Simulation and Technology development of Low Gain Avalanche Detectors (LGAD) for High Energy Physics applications

S. Hidalgo, P. Fernández-Martínez, G. Pellegrini, D. Quirion and M. Baselga

Centro Nacional de Microelectrónica (IMB-CNM-CSIC)
Barcelona, Spain

Silicon Detectors with Internal Gain and Proportional Response

Tracking Detectors

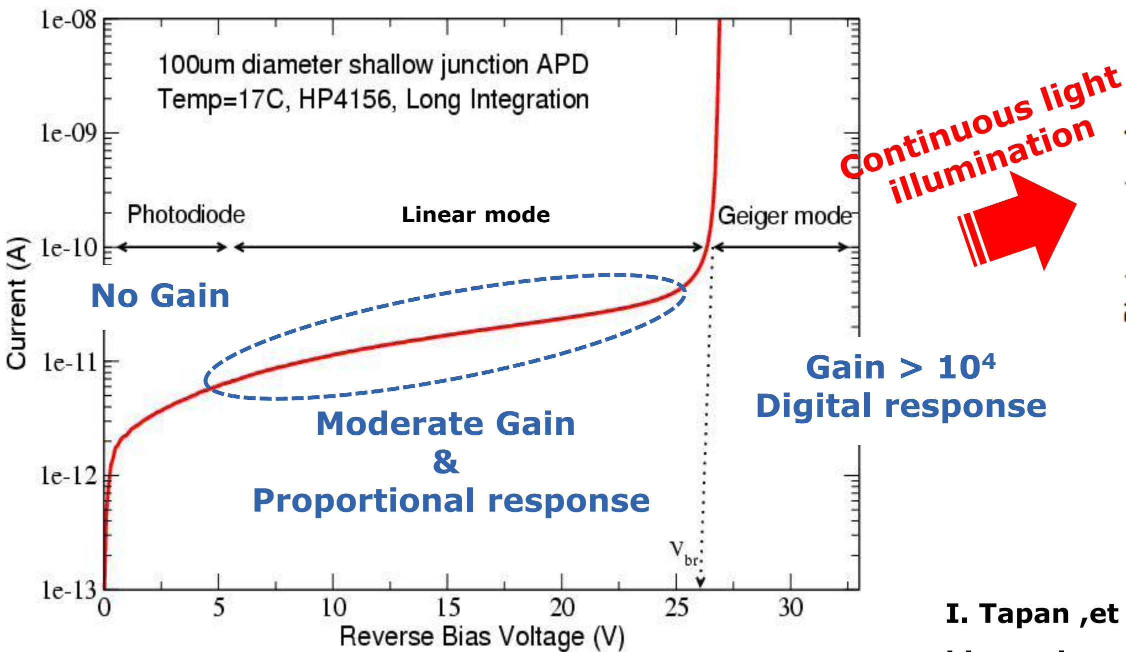
- **PiN based Diodes**
  - → **Proportional Response**
  - → **Good efficiency**
  - → **Good spectral range**
  - → **Segmentation is technologically available (strip and pixel detectors).**
  - → **After Irradiation:**
  - ✗ **Worse signal to noise ratio (lower quality signal + noise increment)**
  - ✗ **Increment of the power consumption**
  - ✗ **Radiation Damage damage (specially relevant on n-on-p structures)**

Internal Gain →

- **Low Gain Avalanche Detectors (LGAD)**
  - → **Proportional Response (linear mode operation)**
  - → **Good efficiency**
  - → **Good spectral range**
  - ✓ **Better Sensibility**
  - ✓ **Thin detector integration with the same signal and higher collection efficiency**
  - ✓ **Better signal/noise ratio**
  - → **After Irradiation**
  - ✓ **Similar pre & post irradiation signal (higher quality signal + lower noise increment)**
  - ✓ **Lower increment of the power consumption**
  - ✗ **Radiation Damage (specially relevant on n-on-p structures)**

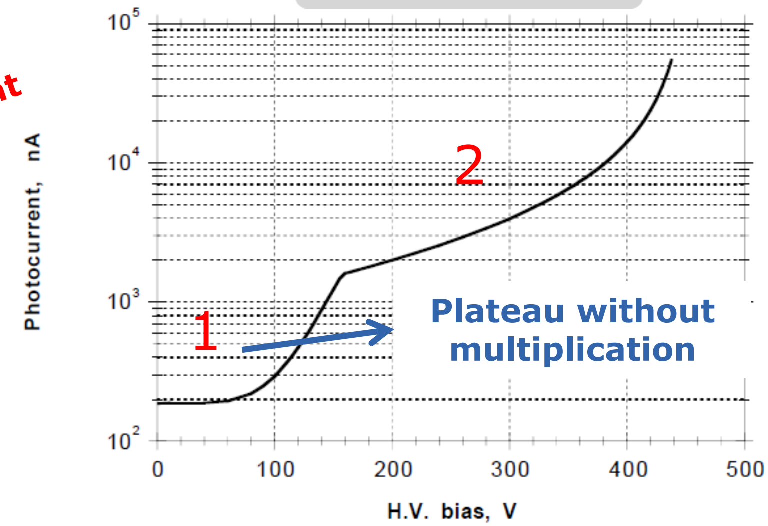
Linear Mode Operation. Gain Definition

- **Diodes with multiplication can operate in Linear or Geiger mode**
  - **Linear mode: Moderate gain & Proportional response**
  - **Geiger mode: Very high gain & Digital response**



[1] A.G. Stewart et al. in Proc. of SPIE, Vol. 6119, 2006

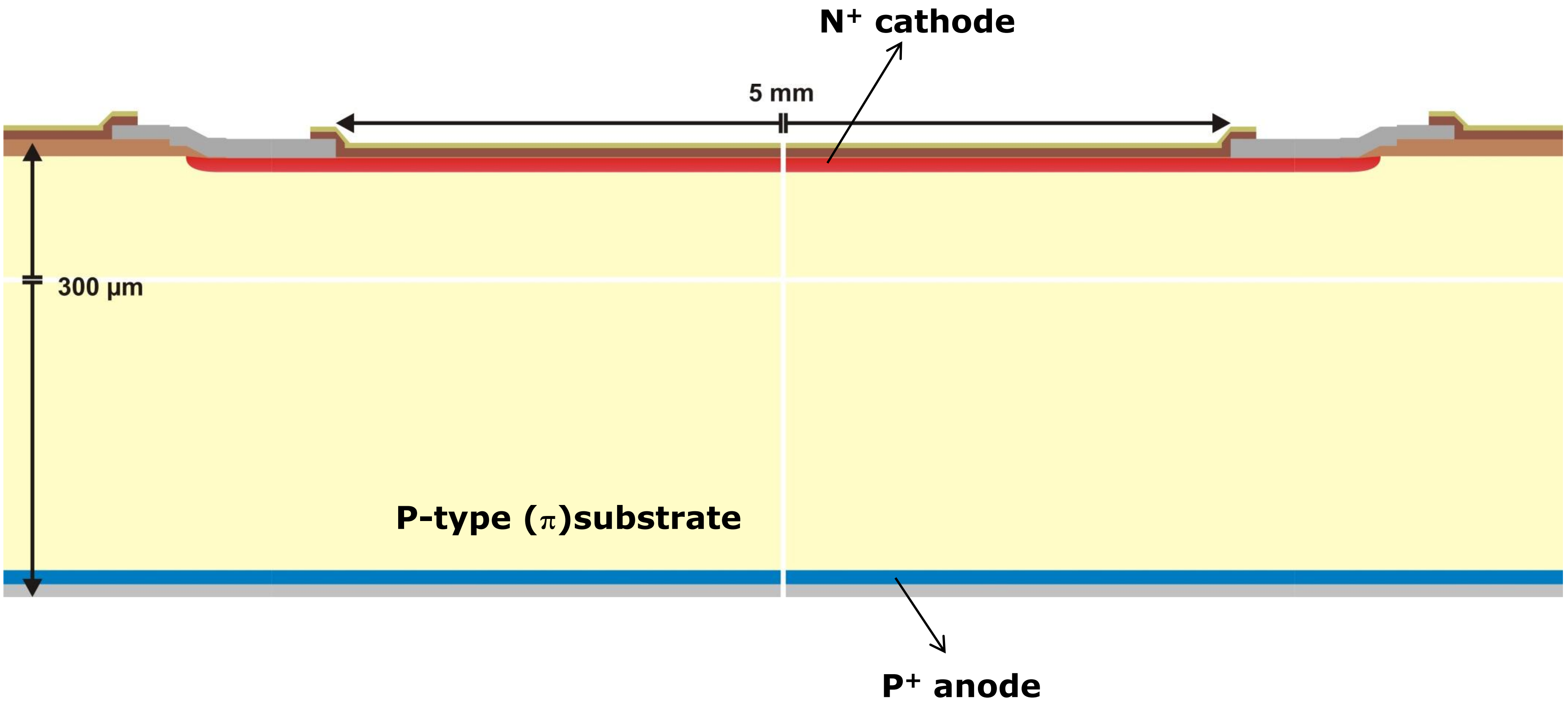
Gain Definition



I. Tapan ,et al. NIMA 388 (1997) 79-90: "The plateau for low bias voltage may be taken to correspond to unit gain [...] and the gain for higher bias measured simply as the ratio of the pulse size to that plateau"

