Latest measurements of LGAD diodes fabricated at IMB-CNM

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Advanced Silicon Radiation Detectors

Centro Nacional de Microelectrónica CSIC

CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Tracking Silicon Detectors → PiN Diodes

Introduction

- **PiN detectors** used **for tracking applications**
  - Proportional response
  - Good efficiency
  - Segmentation technologically available (strips and pixels)

➢ *After irradiation* → Radiation Damage

→ Worsening of signal to noise ratio (S/N)

- Need to **improve performances after irradiation** of PiN diode for radiation detection.

Avalanche Diodes with Low Internal Gain

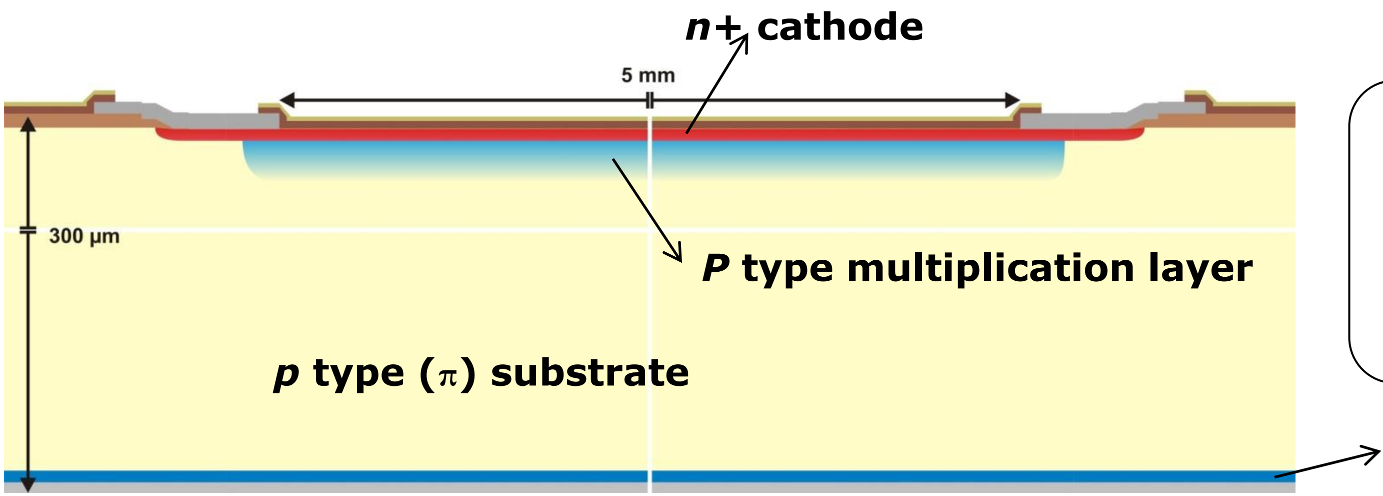
- Exploit **avalanche** phenomenon of a **pn junction** polarized **in reverse mode**.
  - **LGAD = Low Gain Avalanche Diode**
- Diodes with **internal gain** are more **radiation hard**
  - Charge multiplication compensates charge loss due to trapping;
  - Higher electric field => Shorter collection times
    => Lower trapping probability
- Have higher **signal to noise ratio** (S/N) => Better spatial resolution
- **Low gain** (<10) → Good for particle physics
  - High gain => Higher noise (lower S/N)
    => Longer collection times
    => Higher trapping probability

Structure of LGAD

- The goal: a diode with multiplication working in linear mode.
- Starting point : PiN-PAD diode with an area of 5mm x 5mm.

  - **Structure**: highly resistive *p*-type substrate
    - ***n*+ well** for the cathode
    - ***p* diffusion** under the cathode

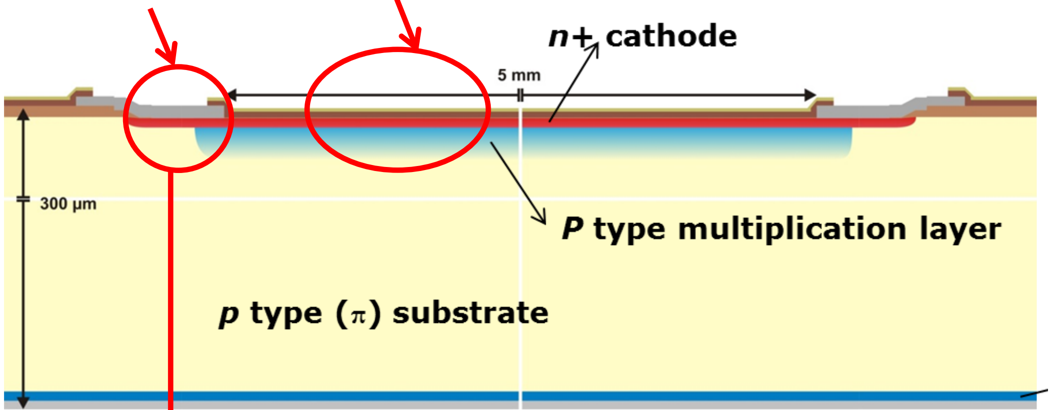
      => enhance electric field => **multiplication layer**

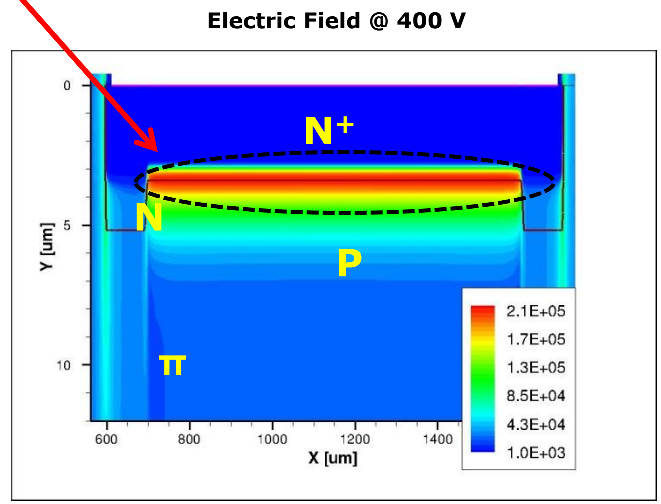


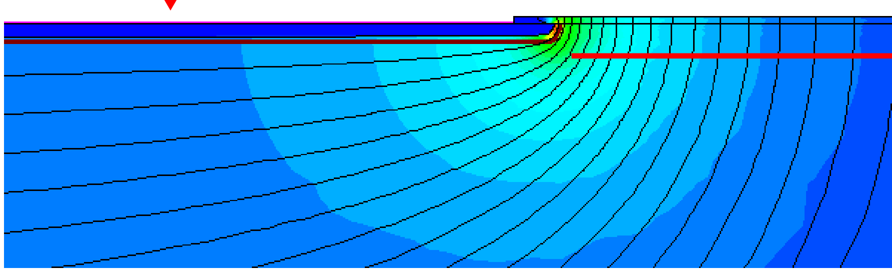
The doping profile of this layer is a very **critical** technical **parameter**

