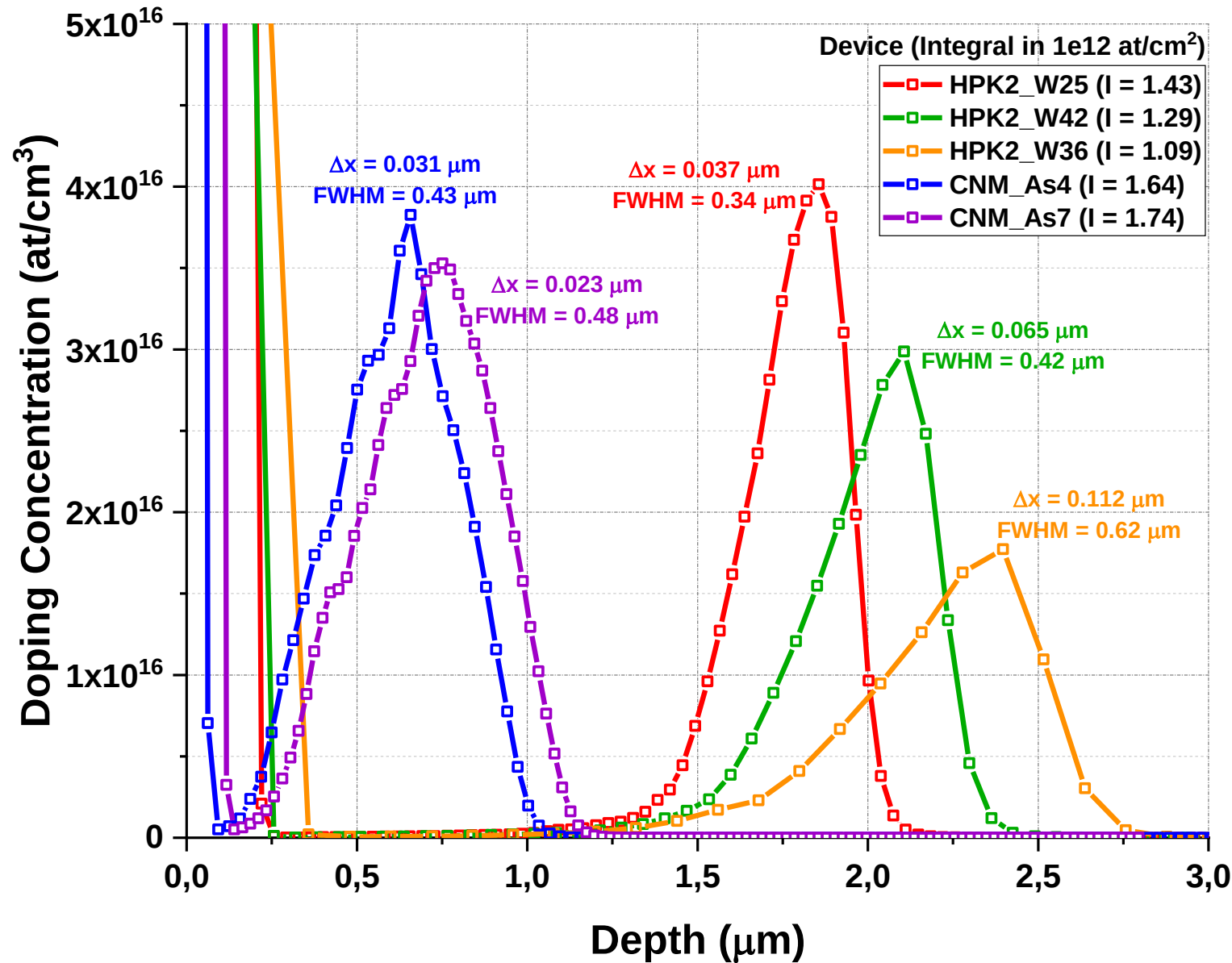
Implant the gain layer at higher energy $> 1 \text{ MeV}$



HPK2 dLGADs: I-V and C-V @ 20°C



SRP: HPK2 & CNM 6DLG2v2 samples

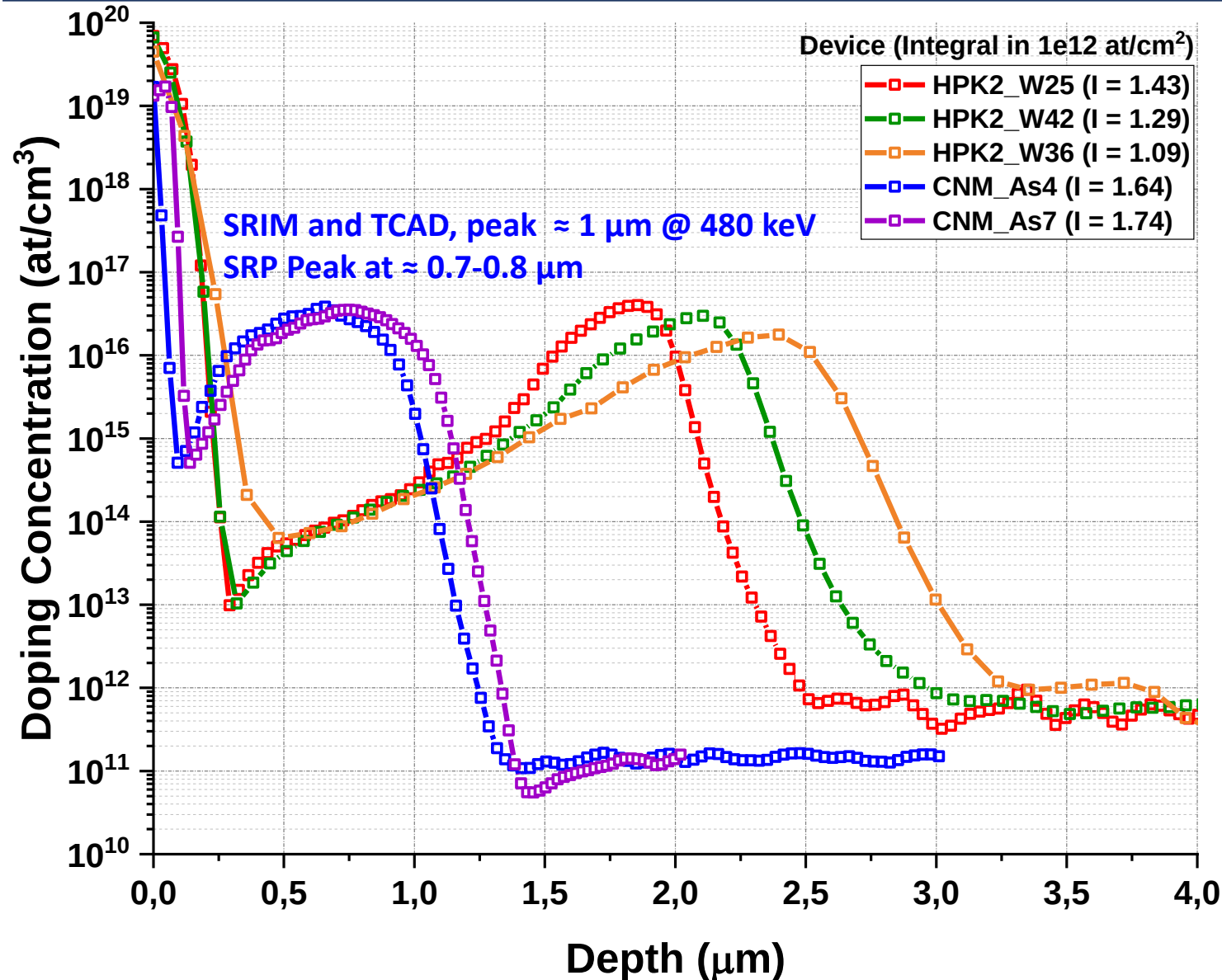


CNM R17591 6DLG2v2 samples

- Carbonated (5e13 at/cm², 480 keV)
- Spikes (no IV/CV to show for them)
- Charge integral does not match boron implantation dose (2.5e12 at/cm²), and there is no SRP set of models that make it match
- Have a greater charge integral than HPK ones



SRP: HPK2 & CNM 6DLG2v2 samples

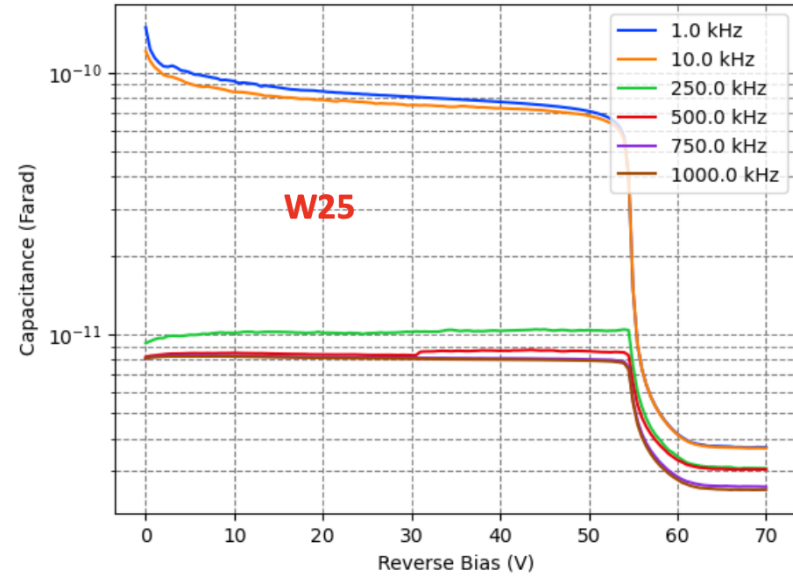


CNM R17591 6DLG2v2 samples

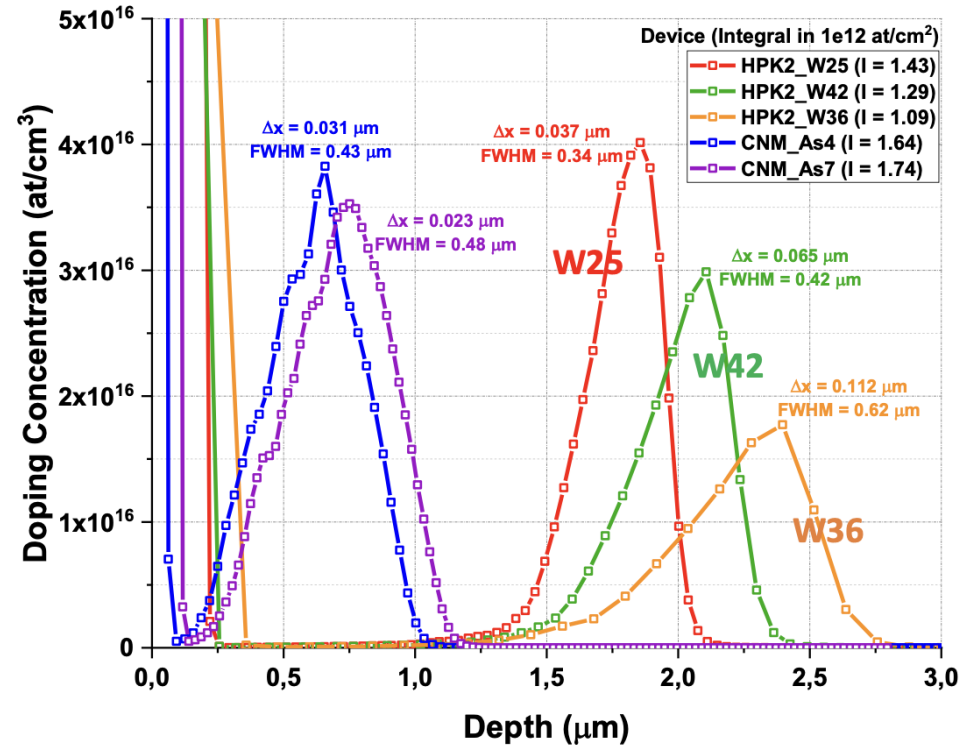
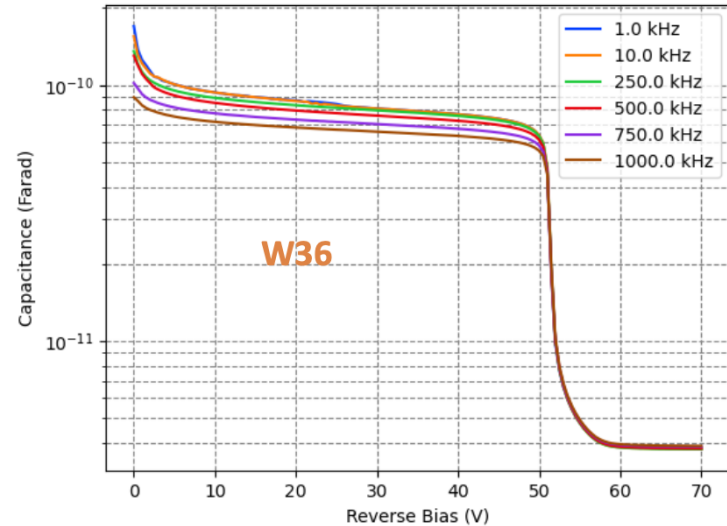
- Carbonated ($5e13 \text{ at/cm}^2$, 480 keV)
- Spikes (no IV/CV to show for them)
- Charge integral does not match boron implantation dose ($2.5e12 \text{ at/cm}^2$), and there is no SRP set of models that make it match
- Have a greater charge integral than HPK ones
- Have a lower doping concentration in the active thickness

SRP: HPK2 & CNM 6DLG2v2 samples

HPK W25 CV Parallel Mode 200mV



HPK W36 CV Parallel Mode 200mV

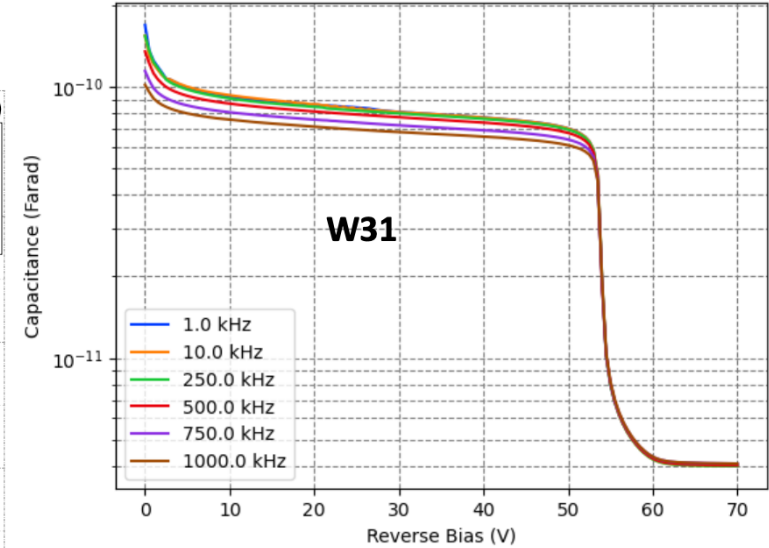


Presence of defects but with less impact than in CNM devices

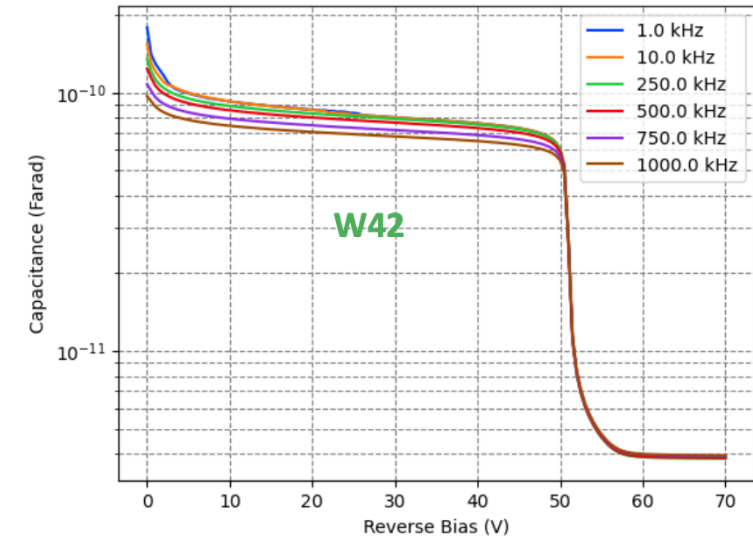


Longer annealings to repair damages ?

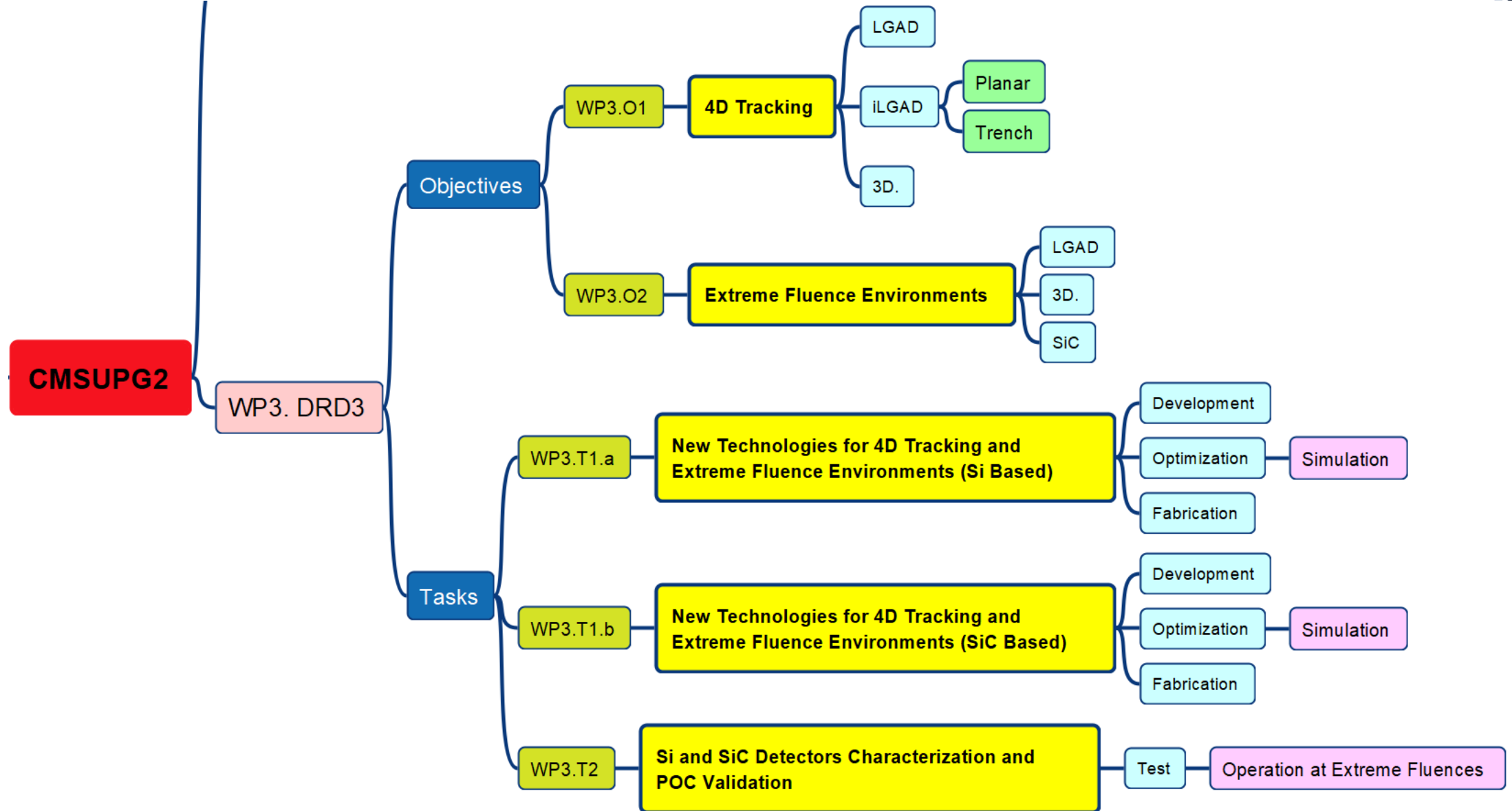
HPK W31 CV Parallel Mode 200mV



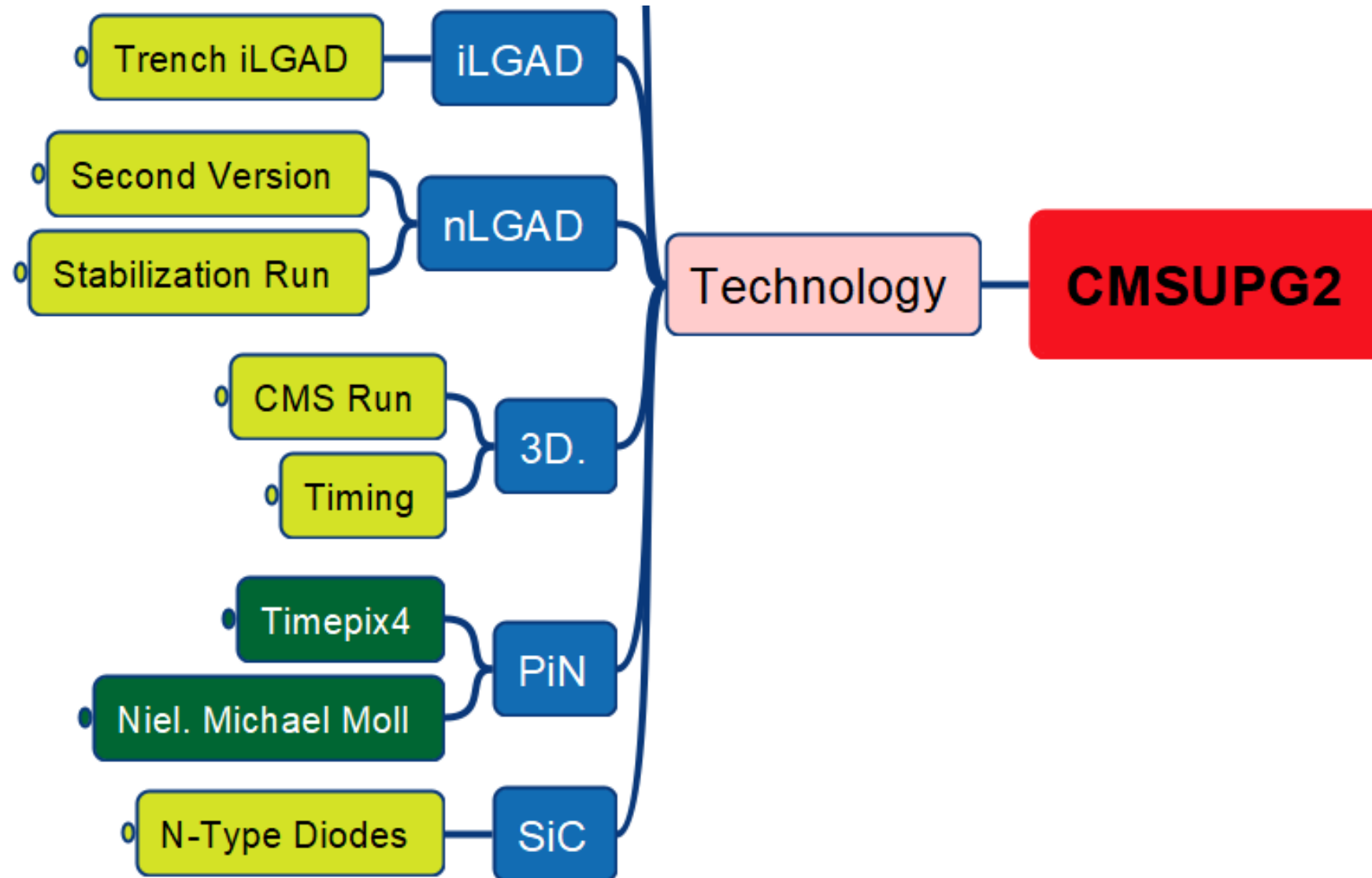
HPK W42 CV Parallel Mode 200mV



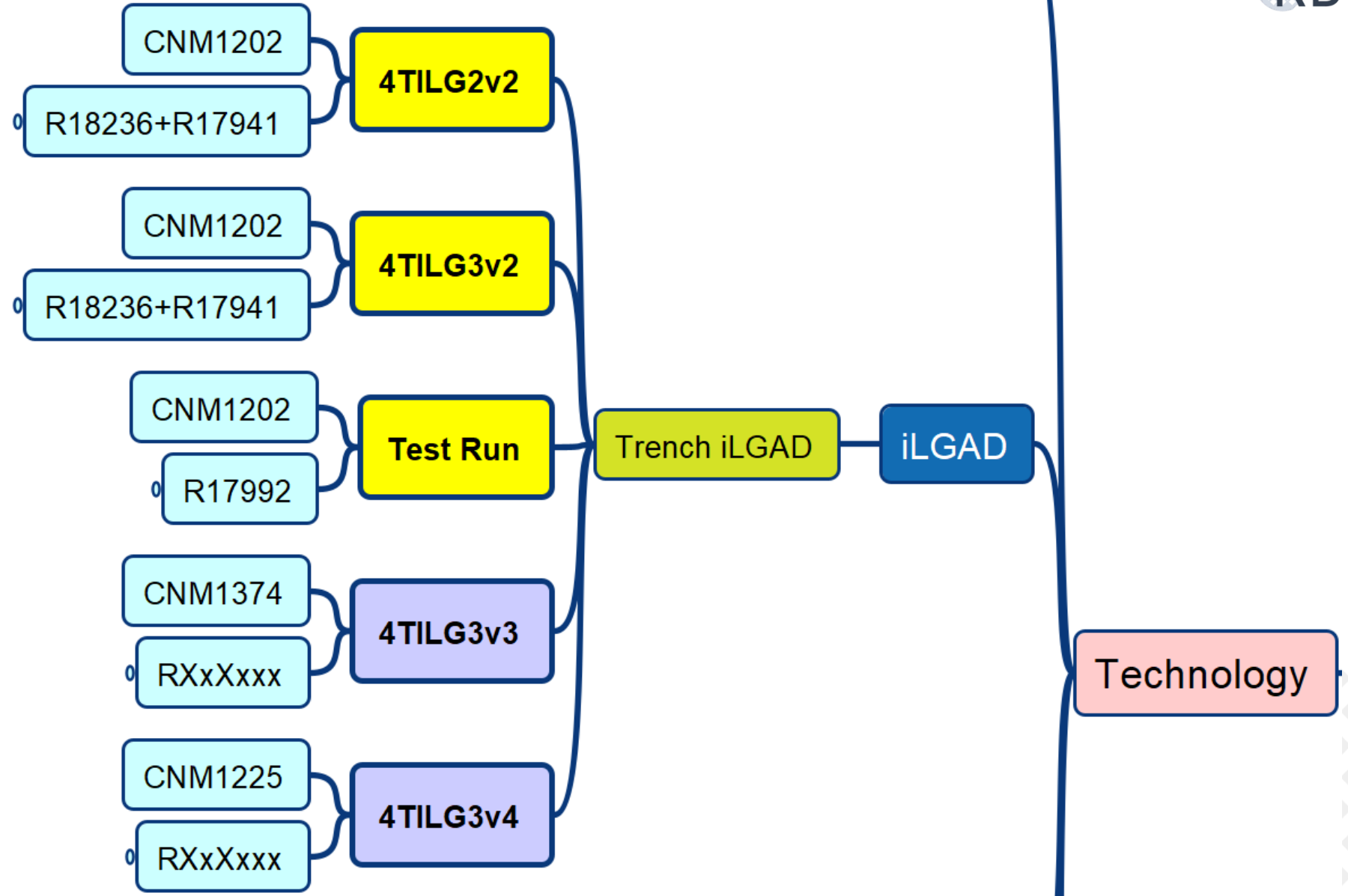
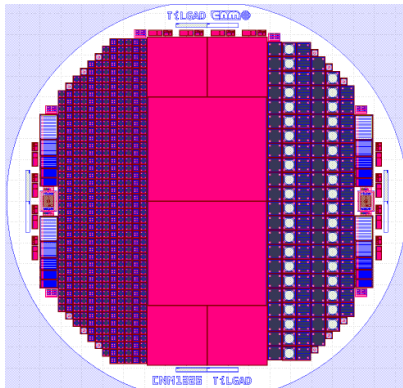
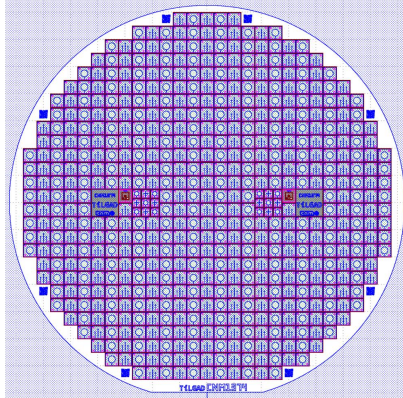
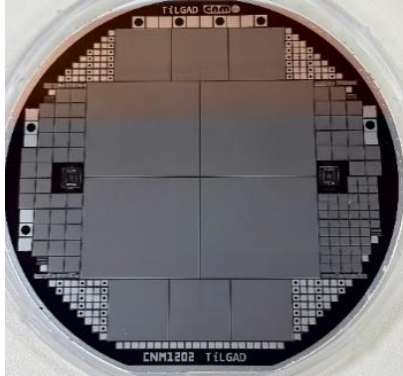
Subproject Objectives. WP3

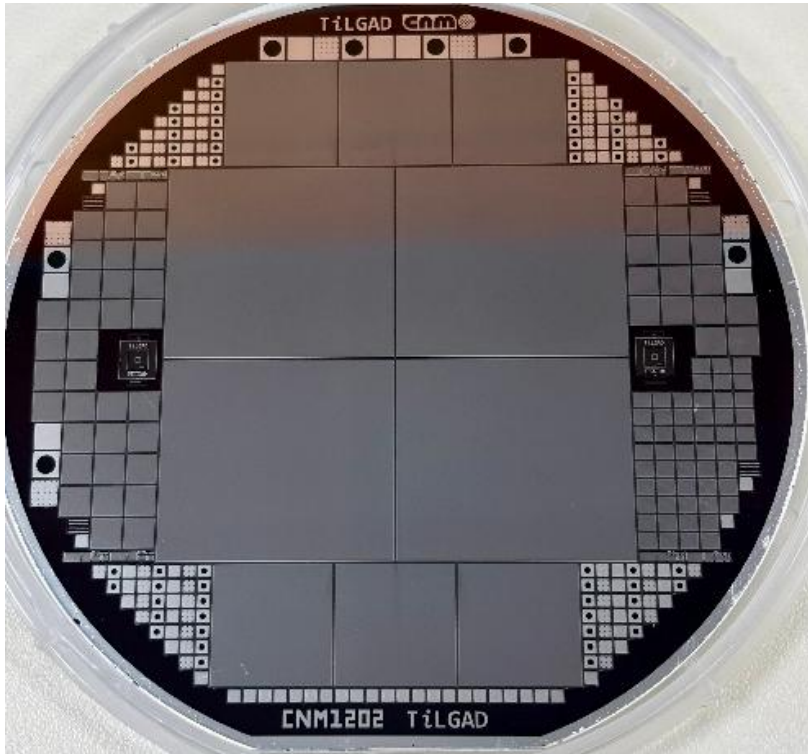


Subproject Objectives. WP3

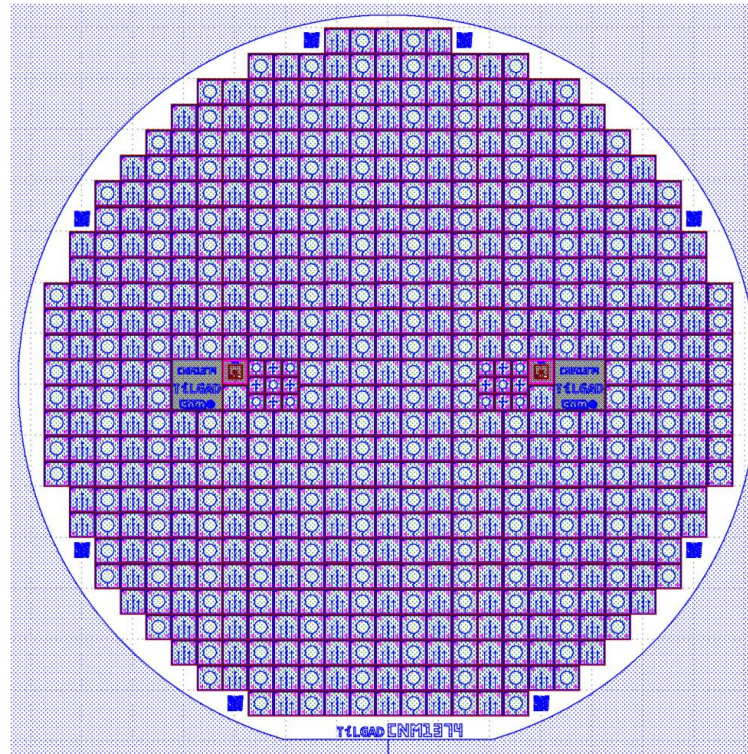


WP3. Technologies Developed. iLGAD

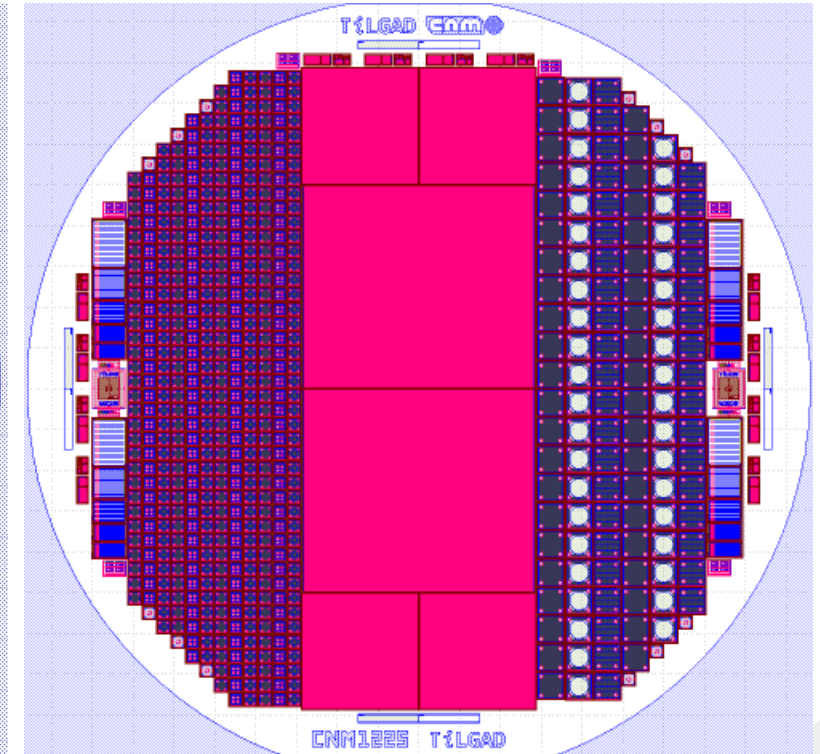




Oblea de 100 mm de diámetro en la que se integran prototipos de detectores Trench iLGAD con diseño Timepix4, primera generación



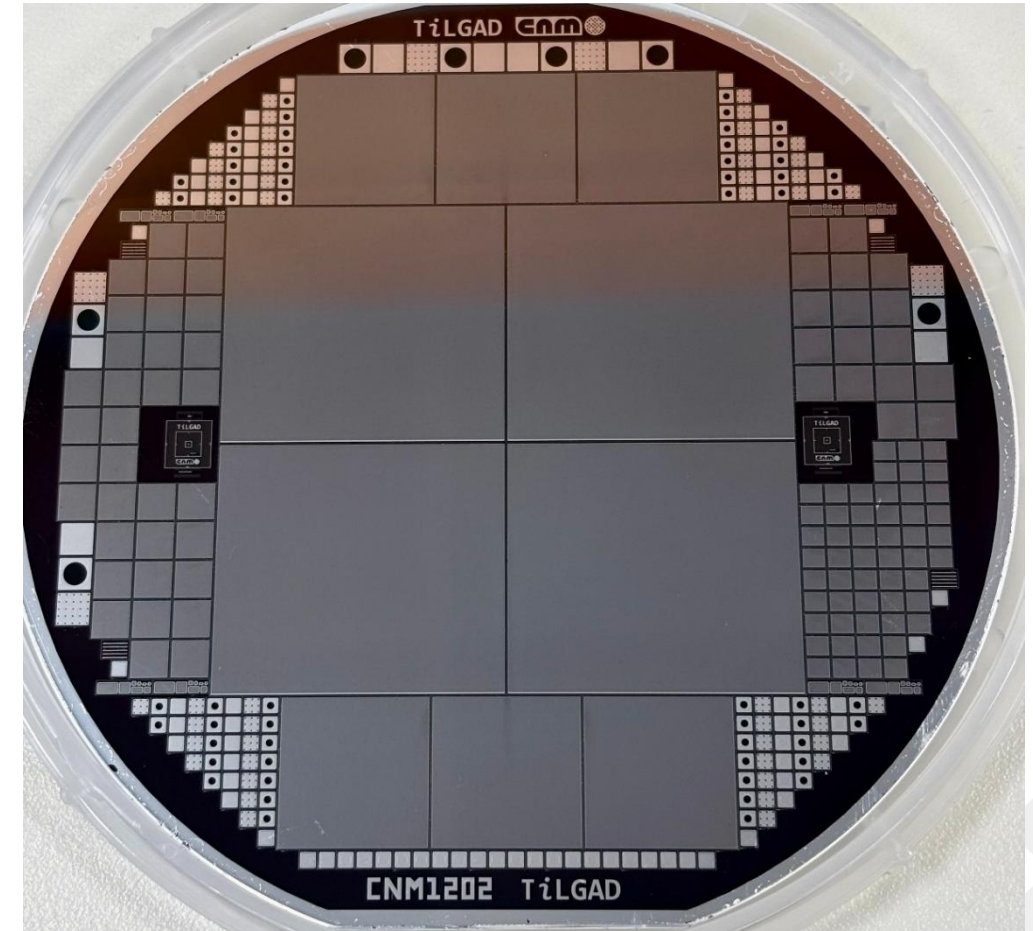
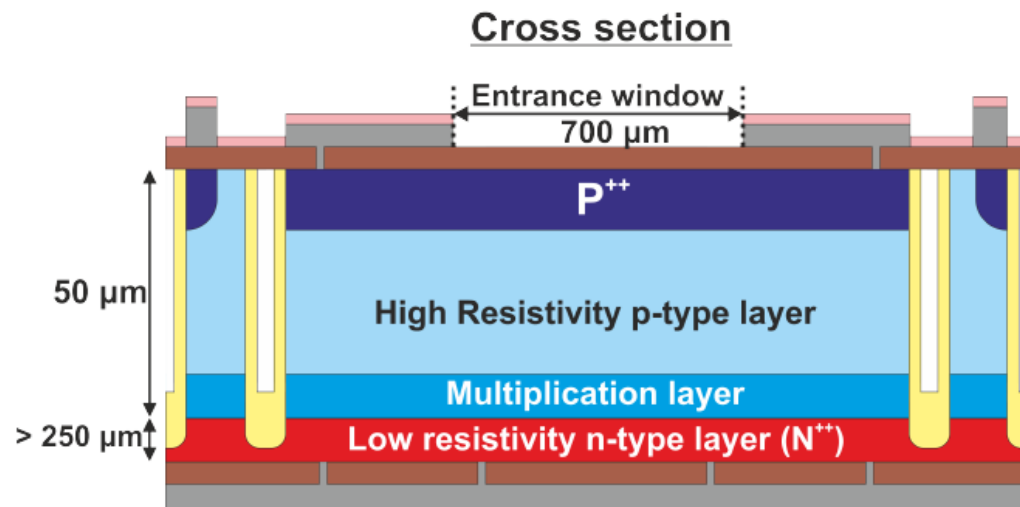
Oblea de 100 mm en la que se integraran prototipos de detectores Trench iLGAD con diseño Single Pad. Segunda Generación. Tecnología 4TILG3v3



Oblea de 100 mm de diámetro en la que se integran prototipos de detectores Trench iLGAD con diseño Timepix4, segunda generación

4TiLG(2,3)v2 (R17941+R18236)

- 5 wafers
 - 3 Epitaxial wafers
 - 2 Si-Si wafers implanted with boron doses of 3.7 and 3.9×10^{14} at/cm²
- The 2nd TiLGAD run focused on finding a **better thermal process**, for both wafers, to obtain LGAD behavior rather than APD or PiN
- Additional mask to **remove the silicon in the dicing path**
- Mask Set at Clean Room (CNM1202)

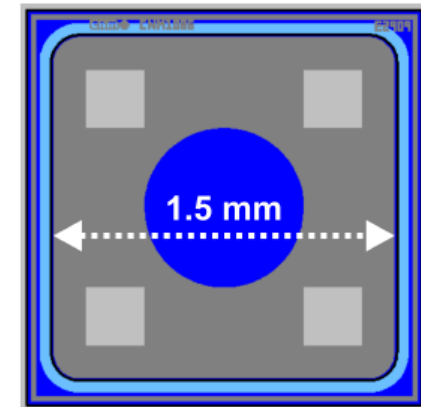
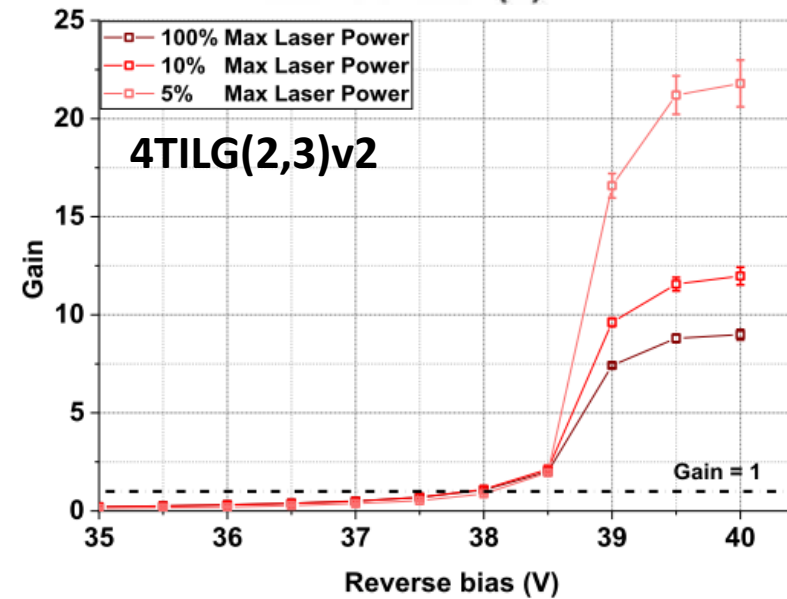
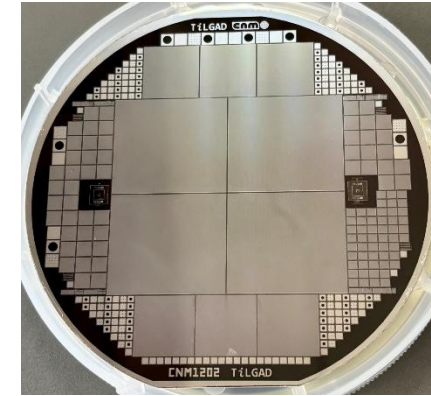
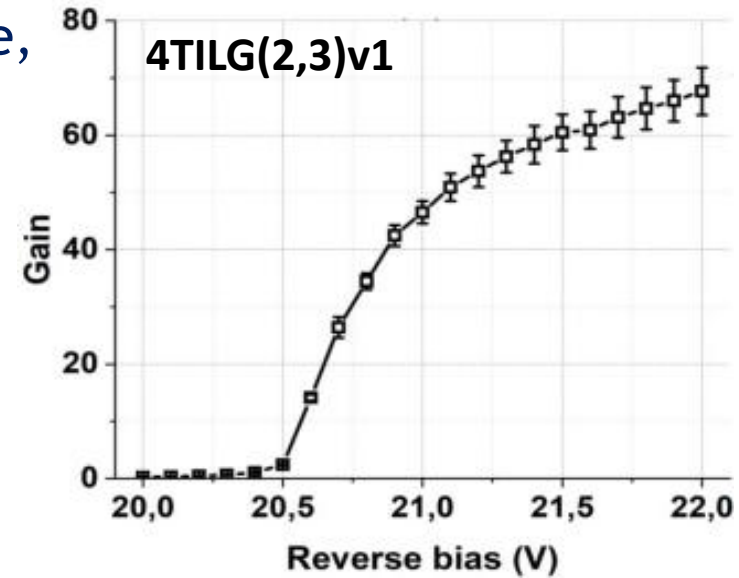
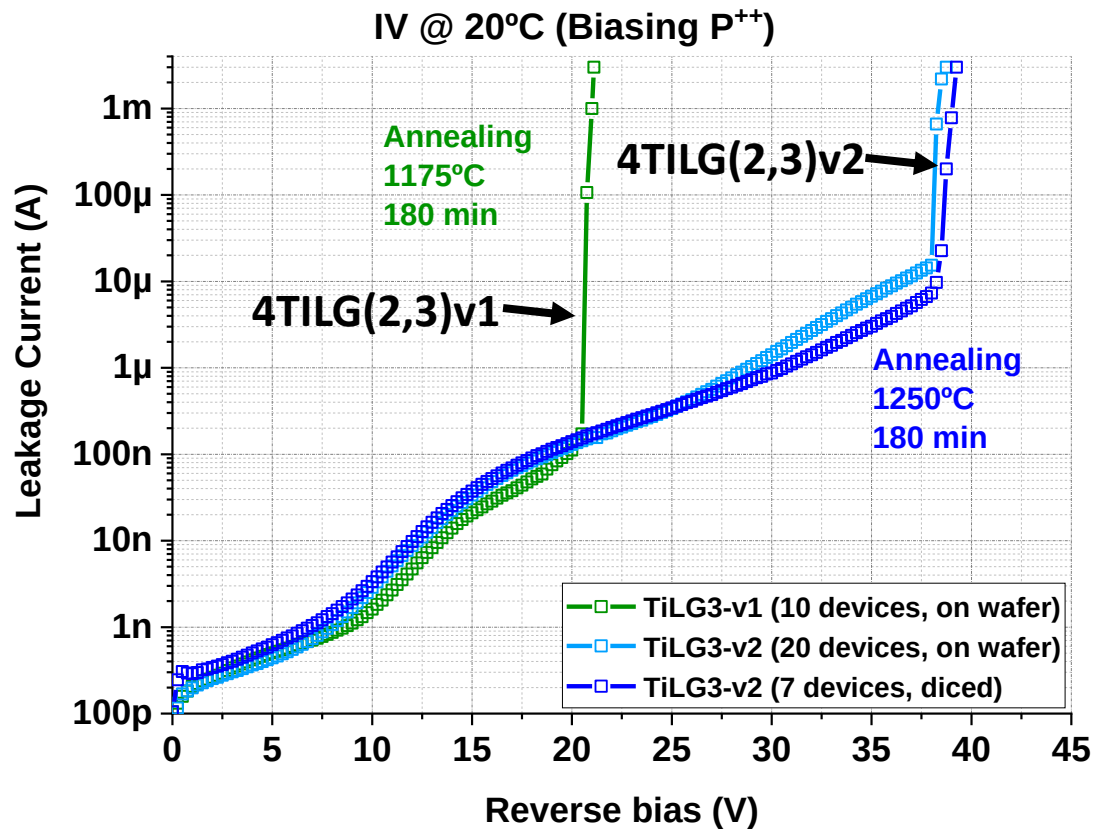


4TILG(2,3)v2 (R17941+R18236)

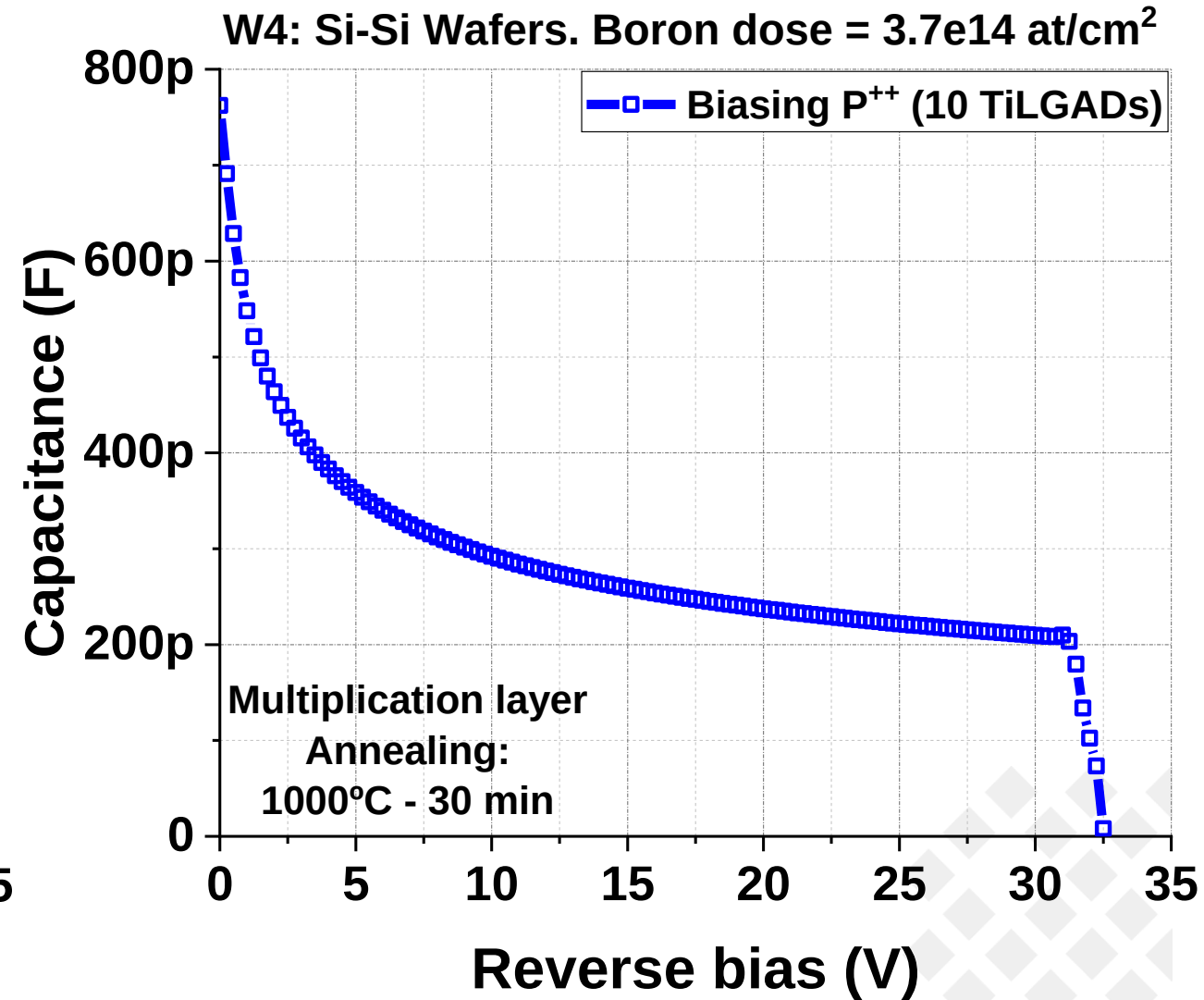
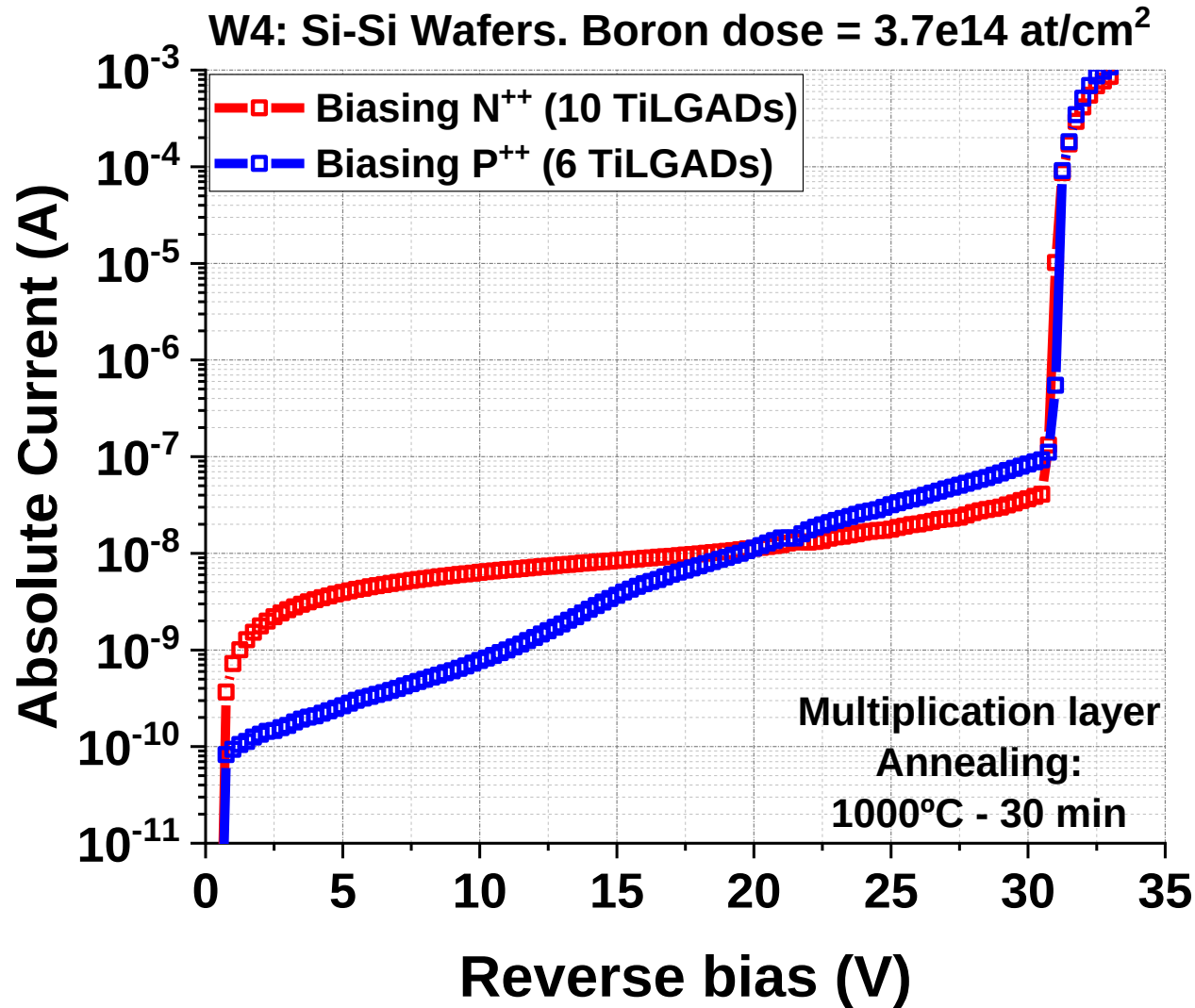
Wafer	Type	Active volume	Multiplication layer	Boron dose/energy (Mult layer)	N ⁺⁺ dopant (handle wafer)	Pre-conditioning thermal step	Cleanliness	Thermal reprocess
1	Epitaxial	<u>thickness</u> $50 \pm 5 \mu\text{m}$ <u>doping concentration</u> $< 1\text{e}13 \text{ at/cm}^3$	Epitaxially grown <u>thickness</u> $3.0 \pm 0.3 \mu\text{m}$ <u>doping Concentration</u> $3.75 \pm 0.75\text{e}16 \text{ at/cm}^3$	N/A	Arsenic	<u>1250°C - 3h</u>	MNC (no passivation)	No
2							CMOS	
3							CMOS	
4	Si-Si		Implanted	$3.7\text{e}14 \text{ at/cm}^2$ 150 keV	Phosphorus	1000°C - 0.5h	MNC (no passivation)	Yes 1100°C - 1h
5				$3.9\text{e}14 \text{ at/cm}^2$ 150 keV			CMOS	No

4TILG(2,3)v2 (R17941+R18236)

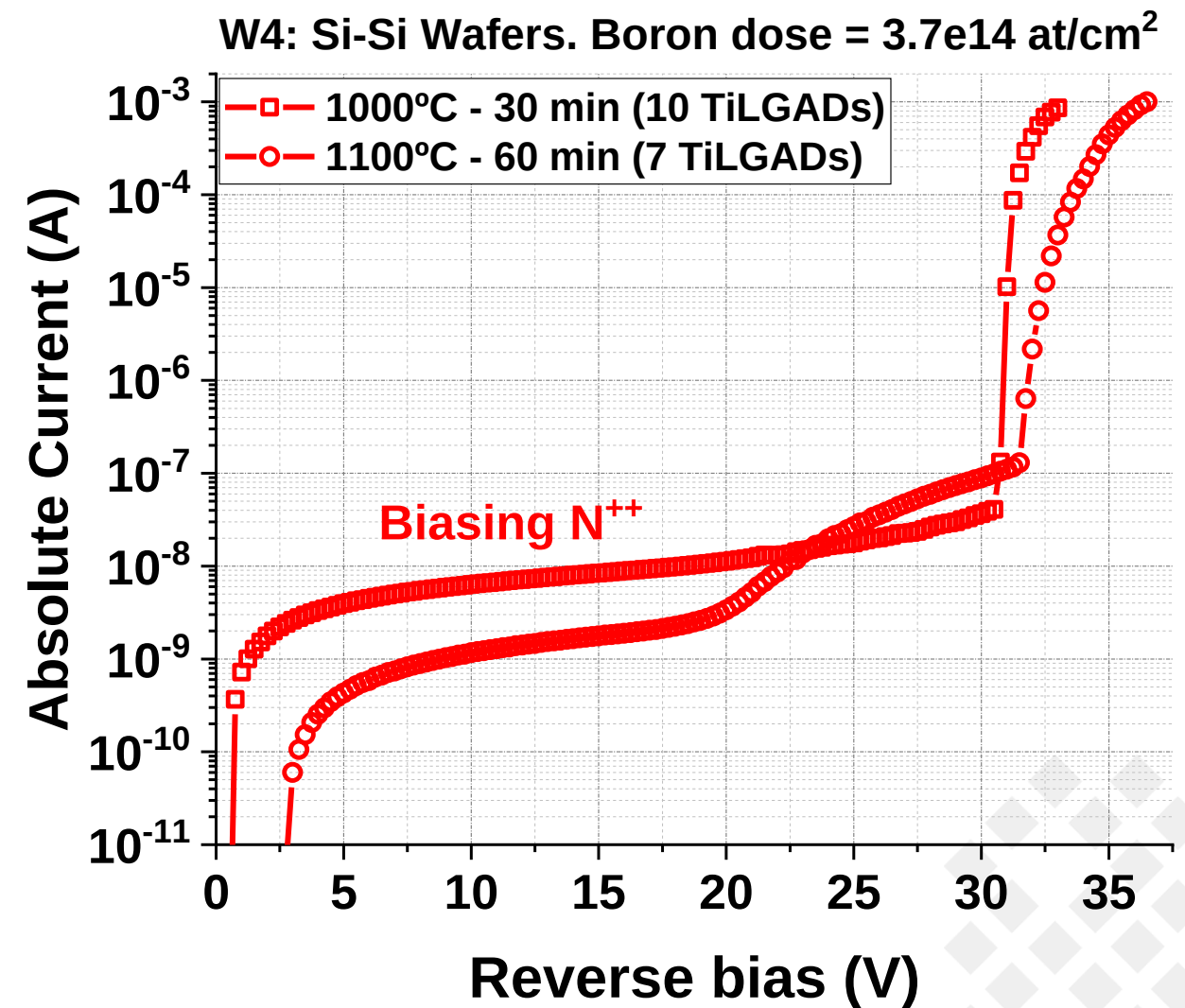
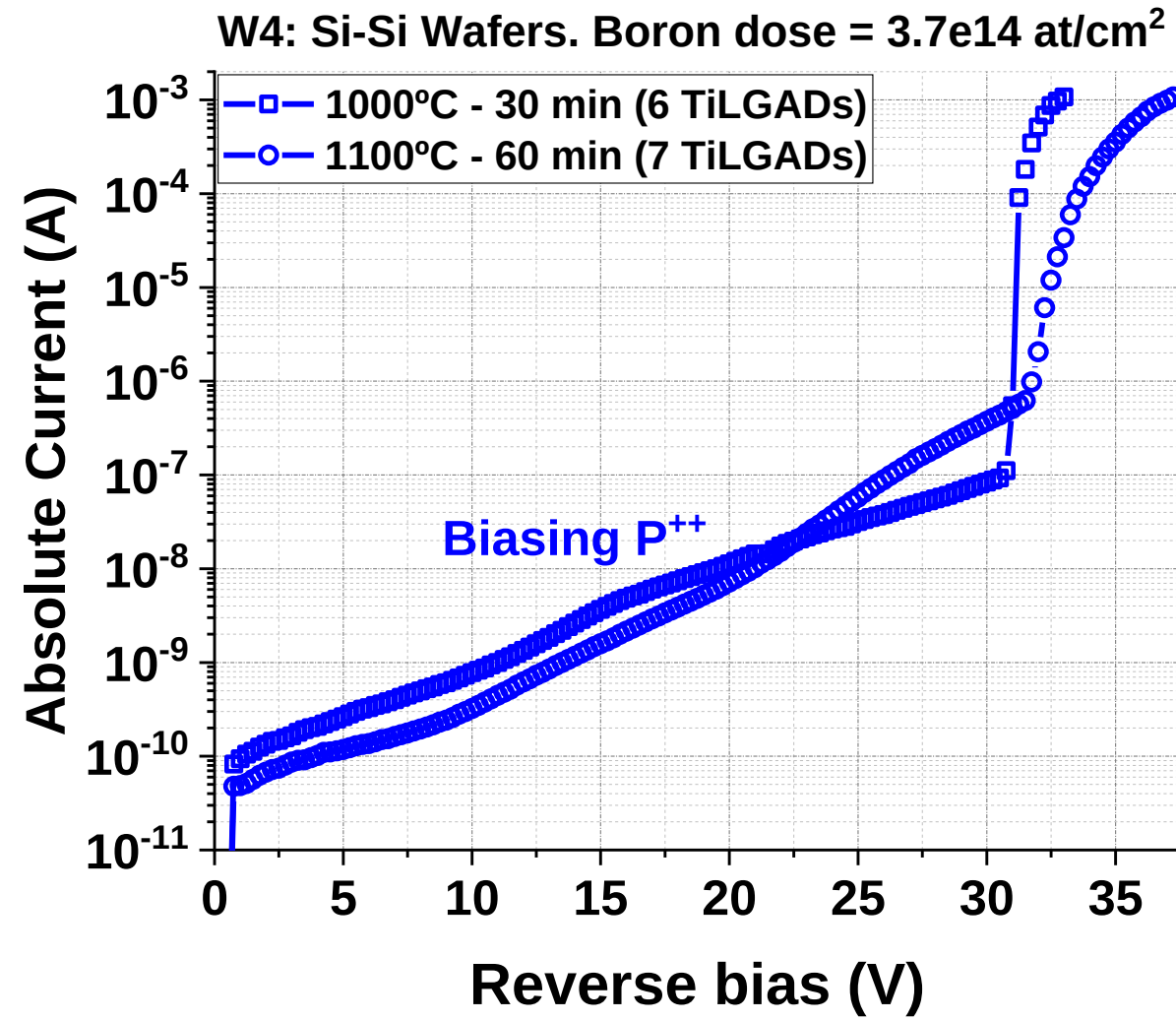
- TiLGAD Gain evolution with operating voltage, based on the substrate used
 - Silicon-Silicon (4TILG2v2)
 - Epitaxial wafer (4TILG3v2)
- Early Breakdown at ≈ 38 V



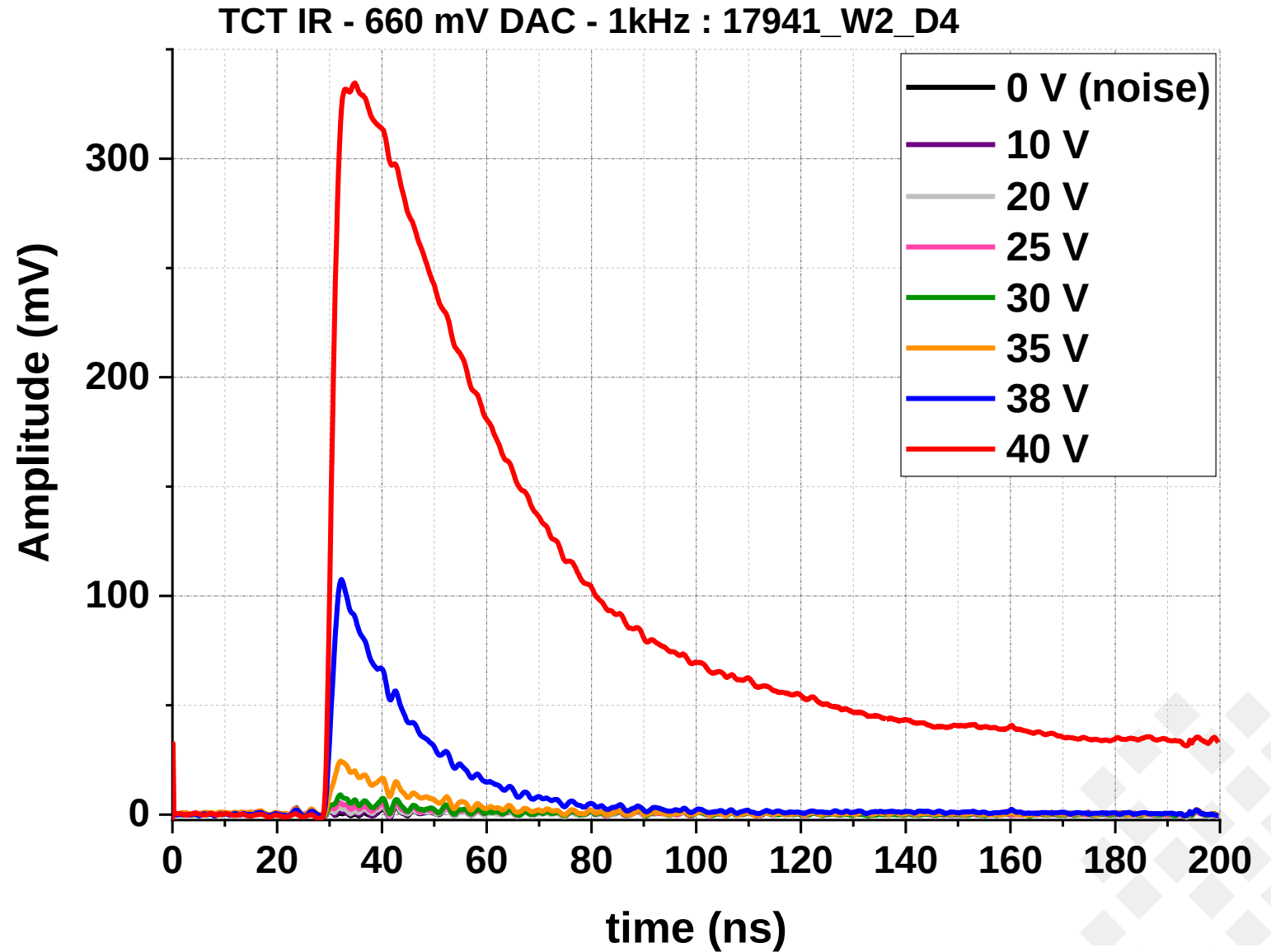
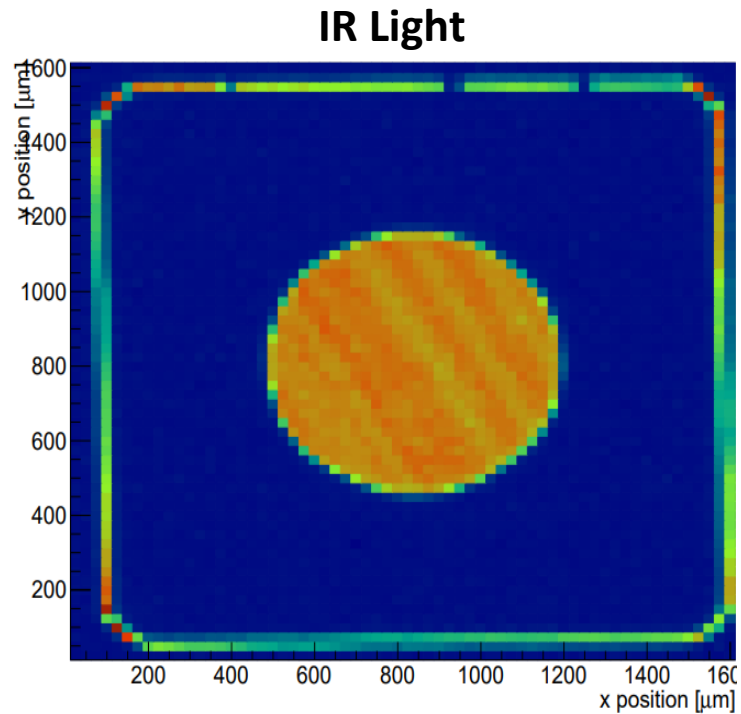
4TiLG(2,3)v2 (R17941+R18236). I-V. C-V



4TiLG(2,3)v2 (R17941+R18236). I-V

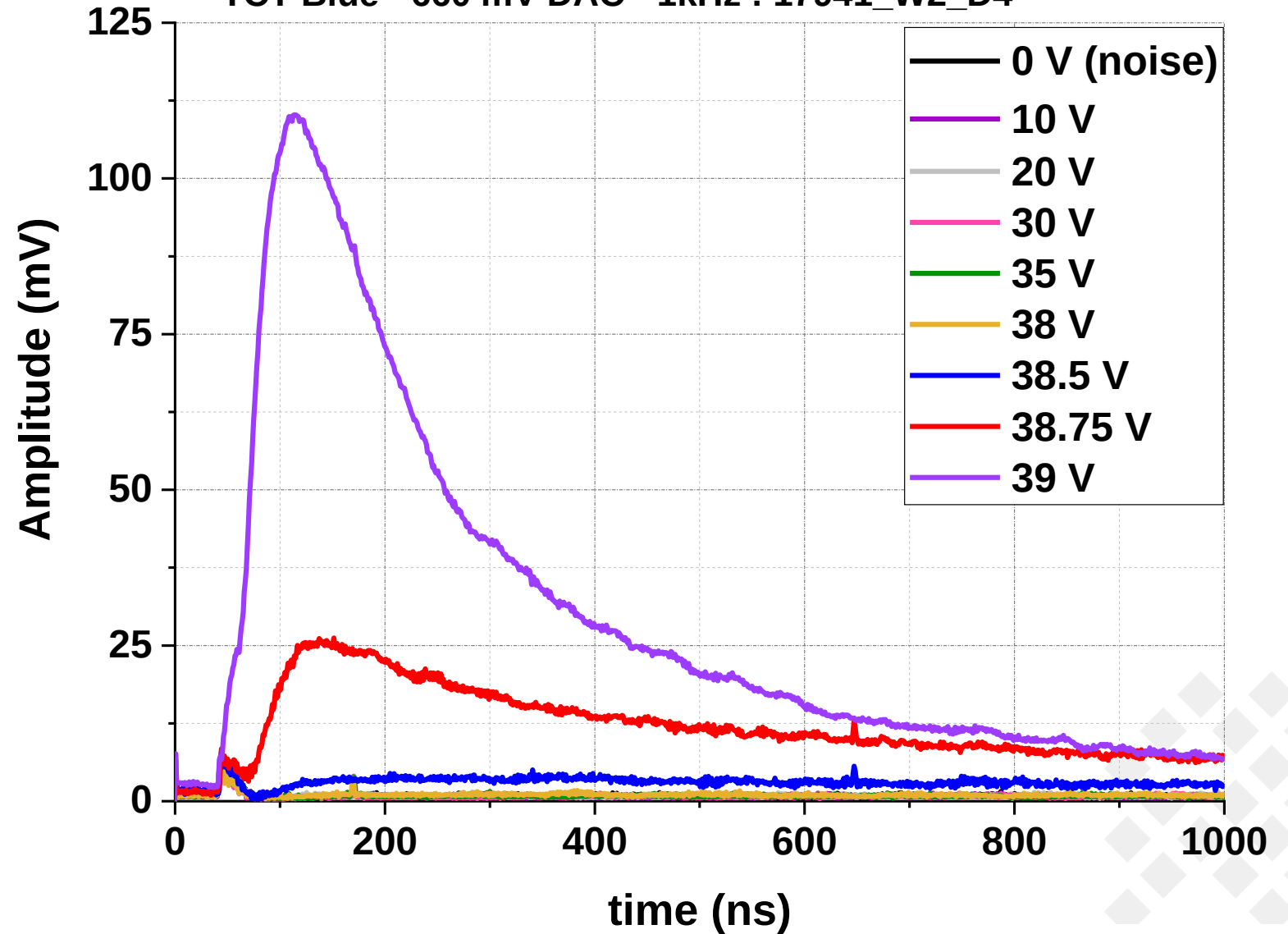
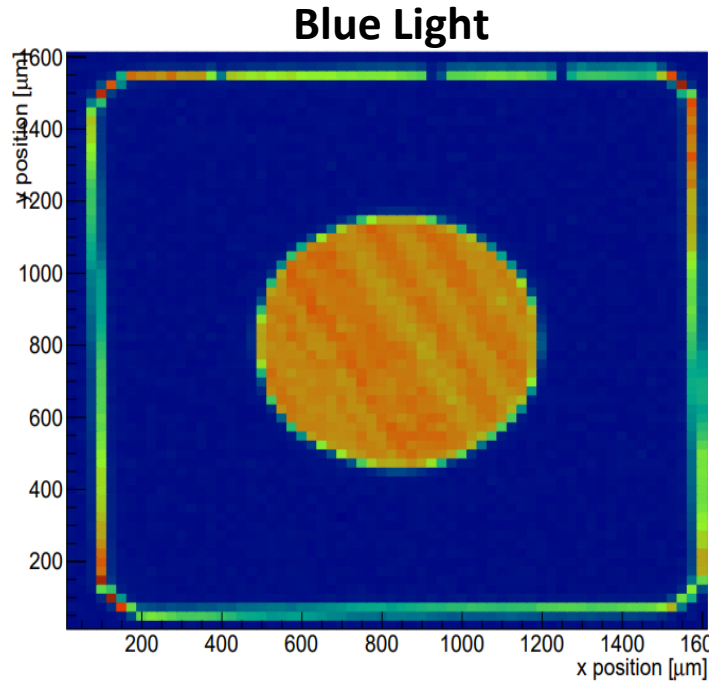