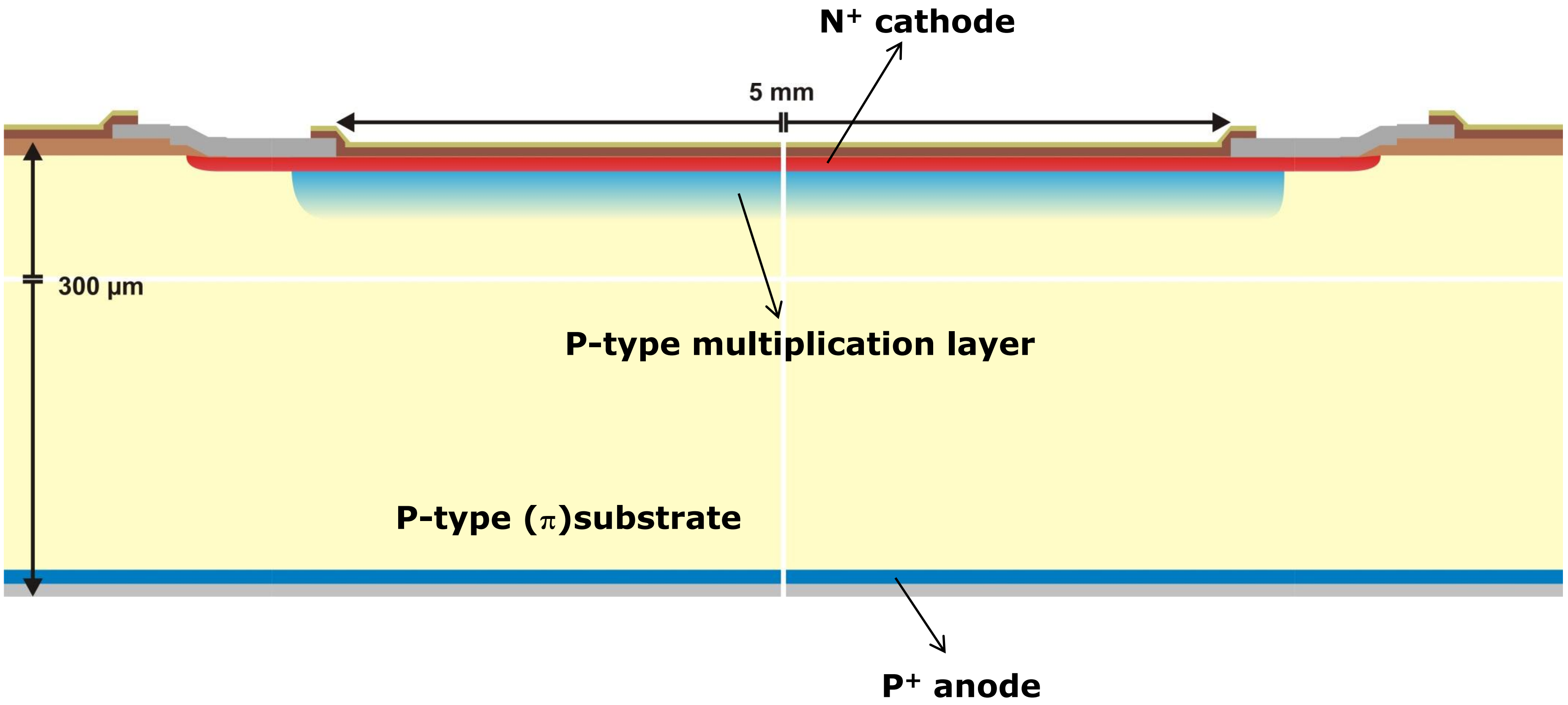
Pad Diodes with internal Gain

- **M. Bruzzi, IEEE TNS-48(4) 2001: "The general approach followed by the HEP community in radiation–damage studies has been to investigate the radiation effects in silicon detectors using the simplified geometry of a single pad detector."**



Pad Diodes with internal Gain

- M. Bruzzi, IEEE TNS-48(4) 2001: "The general approach followed by the HEP community in radiation–damage studies has been to investigate the radiation effects in silicon detectors using the simplified geometry of a single pad detector."

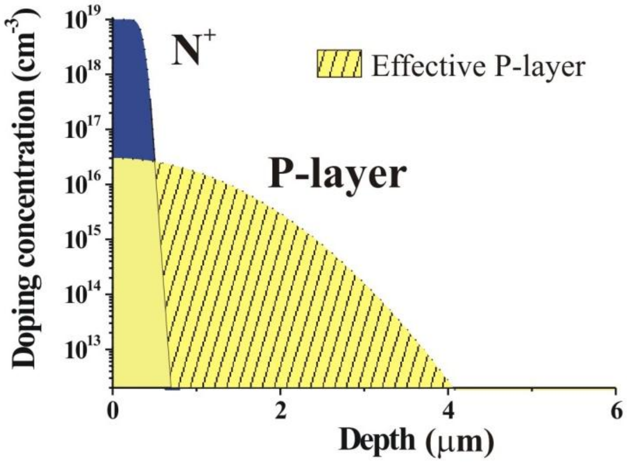


Design of the Multiplication Region

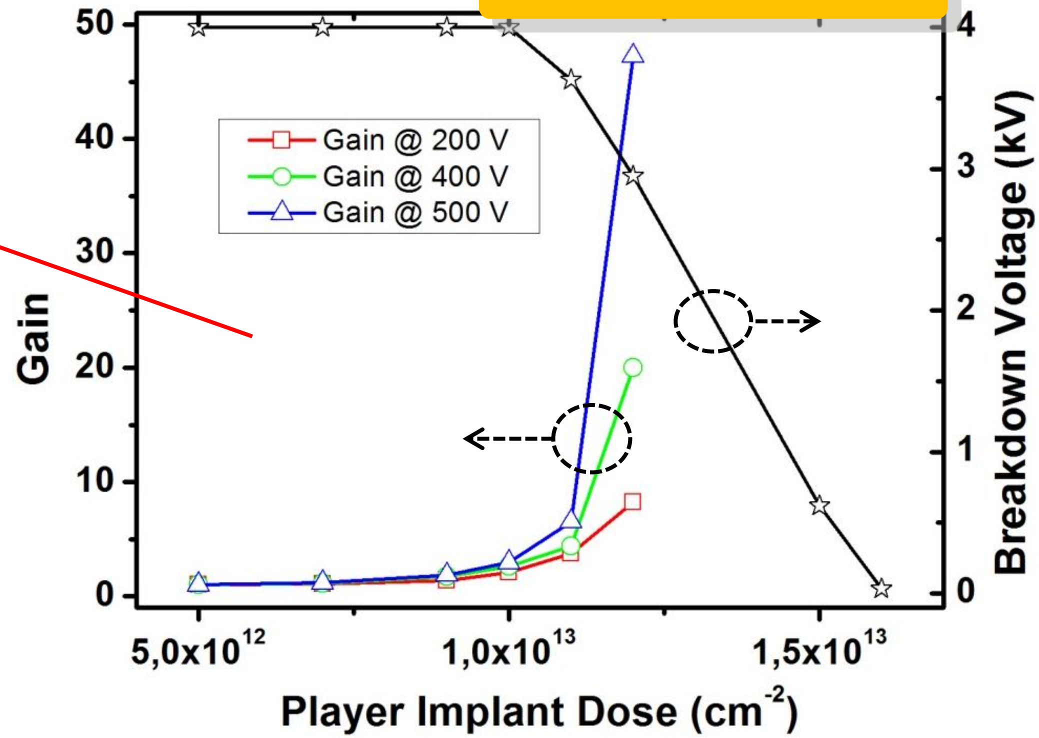
Gain/V_{BD} trade-off

- ✓ If implant dose increases:
  - Gain increases
  - V_{BD} decreases

- ❑ **Technological adjust of the multiplication region p-layer becomes critical.**



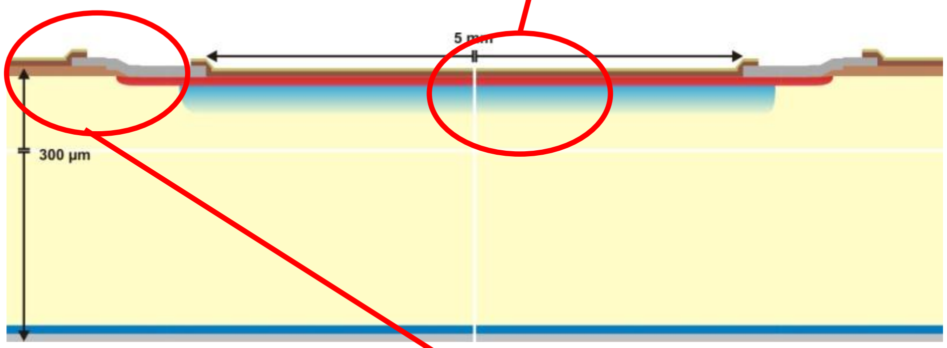
1D Simulation @ Pad Centre



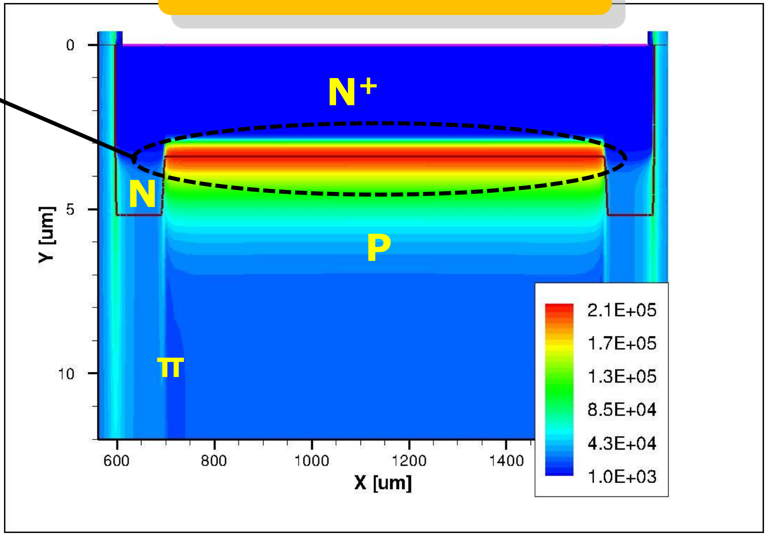
Small modifications in the Boron implant dose (~ 2 × 10^{12} cm^{-2}) induce great changes in Gain and V_{BD}

Design of the Edge Termination

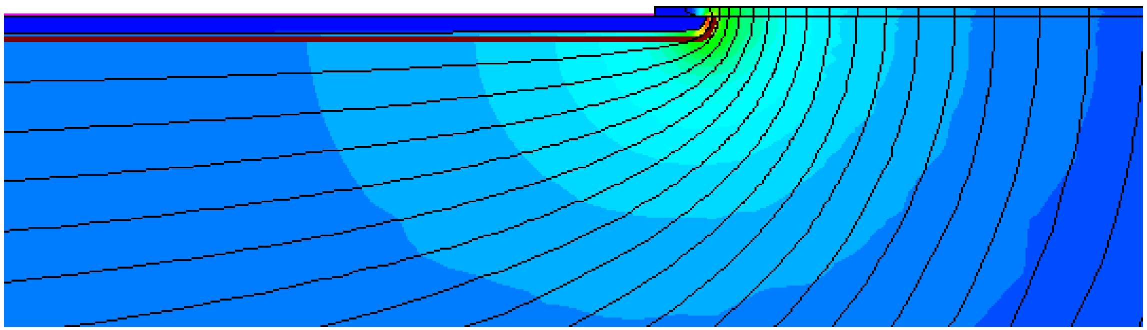
Planar and uniform electric field distribution, high enough to activate charge multiplication