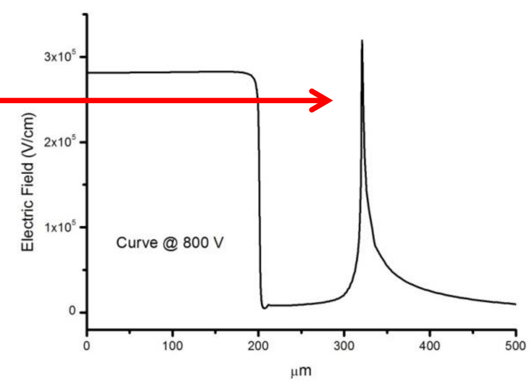
Design of the Edge Terminations

- Two regions → different junctions:
  - **Central area** → uniform electric field, high enough to activate mechanism of charge multiplication
  - **Periphery**





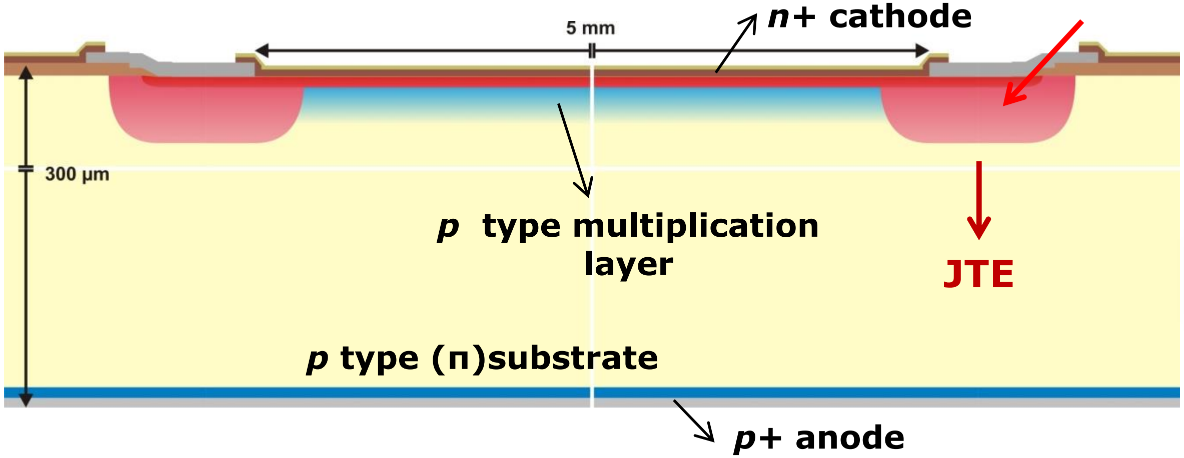




- We want: $V_{BD}|_{Central} \ll V_{BD}|_{Termination}$

Design of the Edge Terminations

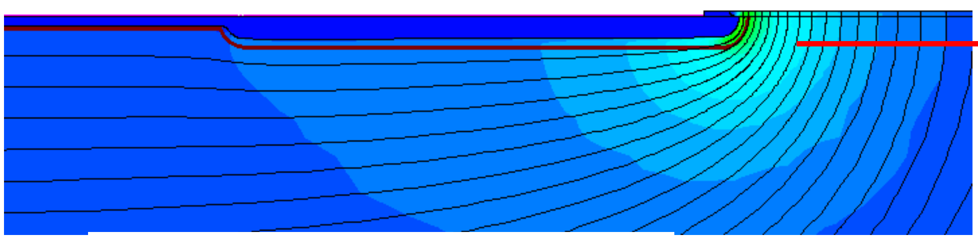
- We want: $V_{BD}|_{\text{Central}} \ll V_{BD}|_{\text{Termination}}$ ➡ Low doping ***n* well in the periphery** of the cathode

