Silicon Sensor Technology Developments: APDs and Strip sensors with charge multiplication

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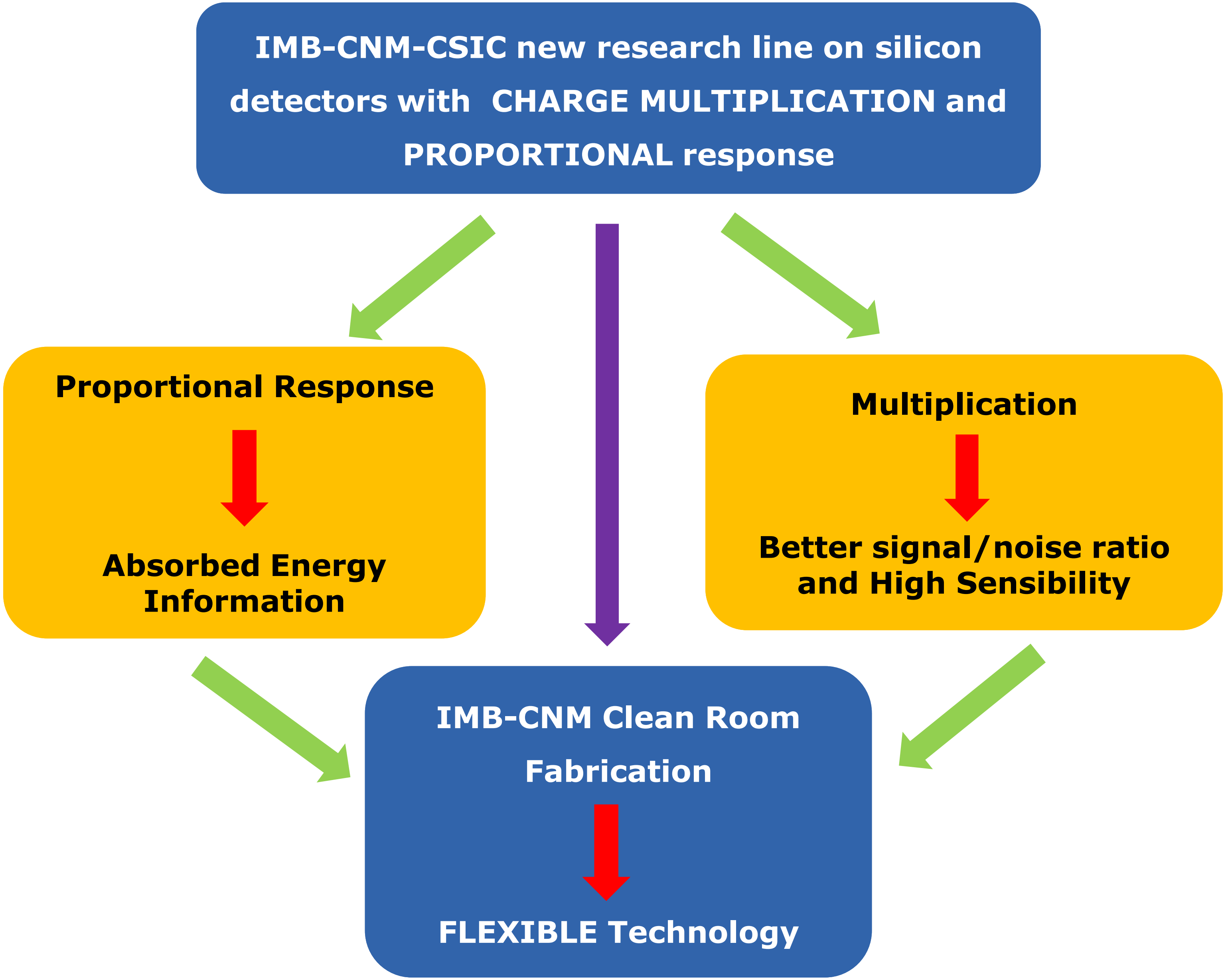


IMB-CNM-CSIC new research line on silicon detectors with CHARGE MULTIPLICATION and PROPORTIONAL response

Proportional Response

Absorbed Energy Information

Multiplication

Better signal/noise ratio and High Sensibility

IMB-CNM Clean Room Fabrication

FLEXIBLE Technology

Basic Activity Lines

Photon Detection

☐ **PIN Diode**
- → **Proportional Response**
- → **Good efficiency**
- → **Good spectral range**

↓ **Multiplication**

☐ **APD linear mode**
- → **Proportional Response**
- → **Good efficiency**
- → **Good spectral range**
- → **Better Sensibility**
- → **Better signal/noise ratio**

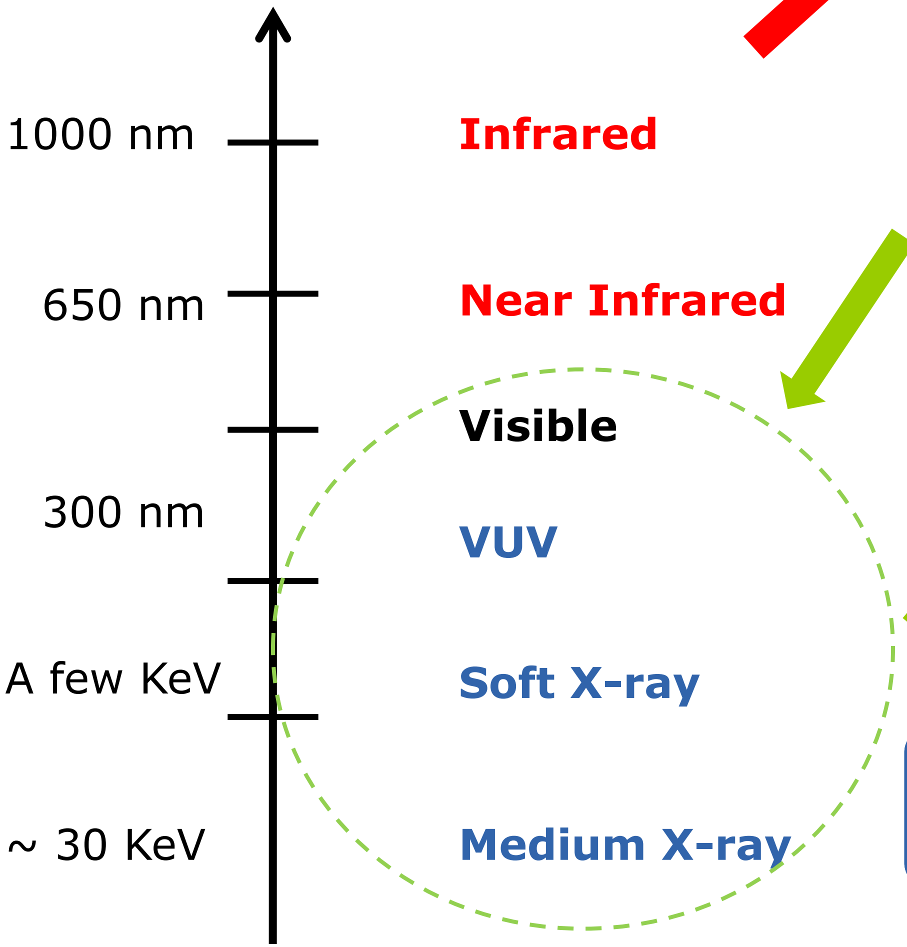
Particle Detection

☐ **Strip Detectors**
- ✗ **TID damage**
- ✗ **Post-irradiation Lower quality signal**

↓ **Multiplication**

☐ **Strip Detectors with multiplication control**
- ✓ **Pre & Post irradiation same signal**
- ✓ **Thin Strip Detectors Integration with the same signal**