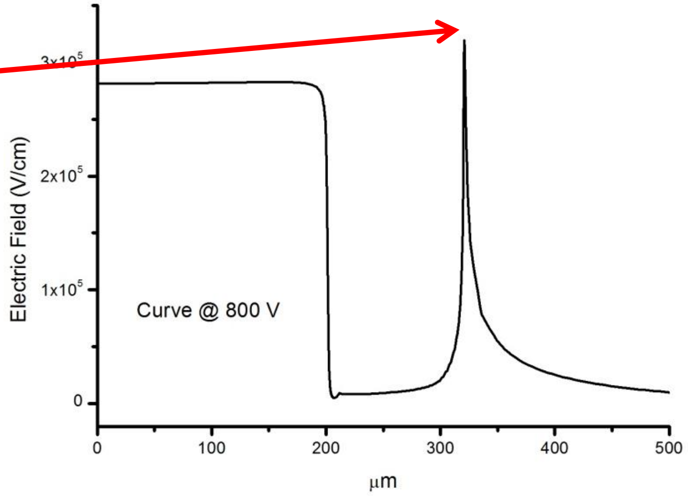


Electric Field @ 400 V



$$V_{BD}|_{Central} \ll V_{BD}|_{Termination}$$





Design of the Edge Termination

- **Junction Termination Extension (JTE). Peripheral low doping N-well to increase the voltage capability of this area, reducing the Electric Field in the periphery, allowing the maximum Electric Field is reached in the multiplication area (N^+/P junction).**

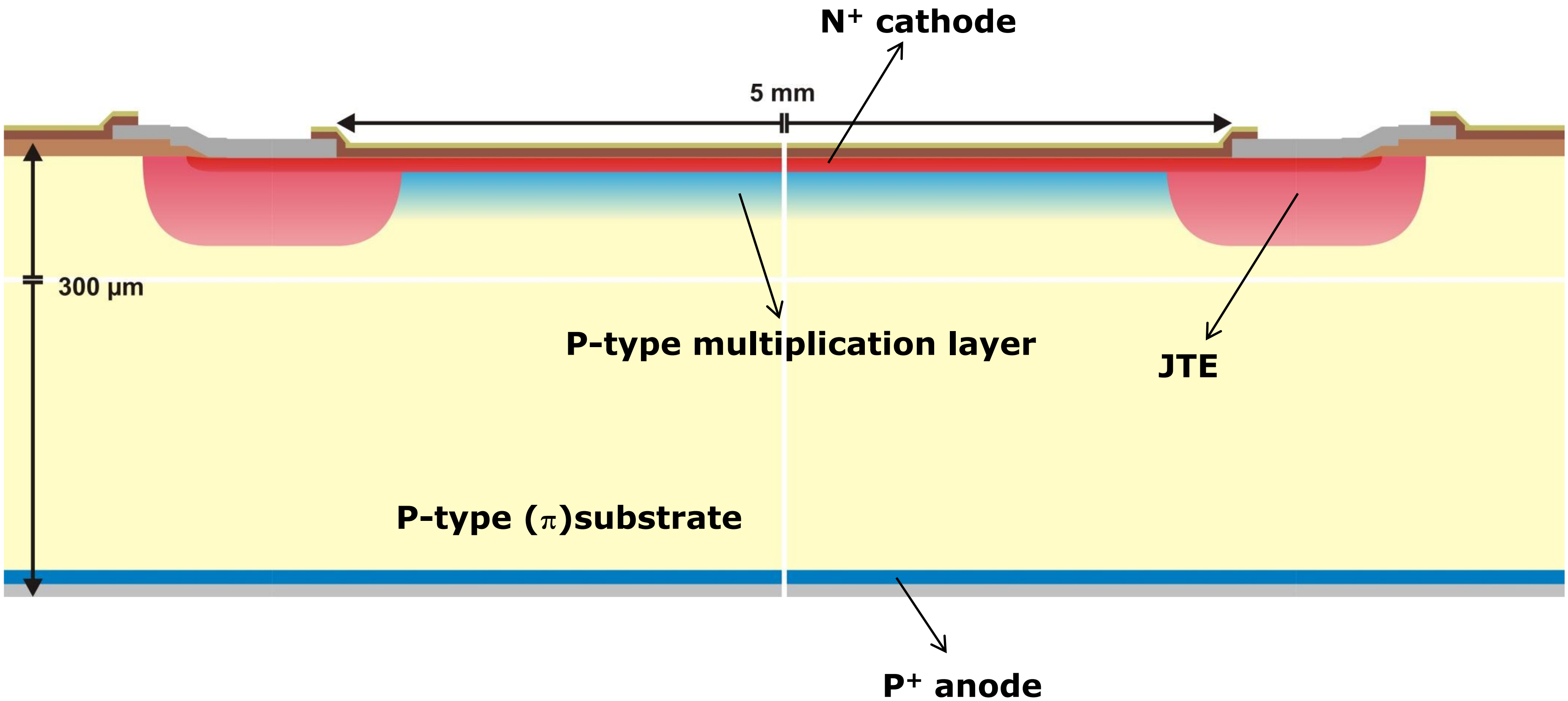


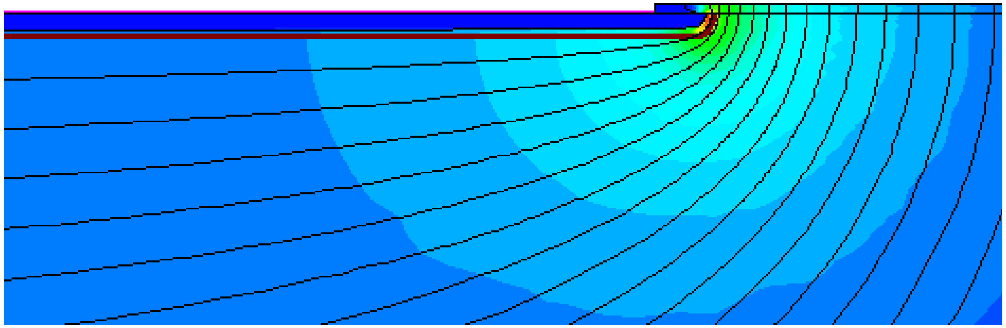
TABLE 3.1. High-Voltage Device Termination Techniques

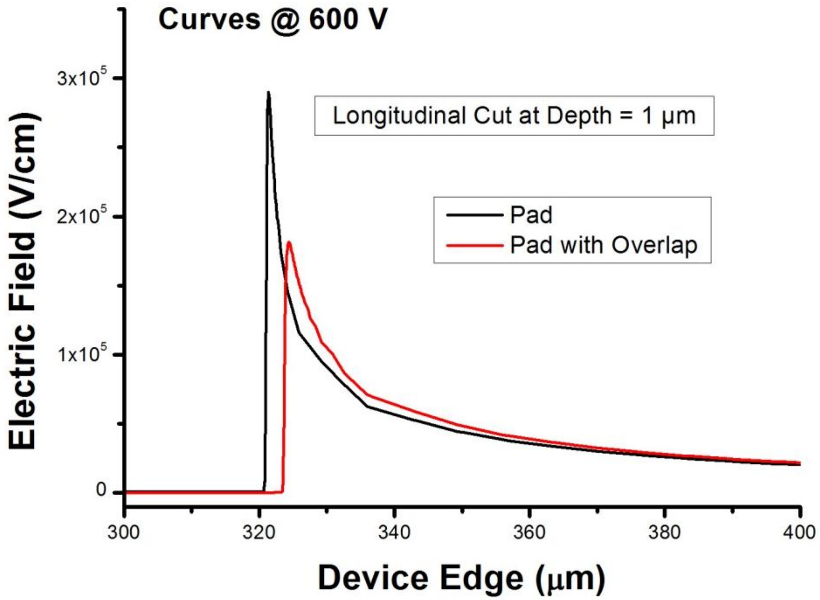
Technique	Typical Breakdown Voltage (%)[a]	Peak Surface Electric Field (%)[b]	Typical Device Size	Device Types	Remarks
Planar junction	50	80	Small (<100 mils)	BJT, MOSFET	Seldom used for high-voltage devices
Planar junction with field ring	80	80	Medium (≤1 in.)	BJT, MOSFET, SCR	Well suited for a large number of devices per wafer
Planar junction with field plate	60	80	Medium (≤1 in.)	BJT, MOSFET	Usually used in conjunction with field ring
Positive bevel	100	50	Large (>1 in.)	Rectifier, SCR	Well suited for single device per wafer
Negative bevel	90	60	Large (>1 in.)	SCR	Well suited for single device per wafer
Double positive bevel	100	80	Large (>1 in.)	SCR	Well suited for single device per wafer only
Positive etch contour	90	60	All	BJT, MOSFET, SCR	Well suited for a large number of devices per wafer
Negative etch contour	80	60	All	BJT, MOSFET, SCR	Well suited for a large number of devices per wafer
Junction termination extension	95	80	All	BJT, MOSFET, SCR	Well suited for both single devices and a large number of devices per wafer; high leakage current; passivation sensitive

[a] As percentage of parallel-plane case.
[b] As percentage of bulk.