4TILG(2,3)v2 (R17941+R18236). TCT



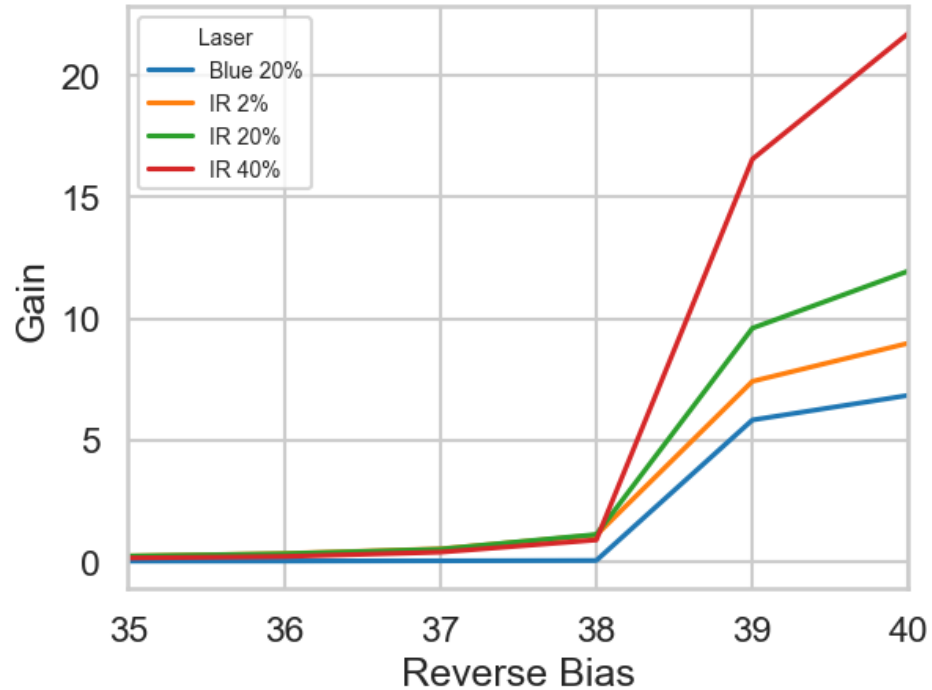
4TILG(2,3)v2 (R17941+R18236). TCT

TCT Blue - 660 mV DAC - 1kHz : 17941_W2_D4

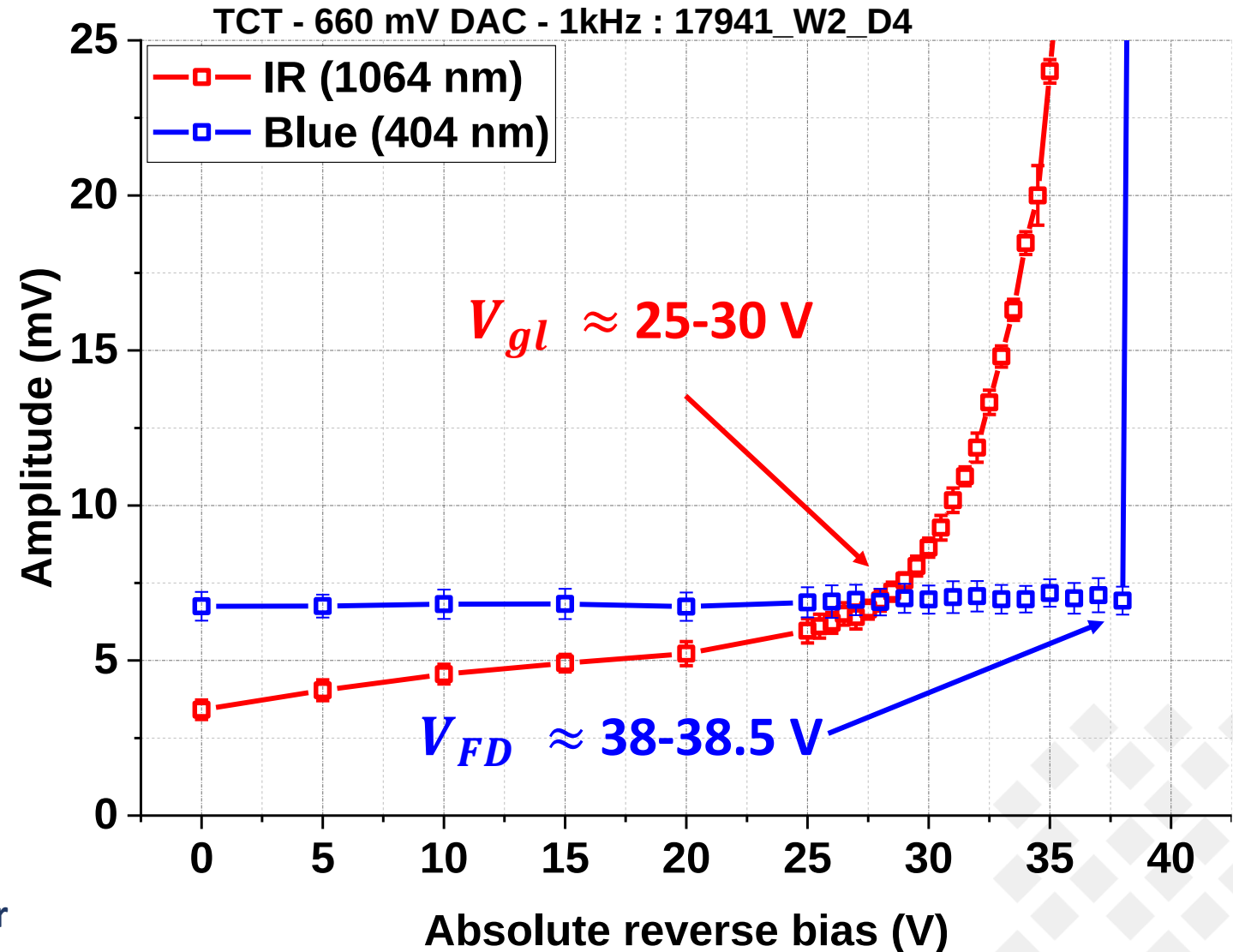


4TILG(2,3)v2 (R17941+R18236). TCT

Gain vs Reverse Bias

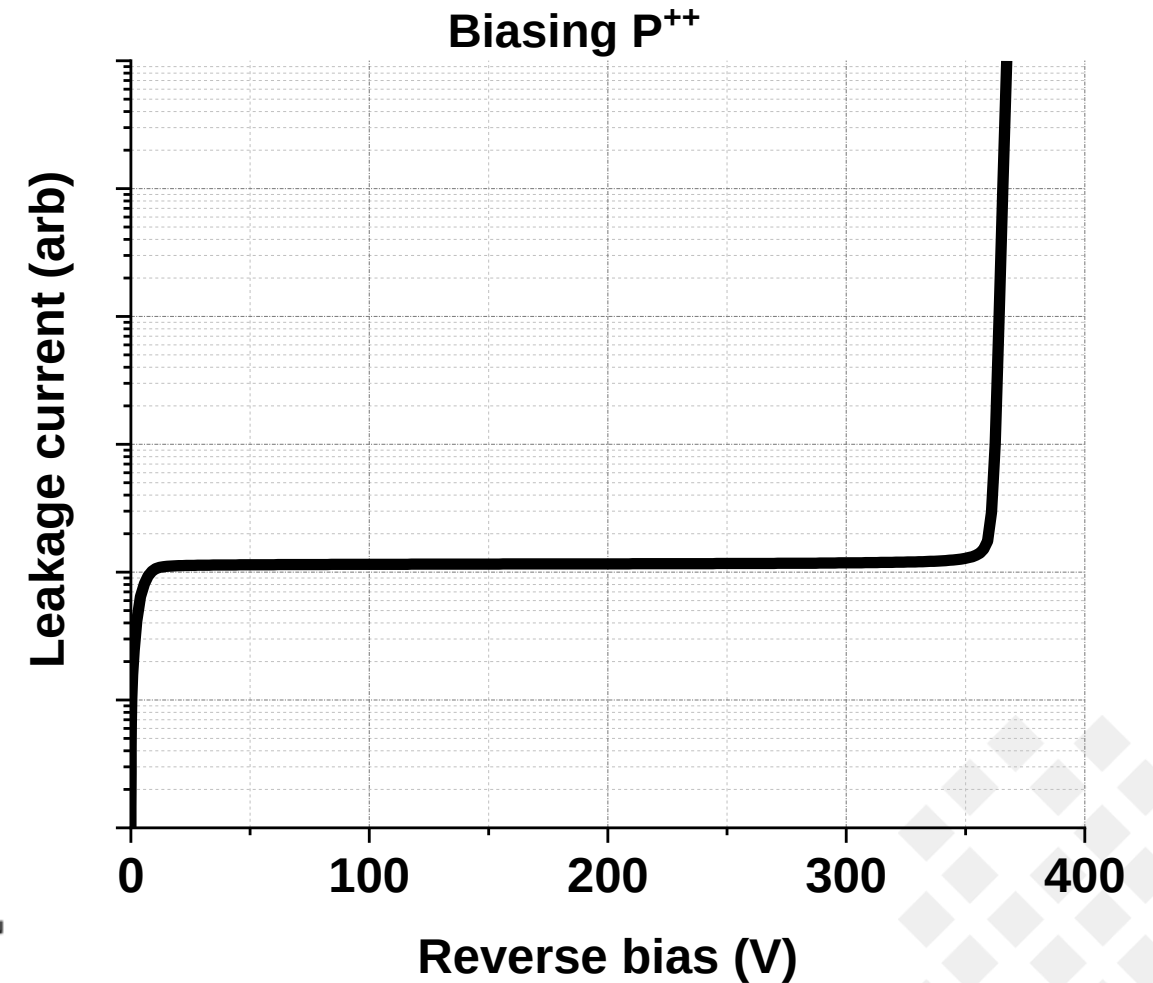
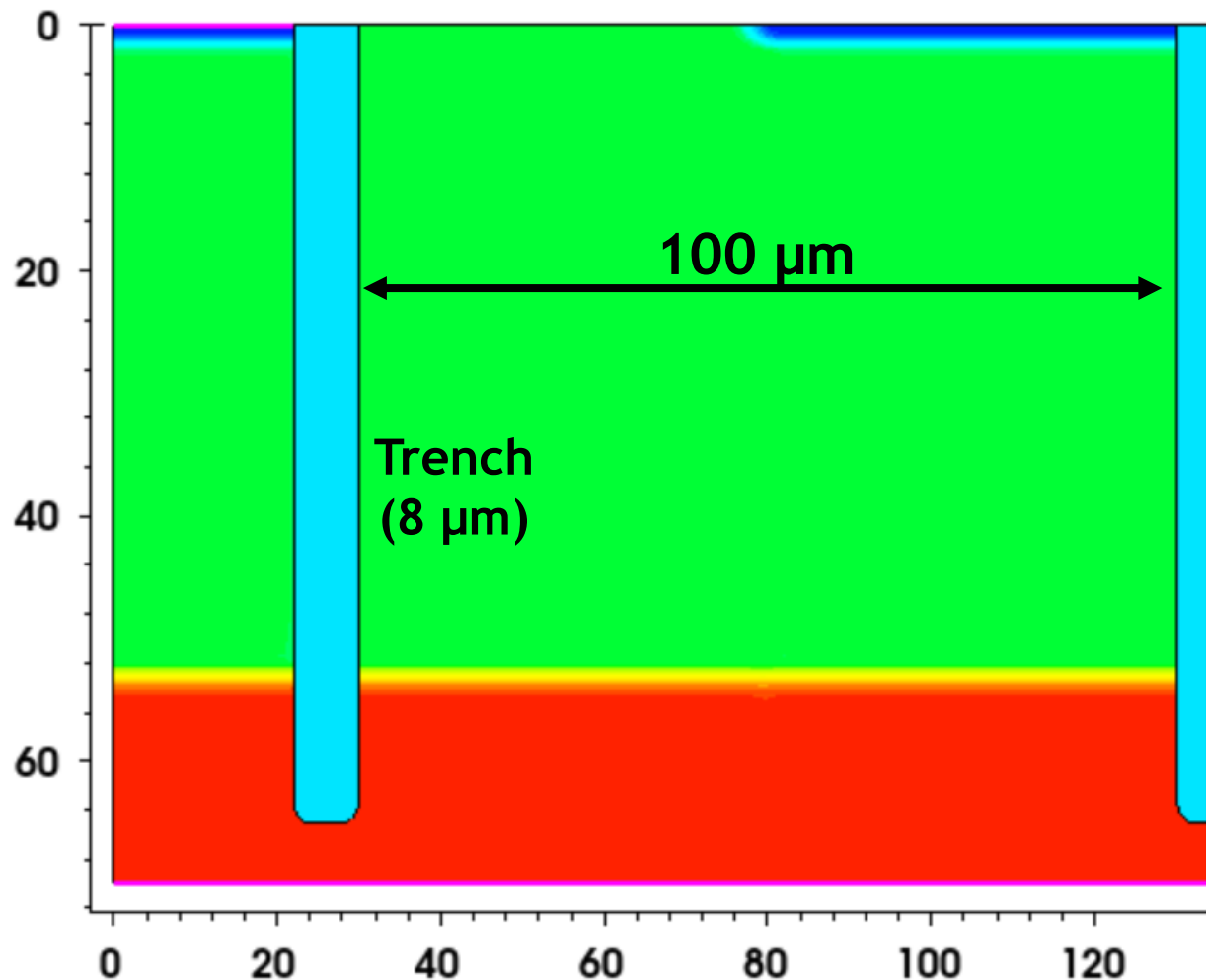


- Gain computed with 50 μm reference PiN diode from R13002
- **Gain suppression** for 2 % and 20 % IR Laser
- **Gain > 20** for 40 % IR Laser
- **Better gain response for IR laser than Blue laser**



4TILG(2,3)v2. Early Breakdown. TCAD

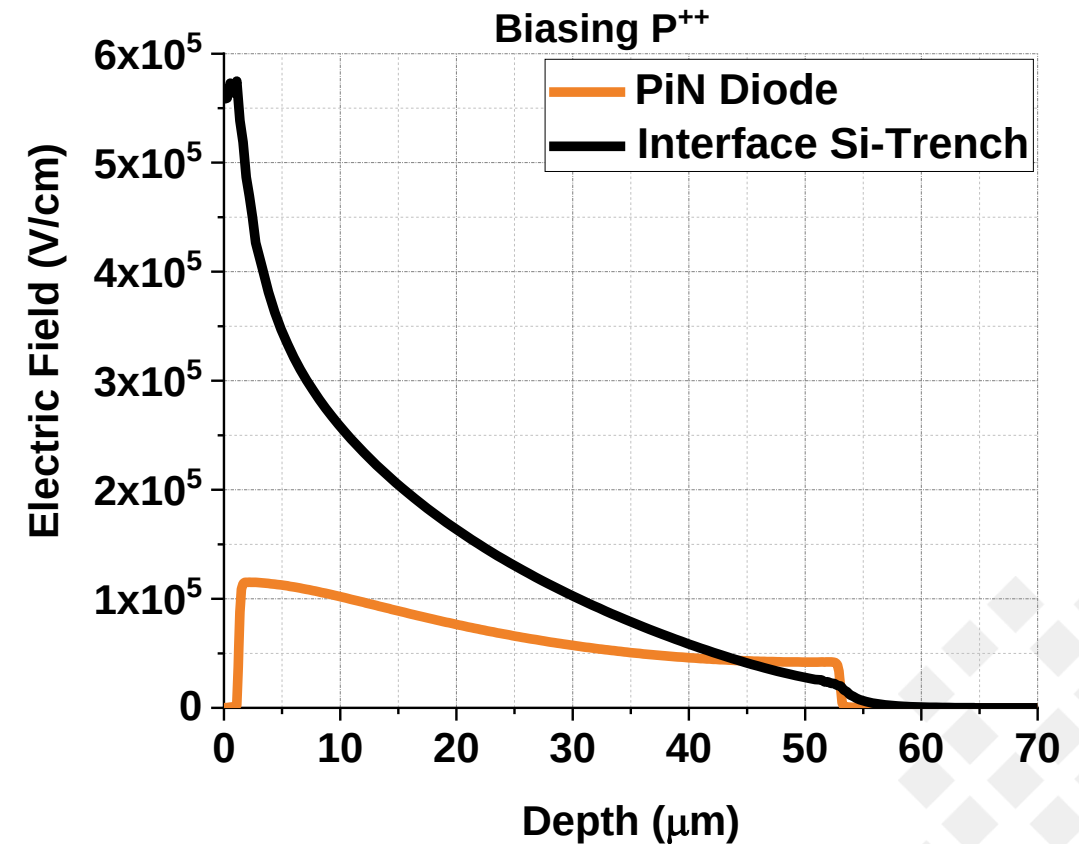
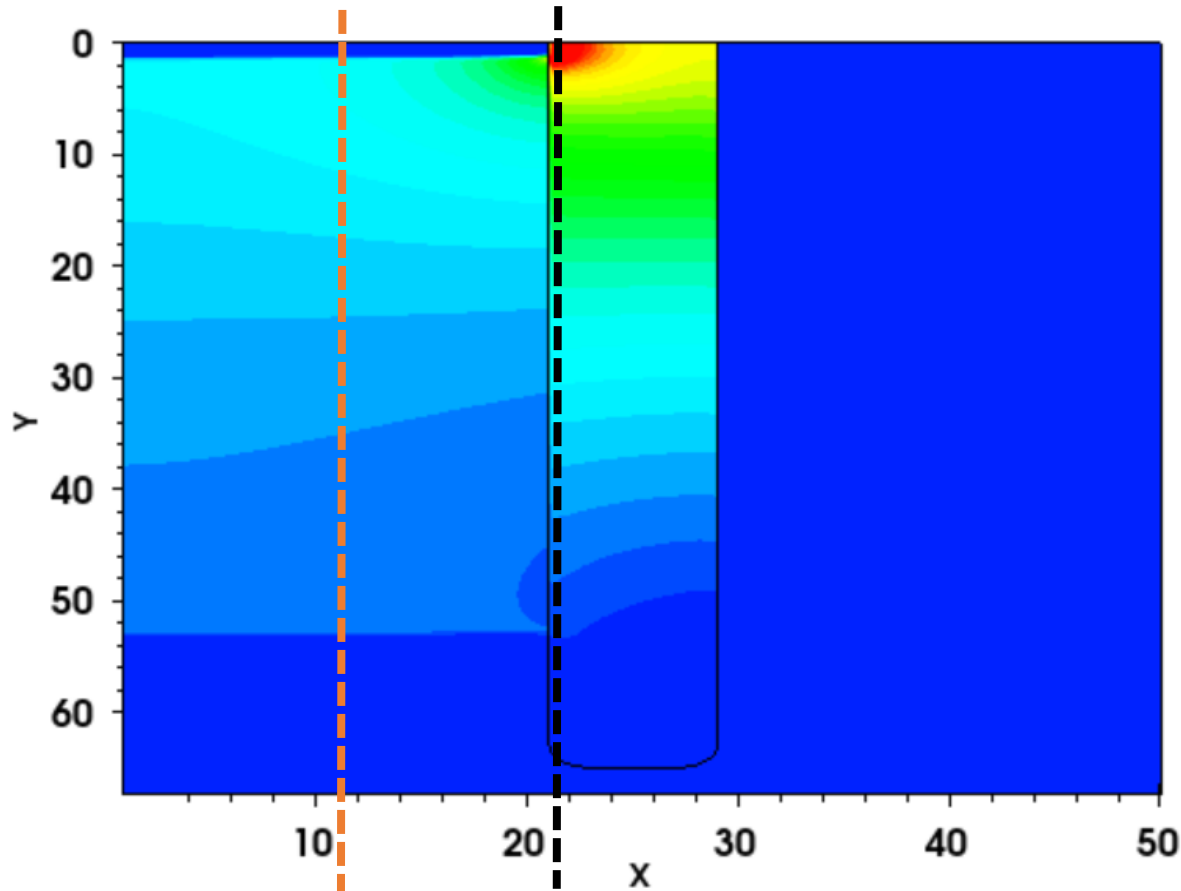
- PiN structure to find root cause of early breakdown



4TILG(2,3)v2. Early Breakdown. TCAD

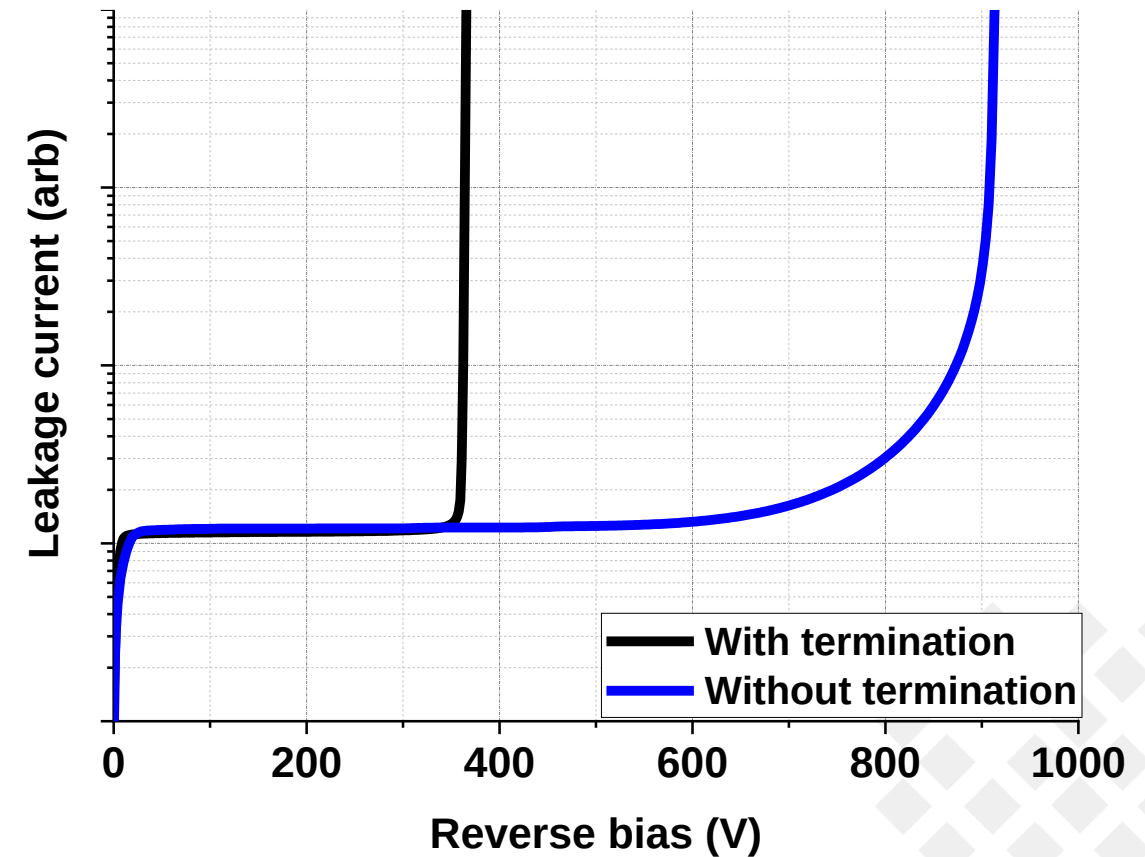
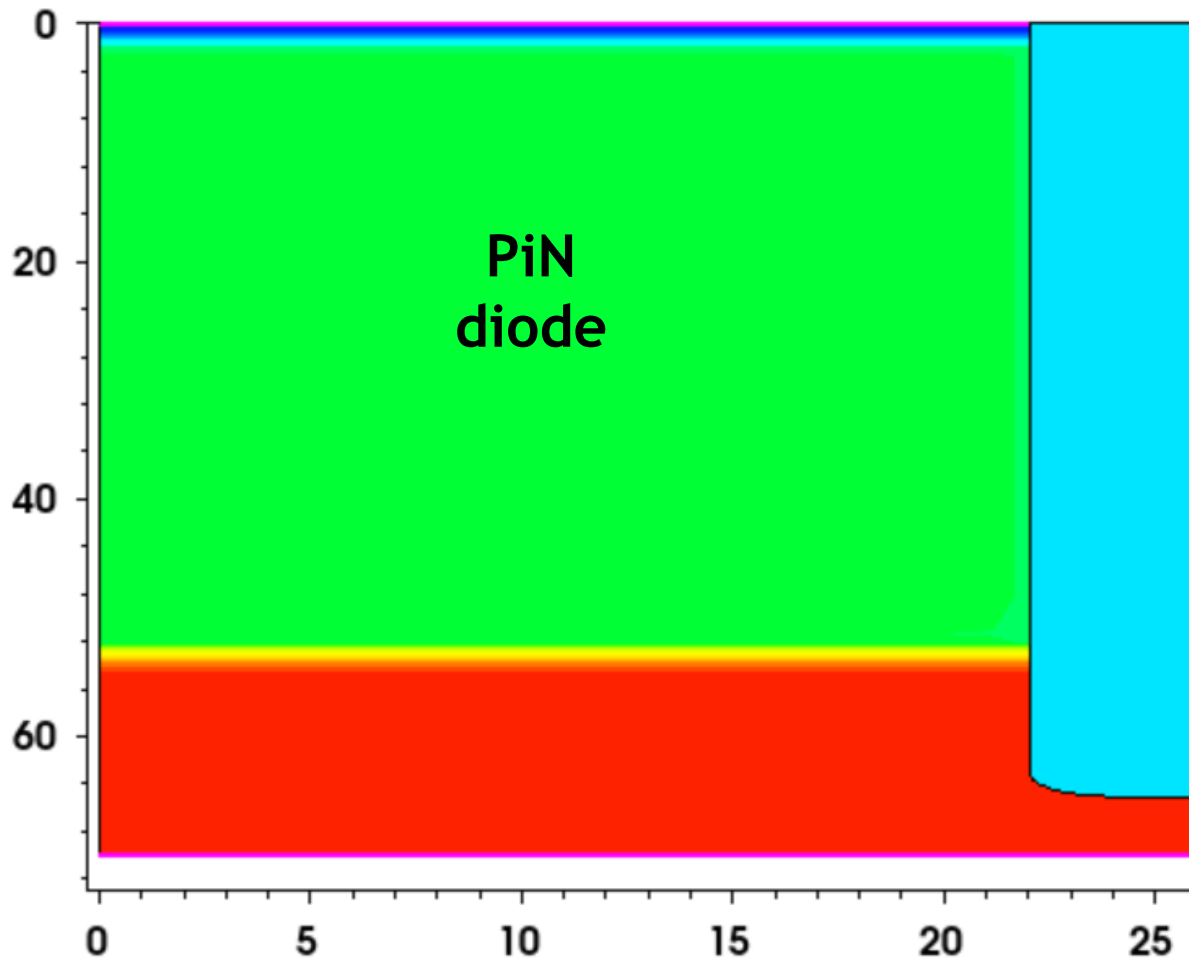
- Early Breakdown happening at the **Silicon-Trench interface**

Electric Field at 350 V



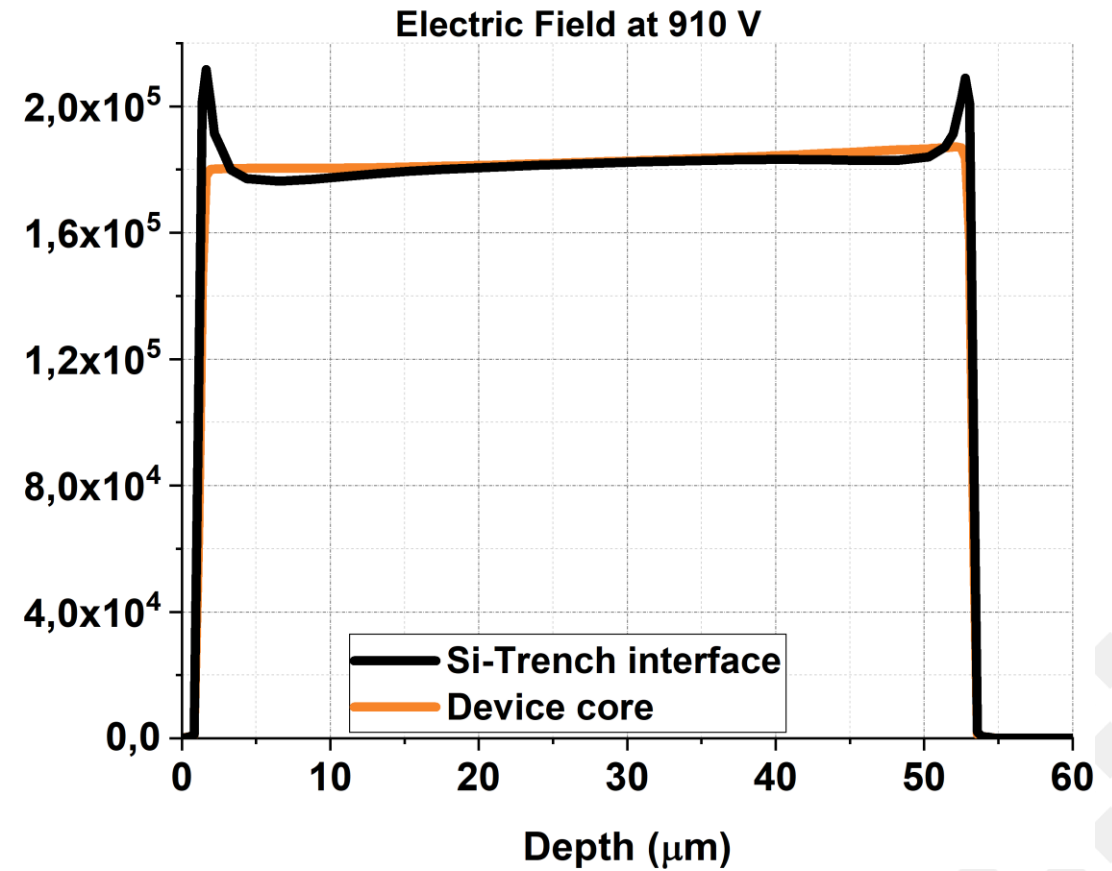
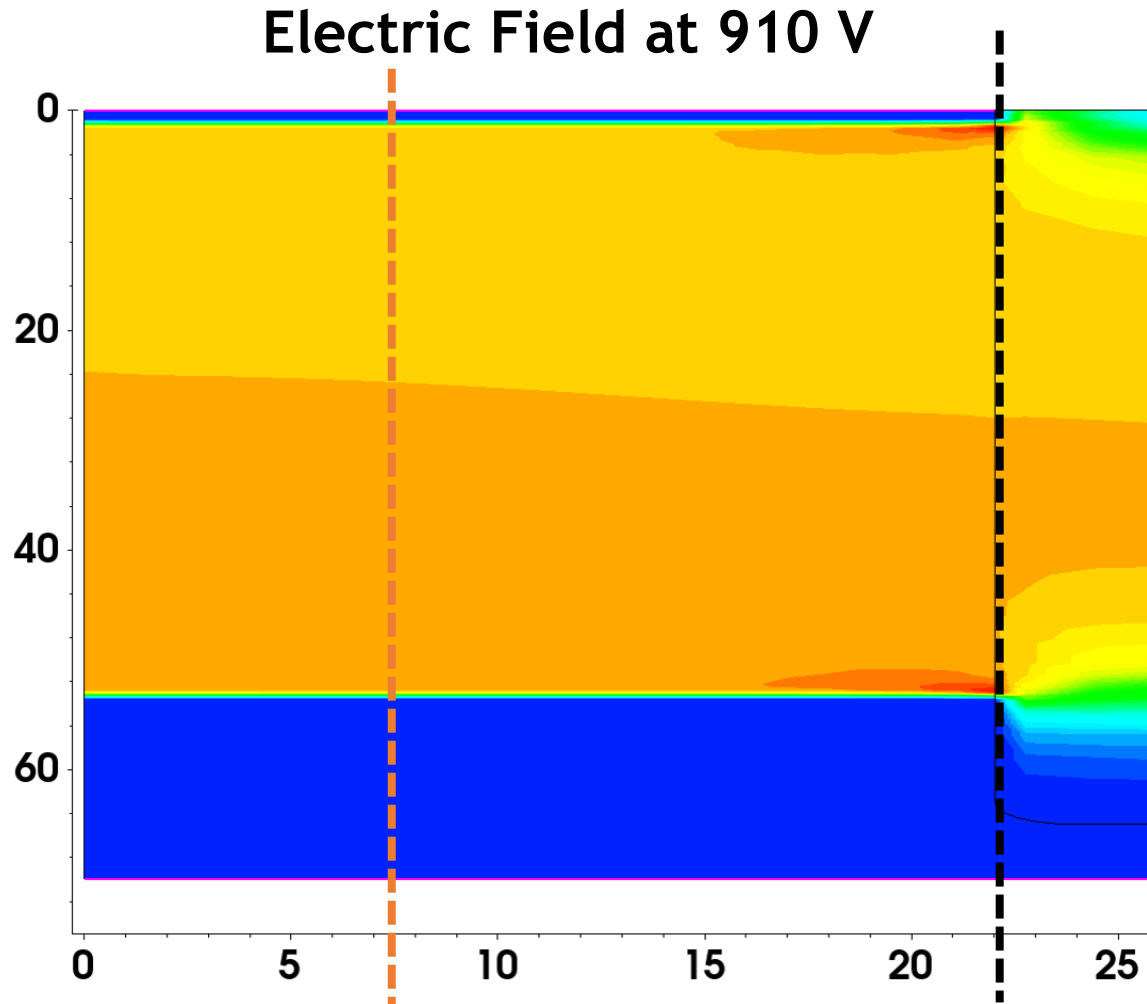
4TILG(2,3)v2. Early Breakdown. TCAD

- Design of the **silicon-free termination** between the trenches at the periphery

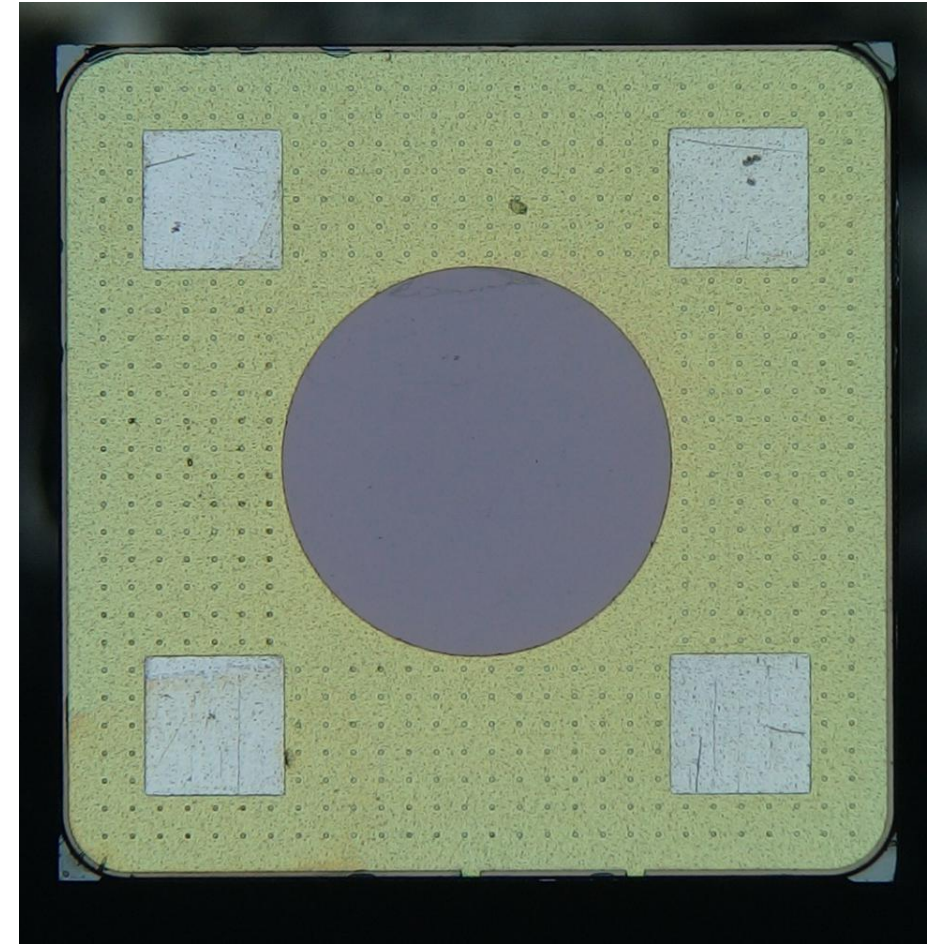
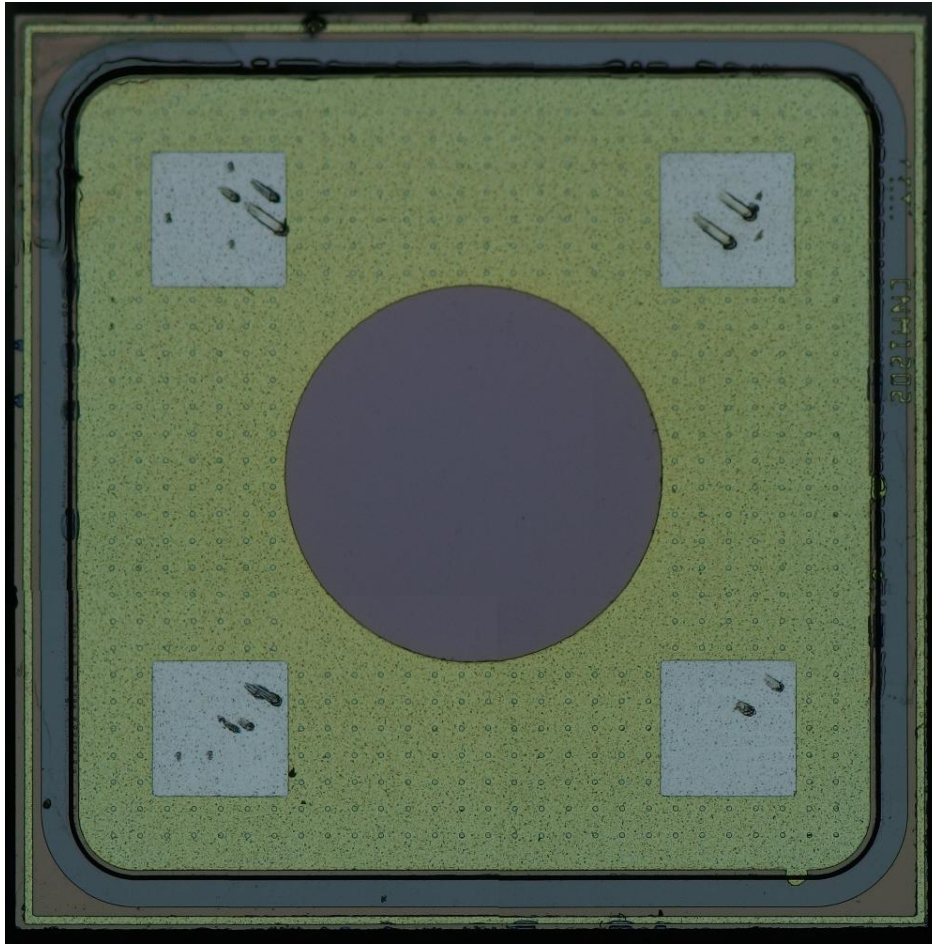


4TILG(2,3)v2. Early Breakdown. TCAD

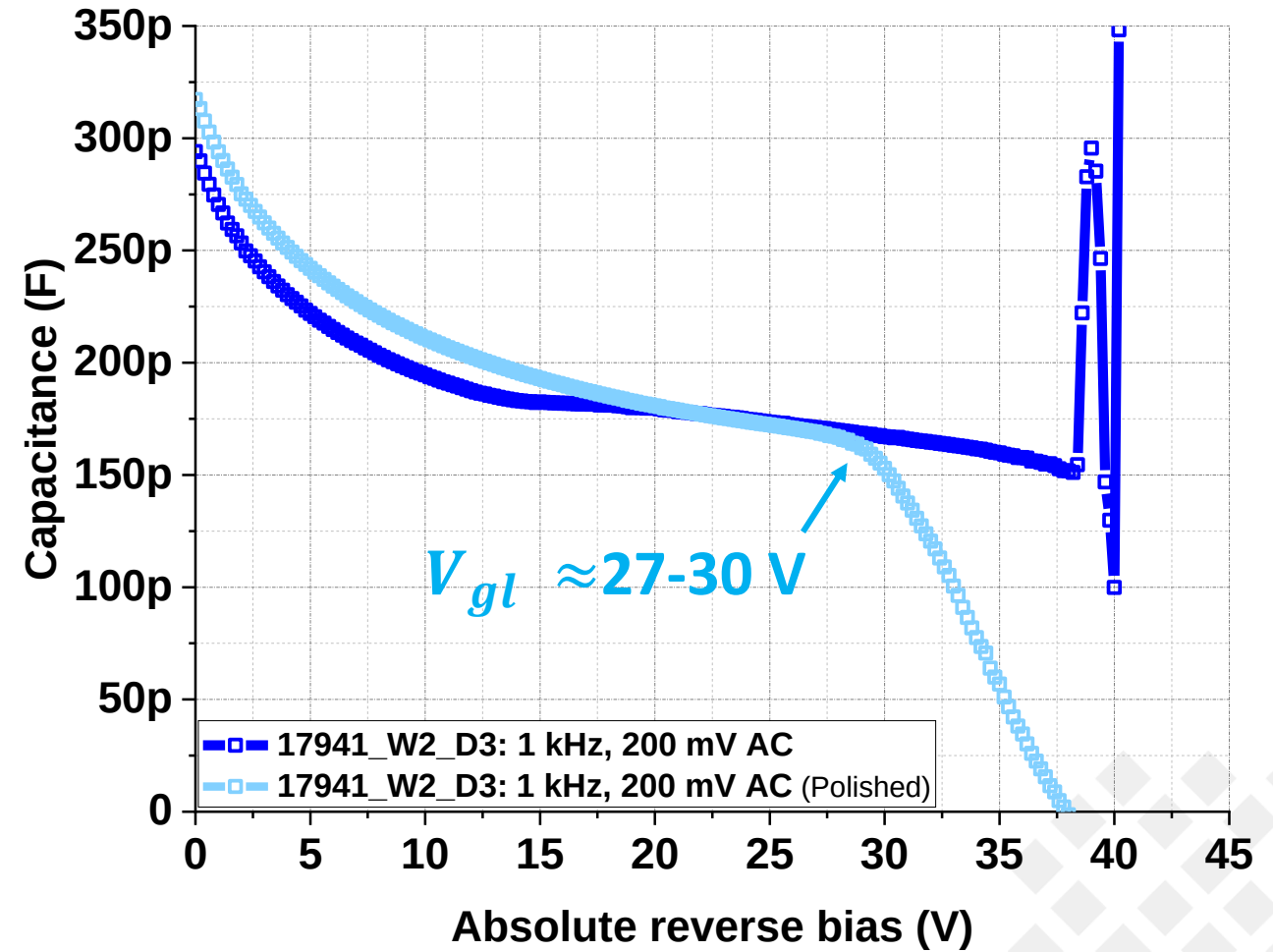
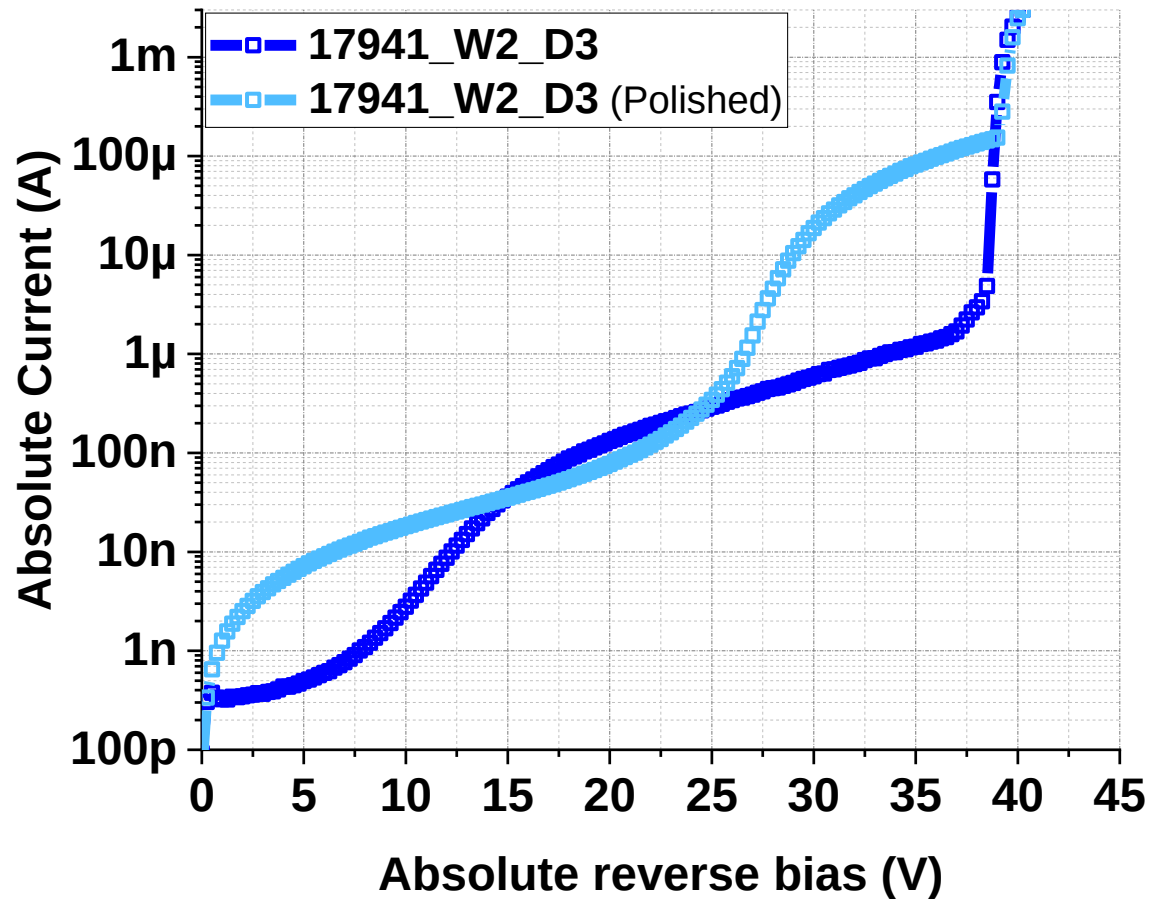
- Design of the **silicon-free termination** between the trenches at the periphery



4TILG(2,3)v2. Polishing @ Periphery

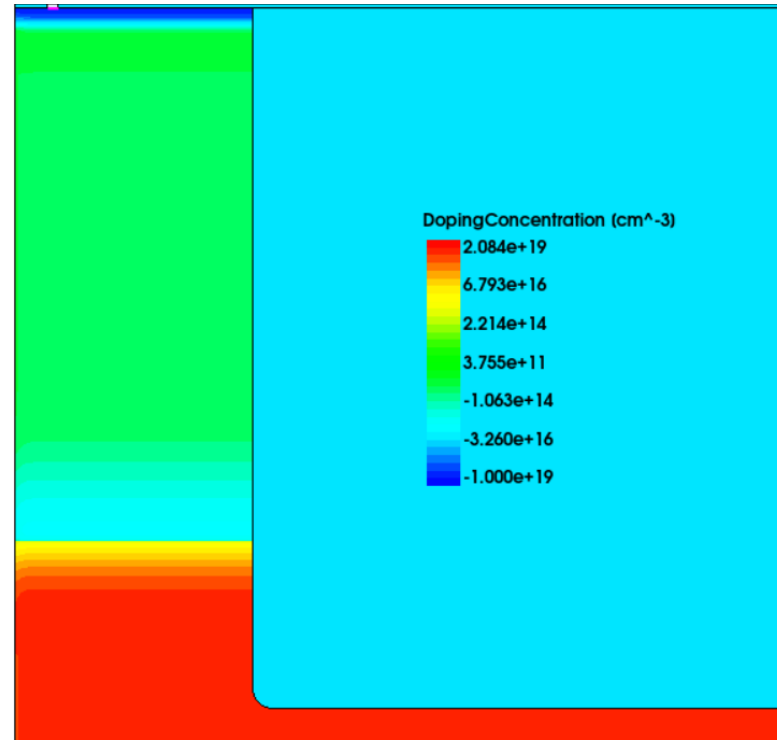


4TILG(2,3)v2. Polishing @ Periphery

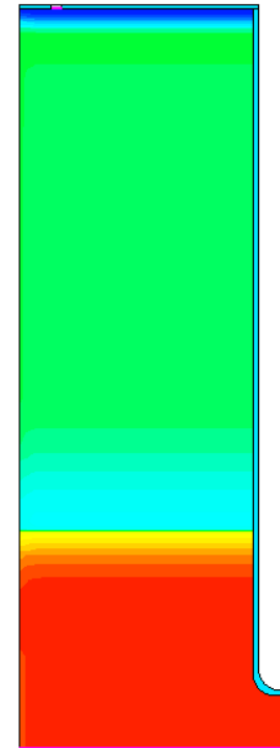


4TILG(2,3)v3. New Design @ Termination. TCAD

- New design of the termination at the periphery
- Two trench designs simulated:
 - Fabrication of **wide trench** is difficult
 - Trench etched through **Bosch process** is possible



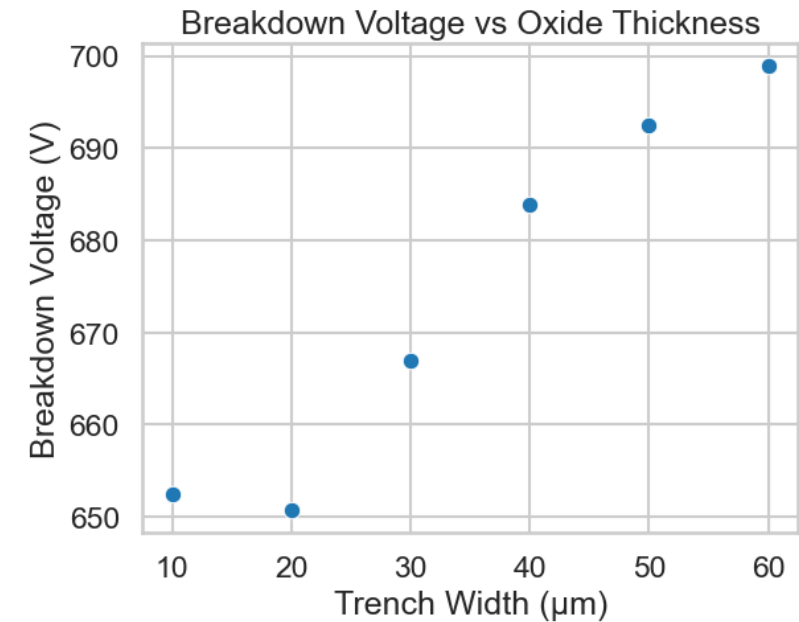
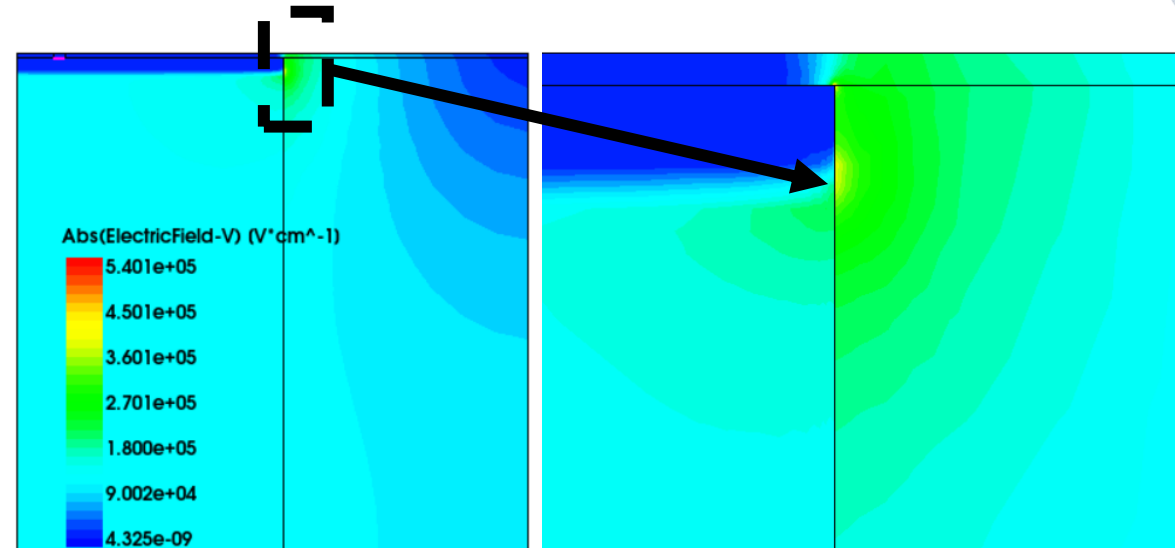
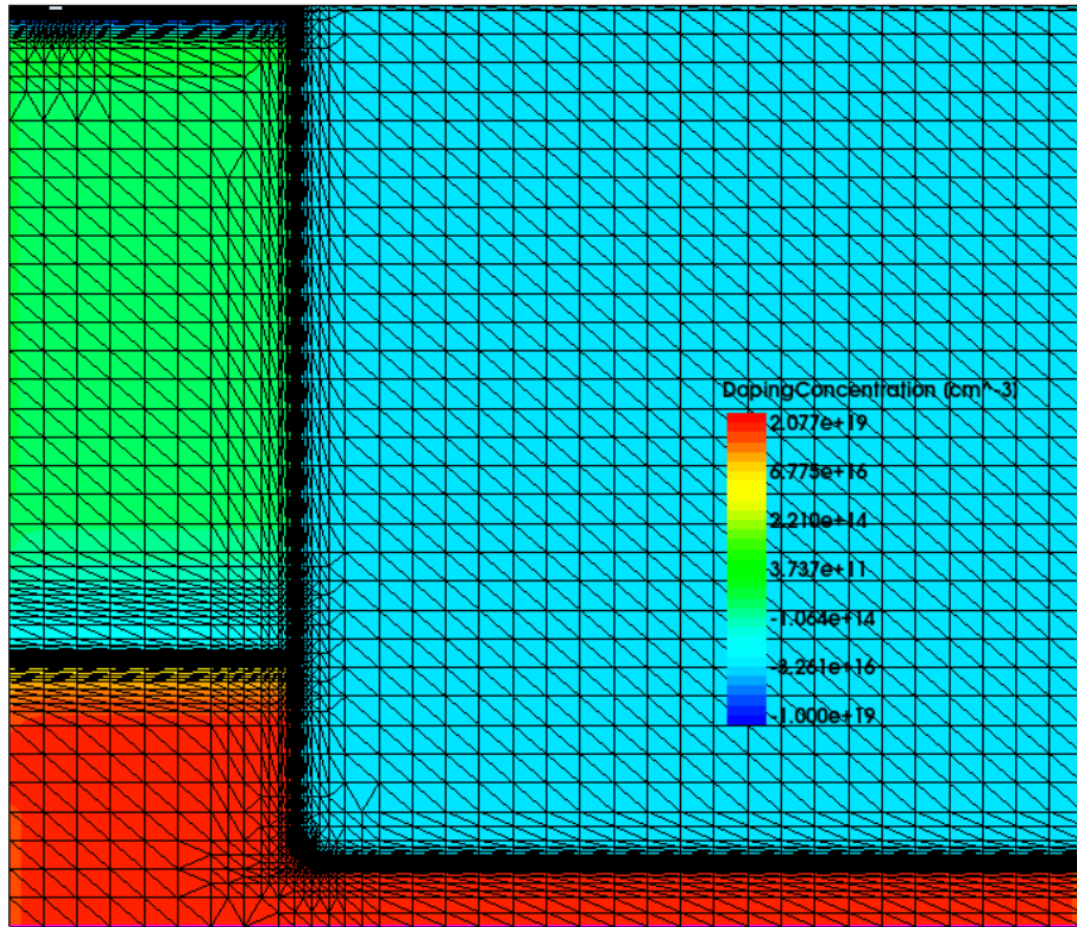
Wide Oxide Trench



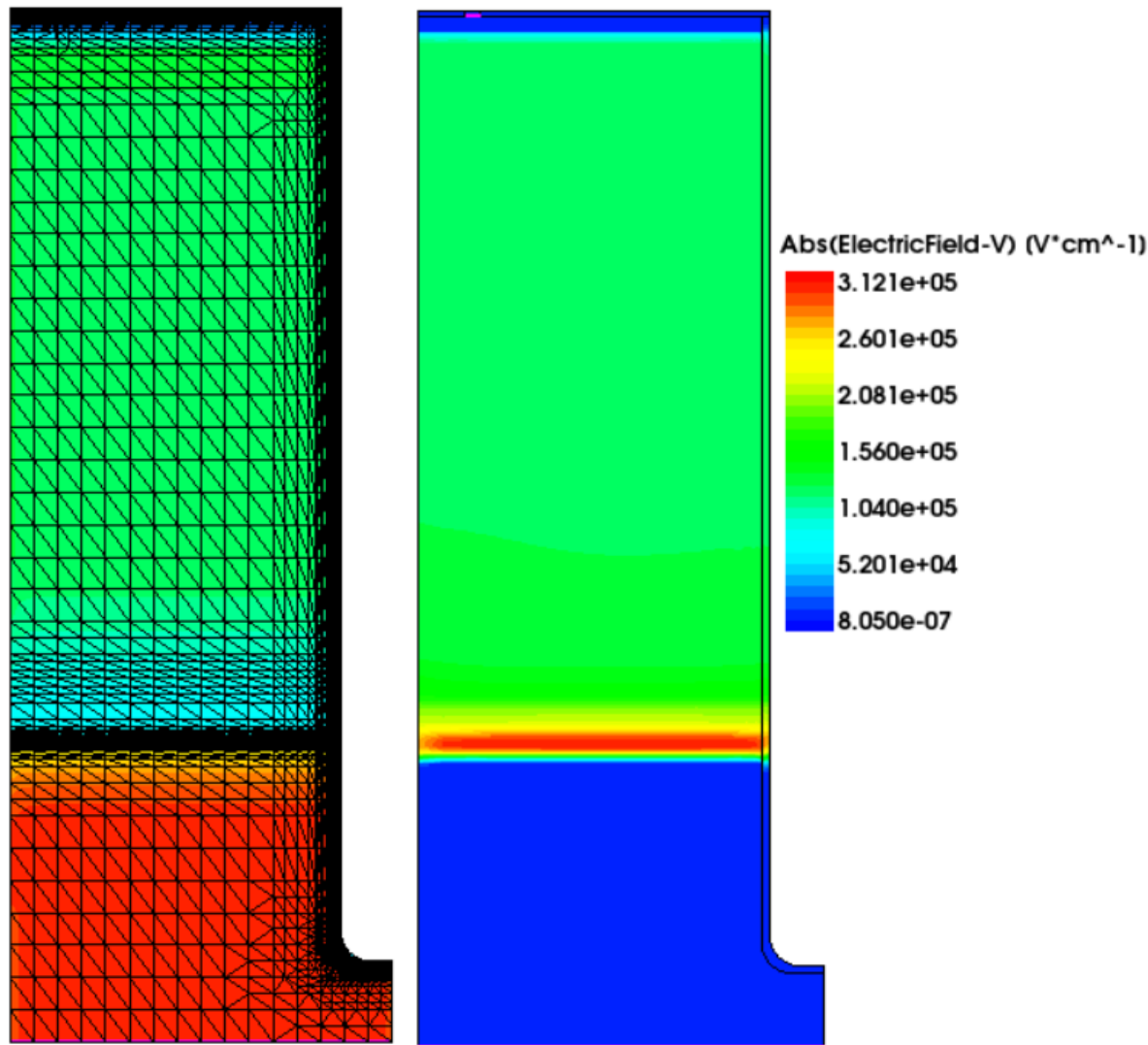
Bosch Oxide Trench



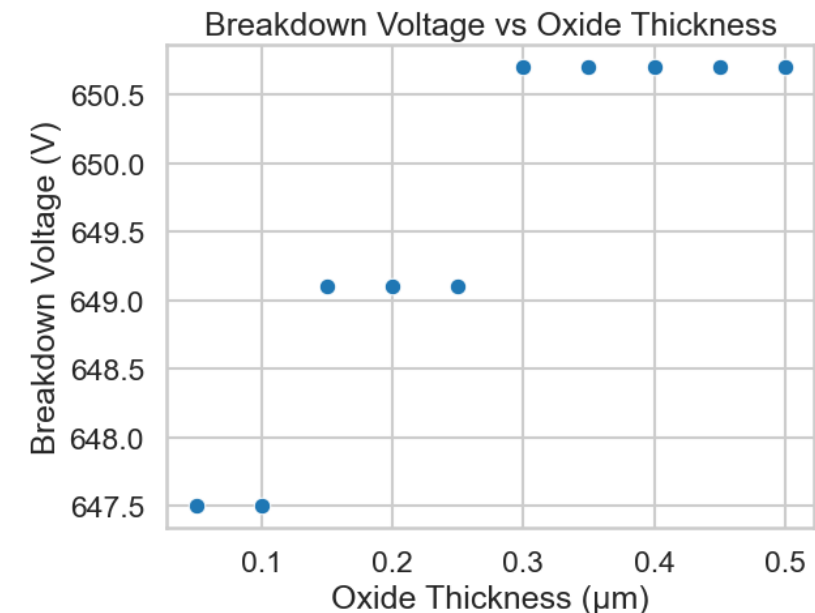
4TILG(2,3)v3. New Design. TCAD. Wide Trench



4TILG(2,3)v3. New Design. TCAD. Bosch Trench

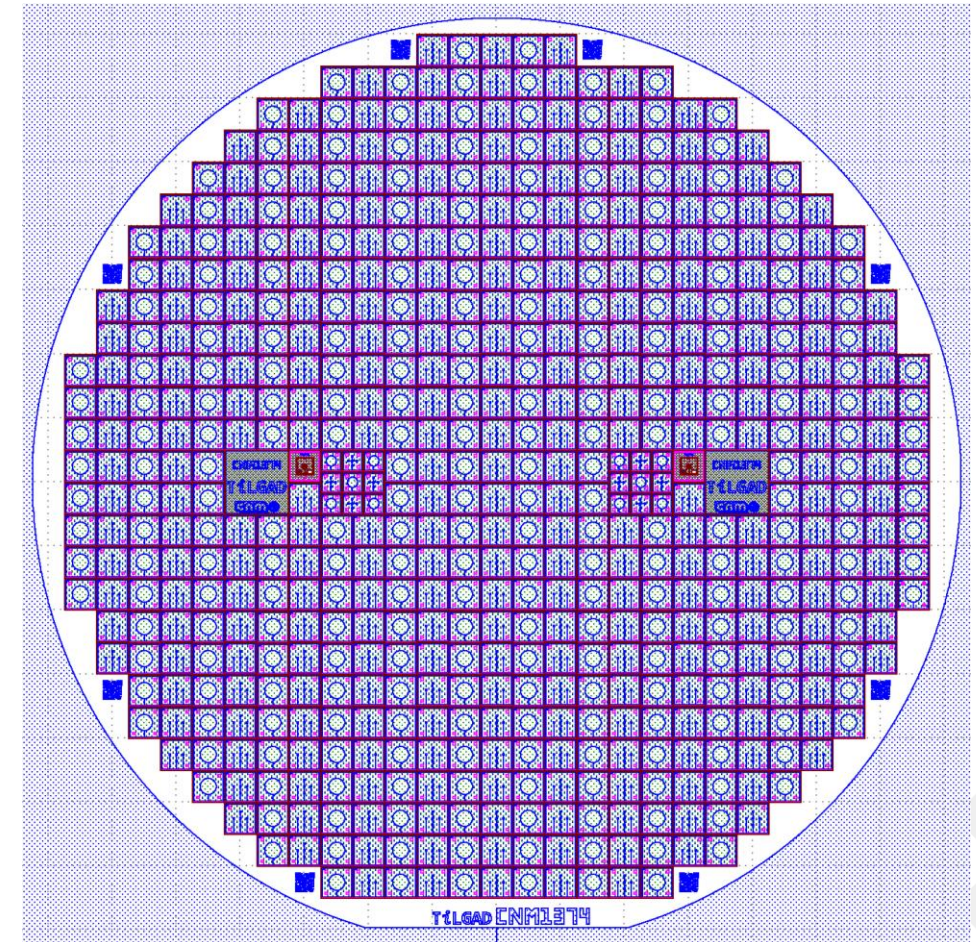


- Passivation layer: Oxide
- Variation of the passivation layer thickness
✓ 0.05 to 0.5 μm , step of 0.05 μm
- Voltage: 650 V
- Highest Electric Field along the multiplication layer $\approx 3e5 V/cm$
- Issue of breakdown voltage at the periphery fixed with this design



Next Step. 4TiLG3v3

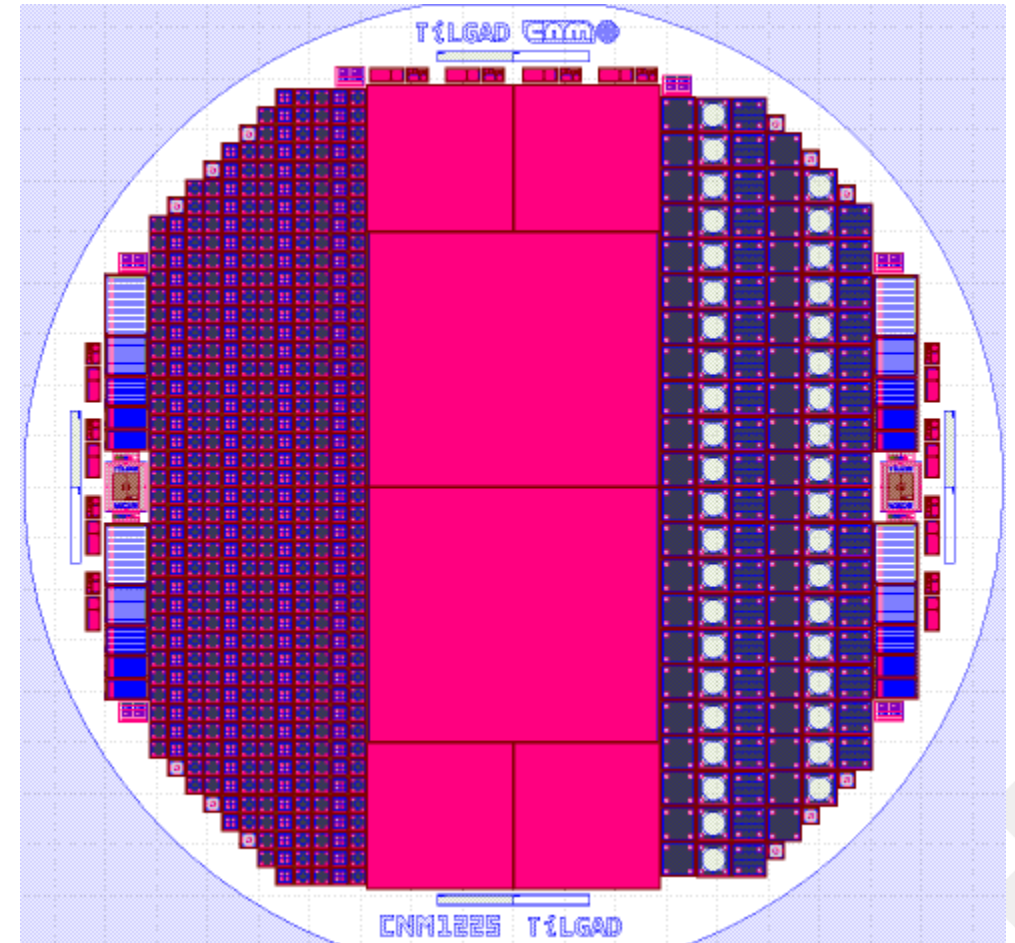
- 6 Epitaxial wafers
- Pad devices
- The 3rd TiLGAD run focused on optimizing the **Peripheral Trench Formation** to obtain LGAD behavior rather than APD or PiN
- Trench definition during the final steps of the fabrication process => **Bosch Process**
- Run Planned
- Mask Set at Clean Room (CNM1374)



Oblea de 100 mm en la que se integraran prototipos de detectores Trench iLGAD con diseño Single Pad. Segunda Generación. Tecnología 4TiLG3v3

Next Step. 4TiLG3v4

- 6 Epitaxial wafers
- Timepix3, Timepix4 devices
- The 4th TiLGAD run focused on optimizing the Thermal Process to obtain LGAD behavior rather than APD or PiN
- Trench definition during the final steps of the fabrication process => Bosch Process
- Run Planned
- Mask Set at Clean Room (CNM1225)

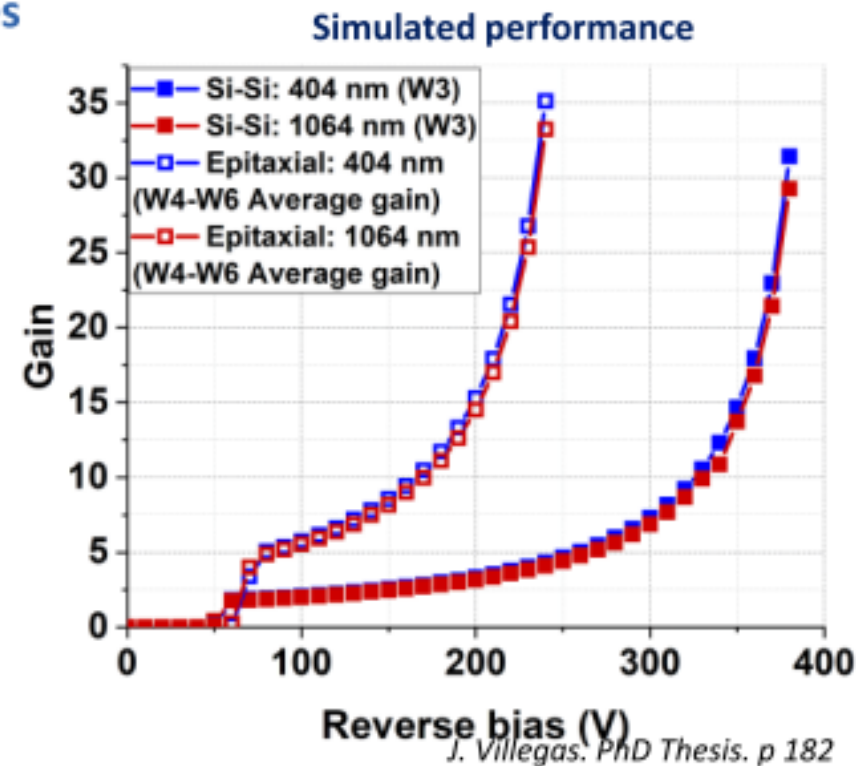
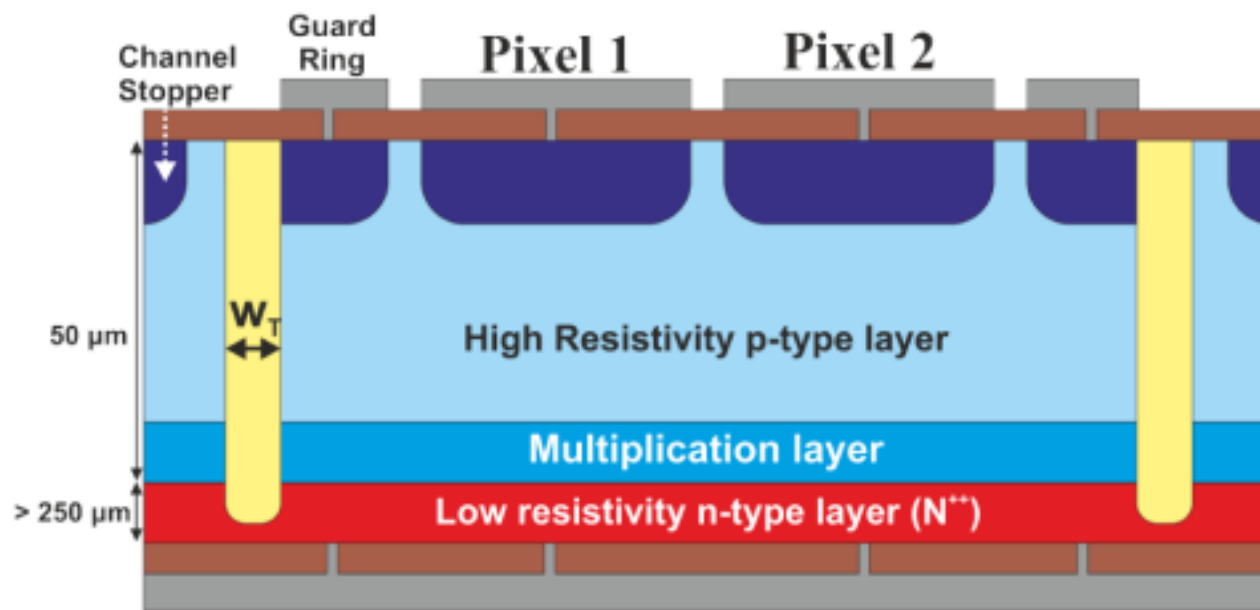


Oblea de 100 mm en la que se integraran prototipos de detectores Trench iLGAD con diseño Timepix4. Segunda Generación. Tecnología 4TiLG3v4

Trench iLGAD for High- and Low- Penetrating Particles

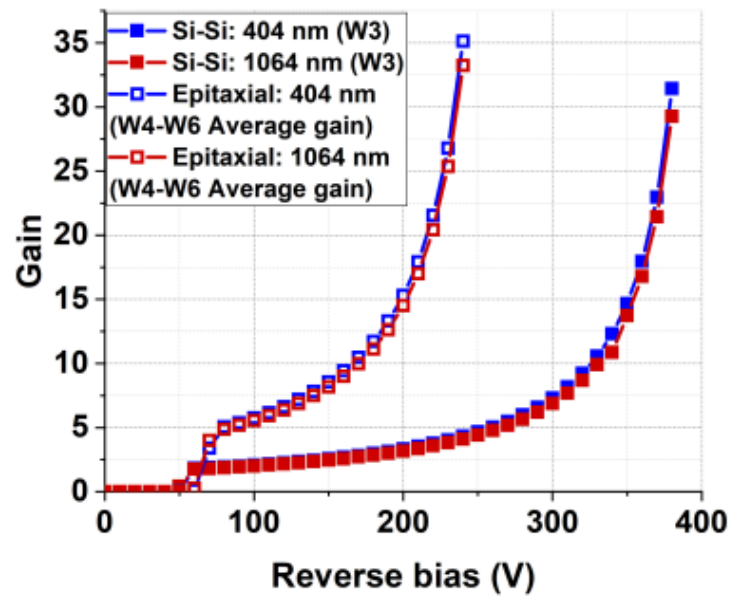
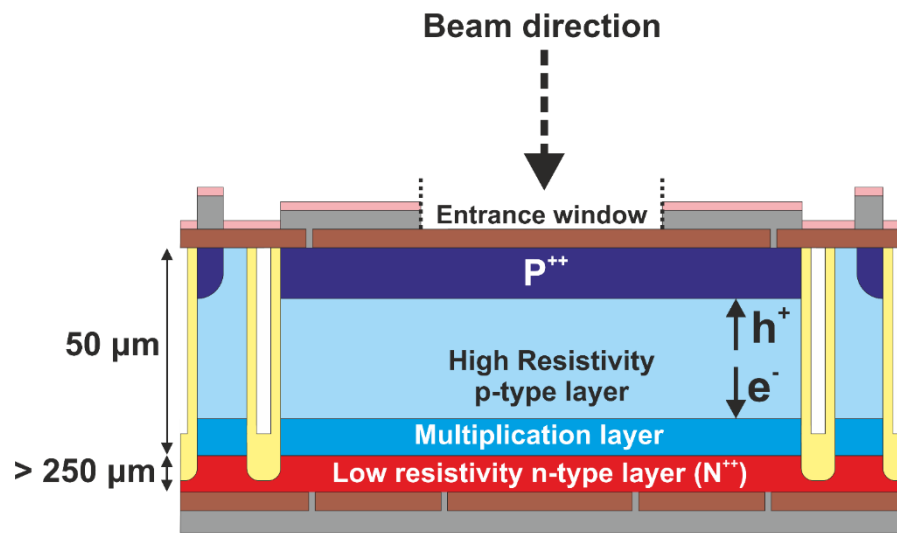
Concept: **Inverse LGAD** (pixels on the P+ electrode) + **isolation of active area with trenches**

- **Multiplication region** is fully **isolated**.
- Nominally **100% fill factor**
- **Simpler single-side** and **50% less** fabrication steps than iLGADs with planar termination
- Optimization of the **multiplication layer is independent of charge collection and cross-talk at the electrodes**
- **Good performance for both high and low penetrating particles**



Trench iLGAD for High- and Low- Penetrating Particles

- LGADs from 6LG1v1 (R18399,W11-W12) can be illuminated with TCT light from the BACKSIDE
- For both low (TCT 404 nm blue) and high (TCT 1064 nm) penetrating particles, electrons will be the major contributor to trigger avalanche multiplication, just like in the TiLGAD structure
- Hypothesis to test: For a TiLGAD-like structure, the gain response is enhanced for both low- and high-penetrating particles