Linear Mode APDs



Infrared

Near Infrared

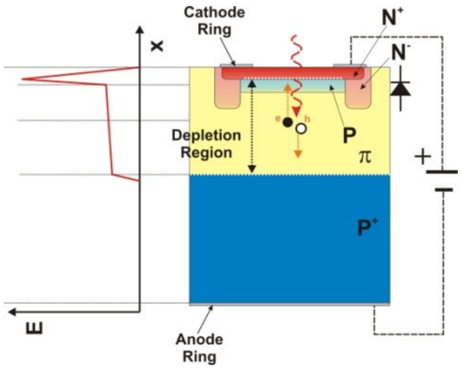
Visible

VUV

Soft X-ray

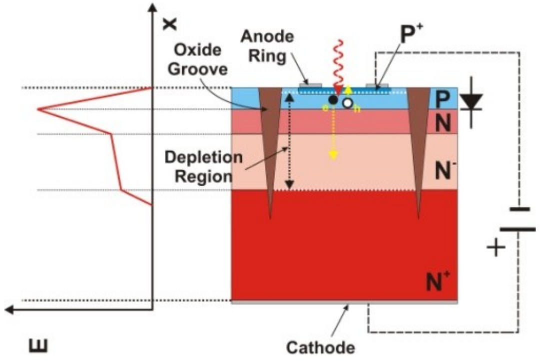
Medium X-ray

Reachthroug-APD



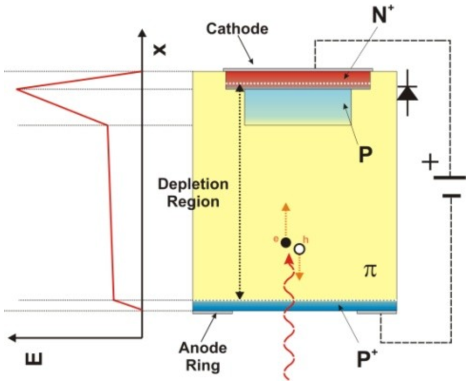
HEP Aplication

Reverse RT-APD



X Ray Direct Detection

Reachthroug-APD

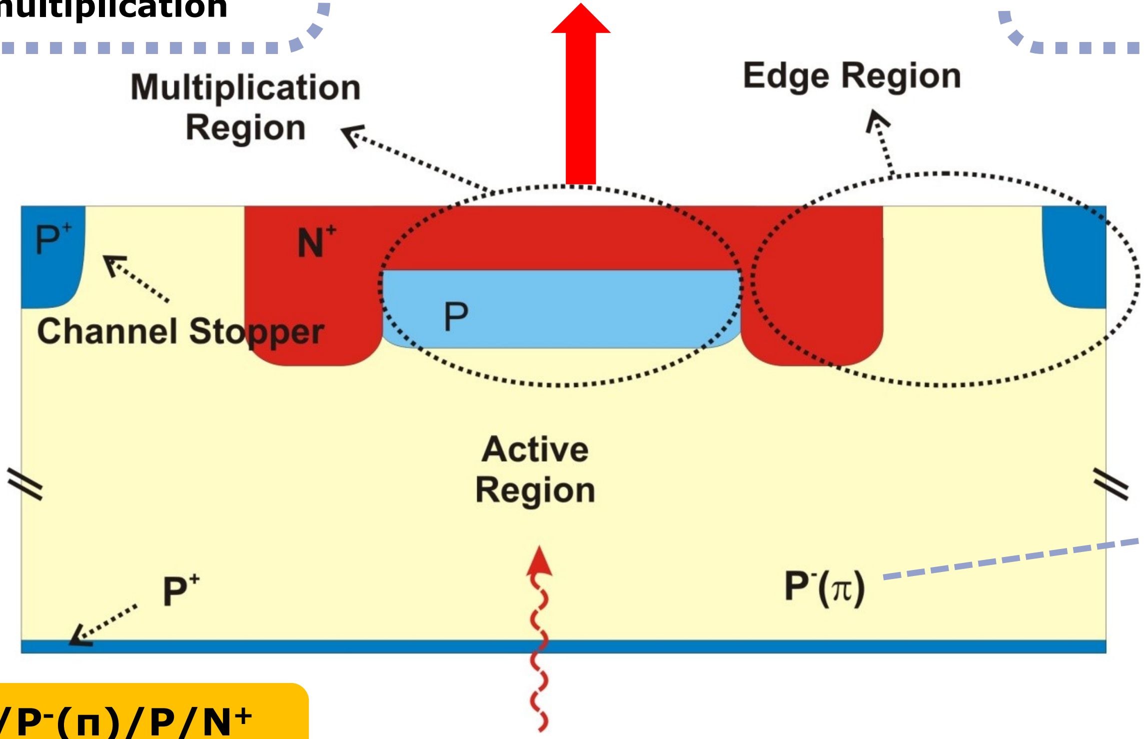


Reach-Through Avalanche Photodiodes (RT-APD)

High electric field values at the junction enhanced avalanche multiplication

Signal proportional to the absorbed energy

Edge termination structures ensure the gain stability and uniformity



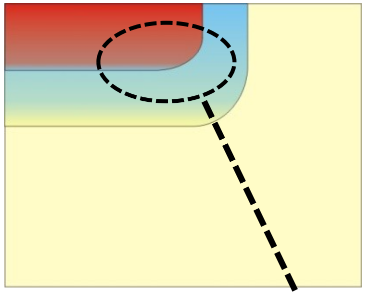
High resistivity substrate (~ 15 kΩ·cm, 1.3E12 cm^{-3})

Reverse Biased

Depletion region reaches the P$^+$ anode diffusion through the active region

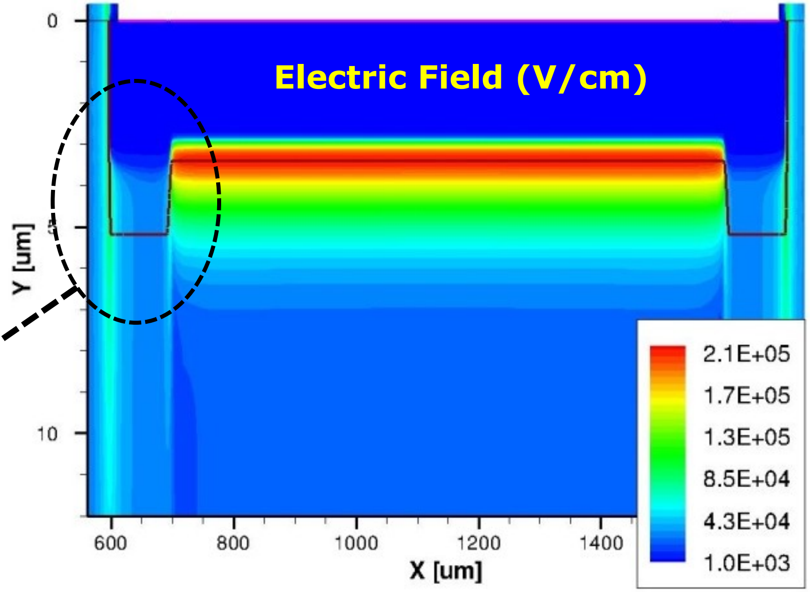
$P^+/P^-(\pi)/P/N^+$ diode structure

Device Optimisation: Edge termination structures



N$^+$ and P layers laterally diffuse constituting a cylindrical junction

- ❑ **Cylindrical Junction**
  - **50% breakdown reduction**
  - **80% electric field increase at the junction edge**



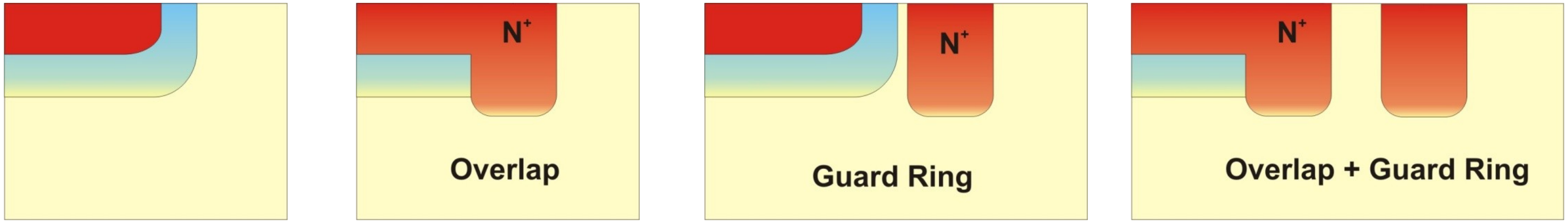
Electric Field (V/cm)

Edge termination structures should be implemented to ensure gain stability and uniformity

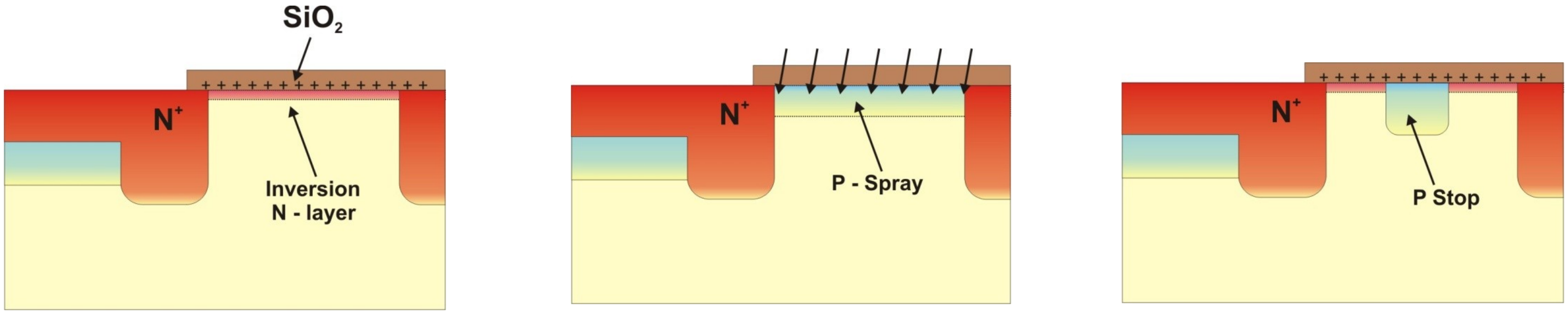
- ❑ **Edge termination techniques reduce the parasitic effects induced by the charge and defects at the passivation layers and interfaces.**

Device Optimisation: Edge termination structures

- **Overlap and Guard Ring structures should be placed at optimized distance to avoid cylindrical breakdown and undesired electric field peaks at the multiplication junction edge.**



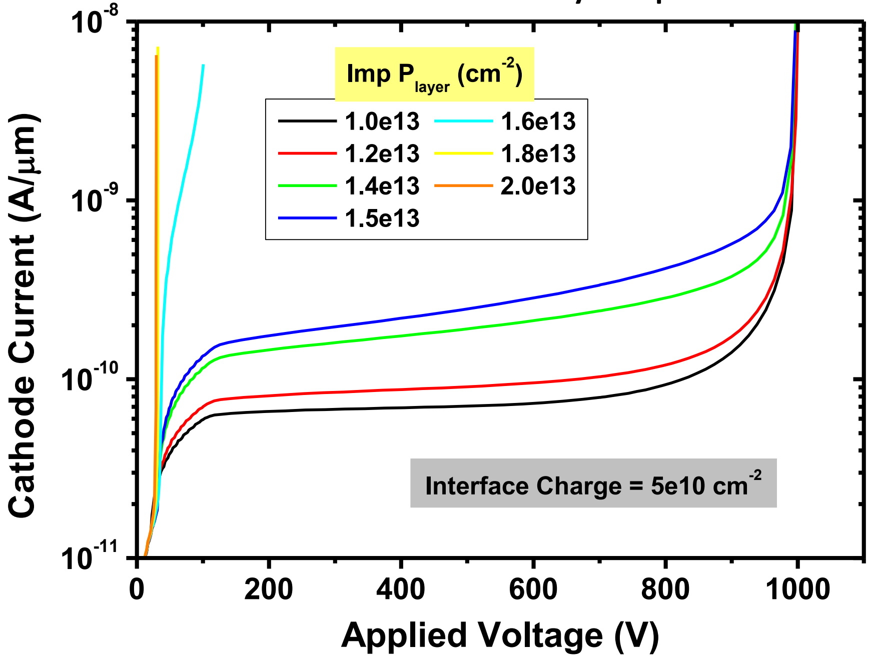
- **Positive fixed charges at the Si/SiO$_2$ interface induce a shallow N-type inversion layer that short-circuits the edge termination structures and accelerates the substrate lateral depletion.**
- **P-type shallow diffusions as P-spray or P-stop should be included to ensure the edge termination structures effectiveness.**