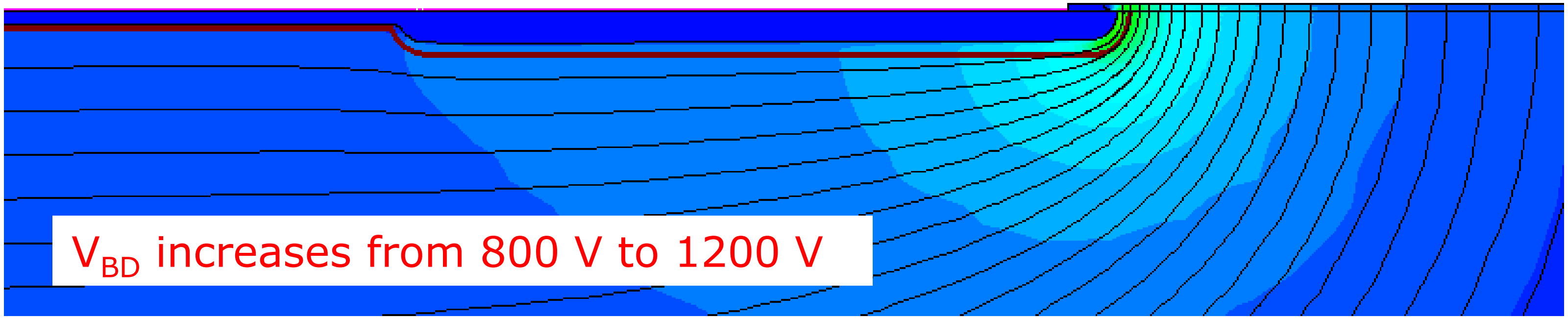
Design of the Edge Termination

PiN Diode



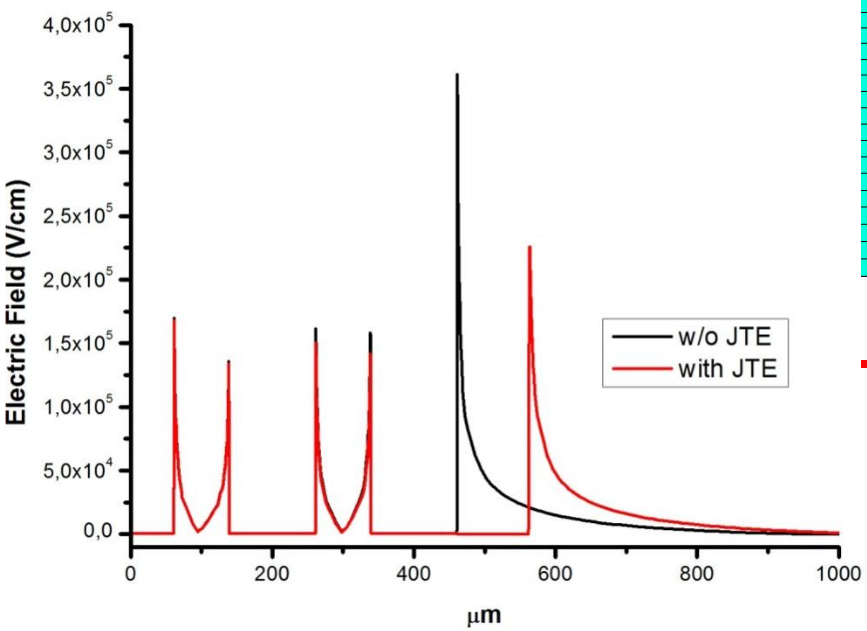


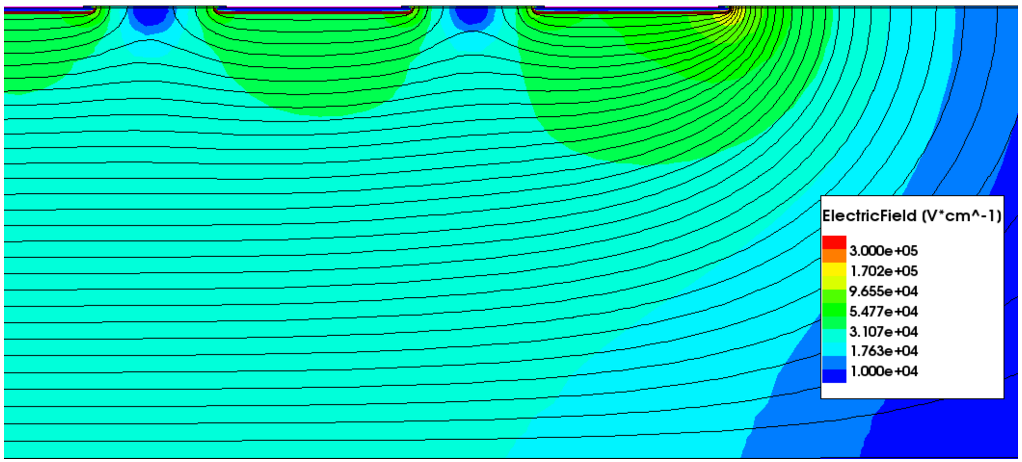
PiN Diode with JTE



V_{BD} increases from 800 V to 1200 V

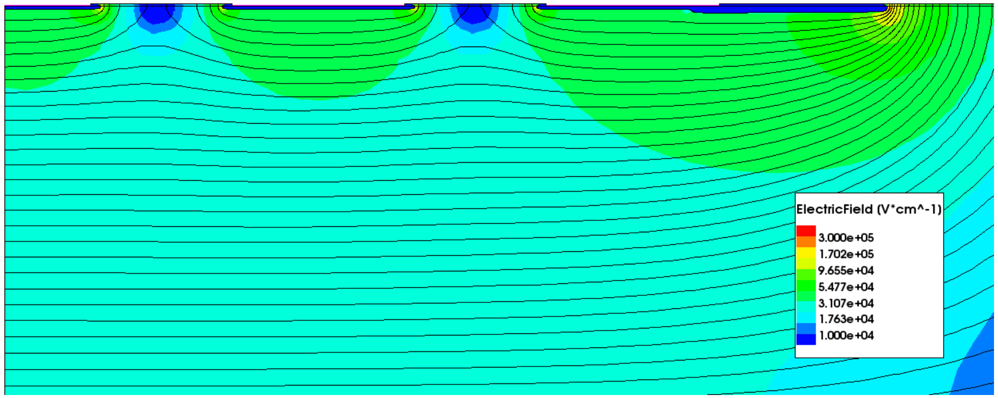
Strip Detectors Edge Termination





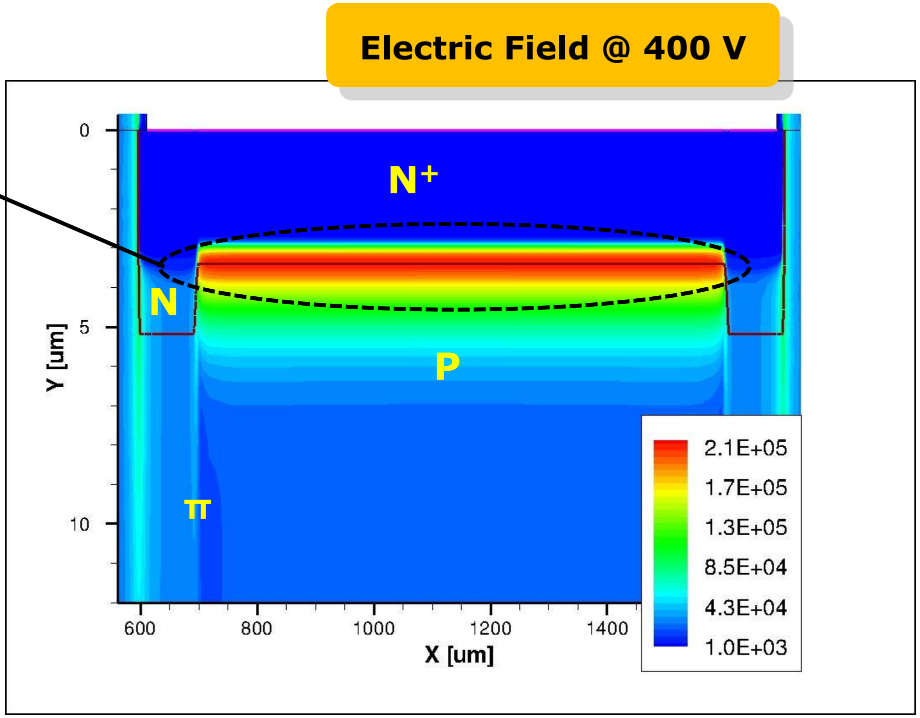
Micro Strip Diode

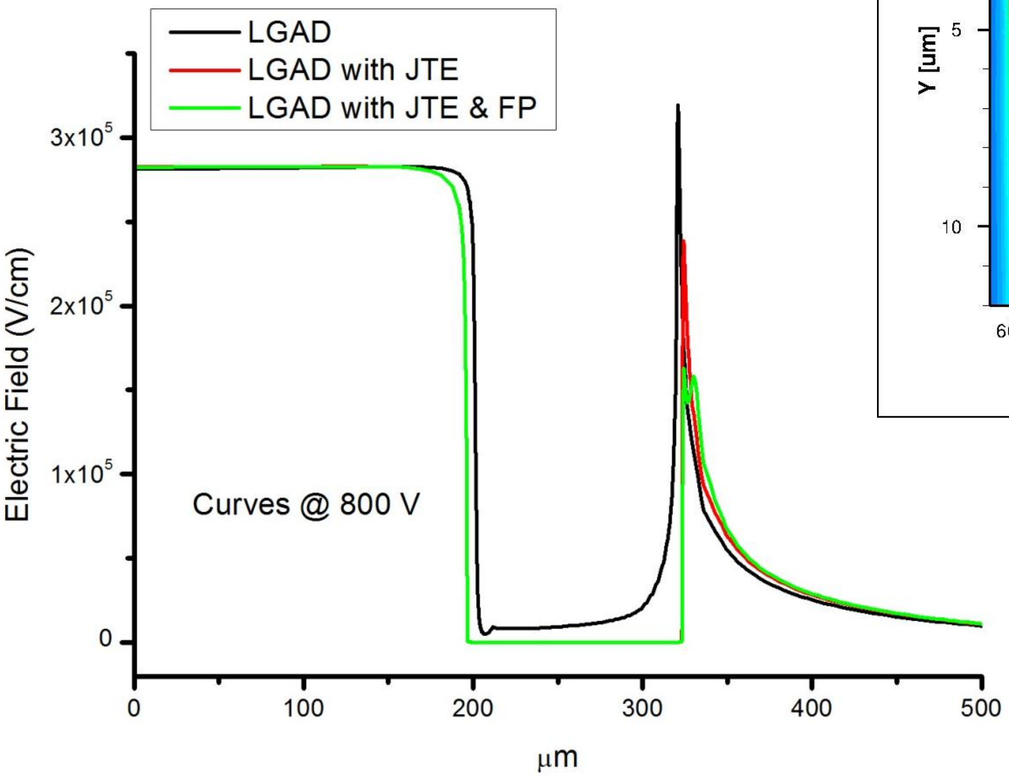
Micro Strip Diode with JTE



Design of the Edge Termination

Planar and uniform electric field distribution, high enough to activate charge multiplication