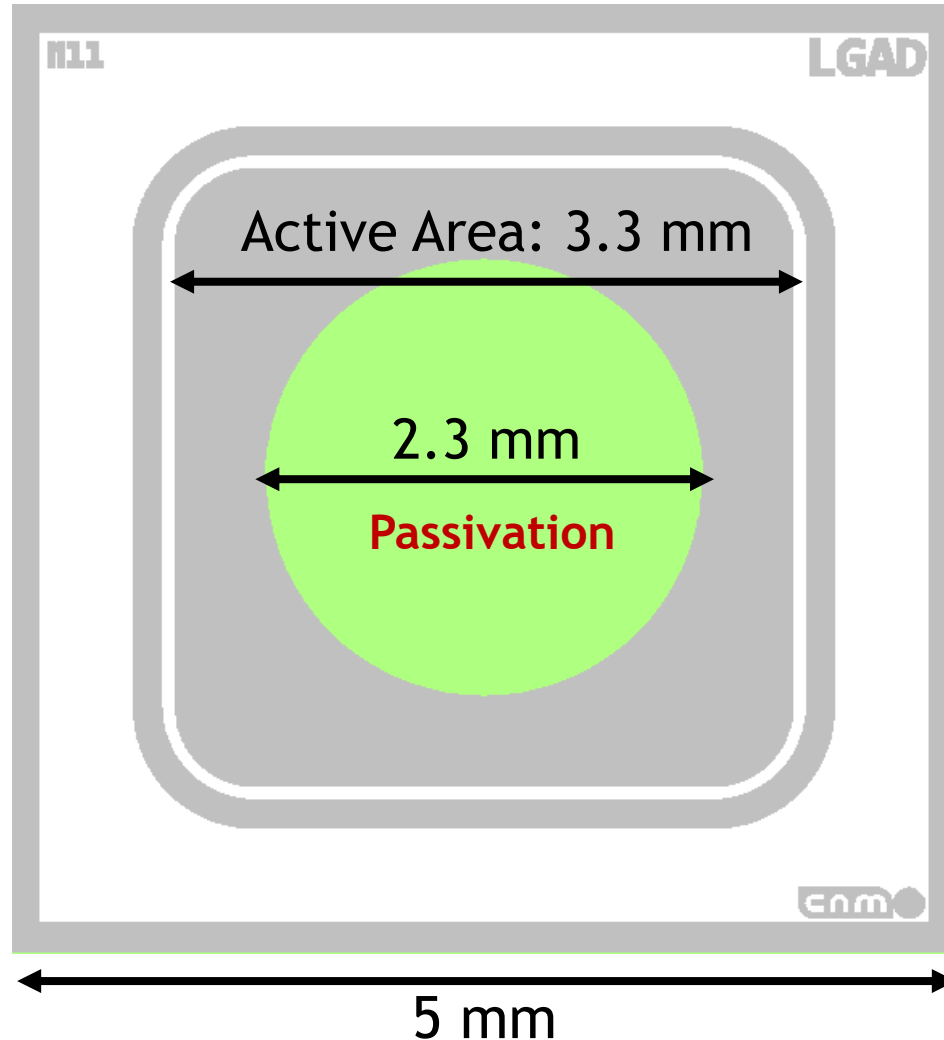


Wafer		Type	T _{ML} (Å)	T _N (Å)
11	CNM (Us)	6'' FZ wafers 300 μm active thickness No handle wafer	Regular screen oxide annealing (expected ≈ 200 Å)	NEW (≈ 600 Å)
12				Regular (≈ 100 Å)

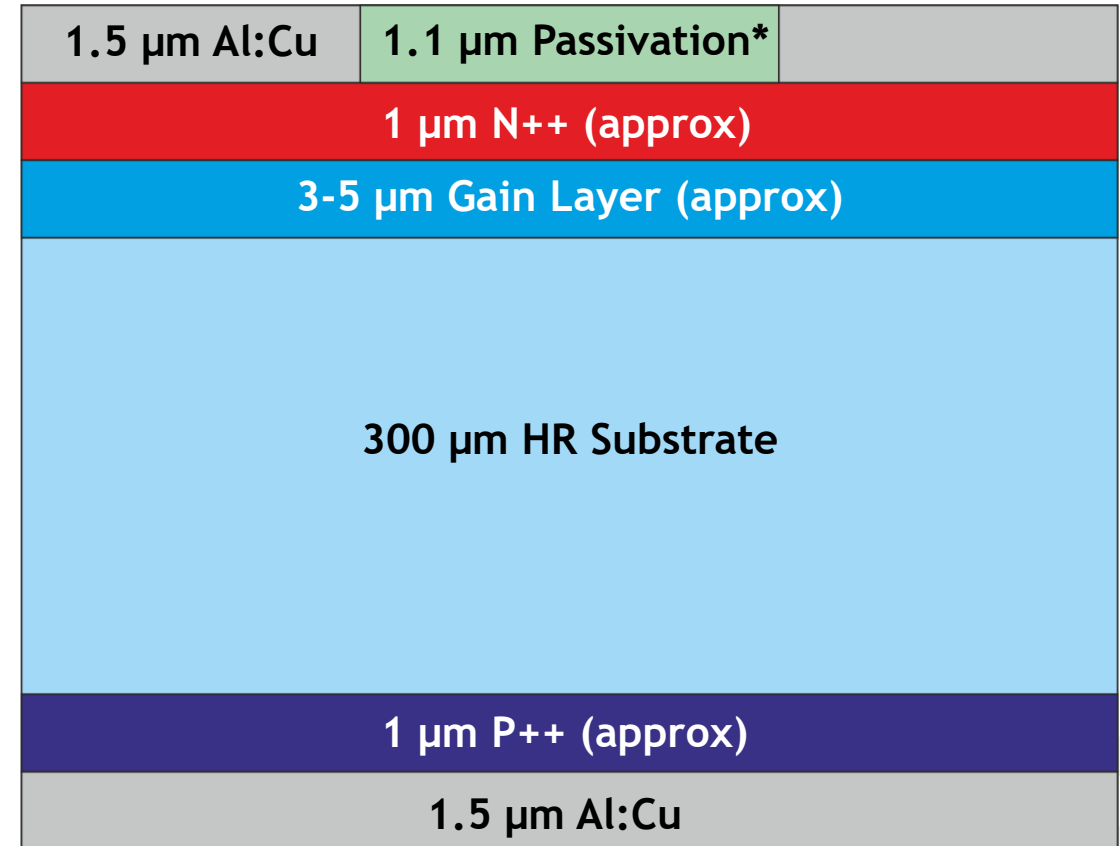


CMS 6LG1v1. Alphas Measurements

Frontside



Backside



* 0.7 μm Silicon Nitride over 0.4 μm SiO₂

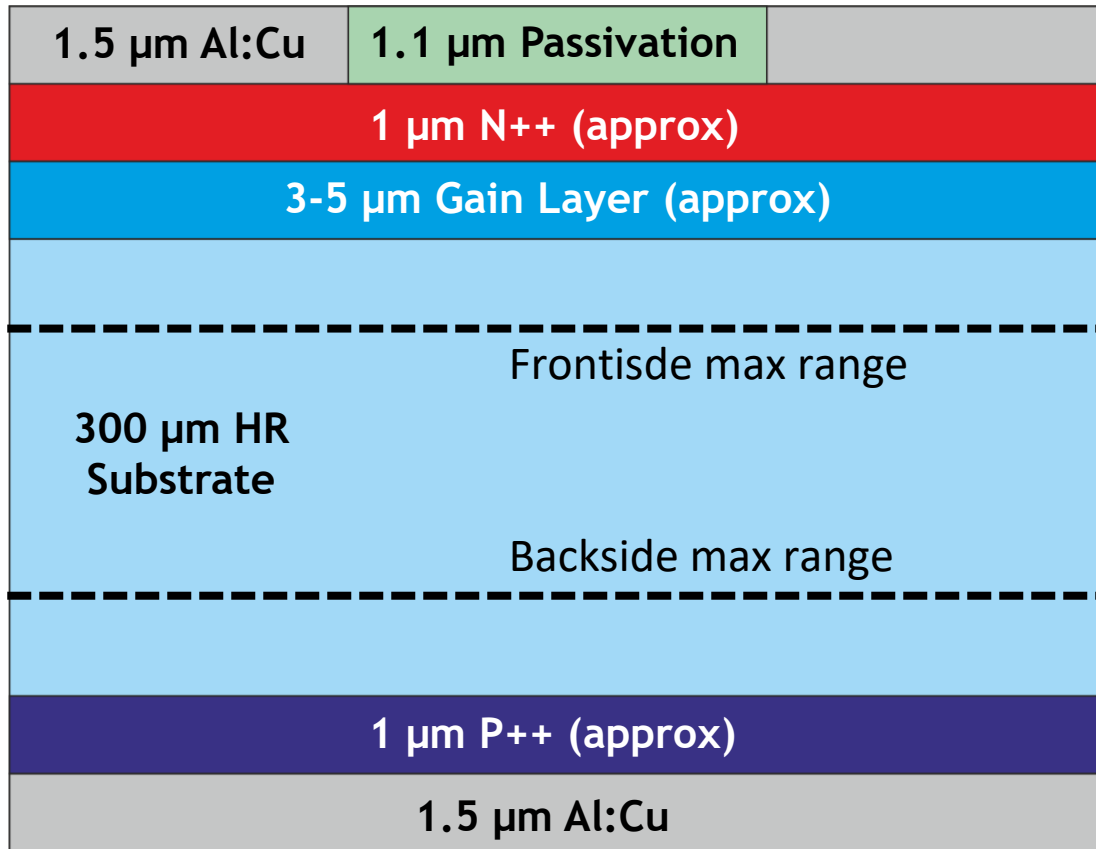
CMS 6LG1v1. Alphas Measurements



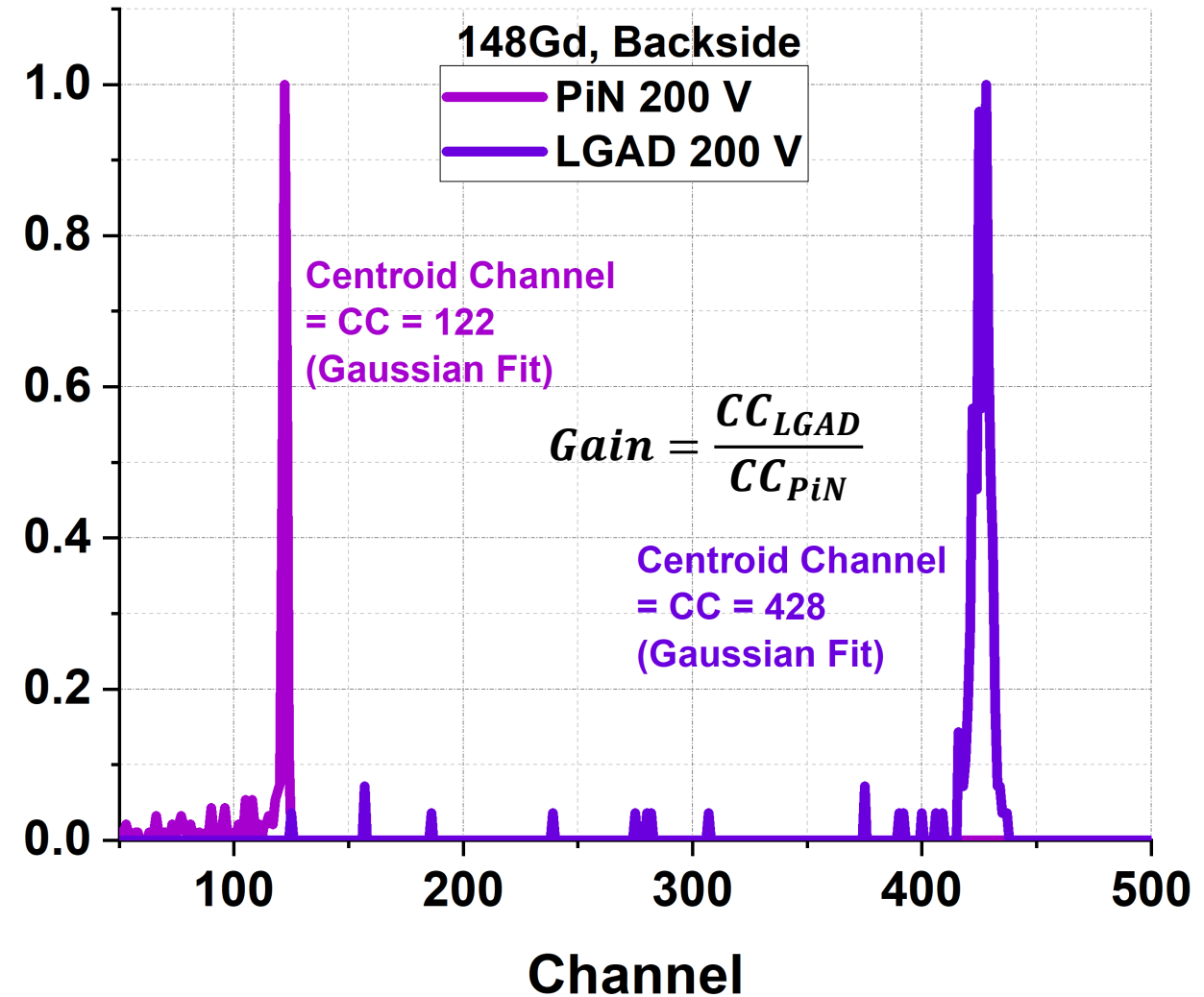
Source	Alpha Energy (MeV)	Range in Silicon (μm)
148Gd	3.18	≈ 12
239Pu	5.16	≈ 24
241Am	5.49	≈ 27
244Cm	5.81	≈ 30
232U	6.29	≈ 34
	6.78	≈ 38
	8.78	≈ 57



CMS 6LG1v1. Alphas Measurements

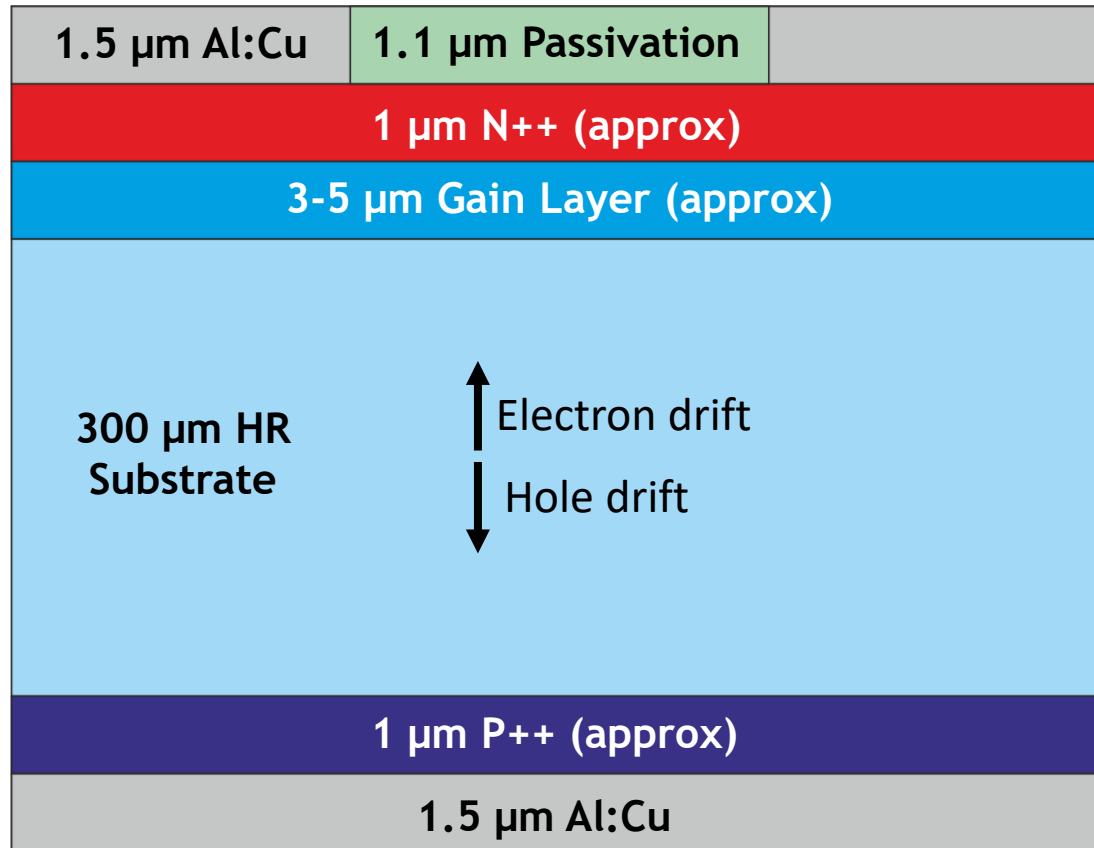


Normalized Spectra

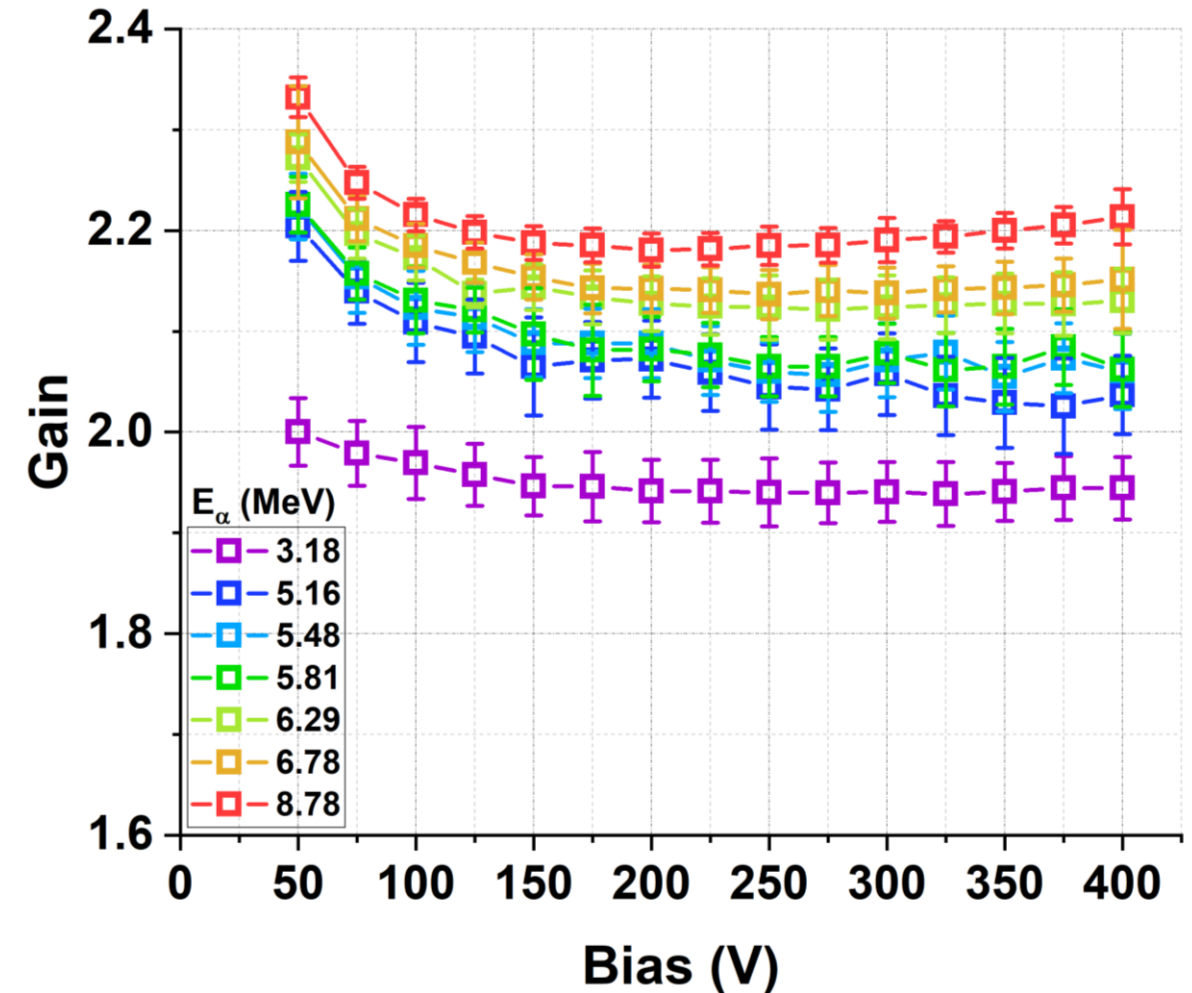


CMS 6LG1v1. Alphas Measurements

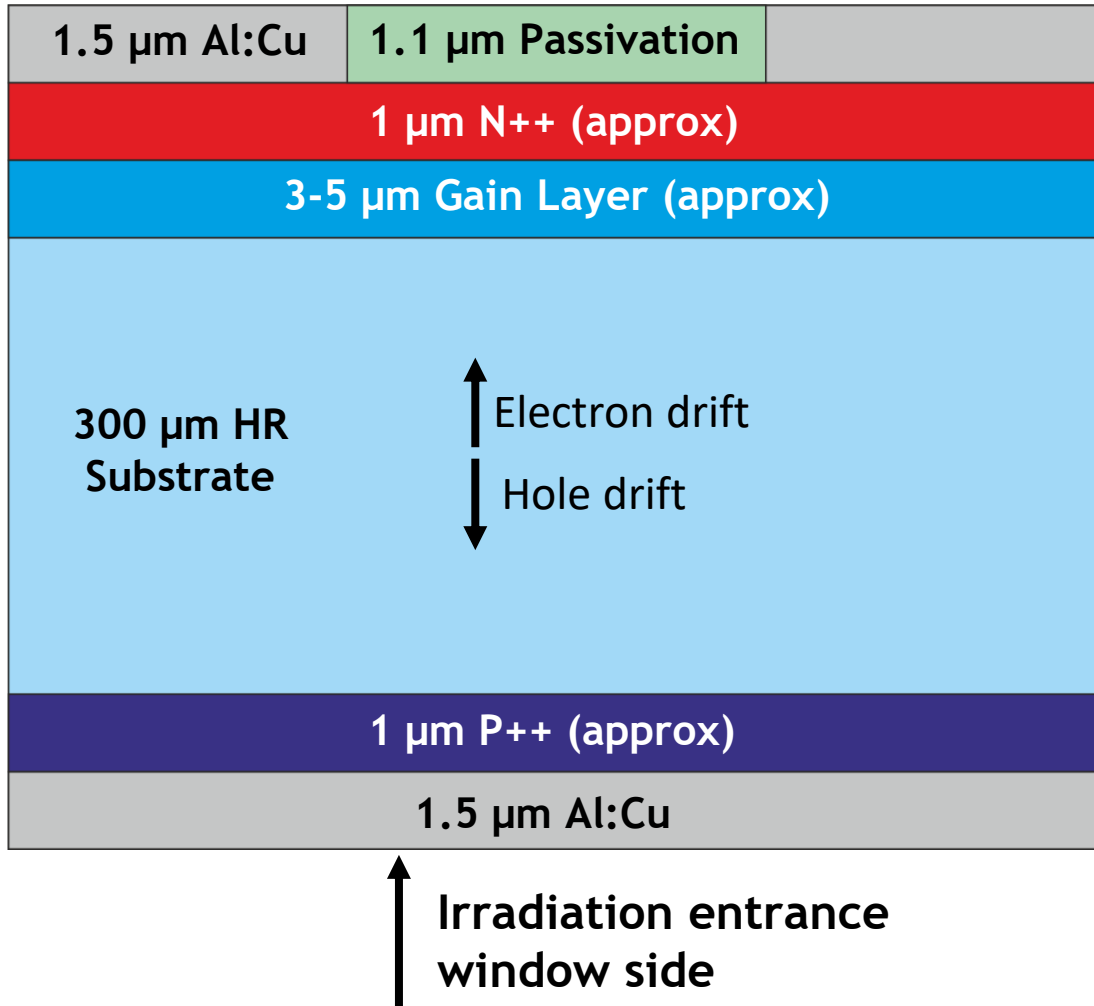
Irradiation entrance
window side



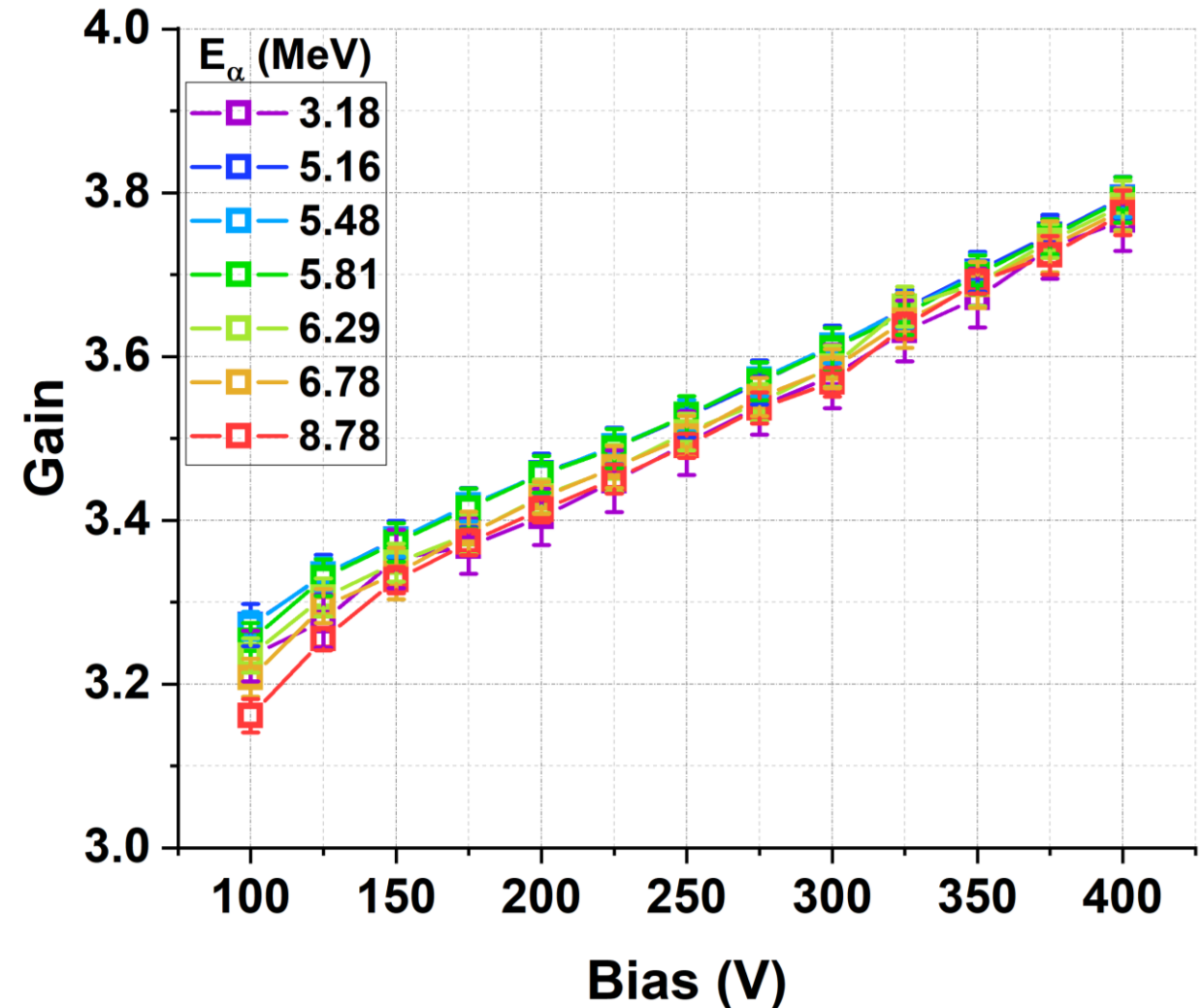
Very low gain and dependent on particle energy
(expected)



CMS 6LG1v1. Alphas Measurements



Higher Gain and less dependent on particle energy



CMS 6LG1v1. Alphas Measurements

Average Energy Resolution in the range [100-400 V]

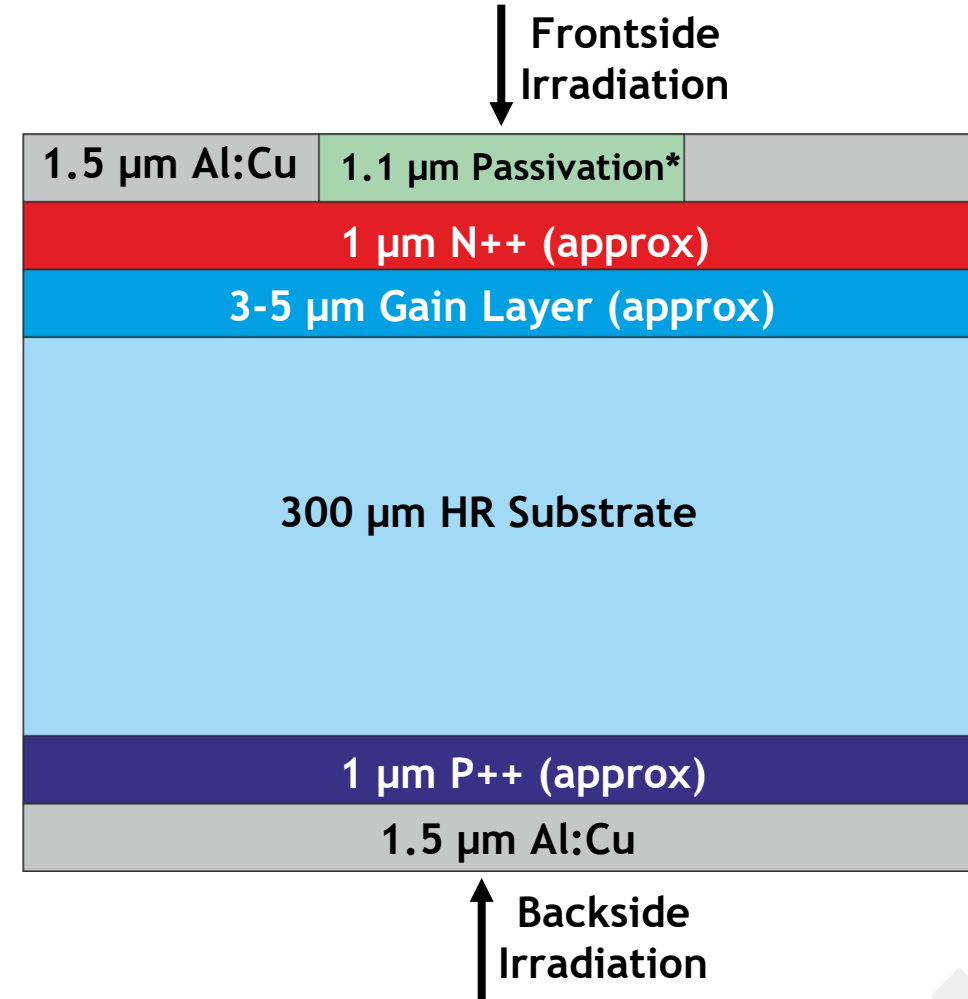
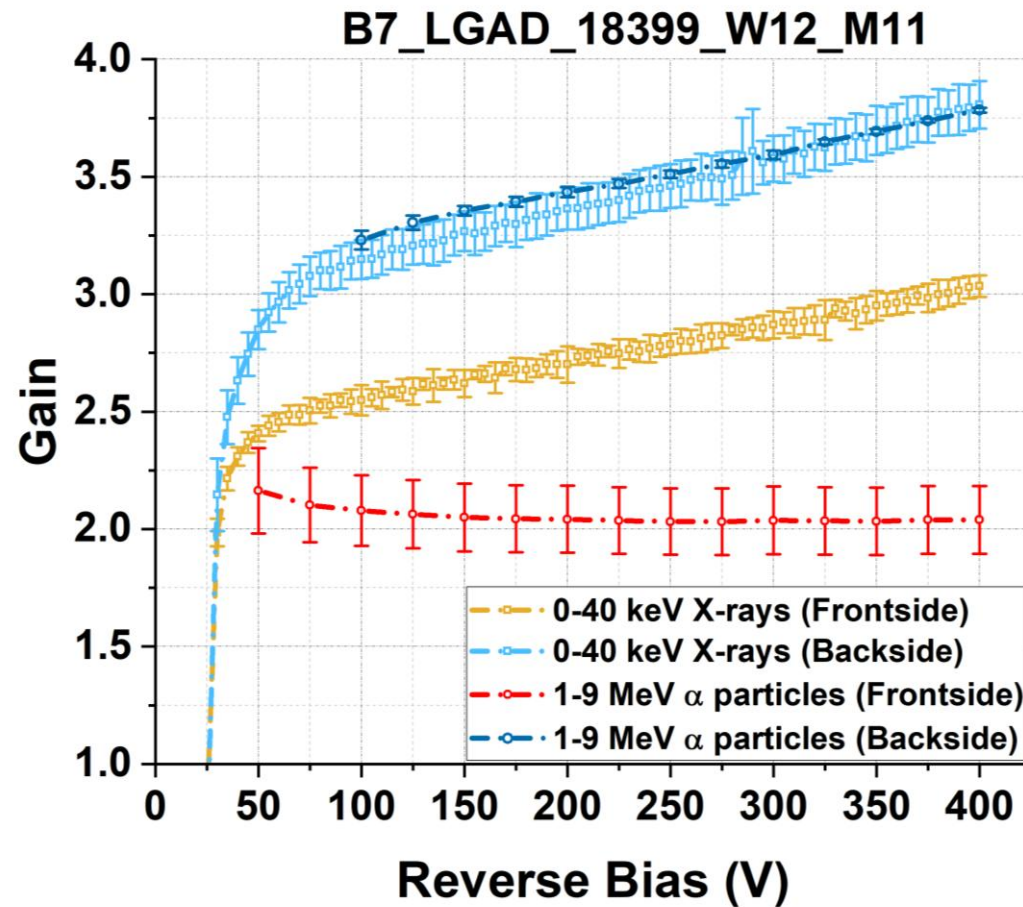
Device	148Gd (3.18 MeV)	239Pu (5.16 MeV)	241Am (5.48 MeV)	244Cm (5.81 MeV)	232U (6.29 MeV)	232U (6.78 MeV)	232U (8.78 MeV)
PiN (Backside)	1.6	1.3	1.0	1.1	1.4	1.2	0.7
LGAD (Backside)	1.8	1.0	1.0	1.1	1.3	1.3	0.9
PiN (Frontside)	1.3	Two overlapped peaks (passivation + metal)*					
LGAD (Frontside)	2.6	Two overlapped peaks (passivation + metal)*					

Similar resolution (defined as FWHM/CC)
for LGAD Backside and PiN

- LGAD typically discarded for Ion Spectrometry because
 - **Gain suppression:** Non linearity between deposited energy and gain
 - **Worse energy resolution** than standard PiN
 - **Gain dependence on Incidence Angle**, also linked to gain suppression → to be tested on iLGADs

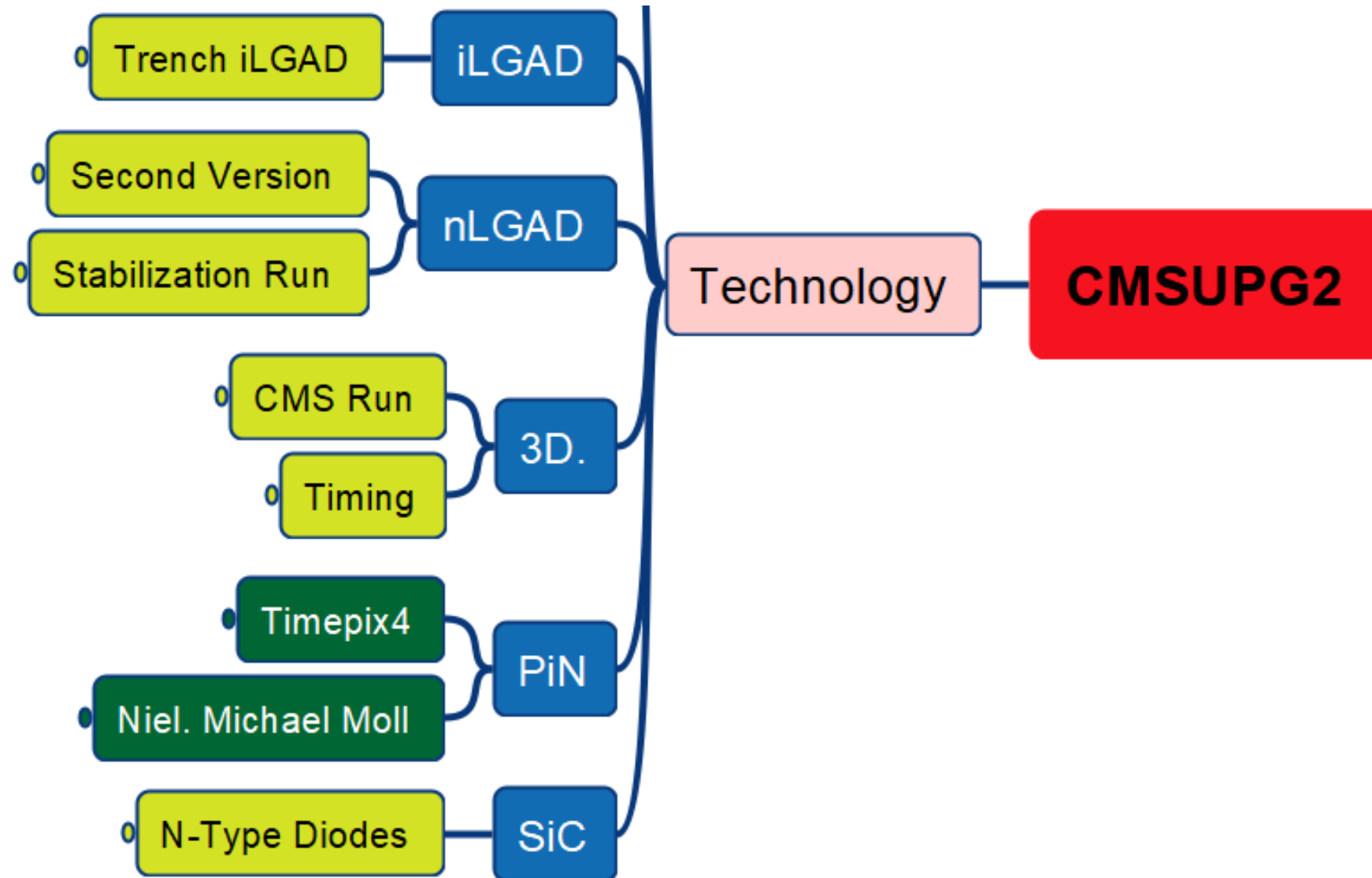


CMS 6LG1v1. X-Rays & Alphas Measurements

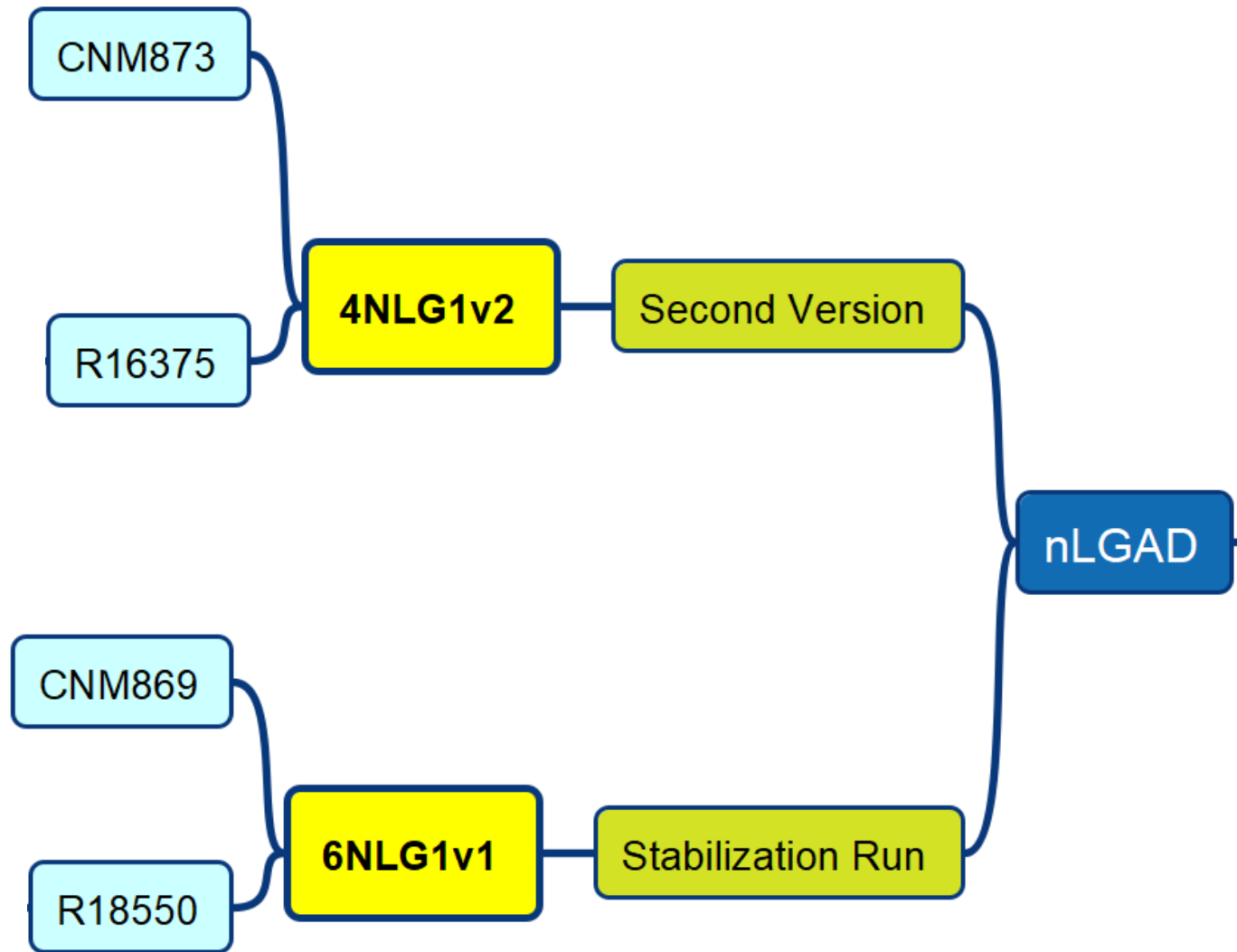
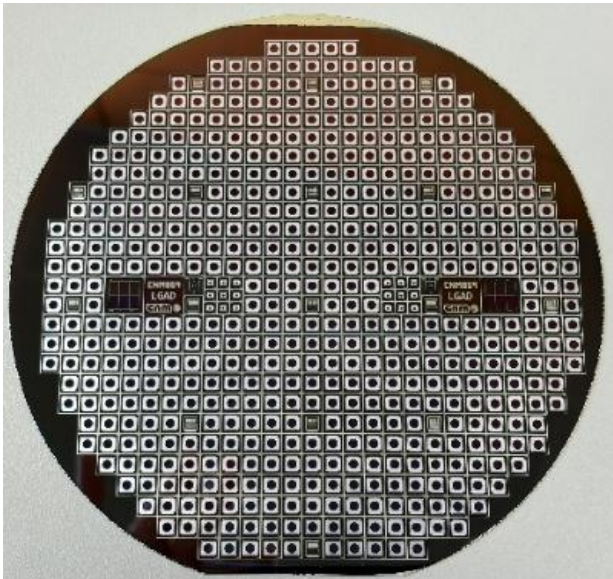
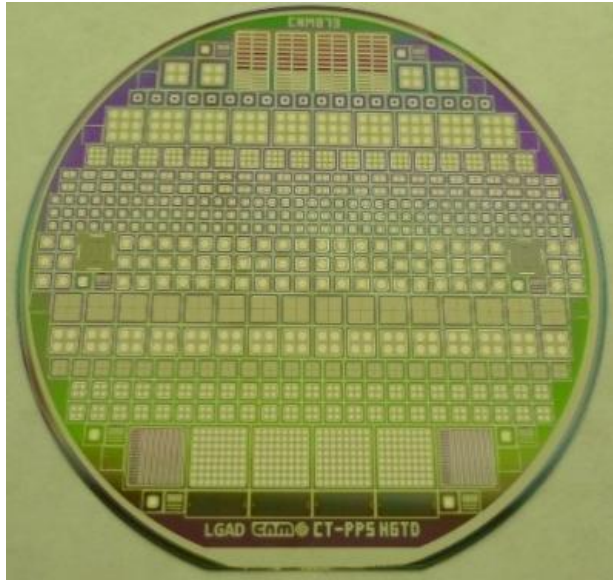


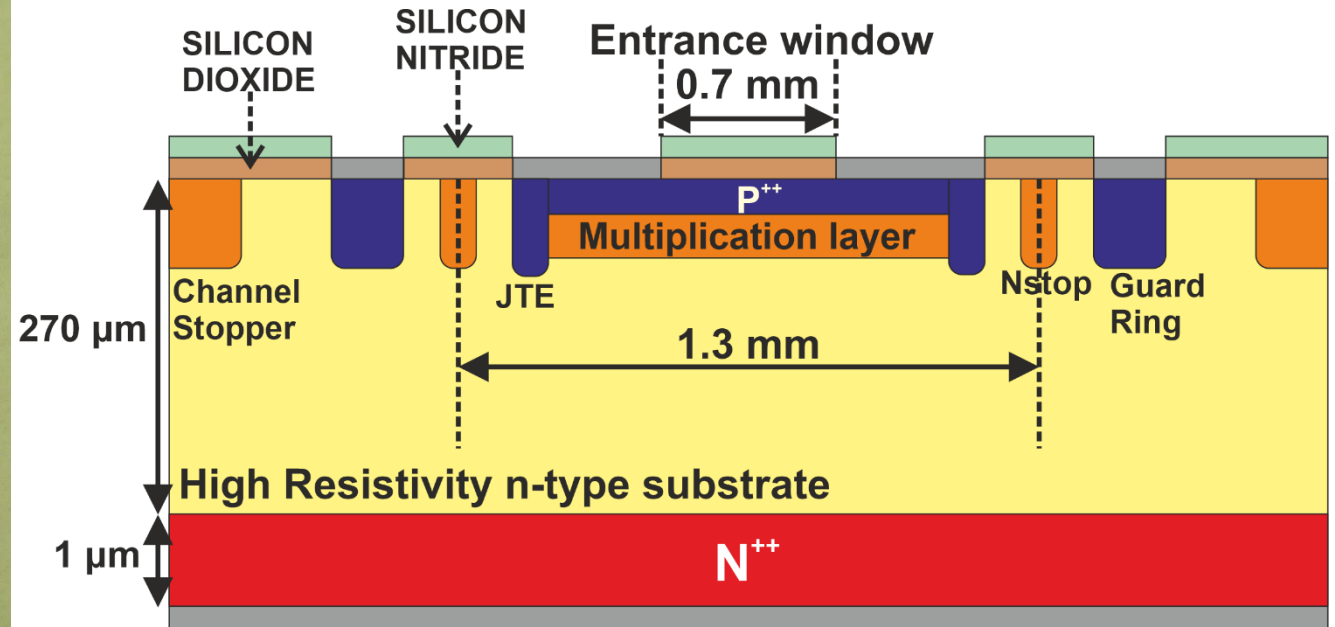
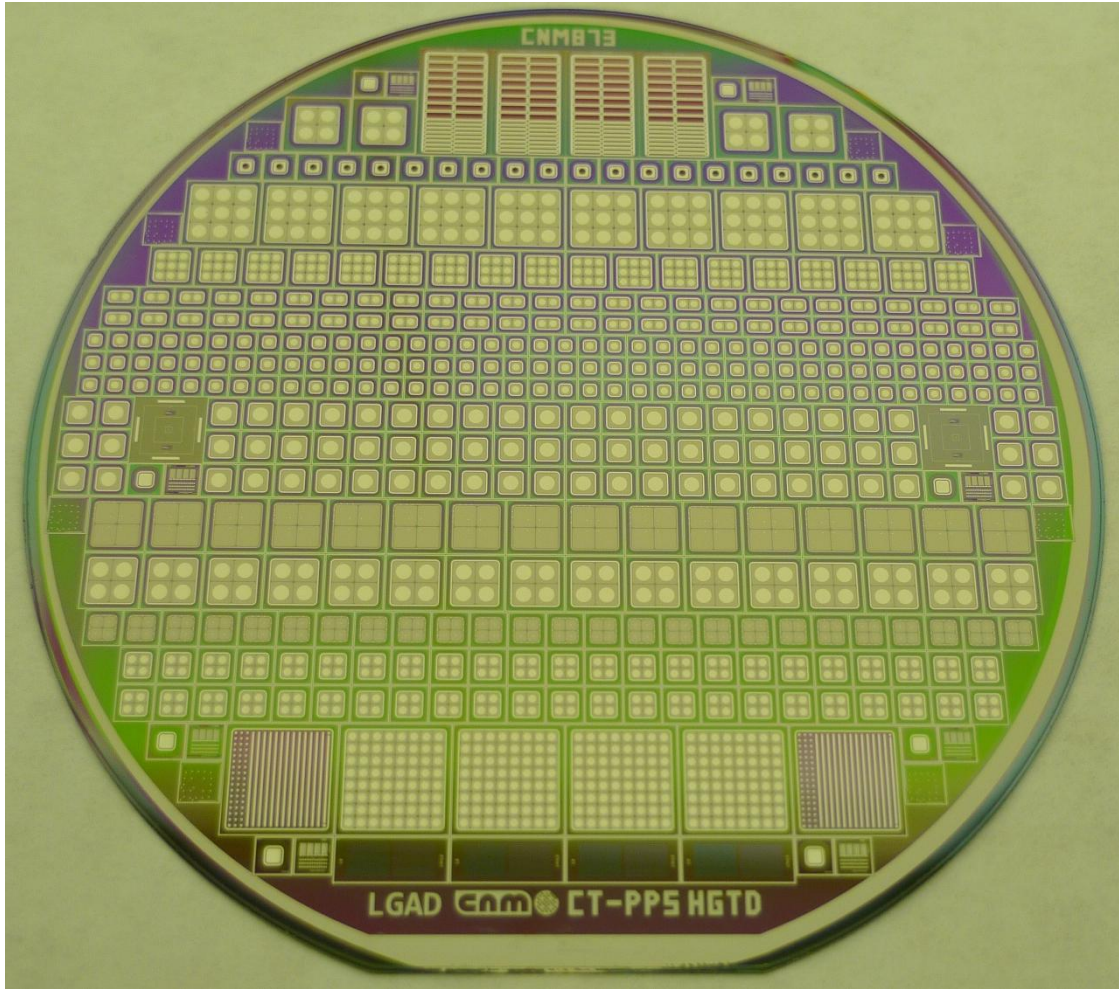
- **No Gain suppression observed** between x-rays and Alpha particles for backside irradiation!
- **Alpha particle results are submitted to Radiation Physics and Chemistry Journal (under review)**
- Results were also presented at 5th DRD3 workshop: indico.cern.ch/event/1634258/contributions/7136734/

Subproject Objectives. WP3



WP3. Technologies Developed. nLGAD



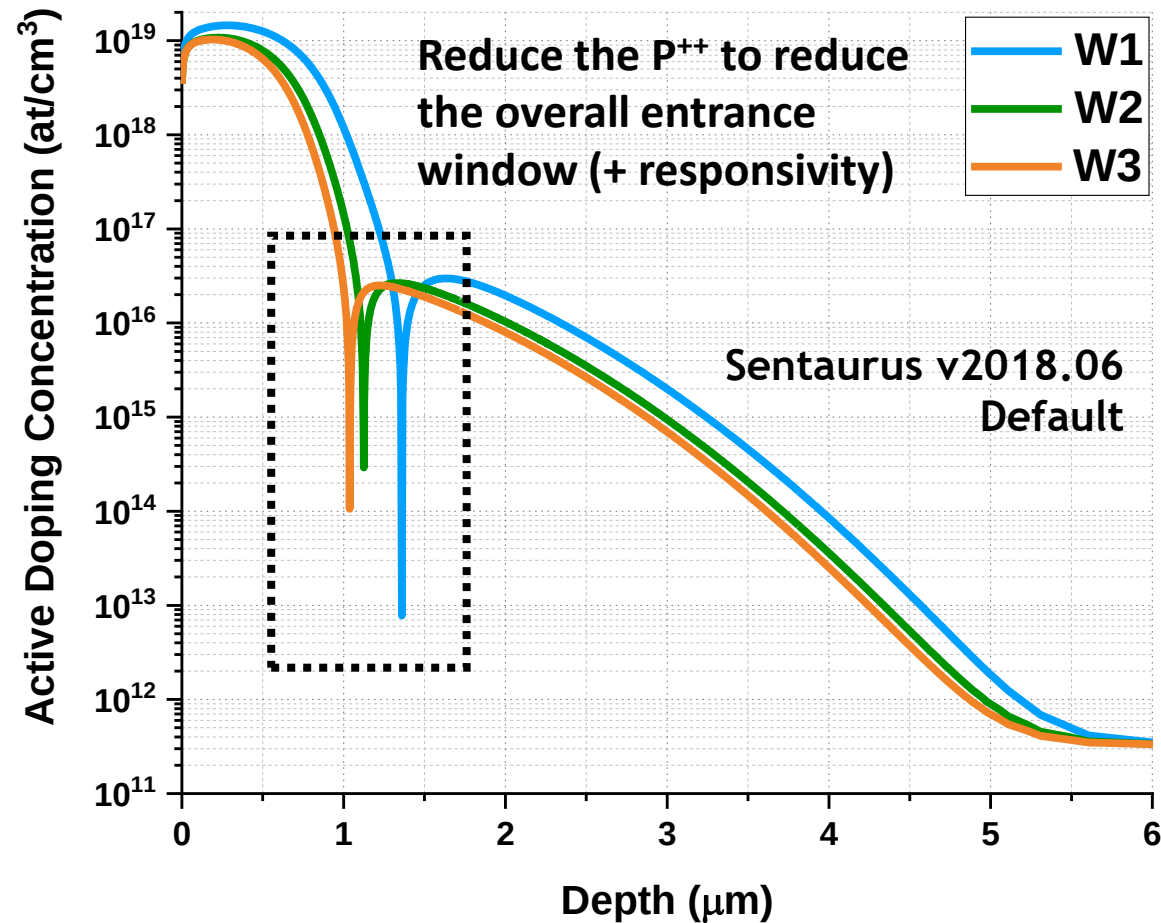


Cross section

Wafer resistivity (measured)

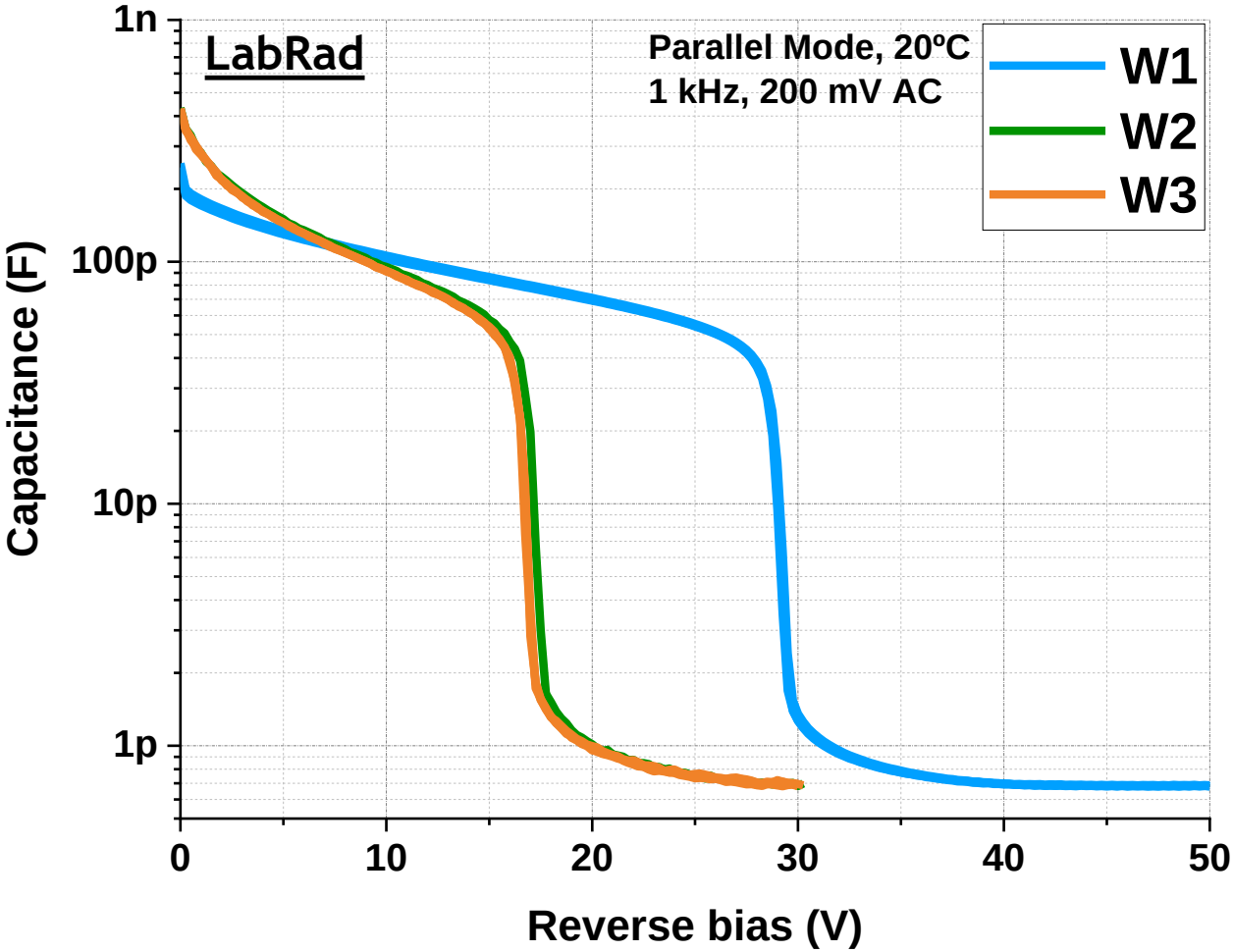
$$27.8 \pm 3.5 \text{ k}\Omega \cdot \text{cm}$$

$$1.6 \pm 0.2 \cdot 10^{11} \text{ at/cm}^3$$



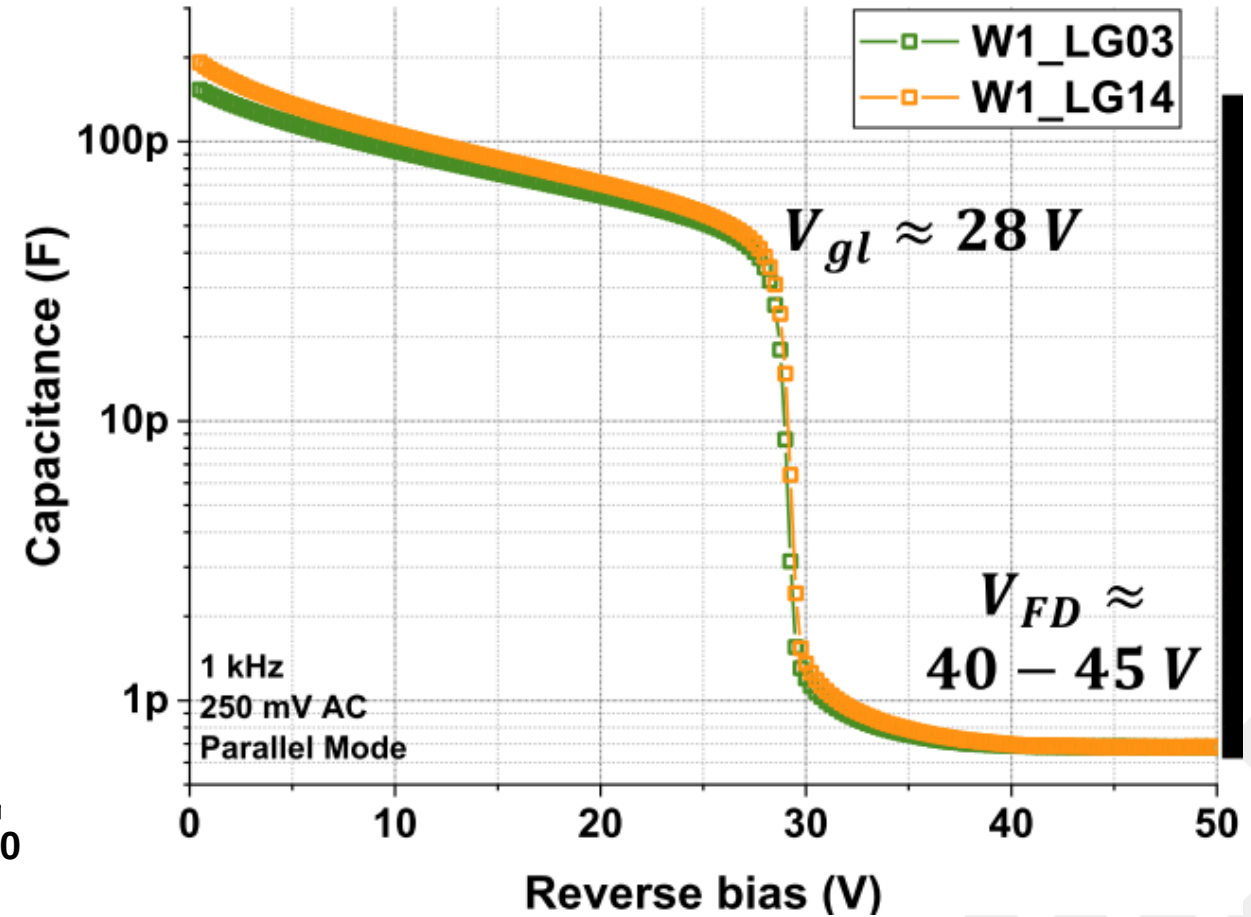
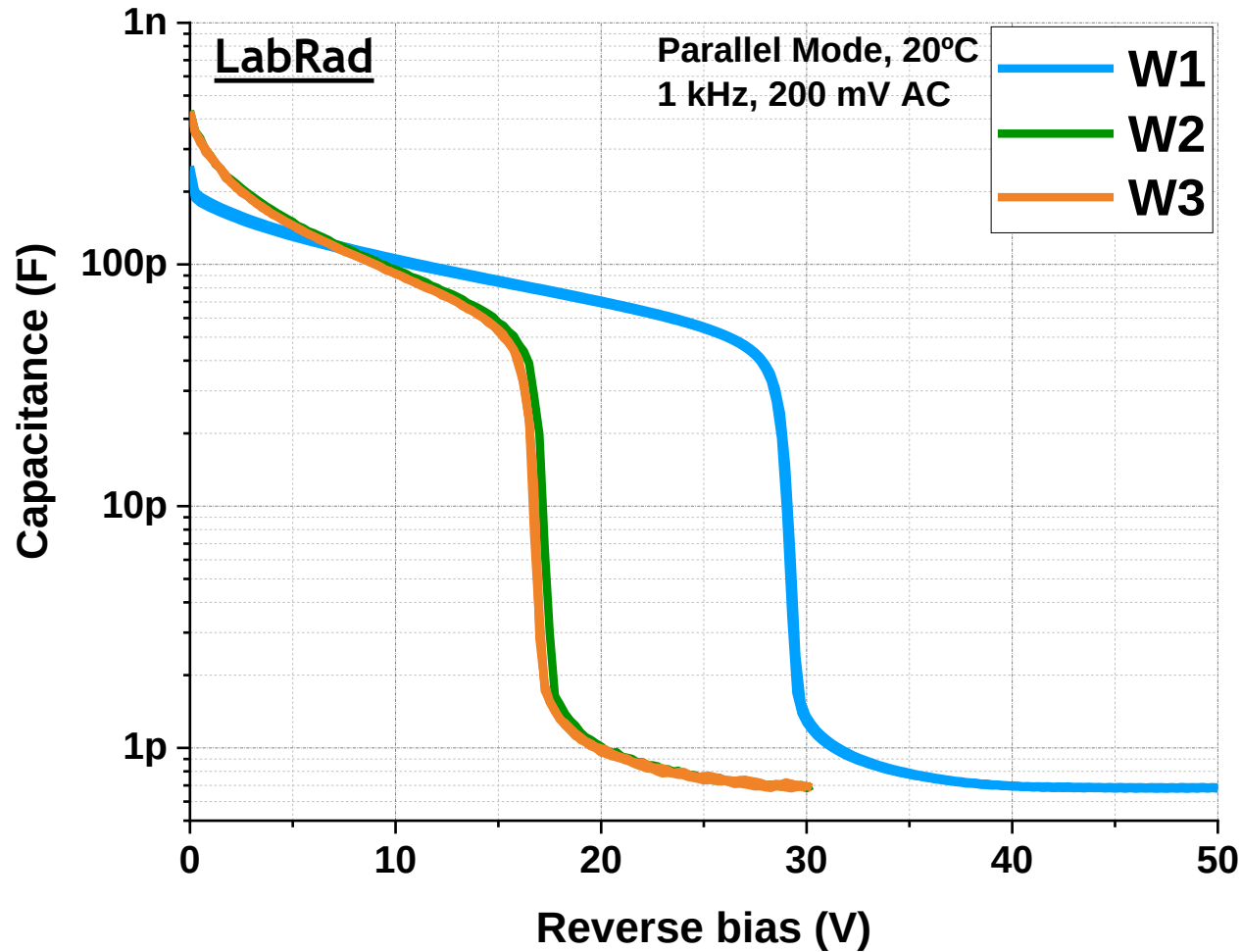
Wafer	Multiplication layer	p ⁺⁺
1	E _{Phos} = 100 keV D _{Phosp} = 1.8e13 at/cm ²	E _{Boron} = 70 & 150 keV D _{Boron} = 1e15 & 5e14 at/cm ²
2	E _{Phos} = 100 keV D _{Phosp} = 1.0e13 at/cm ²	E _{Boron} = 70 keV D _{Boron} = 1e15 at/cm ²
3	E _{Phos} = 100 keV D _{Phosp} = 0.8e13 at/cm ²	E _{Boron} = 50 keV D _{Boron} = 1e15 at/cm ²
4	PiN	

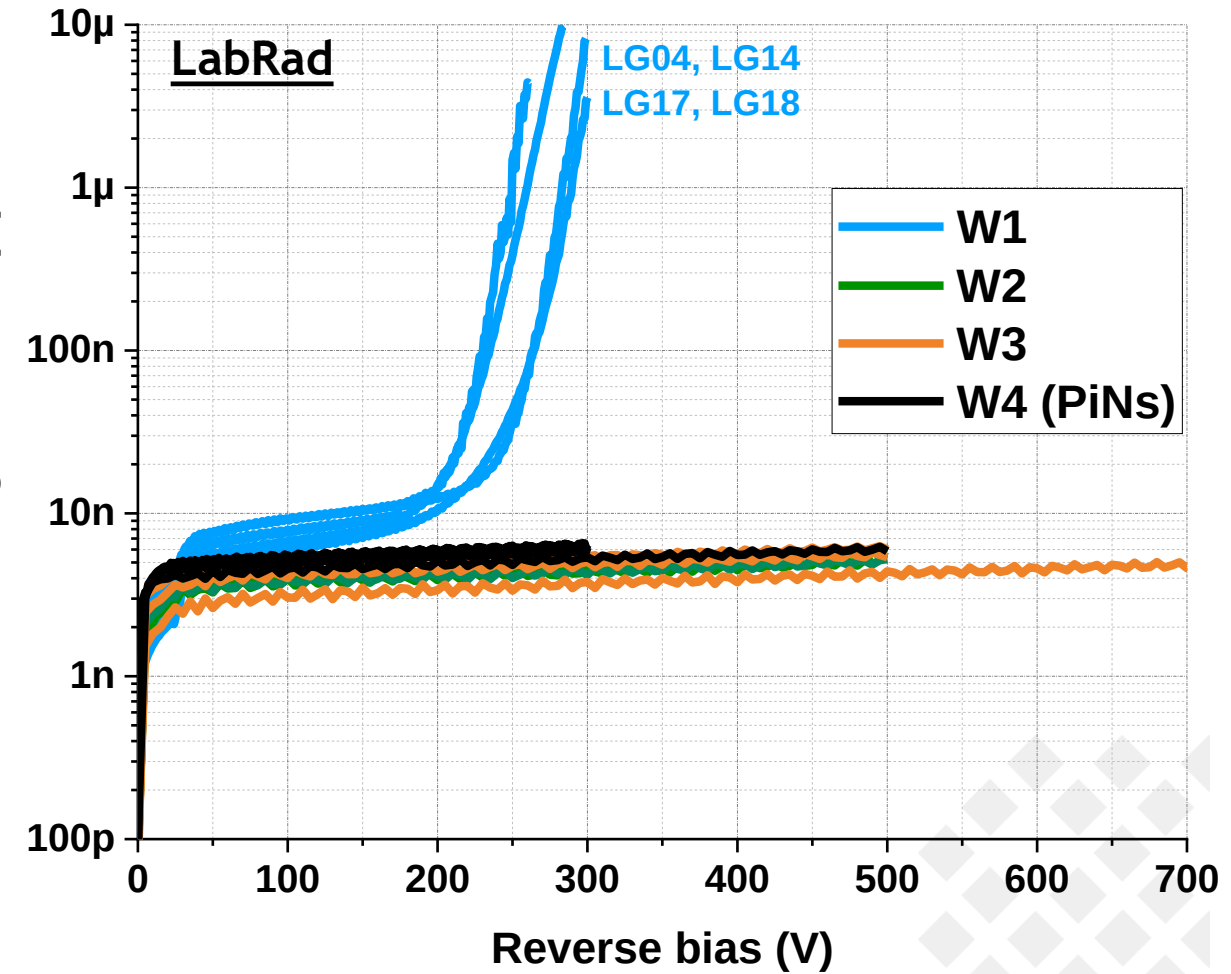
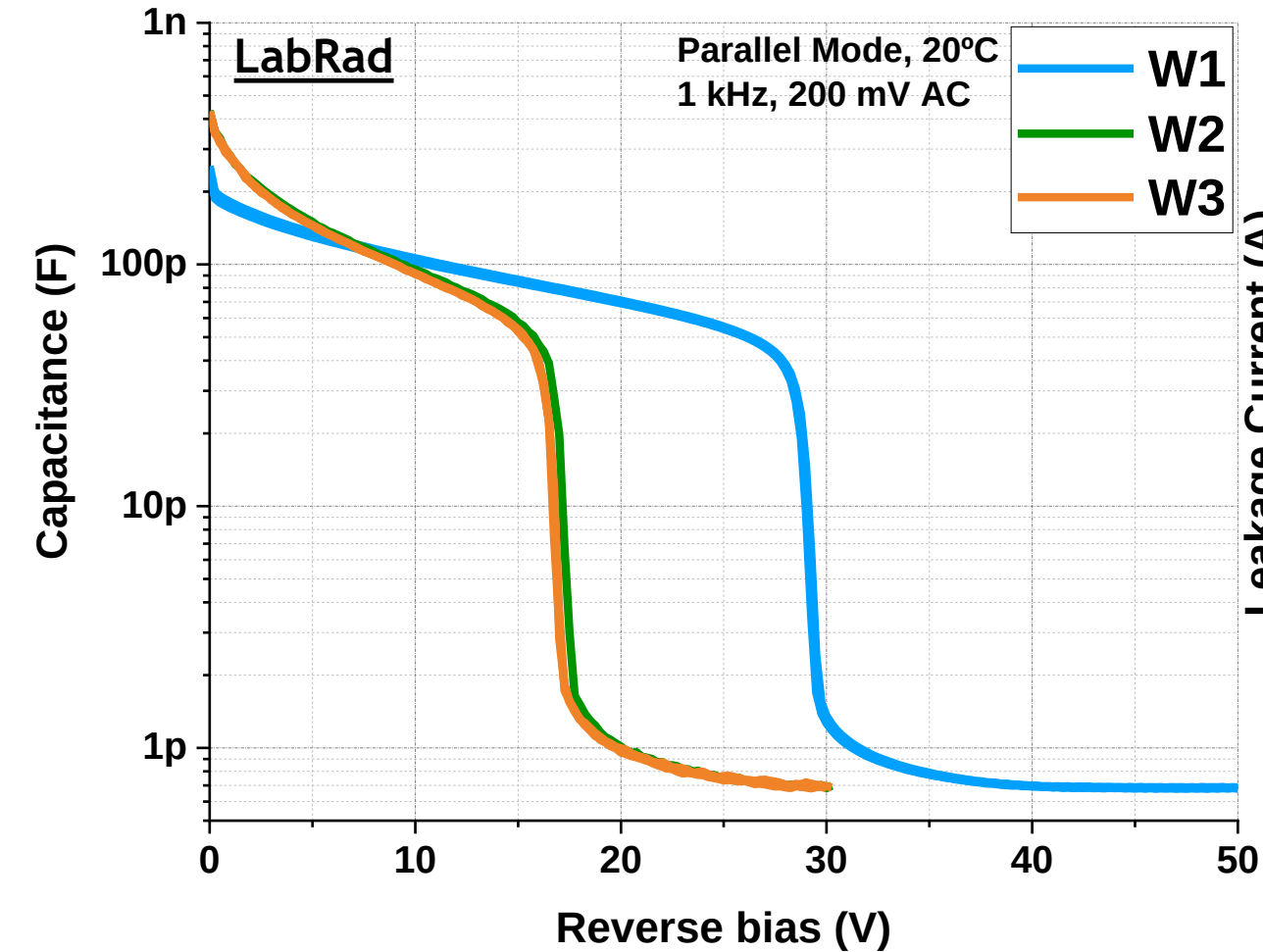
JTE diffusion: 1000°C for 4h (intended for dNLGAD)



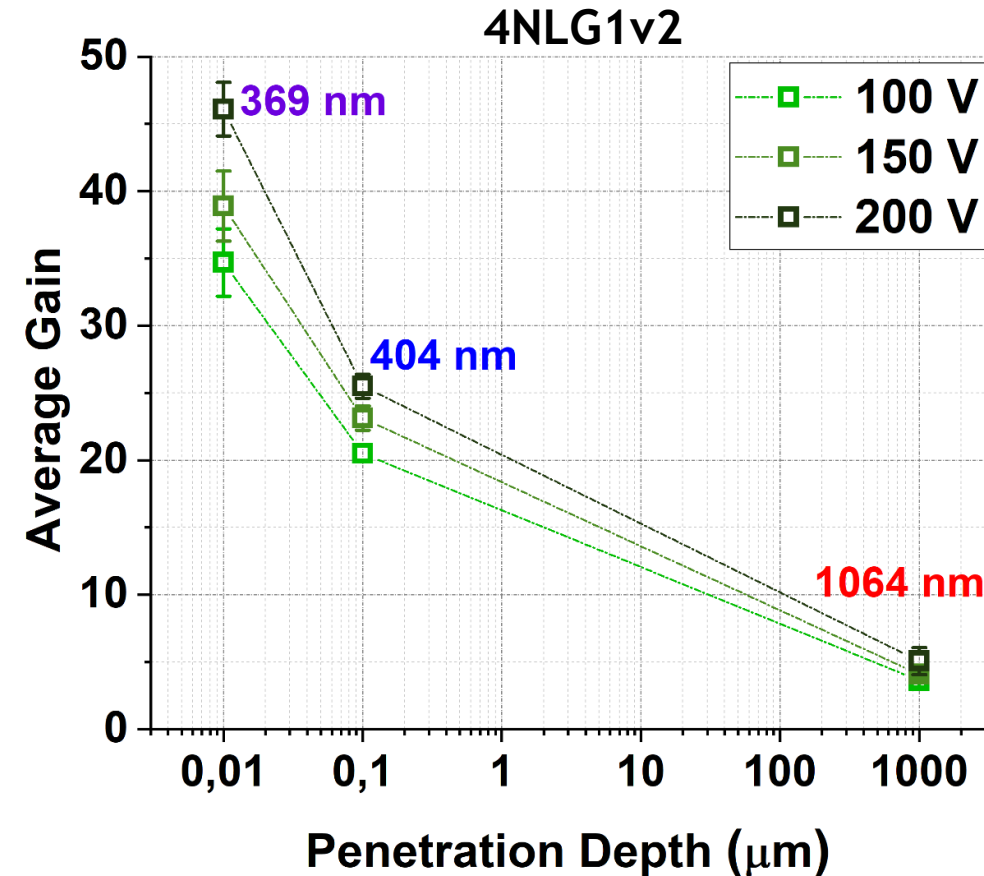
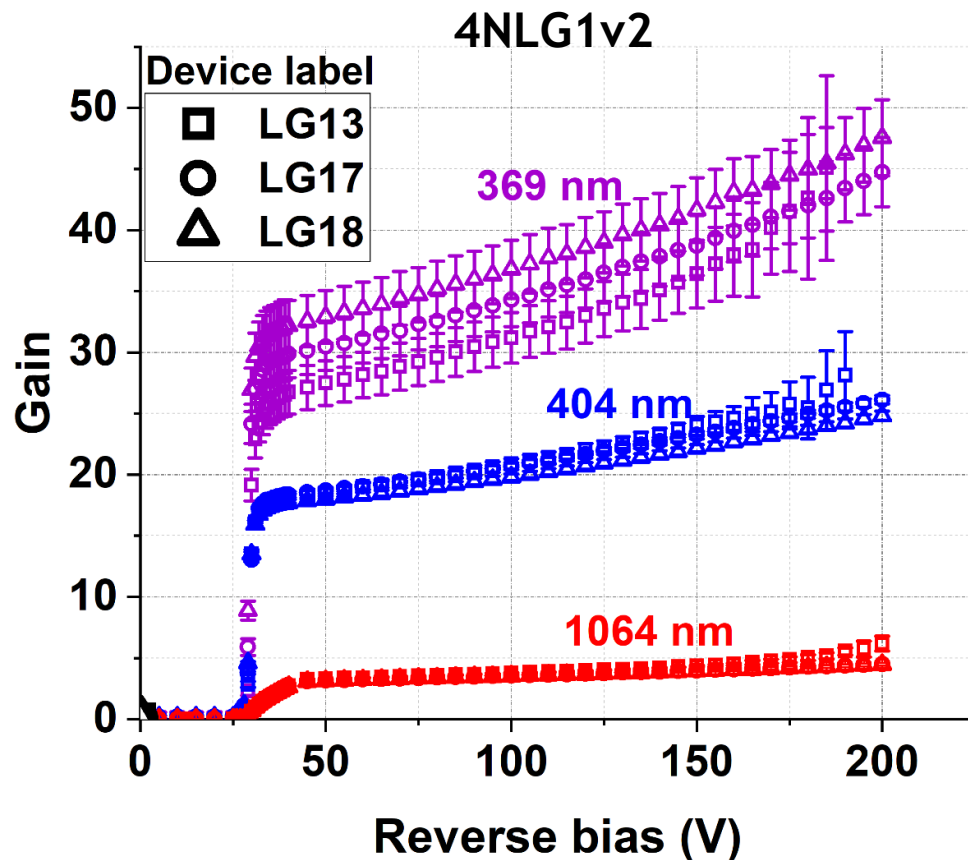
Wafer	Multiplication layer	p ⁺⁺
1	E _{Phos} = 100 keV D _{Phosp} = 1.8e13 at/cm ²	E _{Boron} = 70 & 150 keV D _{Boron} = 1e15 & 5e14 at/cm ²
2	E _{Phos} = 100 keV D _{Phosp} = 1.0e13 at/cm ²	E _{Boron} = 70 keV D _{Boron} = 1e15 at/cm ²
3	E _{Phos} = 100 keV D _{Phosp} = 0.8e13 at/cm ²	E _{Boron} = 50 keV D _{Boron} = 1e15 at/cm ²
4	PiN	