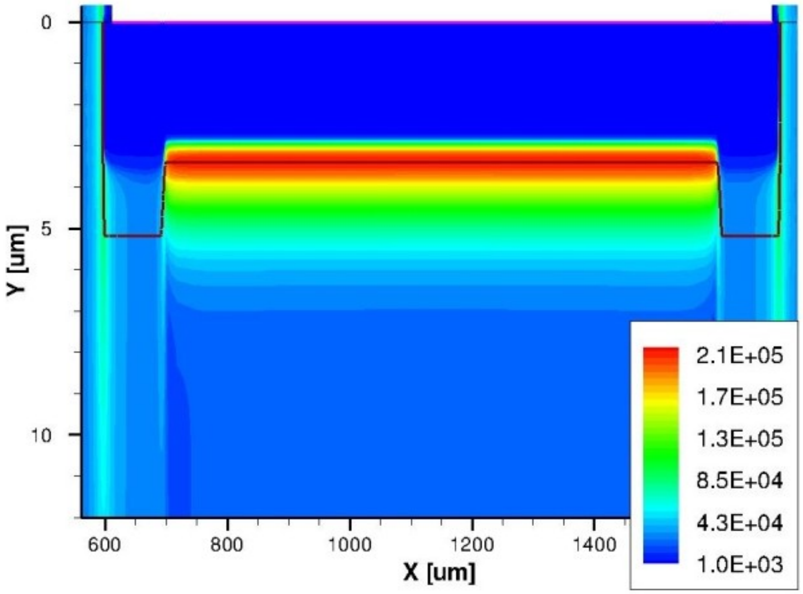
Device Optimisation: Breakdown & Dark Current

☐ By an iterative process, the doping profiles and edge termination characteristics are adjusted to optimize the electrical performances

Simulated IV for different P-layer implant doses.



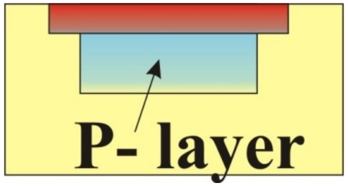
Simulated Electric Field distribution at 800 V

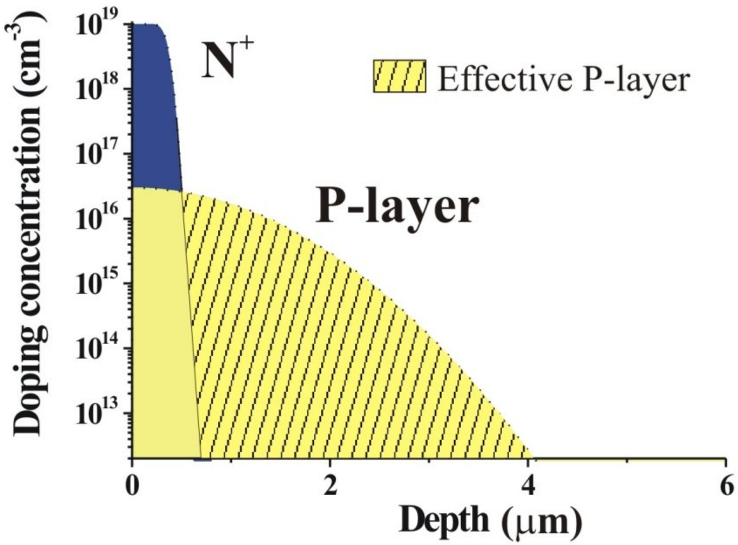


High resistivity substrate (~ 15 kΩ·cm, 1.3E12 cm^{-3})

Device Optimisation: Gain fitting

- ❑ N^+ and P – layer diffusion profiles determine the electric field distribution at the multiplication region
- ❑ In order to fit the expected gain, multiplication region diffusions should be adjusted.

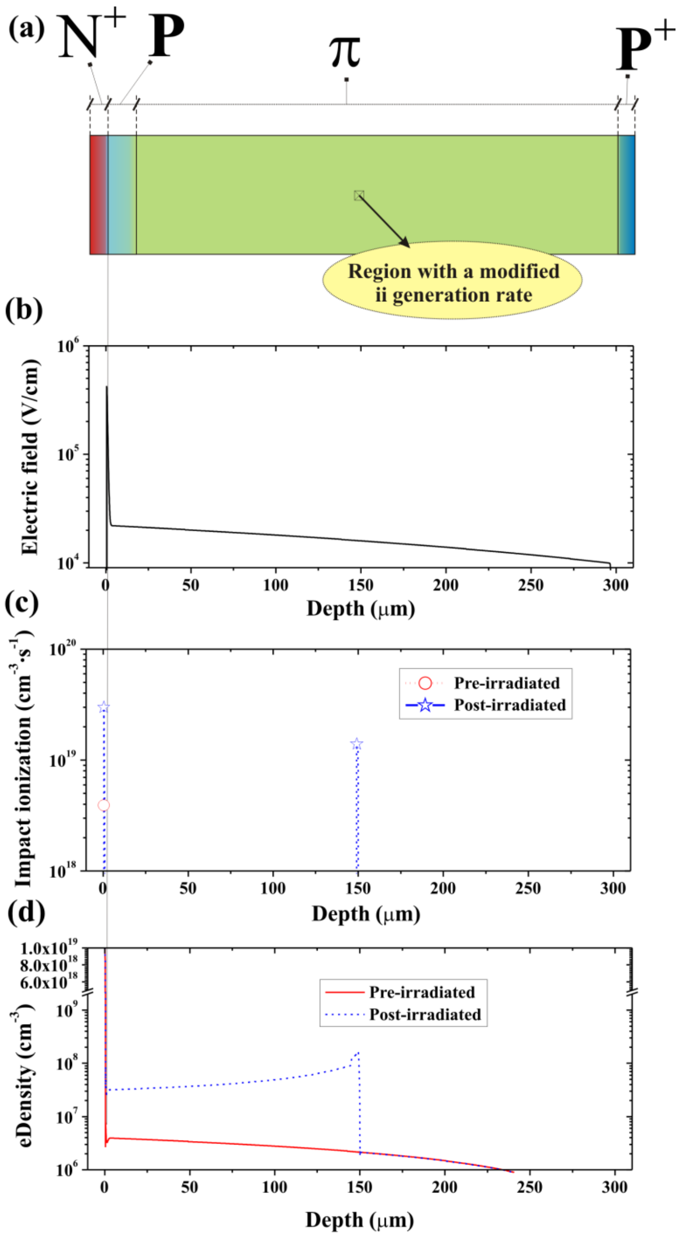




Effective charge at the P-layer determines the multiplication factor

- ❑ A TCAD Sentaurus simulation methodology has been devised in order to fit the final gain of the device.

Device Optimisation: Gain fitting

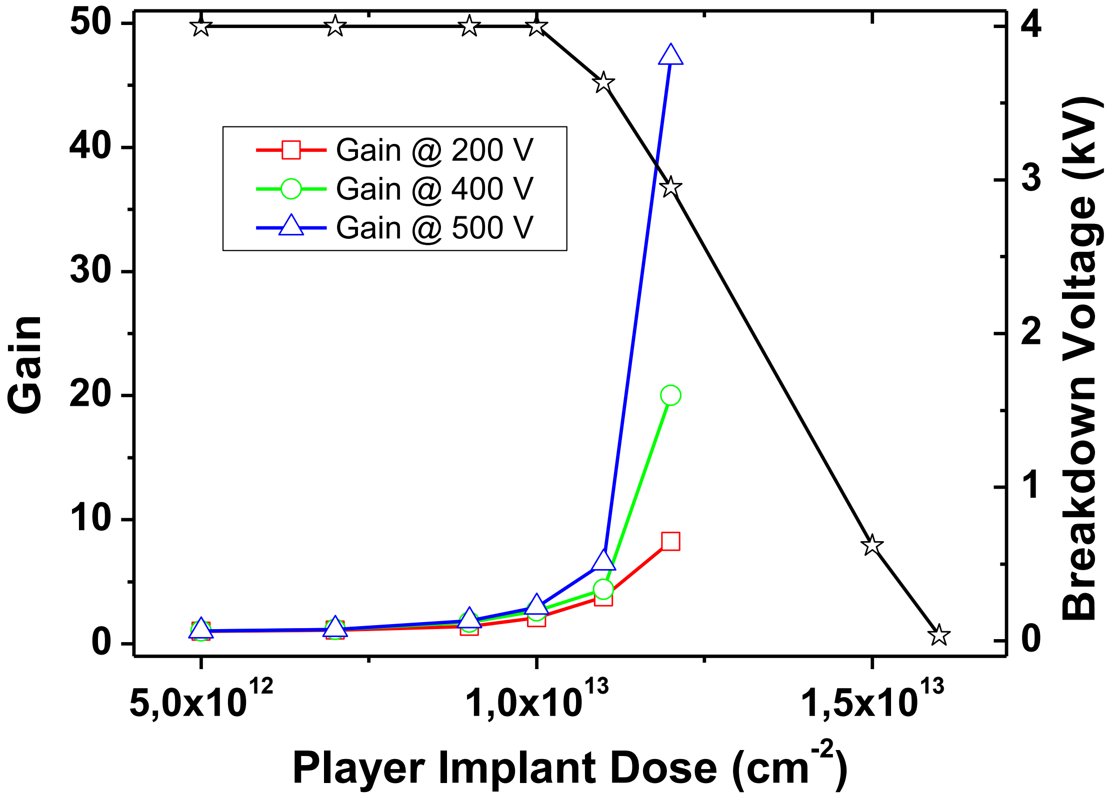


Gain Simulation Procedure

Post – illuminated device: Region with higher virtual impact ionization rate to emulate the electron – hole generation due to X-ray absorption

Post and Pre – illuminated behavior are compared.