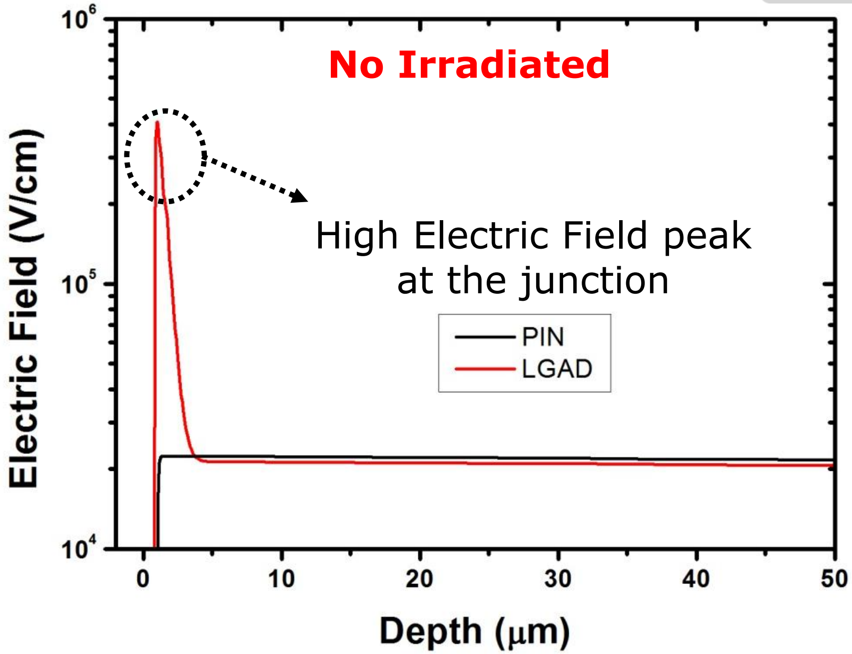


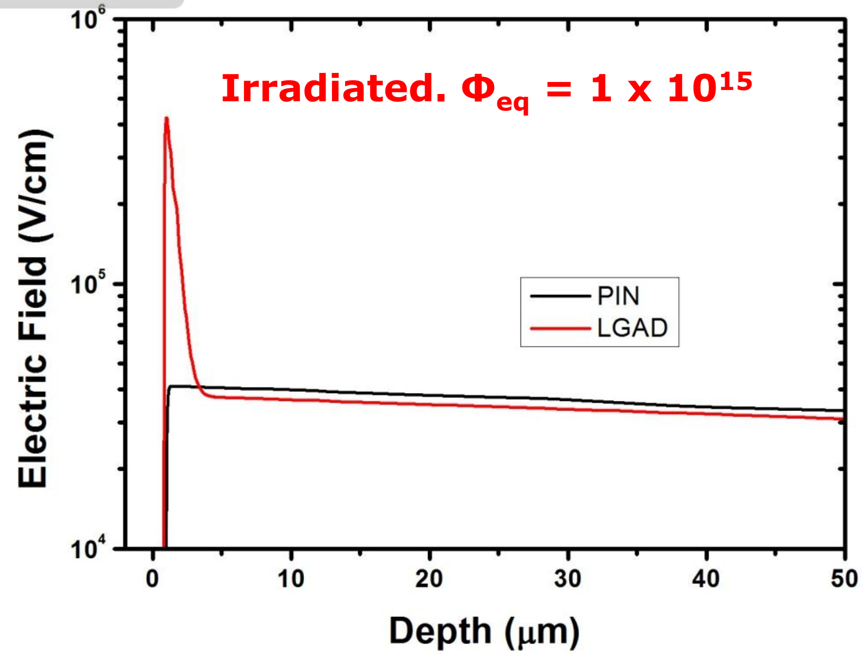


$$V_{BD}|_{Central} \ll V_{BD}|_{Termination}$$

Simulation of the Irradiated Devices

Curves @ 600 V





- **PiN**: electric field strength at the junction increases after irradiation
- **LGAD**: electric field strength at the junction is held after irradiation

▪ **Irradiation Trap Model (Perugia Model):**

Acceptor;	$E = E_c + 0.46$ eV;	$\eta=0.9$;	$\sigma_e = 5 \times 10^{-15}$;	$\sigma_h = 5 \times 10^{-14}$
Acceptor;	$E = E_c + 0.42$ eV;	$\eta=1.613$;	$\sigma_e = 2 \times 10^{-15}$;	$\sigma_h = 2 \times 10^{-14}$
Acceptor;	$E = E_c + 0.10$ eV;	$\eta=100$;	$\sigma_e = 2 \times 10^{-15}$;	$\sigma_h = 2.5 \times 10^{-15}$
Donor;	$E = E_v - 0.36$ eV;	$\eta=0.9$;	$\sigma_e = 2.5 \times 10^{-14}$;	$\sigma_h = 2.5 \times 10^{-15}$