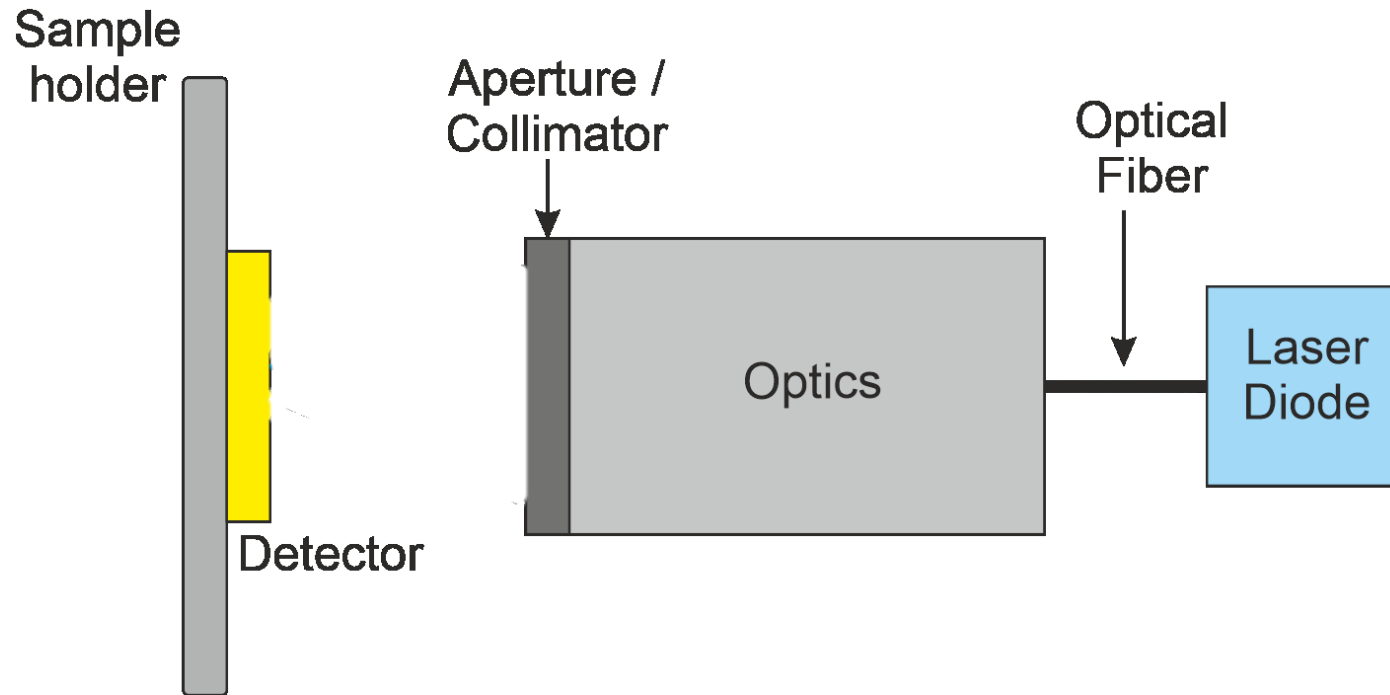
JTE diffusion: 1000°C for 4h (intended for dNLGAD)



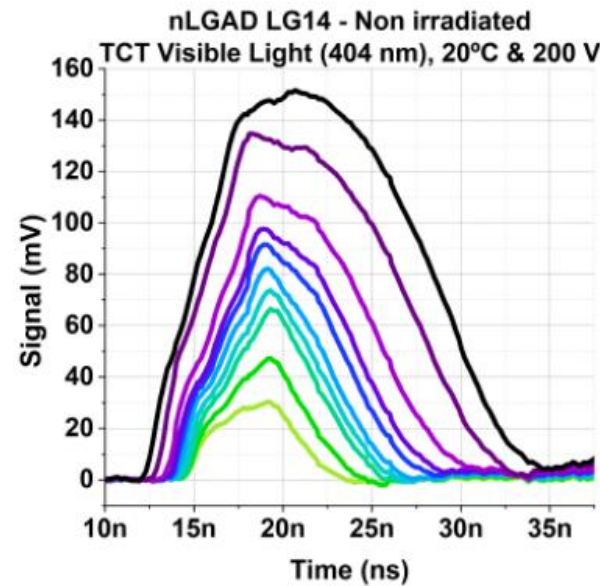
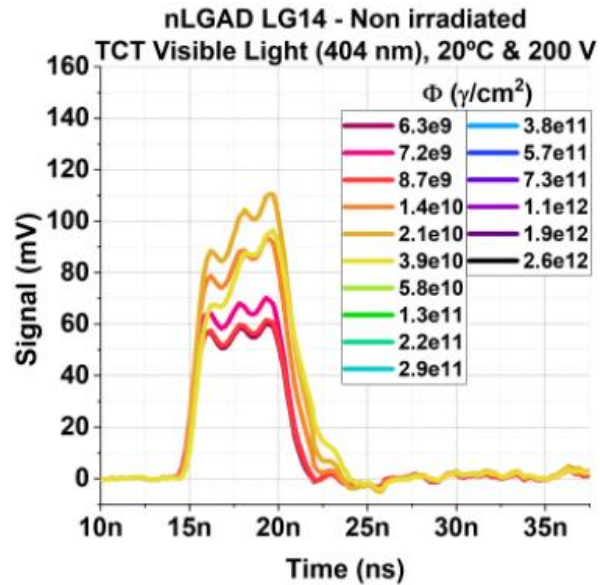


- TCT measurements, 20°C, maximum power for every laser diode
- Samples from both nLGAD runs (4NLG1v1, 4NLG1v2) measured under similar conditions have similar gain response

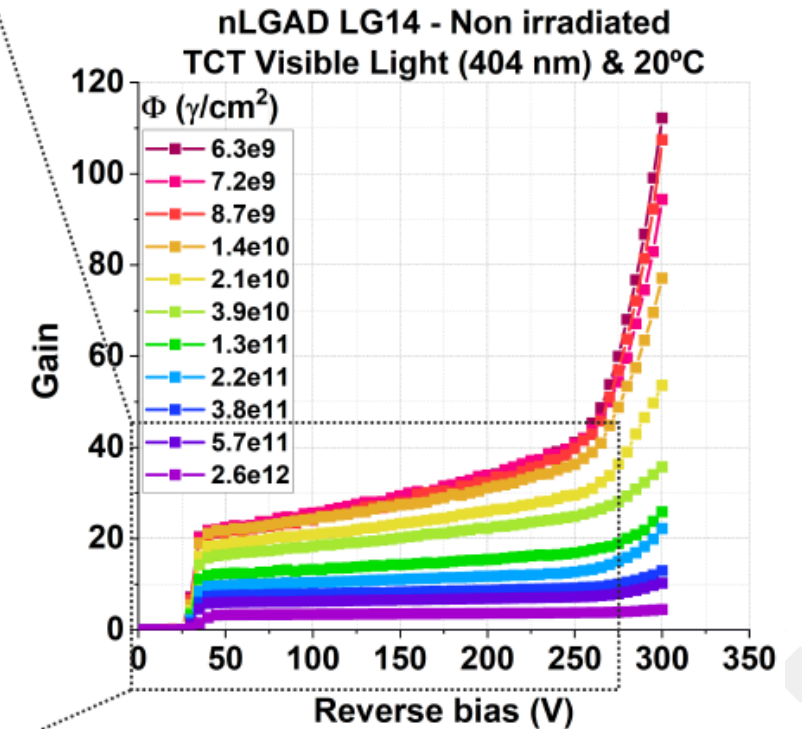
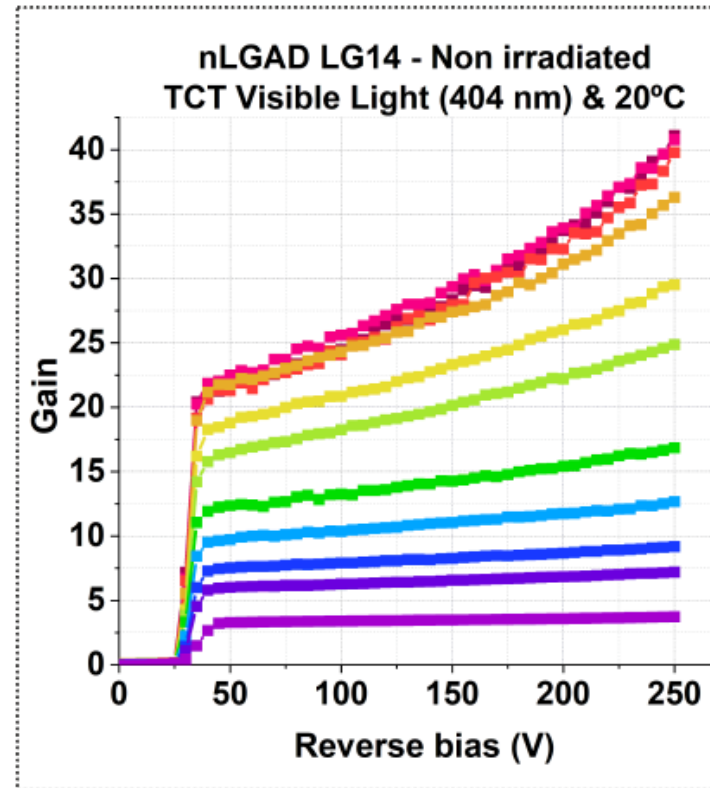




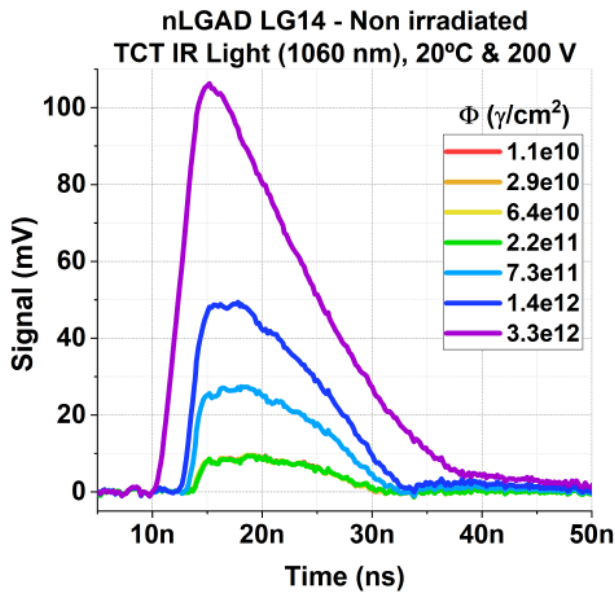
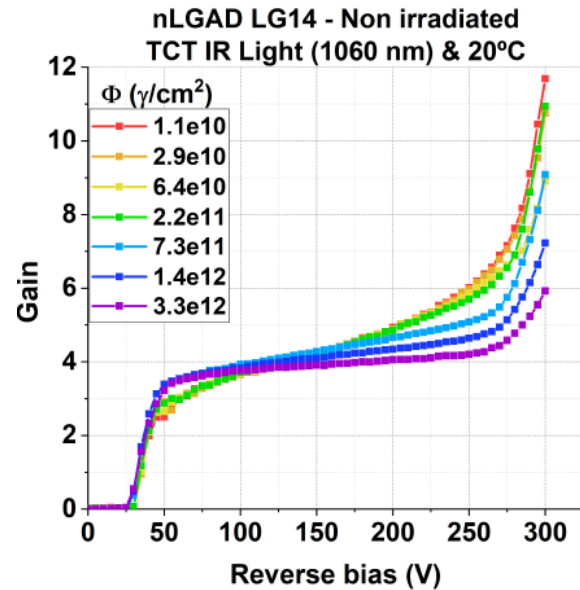
- 400-1100 nm wavelength
- Integrated Si detector
- Accuracy of 5%



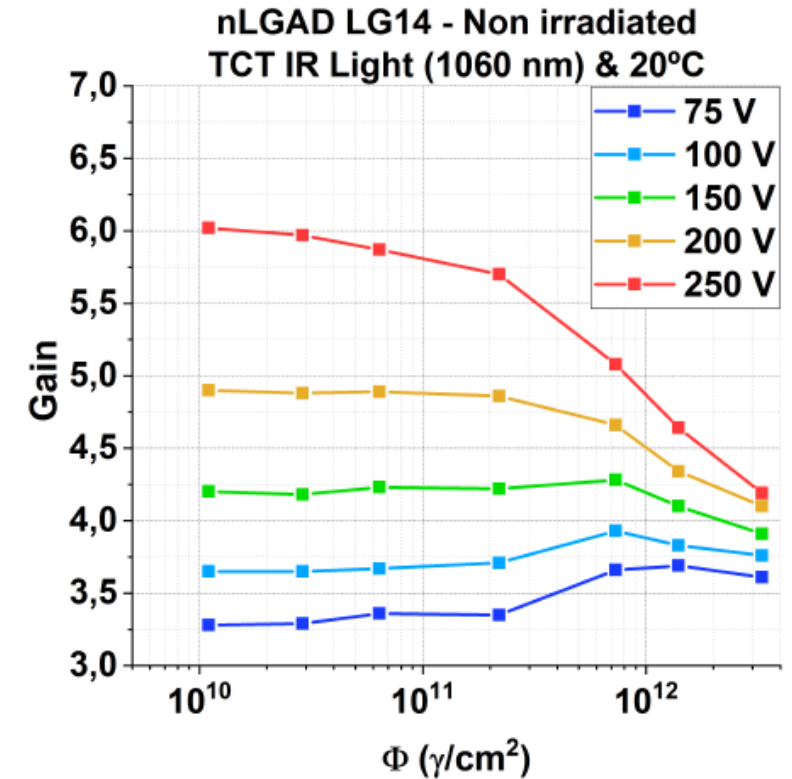
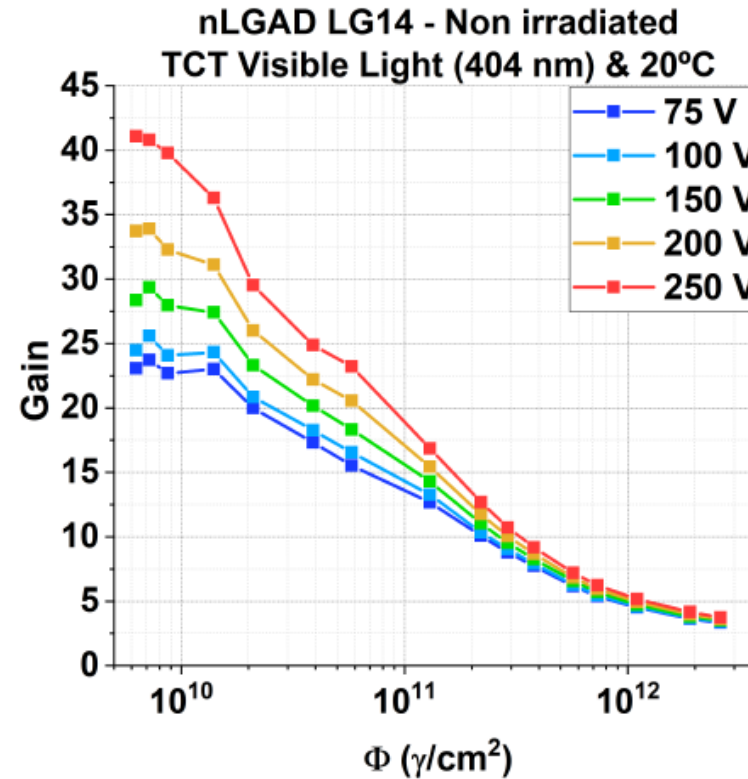
Gain Measurements with Blue Light



Gain Measurements with IR Light

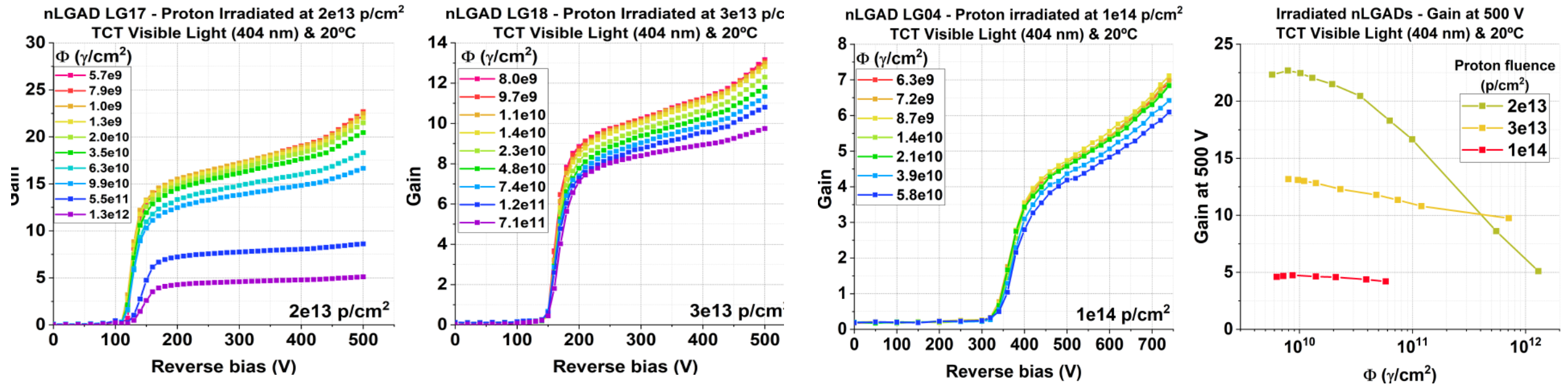


Gain Suppression

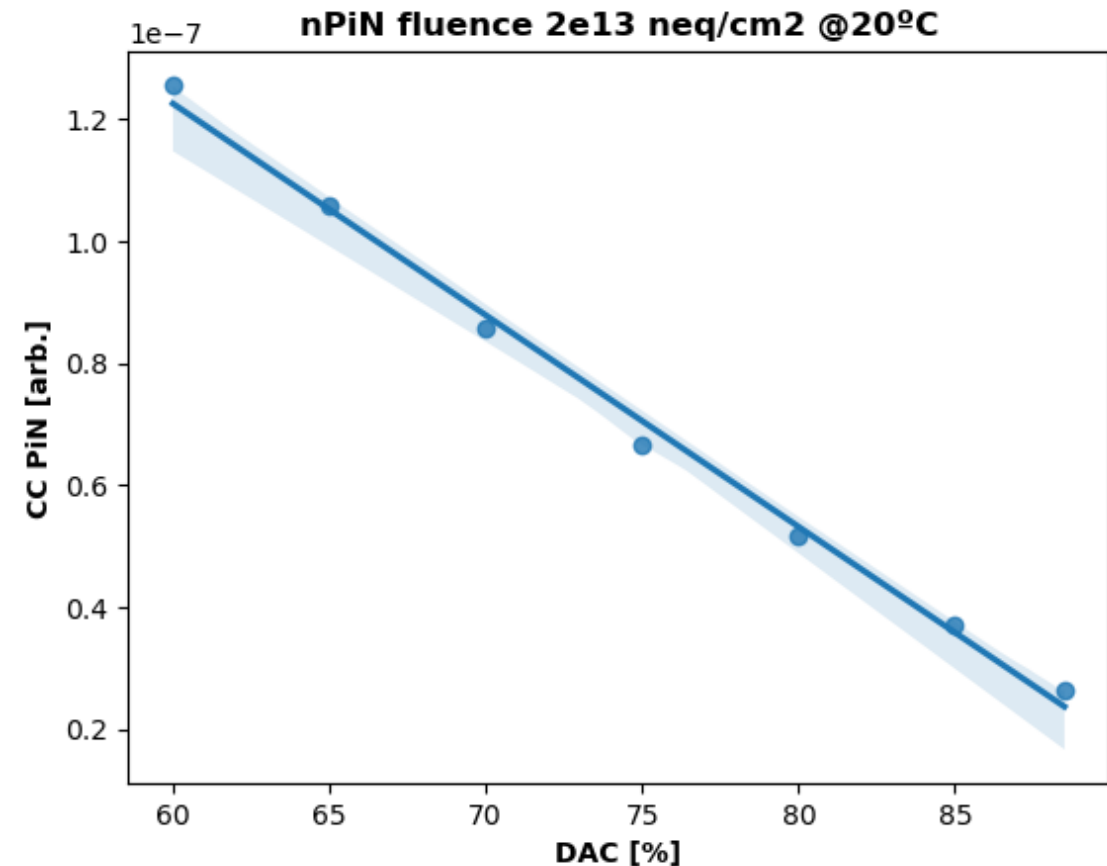
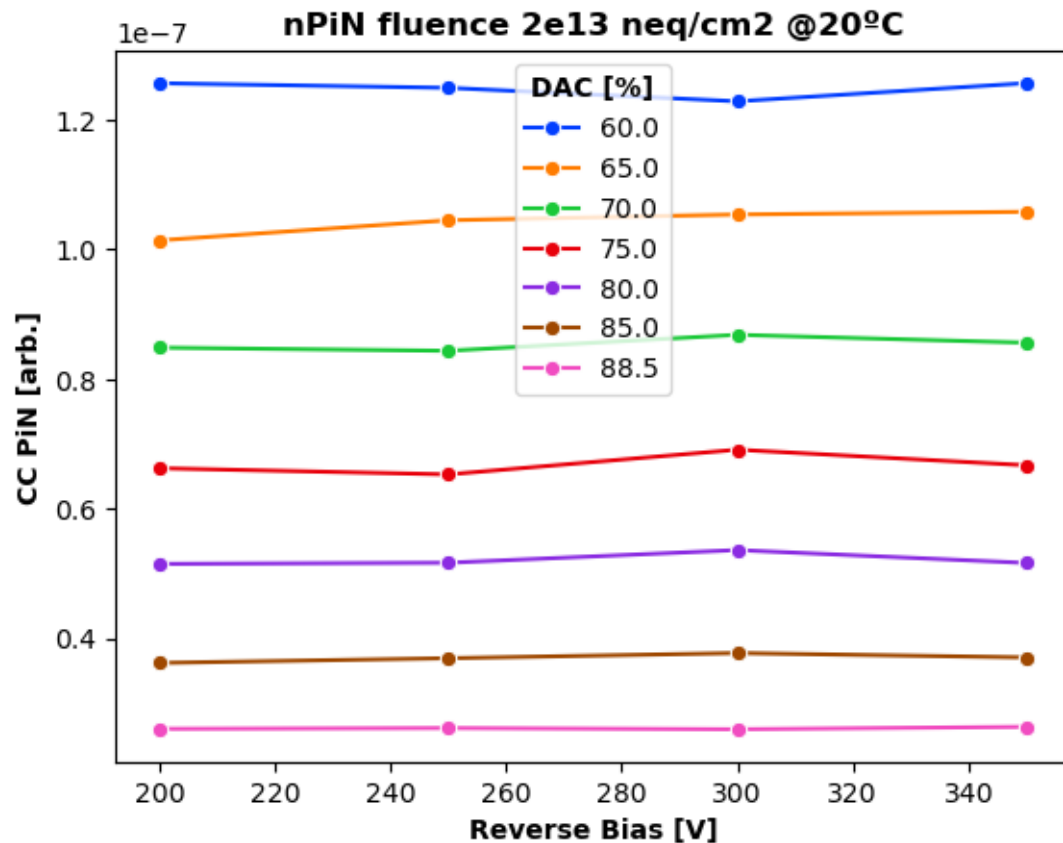


4NLG1v2. Blue/IR. Proton Irradiation @ CERN

- Proton irradiation at the PS-IRRAD facility at CERN with a primary proton beam of 23 GeV
 - Fluences within a 10% margin:
 - $2e13 \text{ p/cm}^2 \rightarrow 1.2e13, 1 \text{ MeV } n_{eq}/\text{cm}^2$
 - $3e13 \text{ p/cm}^2 \rightarrow 1.9e13, 1 \text{ MeV } n_{eq}/\text{cm}^2$
 - $1e14 \text{ p/cm}^2 \rightarrow 6.2e13, 1 \text{ MeV } n_{eq}/\text{cm}^2$
 - Annealing of 4 mins at 80 °C performed after irradiation

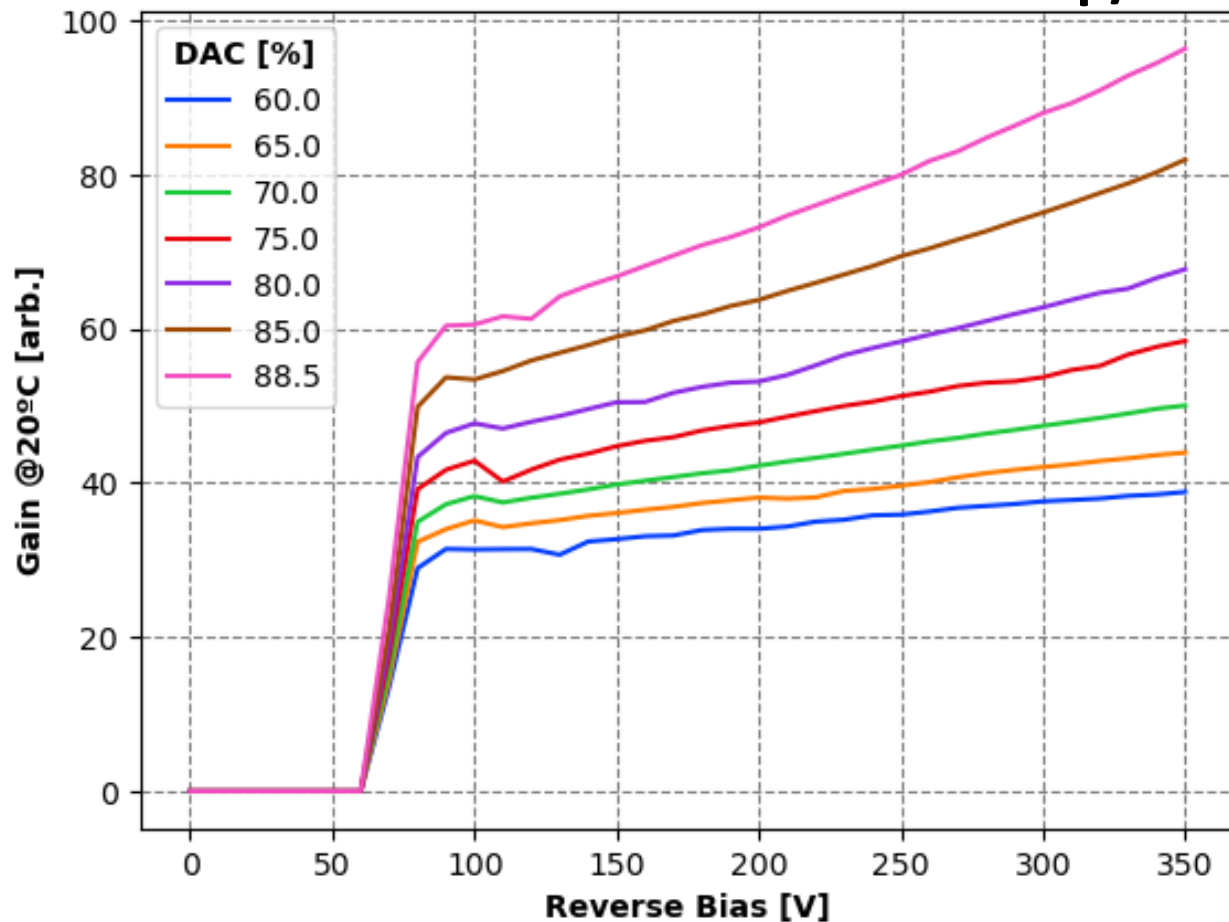


4NLG1v2. Gain Studies. UV. Proton Irradiated

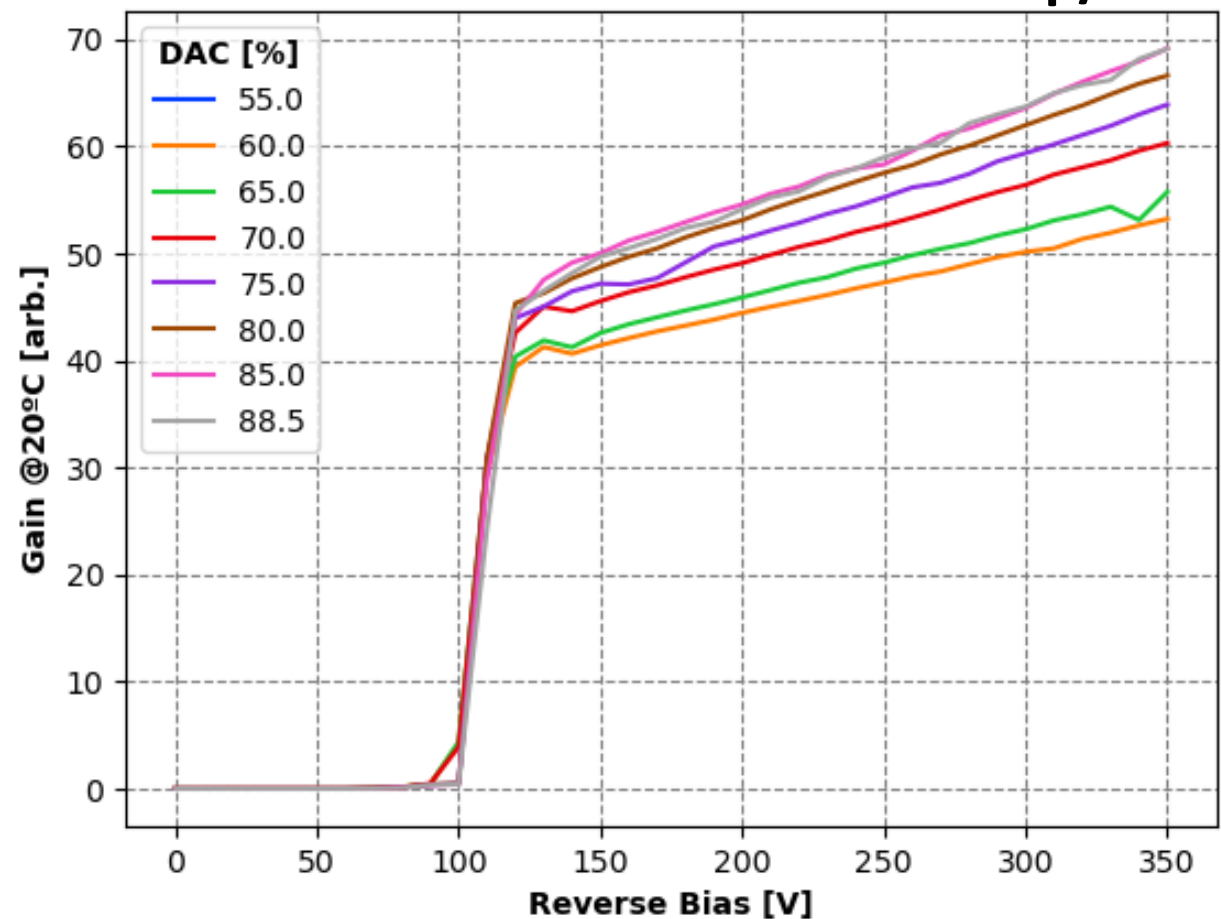


4NLG1v2. Gain Studies. UV. Proton Irradiated

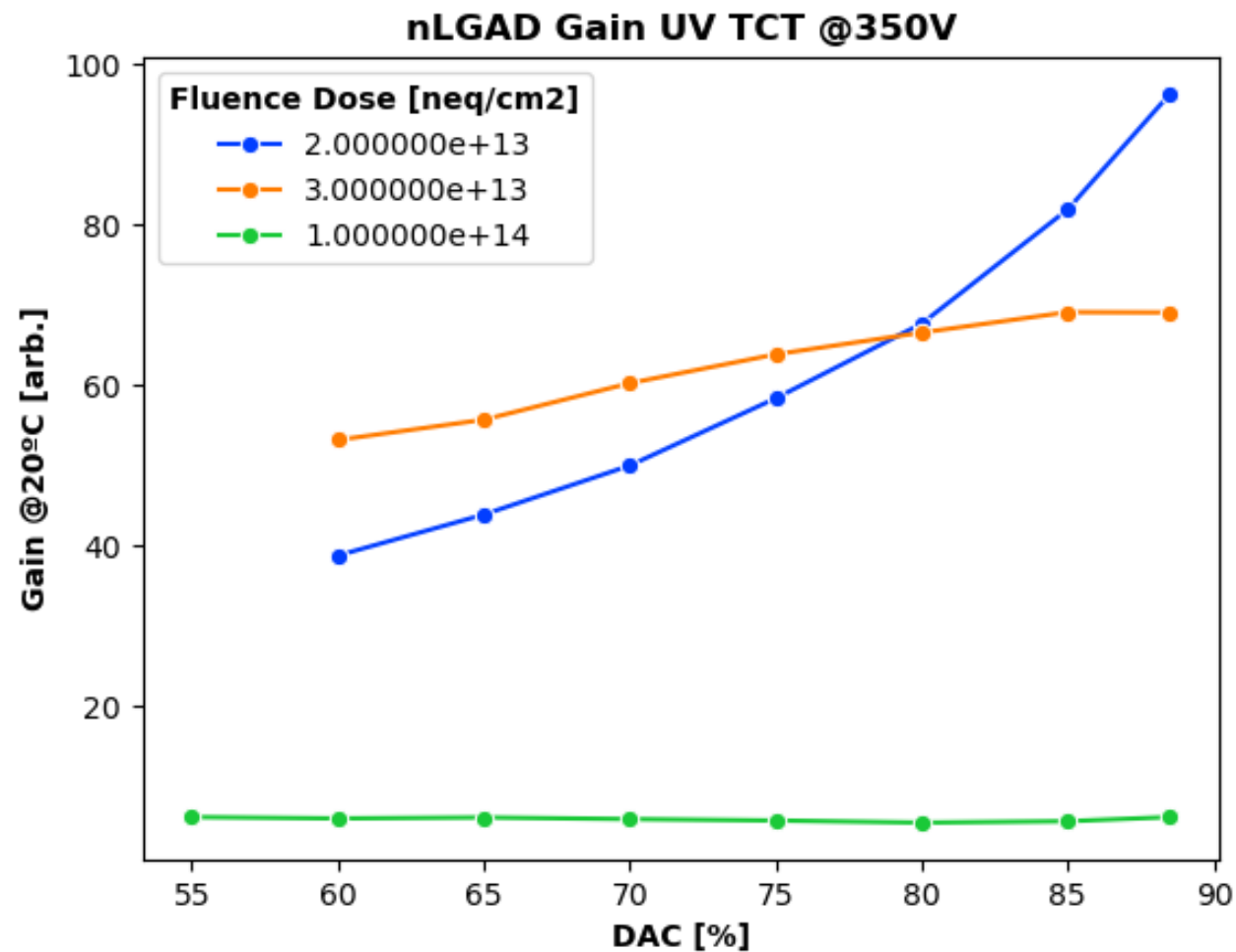
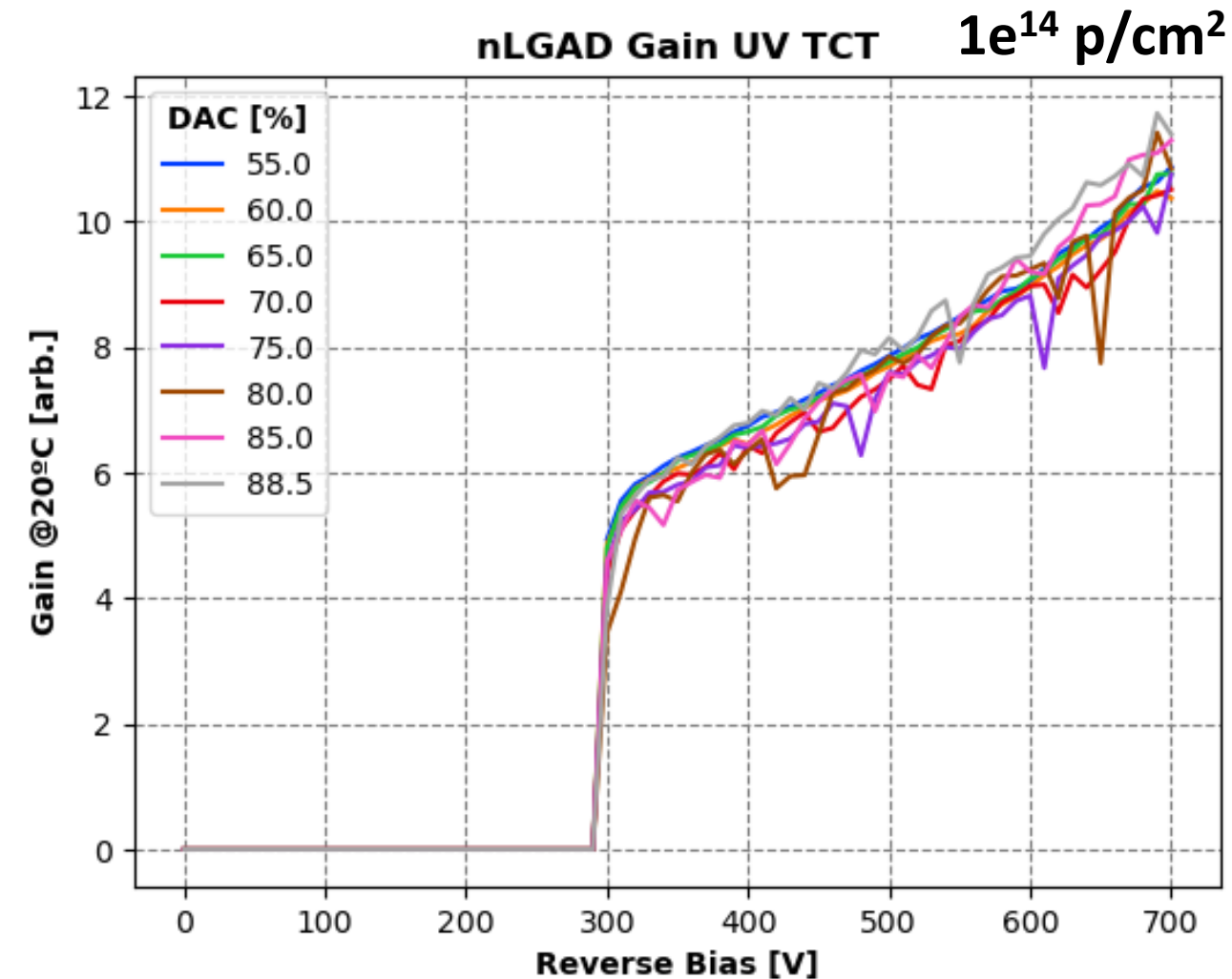
nLGAD Gain UV TCT $2e^{13} \text{ p/cm}^2$



nLGAD Gain UV TCT $3e^{13} \text{ p/cm}^2$



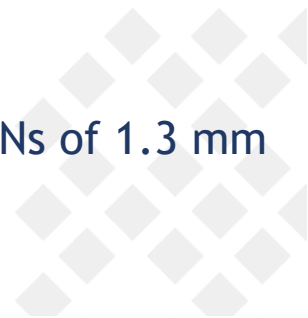
4NLG1v2. Gain Studies. UV. Proton Irradiated



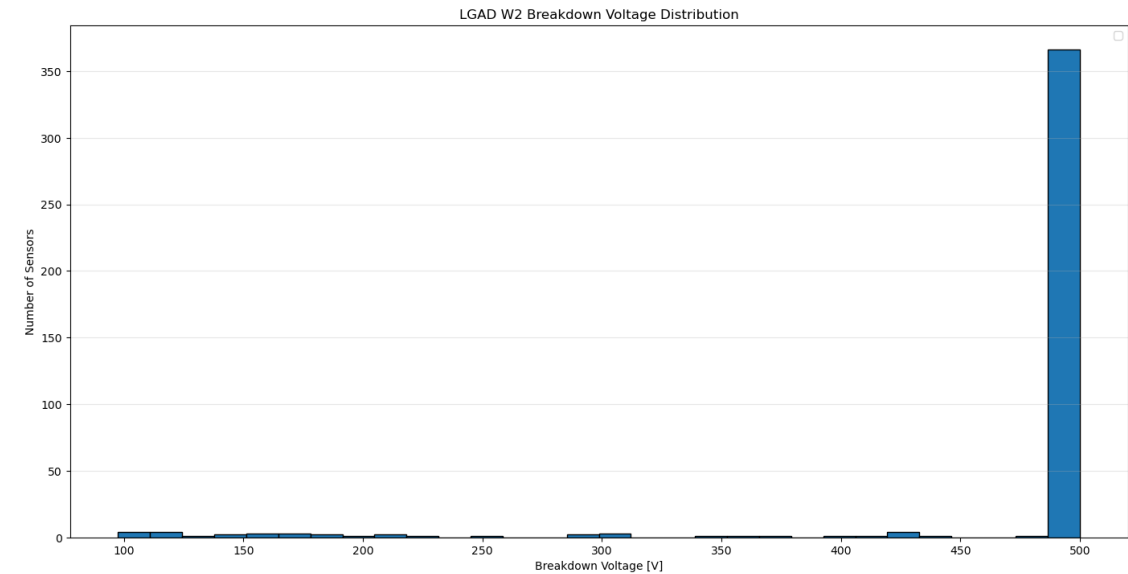
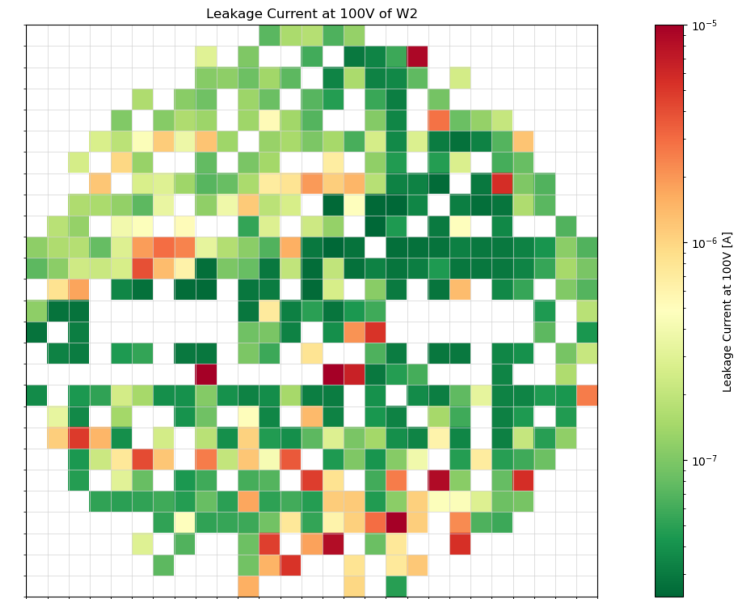
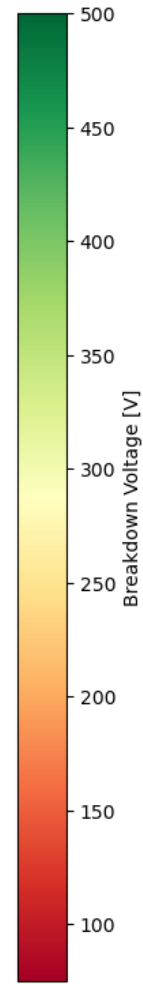
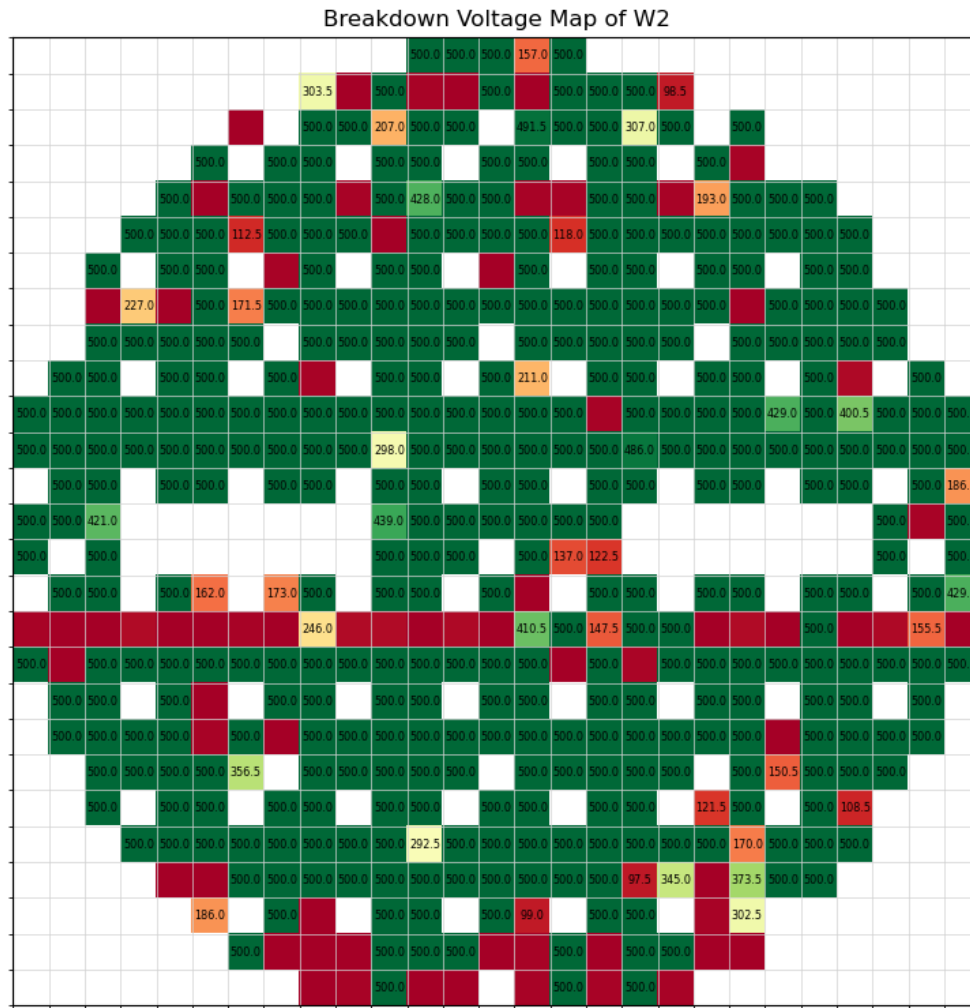
nLGAD. 6NLG1v1. R18550

Wafer	Multiplication layer	P ⁺⁺	Passivation
1	$E_{\text{Phos}} = 100 \text{ keV}$ $D_{\text{Phosp}} = 1.8\text{e}13 \text{ at/cm}^2$	$E_{\text{Boron}} = 70 \text{ \& } 150 \text{ keV}$ $D_{\text{Boron}} = 1\text{e}15 \text{ \& } 5\text{e}14 \text{ at/cm}^2$	Standard 7000 Å Nitride over 4000 Å Oxide
2			
3			1000 Å Nitride over 1000 Å Oxide
4			30 Å Hafmiun Oxide
5	$E_{\text{Phos}} = 100 \text{ keV}$ $D_{\text{Phosp}} = 1.0\text{e}13 \text{ at/cm}^2$	$E_{\text{Boron}} = 50 \text{ keV}$ $D_{\text{Boron}} = 1\text{e}15 \text{ at/cm}^2$	30 Å Hafmiun Oxide
6	$E_{\text{Phos}} = 100 \text{ keV}$ $D_{\text{Phosp}} = 1.15\text{e}13 \text{ at/cm}^2$		
7	$E_{\text{Phos}} = 100 \text{ keV}$ $D_{\text{Phosp}} = 1.25\text{e}13 \text{ at/cm}^2$		

- 150 mm High Resistivity 300 μm FZ wafers (SEN HRN6-300 (06/22))
- Screen oxide measurements in all stages
- **Wafers 1-4:** Reduction of dead entrance by reducing the passivation
- **Wafers 5-7:** Reduction of dead entrance by reducing the P⁺⁺
- Mask **CNM869**. Single-pads only
- > 400 LGADs of 3.3 mm and 16 LGADs of 1.3 mm
- 64 PiNs of 3.3 mm and 2 PiNs of 1.3 mm

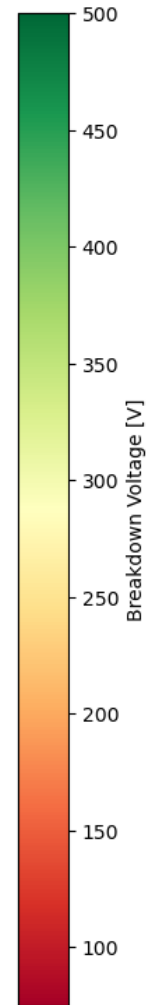
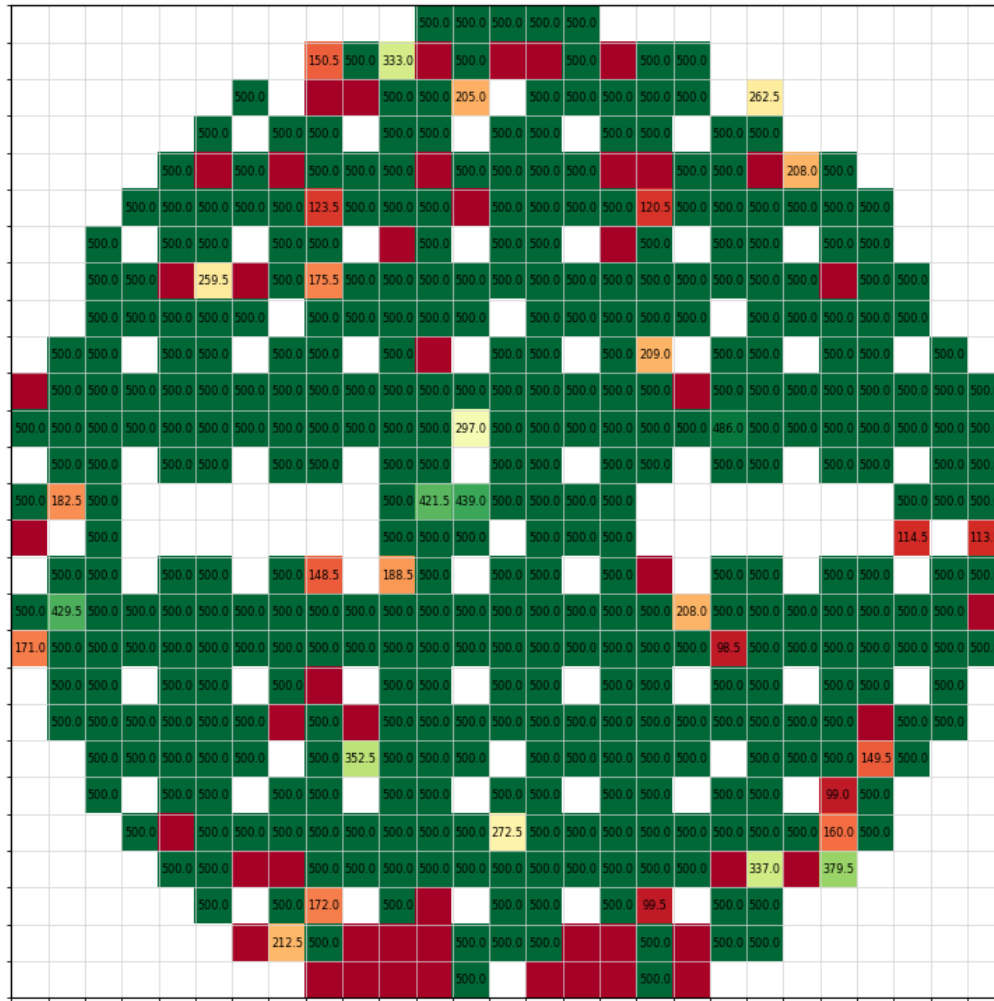


nLGAD. 6NLG1v1. R18550. W2. I-V

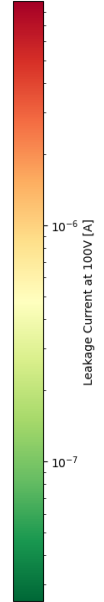
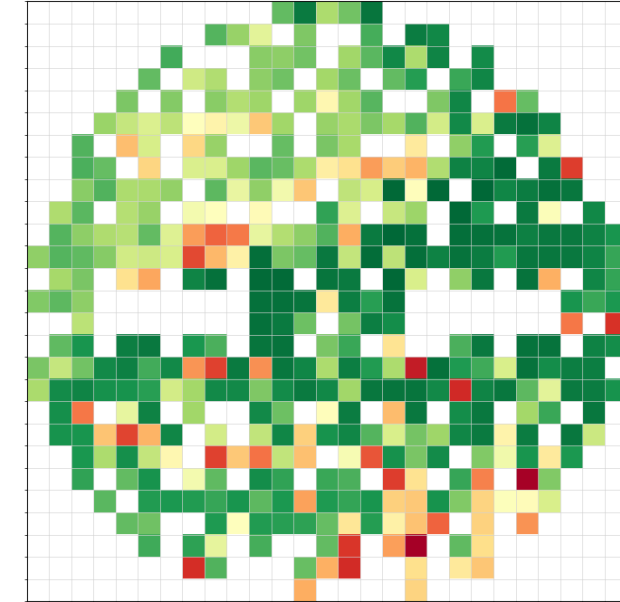


nLGAD. 6NLG1v1. R18550. W3. I-V

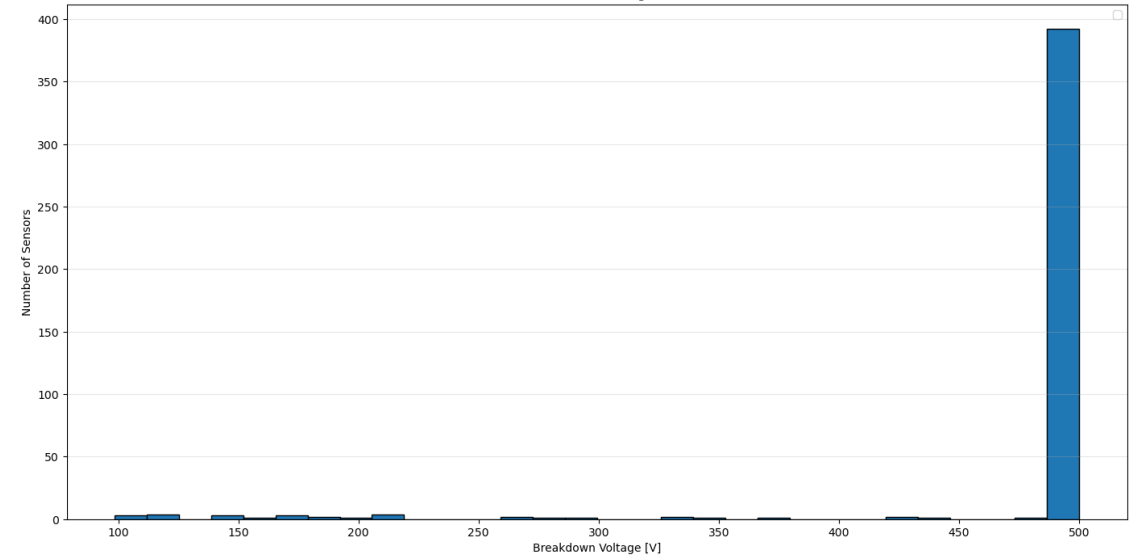
Breakdown Voltage Map of W3



Leakage Current at 100V of W3

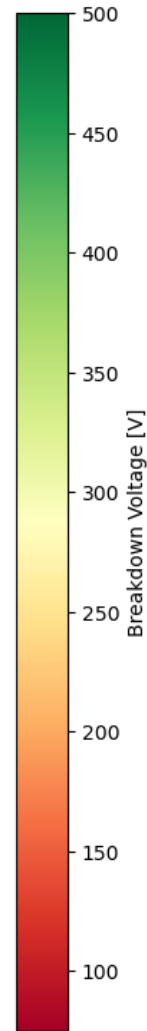
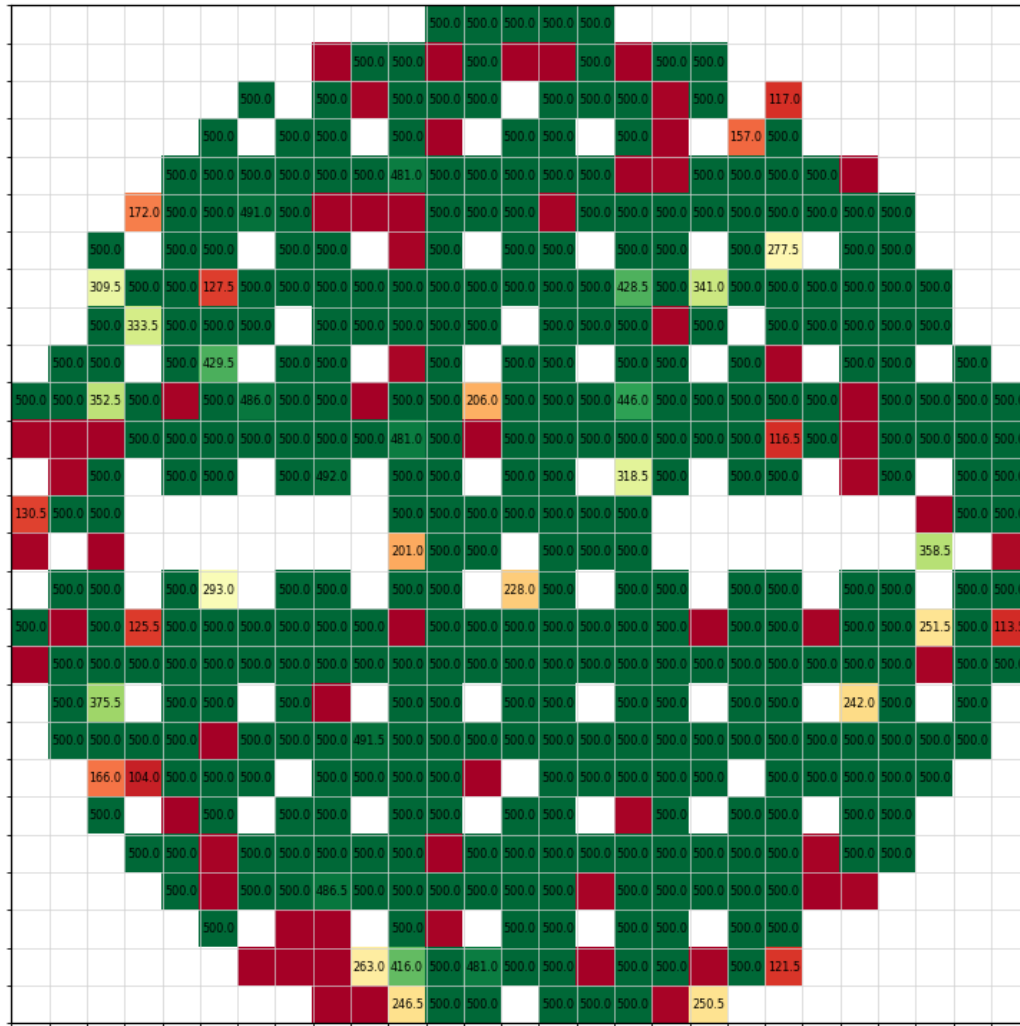


LGAD W3 Breakdown Voltage Distribution

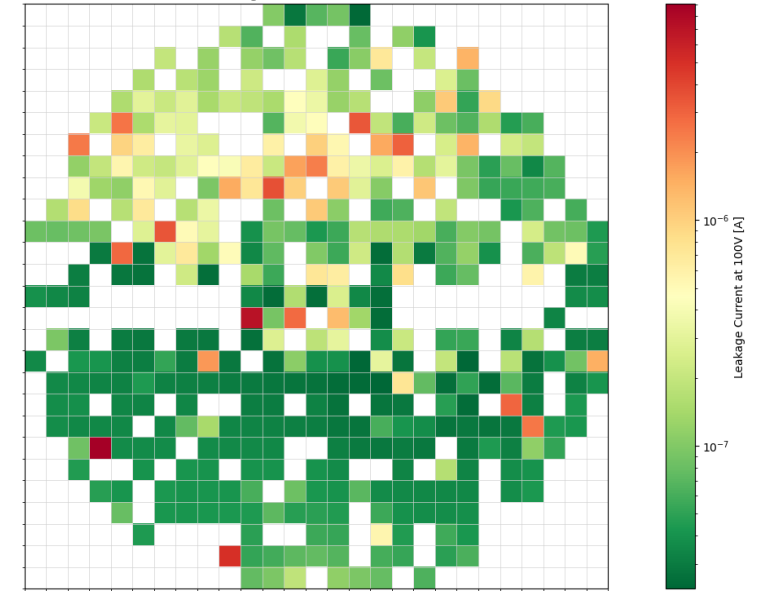


nLGAD. 6NLG1v1. R18550. W4. I-V

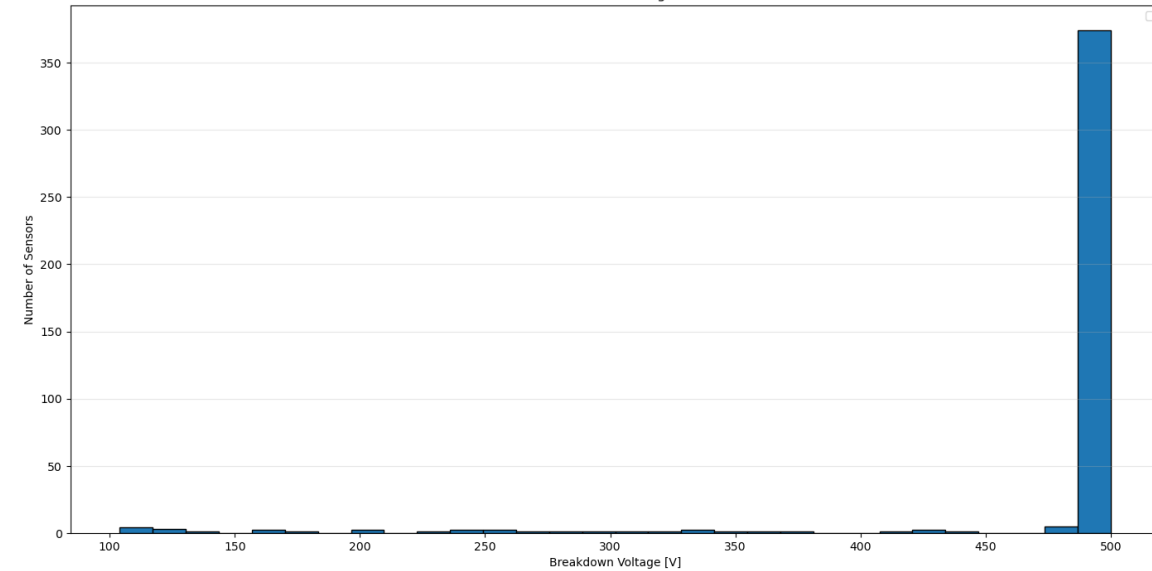
Breakdown Voltage Map of W4



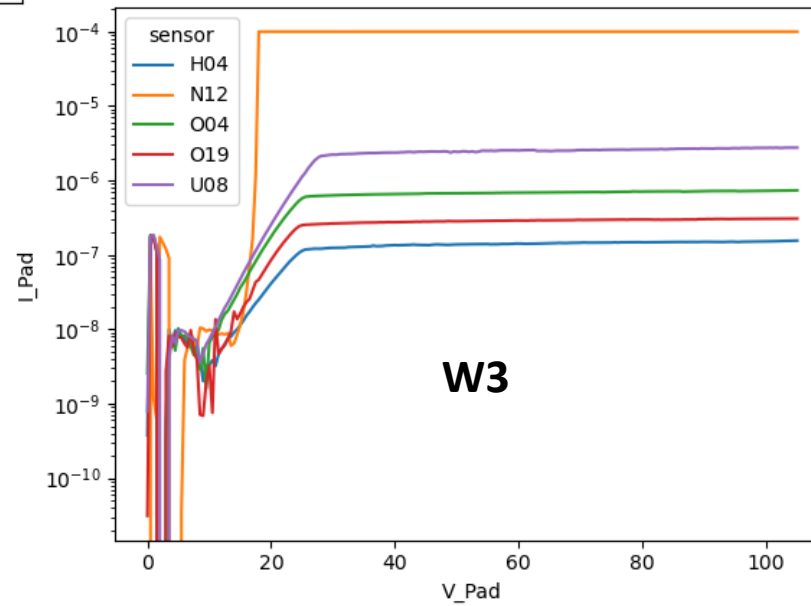
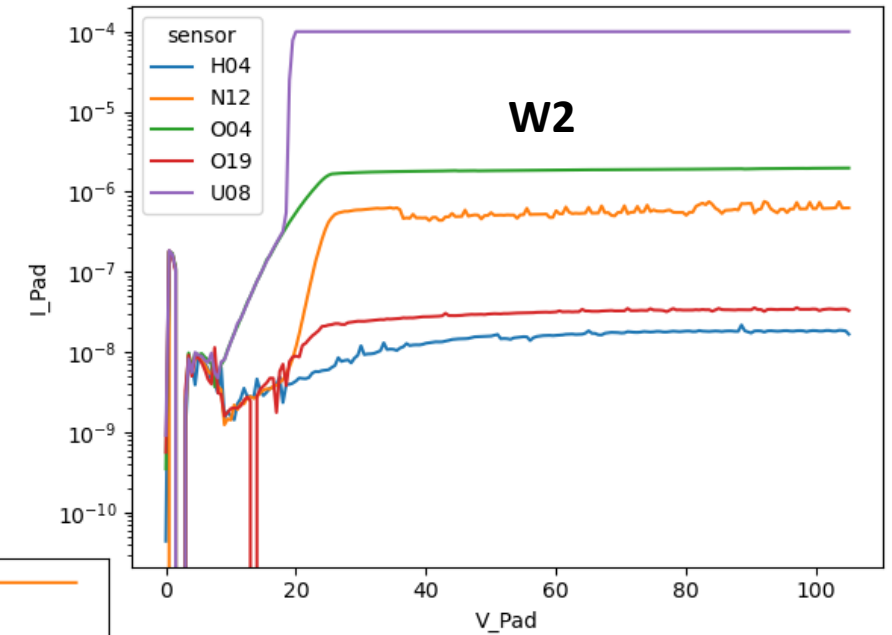
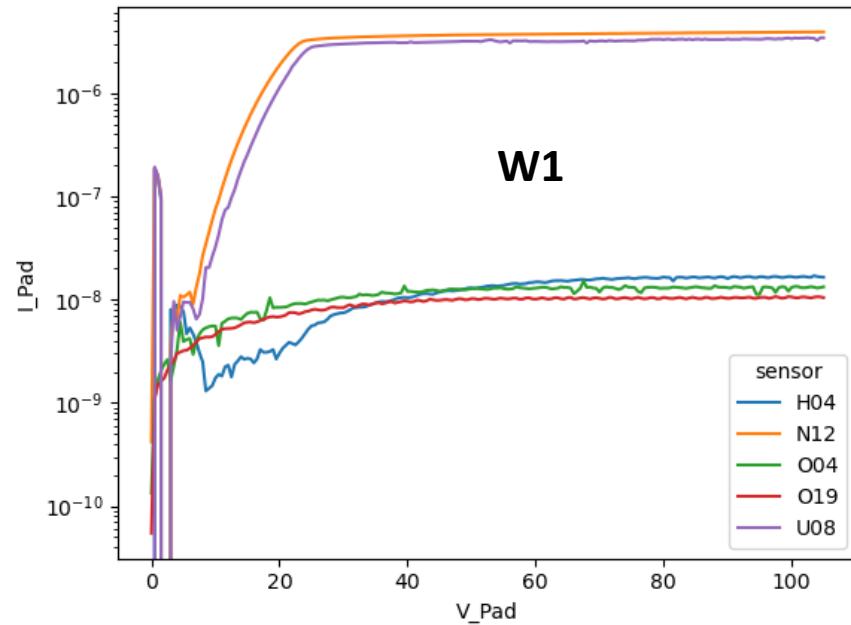
Leakage Current at 100V of W4



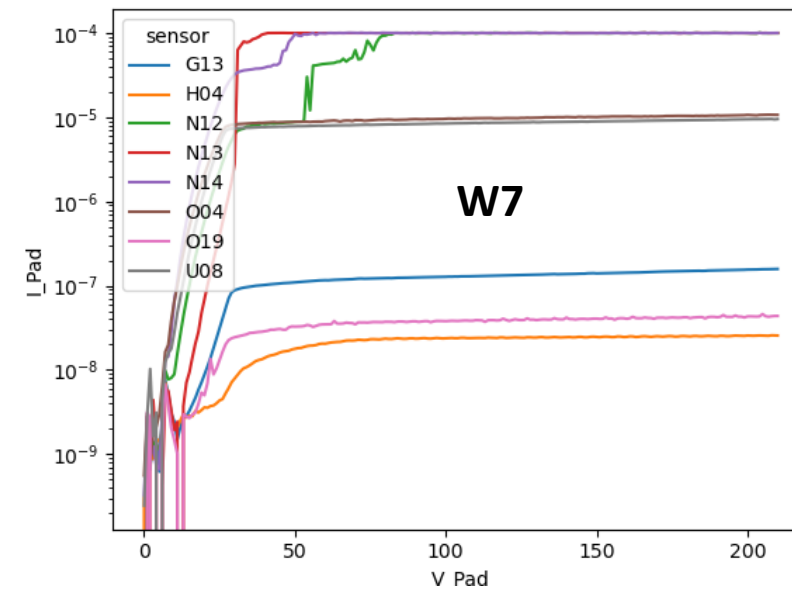
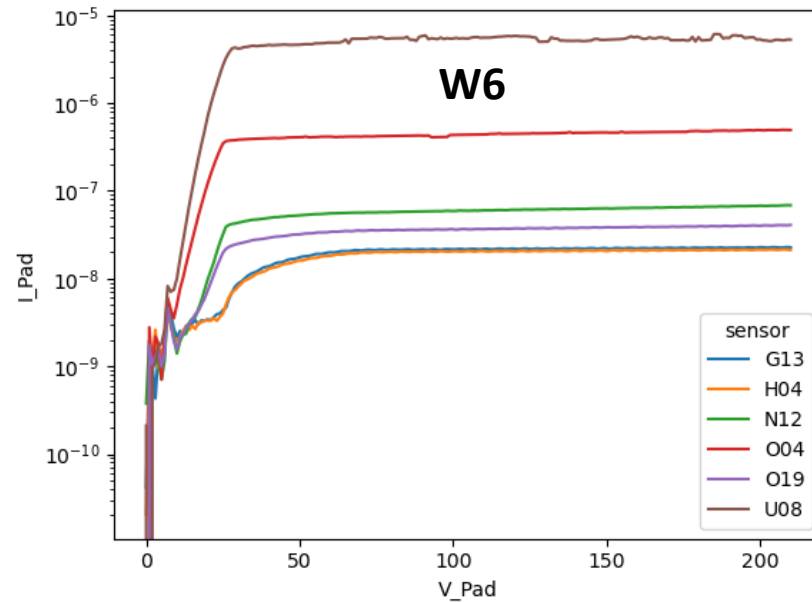
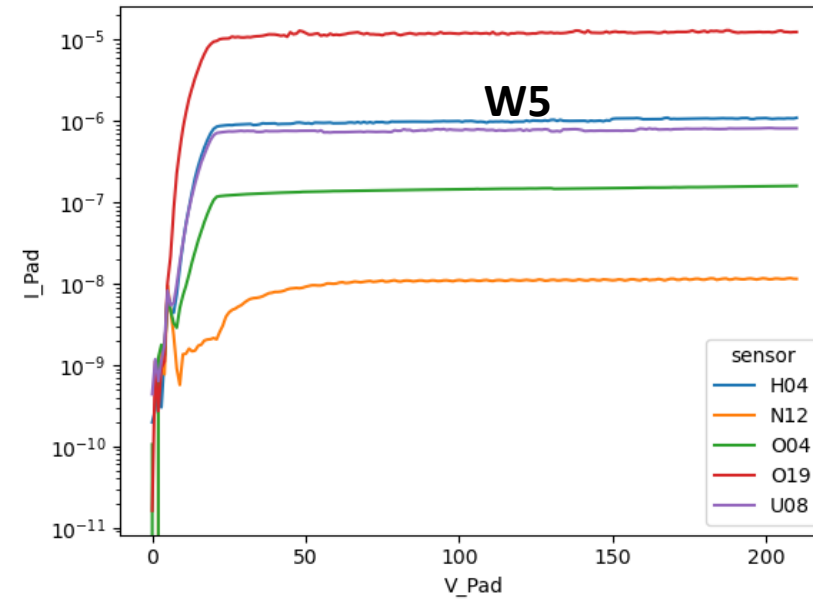
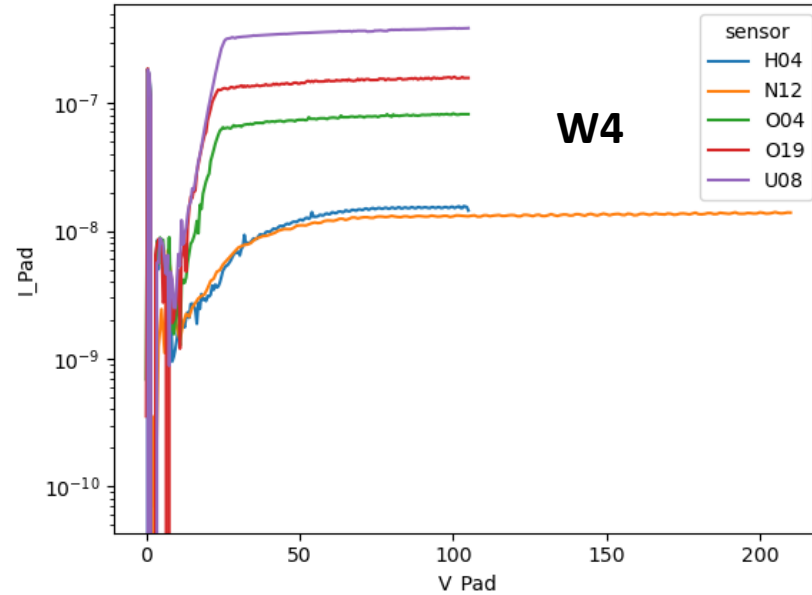
LGAD W4 Breakdown Voltage Distribution



nLGAD. 6NLG1v1. R18550. I-V

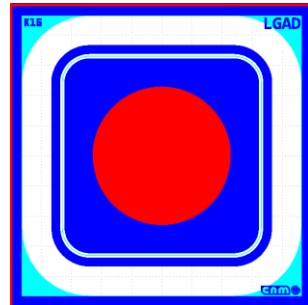


nLGAD. 6NLG1v1. R18550. I-V



LGAD & nLGAD Measurements @ ELI

- Study on LGAD and nLGAD sensors fabricated at IMB-CNM
 - Single pad configuration
 - Metal window of 2.2 mm for characterization with TCT
- LGAD: **6LG3v3** (R18399)
- nLGAD: **6NLG1v1** (R17217). Samples with same electrical characteristics than R18550 ones