1D Simulated Gain and Breakdown voltage with respect to the Boron implant dose



❑ **Main technological parameters**

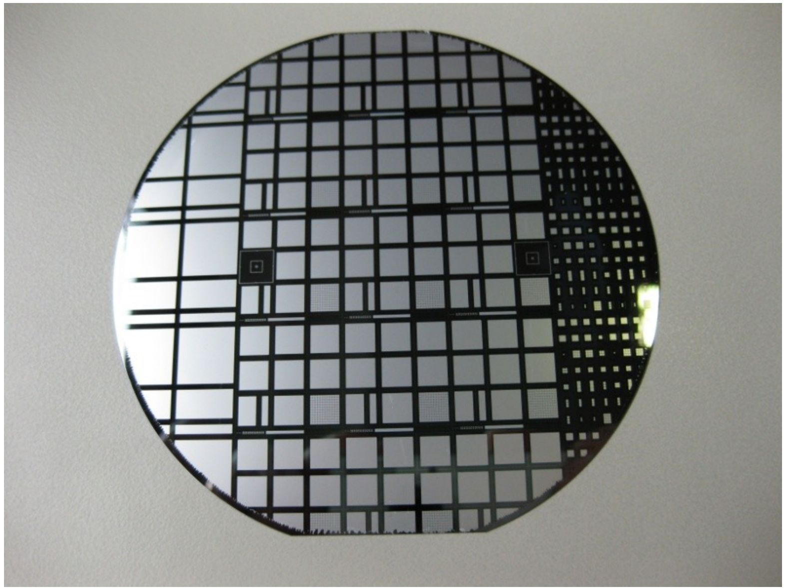
- → **Wafer thickness: 300 µm**
- → **Substrate doping concentration: 1.3E12 cm^{-3}**
- → **P layer implant dose: 1.2E13 cm^{-2}**
- → **N+ layer doping concentration: 1e19 cm^{-3}**

Device Fabrication

First technological processes (2 runs)

- ☐ **Different sizes and layouts**
  - **Square (10×10 mm², 5×5 mm², 1×1 mm² & 0,3×0,3 mm²)**
  - **Rectangular (10×5 mm², 10×1 mm², 5×3 mm² & 5×1 mm²)**
- ☐ **Different edge termination structures**
  - **Overlap (20 µm, 50 µm & 100 µm)**
  - **Guard ring (at 10 µm, 20 µm & 30 µm)**
- ☐ **Different doping profiles to adjust the P-layer effective charge → Gain fitting**
  - **Single Phosphorus implant for a Gaussian N^+ layer**
  - **Double Phosphorus implant for a step N^+ layer**
  - **Different Boron implants for the P-layer**
- ☐ **Wafers with p-spray to avoid the inversion layer and P-stop at the edge to reduce the peripheral leakage current**

Devices fabricated at the IMB-CNM Clean Room

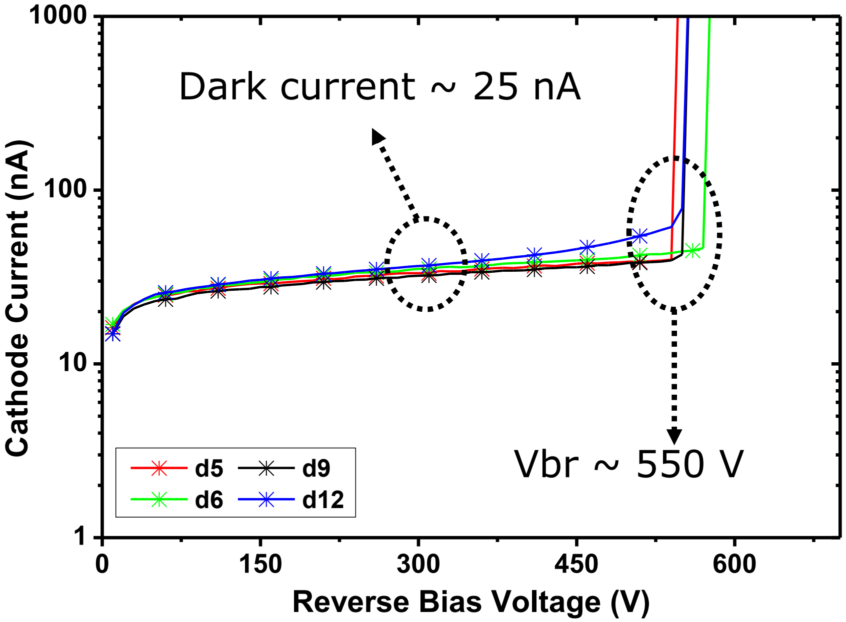


A new technological process will be defined with the improvements derived from simulation and experimental results.

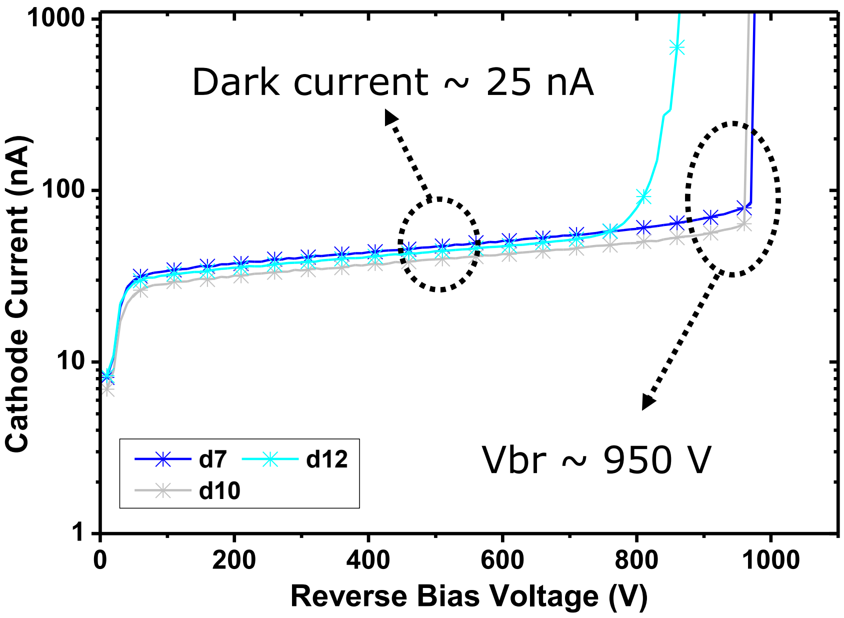
First Characterisation Results

On-wafer electric characterisation (Dice size = 5 x 5 mm)

PIN diode (with P-spray)



APD diode (without P-spray)

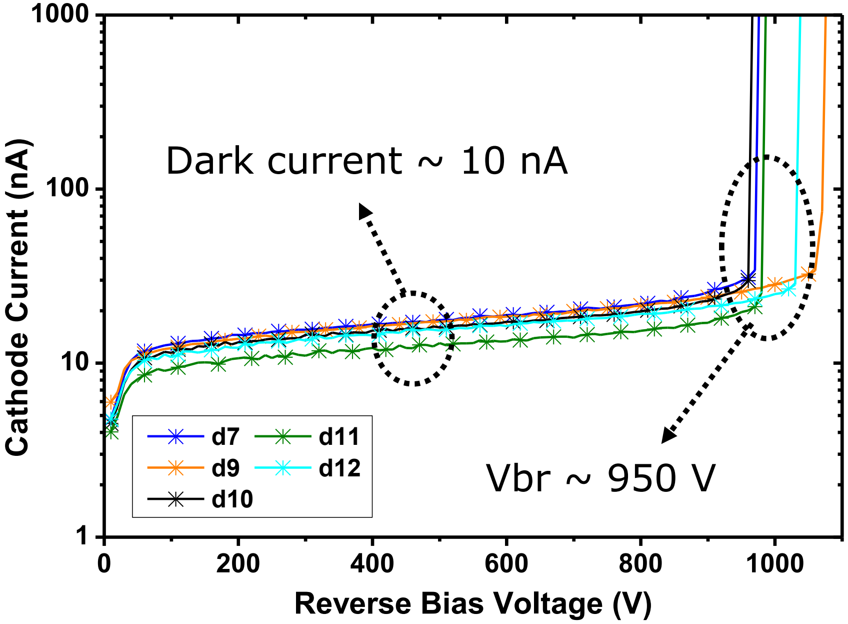


- ✓ **High and stable breakdown voltage (≥ 800 V)**
- ✓ **Good dark current levels (20-40 nA) @ operation voltage range (300 - 500 V)**
- ✓ **Relatively good processing yield within the wafer**