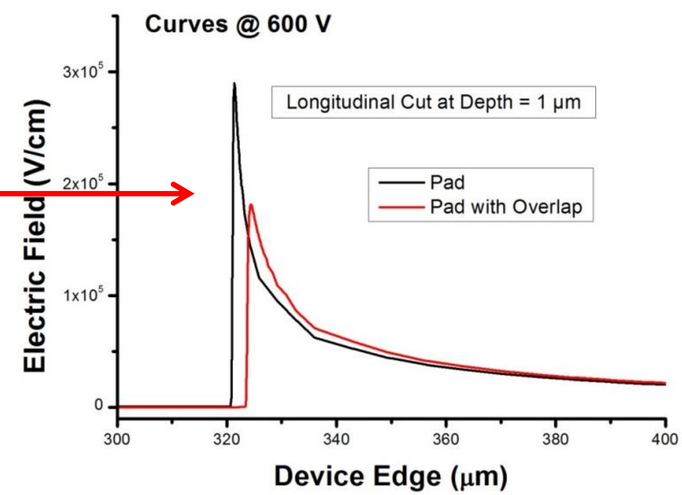


➡ higher voltage capability

Junction Termination Extension

PiN Diode with JTE

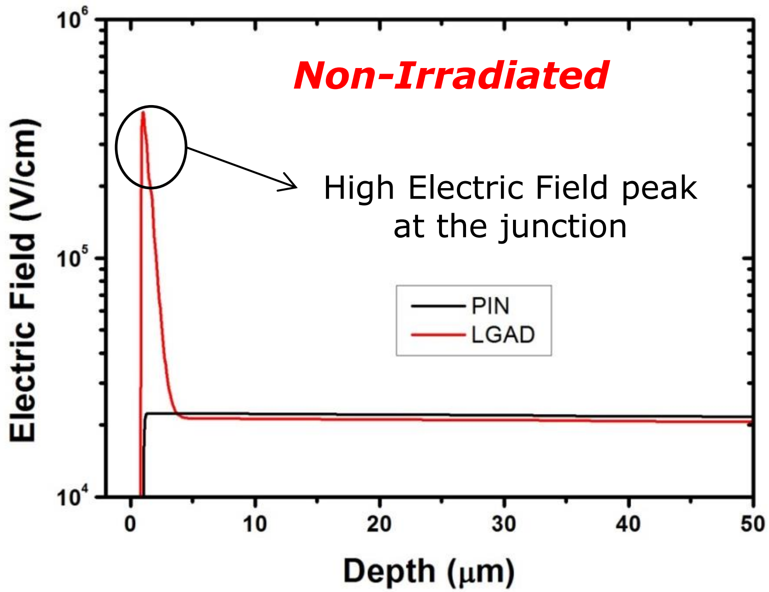


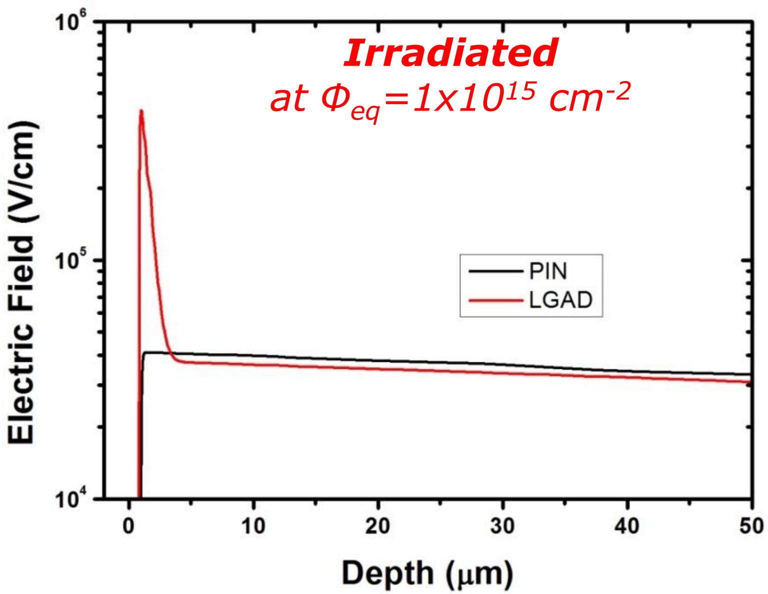


- 2D Simulation: ➡ Lower electric field peak

Simulation of Irradiated Devices

Curves @ 600 V

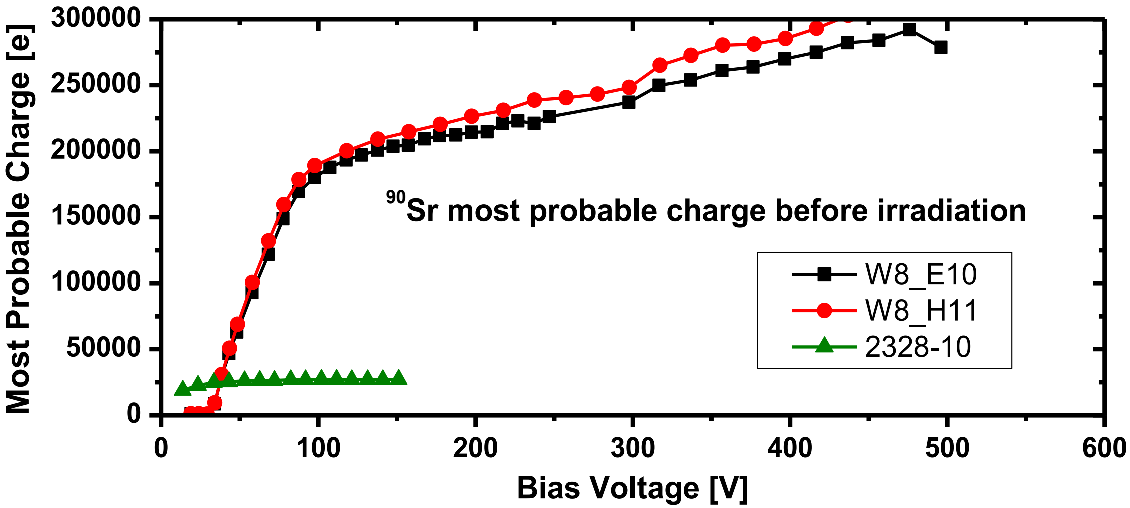


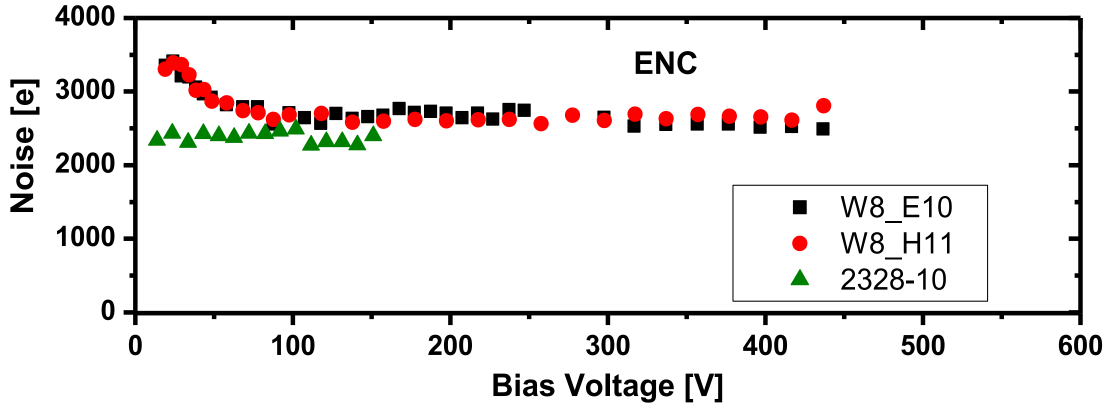


- **PiN** → electric field at the junction higher after irradiation
- **LGAD** → electric field at the junction → after irradiation = before irradiation

Effects of Radiations

- Charge collection measurements of MIPs with **^{90}Sr source**





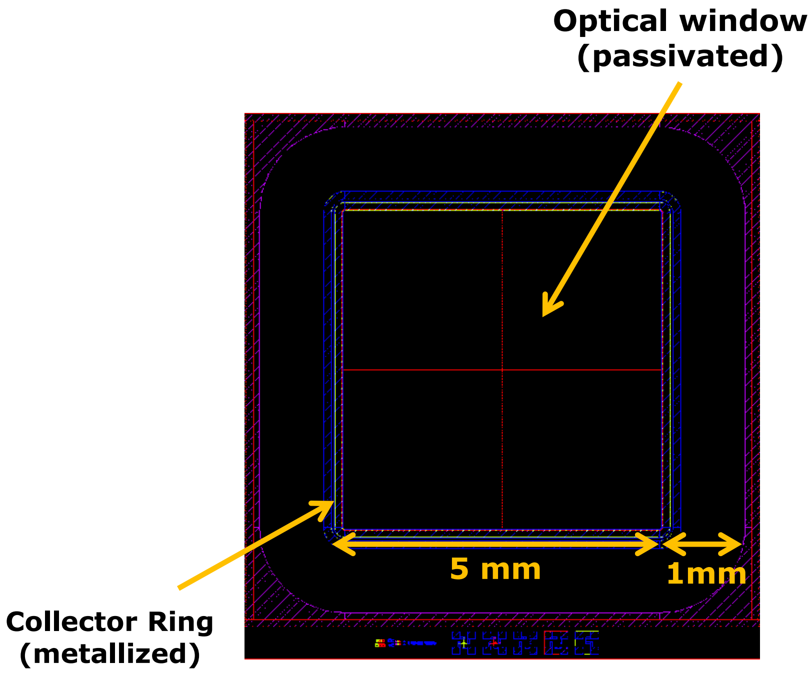
Performed at the "Jozef Stefan" Institut, in Ljubljana, Slovenia