▪ **Impact Ionization Model:**
Universty of Bolonia

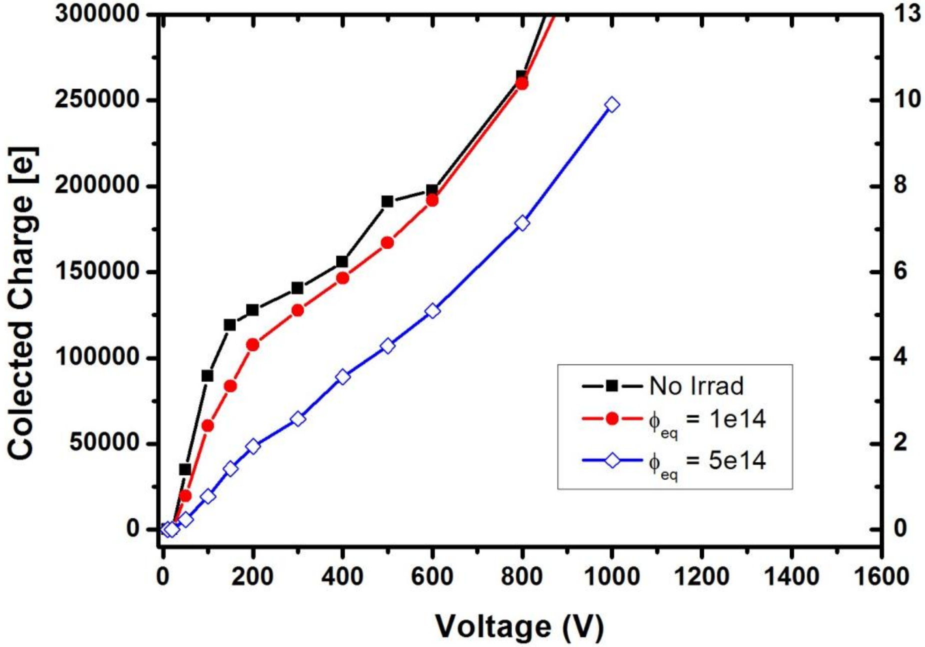
$$Conc = \eta \cdot \phi$$

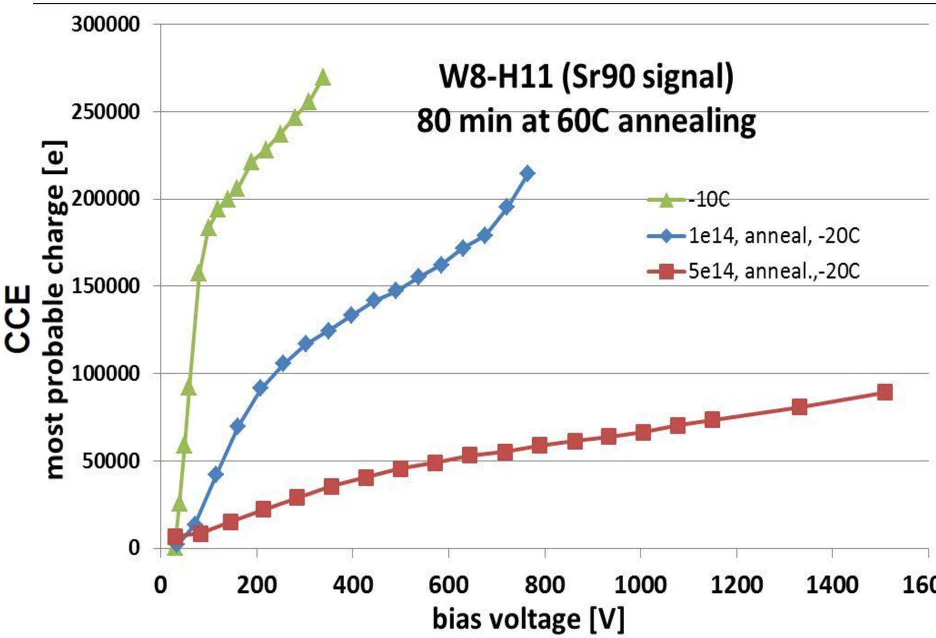
Simulation of the Irradiated Devices

Numerical Simulations

LGAD Wafer 8

Experimental Measurements





CCE @ 400 V

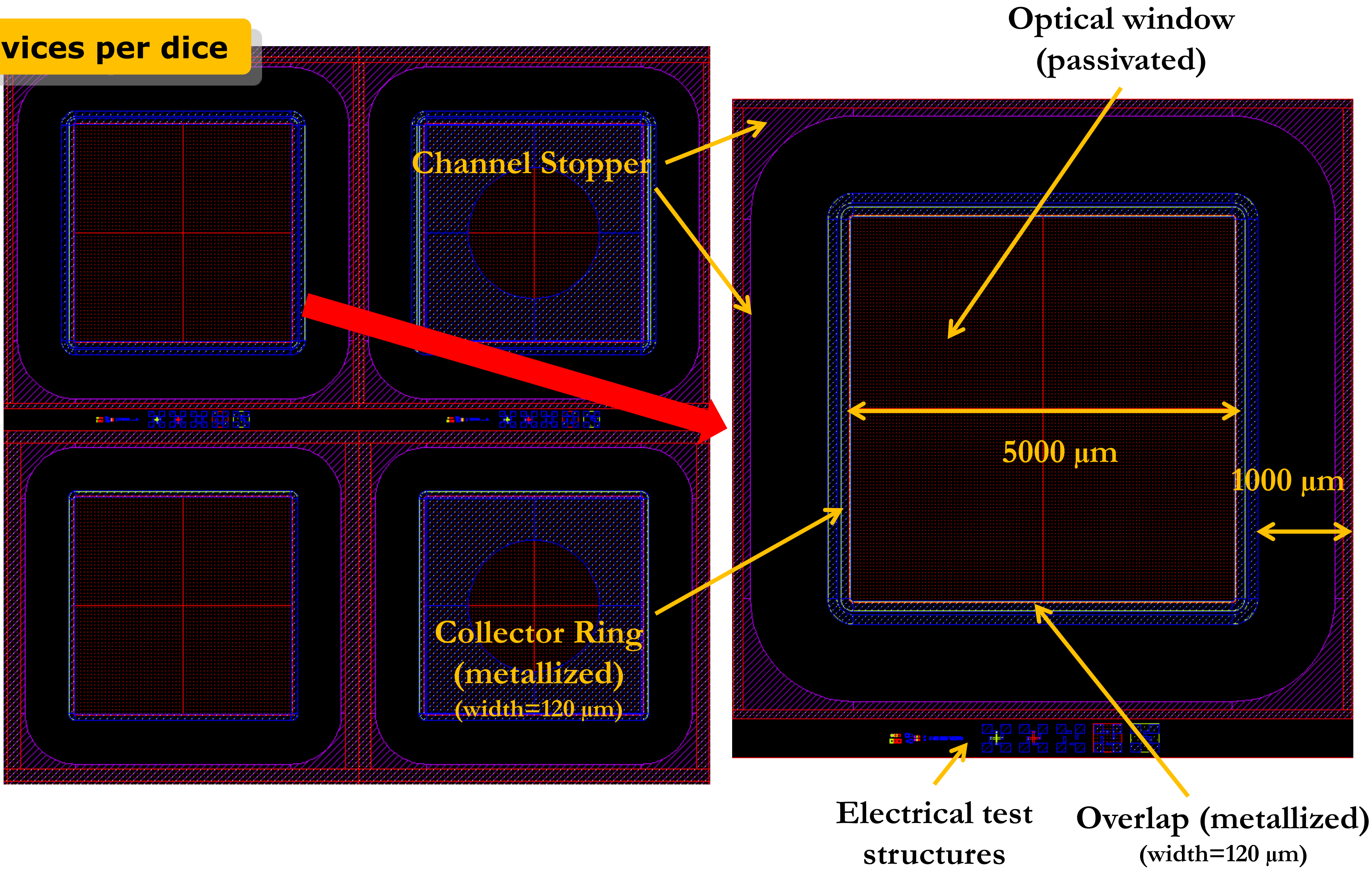
Φ_{eq} [cm^{-2}]	Simulated	Measured
No Irrad	7	10
1e14	6	6
5e14	3	2

See G. Kramberger Talk

First estimation by simulation. We must work to enhance this study

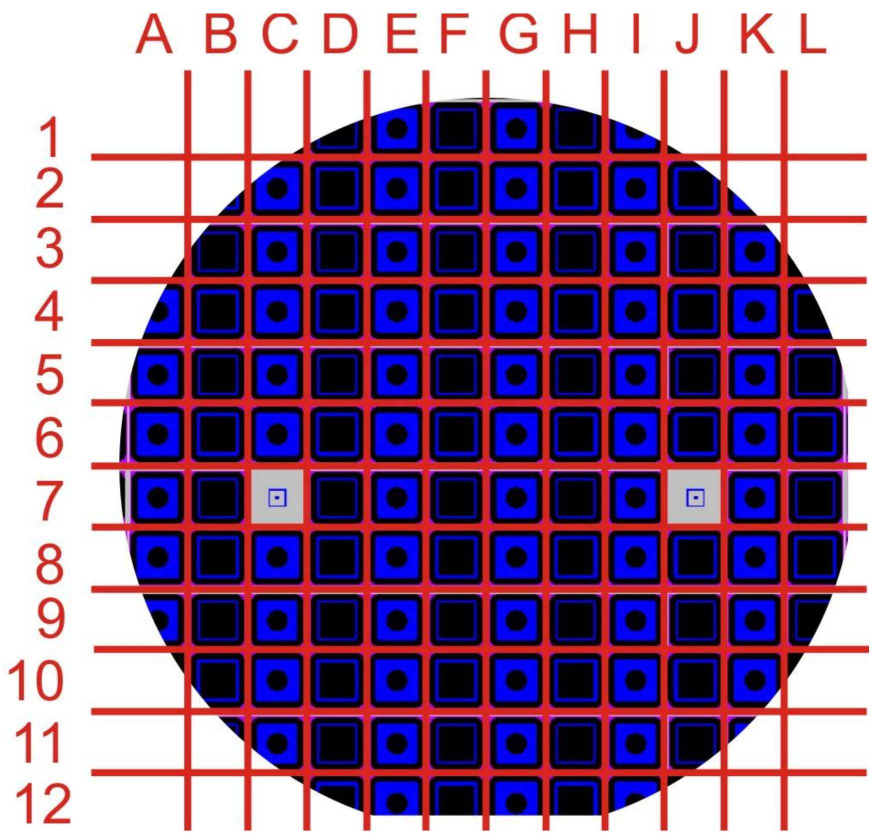
Fabrication (I)

4 Devices per dice

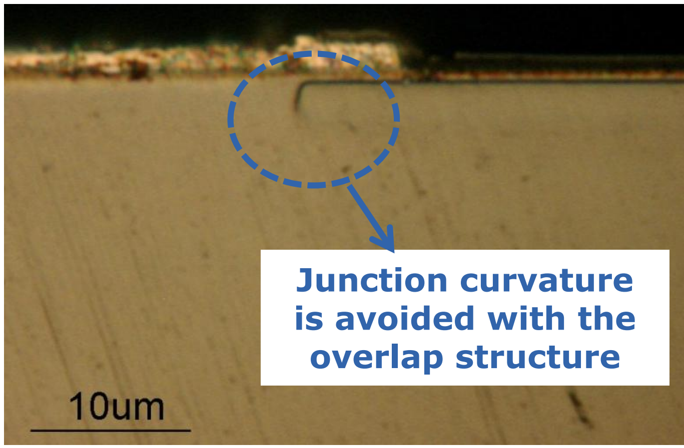


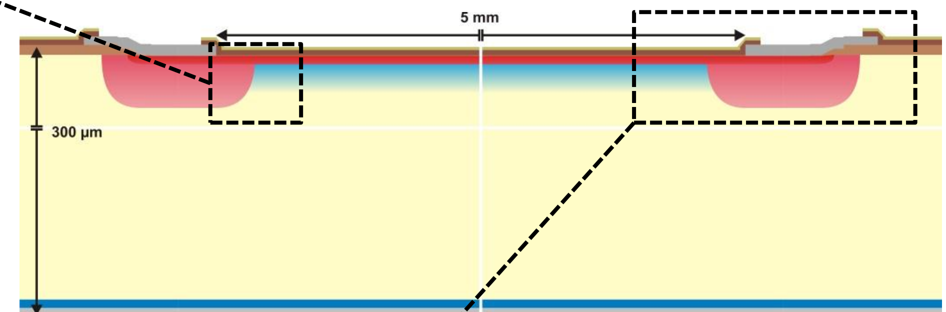
Fabrication (II)

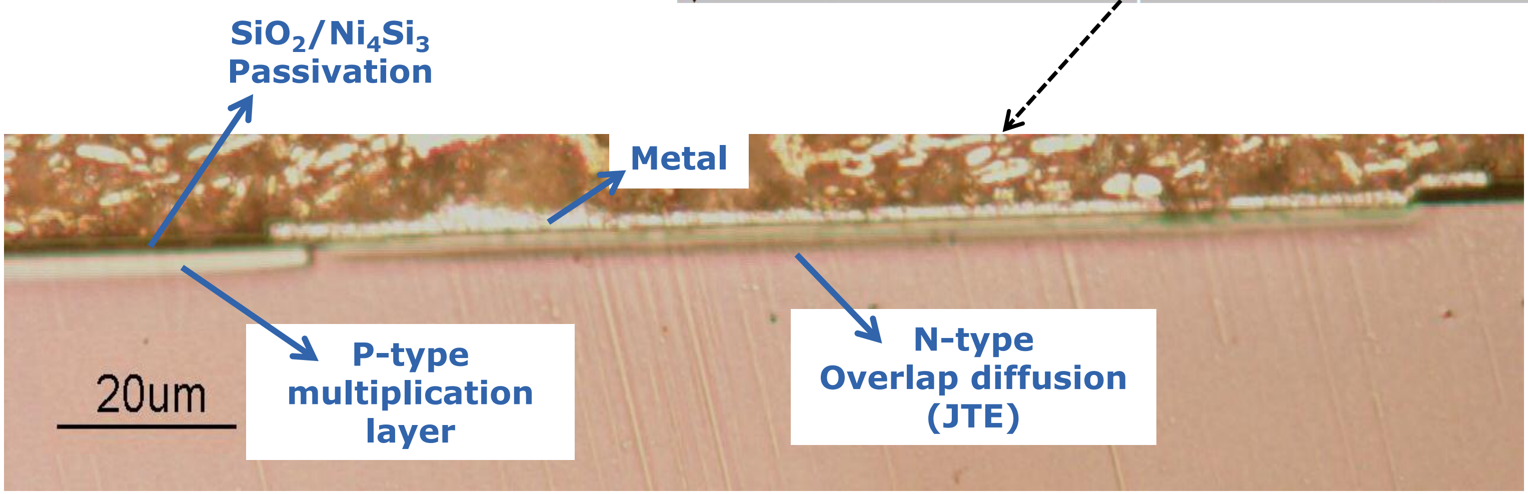
Wafer Number	P-layer Implant (E = 100 keV)	Substrate features
1	1.0×10^{13} cm^{-2}	HRP 300 (FZ; ρ>10 KΩ·cm; <100>; T = 300±10 μm)
2	1.1×10^{13} cm^{-2}	HRP 300 (FZ; ρ>10 KΩ·cm; <100>; T = 300±10 μm)
3	1.2×10^{13} cm^{-2}	HRP 300 (FZ; ρ>10 KΩ·cm; <100>; T = 300±10 μm)
4	1.3×10^{13} cm^{-2}	HRP 300 (FZ; ρ>10 KΩ·cm; <100>; T = 300±10 μm)
5	1.4×10^{13} cm^{-2}	HRP 300 (FZ; ρ>10 KΩ·cm; <100>; T = 300±10 μm)
6	1.5×10^{13} cm^{-2}	HRP 300 (FZ; ρ>10 KΩ·cm; <100>; T = 300±10 μm)
7	1.6×10^{13} cm^{-2}	HRP 300 (FZ; ρ>10 KΩ·cm; <100>; T = 300±10 μm)
8	2.0×10^{13} cm^{-2}	HRP 300 (FZ; ρ>10 KΩ·cm; <100>; T = 300±10 μm)
9	----- (PIN wafer)	HRP 300 (FZ; ρ>10 KΩ·cm; <100>; T = 300±10 μm)
10	1.1×10^{13} cm^{-2}	HRP OXG (DOFZ; ρ = 5-15 KΩ·cm; <100>; T = 285±25 μm)
11	1.3×10^{13} cm^{-2}	HRP OXG (DOFZ; ρ = 5-15 KΩ·cm; <100>; T = 285±25 μm)



Technological Characterization







Electrical Characterization

- **Fabrication yield worsens with increasing implant dose for the p-type multiplication layer.**

Measured Current [nA] at 200 V

0	100	200	500	800	1000	2000	5000	8000	10000

[100 nA] [1μA] [10 μA]

Wafers were fabricated in the same run, following exactly the same fabrcation steps. Only difference between W9 and W8 is that PiN wafer was not implanted with the multiplication implantation.