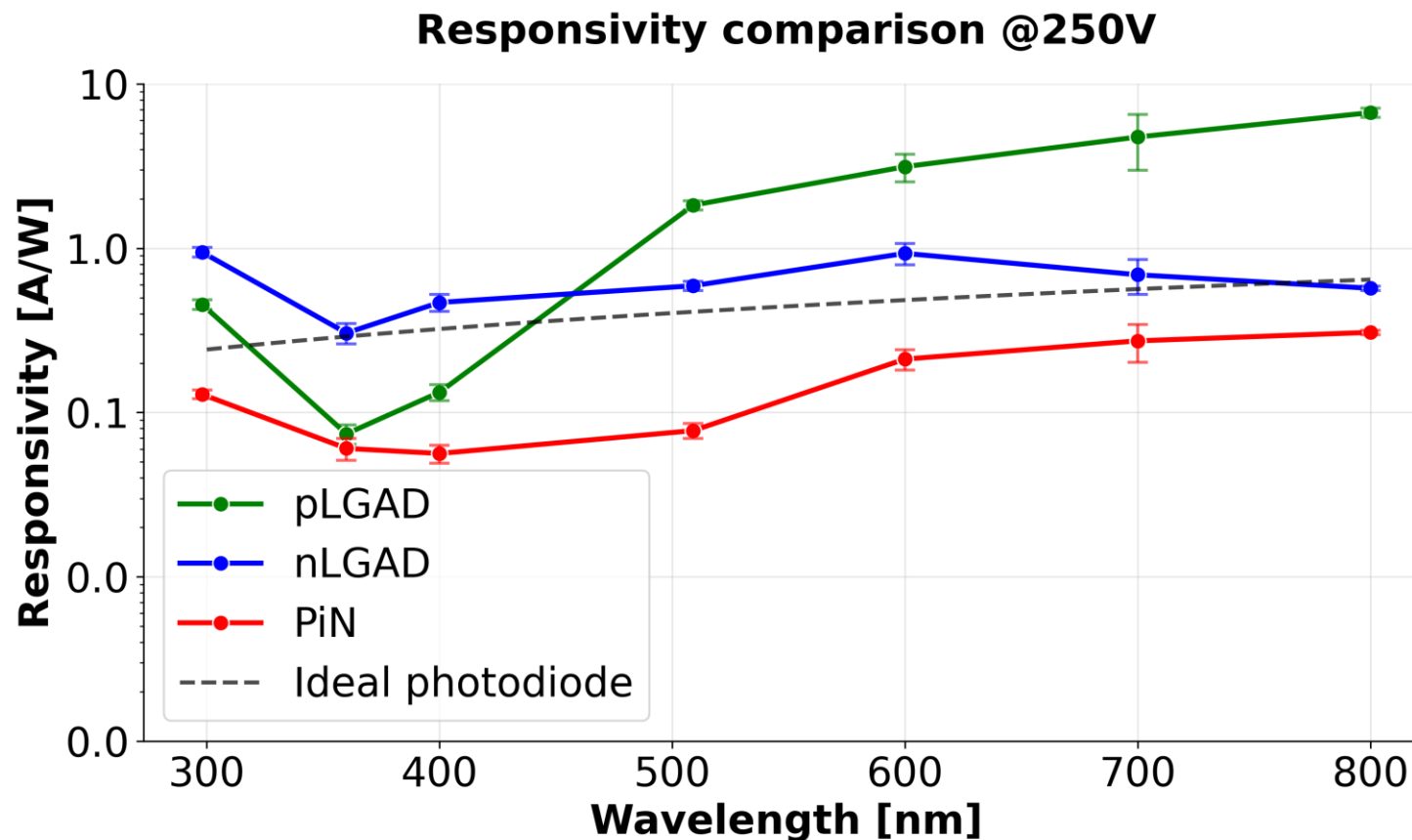


Sensor	V_{GL}	V_{BD}	Active Area	Active Thickness	Run
p-type LGAD	≈ 32	≈ 300	3.3×3.3 mm	50 μm	18399
n-type LGAD	≈ 28	≈ 300	3.3×3.3 mm	300 μm	17217
p-type PiN	No Gain Layer	> 500	3.3×3.3 mm	50 μm	18399
n-type PiN	No Gain Layer	> 500	3.3×3.3 mm	300 μm	17217

LGAD & nLGAD. Responsivity

- Collected Charge from the pulse integration of DUT
- Energy from the pulse integration of REF and calibrated responsivity of the Photodiode

$$R = \frac{I_{ph}}{P_{opt}} \quad R = \frac{\eta e}{h\nu} = \frac{\eta e \lambda}{hc}$$

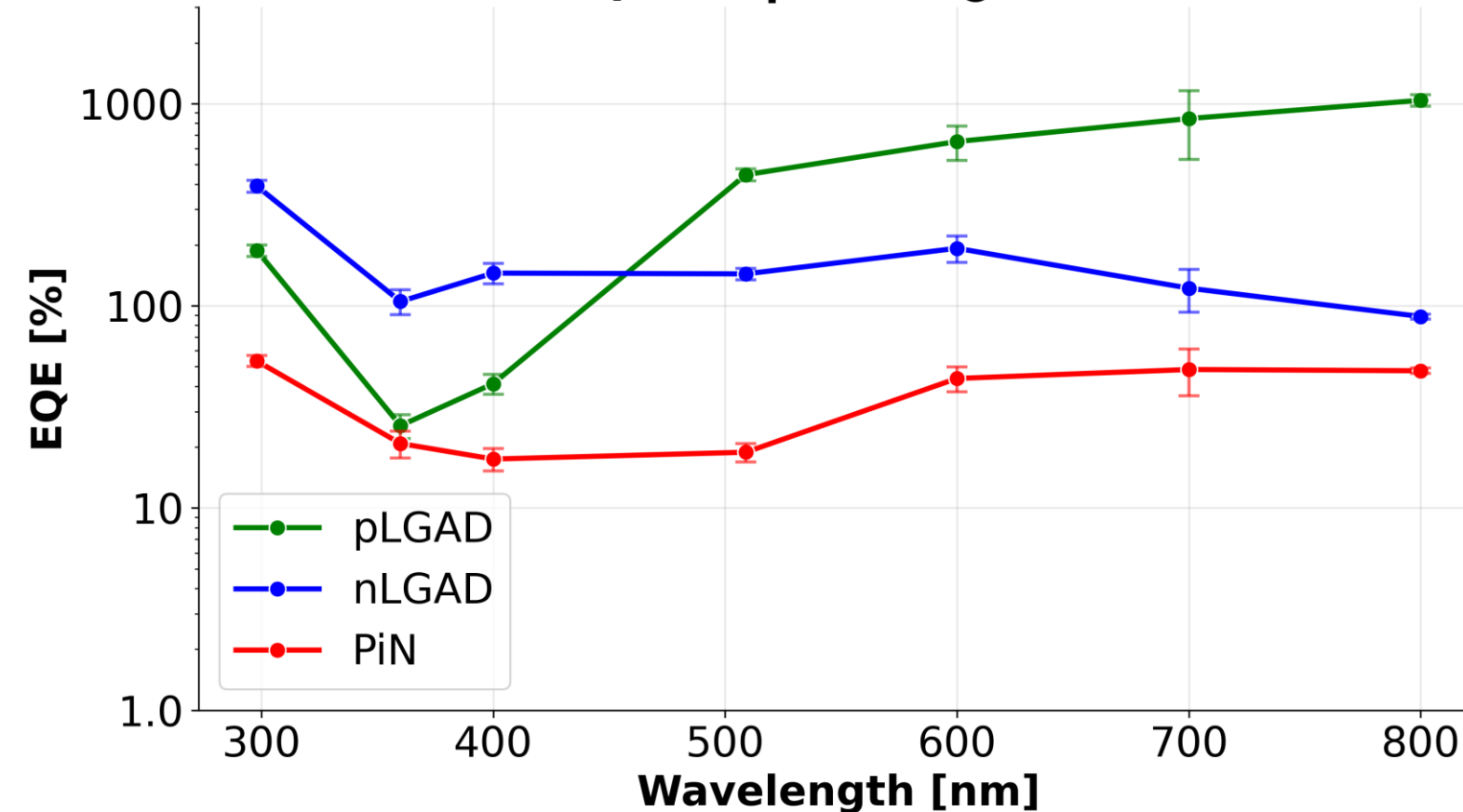


- **Better performance of the p-type LGAD for $\lambda > 500$ nm**
- **Constant responsivity of the n-type LGAD across the spectrum**

LGAD & nLGAD. External Quantum Efficiency

$$\text{EQE} = \frac{\text{Collected Electrons}}{\text{Incident Photons}} \quad R = \frac{\eta e}{h\nu} = \frac{\eta e \lambda}{hc} \quad \eta = \phi_c / \phi_{ph} = \frac{I_p / q}{P_{opt} / h\nu}$$

EQE comparison @250V

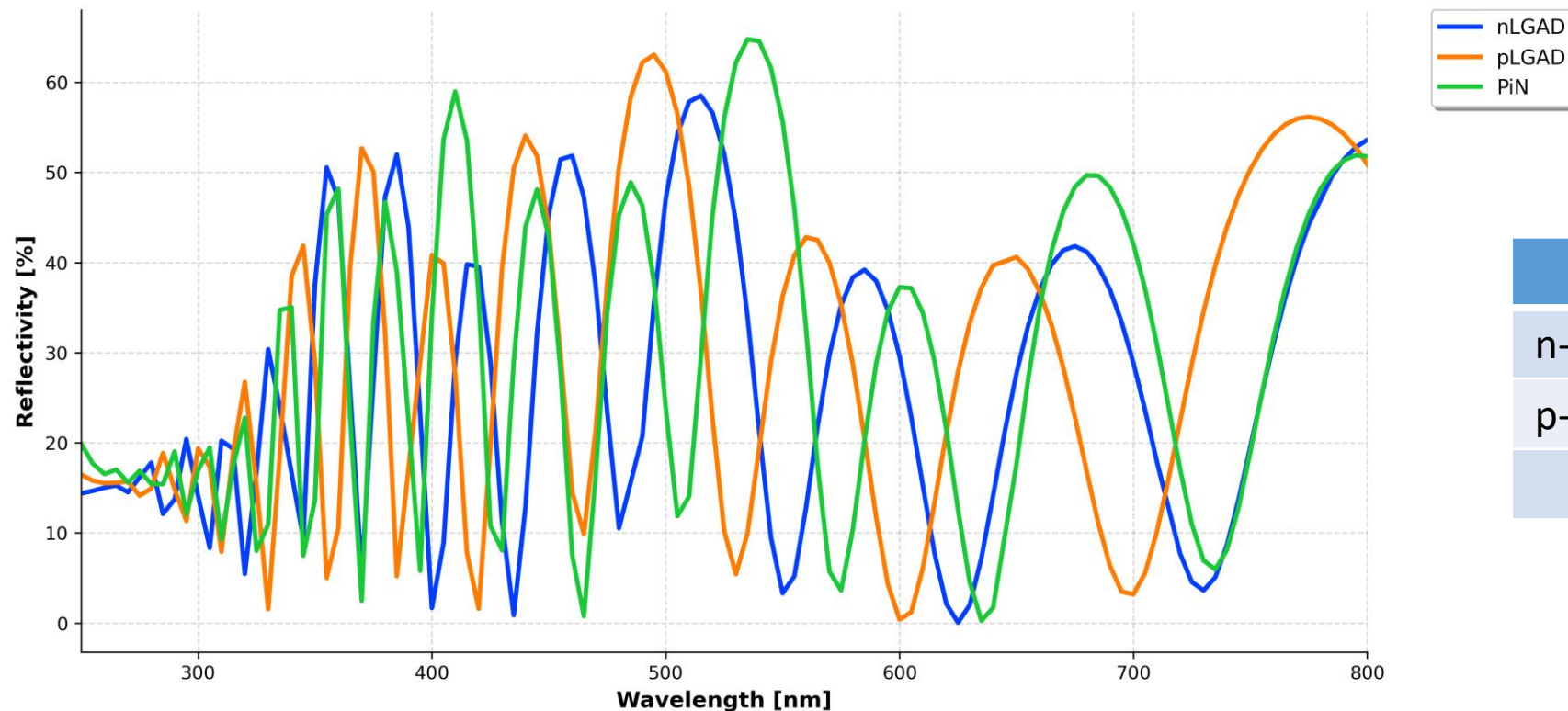


- Better performance of the **p-type** LGAD for $\lambda > 500$ nm
- EQE of the **n-type** LGAD across the spectrum is **less dependant** than the p-type LGAD

LGAD & nLGAD. Ellipsometry

- Incidence angle fixed at 0° (normal to the plane of the DUT)
- **Small variation and reflectivity < 20 % for $\lambda < 300$ nm**
- Very high variation of reflectivity from one sensor to the other for visible and Near-Infrared, coming from the small variations of thicknesses

Reflectivity from the passivation

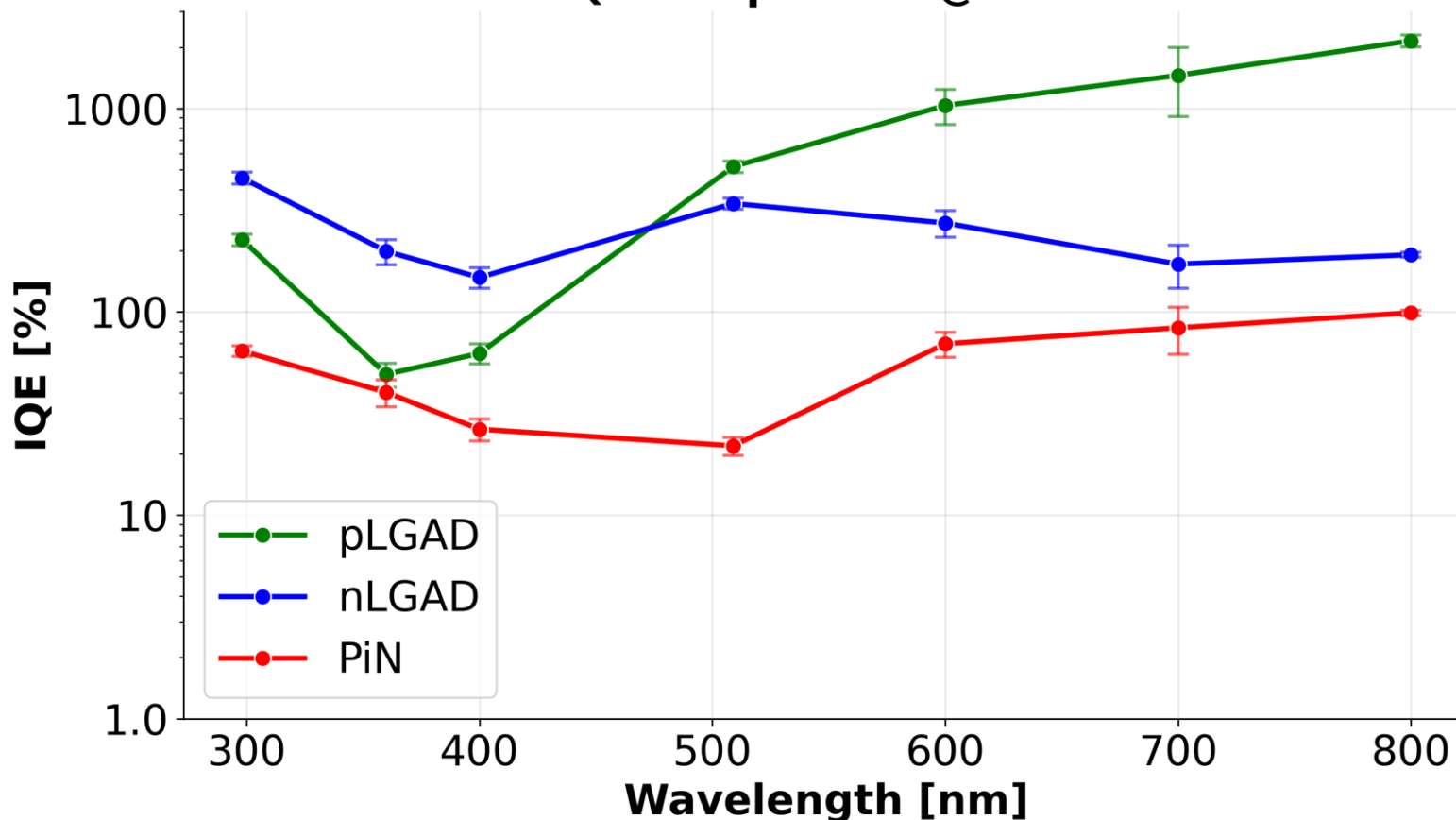


Sensor	Si ₃ N ₄ (nm)	SiO ₂ (nm)
n-type LGAD	706.4	420.4
p-type LGAD	661.3	409.6
PiN	711.7	634.1

LGAD & nLGAD. Internal Quantum Efficiency

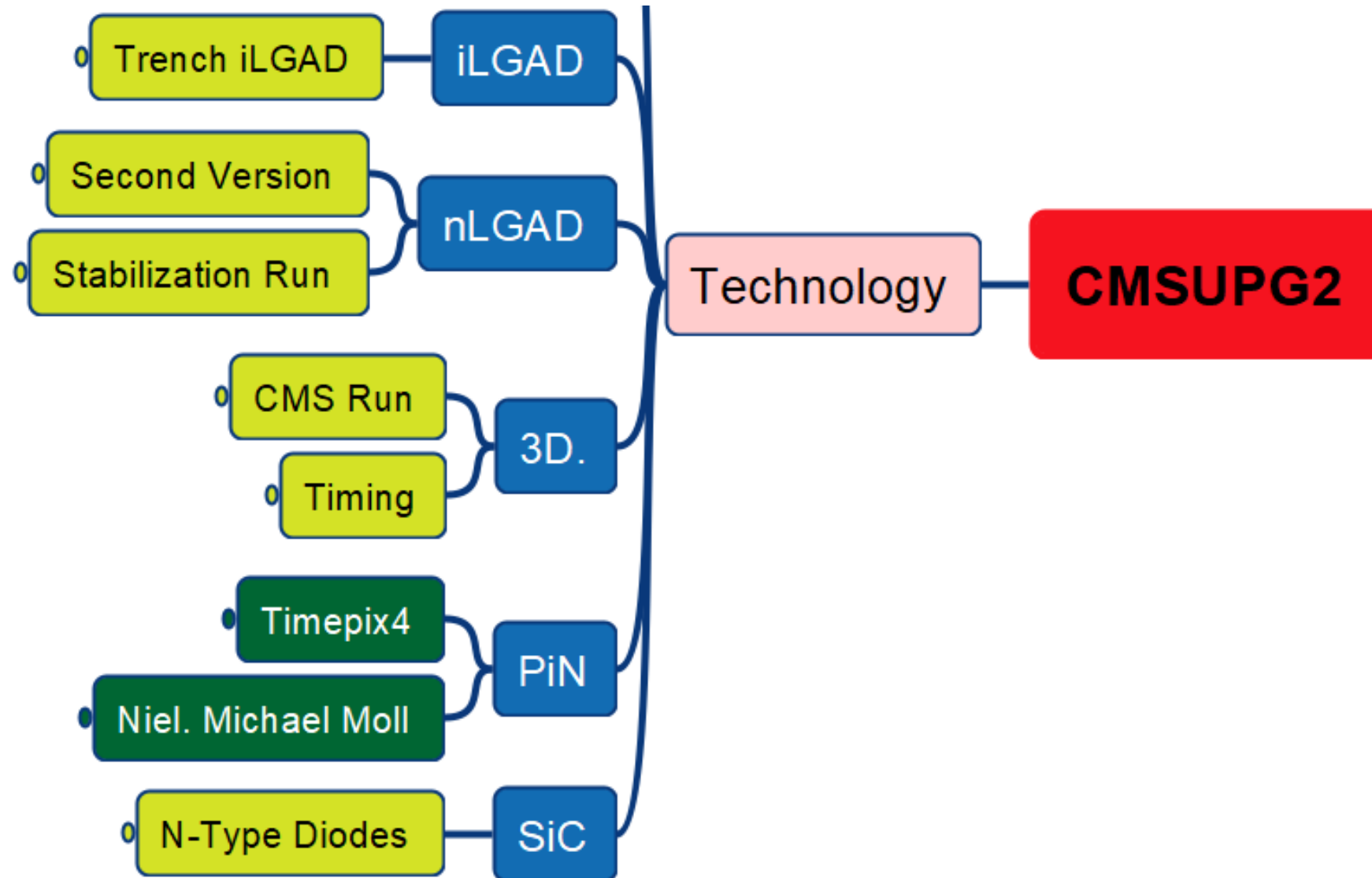
$$IQE = \frac{\text{Number of Collected Charge Carriers}}{\text{Number of Absorbed Photons}} \quad IQE(\lambda) = \frac{EQE(\lambda)}{1 - R_f(\lambda)}$$

IQE comparison @250V

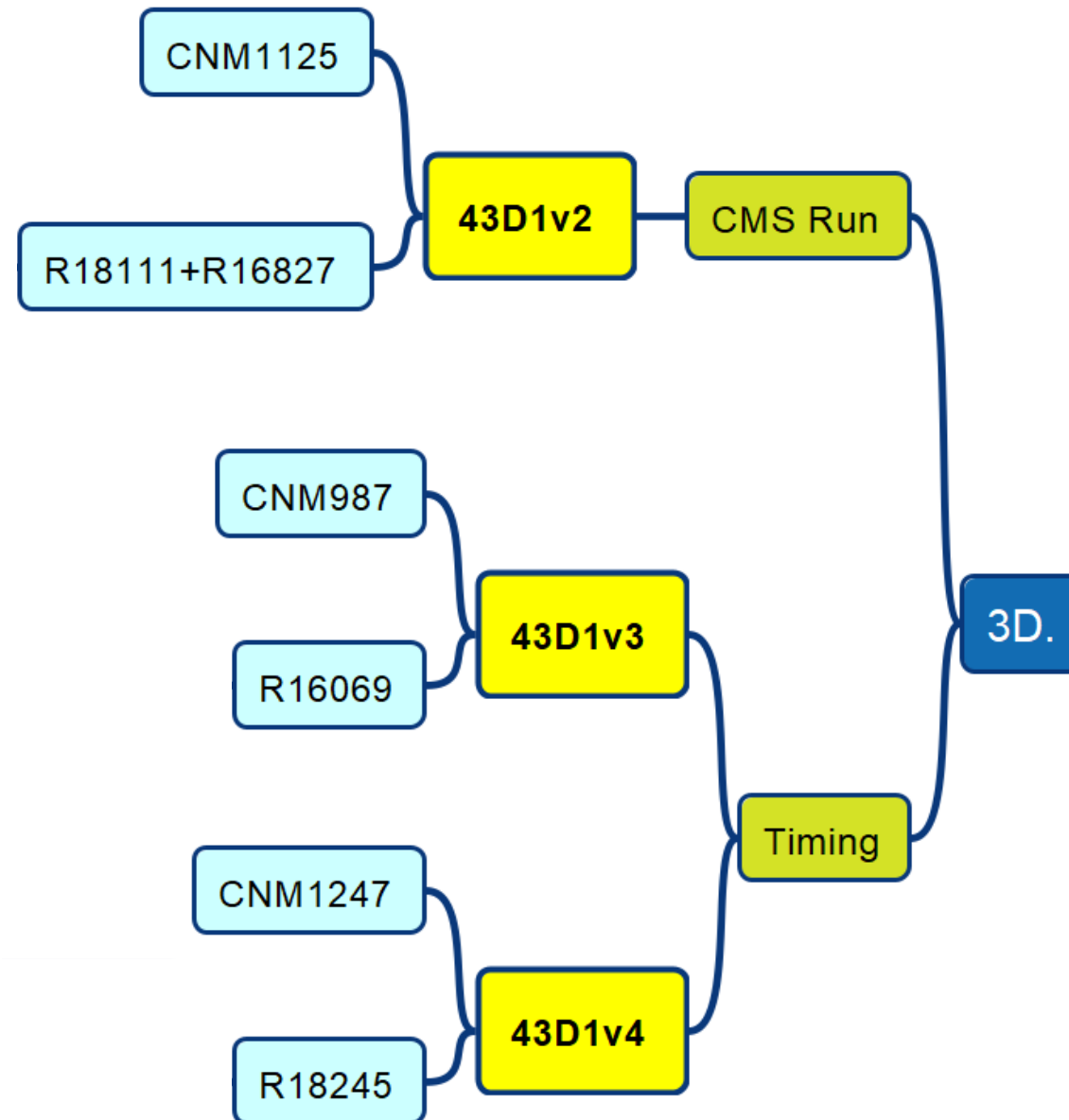
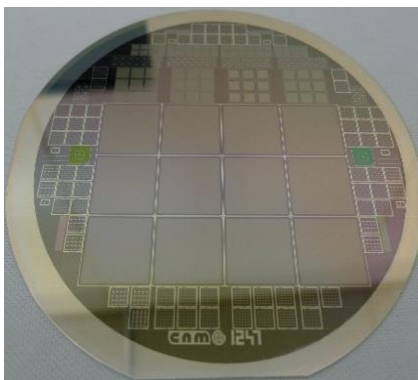
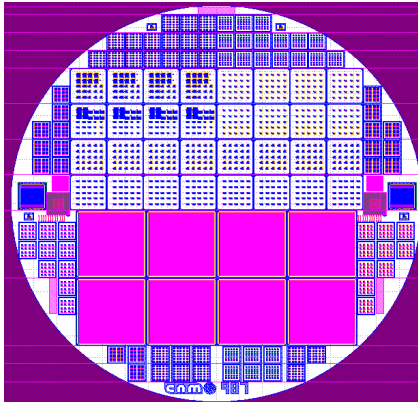
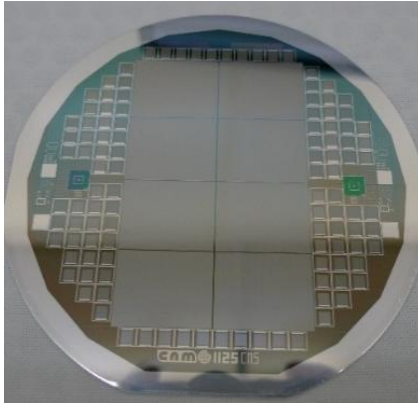


- Confirm the behavior seen with the responsivity and EQE:
 - Better performance of the **p-type** LGAD for $\lambda > 500$ nm
 - **n-type** LGAD across the spectrum **shows a lower dependance** on the wavelength.

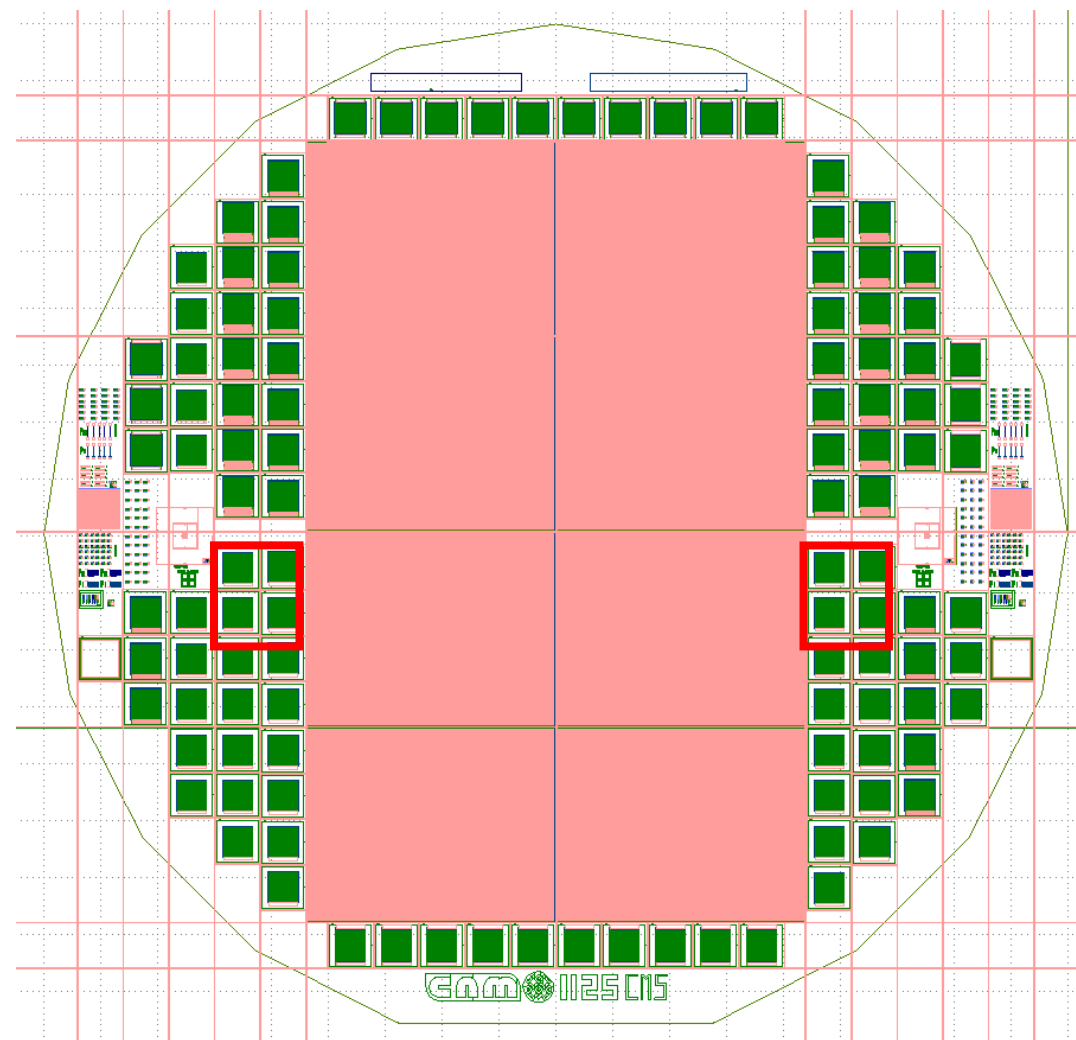
Subproject Objectives. WP3



WP3. Technologies Developed. 3D

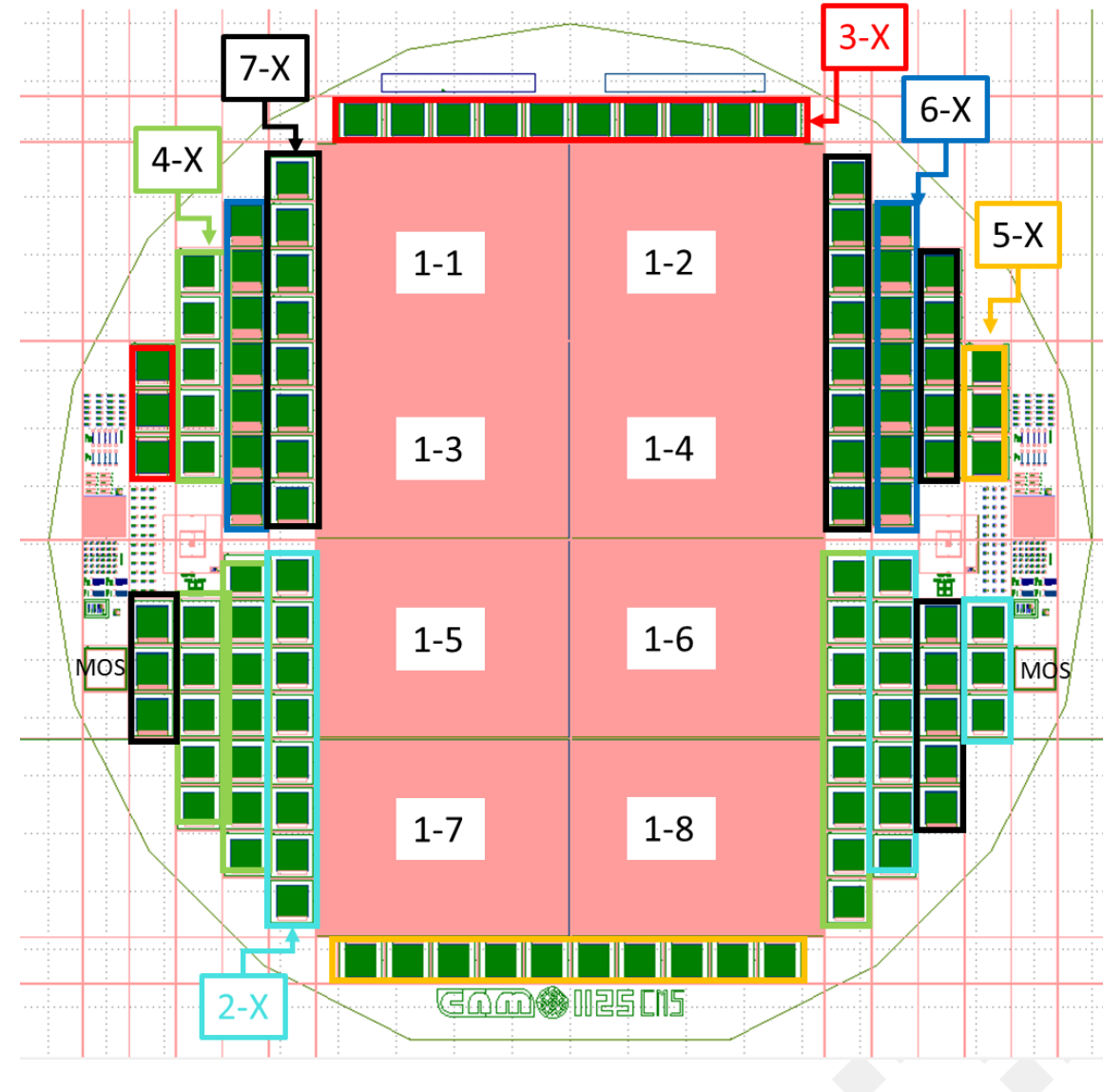


- 12 wafers on SiSi wafers 350 μ m (150 μ m active layer + 200 μ m handle wafer)
- Started in June 2023 (as R16827)
- Delayed do to Sentech/Alcatel reactor and Tempress furnace
- First 3D run fabricated using “new” equipment in CR (Sentech for the DRIE, Tempress furnace for poly deposition and the B/P doping process)
- Concluded in December 2025
- Metallization and passivation done
- Temporary metal to be deposited (to be discussed)
- Measurements in CR of some diodes

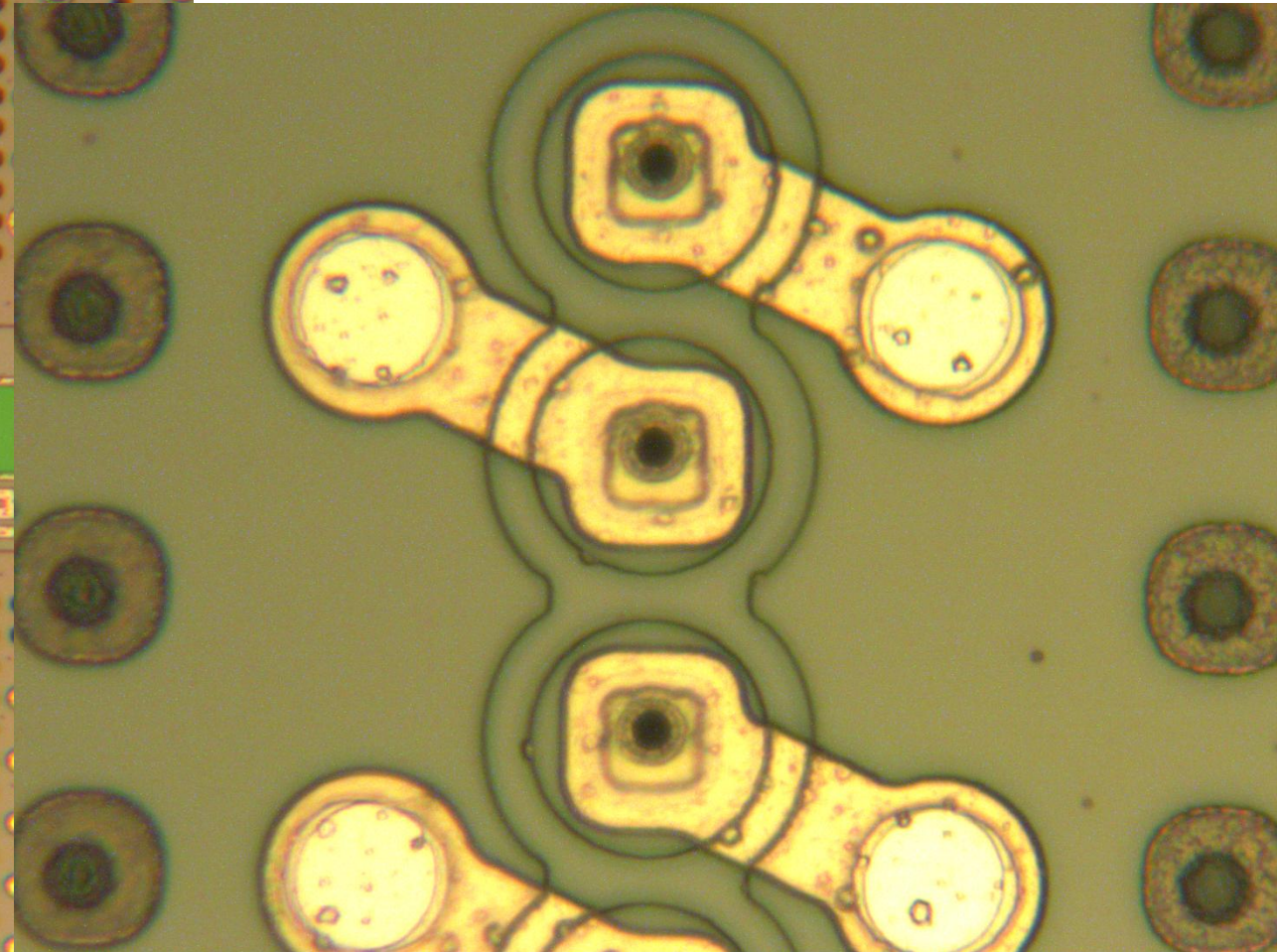
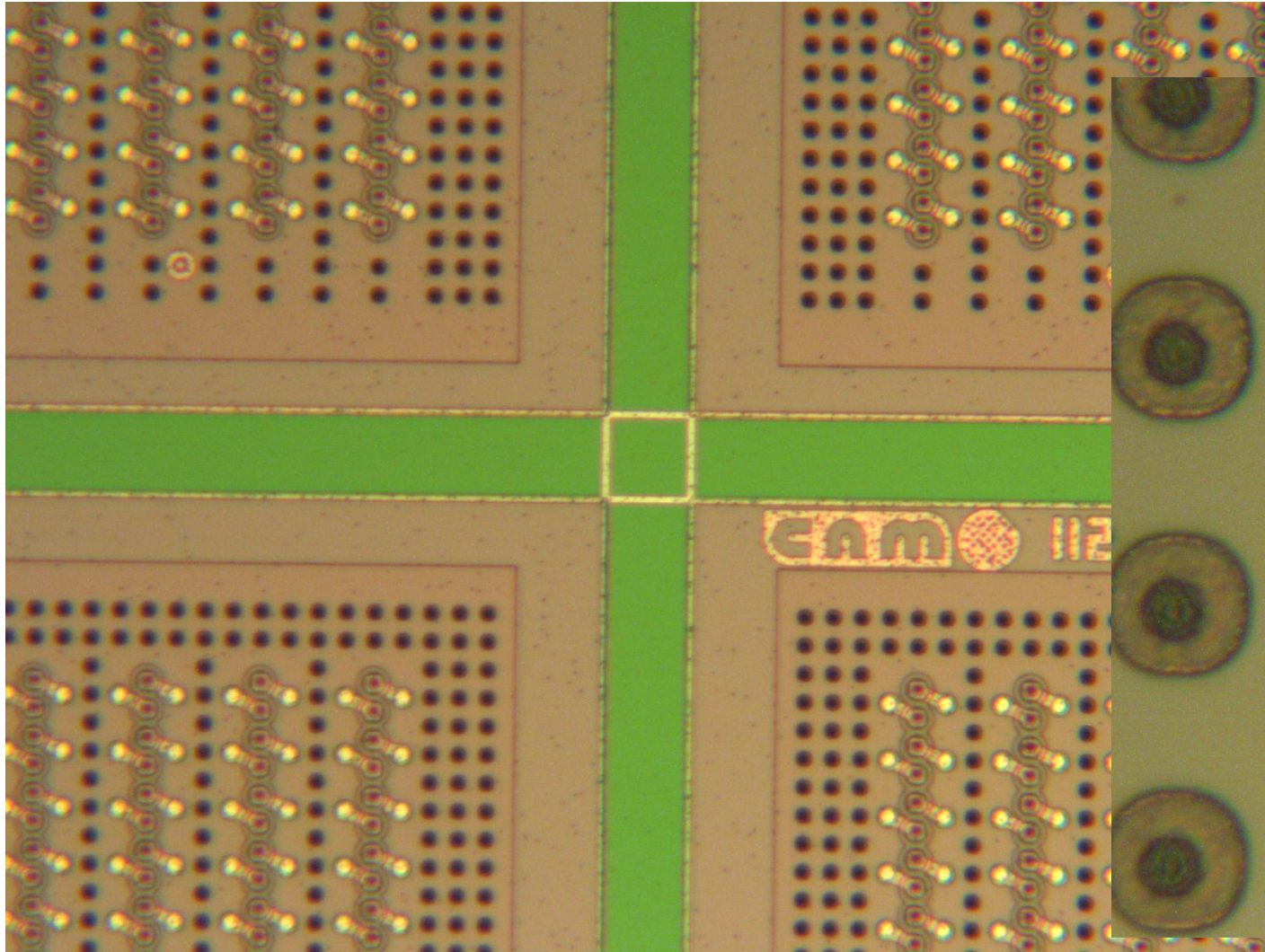


CMS 43D1v2. R16827+R18111. 3D-SS 4 CROC

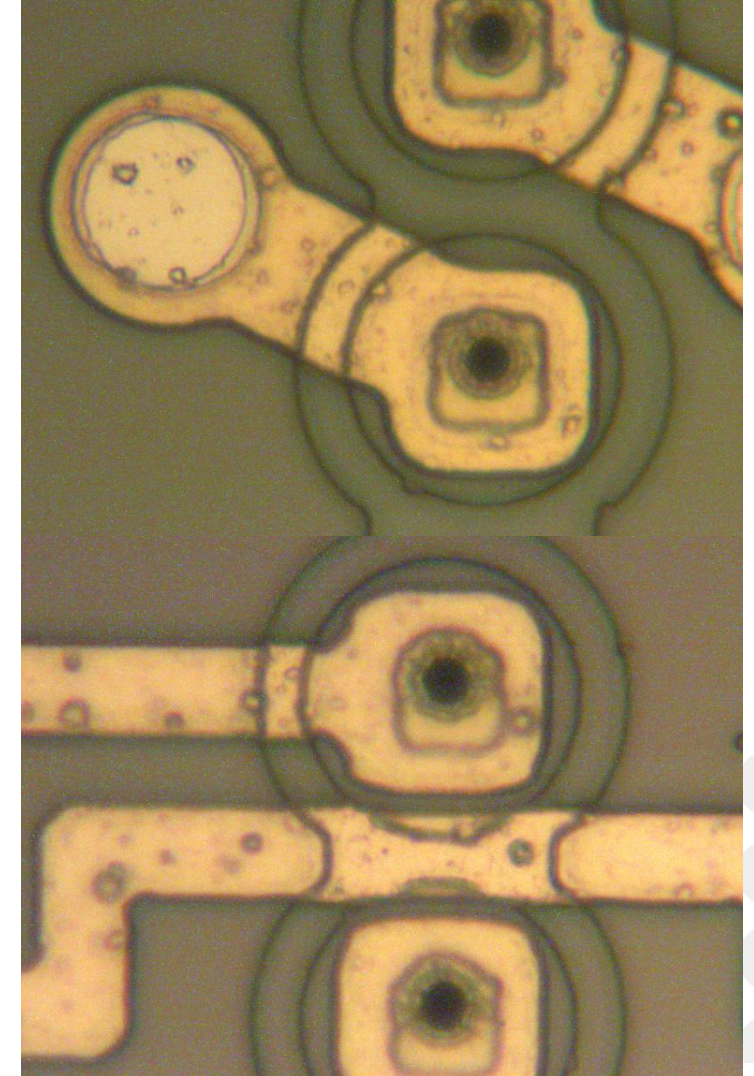
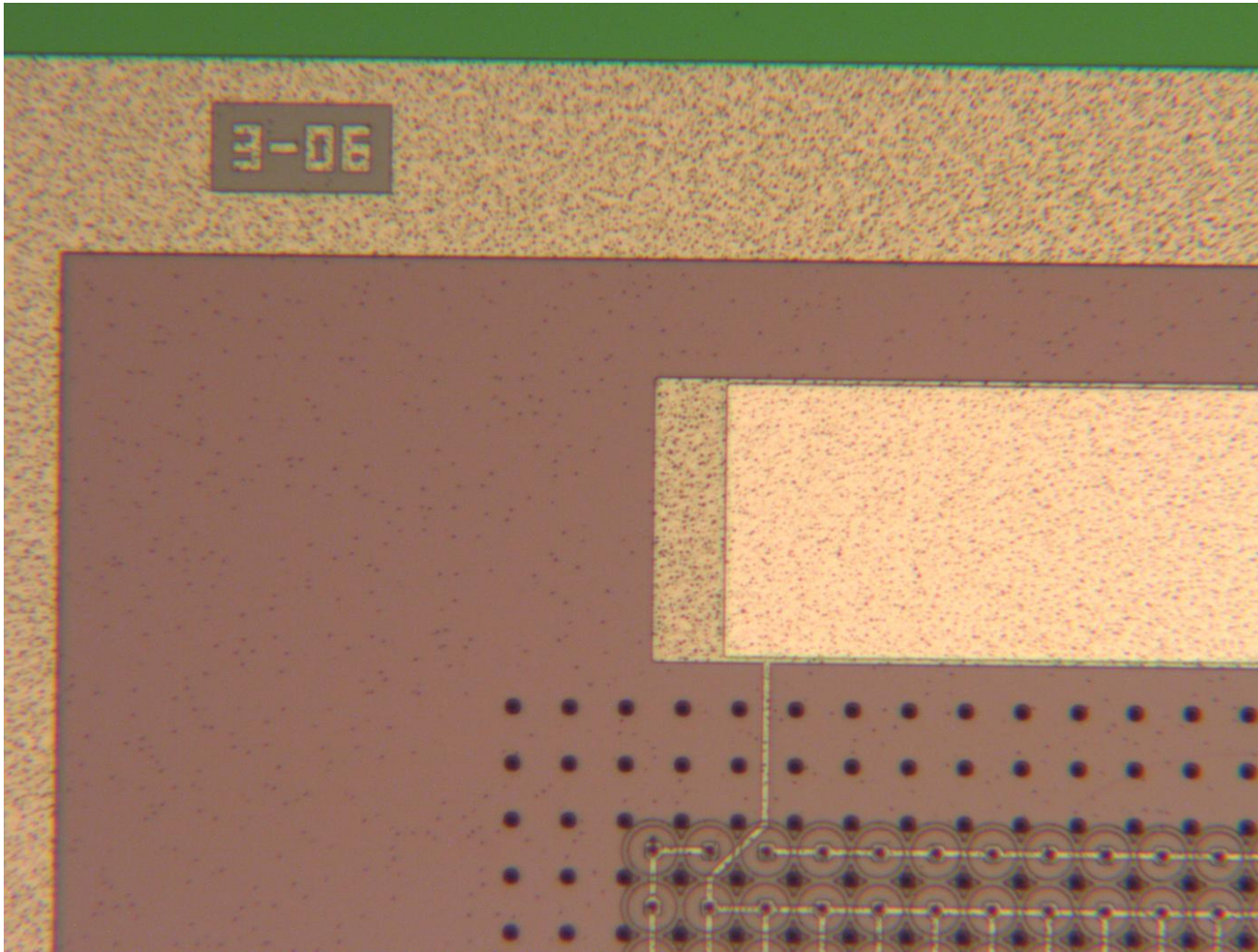
- 8 CMSROC Single (25x100) μm 1-X
- 18 Diodes (50x50) μm 2-X
- 13 Diodes (50x50) μm - GR 3-X
- 25 Diodes (25x100) μm 4-X
- 13 Diodes (25x100) μm - GR 5-X
- 14 Microstrips (25x100) μm 6-X
- 29 Microstrips (50x50) μm 7-X
- 2 MOS
- Pads 3x3 (50x50) μm
- Pads 3x3 (25x100) μm
- Test structures



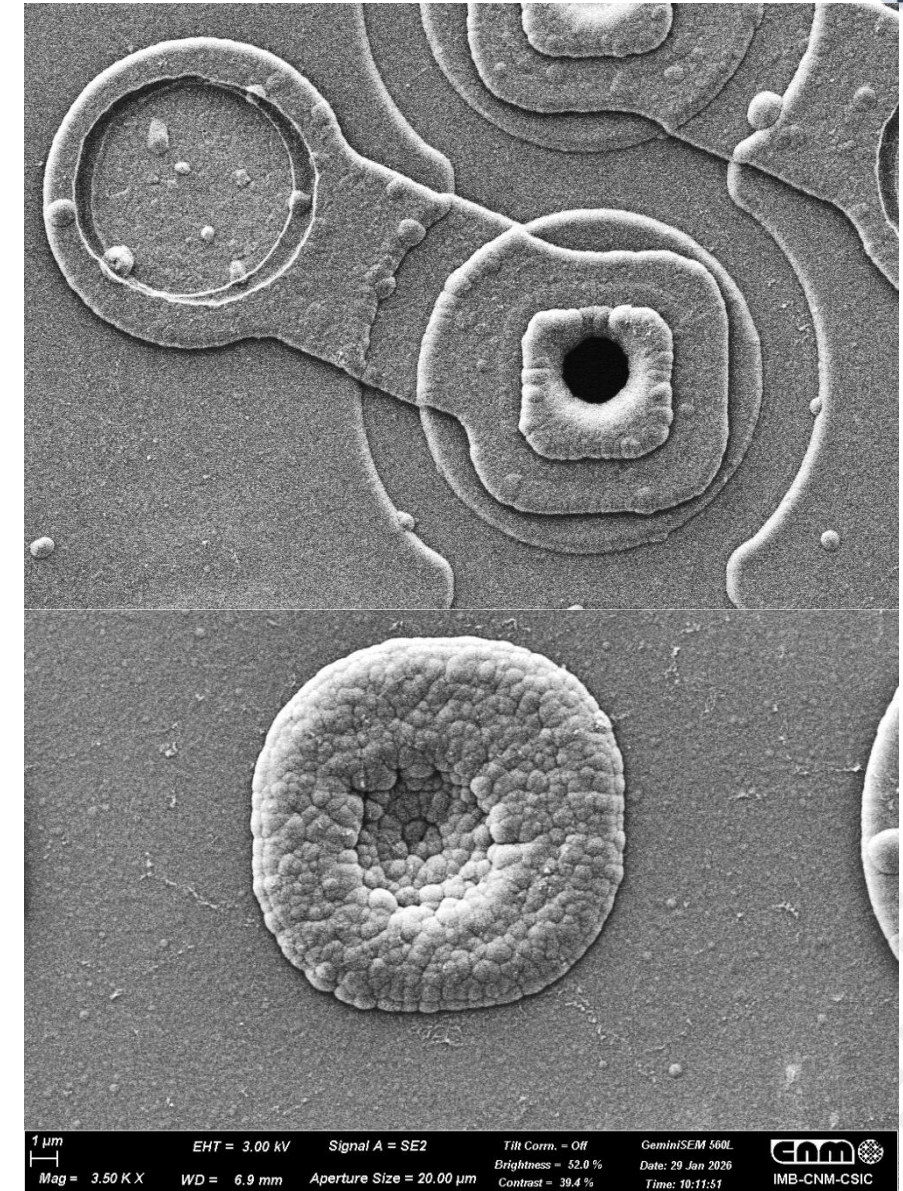
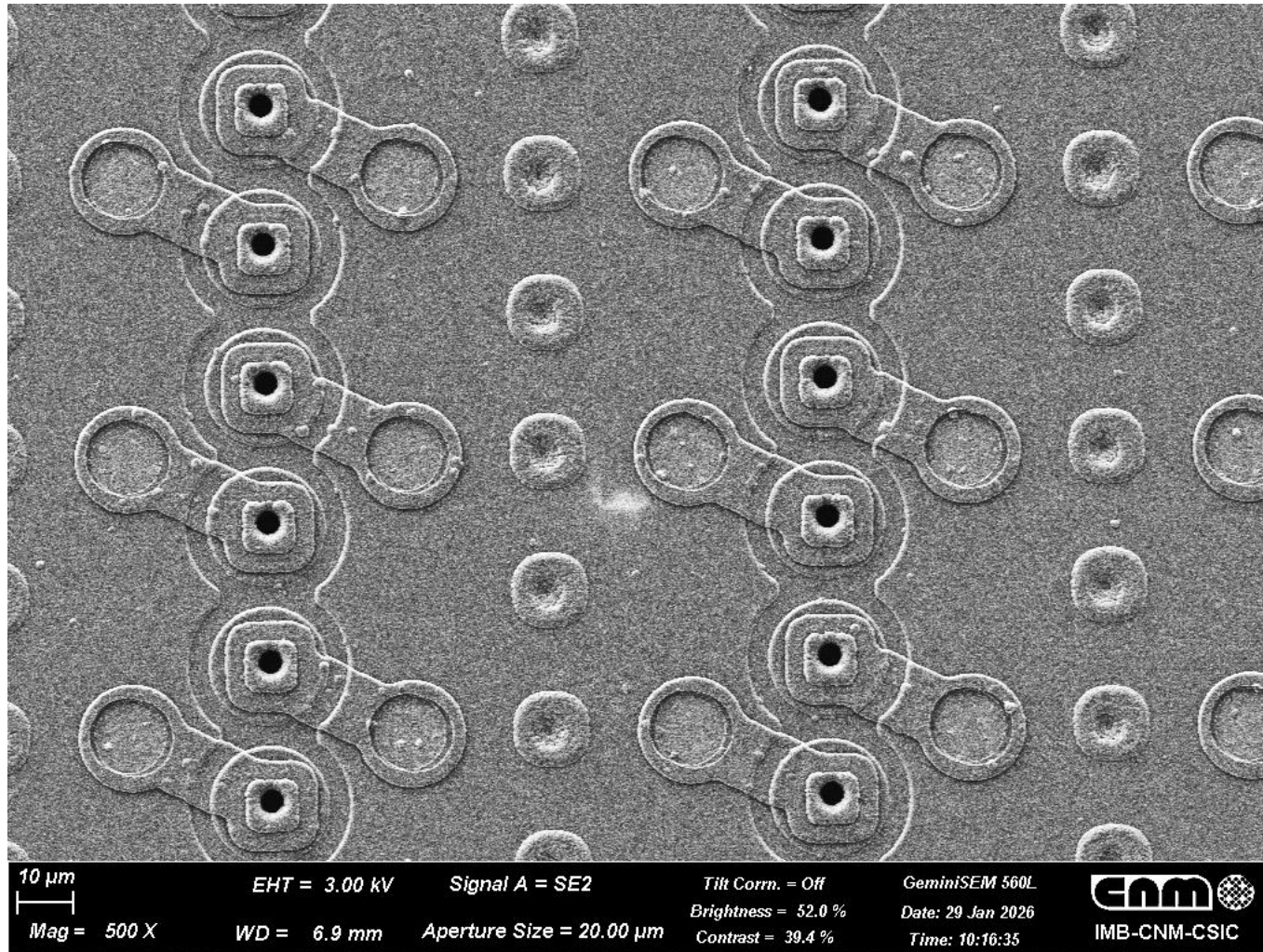
- Metallization and passivation: inspection by optical microscopy



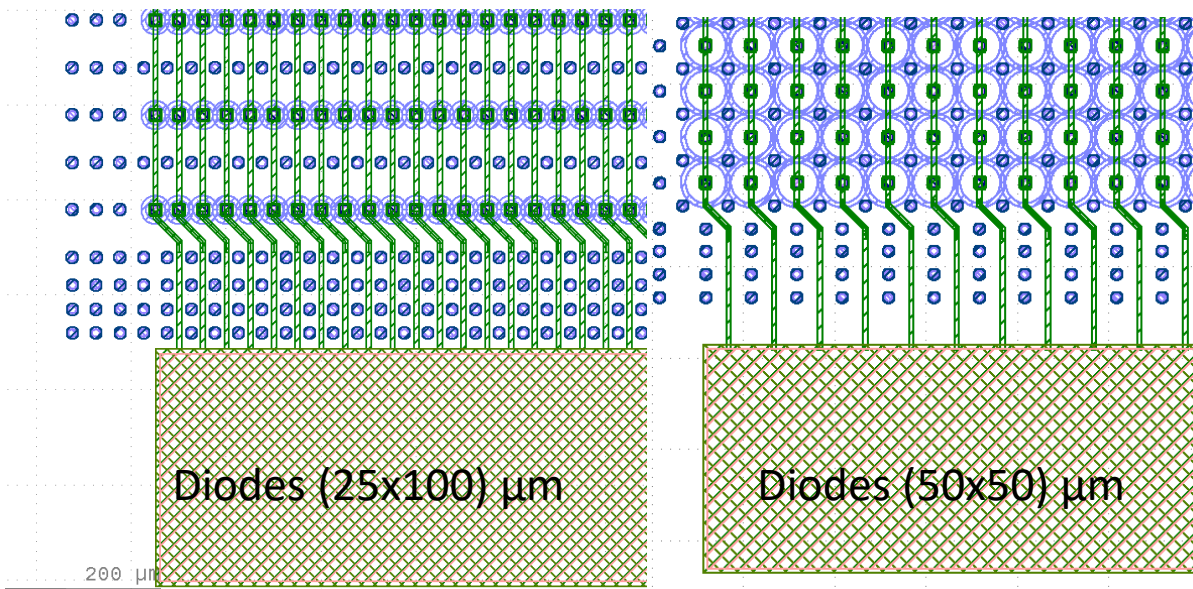
- Metallization and passivation: inspection by optical microscopy



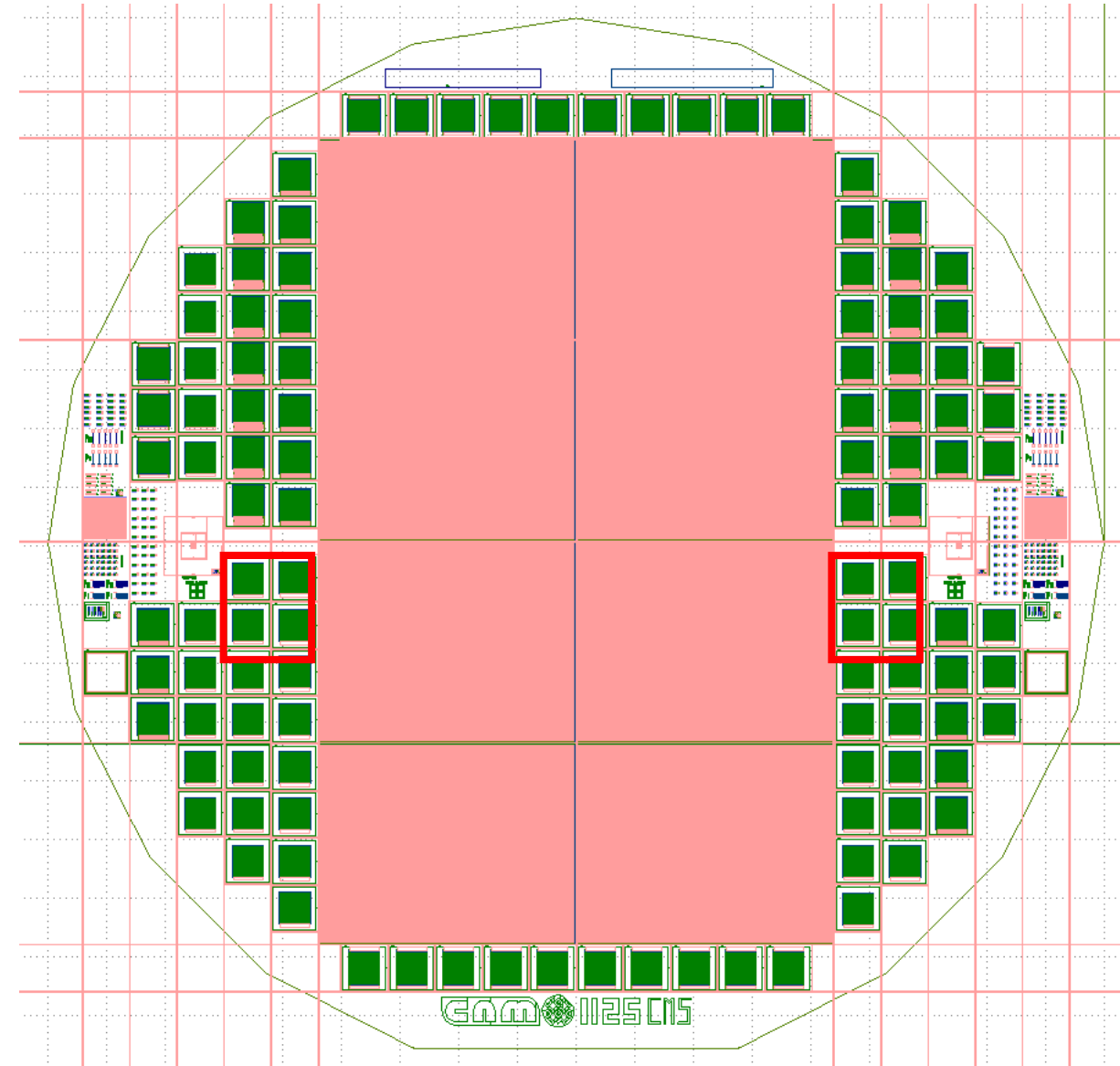
- Metallization and passivation: inspection by SEM



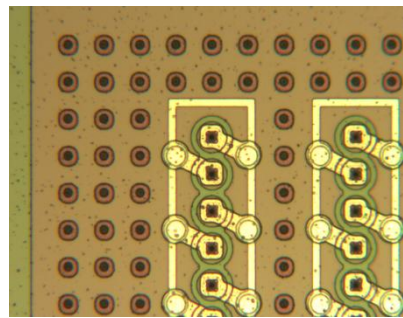
- IV measurements
- Done in CR
- Measured wafers 1, 2, 3, 7, 12
- 8 diodes for each wafer



- $I(@25\text{V}) \approx 40 \mu\text{A}$, $V_{bd} > 150\text{V}$



-

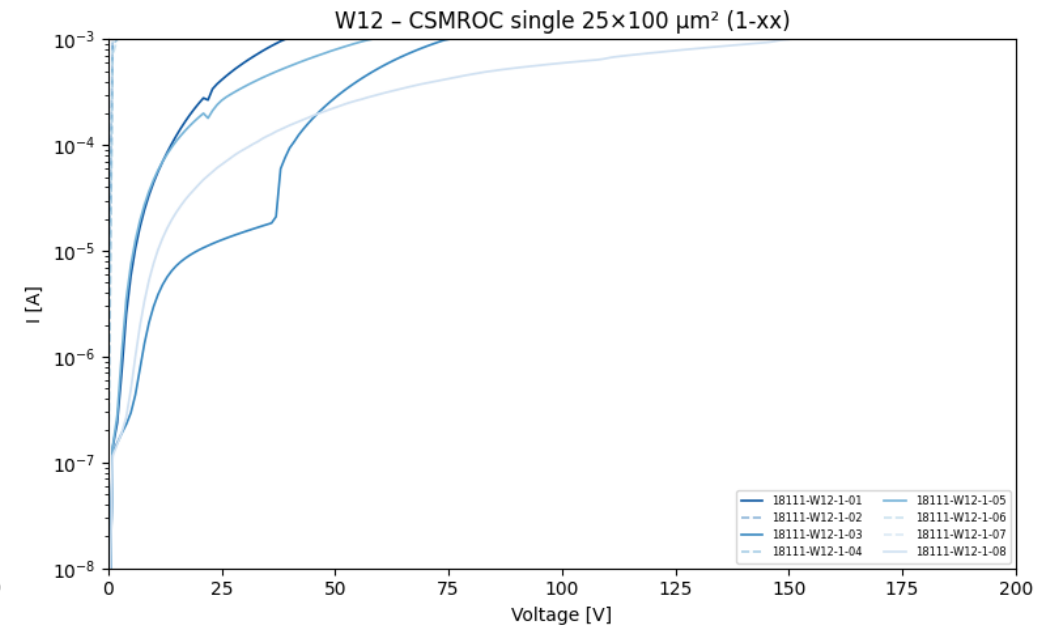
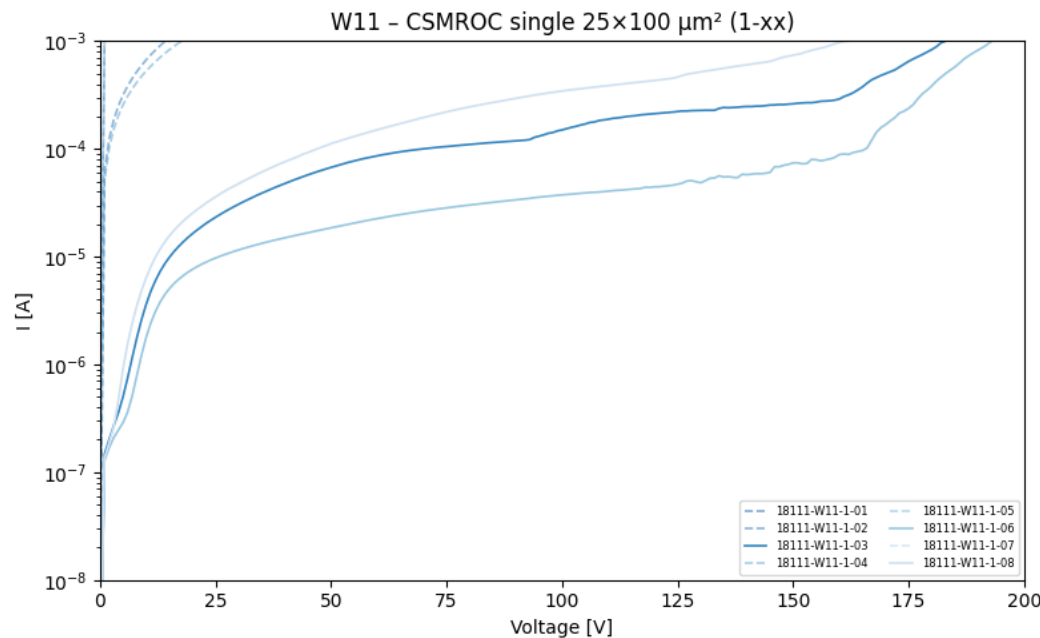


10 μ m

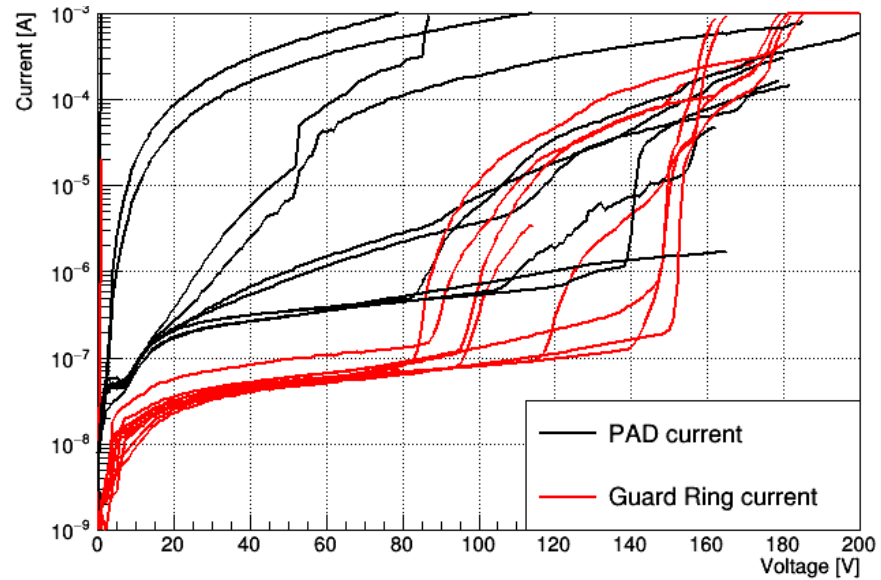
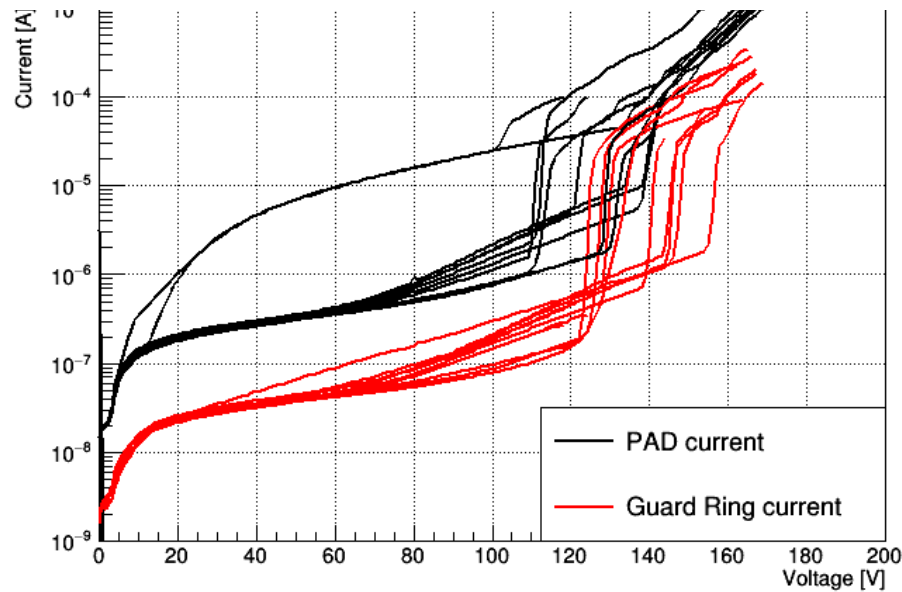
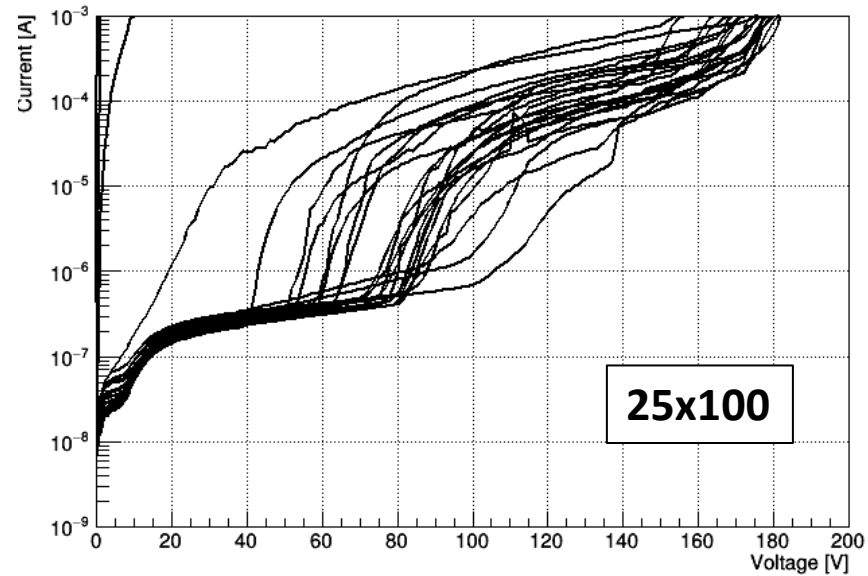
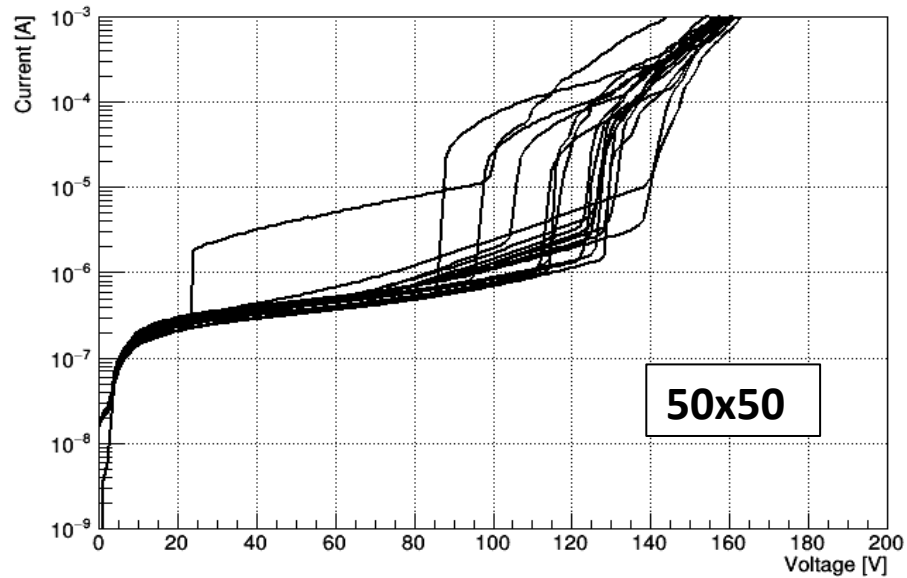
Scale: 1.00 kV X1.50K 10.0 μ m X2.50K
Mag: 1.00 kV X1.50K X2.50K
Signal: 4.0 kV X2.50K
Aperture: 10.0 μ m X2.50K
Date: 10/10/00
Time: 10:10:10
cm

Figure 10 is a plot of current I [A] versus Voltage [V] for the W11 device. The y-axis is logarithmic, ranging from 10^{-8} to 10^{-3} A. The x-axis is linear, ranging from 0 to 200 V. The plot shows several curves corresponding to different values of x (0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08). The current increases with voltage and decreases as x increases. Shaded regions around the curves indicate uncertainty.

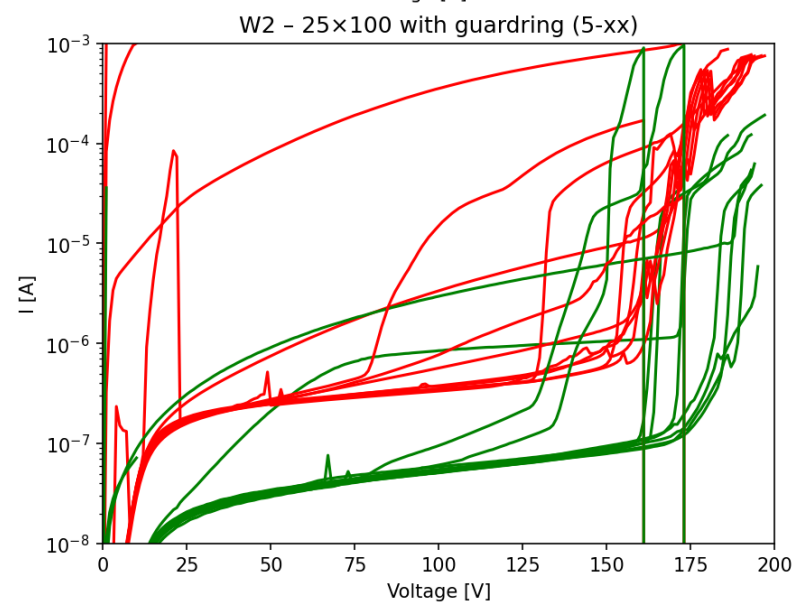
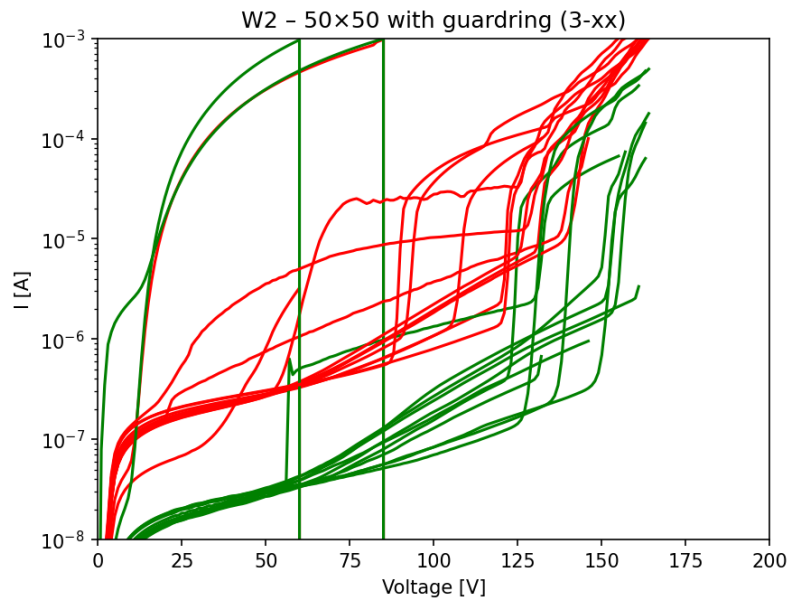
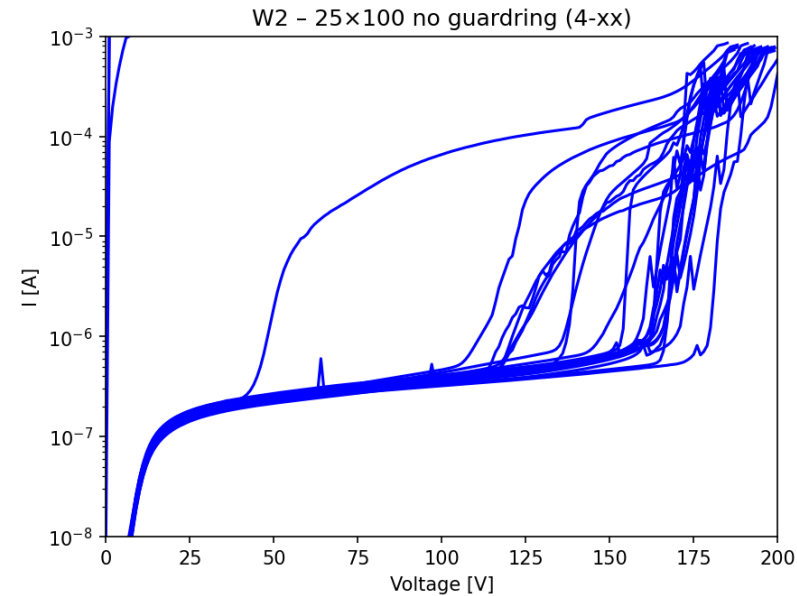
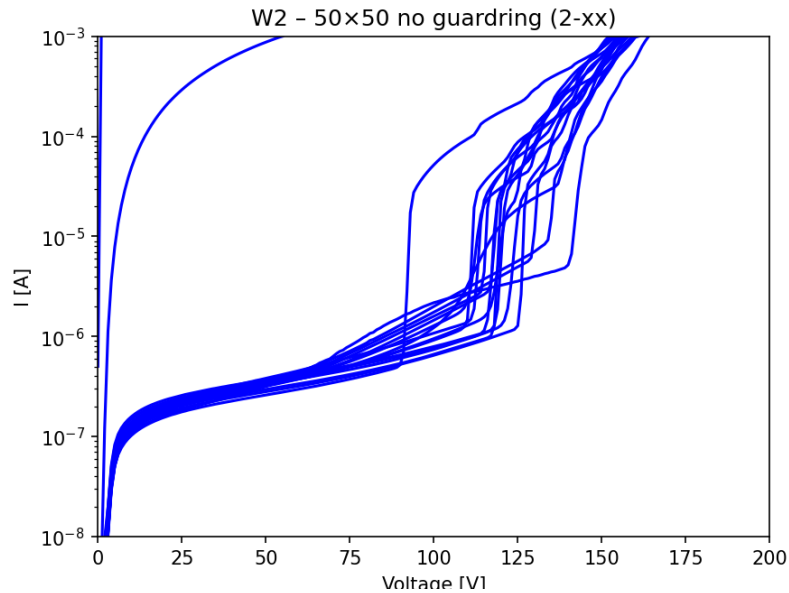
- 11-12 wafers with temporary metal -> CMSROC IVs
- No degradation or scaling effect on leakage current is observed when increasing number of columns from diode 2.5k to CSMROC >145k pixels; the current per pixel remains at the same order ($\approx 10^{-11}$ A).
- The IVs of the diodes with and w/o temporary metal are similar. The temporary metal do not affect the measurement.
- An investigation about the surface current is on-going.