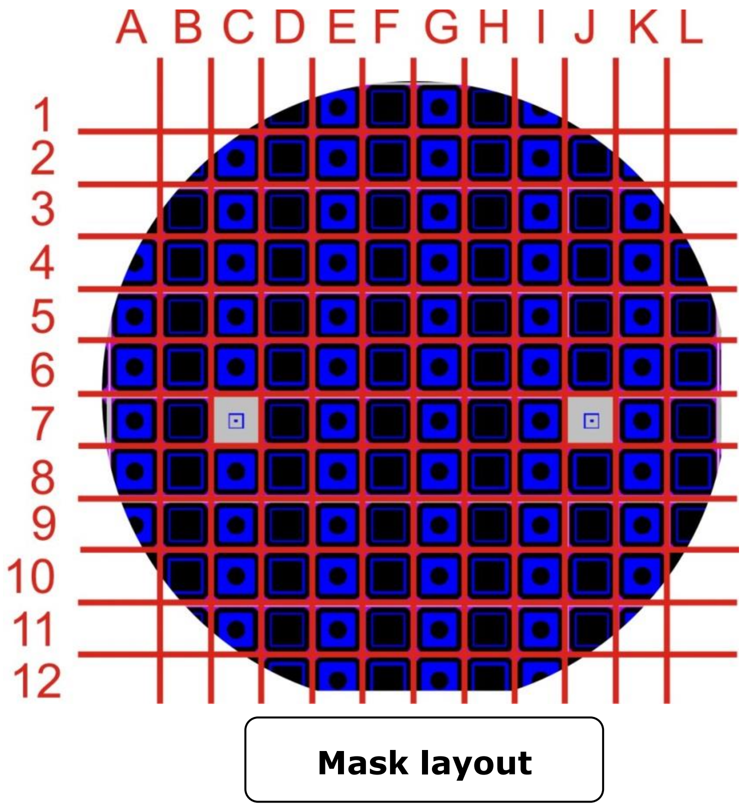
- Before irradiation:
  Improvement of signal
  → a factor 8 at 300V

- After irradiation: **no** significant **increase of the noise**

Fabrication Layout

- Devices with active area of 5mmx5mm
- Window in the cathode metallization for light source characterization





Fabrication Runs

- Various fabrication runs to improve the characteristics of the LGAD devices.
  - Latest run:
    - High resistivity p-type substrate; 300μm thick;
    - 3 couples of wafers with increasing p-layer doping
    - A PiN wafer for reference

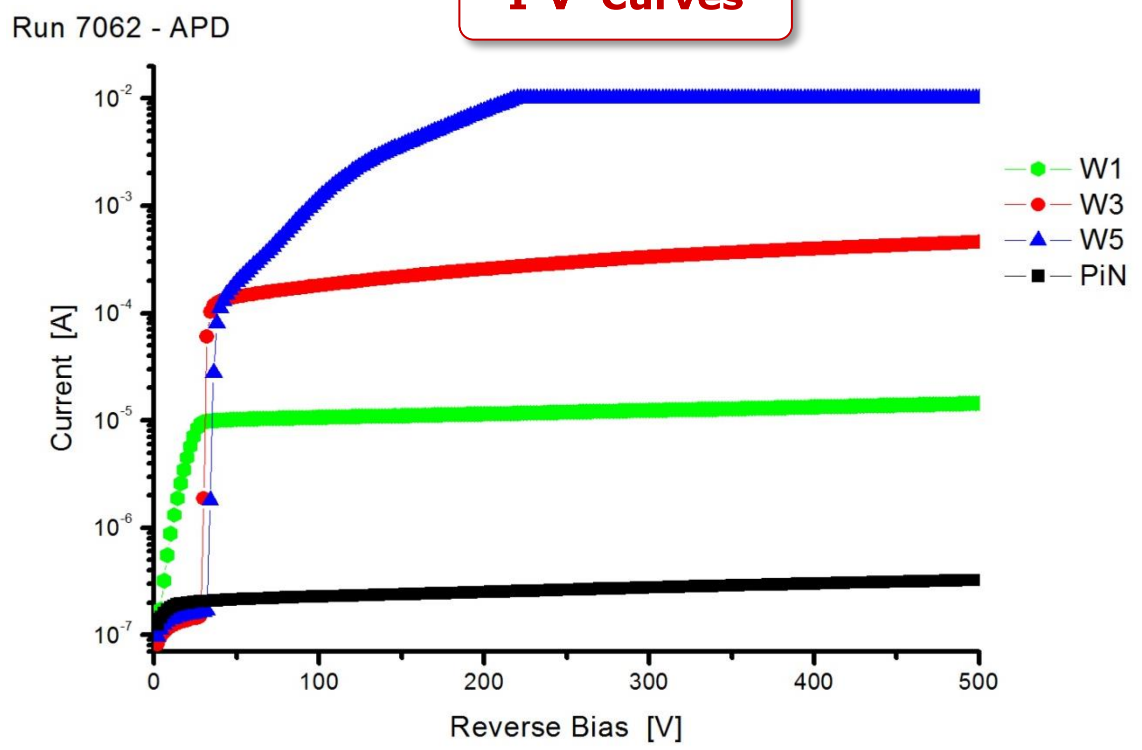
Wafer Number	P-layer Implant (E = 100 keV)	Substrate features	Expected Gain
1-2	1.6×10^{13} cm^{-2}	HRP 300 (FZ; ρ>10 KΩ·cm; <100>; T = 300±10 μm)	2 – 3
3-4	2.0×10^{13} cm^{-2}	HRP 300 (FZ; ρ>10 KΩ·cm; <100>; T = 300±10 μm)	8 – 10
5-6	2.2×10^{13} cm^{-2}	HRP 300 (FZ; ρ>10 KΩ·cm; <100>; T = 300±10 μm)	15
7	(---) PiN Wafer	HRP 300 (FZ; ρ>10 KΩ·cm; <100>; T = 300±10 μm)	No Gain

Electrical Characterization

- I-V curves → 3 different p-doping wafers and PiN wafer
  - Increasing current, but plateau reached;
  - High breakdown.

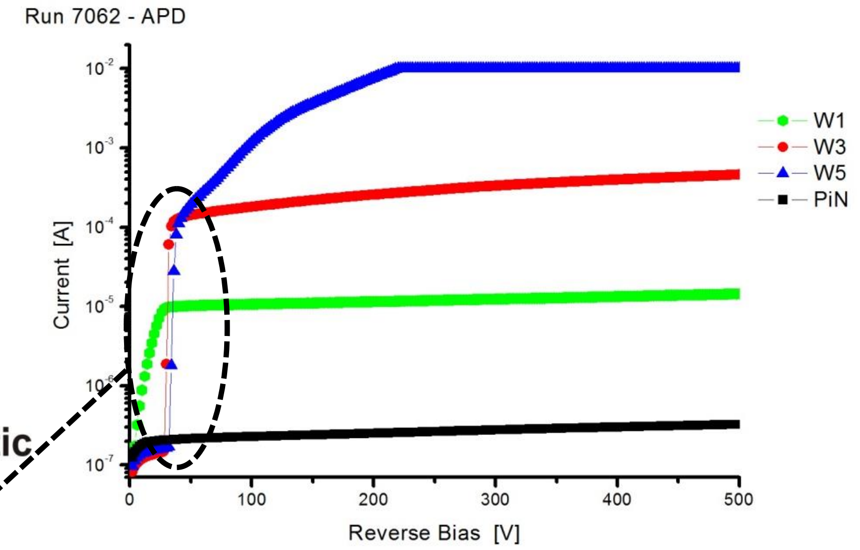
Wafer Number	P-layer Implant (E = 100 keV)
W1	1.6×10^{13} cm^{-2}
W3	2.0×10^{13} cm^{-2}
W5	2.2×10^{13} cm^{-2}
W7	(---) PiN Wafer