	A	B	C	D	E	F	G	H	I	J	K	L
1												
2				198	132	120	90	107	111			
3			225	138	87	87	66	107	71	100		
4		361	144	108	80	79	66	87	71	107	128	
5		176	99	97	76	88	63	80	63	414	82	
6		165	104	107	83	91	2952	328	68	111	83	####
7		164		106	70	84	61	91	69		96	####
8		203	136	112	69	74	59	69	194	98	133	
9		####	139	115	60	56	50	59	57	215	165	
10			706	123	73	64	54	66	69	184		
11				####	116	89	67	84	####			
12												

PiN Wafer (W9)

	A	B	C	D	E	F	G	H	I	J	K	L
1												
2				3444	2077	####	770	####	####			
3			3863	####	7166	####	####	####	####	####		
4		####	3088	####	####	####	####	####	####	####	498	
5		####	9498	####	####	####	####	####	####	####	####	
6		####	####	####	####	####	####	####	####	####	####	####
7		####		####	####	####	####	####	####		3531	####
8		####	1699	####	####	####	####	####	####	####	414	
9		####	1281	####	####	####	####	####	5249	####	1236	
10			4540	####	264	####	####	####	219	####		
11				####	####	184	181	224	####			
12												

Wafer 8 (Implant dose = 2×10^{13} cm^{-2})

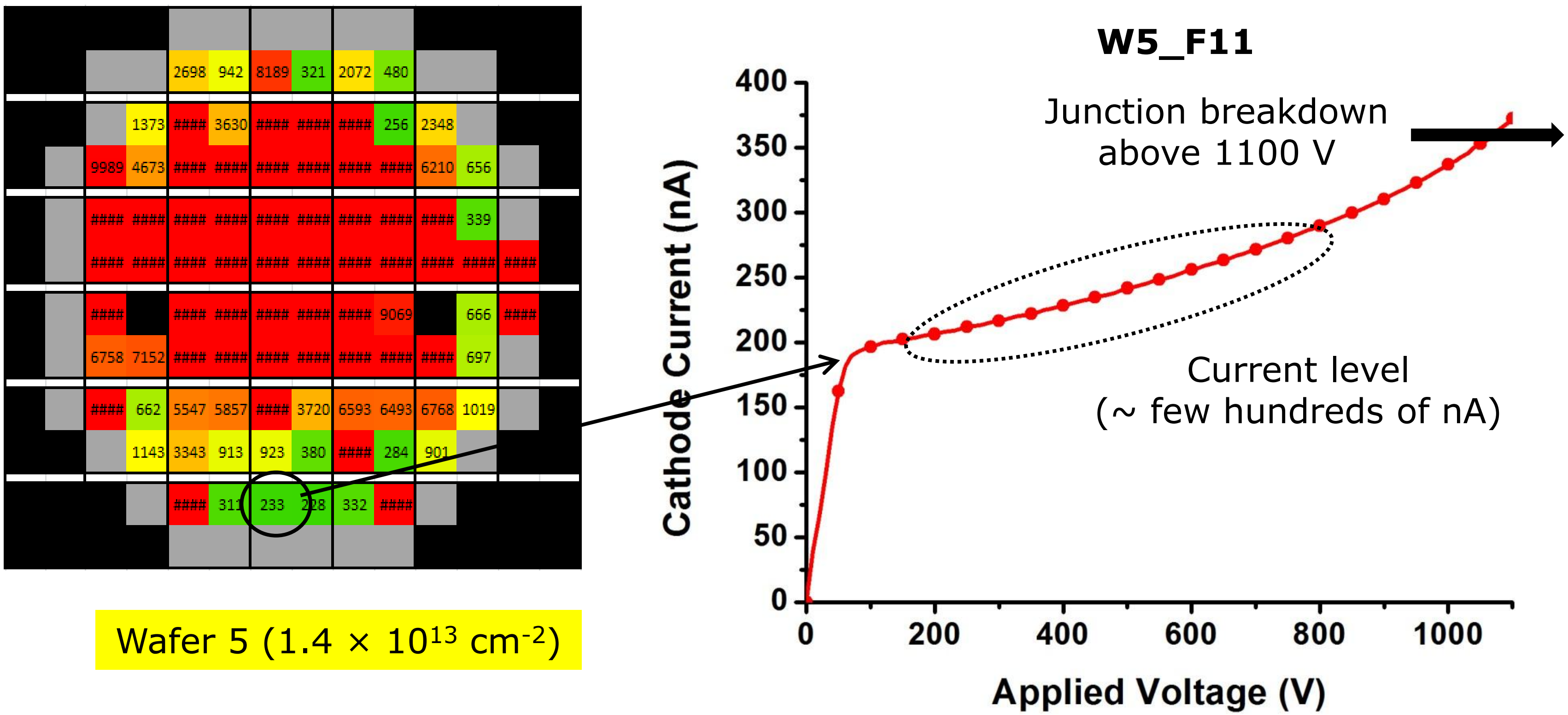
We are working in the yield improvement

Experimental Results (I)

✓ "Good" Devices

→ **Current levels below 1 μA thorough the whole voltage range**

→ **Junction breakdown above 1100 V (*Except Wafer 8: < 800 V, still good)**



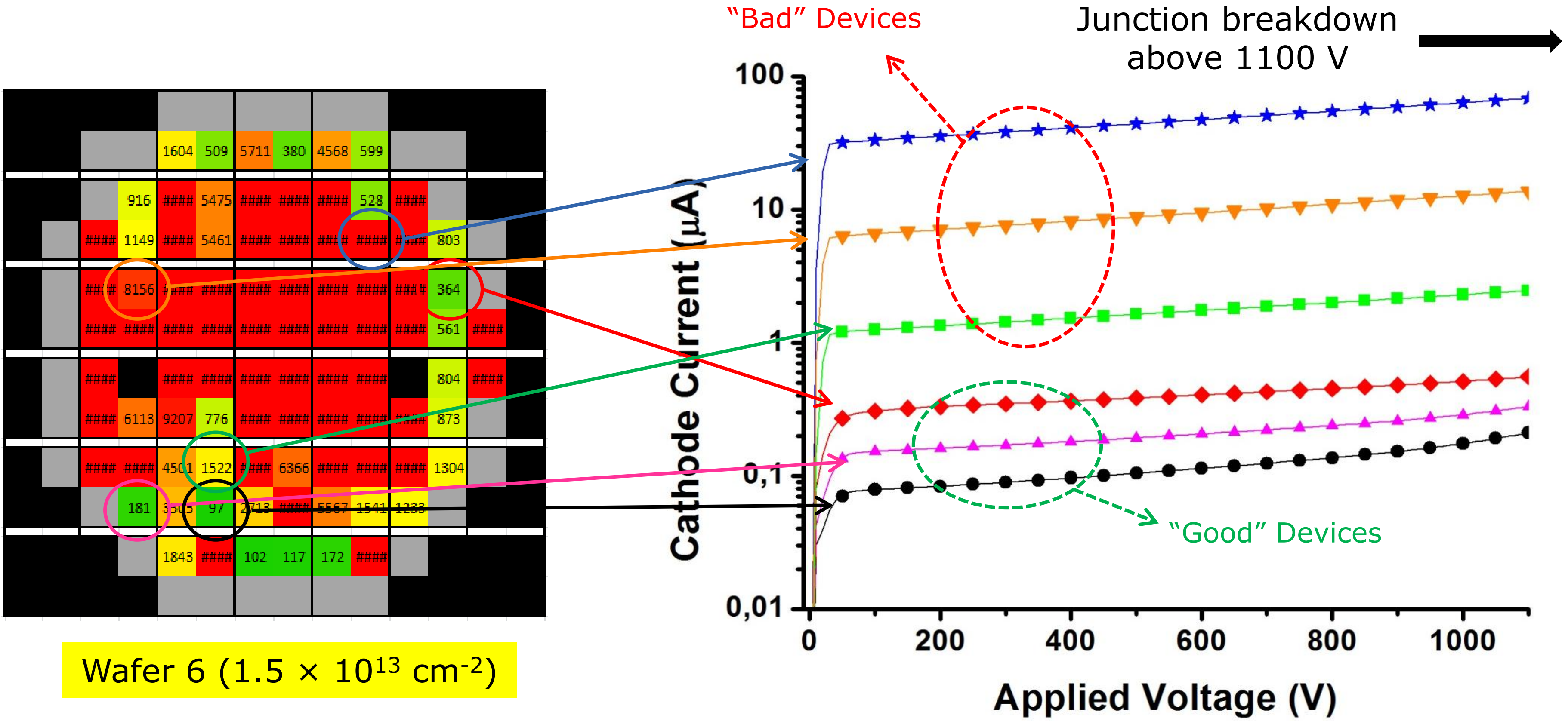
Wafer 5 (1.4×10^{13} cm^{-2})

Experimental Results (II)