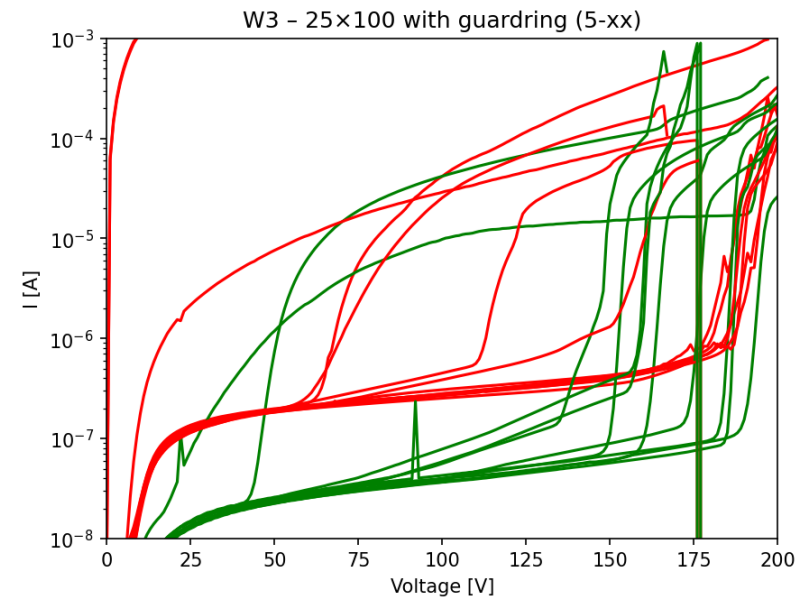
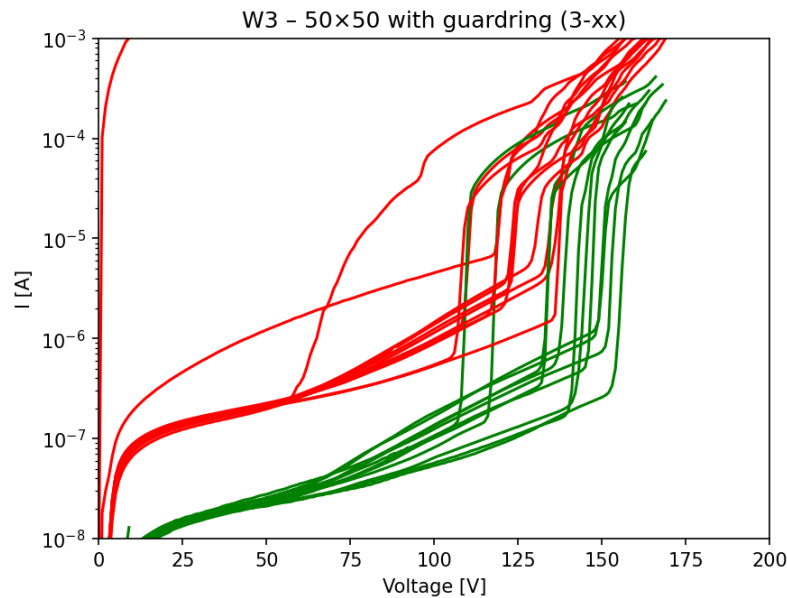
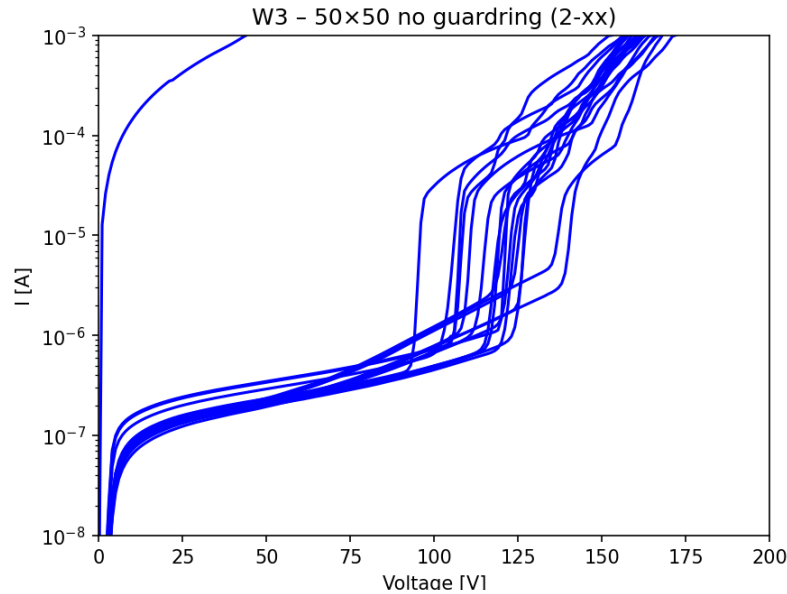
CMS 43D1v2. R16827+R18111. W1. Diodes



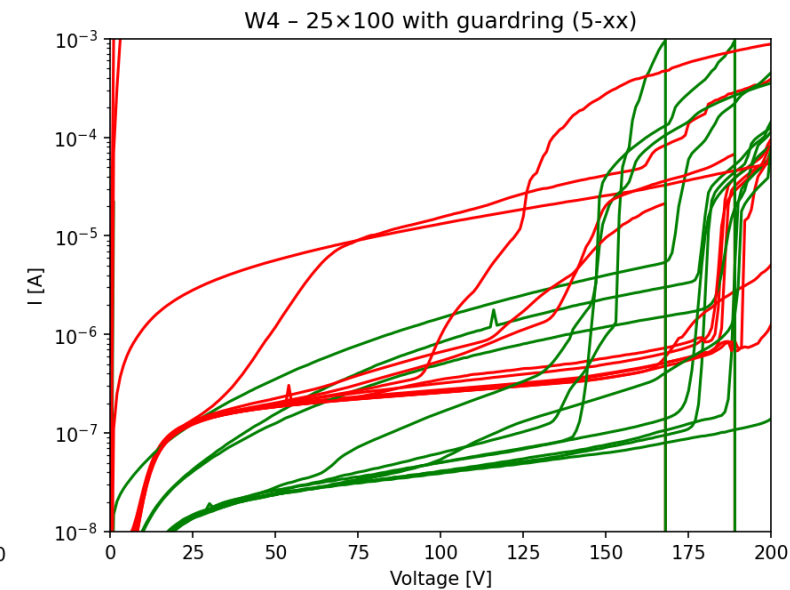
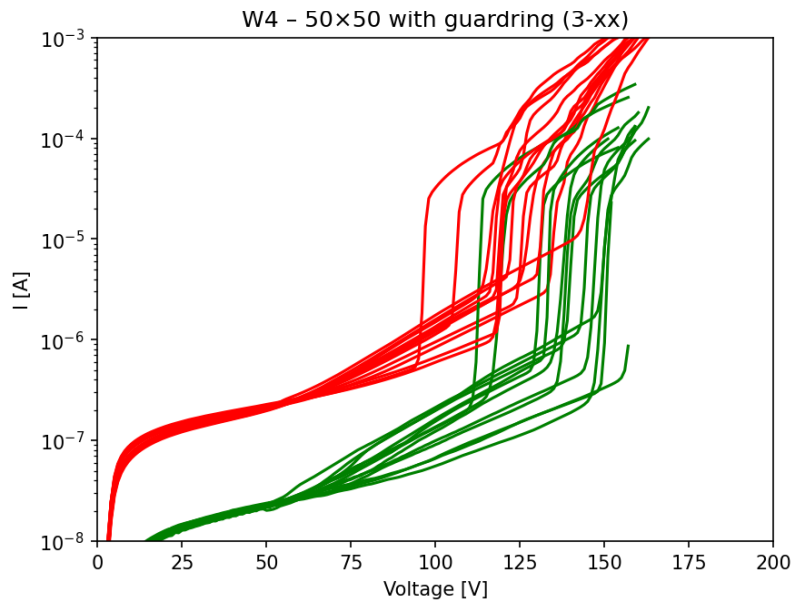
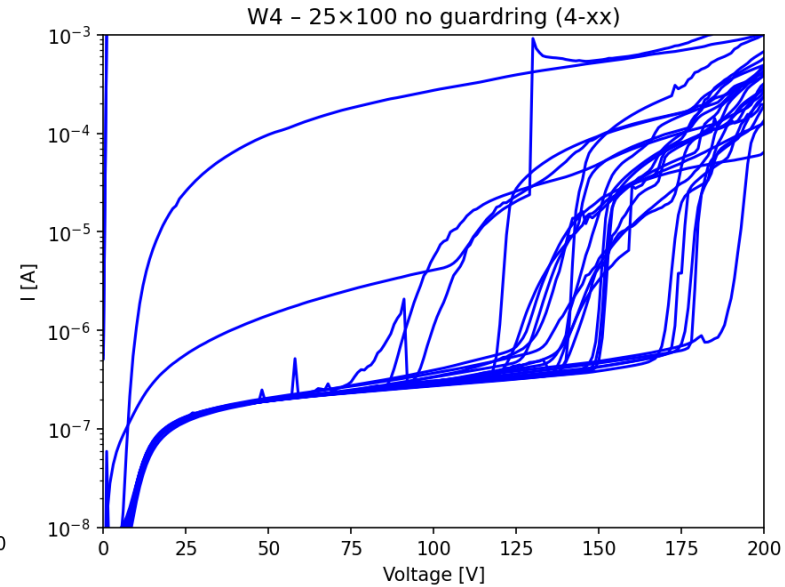
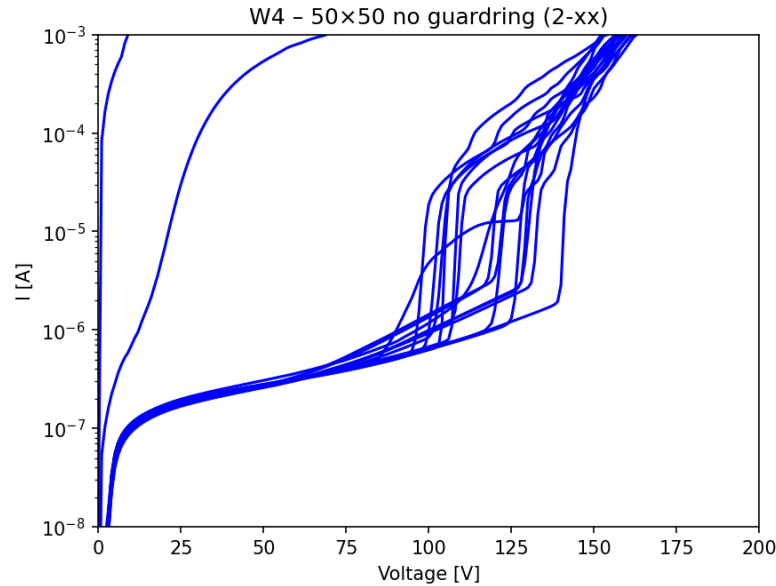
CMS 43D1v2. R16827+R18111. W2. Diodes



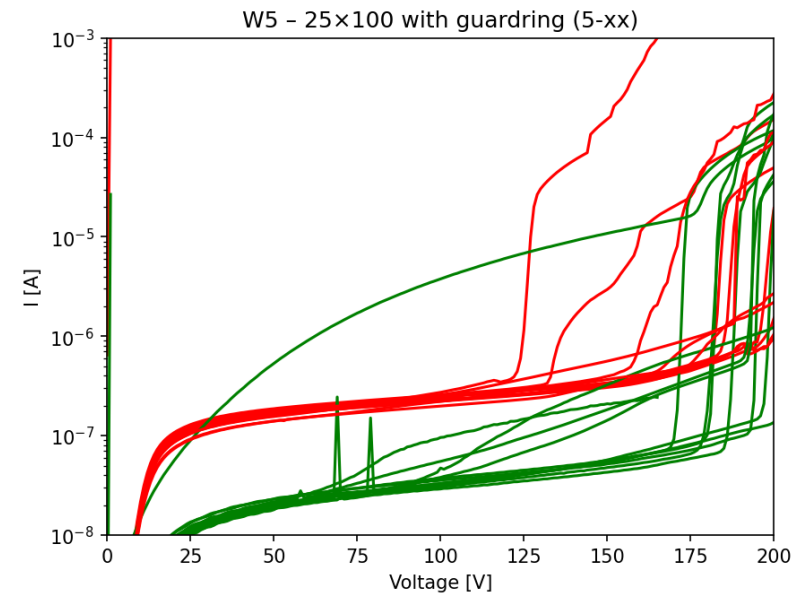
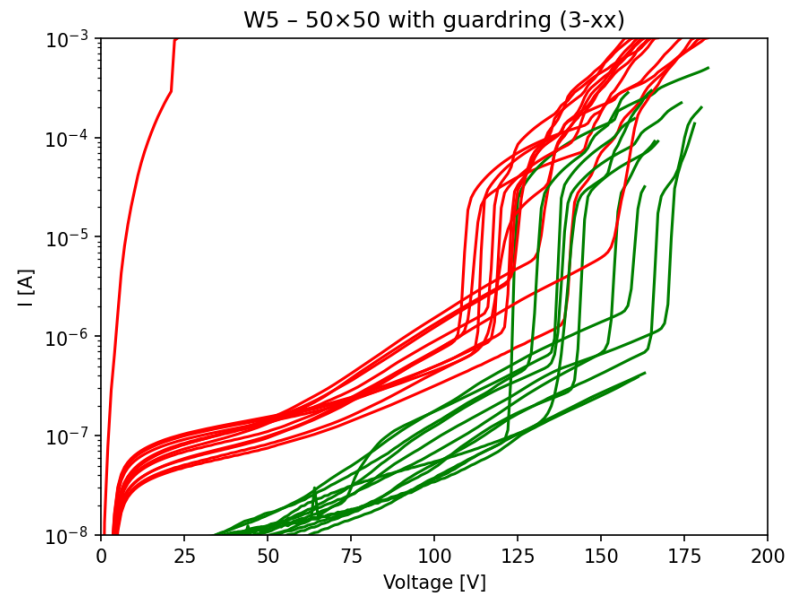
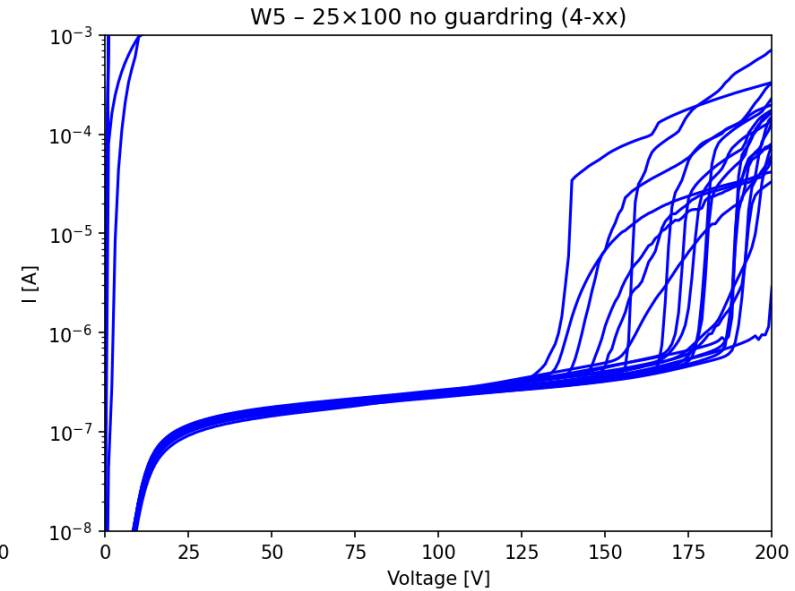
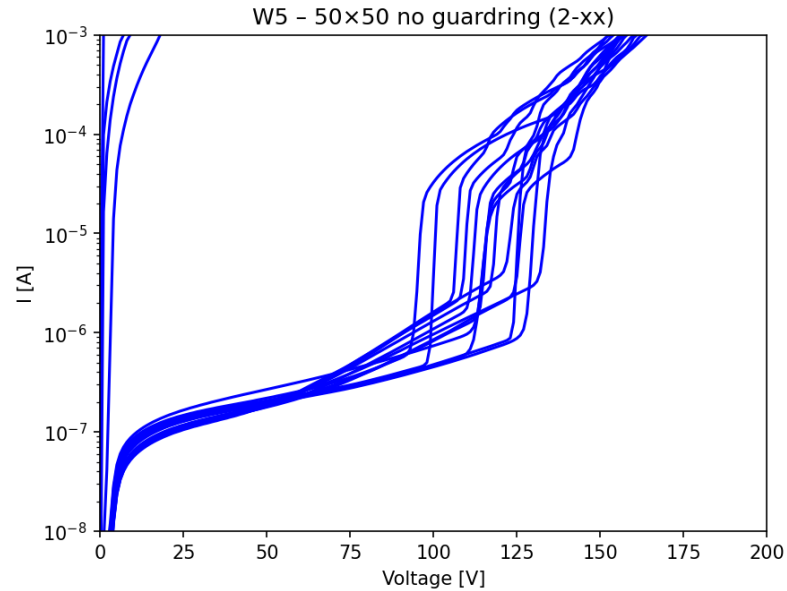
CMS 43D1v2. R16827+R18111. W3. Diodes



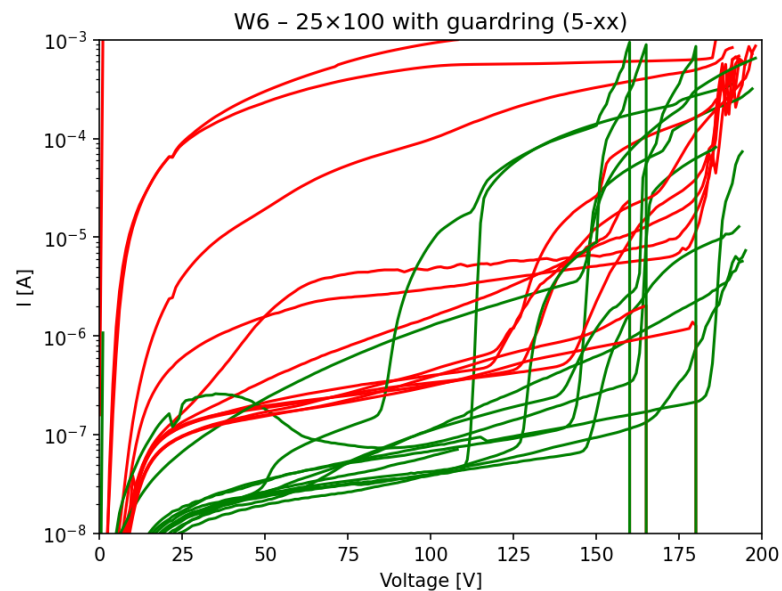
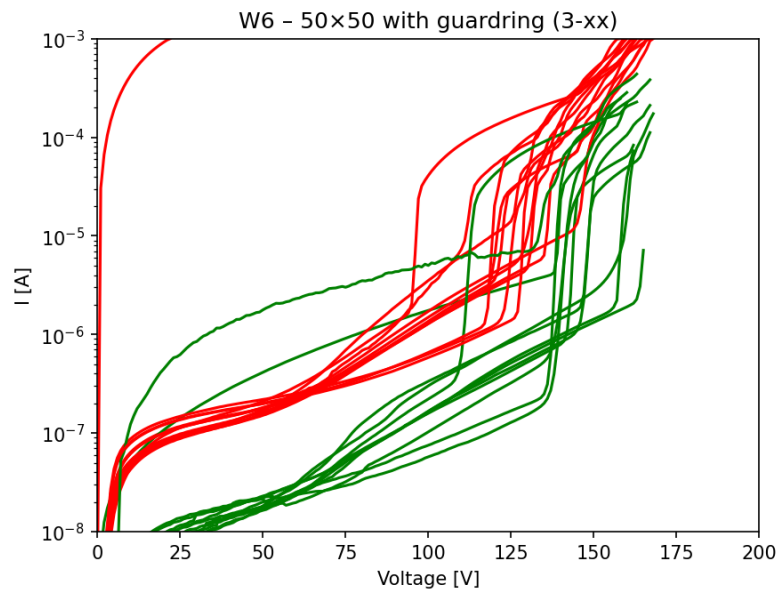
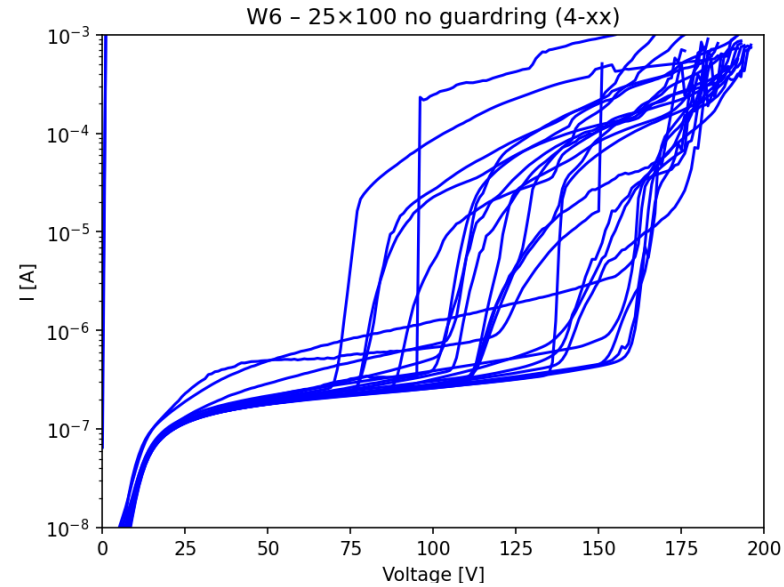
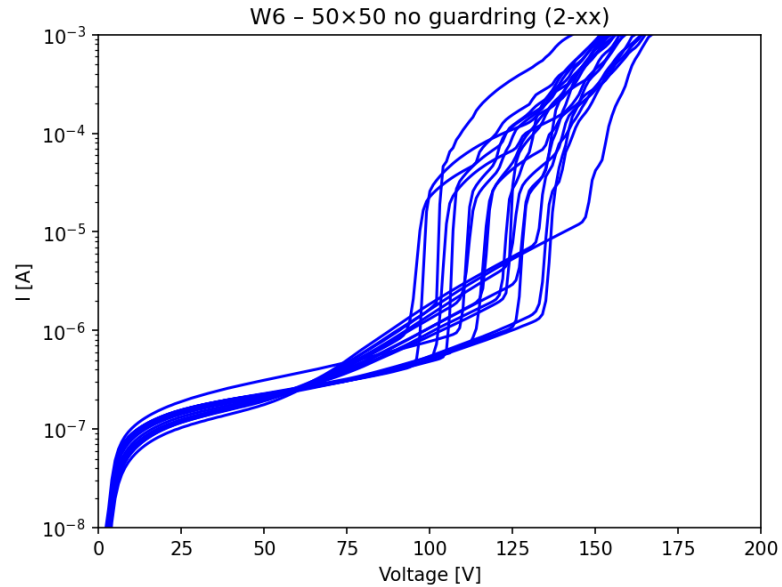
CMS 43D1v2. R16827+R18111. W4. Diodes



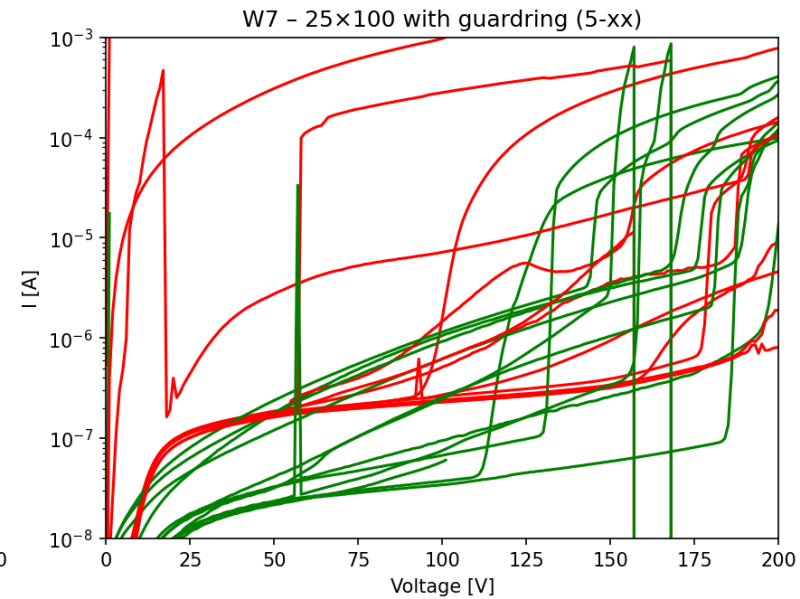
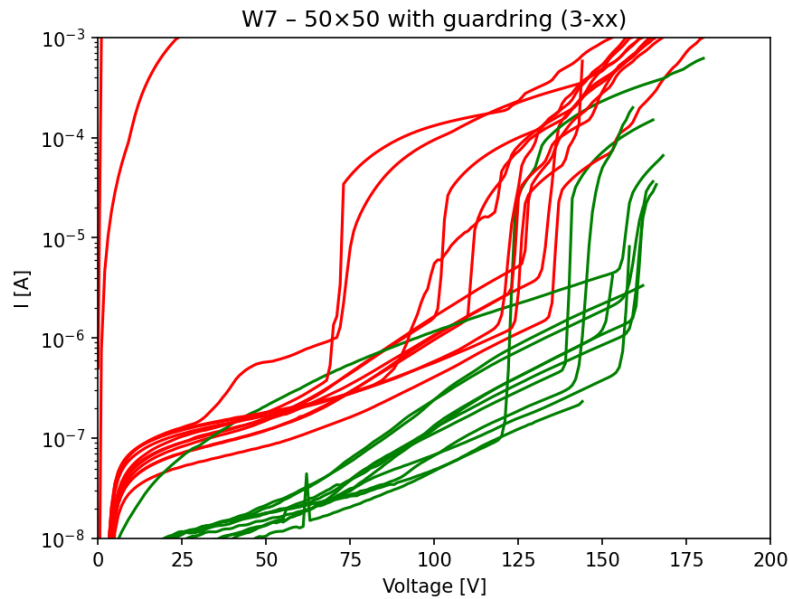
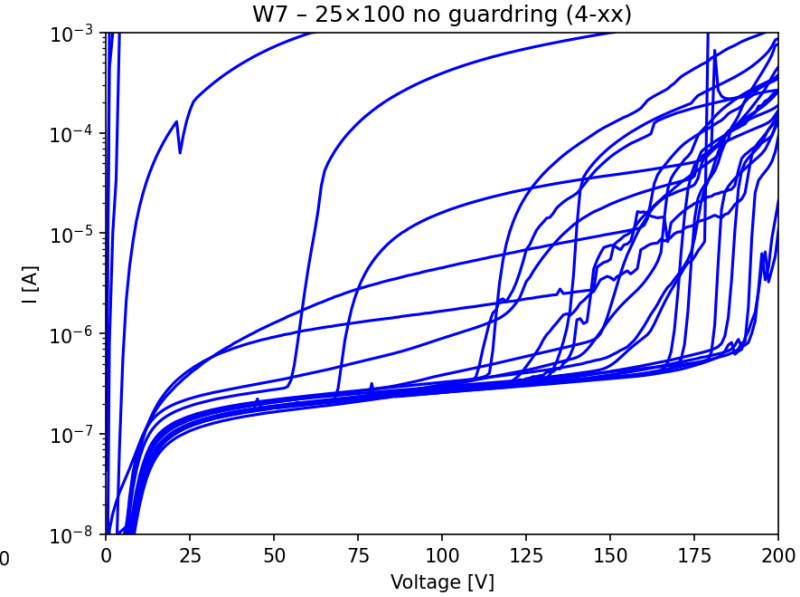
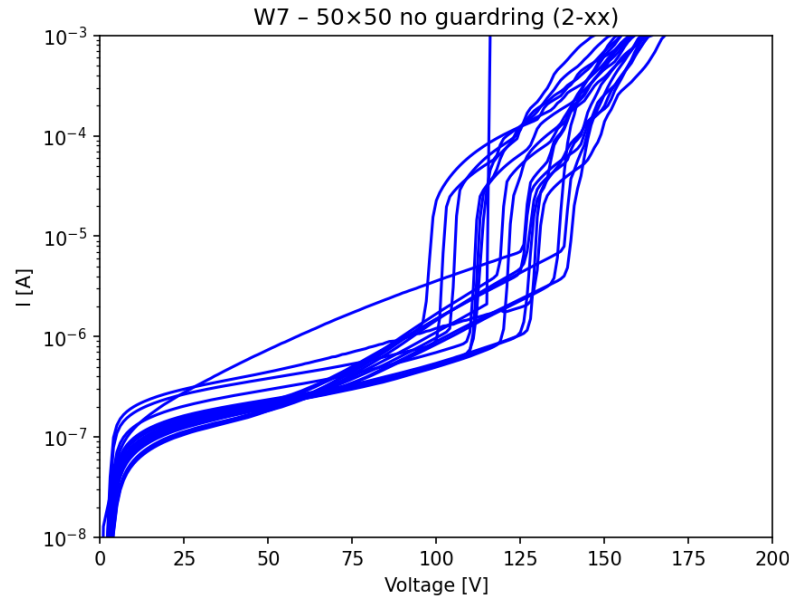
CMS 43D1v2. R16827+R18111. W5. Diodes



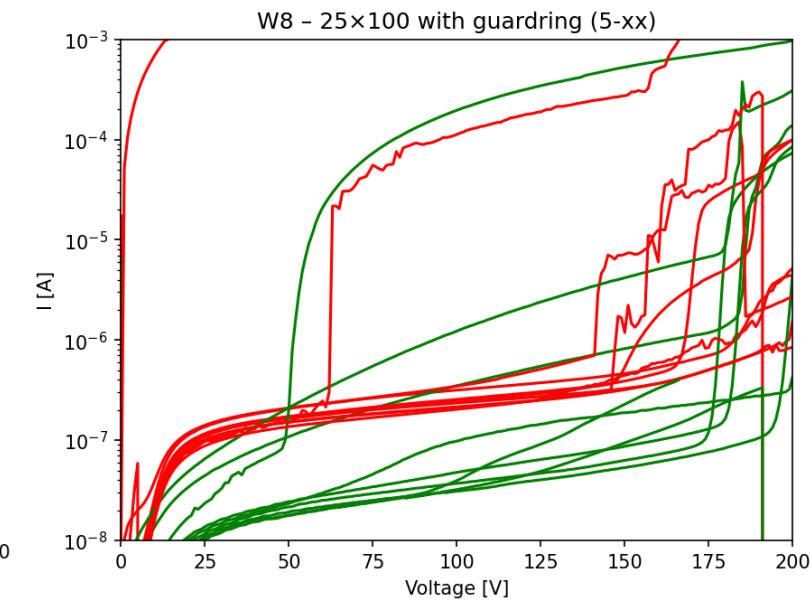
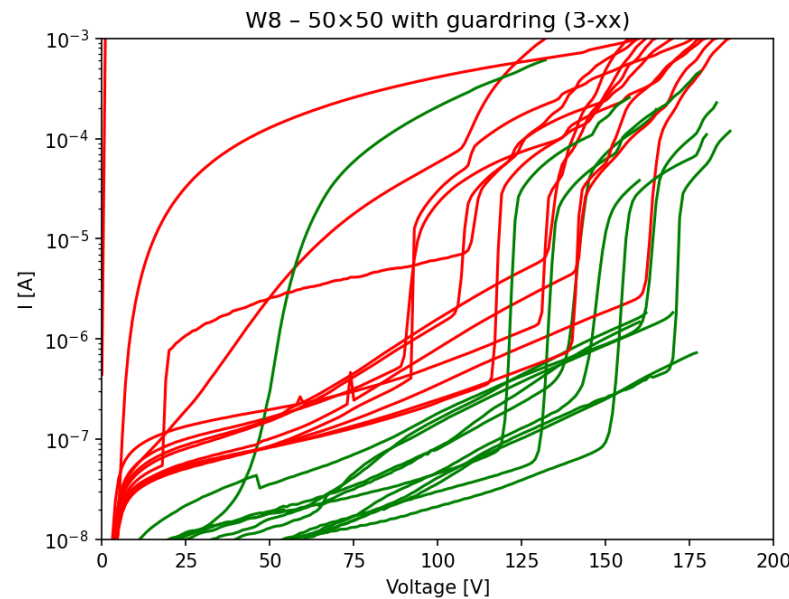
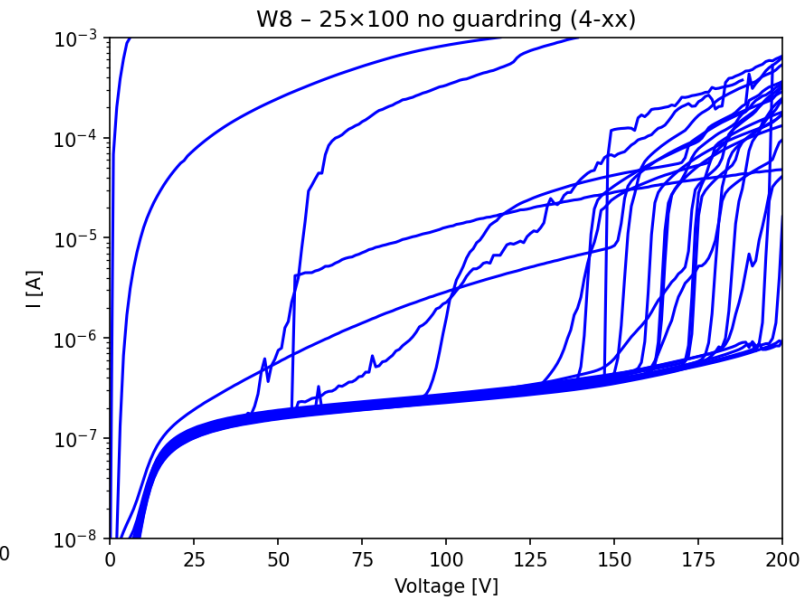
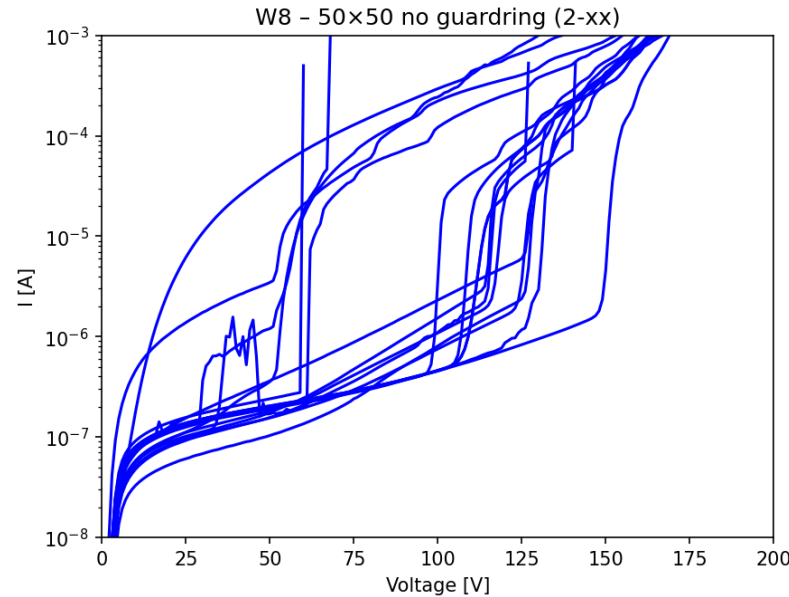
CMS 43D1v2. R16827+R18111. W6. Diodes



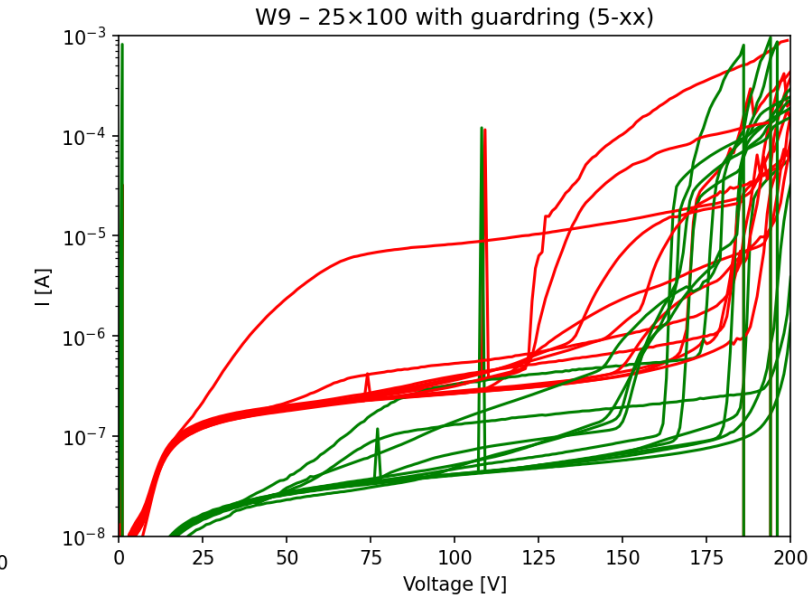
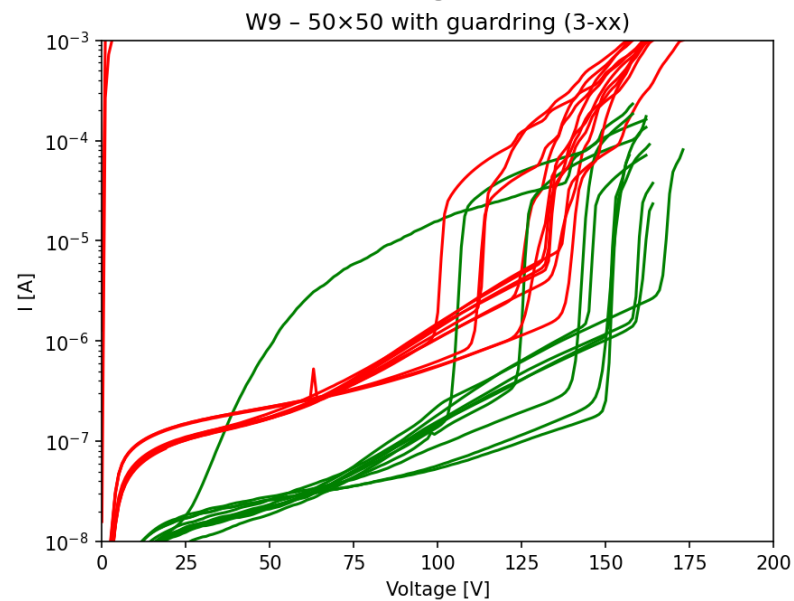
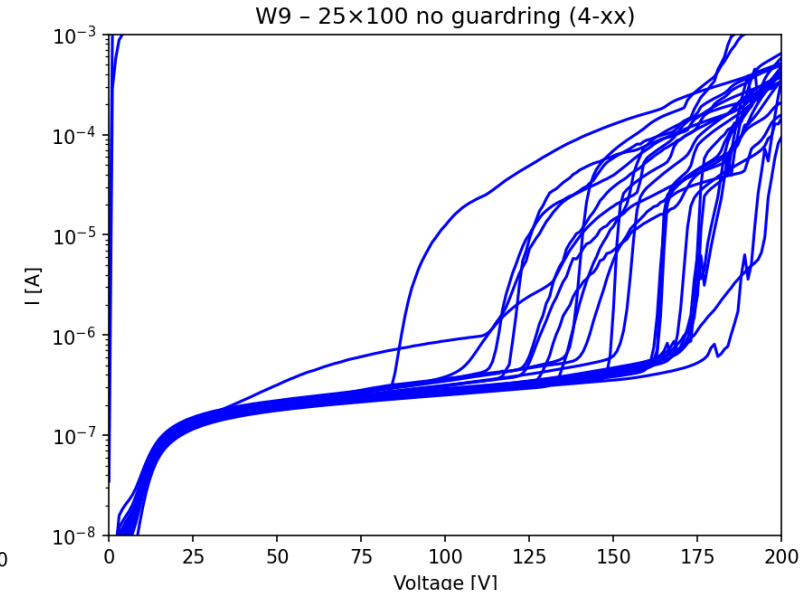
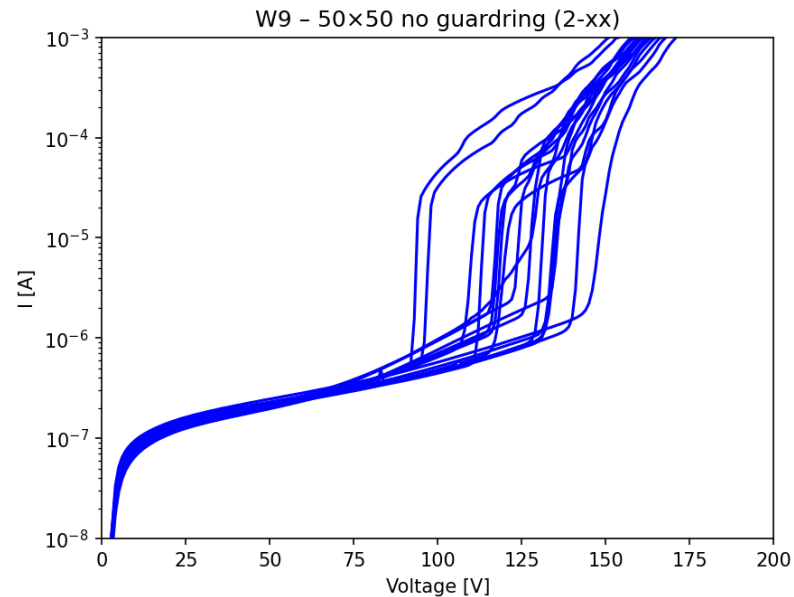
CMS 43D1v2. R16827+R18111. W7. Diodes



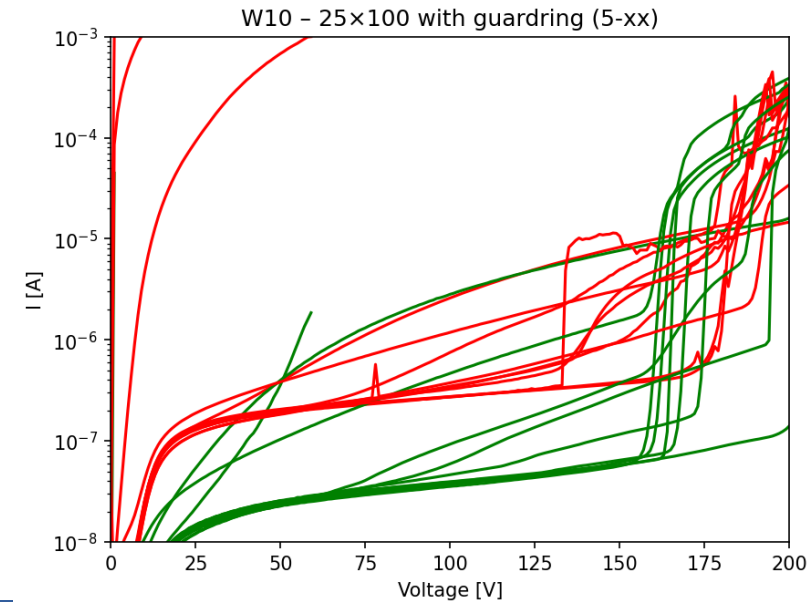
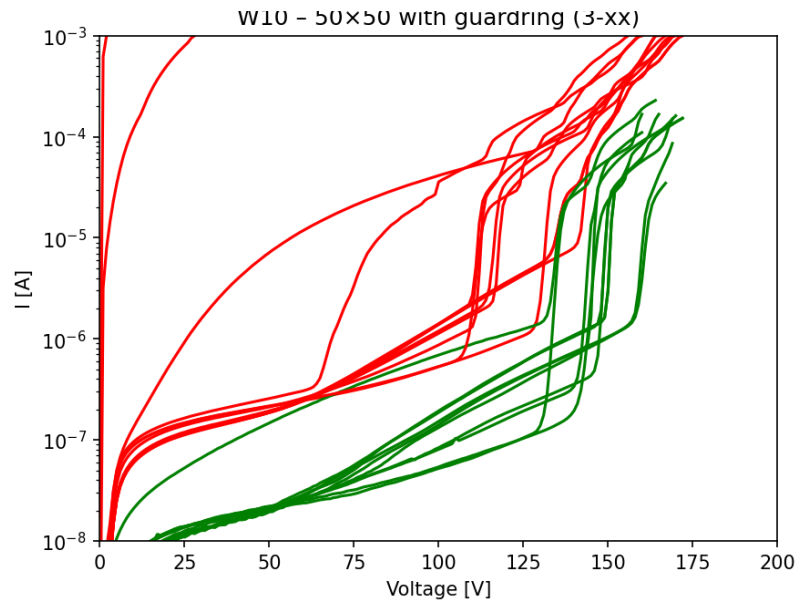
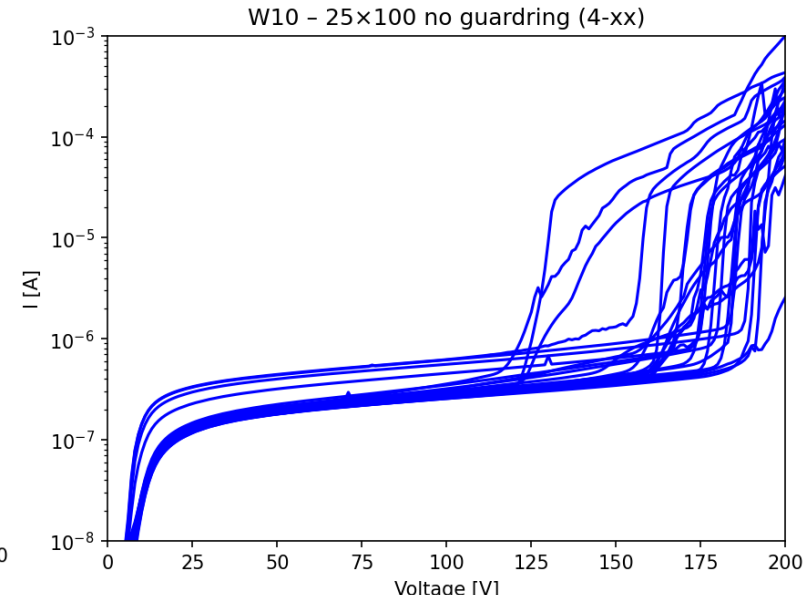
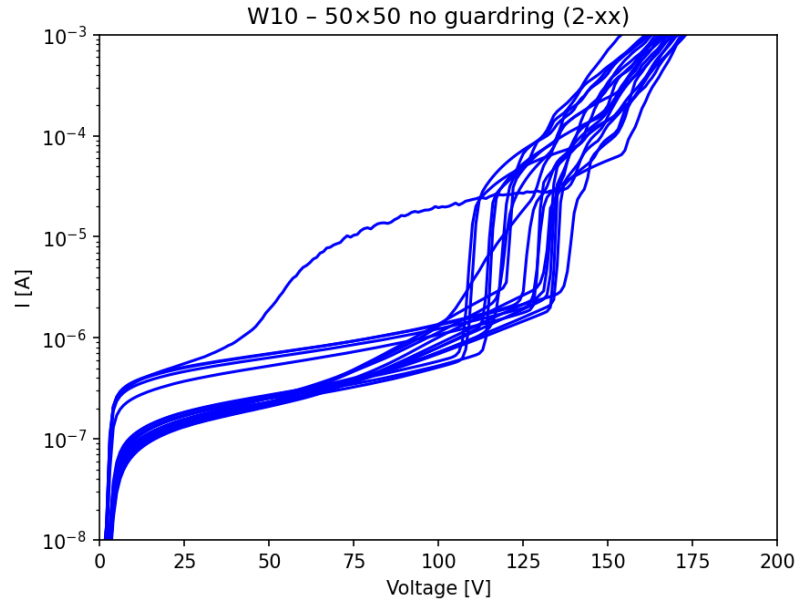
CMS 43D1v2. R16827+R18111. W8. Diodes



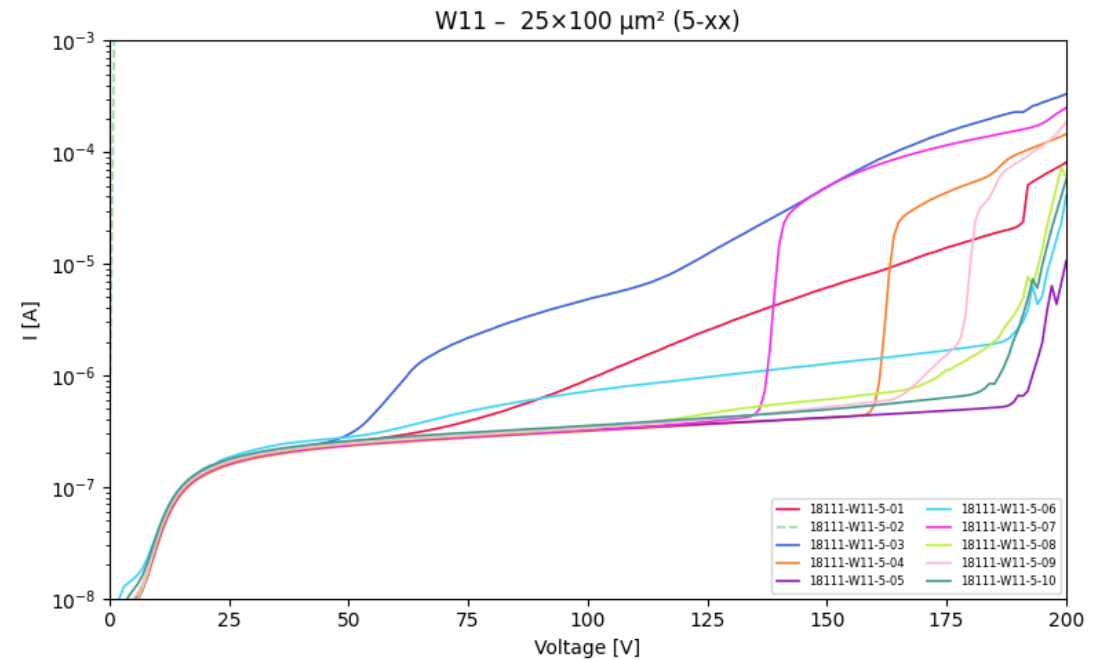
CMS 43D1v2. R16827+R18111. W9. Diodes



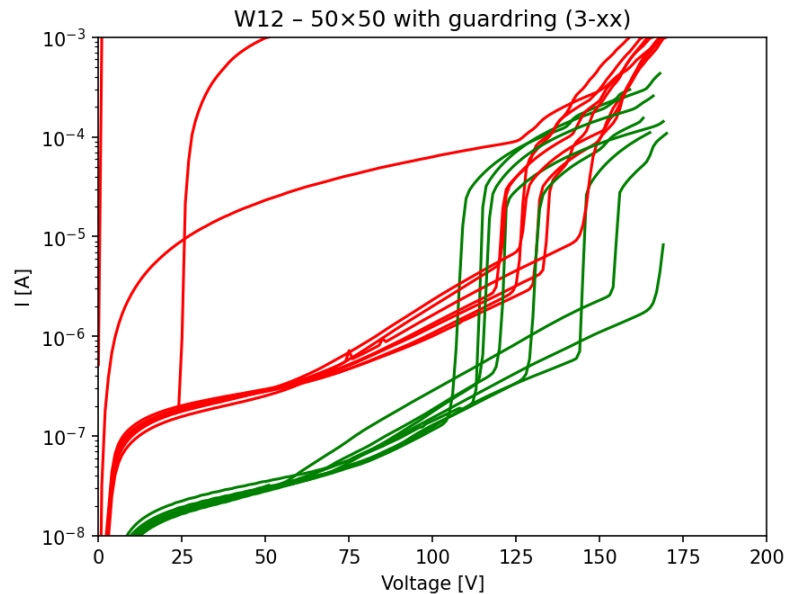
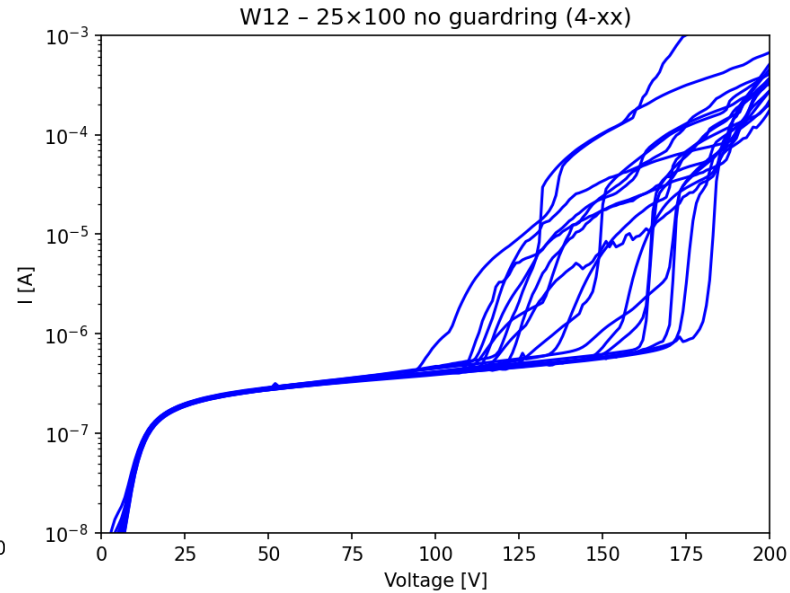
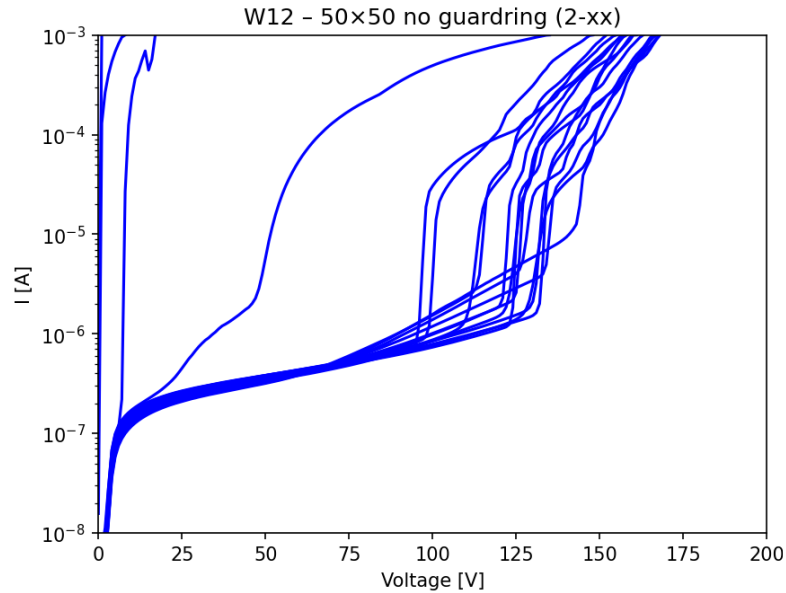
CMS 43D1v2. R16827+R18111. W10. Diodes



CMS 43D1v2. R16827+R18111. W11. Diodes



CMS 43D1v2. R16827+R18111. W12. Diodes



WP3.T1.a. 3D Radiation Hard Timing Detectors

- 3D detectors are great candidates for radiation hard timing detectors for future colliders
- 3Ds with n-on-n configuration have been studied
 - After substrate inversion, full depletion voltage should be lower
- Irradiation campaign was done with sensors irradiated at equivalent fluence levels of
 - $1\text{E}14$, $1\text{E}15$, $5\text{E}15$, $1\text{E}16$, $5\text{E}16$ and $1\text{E}17\text{ n}_{\text{eq}}/\text{cm}^2$
- DUTs
 - Pad diodes arrays of 50×50 pixels with pixel pitch of $50\mu\text{m} \times 50\mu\text{m}$
 - Test structures of 3×3 pixels with pixel pitch of $55\mu\text{m} \times 55\mu\text{m}$
 - I-V and at low temperature (-20°C)
 - C-V could not be performed $\rightarrow$ Noise is higher than a single pixel capacity
- Breakdown voltage highly increase with fluence
- Leakage current
 - Does not increase a lot with high fluence
 - Decreases after irradiation

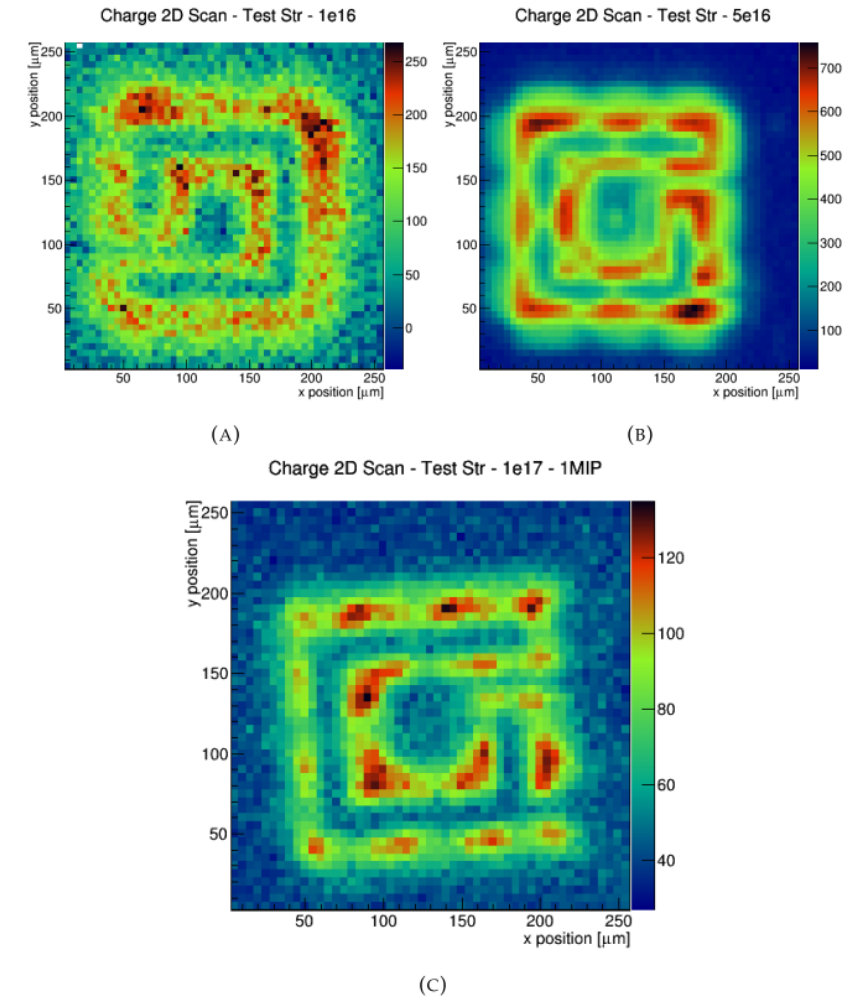
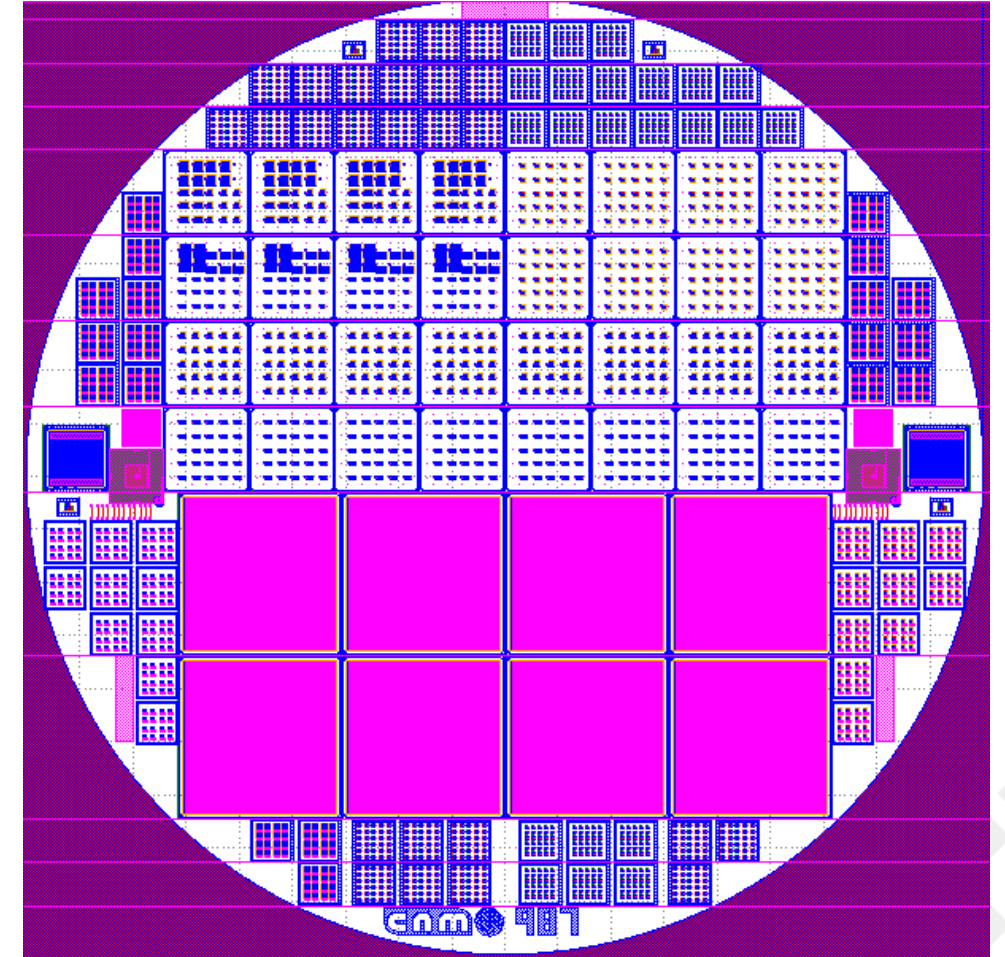
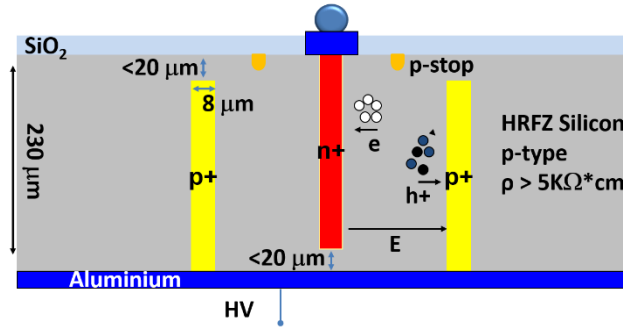


FIGURE 3.16: 2D maps of the charge collected for different fluence levels for the test structures. The operational voltages from lower to the highest fluence level 220V ($1 \cdot 10^{16}\text{ n}_{\text{eq}}/\text{cm}^2$), 300V ($5 \cdot 10^{16}\text{ n}_{\text{eq}}/\text{cm}^2$) and 350V ($1 \cdot 10^{17}\text{ n}_{\text{eq}}/\text{cm}^2$)

- Altiroc1
- Medipix3
- Test structures
- Fabrication on going
 - 285 μm thick Si wafers
 - 240 μm depth columns
 - 8-10 μm columns diameter
 - Double side technology
 - P-Stop isolation
 - Metal layer opening on the back

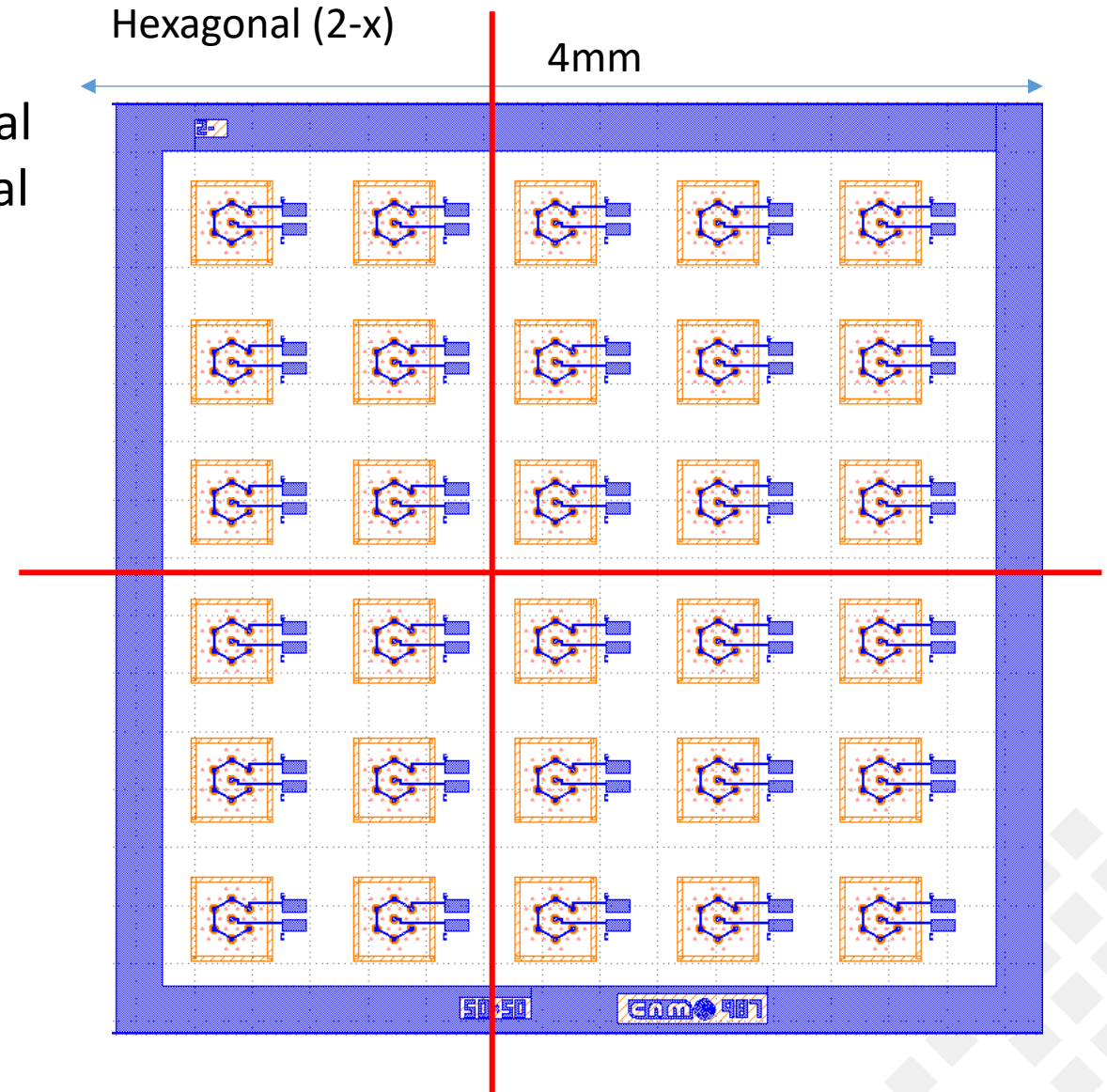
Detectors irradiated with neutrons at different fluences.

Tested in the Aidainnova testbeam, waiting for the analysis of the results but they look very promising.