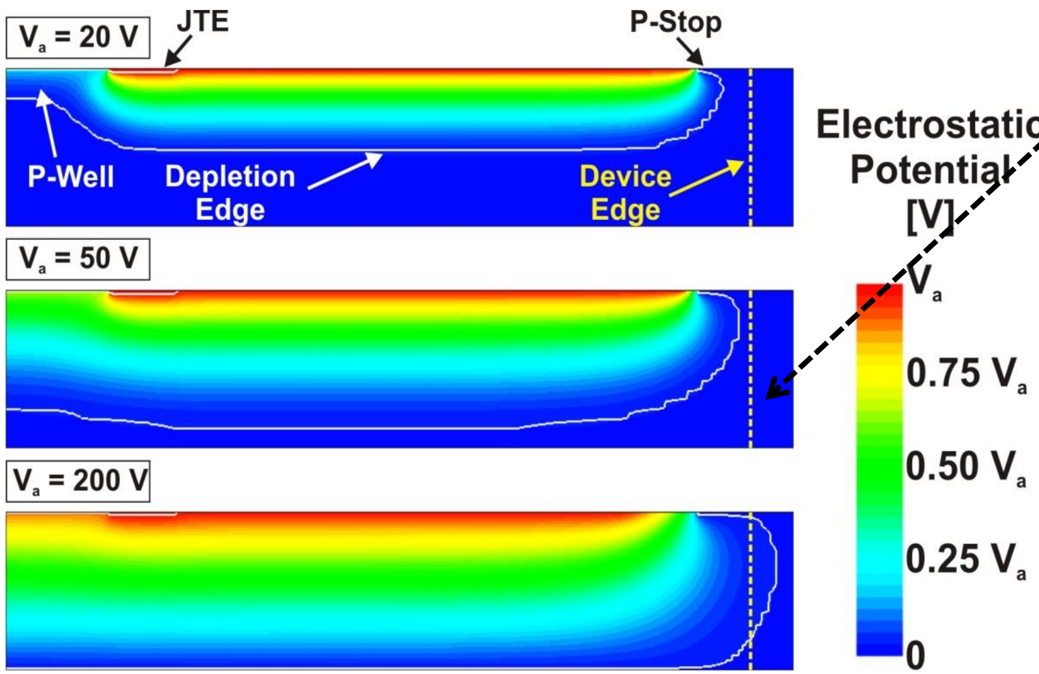
I-V Curves



Electrical Characterization

- I-V curves
  - Abrupt transition at ~40V÷50V





- At~50V the depletion zone reaches the device edge
  - huge surface current

Wafer 1 - Performance Statistics

- Wafer 1 → *1.6 × 10^{13} cm^{-2}*

MAPA DE CORRIENTE A: 100 V

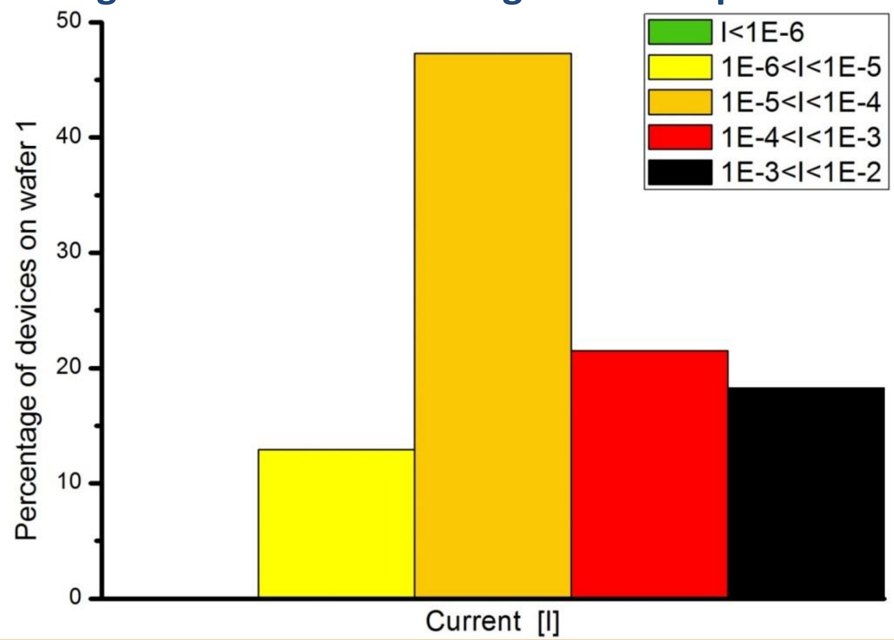
	A	B	C	D	E	F	G	H	I	J	K	L
1						85	199					
2				0,87	305,59	28,82	18,74	772,52	4,20			
3			1,26	1,25	2,24	10,99	26,81	141,93	65,74	11,02		
4		0,88	0,83	23,97	15,22	22,09	17,63	50,36	6,47	12,78	37,86	
5	35	22,19	22,14	89,12	24,23	39,44	15,85	60,24	12,56	8,53	4,81	
6	6	30,63	20,32	70,30	23,60	26,63	21,51	84,06	20,94	4,81	116,86	1857
7	9	31,16		63,27	18,36	37,09	29,98	111,62	23,06		2,43	1186
8		5,14	9,25	24,46	15,12	27,36	18,75	70,06	14,78	4,61	1,92	
9		110,49	4,85	4,65	5,89	30,18	1,01	44,11	11,37	1,51	123,72	
10			#####	3,63	4,81	6,35	4,10	45,28	6,86	3,00		
11				#####	#####	498,40	#####	20,39	133,49			
12												

Unidades 1,00E-06 **A**

0	1	2	5	10	20	50	100	200	500	1000

- Current levels spreading throughout the wafer (from < *10 μA* to > *1 mA*).
- Most detectors → [*10÷100 μA*]