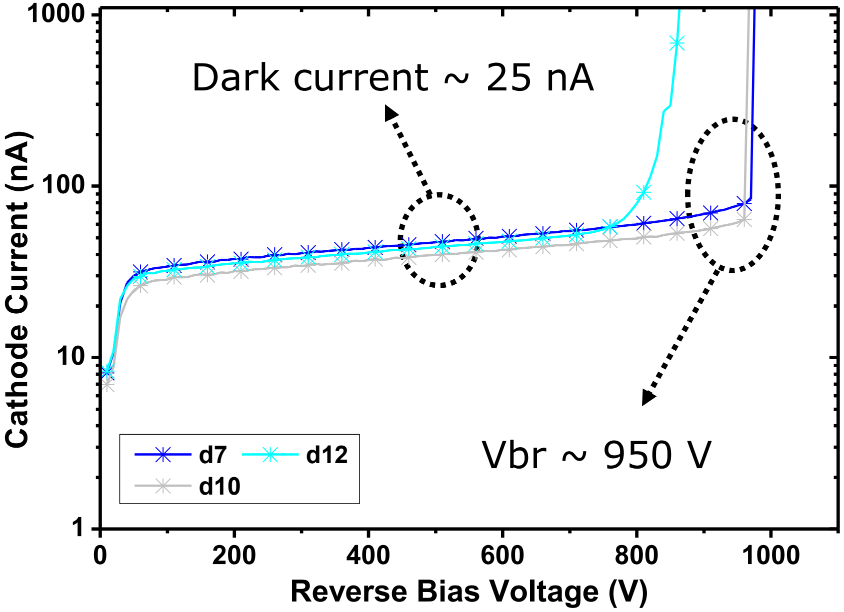
First Characterisation Results

On-wafer electric characterisation

APD diode (3 x 5 mm)



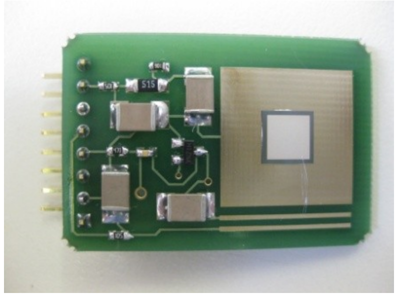
APD diode (5 x 5 mm)



First Characterisation Results

Detection characterisation

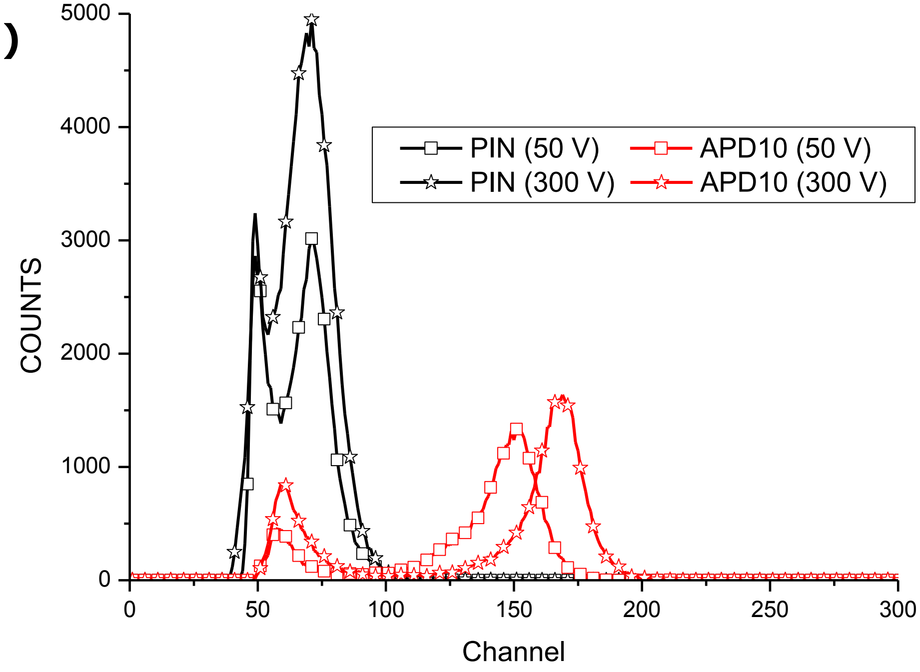
❑ **Packaged devices have been tested with a ^{241}Am source (60 KeV Gamma)**