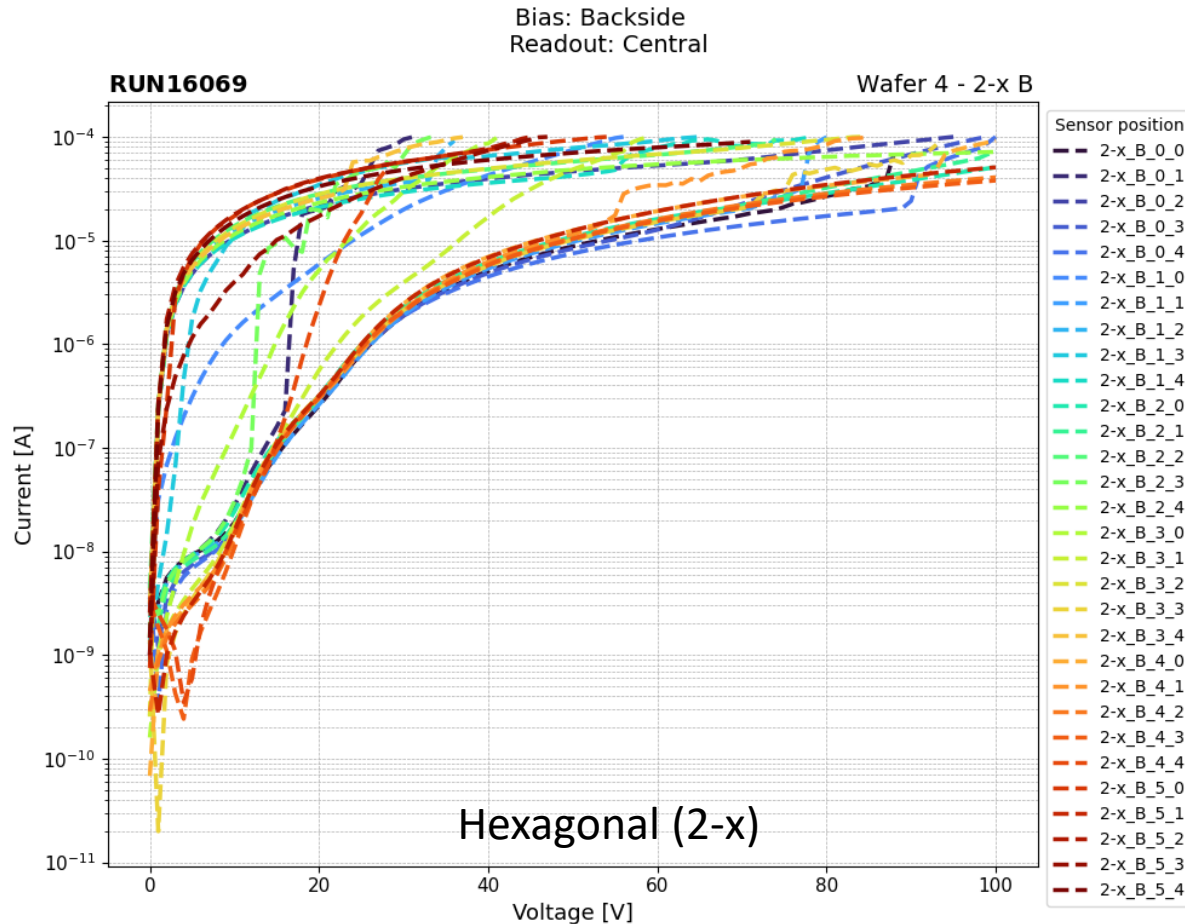


3D Timing. 43D1v3. Samples @ IFCA/CNA

- Available samples:
 - **5** dice with 30 (6x5) 1-pixel devices: hexagonal
 - **1** die with 30 (6x5) 1-pixel devices: orthogonal
- Each die was cut in 4 - Total:
 - **20 mini dice hexagonal** (each 6 or 9 devices)
 - **4 mini dice orthogonal** (each 6 or 9 devices)*(each mini dice is roughly 2x2 mm²)*



- Samples have metal on the ohmic (p+) side
- Most of the devices have very high current! ($> 1 \mu\text{A}$ @ 20 V)



- Proposal:

- **4 orthogonal mini-dice:**

- 1 non-irradiated to IFCA
 - 1 non-irradiated to CNA
 - 1 irradi to $5e15$
 - 1 irradi to $1e16$

- **20 hexagonal mini-dice:**

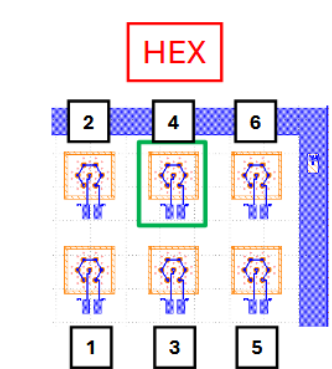
- 2 non-irradiated to IFCA
 - 2 non-irradiated to CNA
 - 2 irradi to $1e15$
 - 2 irradi to $5e15$
 - 2 irradi to $1e16$
 - 8 tbd



3D Timing. 43D1v3. Samples @ IFCA/CNA

- 2 Samples from 16069 sent to CNA
 - 1 Orthogonal + 1 hexagonal
 - Non-irradiated
 - Bonded to ad-hoc PCB board at IMB
 - Sent 27th Nov 2025

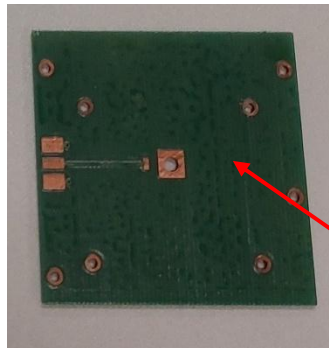
- Samples from 16069 sent to IFCA
 - Backside metal partially removed
 - Non irradiated + irradiated (see table)
 - To be bonded to Santa Cruz boards in IFCA
 - Sent 21st Apr 2026



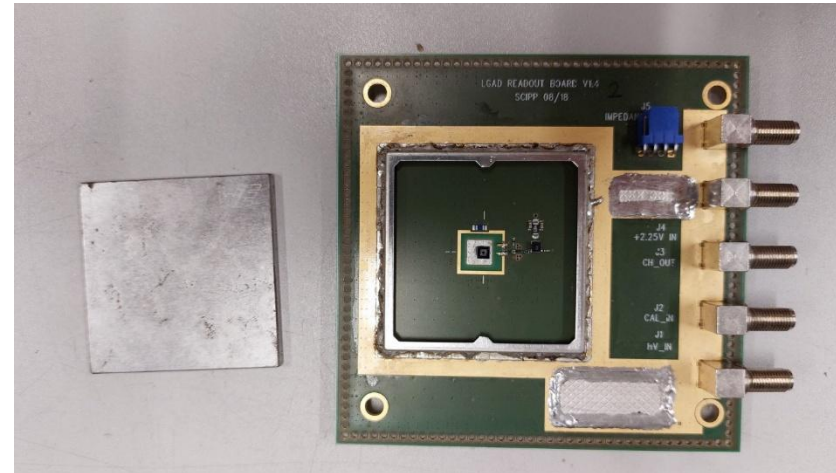
20V	C	G
1	7μA	2μA
2	4,5μA	9μA
3	19μA	9μA
4	0,4μA	0,7μA
5	0,7μA	7μA
6	21μA	11μA

ORT

20V	C	G
1	2,5μA	35μA
2	2μA	30μA
3	0,9μA	1,3μA
4	0,8μA	26μA
5	2,5μA	30μA
6	20μA	10,5μA



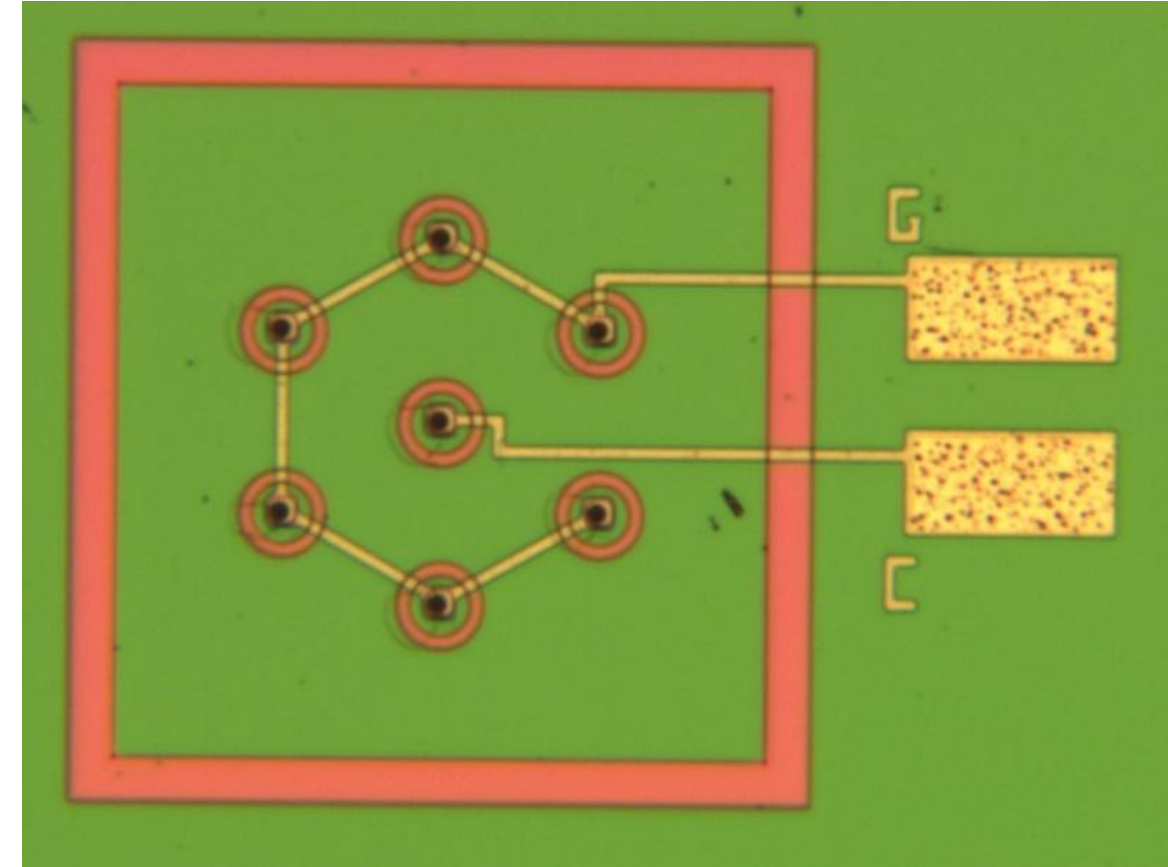
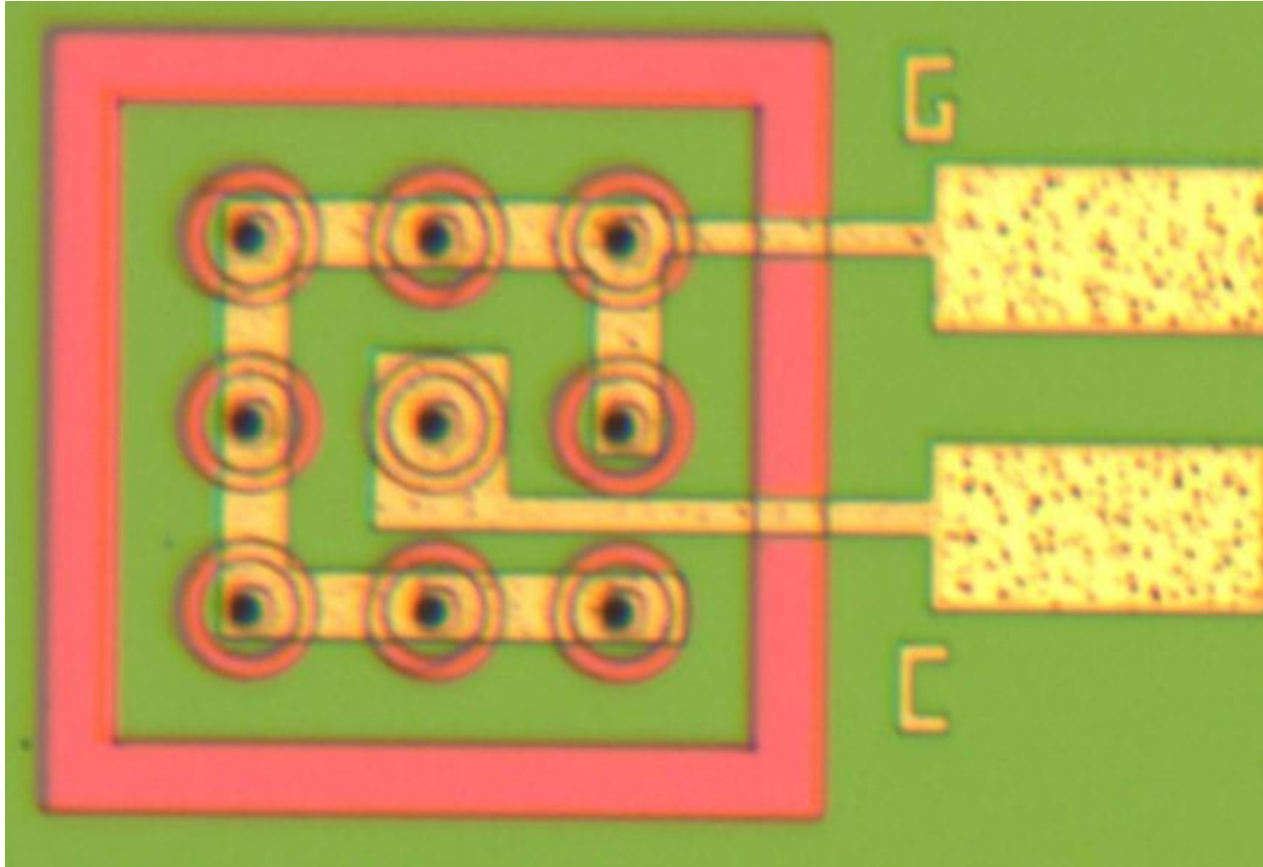
*Modified PCB board with
2 channels (C and G)
[no picture available]*



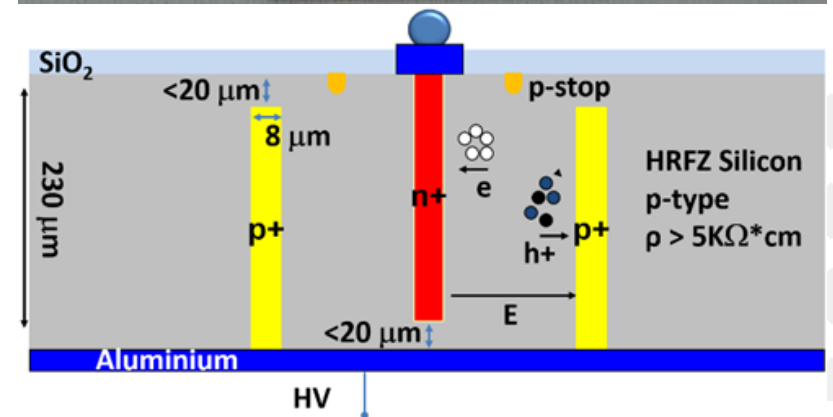
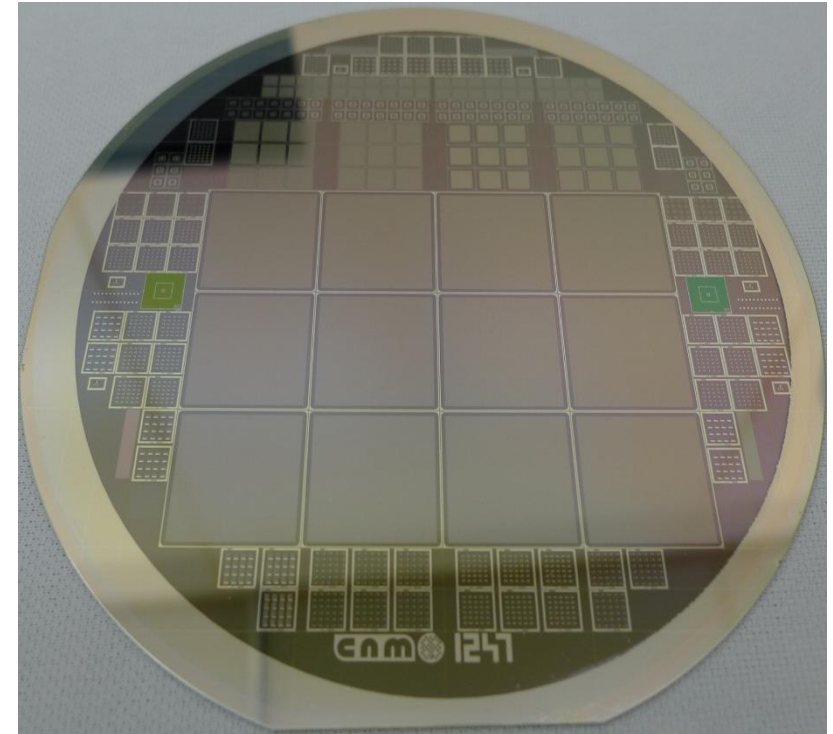
Fluence	Samples
Non Irr	2
1e15	2
5e15	2
1e16	2
2e16	2
5e16	2

*To confirm if hex or orthogonal
(they were all same flavour)*

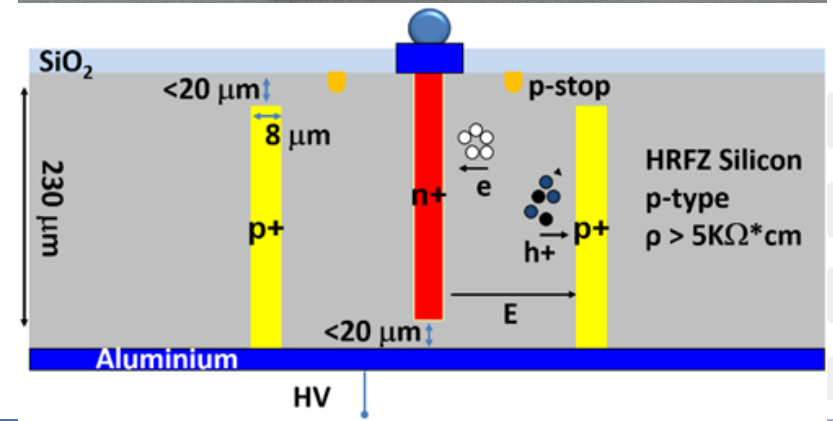
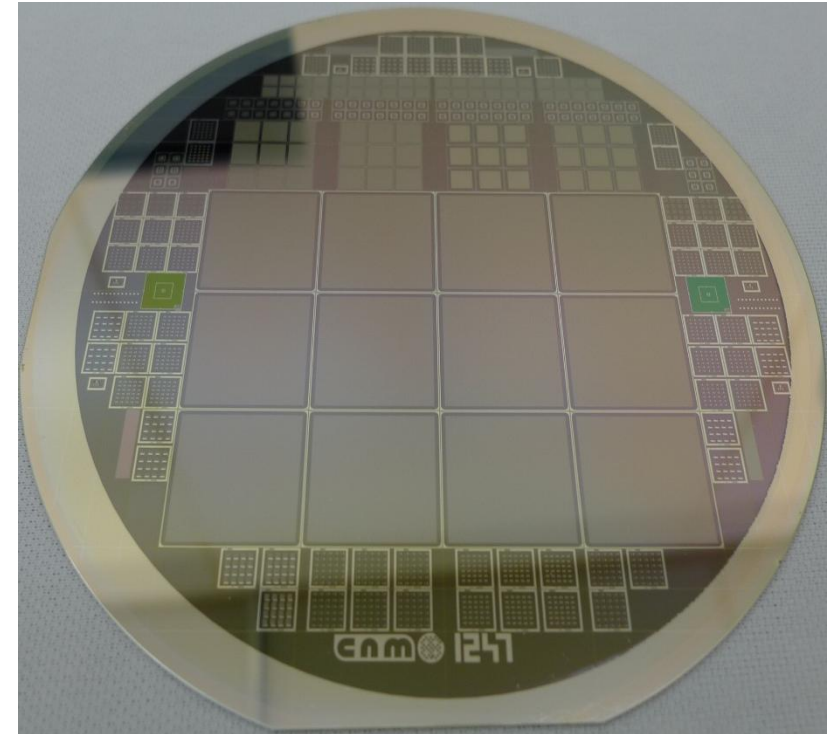
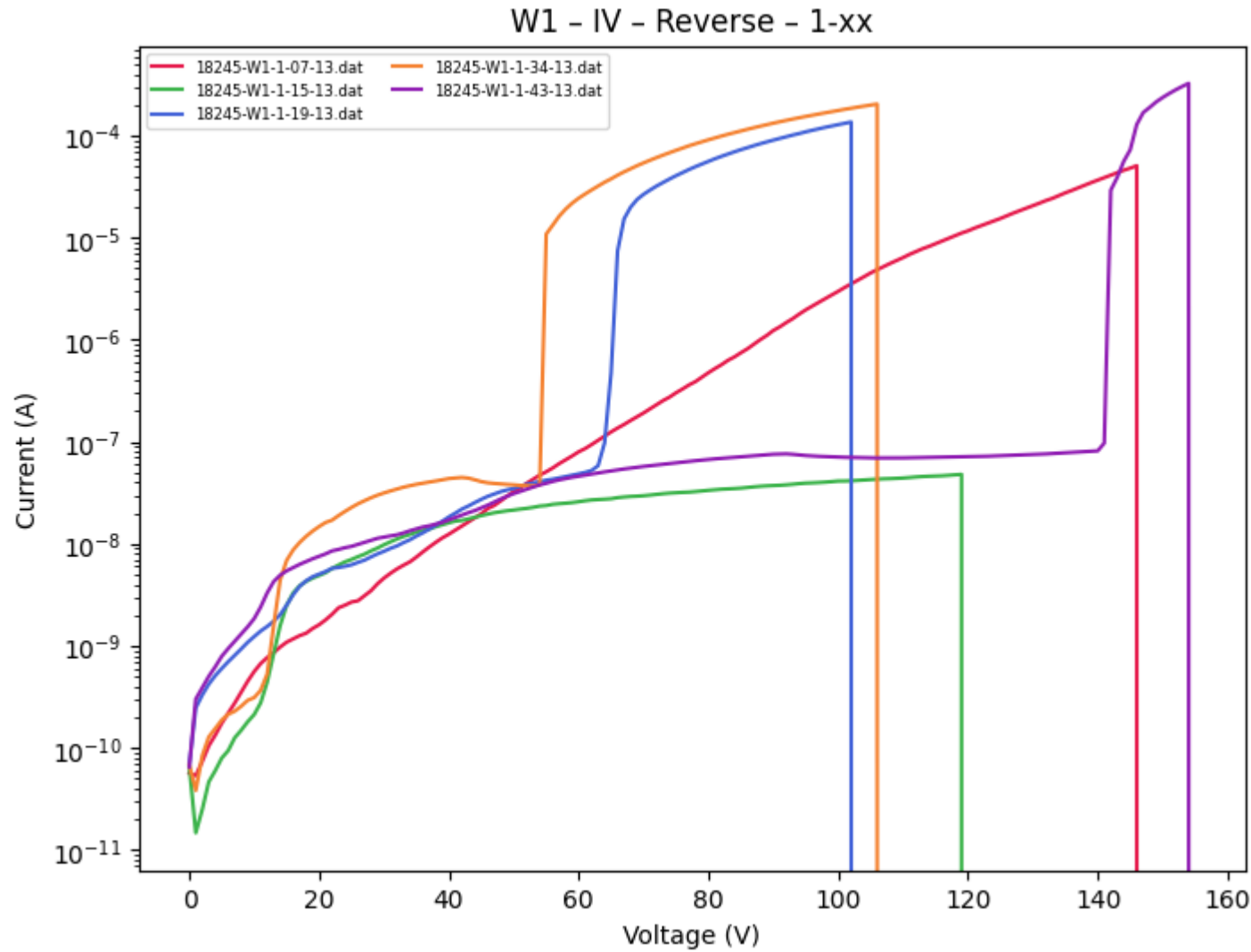
3D Timing. 43D1v3. Samples @ IFCA/CNA



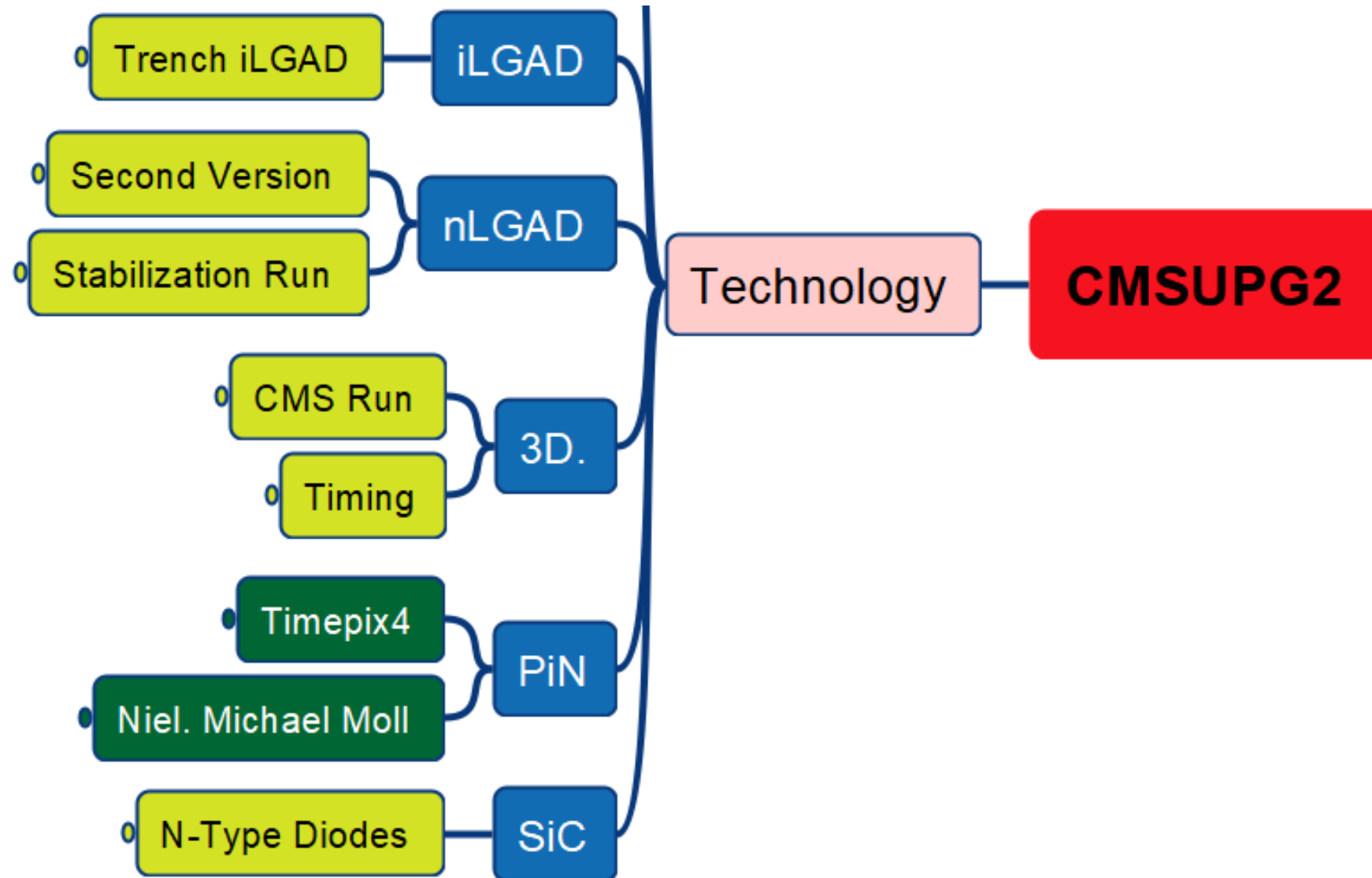
- Decide if to move to 150 mm wafers for the 3D process (285um thick).
- This may delay the fabrication, never tried before although individual steps are ready .
- Try to reduce holes diameter (= increase aspect ratio). New equipment for 150 mm wafers.
- Timepix3. 55x55 μm pitch, 256x256 pixels: 8
- TimeSpot1. 55x55 μm pitch, 37x32 pixels: 60
- PicoPix. 55x55 μm pitch, 64x64 pixels: 18
- Different test structures
- 5 wafers



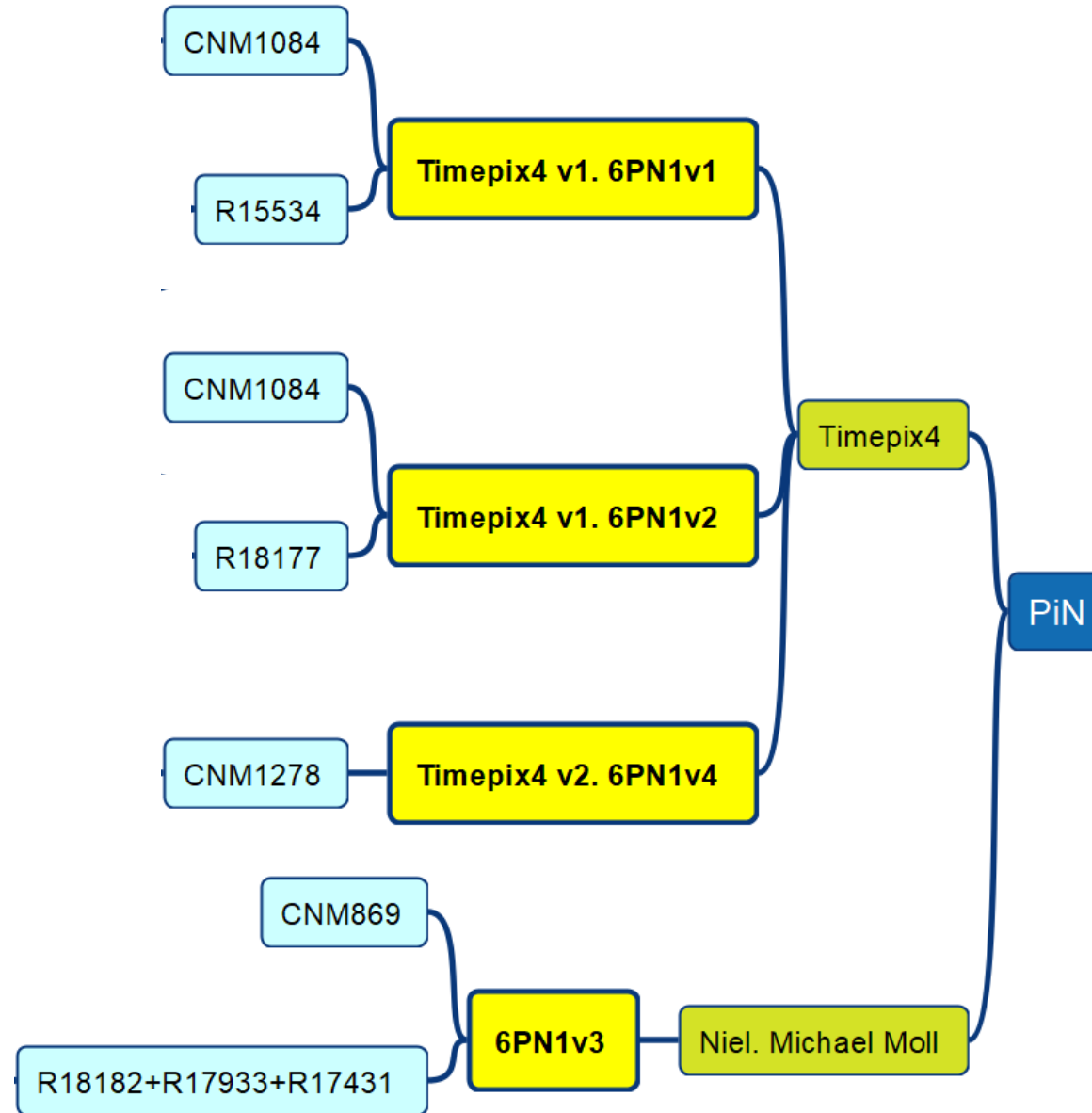
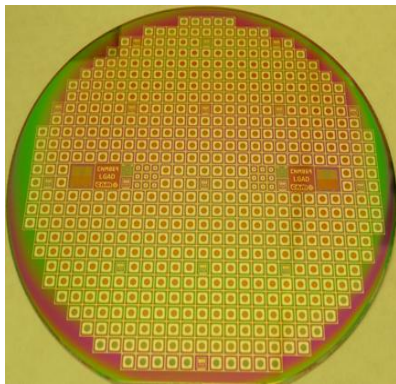
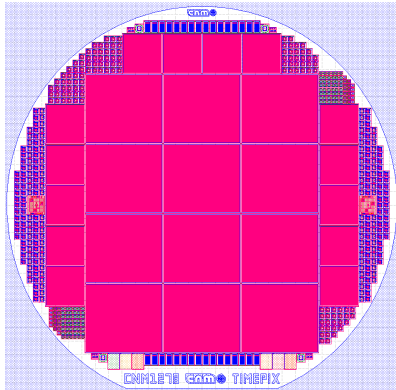
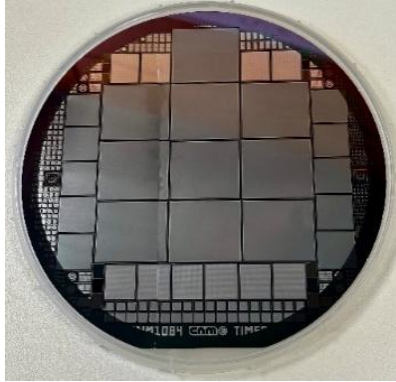
3D-DS Timing. 43D1v4. R18245. Preliminary



Subproject Objectives. WP3

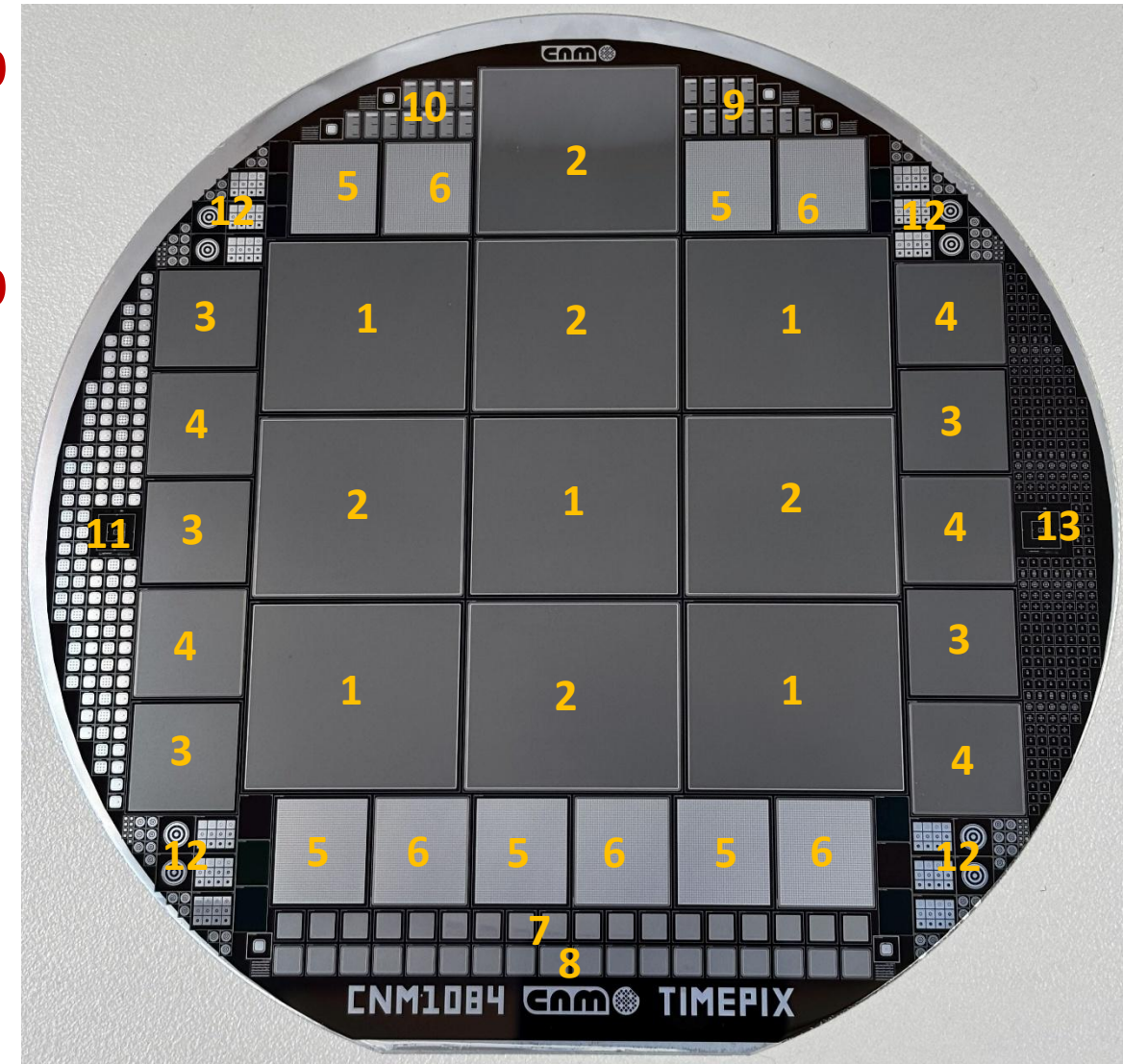


WP3. Technologies Developed. PiN



- **5 Wafers. Designed Structures**

- **Timepix4** (55x55 μm pitch, 512x448 pixels): **10**
 - Passivation Opening for Bump Pad 20 μm
 - A-type: 1 Guard Ring (1)
 - B-type: 4 Guard Rings (2)
- **Timepix3** (55x55 μm pitch, 256x256 pixels): **10**
 - Passivation Opening for Bump Pad 20 μm
 - A-type : 1 Guard Ring (3)
 - B-type : 4 Guard Rings (4)
- **TDCpix** (300x300 μm pitch, 40x45 pixels): **10**
 - Passivation Opening for Bump Pad 20 μm
 - A-type : 1 Guard Ring (5)
 - B-type : 4 Guard Rings (6)
- **UZH-PSI** (100x100 μm pitch, 30x30 pixels): **36**
 - Passivation Opening for Bump Pad 12 μm
 - A-type : 1 Guard Ring (7)
 - B-type : 4 Guard Rings (8)
- **Strips** (80 μm pitch, 20 strips): **22**
 - A-type : 1 Guard Ring (9)
 - B-type : 4 Guard Rings (10)



- 5 Wafers. Designed Structures

- Pad Devices (1300x1300 μm pitch): **108** (11)

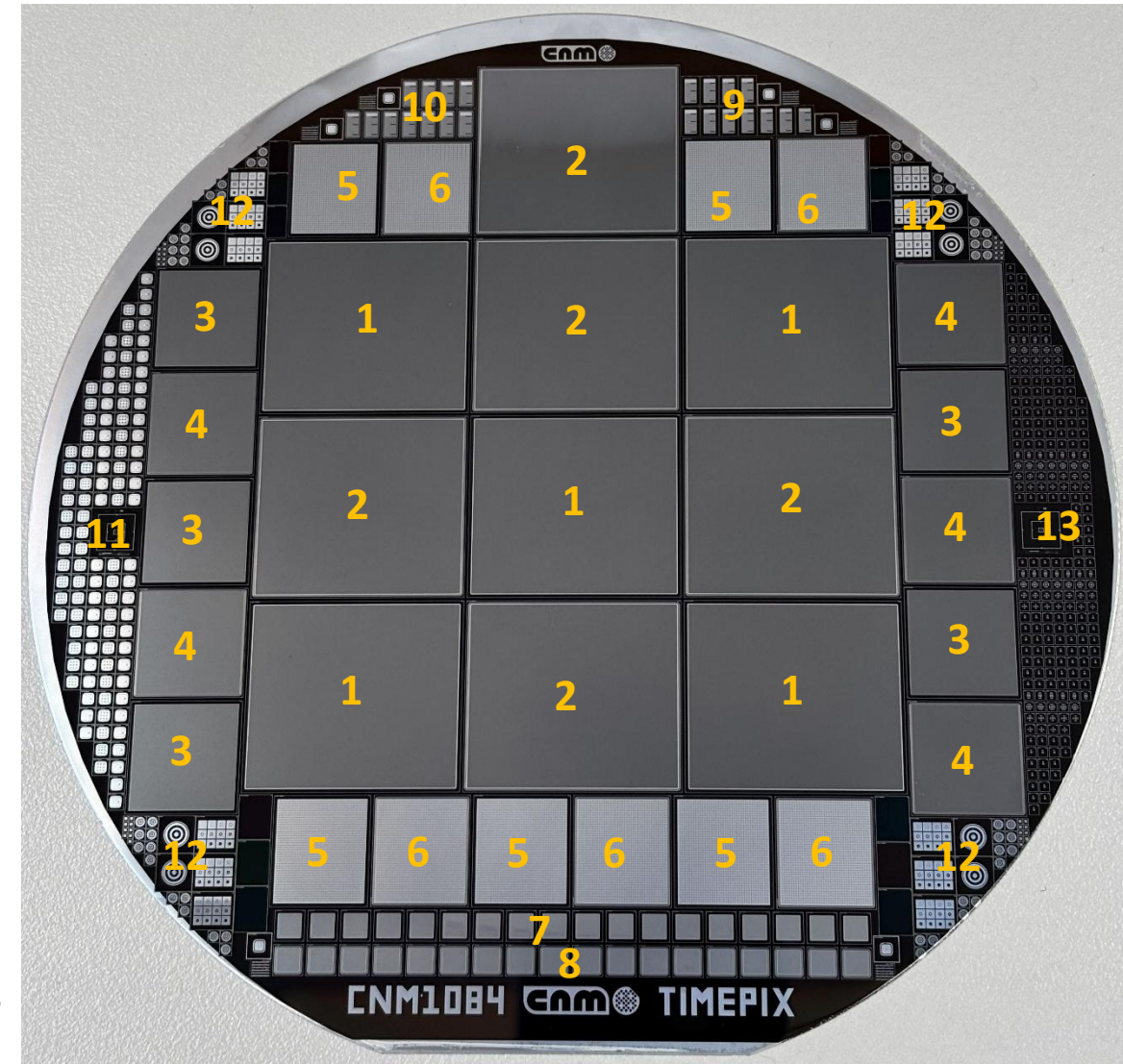
- 1 Metal Window, 1 Pad: 52
 - 9 Metal Windows, 4 Pads: 56

- Test Structures Module 1: **4** (12)

- Inter-pixel Capacitance: 92
 - Test Diodes
 - Small Area: 40
 - Large Area: 8
 - TLM Resistivity Structure 12
 - SIMS and Spreading Resistance 12

- Test Structures Module 2 (13)

- 3x3 Pixel Structure with Periphery Pixels Connected
 - Single Structure (SS): 25
 - 4 SS with 1 Ring: 24
 - SS with Pixel size variations (Centre, Periphery)
 - -5 μm : 21, 21
 - -10 μm : 21, 21
 - -15 μm : 22, 25
 - 3x3, 4x4, 5x5 Pixel Structures with individually Pixels connection: 24 (each)



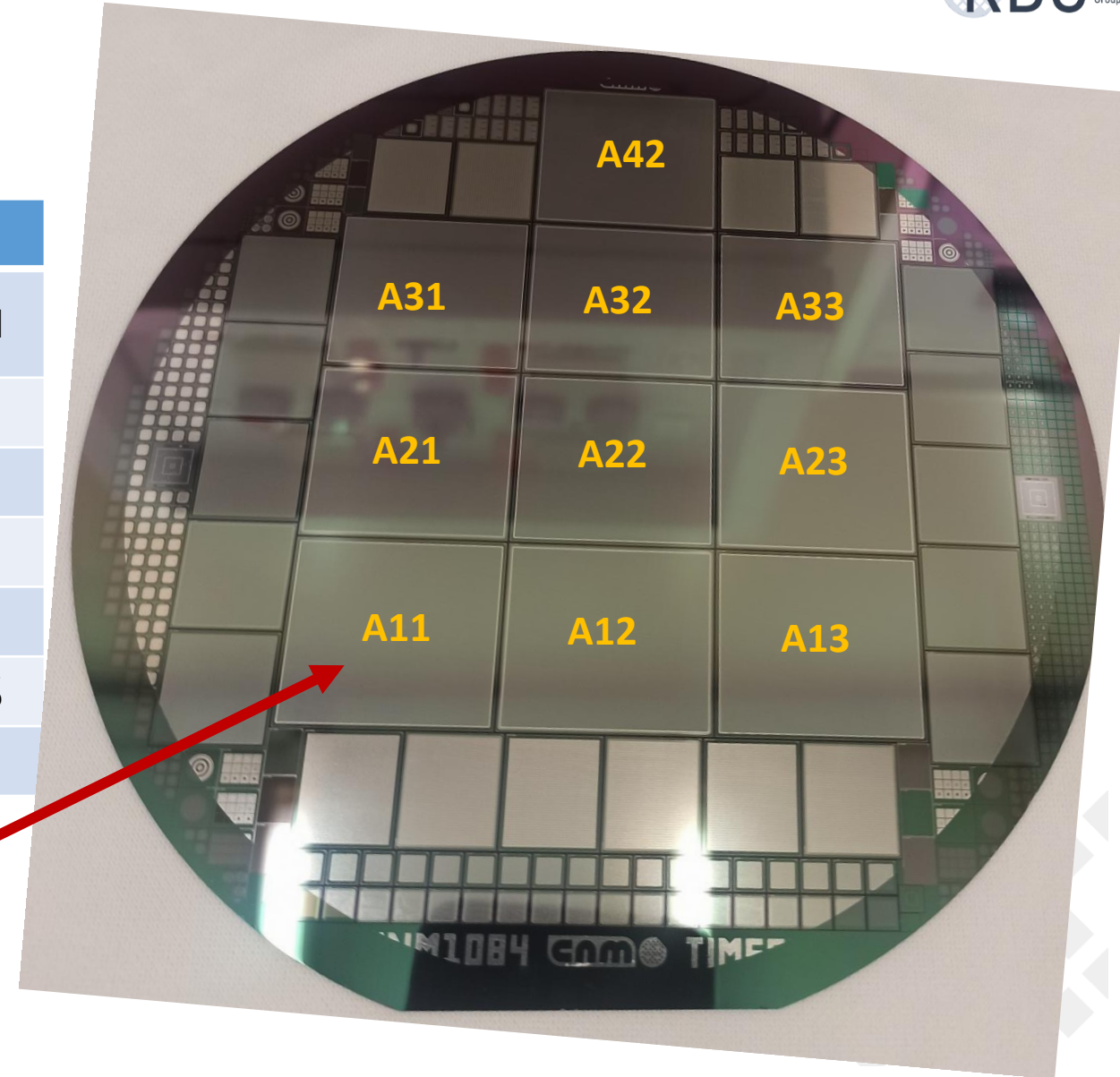
Timepix4. PiN. 6PN1v1. R15334

Yield condition

If they do not exhibit shortcut behaviour &
breakdown voltage > 50 V

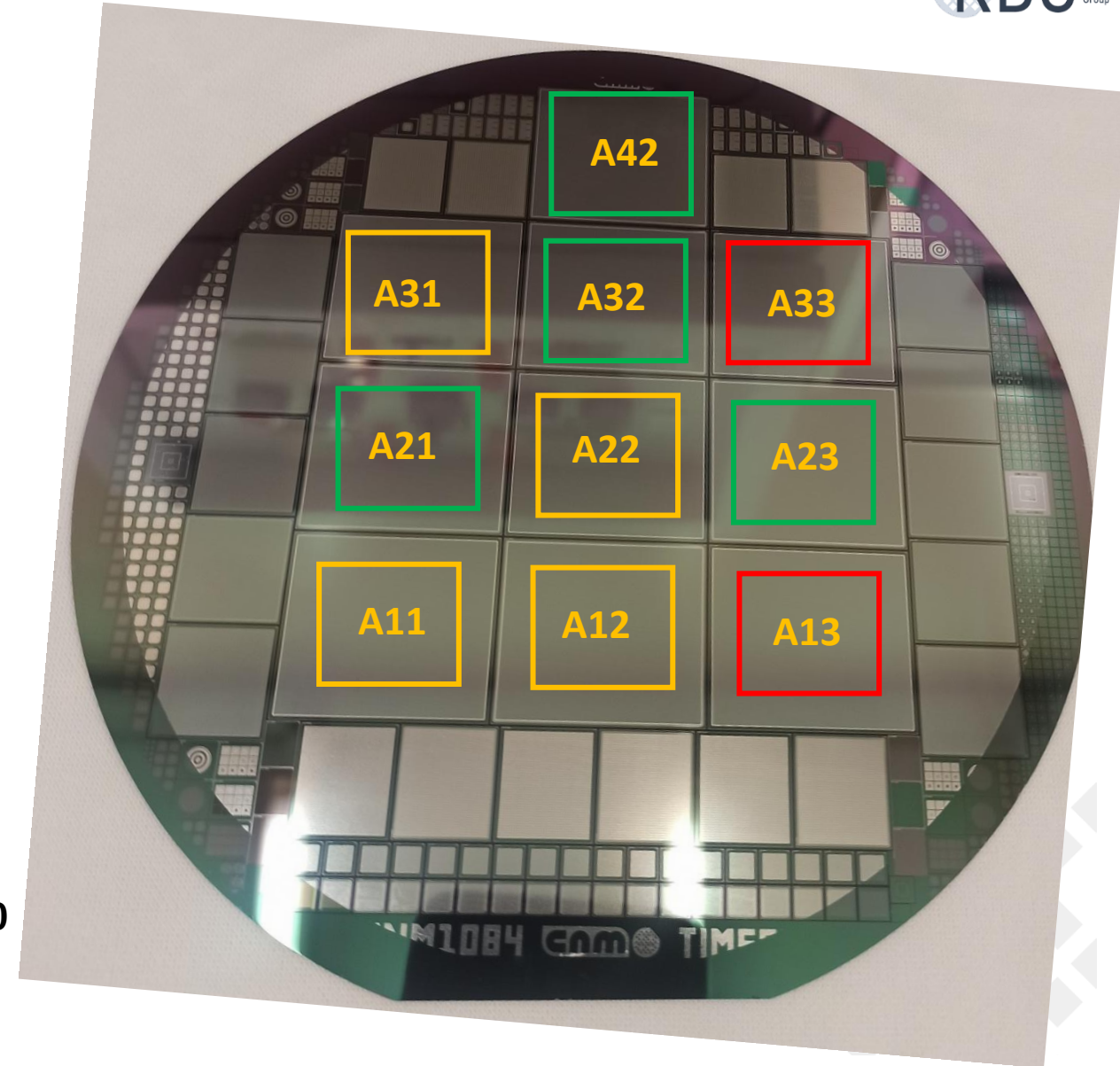
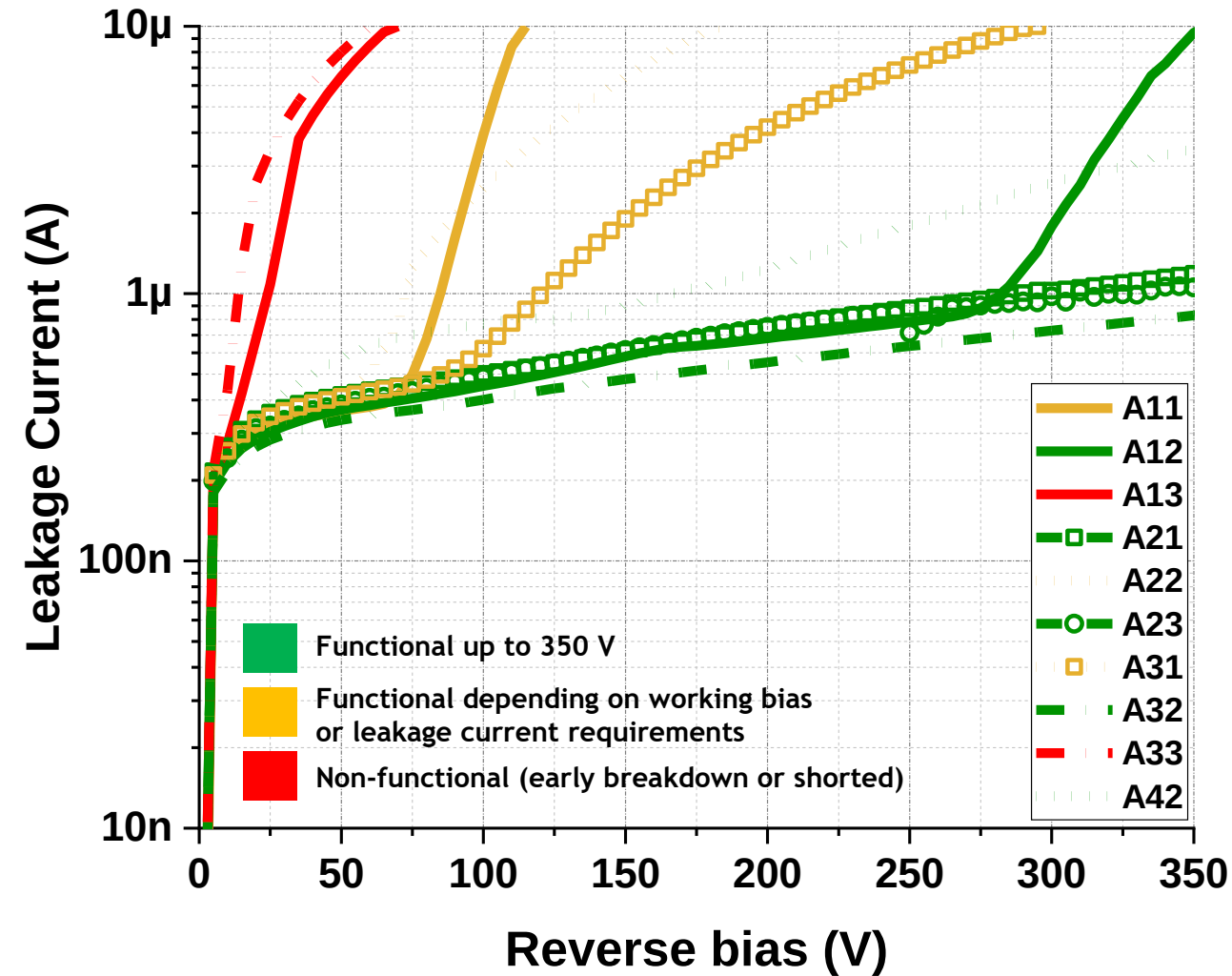
Wafer	TimePix4 (1,2)		TimePix3 (3,4)		TDCPix (5,6)	
	Meas. devices	Yield	Meas. devices	Yield	Meas. devices	Yield
2	10 / 10	60%	4 / 10	100%	6 / 10	50%
3	10 / 10	80%	4 / 10	100%	4 / 10	75%
4	5 / 10	100%	4 / 10	100%	4 / 10	75%
5	5 / 10	100%	4 / 10	100%	4 / 10	75%
6	5 / 10	60%	4 / 10	100%	4 / 10	100%
All	35 / 50	74%	20 / 50	100%	22 / 50	73%

Timepix4 on wafer identification

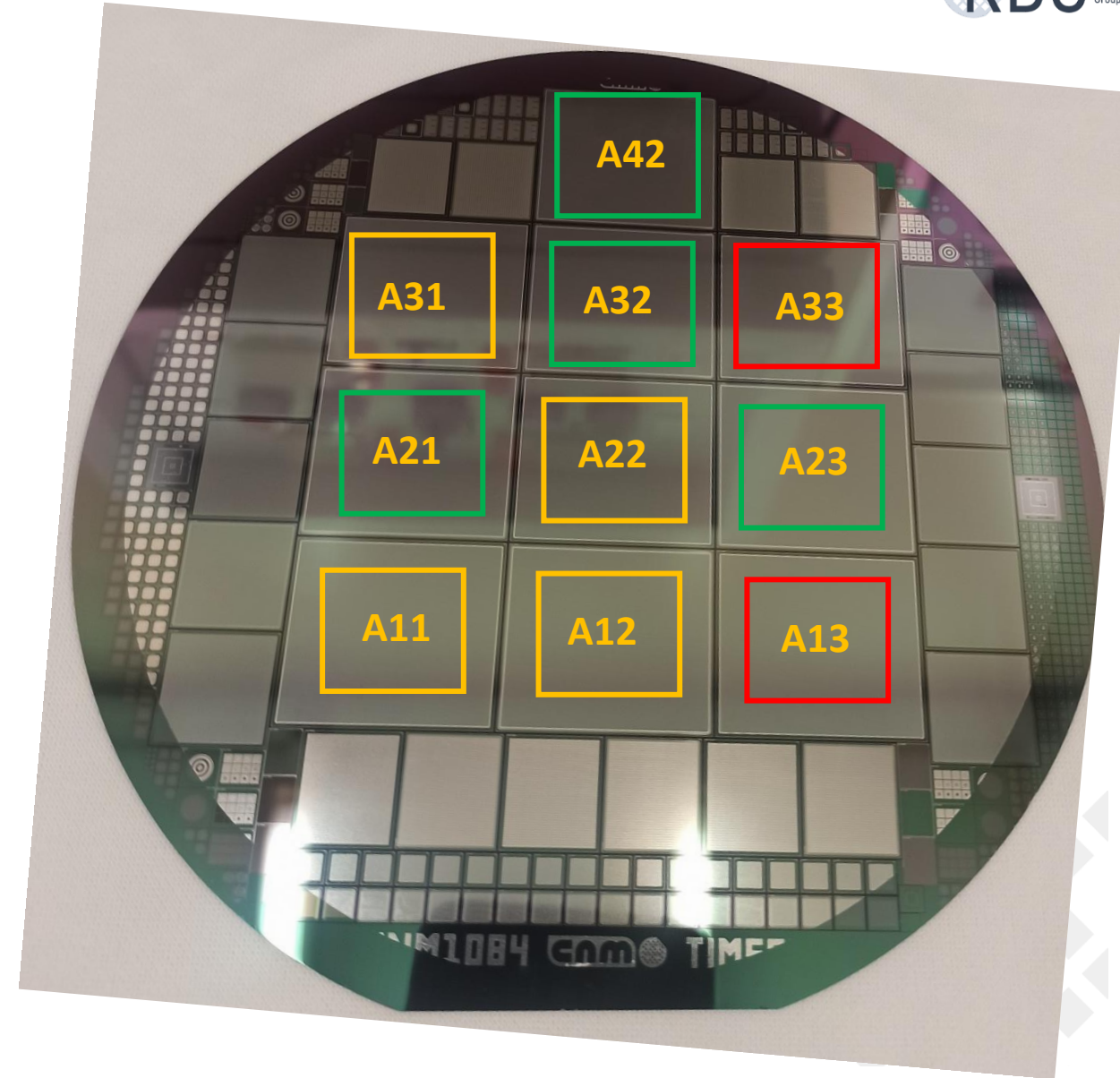
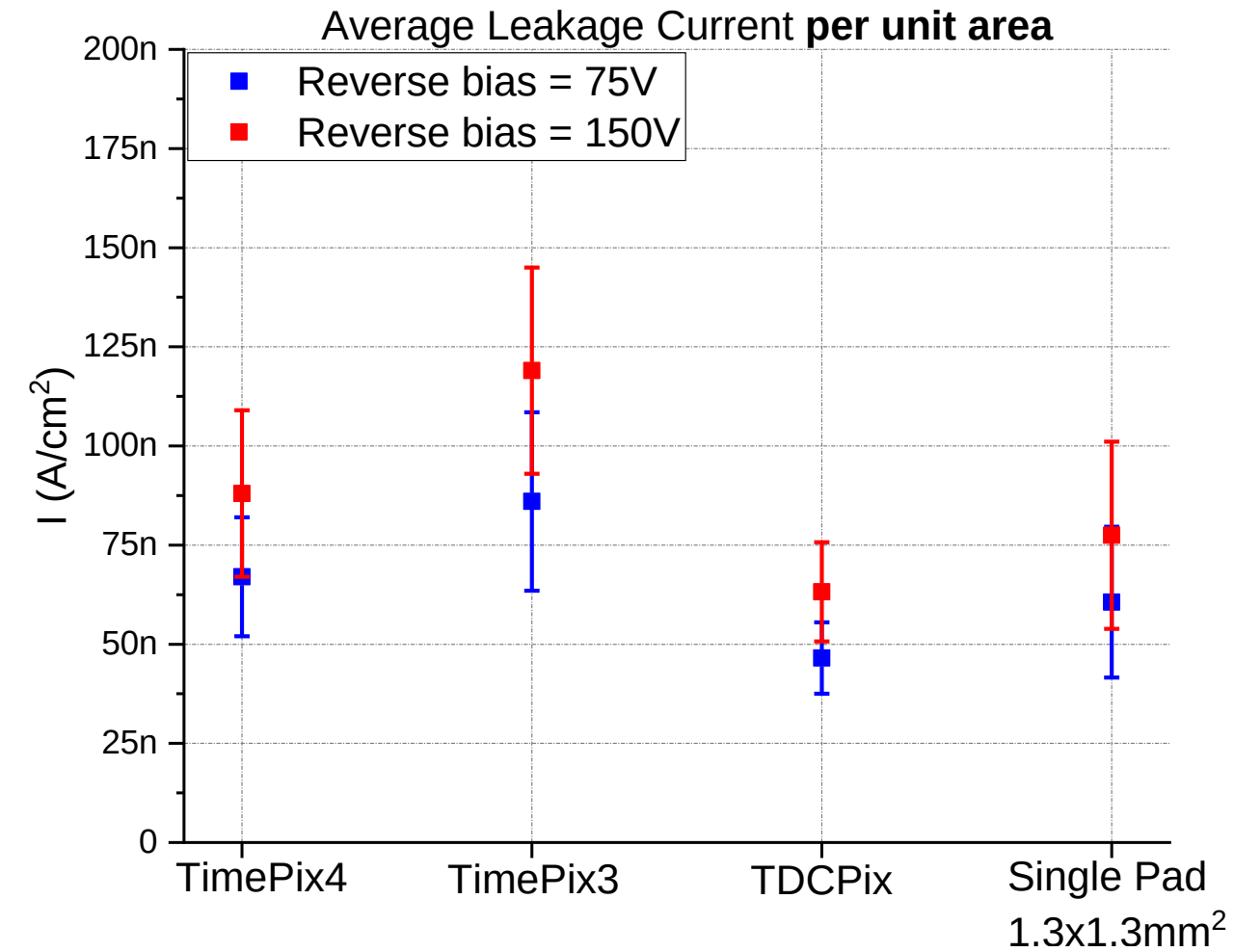


Timepix4. PiN. 6PN1v1. R15334

TimePix4 - W3 (20°C)



Timepix4. PiN. 6PN1v1. R15334

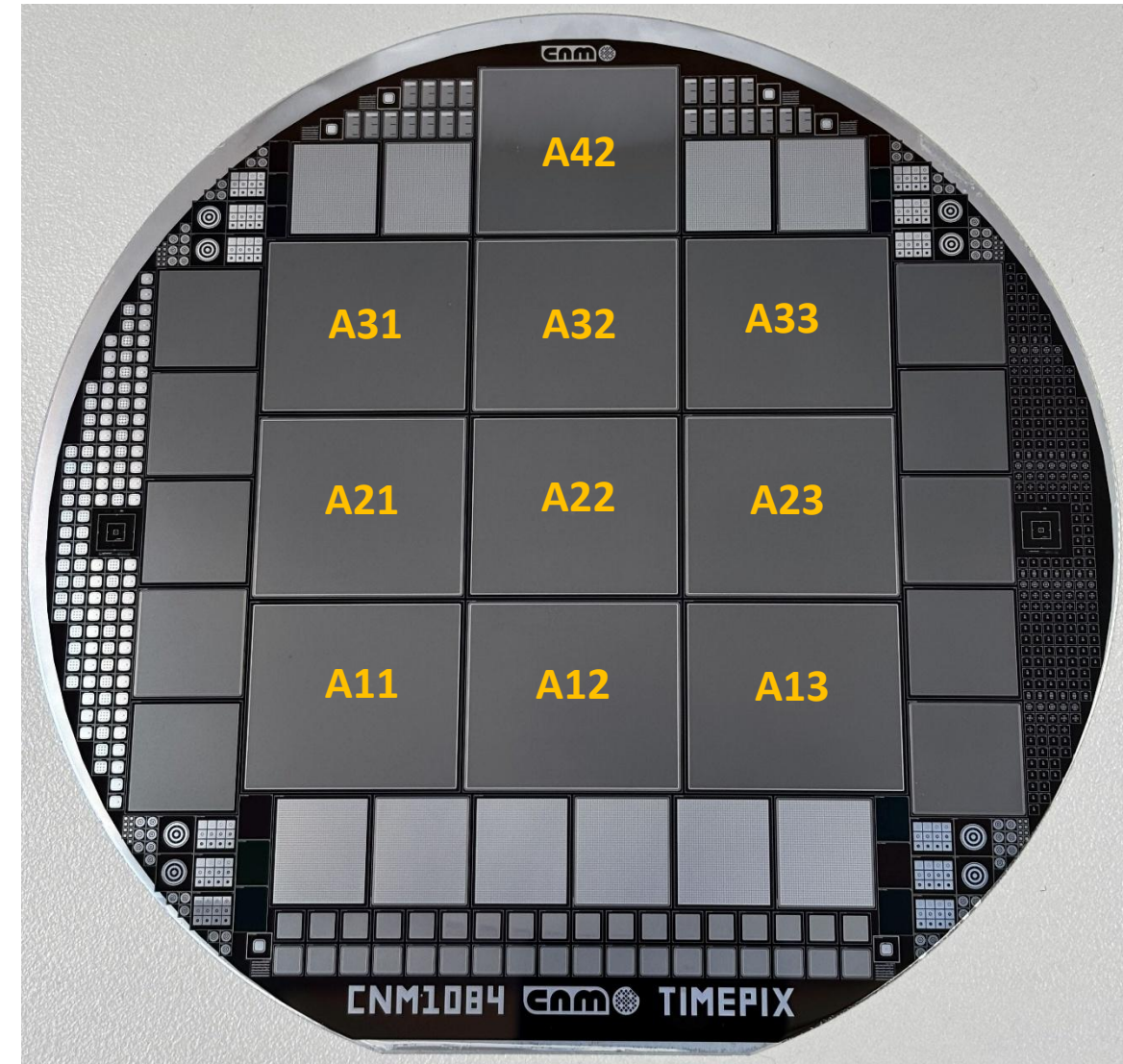


Timepix4. PiN. 6PN1v2. R18177

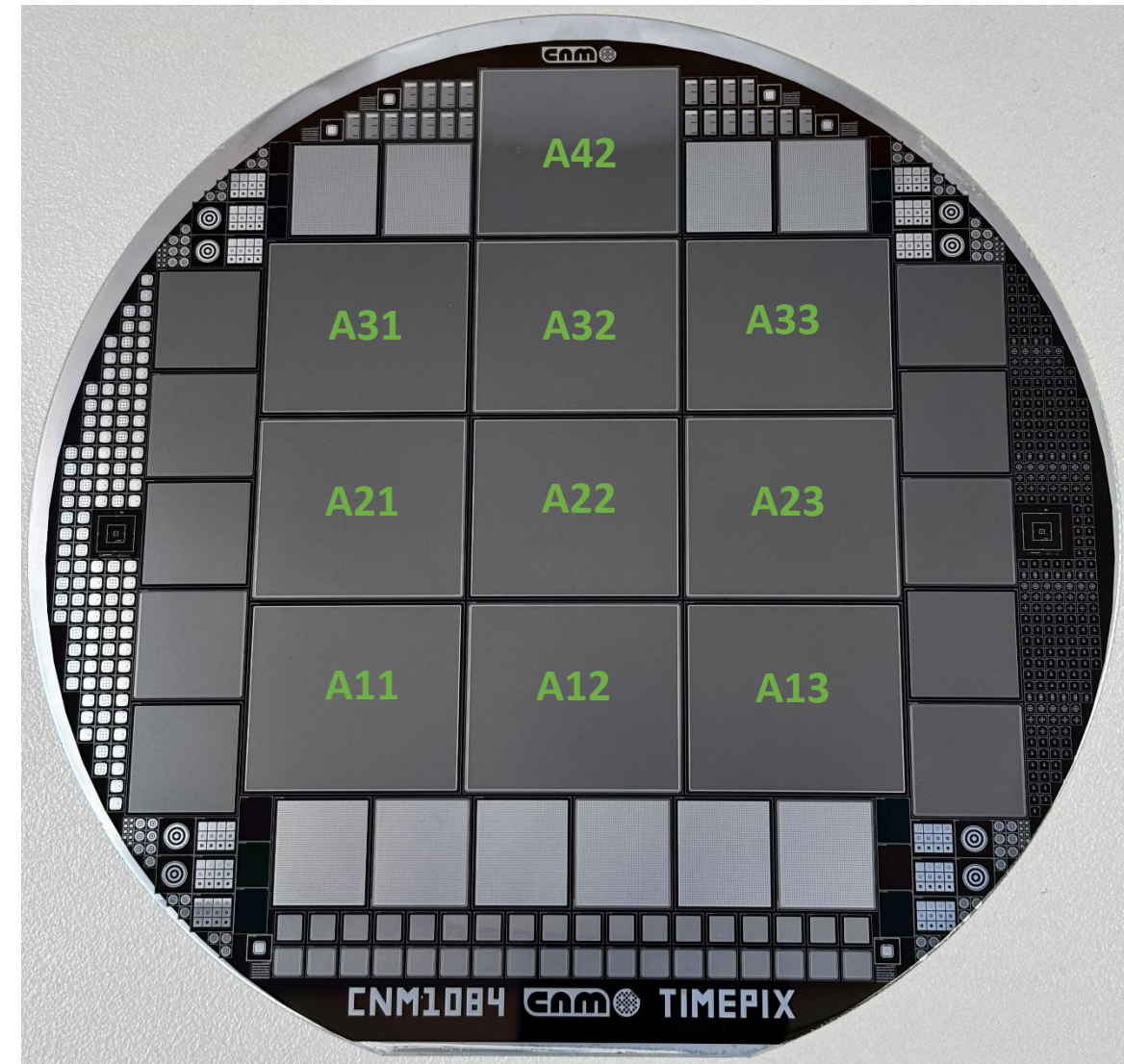
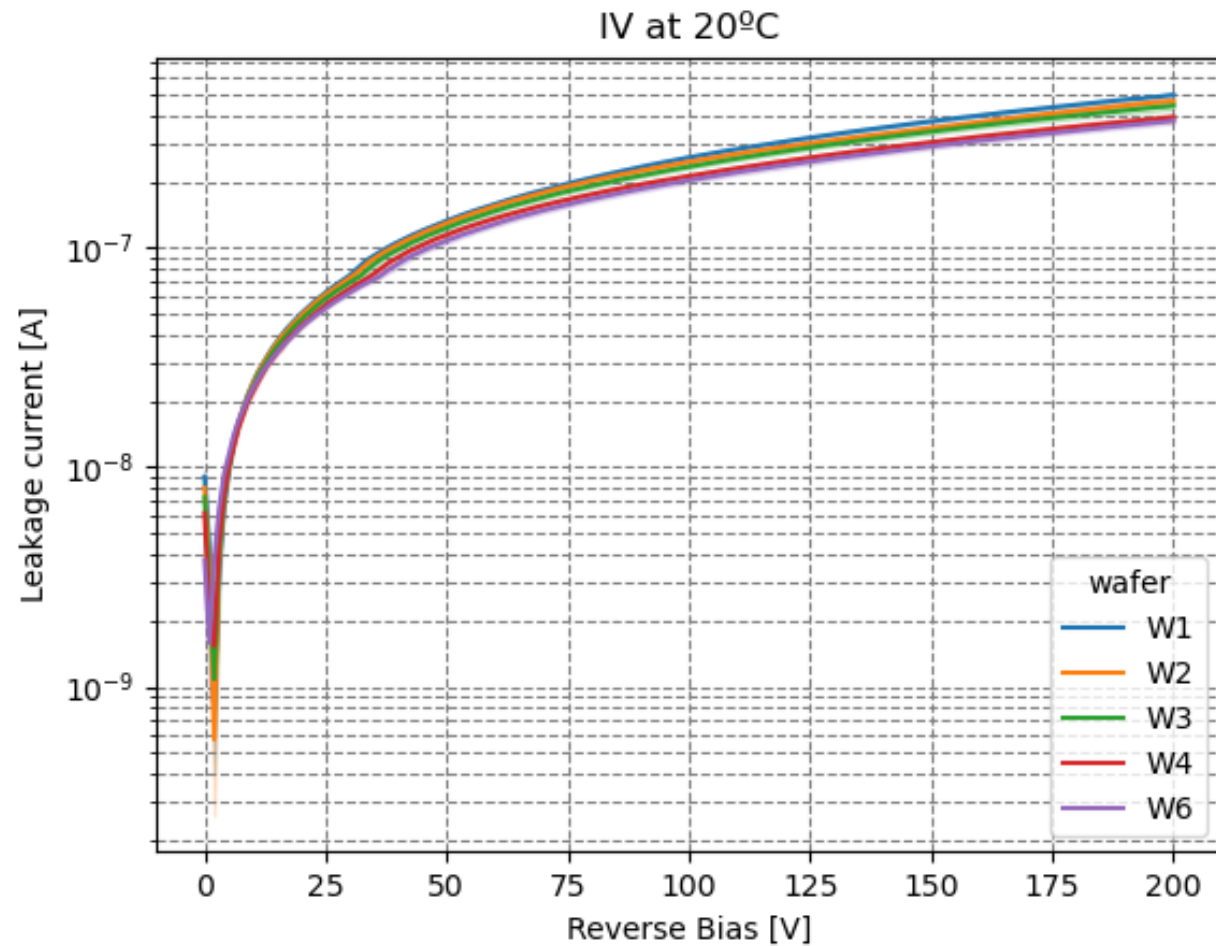
Yield condition

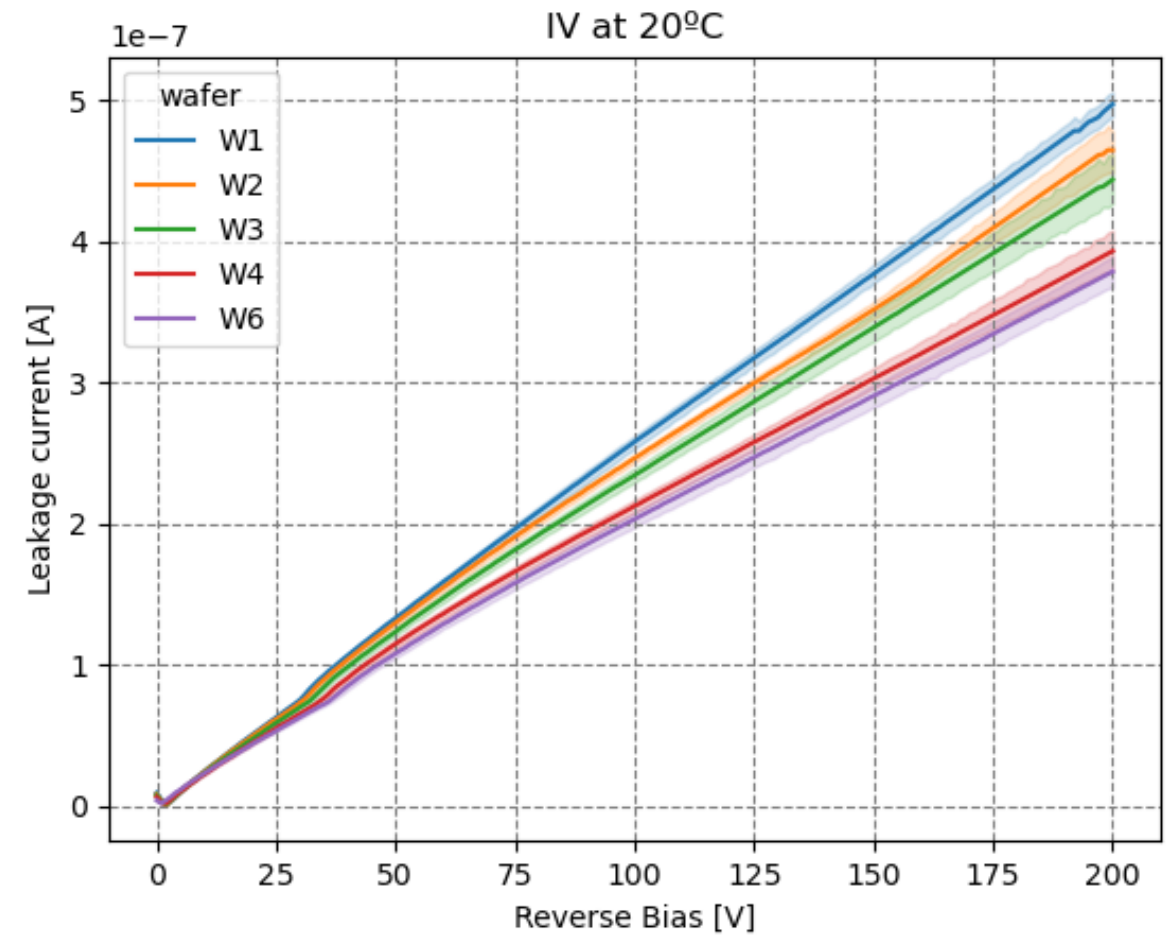
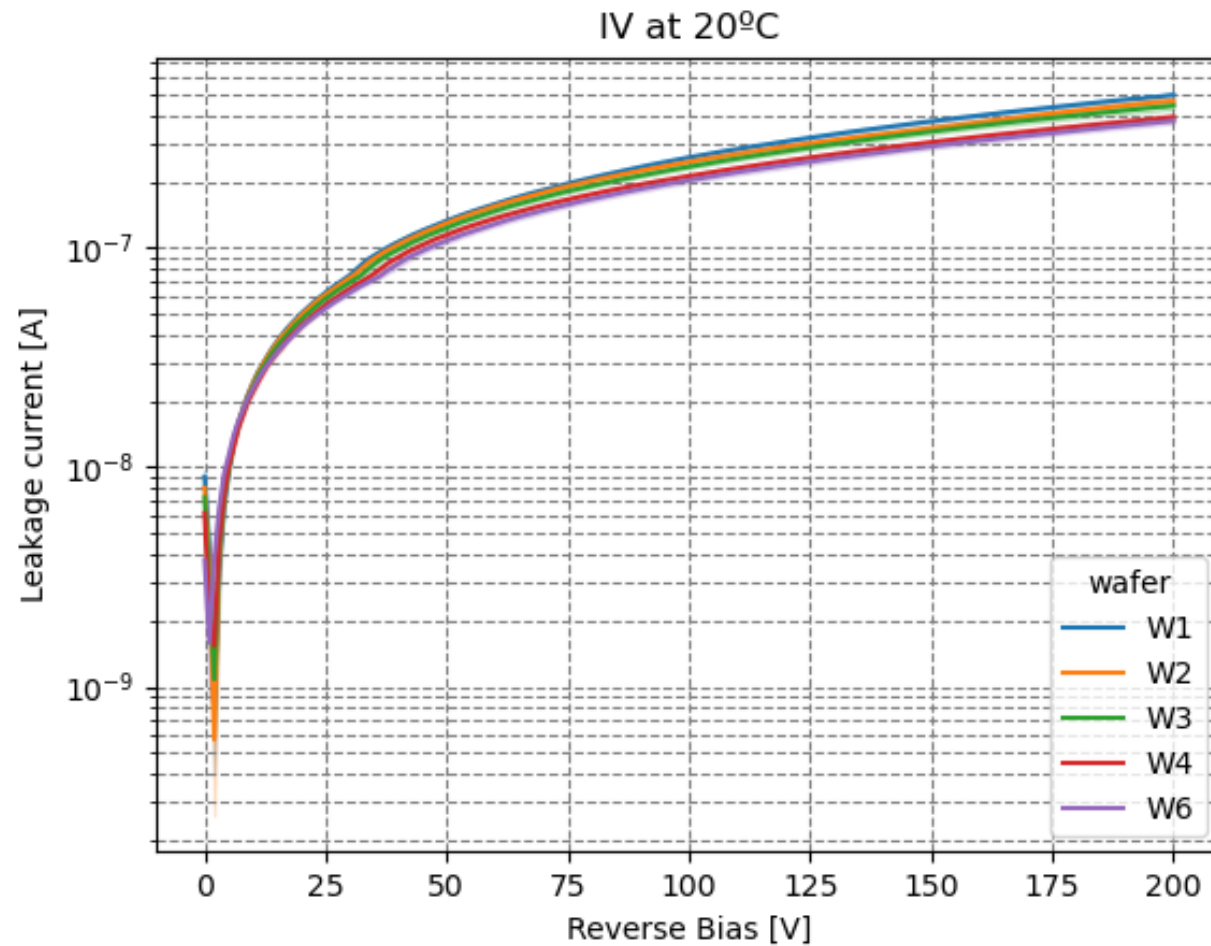
If they do not exhibit shortcut behaviour &
breakdown voltage > 200 V

Wafer	TimePix4 (1,2)	
	Meas. devices	Yield
1	10 / 10	100%
2	10 / 10	100%
3	10 / 10	100%
4	10 / 10	100%
6	10 / 10	100%
All	50 / 50	100%