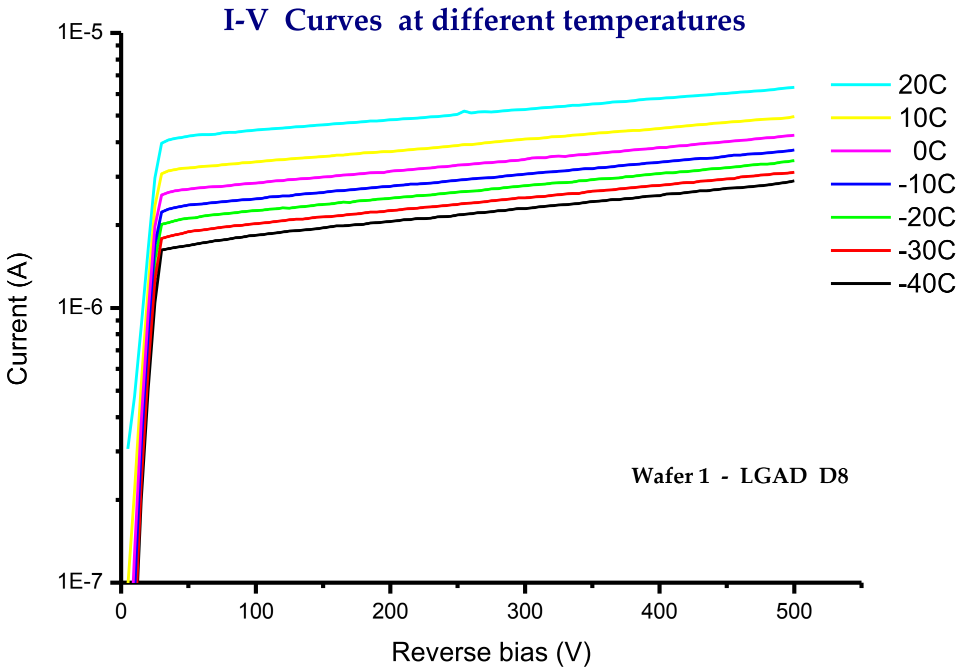
Percentage of detectors on wafer 1 distinguished for current ranges at 500V polarization

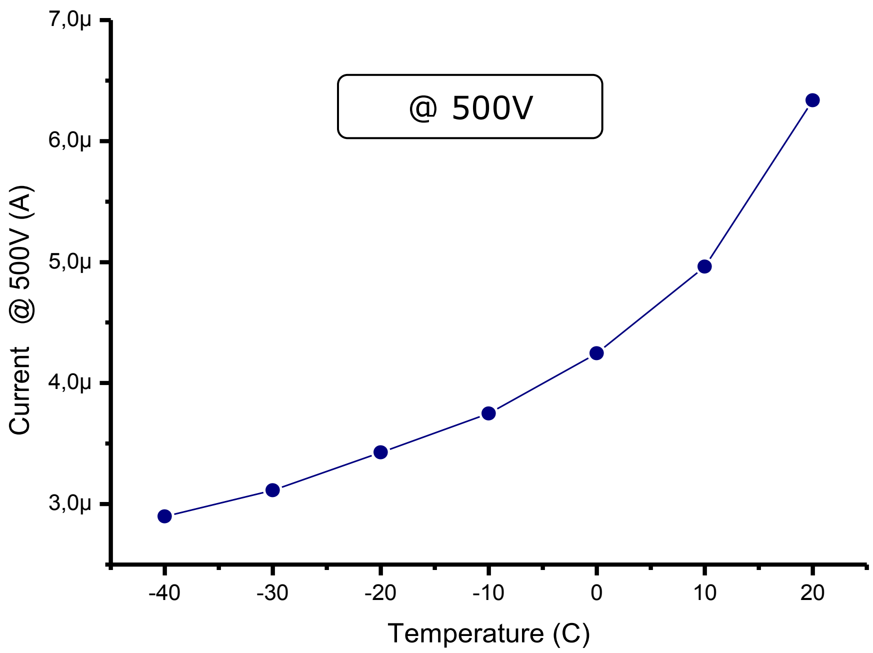


Wafer 1 - Electrical Characterization

- I-V curves → **at different temperatures** (from 20ºC down to -40ºC)