✘ "Bad" Devices

→ **Current levels above 1 μA thorough the whole voltage range**

→ **Junction breakdown above 1100 V (*Except Wafer 8)**

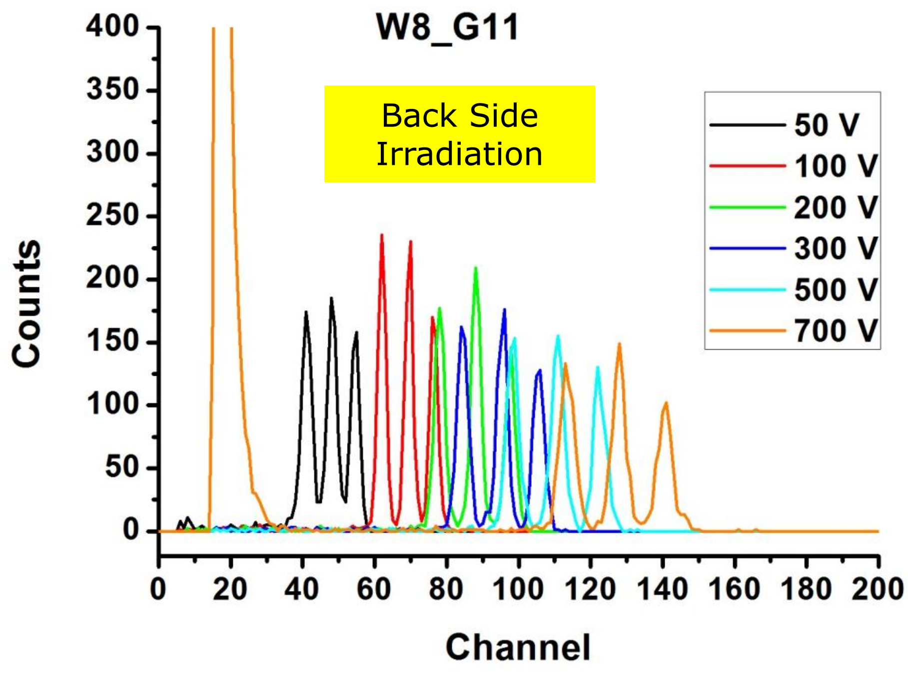


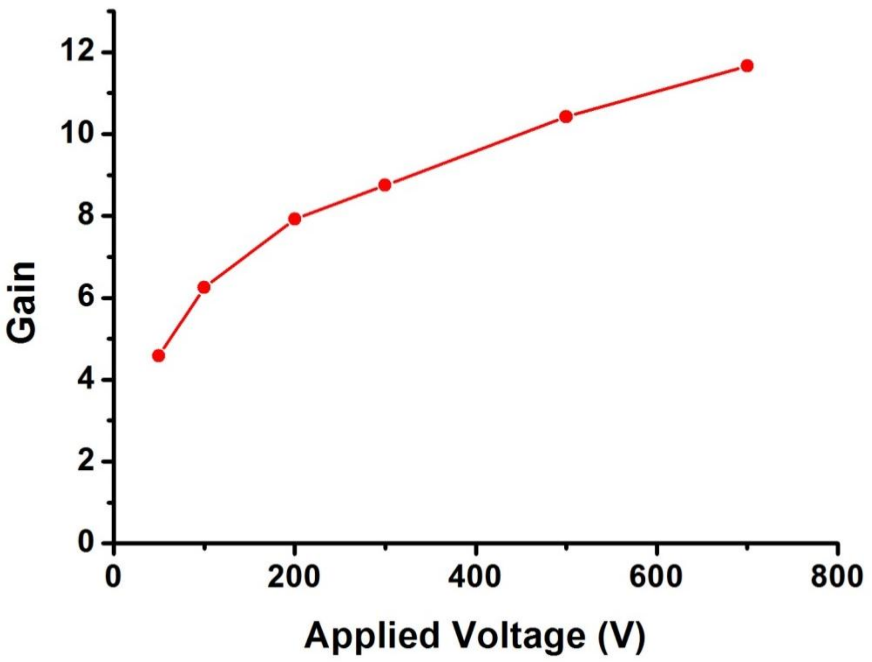
Wafer 6 (1.5 × 10^{13} cm^{-2})

Experimental Results (III)

- **Multiplication factor has been tested with tri-alpha ($^{239}Pu/^{241}Am/^{244}Cm$) source.**
  - → **Irradiation through the anode (back side, 1 µm Aluminum):**

$$Gain_{@V} = \frac{Channel\ Central\ peak_{@V}}{Channel\ Central\ peak_{No\ multiplied}}$$





Experimental Results (IV)

- **Several samples were sent out for different experimental characterizations.**

IJS Institut "Jozef Stefan" Ljubljana (Slovenia)

Device	Type	I @ 400 V	V_{BD} (I=1μA)
W8_E10	LGAD	241 nA	550 V
W8_H11	LGAD	197 nA	490 V

- **Signal measurement**:
  - ^{90}Sr Spectrum
  - α-TCT
  - ^{241}Am X-ray spectrum
- **Irradiation at different fluences**

See G. Kramberger Talk

Santa Cruz Institute of Particle Physics (USA)

Device	Type	I @ 200 V	V_{BD} (I=1μA)
W8_I10	LGAD	472 nA	270 V
W9_E10	PiN	73 nA	> 1100 V

- **C-V and I-V**
- **1064 nm Laser & Comparison with ATLAS07 diodes**

See H. Sadrozinski Talk

Instituto de Física de Cantabria, Santander (Spain)

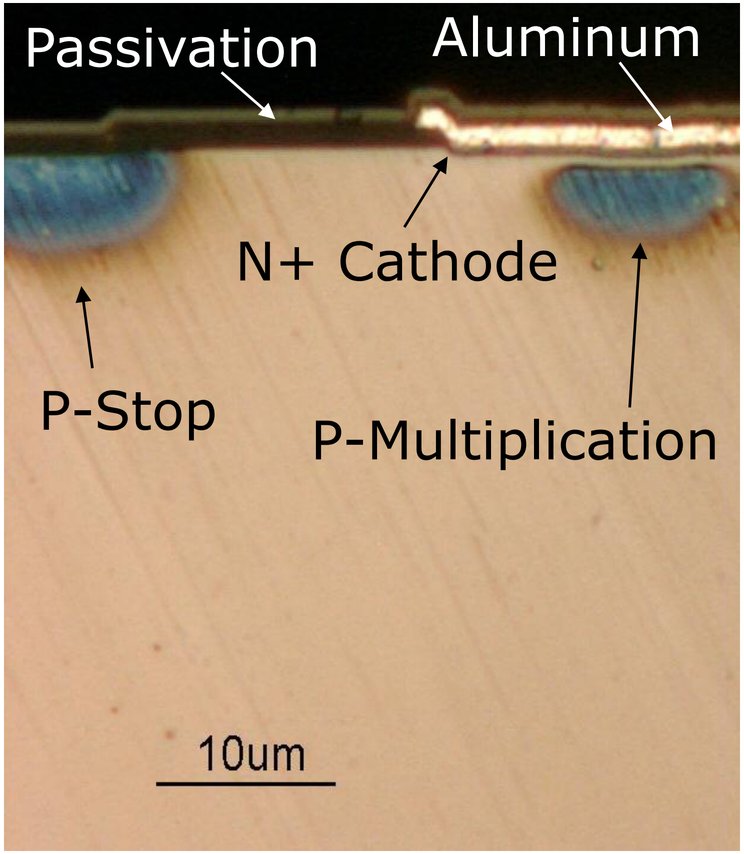
- **Laser TCT**

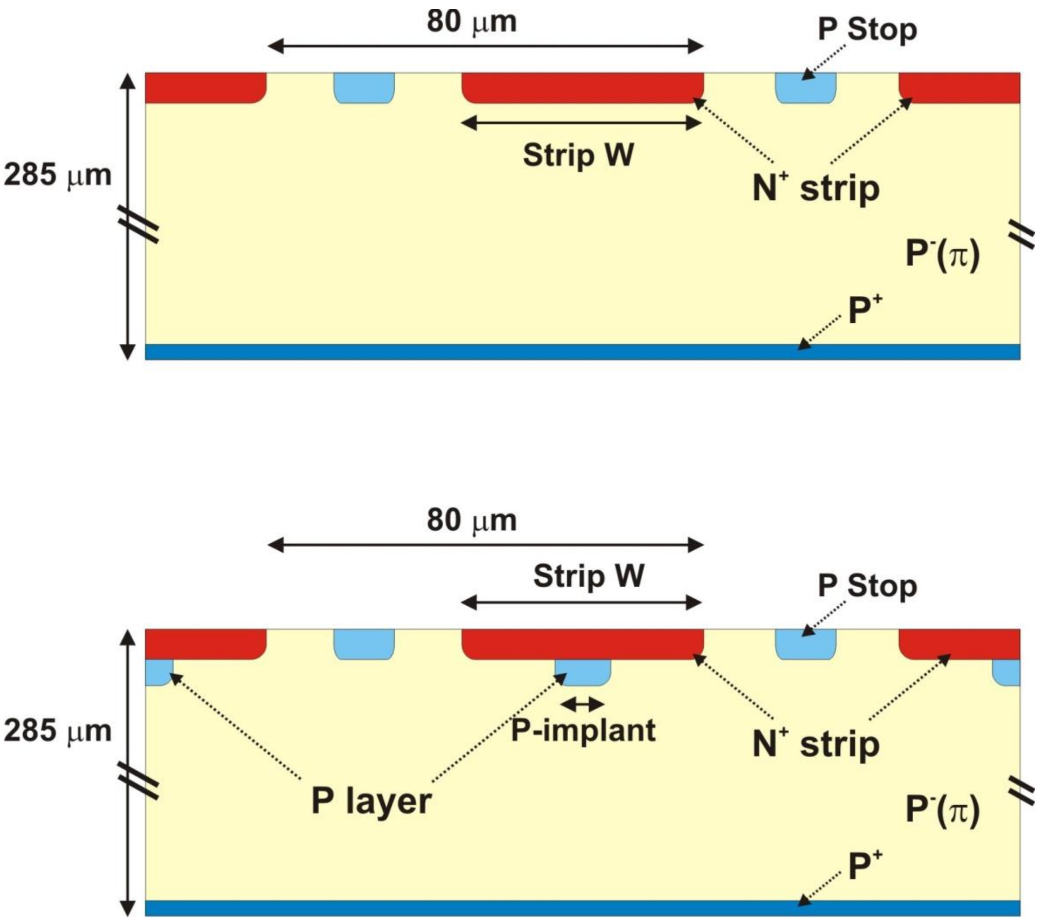
See M. Fernández Talk

Device	Type	I @ 400 V	V_{BD} (I=1μA)
W6_G11	LGAD	117 nA	> 1100 V
W6_H11	LGAD	172 nA	> 1100 V
W7_K9	LGAD	732 nA	> 1100 V
W7_F11	LGAD	421 nA	> 1100 V

Device	Type	I @ 400 V	V_{BD} (I=1μA)
W8_K4	LGAD	674 nA	650 V
W8_K8	LGAD	549 nA	900 V
W9_F9	PiN	61 nA	> 1100 V
W9_G9	PiN	54 nA	> 1100 V

Low Gain Strip Detectors





See G. Pellegrini Talk