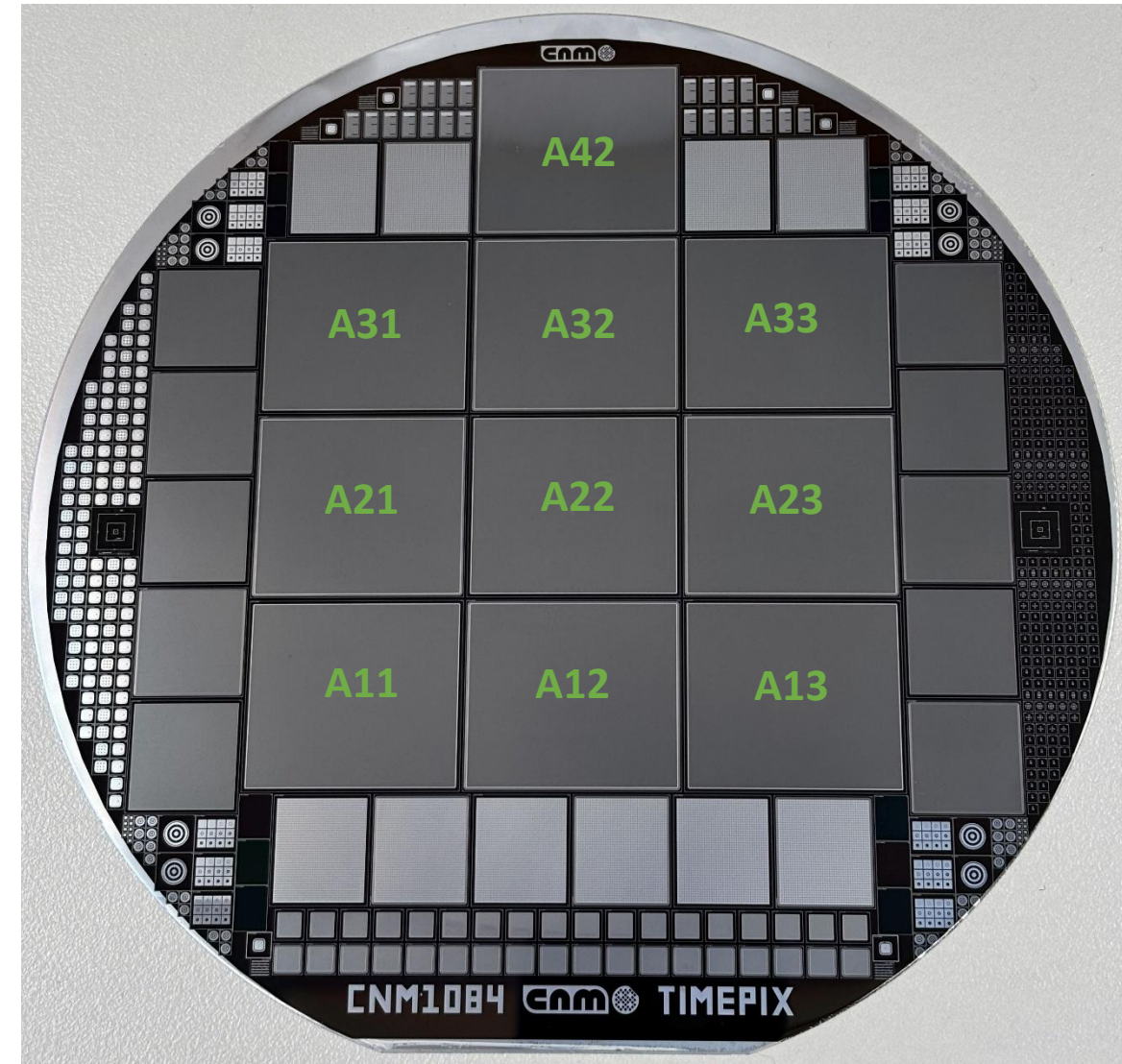
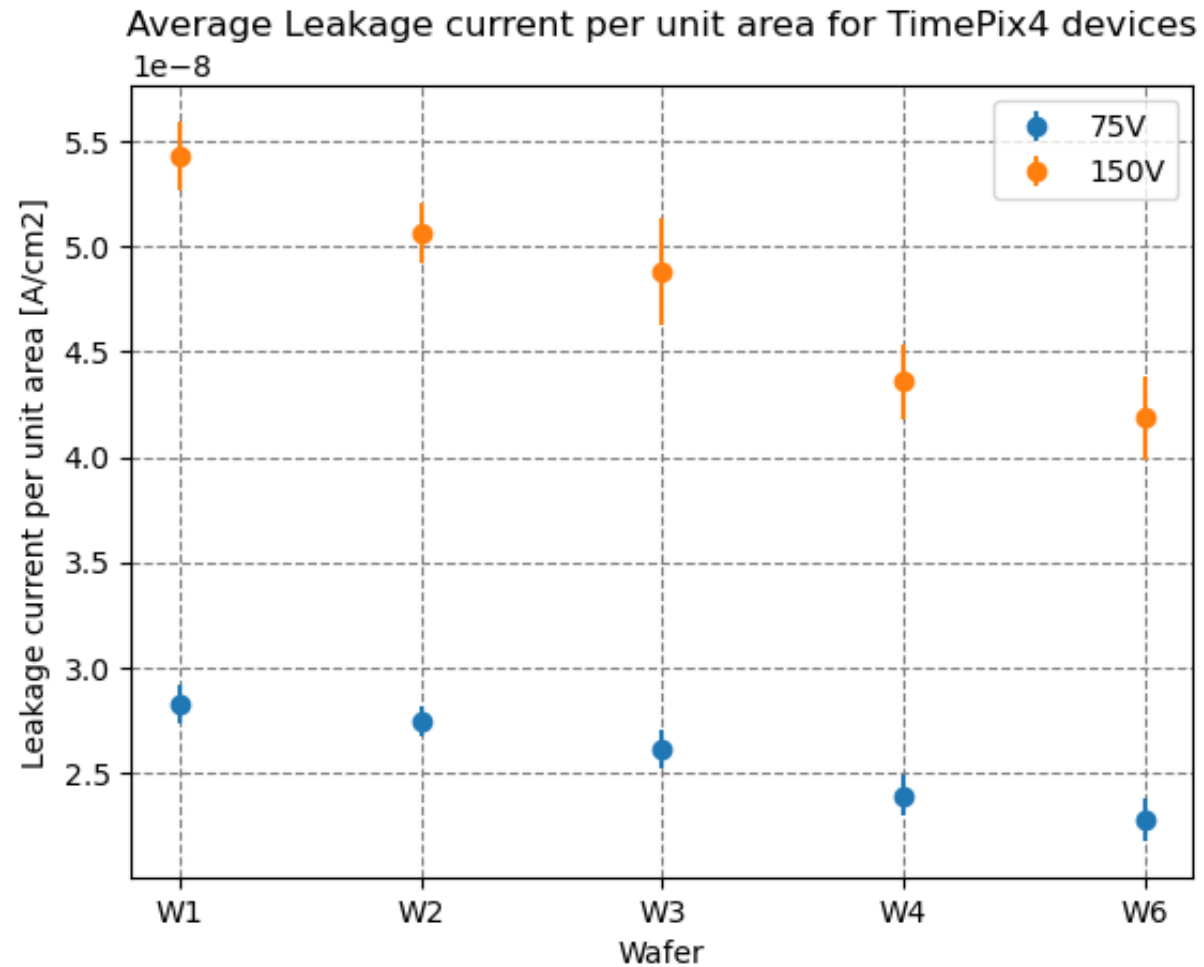
Timepix4. PiN. 6PN1v2. R18177





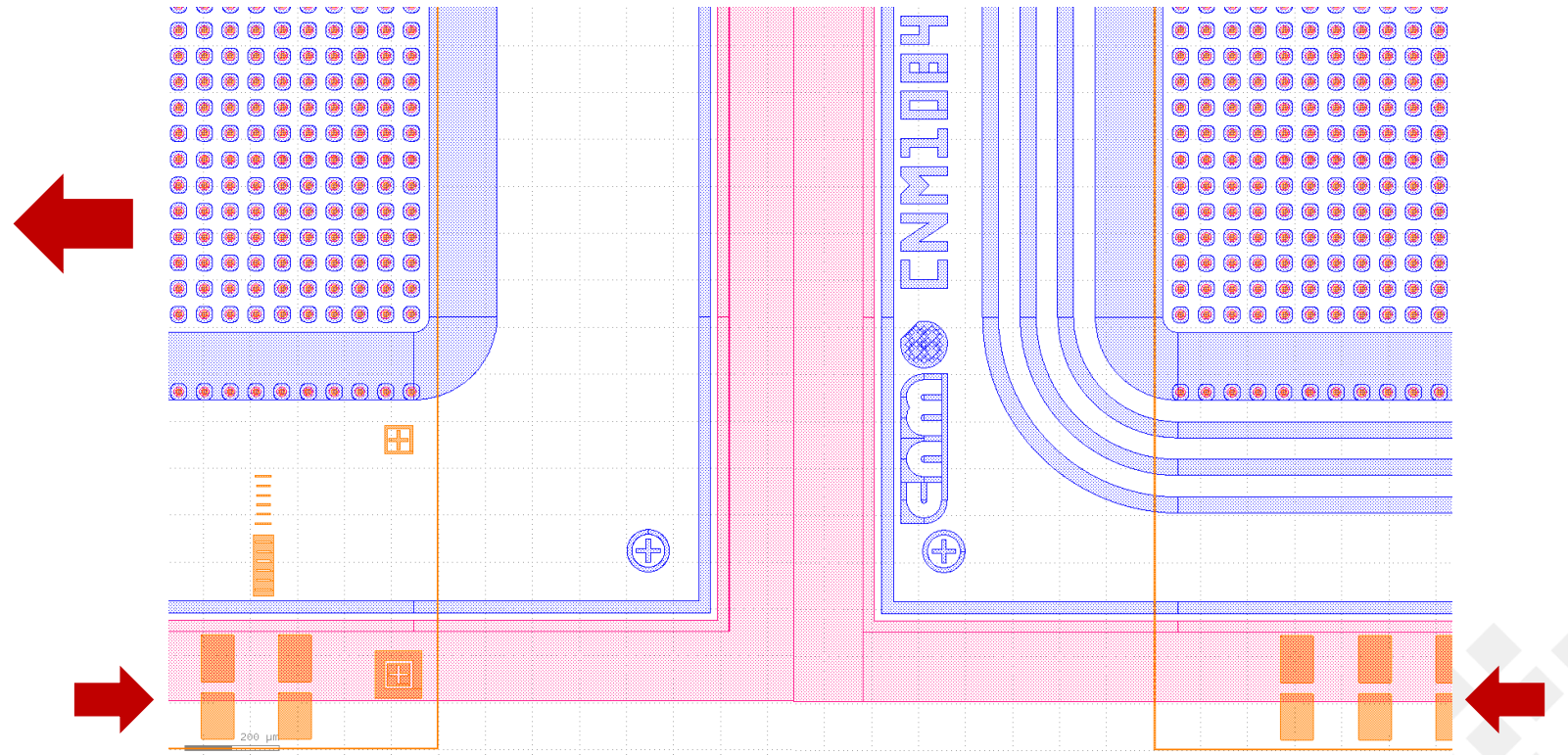
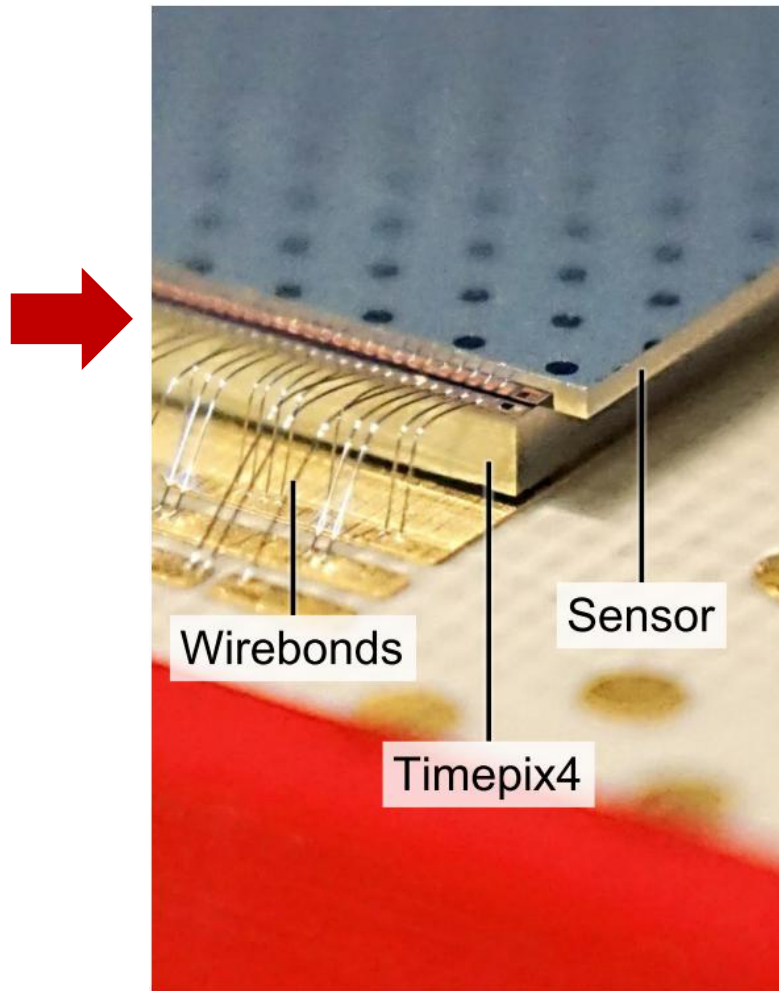
- Average of sensors per wafer with shades showing standard deviation

Timepix4. PiN. 6PN1v2. R18177



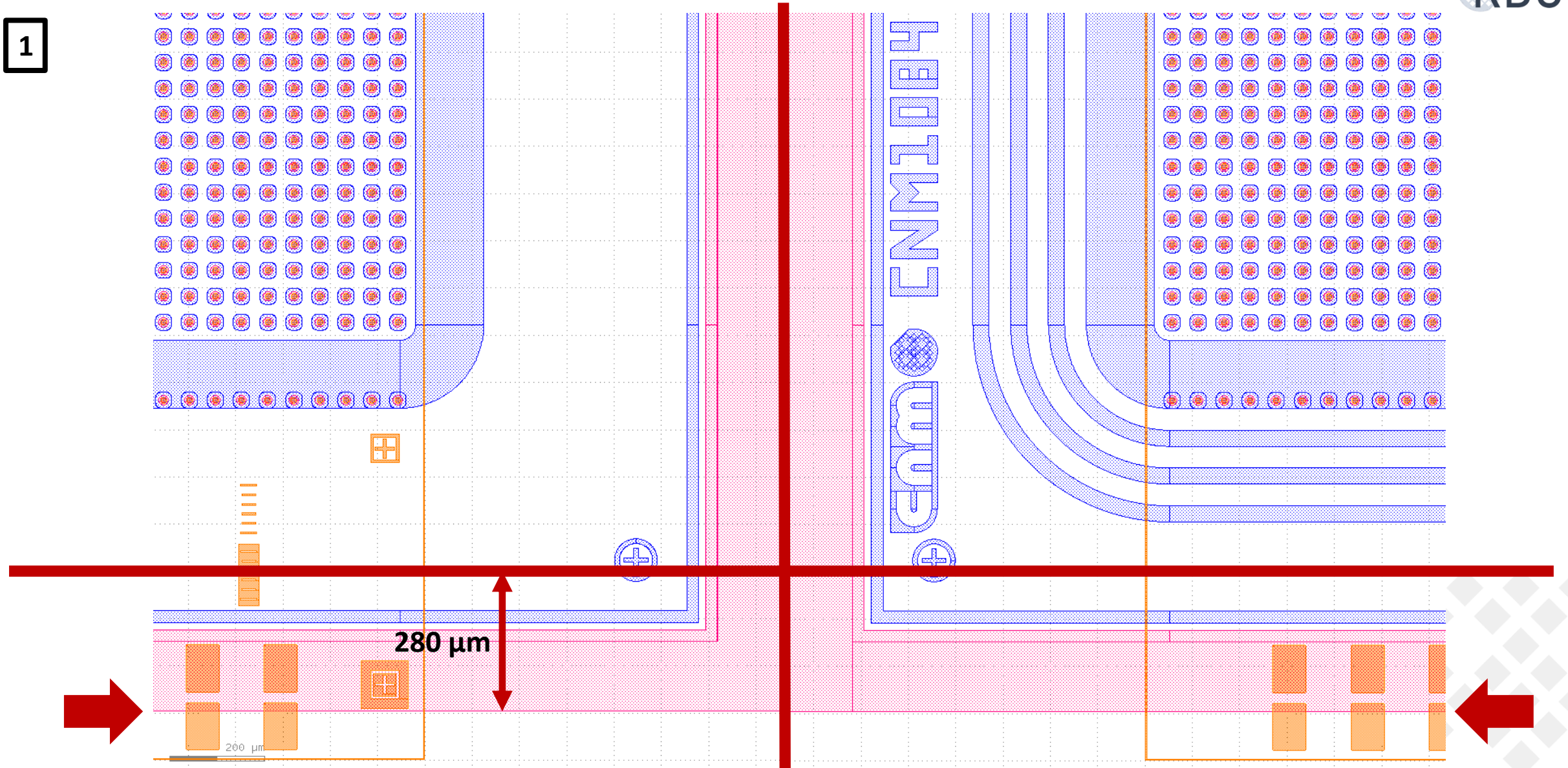
Timepix4. PiN. 6PN1. Die Size Issues

- TimePix4. 55x55 μm pitch, 512x448 pixels
 - Die Size: 29750x26230 μm



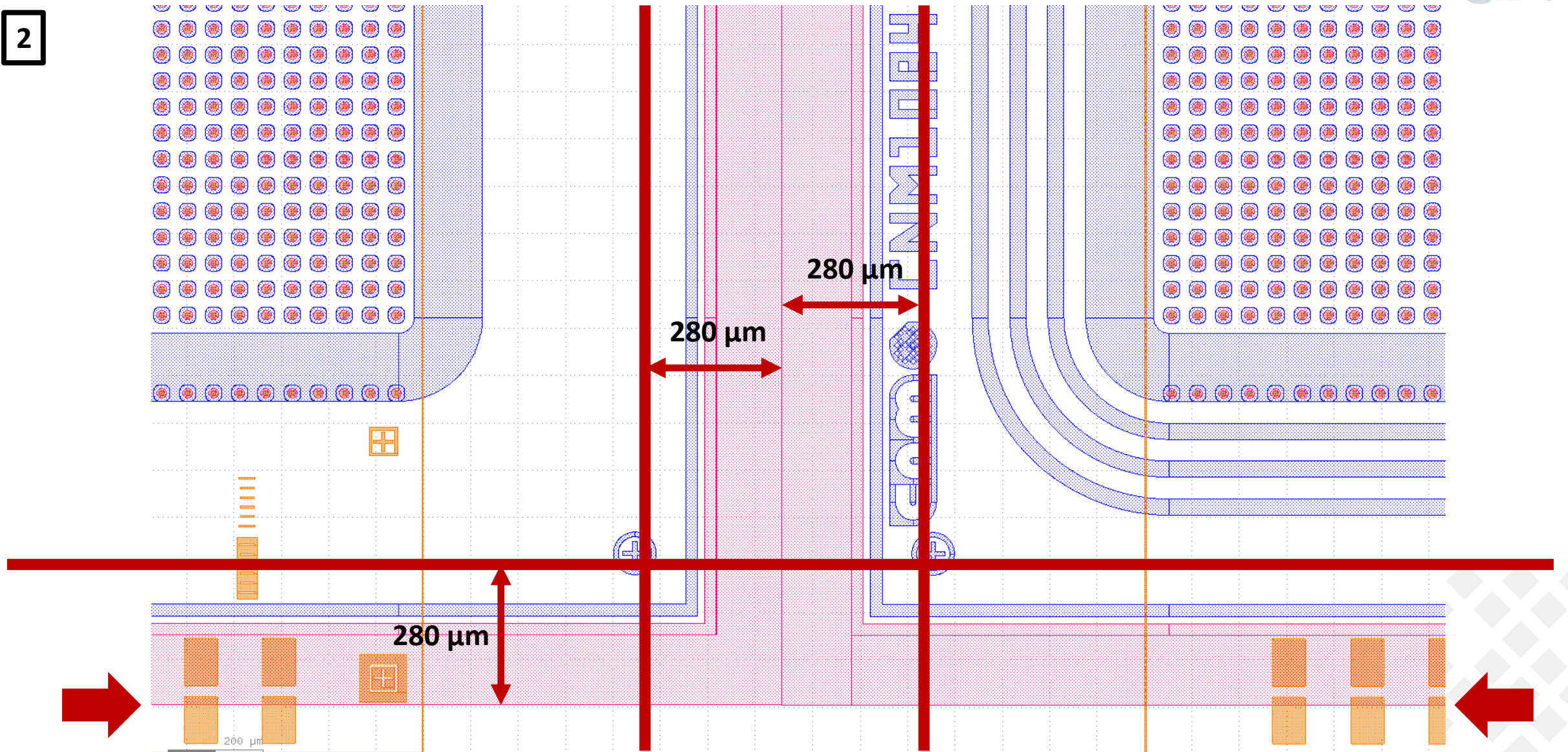
Timepix4. PiN. 6PN1. Dicing Options

1



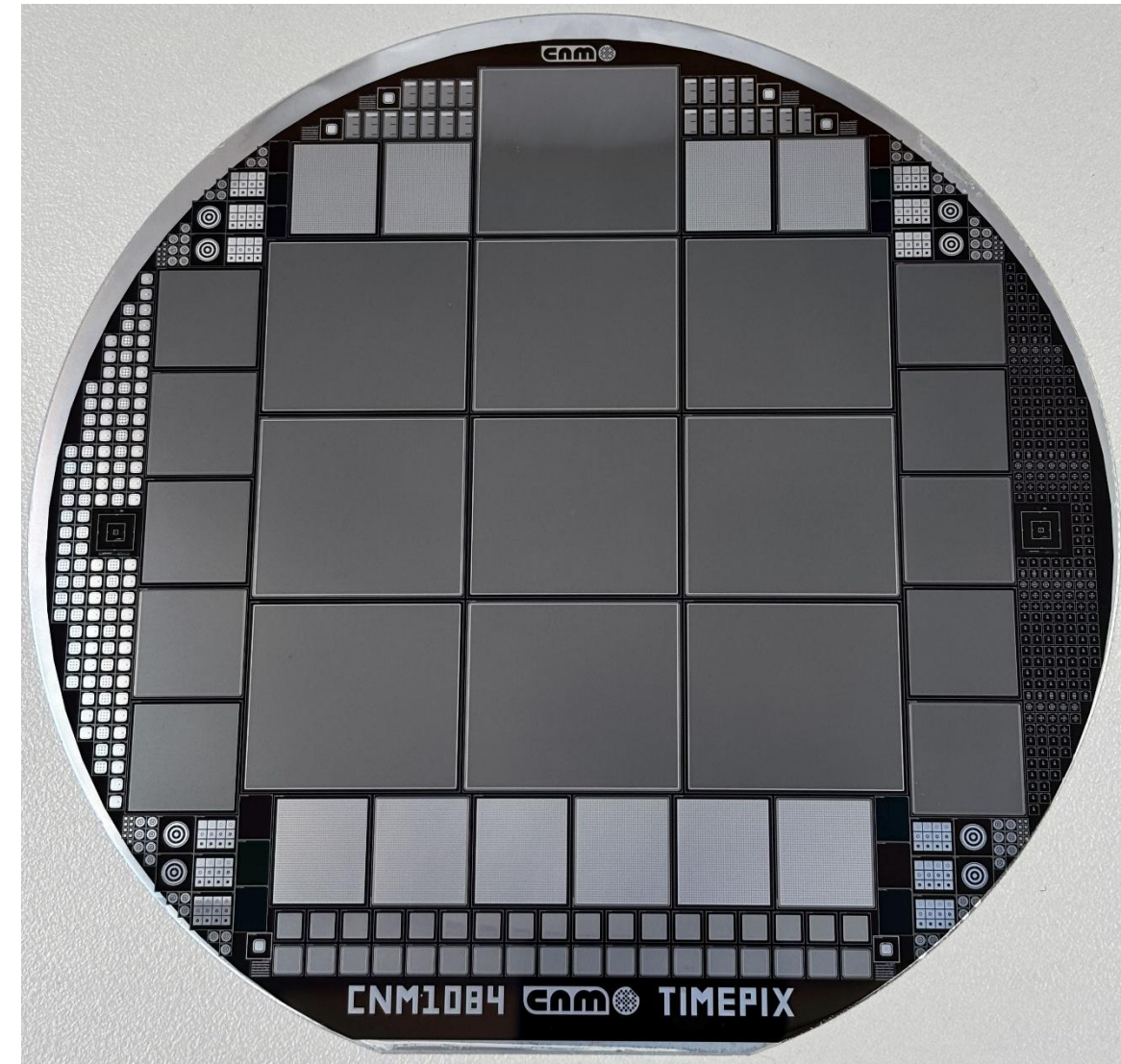
Timepix4. PiN. 6PN1. Dicing Options

2



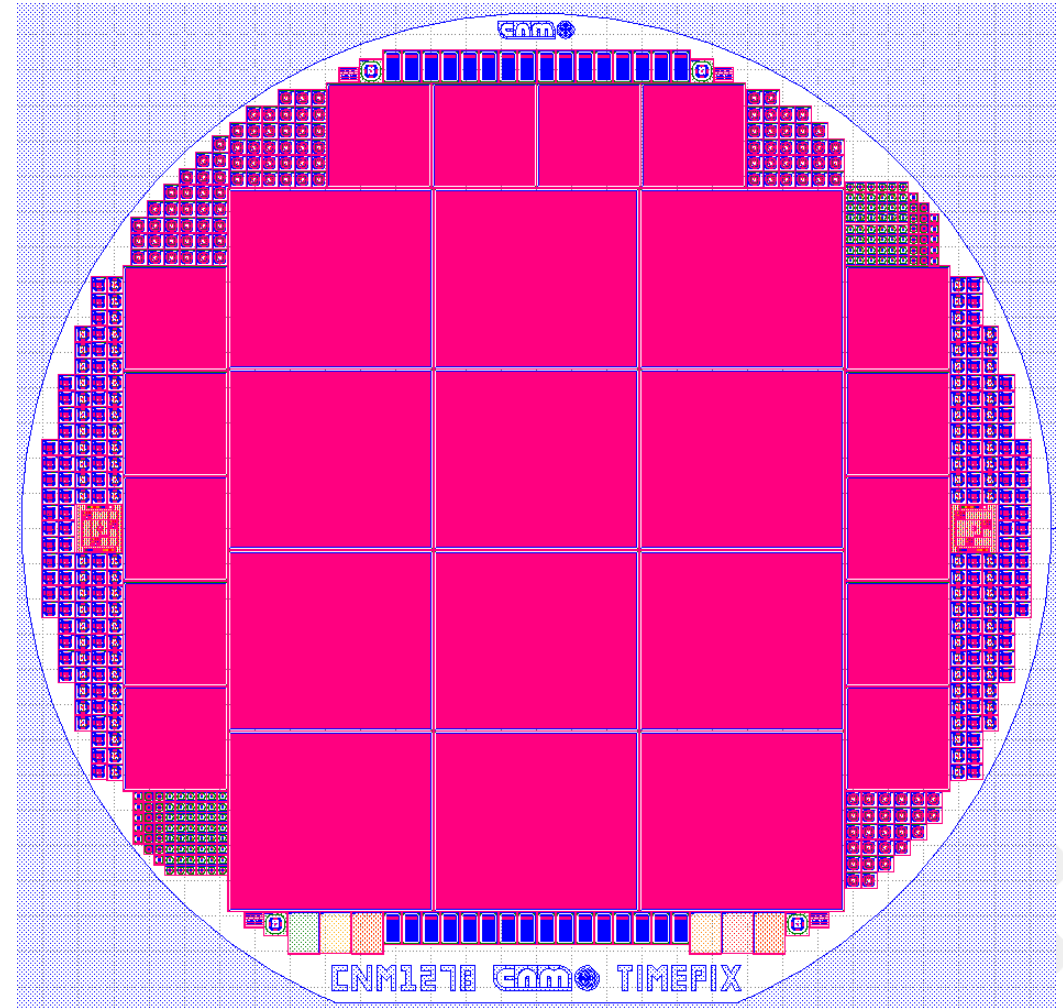
Timepix4. PiN. 6PN1v2. R18177. Next Steps

- UBM
 - IZM
 - Advacam
 - IMB-CNM
 - Other options?
- Dicing Process
 - IMB-CNM
- Flip-Chip
 - IZM
 - IFAE
 - Other options?

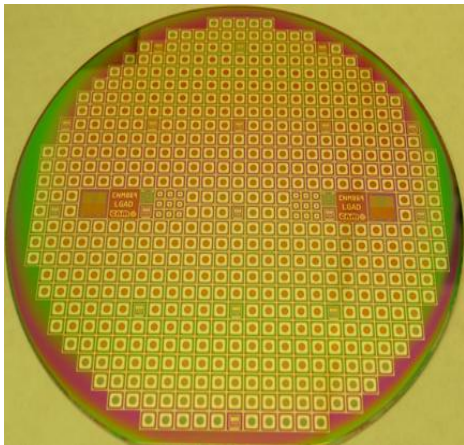


- **6 Wafers. Designed Structures**

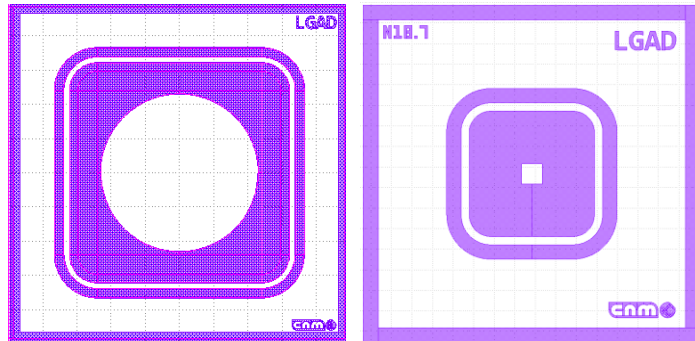
- **Timepix4** (55x55 μm pitch, 512x448 pixels): **12**
 - Passivation Opening for Bump Pad 20 μm
 - A-type: 1 Guard Ring
- **Timepix3** (55x55 μm pitch, 256x256 pixels): **14**
 - Passivation Opening for Bump Pad 20 μm
 - A-type : 1 Guard Ring
- **Strips** (80 μm pitch, 20 strips): **32**
 - A-type : 1 Guard Ring
- **Pad Diodes**
- **Nikhef Test Structures: Left-Down, Right-Top**



6PN1v3. PiNs Sensors for Dosimetry and NIEL

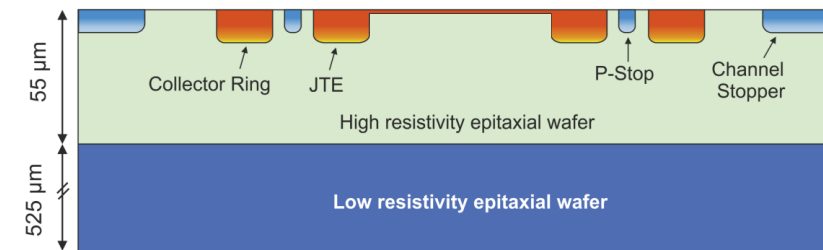


- 10 P-type, High Resistivity Wafers, 150 mm & 300 μm thick substrate
 - 6+1 Mask Levels
 - Without Carbon at the “Multiplication Area”
 - Two die sizes (4950x4950 μm^2 , 3283x3283 μm^2)
 - Pad Devices
 - 586 devices: 5x5 mm² size, 3.3x3.3 mm² active area
 - 18 devices: 3.3x3.3 mm² size, 1.3x1.3 mm² active area

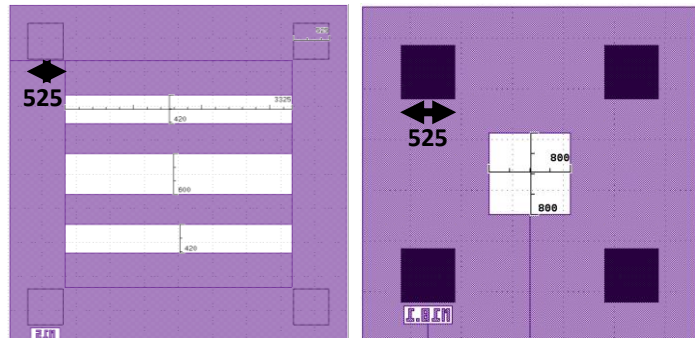


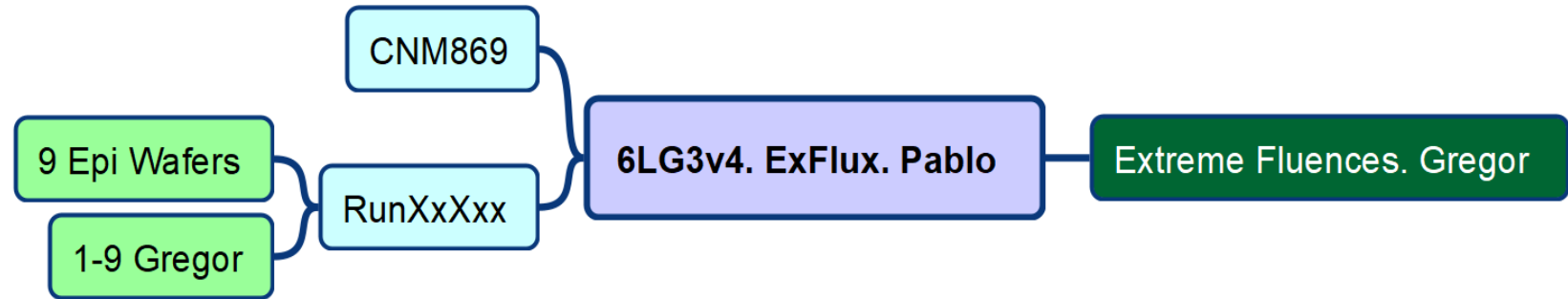
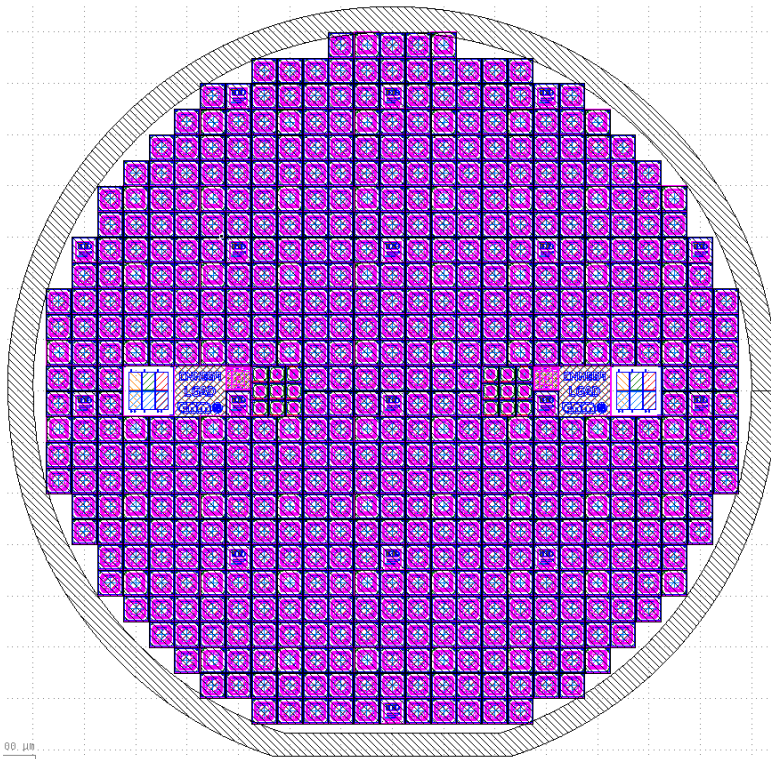
- CNM869. Original Design Top Metal Mask
 - Open Window in the Center
 - Diameters: 2300 μm , 200x200 μm^2

- CNM869. New Back Metal Mask
 - Design with a grid of windows
 - Windows size:

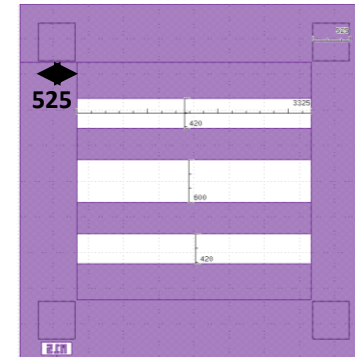
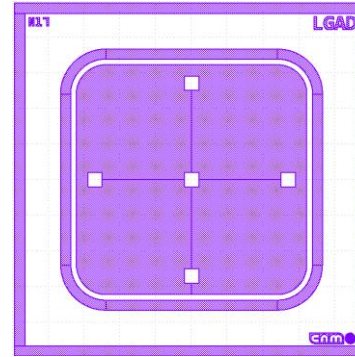
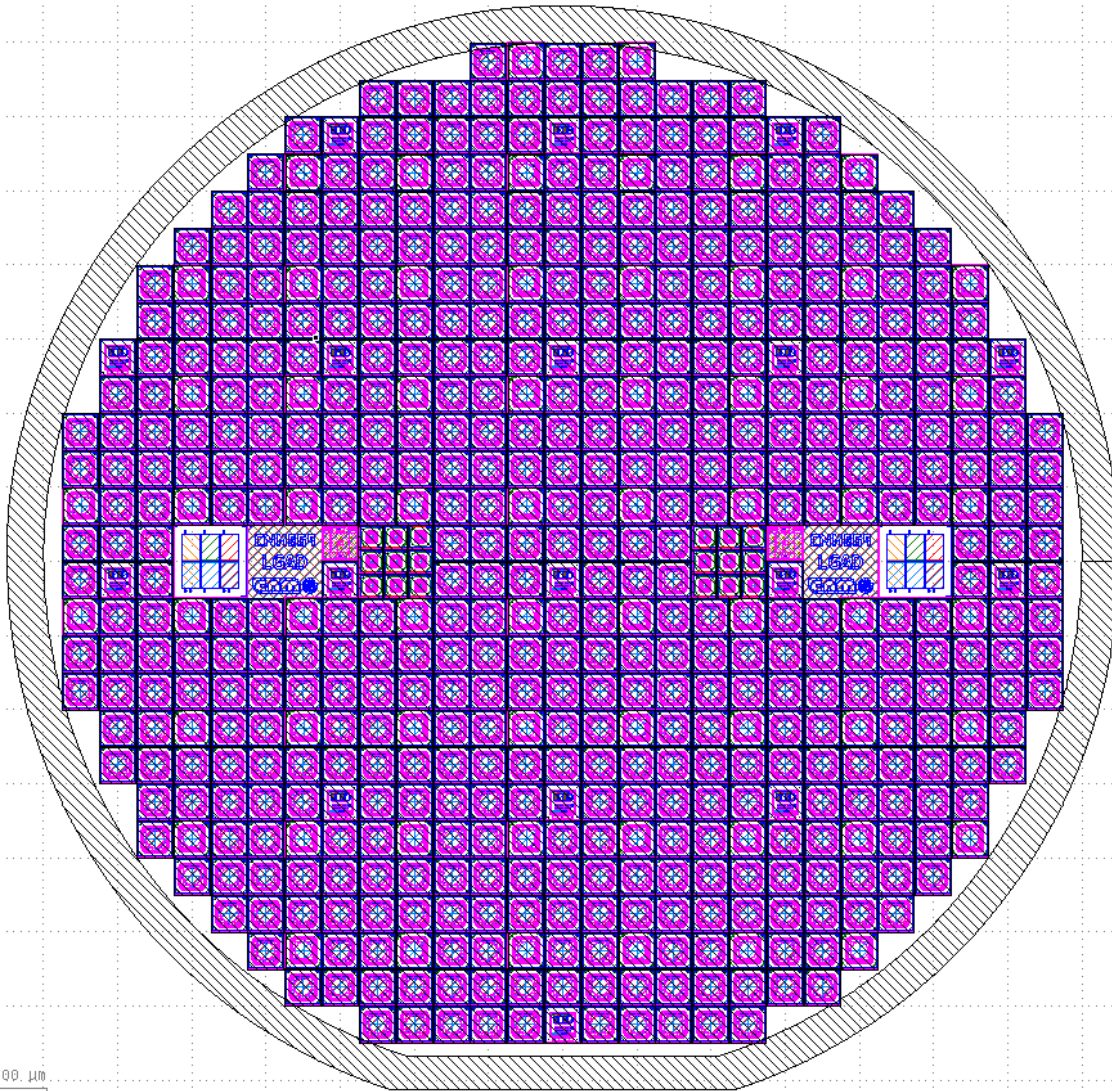


- Big devices: Three windows (3325x420, 3325x600, 3325x420 μm^2)
- Small devices: One central window (800x800 μm^2)

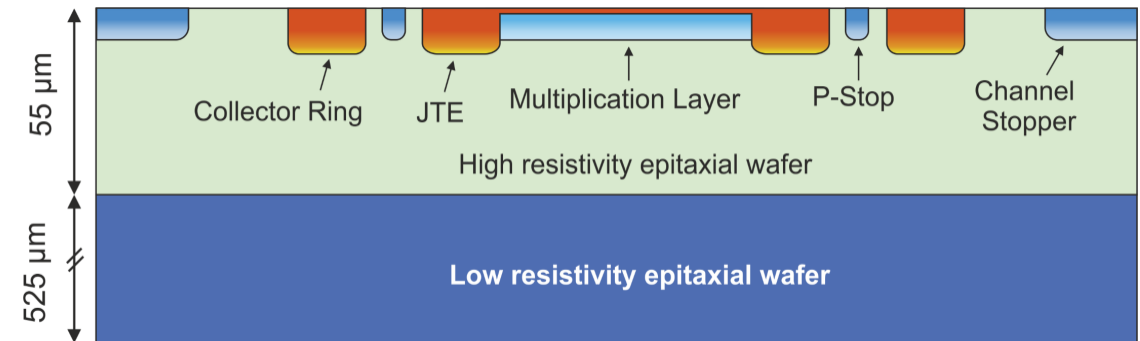




LGADs 4 Extreme Fluences. New Run. 6LG3v4



- LGADs 4 Extreme Fluences. RD50 Project Proposal
 - Main Steps
 - New Metal Layers Design
 - New Run Proposal. 6LG3v4
- Last R18399. 6LG3v3 (+6LG1v1). Standard LGAD
 - Technological Steps
 - Electrical Characterization
 - I-V, Leakage Current
 - C-V, V_{GL}



- In the framework of the project, we propose to process **4 wafers of C-enriched**, **4 wafers of not enriched gain layer** (standard) devices and **1 wafer of C-enriched PIN diodes** produced by CNM. The doping levels [p0+] would range from the **standard shallow gain layer devices** - (standard [p+] boron doping =1 a.u.):
 - 1, 2, 10, 100 a.u. (B+C LGADs)
 - 1, 5, 20, 200 a.u. (B LGADs)
 - 1 a.u. (C-implanted PINs)
- The above doping levels will allow **irradiations to fluences to few $1e16 \text{ cm}^{-2}$** and still retain the amount of initial doping corresponding to the non-irradiated control LGAD ([p+]=1).
- The standard CNM gain layer design which has $c([p+]=1 \text{ a.u.}, [C]=0 \text{ a.u.}) \sim 7e-16 \text{ cm}^2$ as well as $c([p+]=1, [C]=1) \sim 3.5e-16 \text{ cm}^2$ will be used.

LGADs 4 Extreme Fluences. New Run. 6LG3v4

No C-Enriched

C-Enriched

Wafer	Boron	Features		Type	T_{ML} (Å)	T_N (Å)
1	1	Std LGAD $E_{Boron} = 100$ keV $D_{Boron} = 1.9e13$ at/cm ² $E_{Phosp} = 70$ & 150 keV $D_{Phosp} = 1e15$ & $5e14$ at/cm ²		150 mm Epitaxial wafers 55 µm active thickness 525 µm low-resistivity p-type handle wafer	Regular screen oxide annealing (expected ≈ 200 Å)	NEW screen oxide annealing (expected ≈ 600 Å)
2	5					
3	20					
4	200					
5	1	$E_{Carbon} = 150$ keV $D_{Carbon} = 4e14$ at/cm ² 1100°C 180 min Same as Run18399 (6LG2-v3)	RD50 (ExFlux)	PiN Wafer		
6	2					
7	10					
8	100					
9	1		CNM			Regular (≈ 100 Å)
10	1					

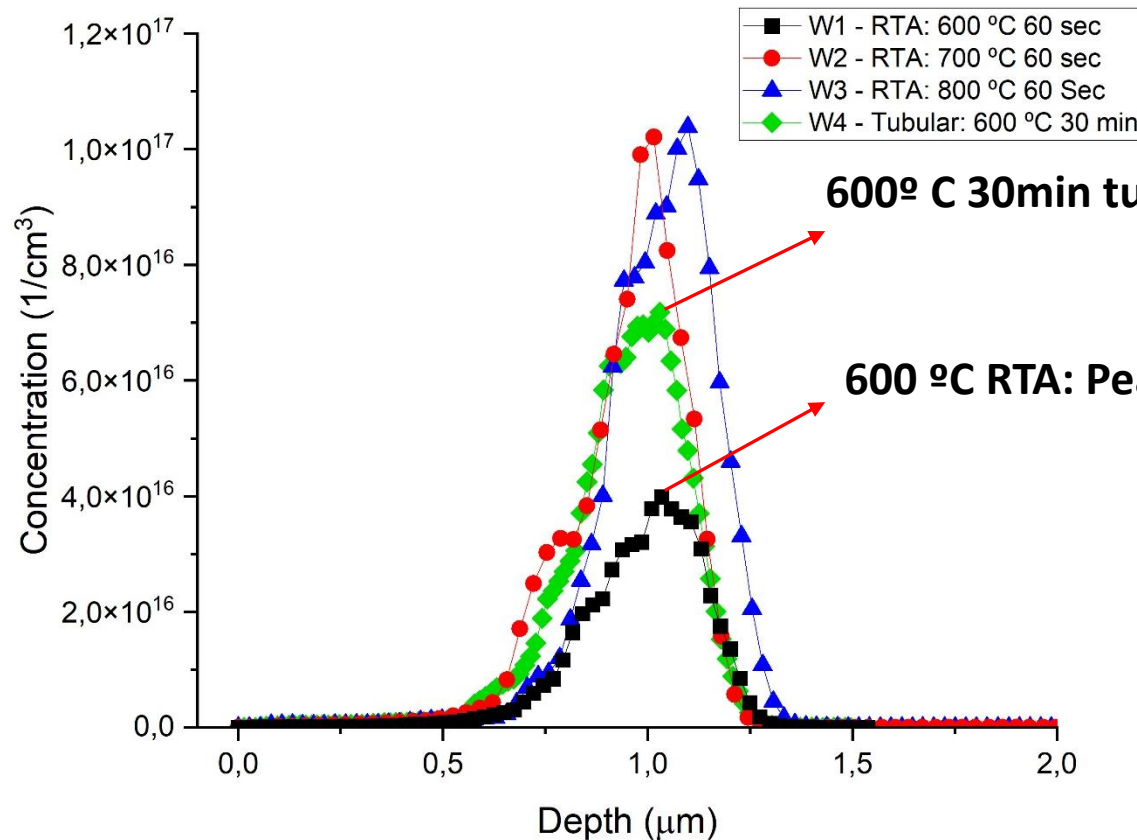


Looking for a Partial Activation Point

- Test run with blank implant on a high-resistivity P-type wafer: looking for a convenient **thermal process with allows partial activation of Boron**

- Deep Boron implant (480 keV)
- Duplicating standard dose $O(5e12 \text{ cm}^{-2})$

Spreading resistance results (p-type wafer)



	Furnace	Temp	Time
1	RTA	600 °C	60 sec
2	RTA	700 °C	60 sec
3	RTA	800 °C	60 sec
4	Tubular	600 °C	30 min

- Similar results for Phosphorus on high-resistivity n-type substrate
- Samples available to irradiate and later SRP analysis**

Partial Activation Point. Test Run

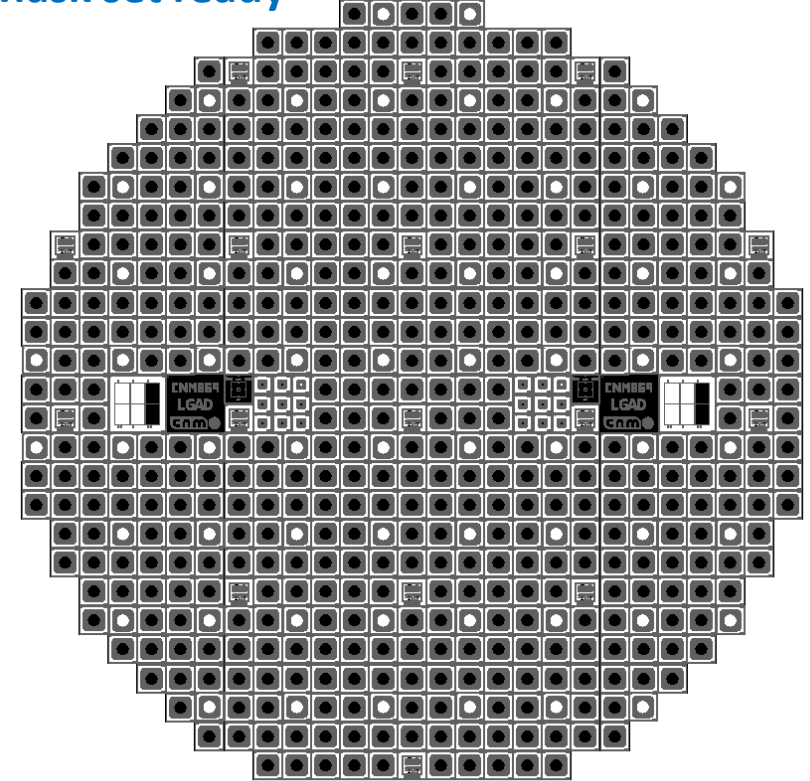
Run Details

- **Boron implant** for mult. layer will **moved to the last step**
- Sequence:
 - JTE Photo. + P implant + traditional thermal annealing
 - N-plus Photo. + screen oxide + **As implant**
 - Mult. Photo. + screen oxide (As activation) + B implant
 - **B implant: deep (480 keV) – split with 3 doses**
 - Traditional dose (control) – 1W
 - Triple dose – 2 W
 - Double dose - 1 W
 - Thermal step for partial activation (different for each wafer):
 - RTA 900 °C (traditional dose, control) – 1W
 - RTA 600 °C (Triple dose) - 1W
 - RTA 500 °C (Triple dose) - 1 W
 - 600 °C tubular (Double dose) - 1W
 - Metal deposition (Ti+ Al)
 - No post metallization annealing
 - Passivation (thermal process at 380°C)



We try to avoid further thermal steps, even if at low T

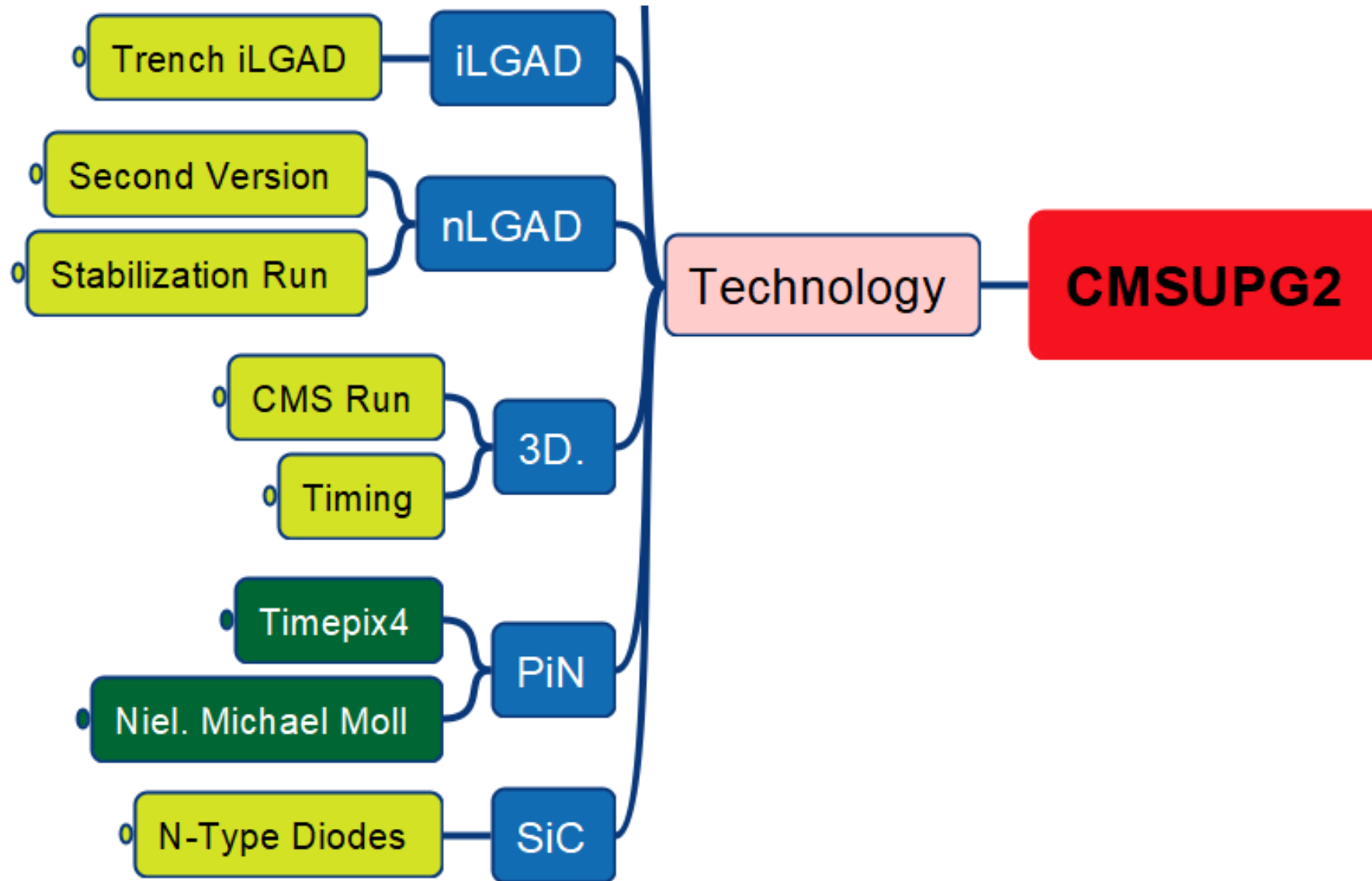
Mask set ready



Epitaxial Wafers, 6 inch.

- Only pad structures
- More than **400** 3.3 mm LGADs
- **16** 1.3 mm LGADs
- **66** PiNs

WP3. Technologies Developed. SiC



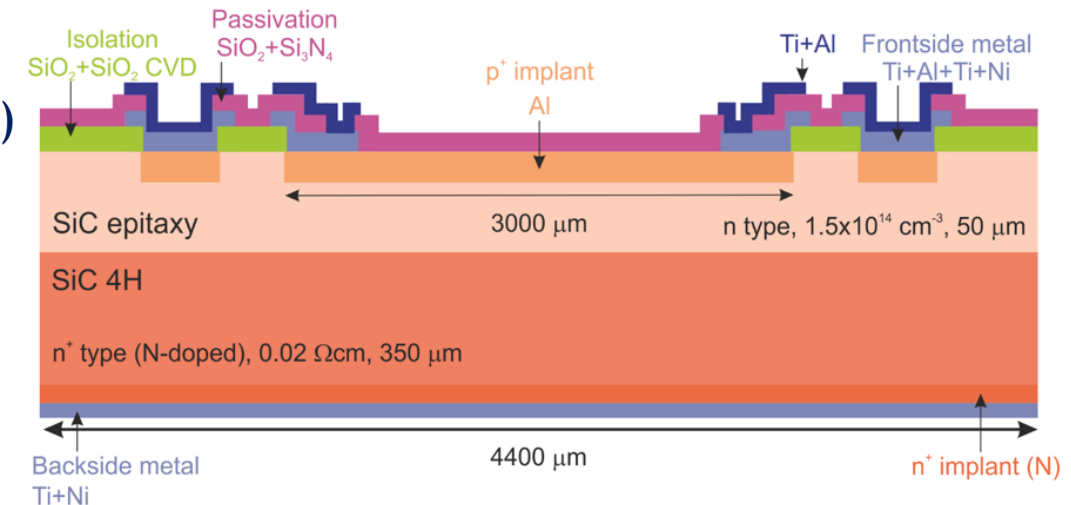
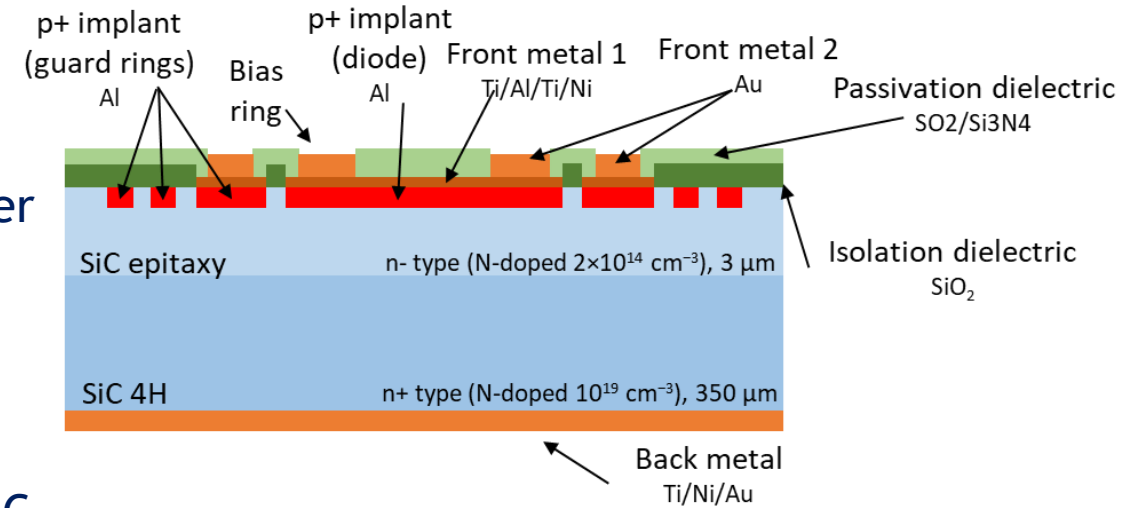
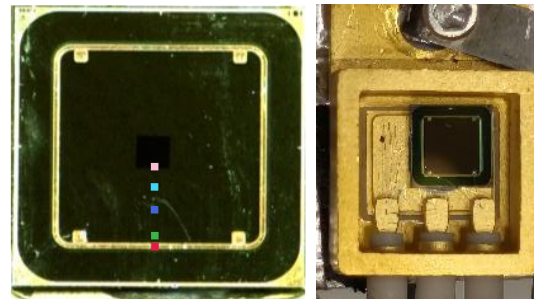
WP3.T1.b. SiC Diodes. X-ray Detection & Beam Monitoring

○ Diodes designed and fabricated @ IMB-CNM

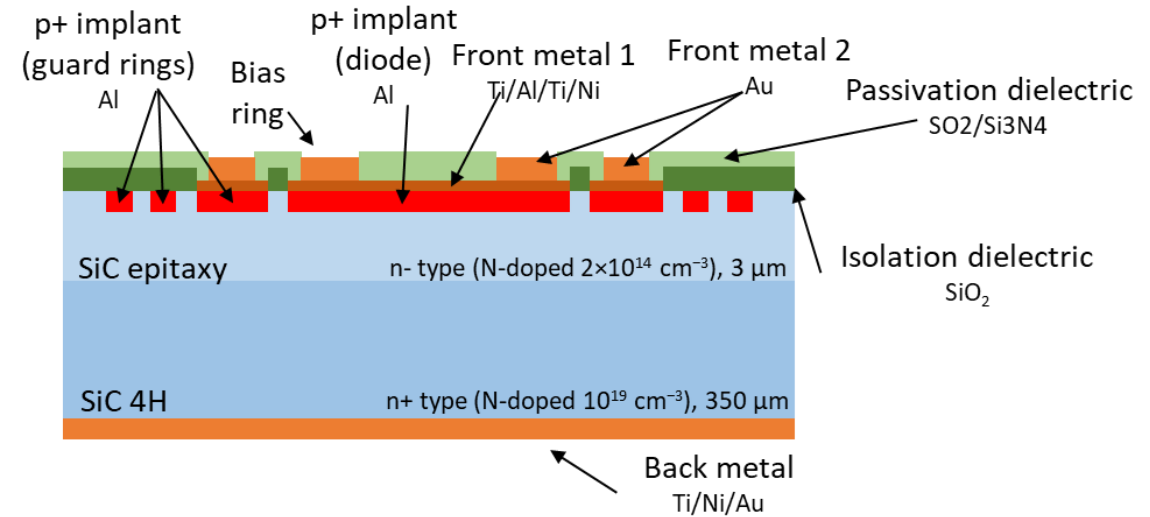
- P-N junction implanted diodes
- 4H-SiC, 100 mm wafers
- 3 and 50 μm thick, high resistivity, n-type doped epilayer
- Technology based on our SiC power diodes

○ Characterization @ CNA

- IBIC validation of TPA-TCT method on Silicon Carbide devices
- Carrier Transport Properties of Neutron-Irradiated 4H-SiC
- Effect of dynamic annealing on 4H-SiC detectors irradiated at different temperatures
- Characterization of ultra-thin (3 μm) 4H-SiC diodes
- Measurements at the Cyclotron Line (Protons of 1-13 MeV)
-> Beam timing shape measurements with SiC diodes and fibers detector



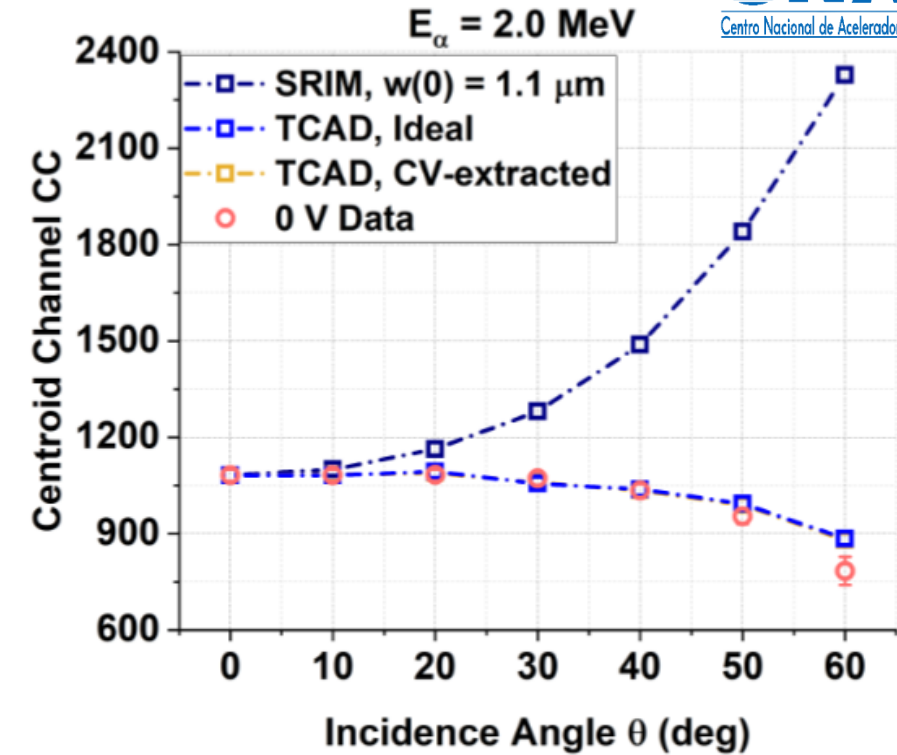
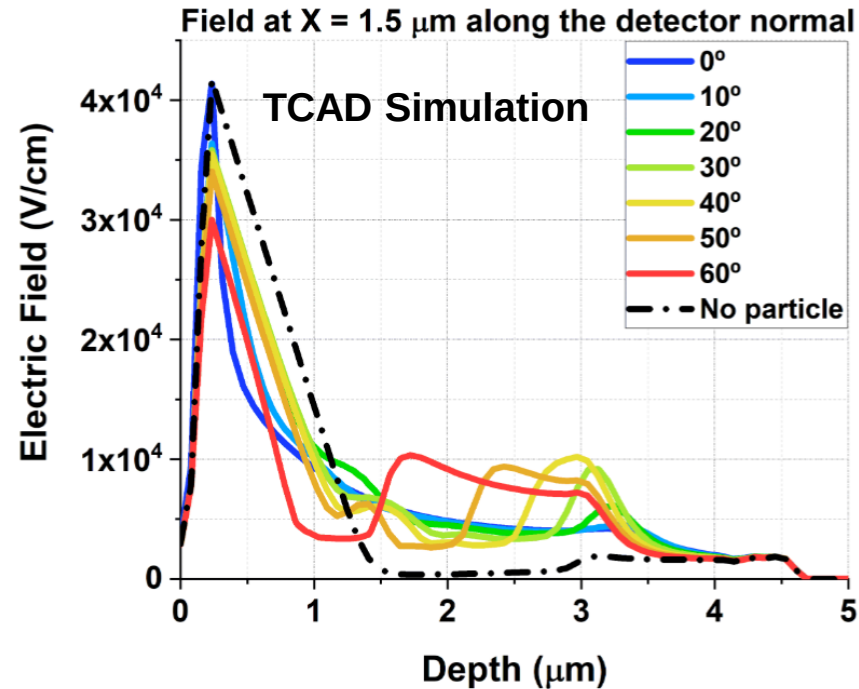
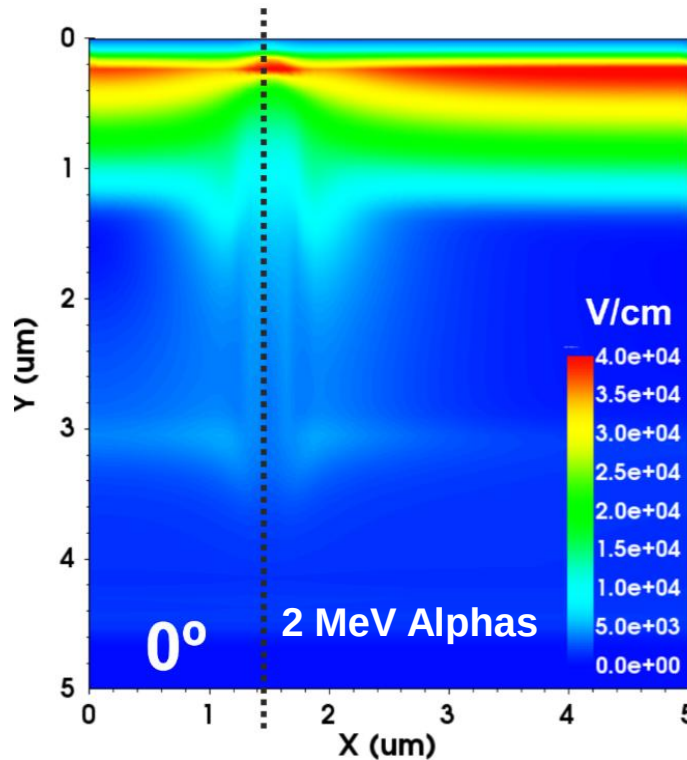
- Diodes designed and fabricated for a FLASH dosimetry project
 - P-N junction implanted diodes
 - 4H-SiC, 100 mm wafers
 - 3 μm high resistivity n-type doped epilayer
 - Technology based on our SiC power diodes
- Looking at other applications
- For example, being investigated for brachytherapy dosimetry in collaboration with IFCA
- IMB-CNM have performed several beam tests ALBA Synchrotron (Celeste) and Diamond Synchrotron (Jairo) to study the viability of SiC diodes as **X-ray detectors and Beam Position Monitors**



- Requirements for X-ray BPMs:
 - ✓ Linearity: response signal proportional to beam intensity
 - ✓ Spatial uniformity: 2D flat response
 - ✓ Spatial resolution
 - ✓ Radiation hardness
 - ❑ Transmission >90-95% TBD

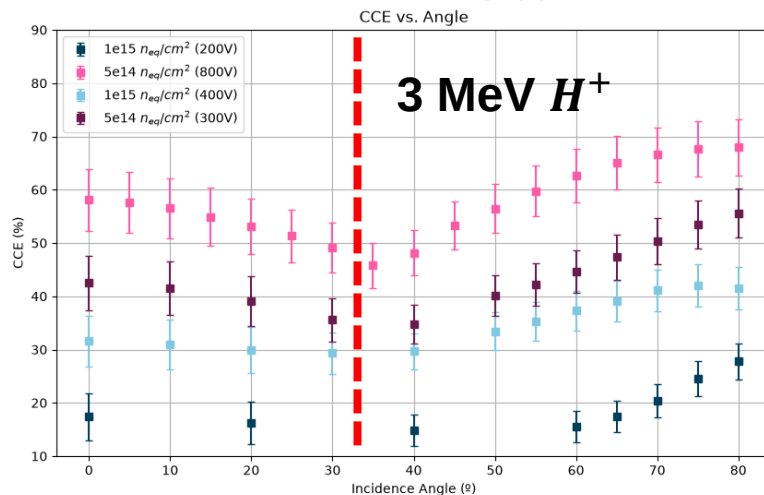
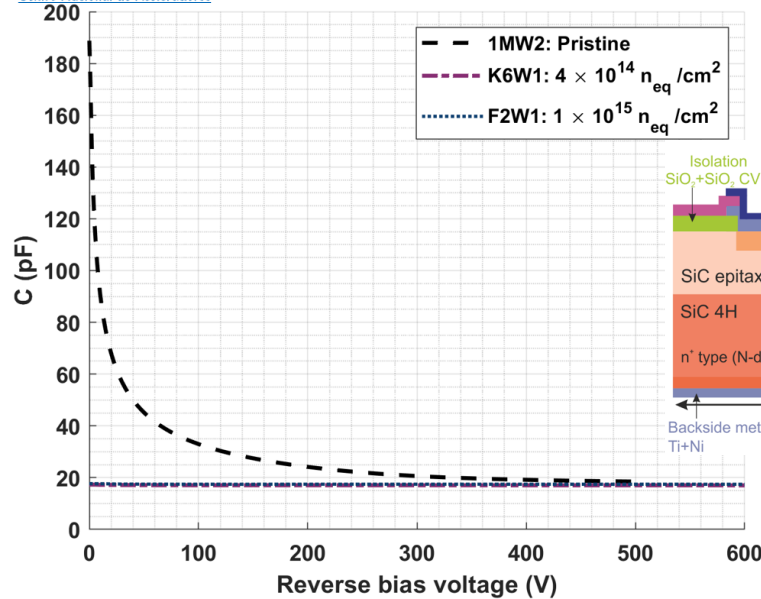


WP3.T1.b. 3 μm SiC Diodes Characterization



- Funnelling effects is present in non-polarized ultra-thin 4H-SiC detectors during alpha particle detection → The electric field gets distorted when a highly ionizing charged particle is traversing a semiconductor, transiently enhancing charge collection
- Results were presented at 5th DRD3 workshop: indico.cern.ch/event/1634258/contributions/7138855/
- Also, the results were submitted to Radiation Physics and Chemistry Journal (under review)

WP3.T1.b. 50 μm SiC Diodes Characterization



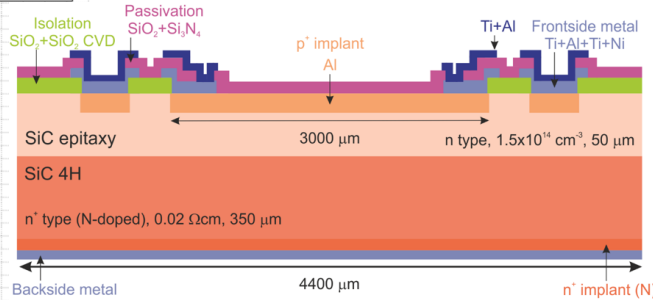
1. Neutron irradiation generates uniform distribution of defects
2. Uniform electric field across the active region (C-V measurements)

Hecht equation ($L_{drift} = (\mu\tau) \cdot E = cte$) [1]

$$CCE(drift) = \frac{1}{E_0} \int_0^w \frac{dE}{dx} dx \left[\frac{L_{e-}}{w} (1 - e^{-\frac{w-x}{L_{e-}}}) + \frac{L_{h+}}{w} (1 - e^{-\frac{x}{L_{h+}}}) \right]$$

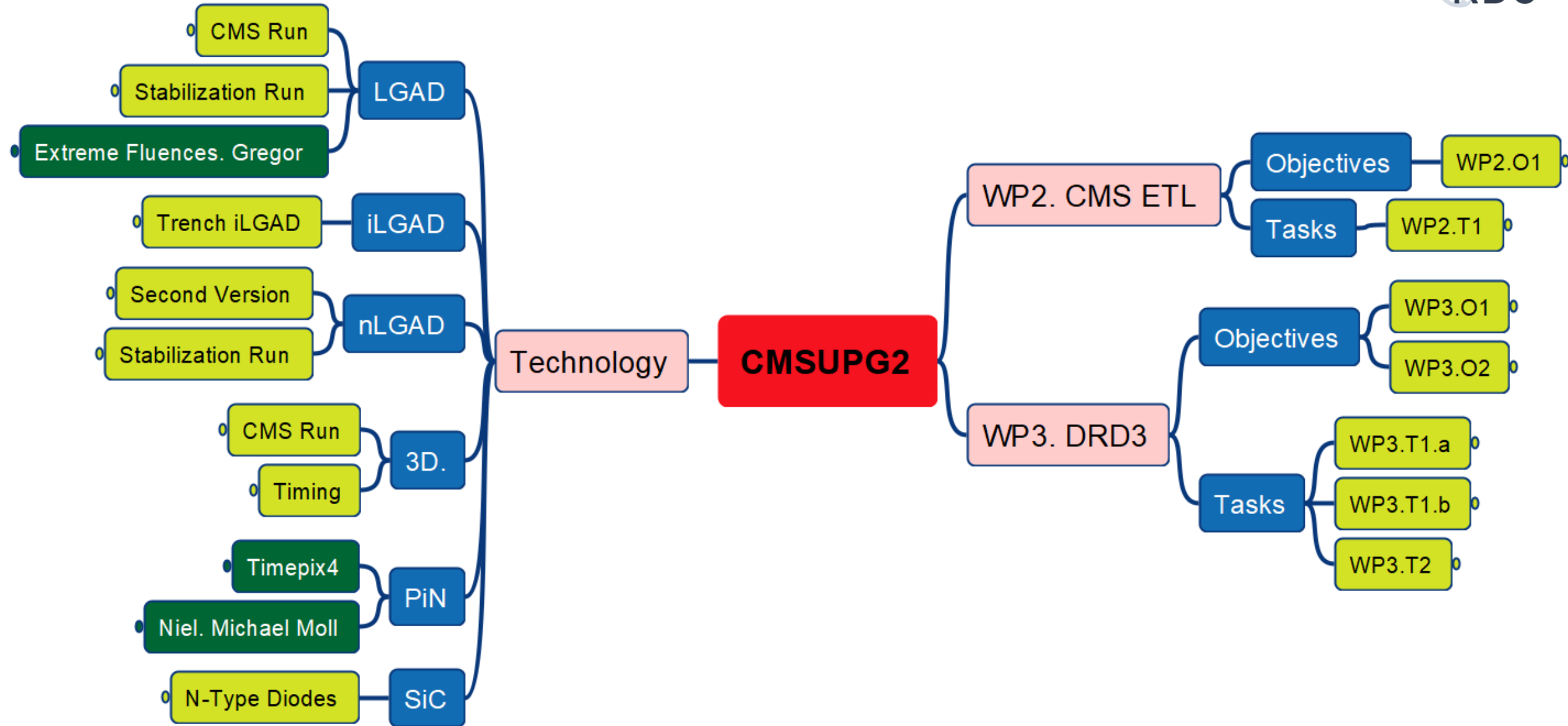
$$\chi(L_{e-}, L_{h+}) = \sum_{i=1}^N \left[\frac{CCE_{exp}(i) - CCE_{model}(i)}{CCE_{exp}(i)} \right]^2$$

- Each angle produces a different ionization profile (SRIM simulation)
- Carrier transport modeled by fitting experimental data using minimization of χ
- Fit parameters: electron and hole drift lengths (L_{e-} , L_{h+})
- Electron drift lengths are consistently 5–8× higher than hole drift lengths across all tested conditions.



Fluence(n_{eq}/cm^2)	V (V)	L_{e-} (μm)	L_{h+} (μm)
5×10^{14}	800	130 ± 40	17 ± 3
5×10^{14}	300	50 ± 8	6.6 ± 1.6
1×10^{15}	400	27.0 ± 1.0	5.3 ± 0.4
1×10^{15}	200	11 ± 2	2.3 ± 1.3

Subproject Objectives



1. C. Lasaosa, J. Duarte-Campderros, M. Fernandez, G. Gomez, I. Vila, S. Hidalgo, G. Pellegrini. "The influence of pixel cell layout on the timing performance of 3D sensors". Journal of Instrumentation. ISSN: 1748-0221. Vol. 20, nº C06080, 27 June 2025. <https://doi.org/10.1088/1748-0221/20/06/C06080>. Open Access. **Colaboración entre PID2023-148418NB-C41 y PID2023-148418NB-C42**
2. V. Kraus, M. Biveinyte, M. Fernandez, S. Hidalgo, M. Moll, J. Villegas, M. Wiehe. "Investigating irradiation effects and space charge sign inversion in n-type Low Gain Avalanche Detectors". Nuclear Instruments and Methods in Physics Research A: Accelerators, Spectrometers, Detectors and Associated Equipment. ISSN: 0168-9002. Vol. 1080, June 2025. <https://doi.org/10.1016/j.nima.2025.170763>. Open Access. **Colaboración entre PID2023-148418NB-C41 y PID2023-148418NB-C42**
3. J. Villegas, F. Dougados, C. Torres, P. Fernandez-Martinez, M.C. Jimenez-Ramos, S. Hidalgo. "The Effects of High-Energy Carbon Co-Doping on IMB-CNM LGAD Fabrication and Performance". Sensors. ISSN: 1424-8220. Vol. 25, 5571, 6 September 2025. <https://doi.org/10.3390/s25175571>. Open Access. **Colaboración entre PID2023-148418NB-C42 y PID2023-148418NB-C44**
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