➡ Little reduction of the current with the temperature

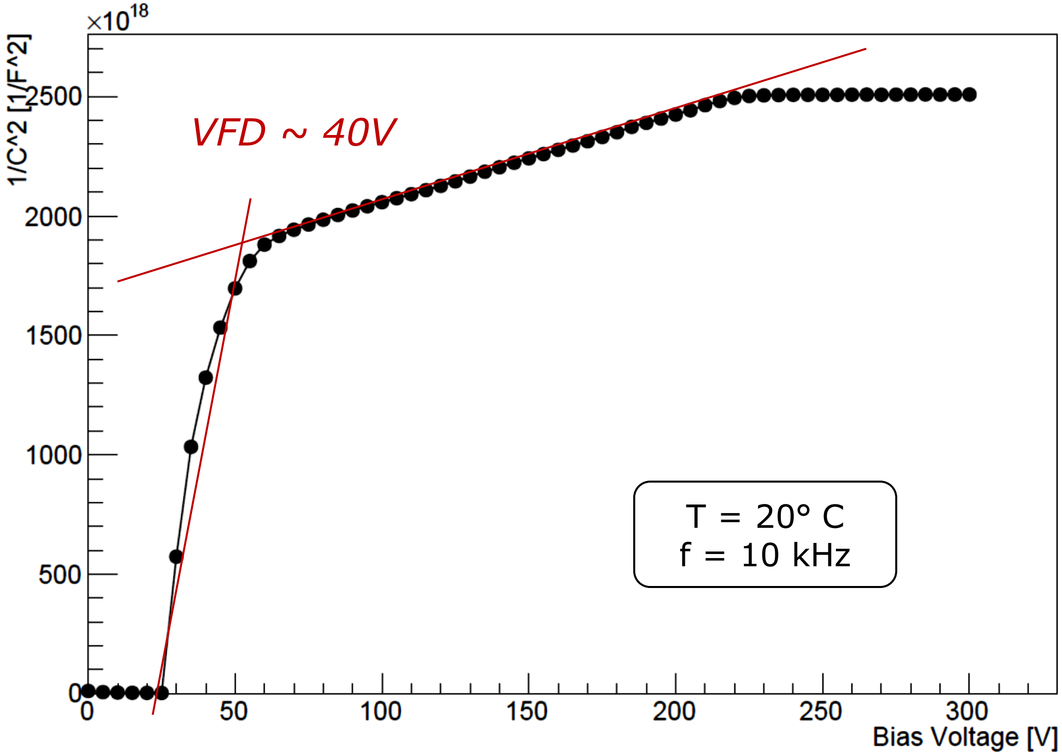




➡ We suppose there is a big contribution of the **surface current**

Wafer 1 - Electrical Characterization

$1/C^2$-V Curve → A detector from wafer 1

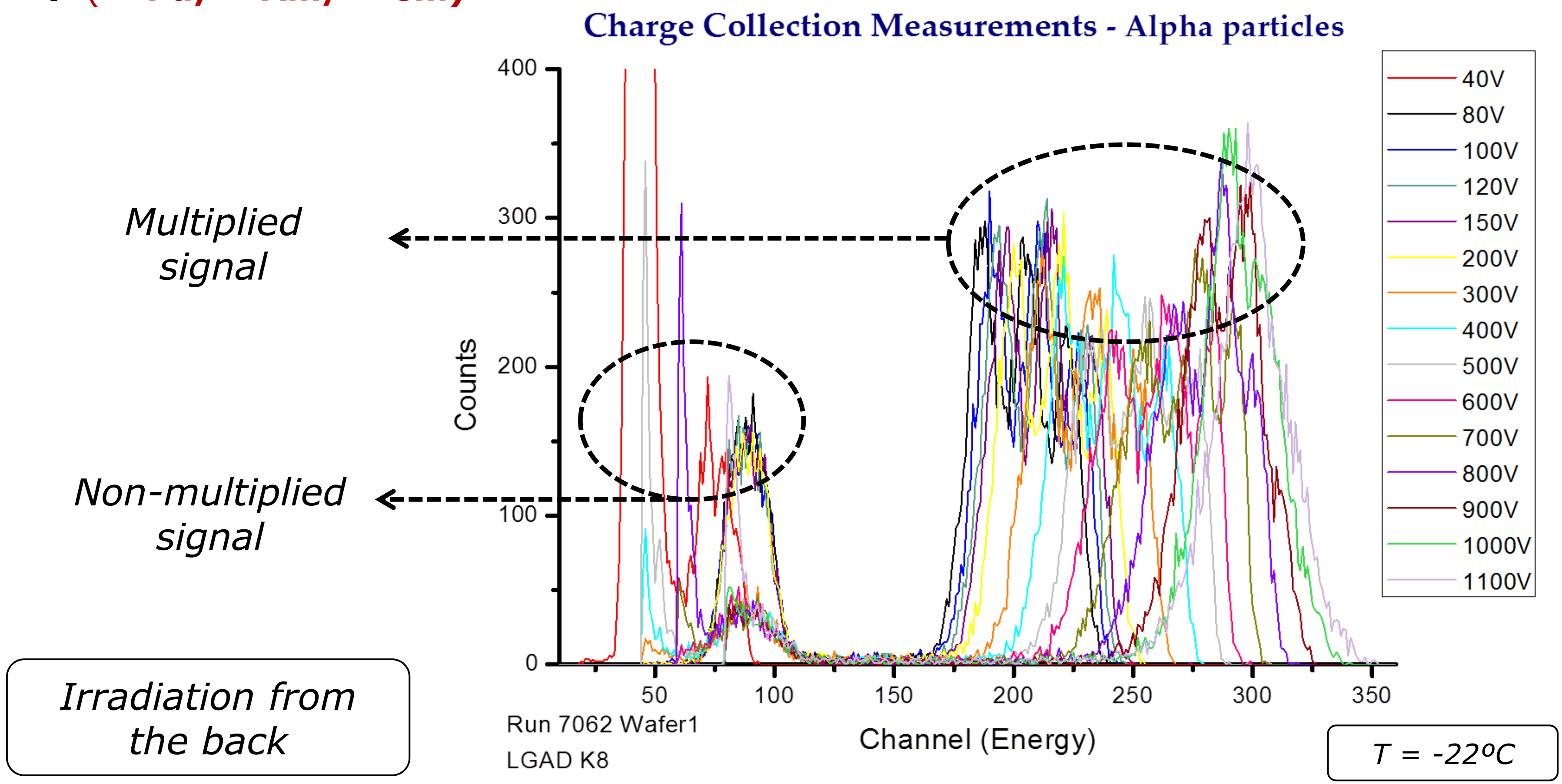


- C ~ 20÷24 pF
- V_{FD} ~ 40V

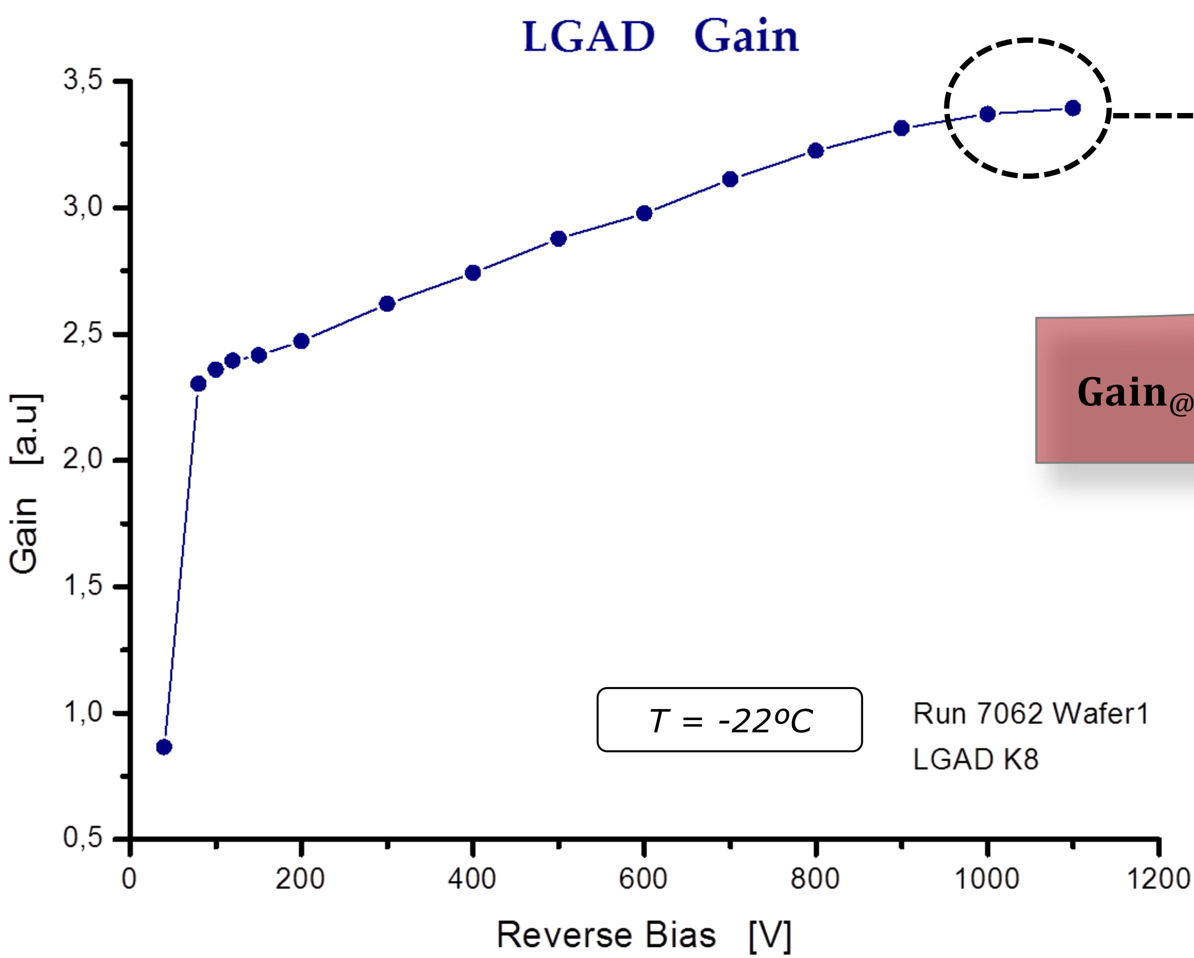
(Method of intercept)