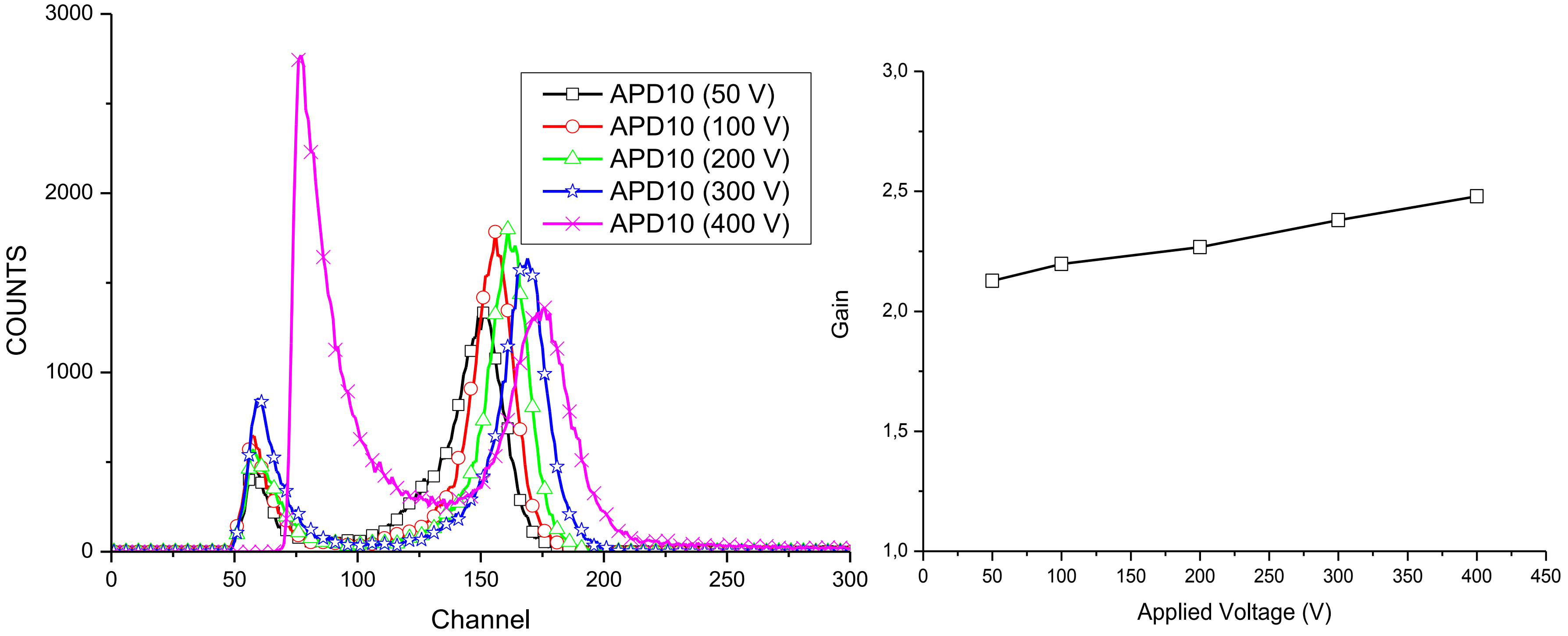
✓ **Good spectrum identification**

✗ **High noise levels**

✗ **Low gain (M ~2.5 @ 400 V)**

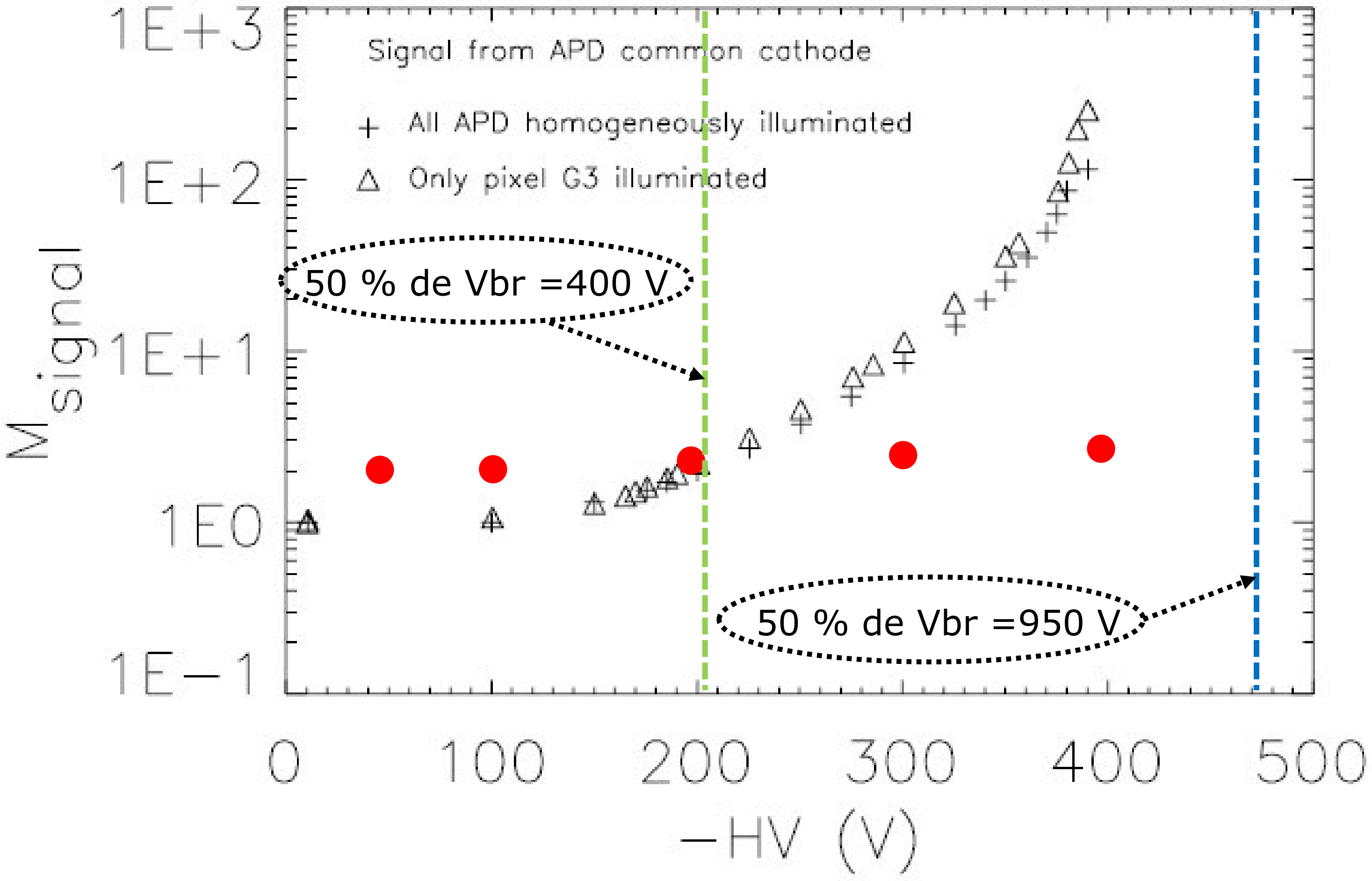


First Characterisation Results



First Characterisation Results

HAMAMATSU S8550

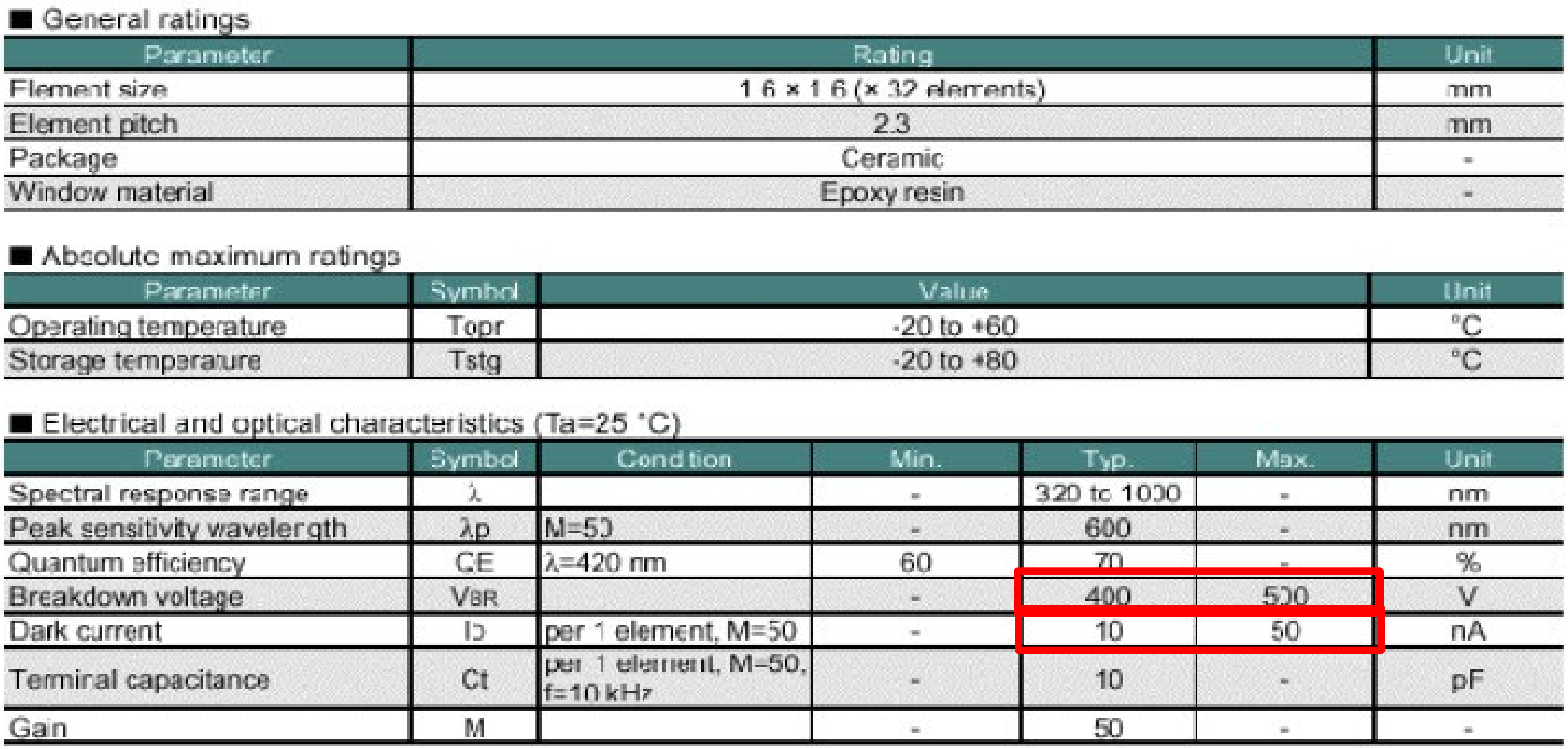


50 % de Vbr =400 V

50 % de Vbr =950 V

First Characterisation Results

HAMAMATSU S8550



■ General ratings

Parameter	Rating	Unit
Element size	1.6 × 1.6 (× 32 elements)	mm
Element pitch	2.3	mm
Package	Ceramic	-
Window material	Epoxy resin	-

■ Absolute maximum ratings

Parameter	Symbol	Value	Unit
Operating temperature	Topr	-20 to +60	°C
Storage temperature	Tstg	-20 to +80	°C

■ Electrical and optical characteristics (Ta=25 °C)

Parameter	Symbol	Condition	Min.	Typ.	Max.	Unit
Spectral response range	λ		-	320 to 1000	-	nm
Peak sensitivity wavelength	λ_p	M=50	-	600	-	nm
Quantum efficiency	QE	λ=420 nm	60	70	-	%
Breakdown voltage	V_{BR}		-	400	500	V
Dark current	I_D	per 1 element, M=50	-	10	50	nA
Terminal capacitance	Ct	per 1 element, M=50, f=10 kHz	-	10	-	pF
Gain	M		-	50	-	-

Strip Sensors

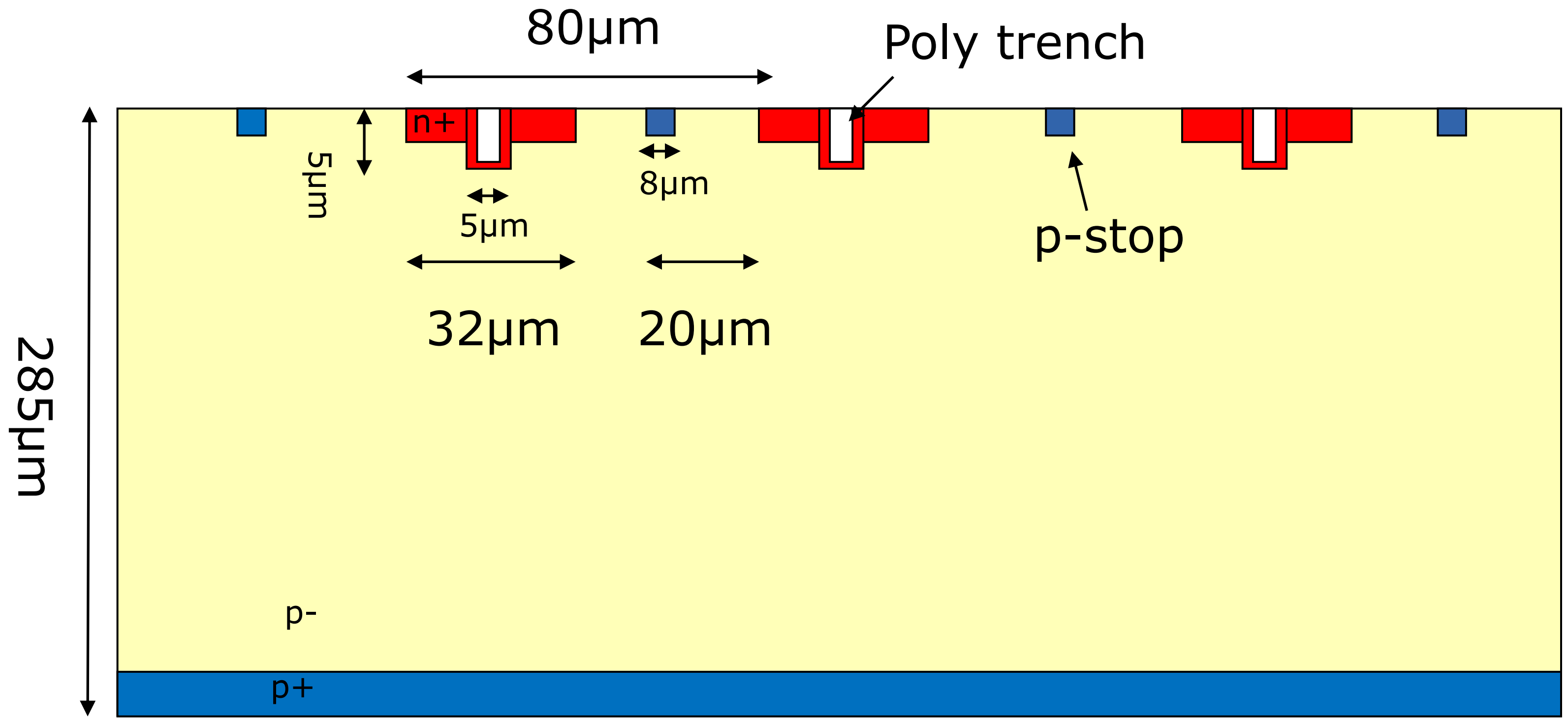
a. **Irradiated devices suffer displacement damage that change their charge collection dynamics**
   - **Defects induced by radiation increase the electric field at the junction of the N^+ diffusion**
   - **The electric field increase leads to a multiplication of the collected charge in irradiated devices**

b. **Project: fabricate a p-type strip detector with small gain → Similar signal before and after irradiation**
   - **Multiplication occurs at low bias voltage**
   - **Gain should be limited between 2 and 10:**
     - **Avoid Crosstalk**
     - **Avoid exceeding the dynamic range of readout electronics**
   - **Capacitance should not increase**
     - **Higher capacitance → Higher noise**