Wafer 1 - Charge Collection

- Multiplication factor measured with **tri-alpha radiation source**
  → **($^{239}Pu/^{241}Am/^{244}Cm$)**



Wafer 1 - Gain



Gain ~ *2,3 ÷ 3,5*

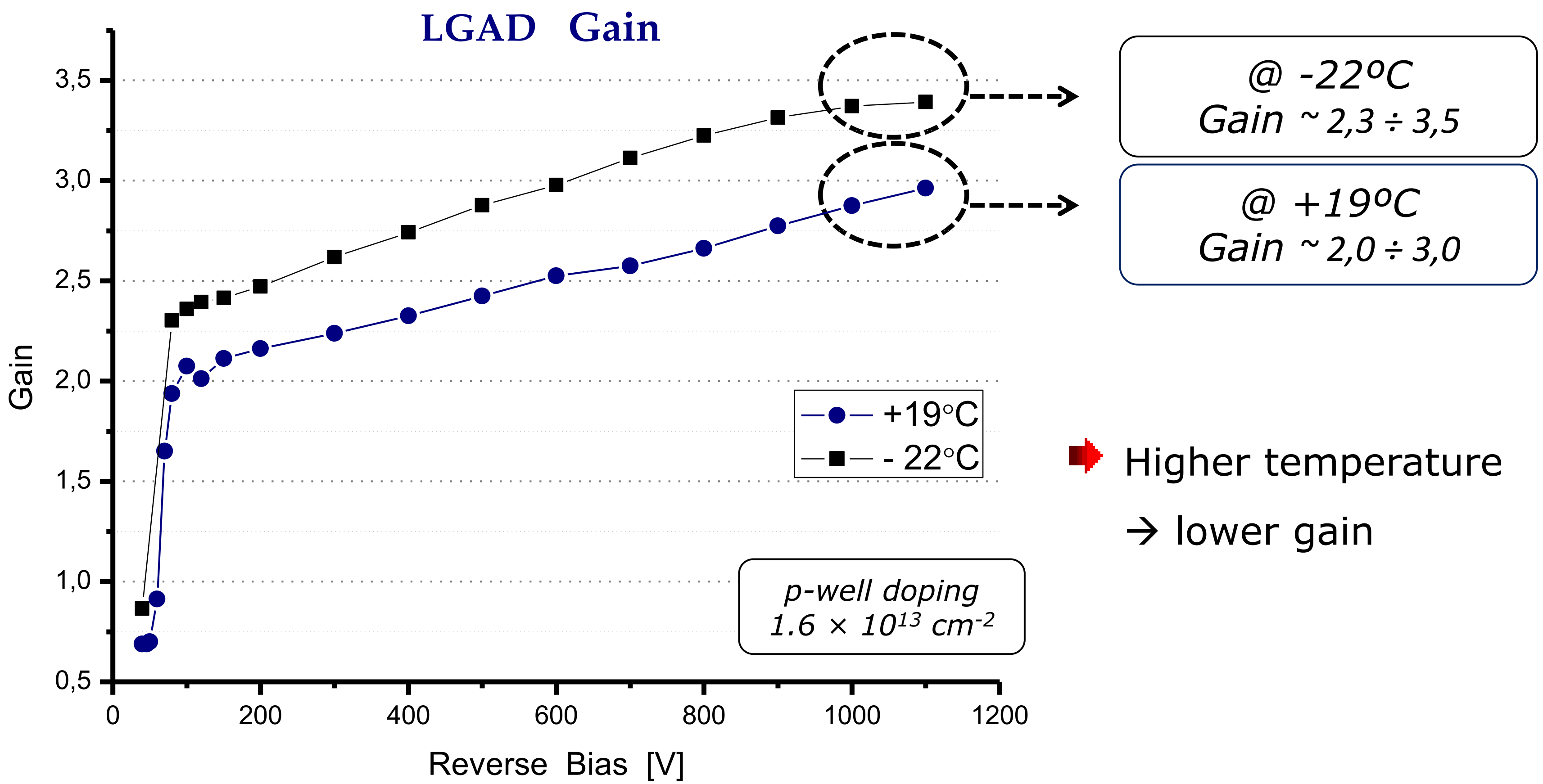
$$\text{Gain}_{@V} = \frac{\text{Central Peak Channel}_{@V}}{\text{Central Peak Channel}_{\text{No mult}}}$$

Wafer Num	P-layer Implant (E=100 keV)	Expected Gain
1-2	1.6×10^{13} cm^{-2}	2 – 3

As expected

Wafer 1 - Gain

- Gain measured for LGAD detector **at different temperatures**:



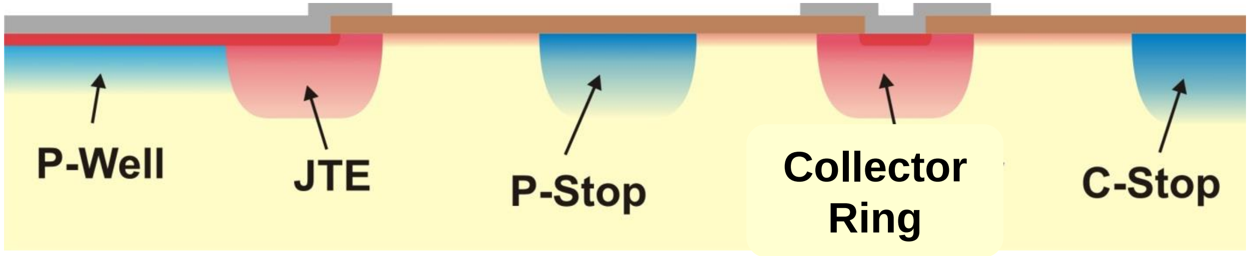
Higher temperature
→ lower gain

Conclusions

- We have presented:
  - the structure of the **LGAD** (**Low Gain Avalanche Diode**):
    - multiplication layer;
    - design of the edge terminations;
  - the **electrical characterization** of LGAD detectors with different p-doping of the multiplication layer and at different temperatures;
  - the results of the **charge collection measurements** performed on the LGAD detector with lower p-doping ($1.6 \times 10^{13}\ cm^{-2}$) of the multiplication layer;
  - the **gain** (at different temperatures) of LGAD detectors with lower p-doping.

Future Work

- Further **characterization with MIPs** of LGAD with low doped multiplication layer.
- Electrical and charge collection measurements of detectors with **higher p-doping** of the multiplication layer. → *Ongoing*
- Study of detectors **after irradiation**. → We have already sent LGAD diodes to be irradiated with protons (in Los Alamos).
- Application of the multiplication mechanism to **segmented detectors** (microstrips and pixels). → *See following talk by M.Baselga*
- **New fabrication run**, with a new geometry that includes **isolation structures** (p-stop, collector ring, channel stop).



- Realization of **low gain thin** (~200µm) detectors.

Applications

- Trackers for high energy physics experiments.
- Direct detection of soft x-rays (<2KeV) → Syncrotron radiation experiments
- More…

Thank you!