Technological proposals

I. Trench filled with doped polysilicon along the centre of the strip pitch

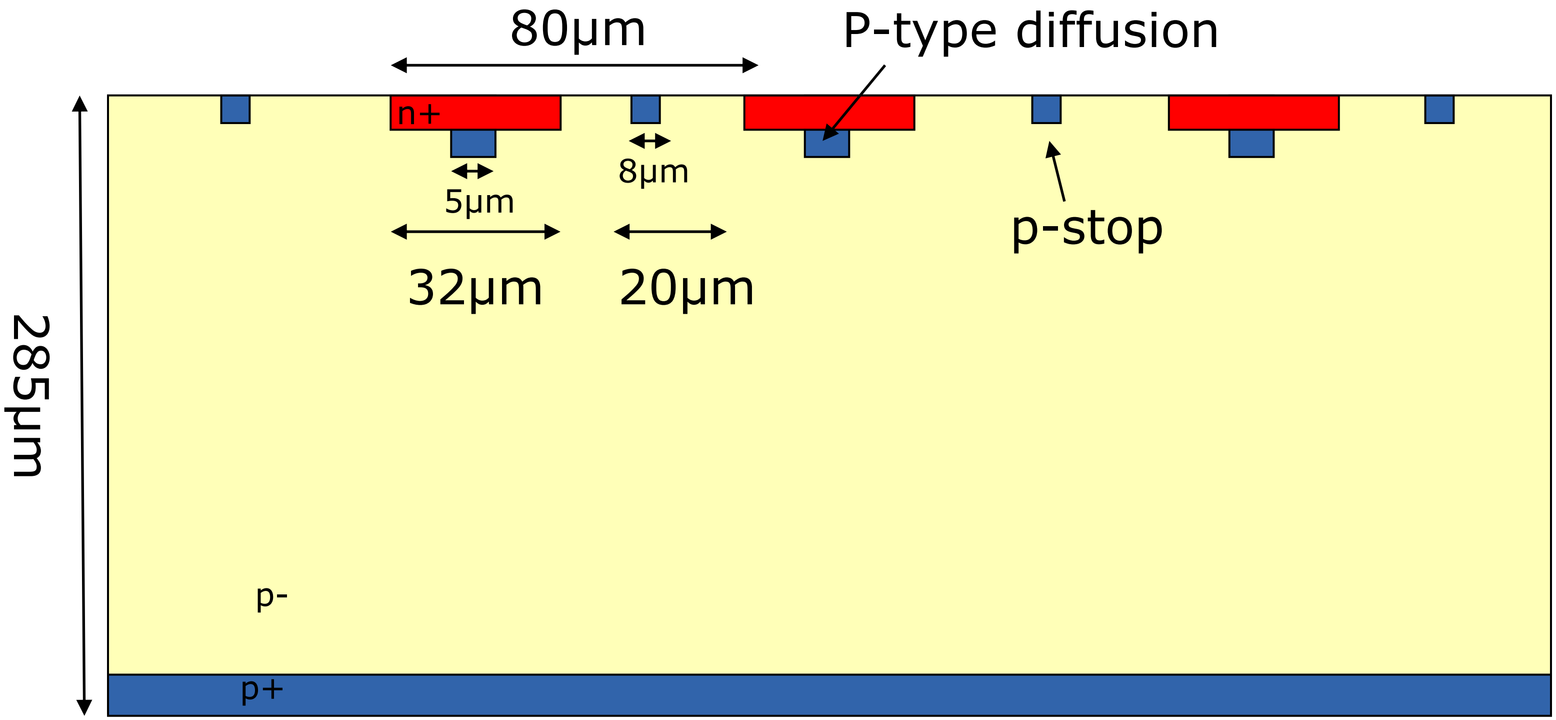
- **A N$^+$ contact is created into the silicon bulk that modifies the electric field in the collection region → multiplication**



Technological proposals

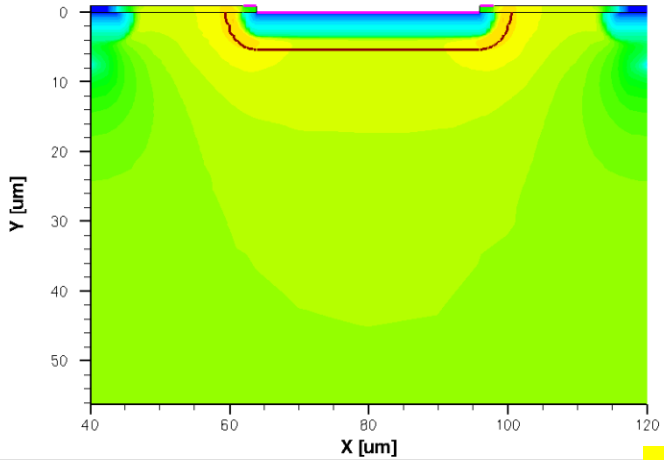
II. P-type diffusion along the centre of the strip pitch

- **Under reverse bias conditions, a high electric field region is created at the N$^+$– P junction → multiplication**

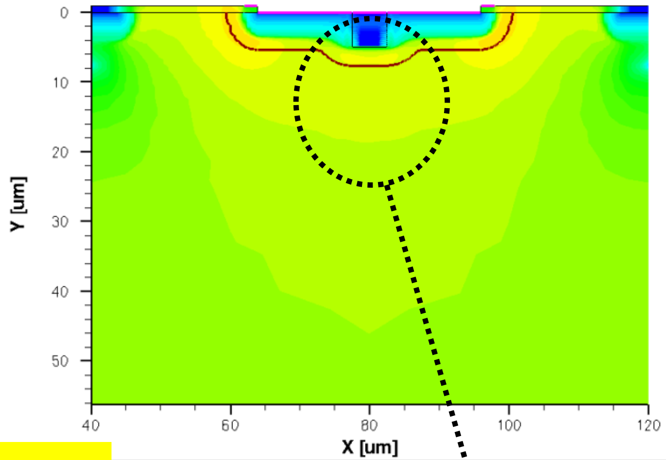


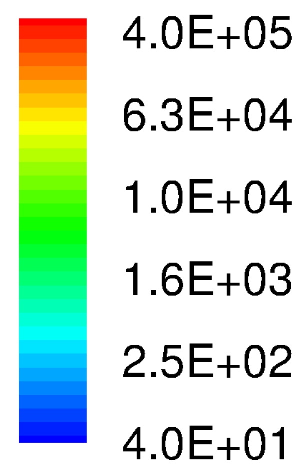
Simulation of the Electric Field

Strip Detector

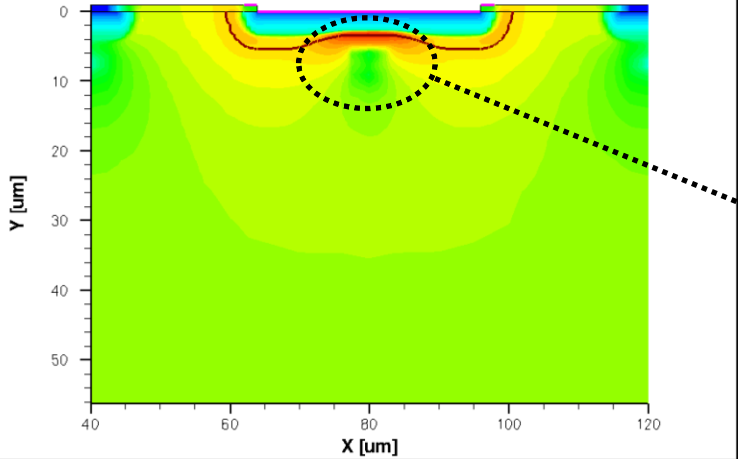


Poly Trench





P diffusion

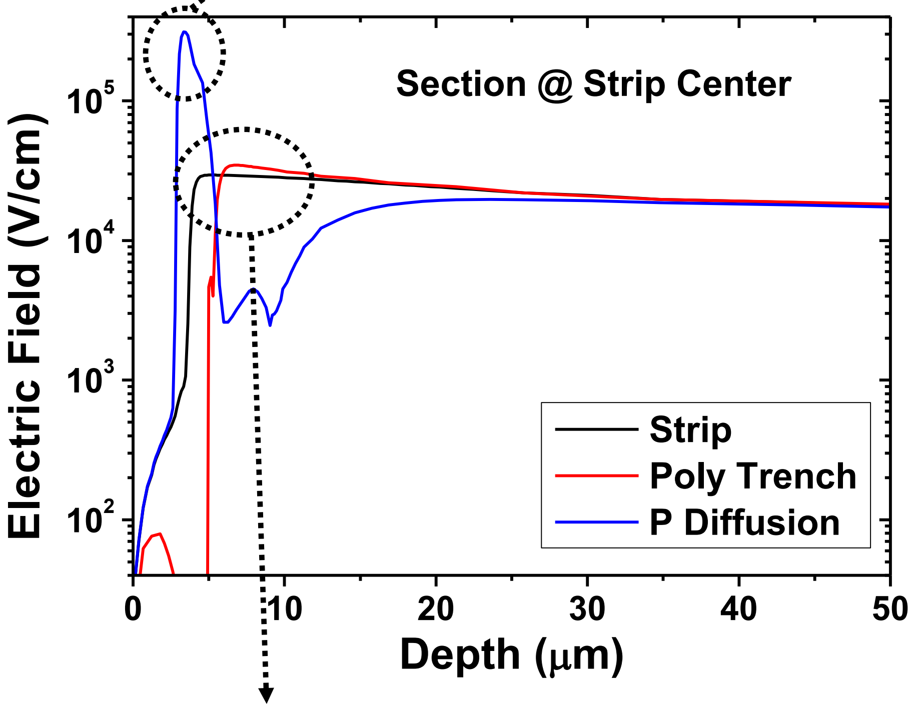


High Electric Field region driven deep in the bulk

High Electric Field peak at the centre of the strip

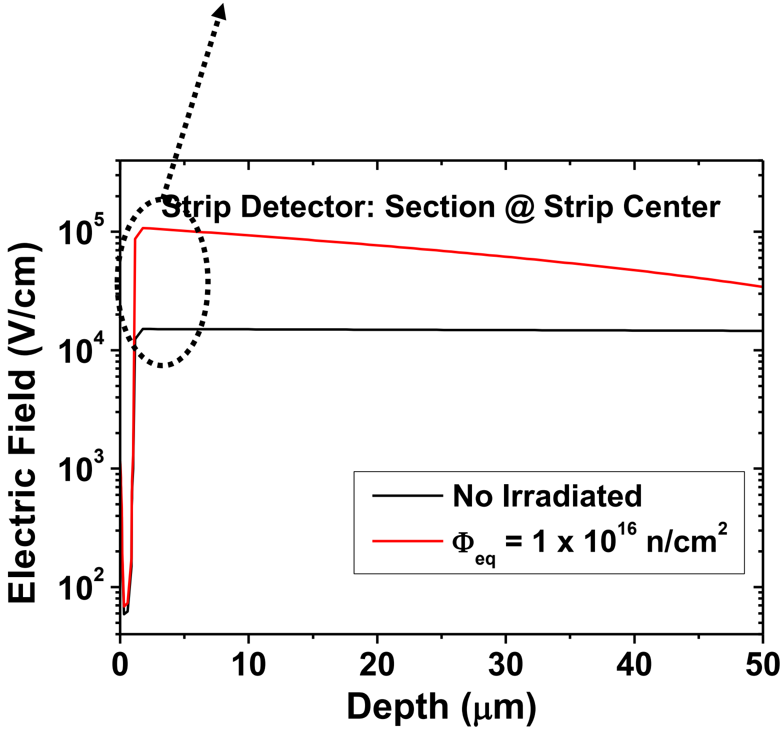
Simulation of the Electric Field

High Electric Field peak at the junction

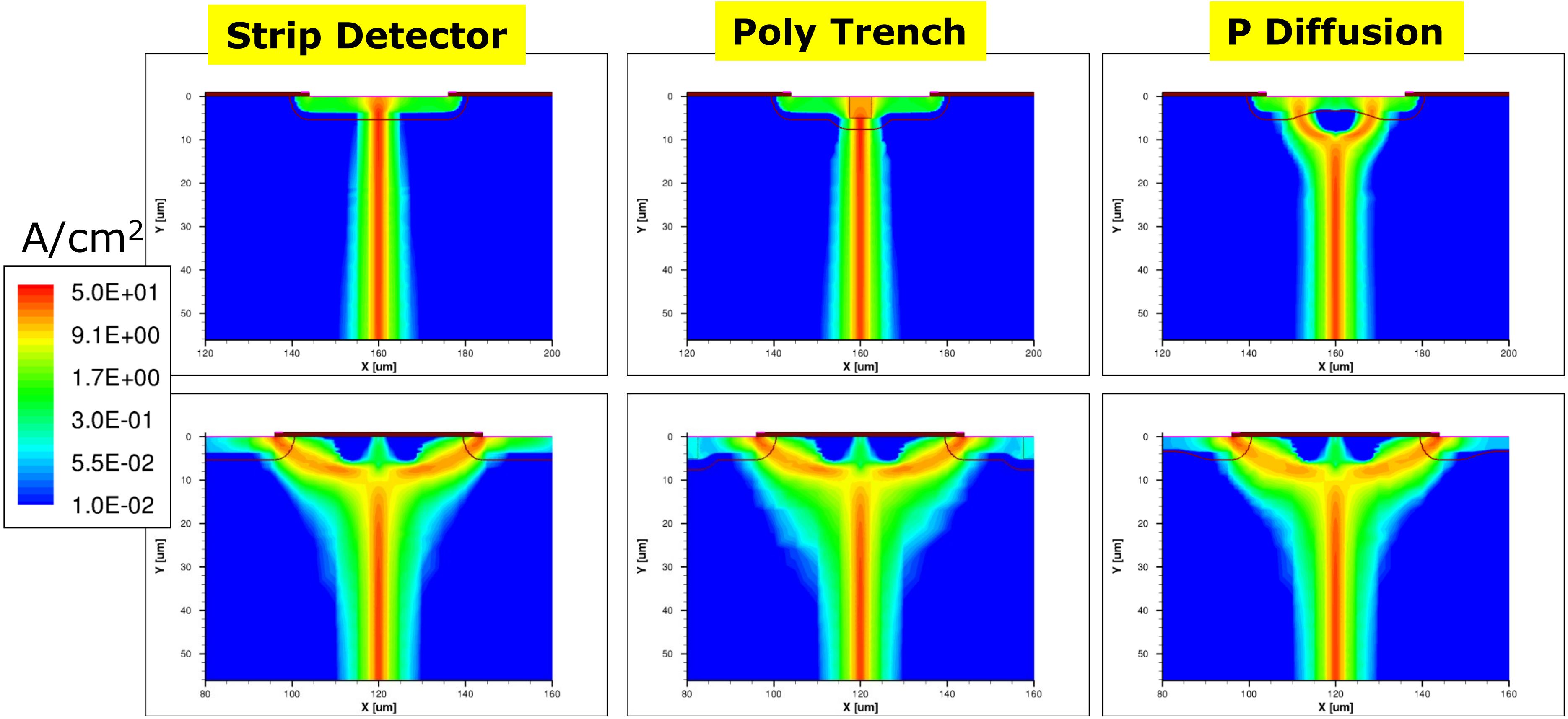


High Electric Field region driven deep in the bulk

Achieved Electric Field values are comparable with the irradiated devices



Simulation of charge collection: MIP

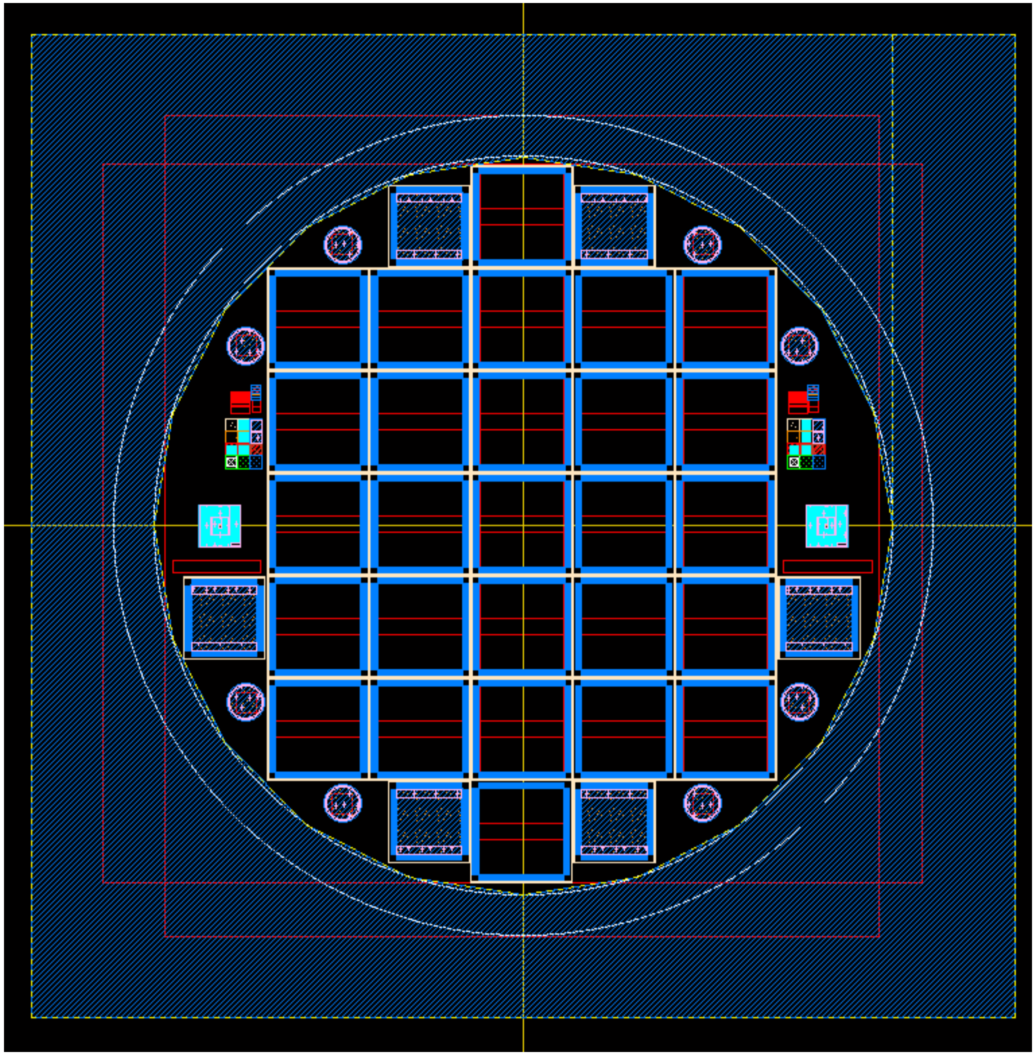


- ✓ We are developing a simulation procedure to obtain the gain value

Status of the Work: Fabrication

The fabrication run includes:

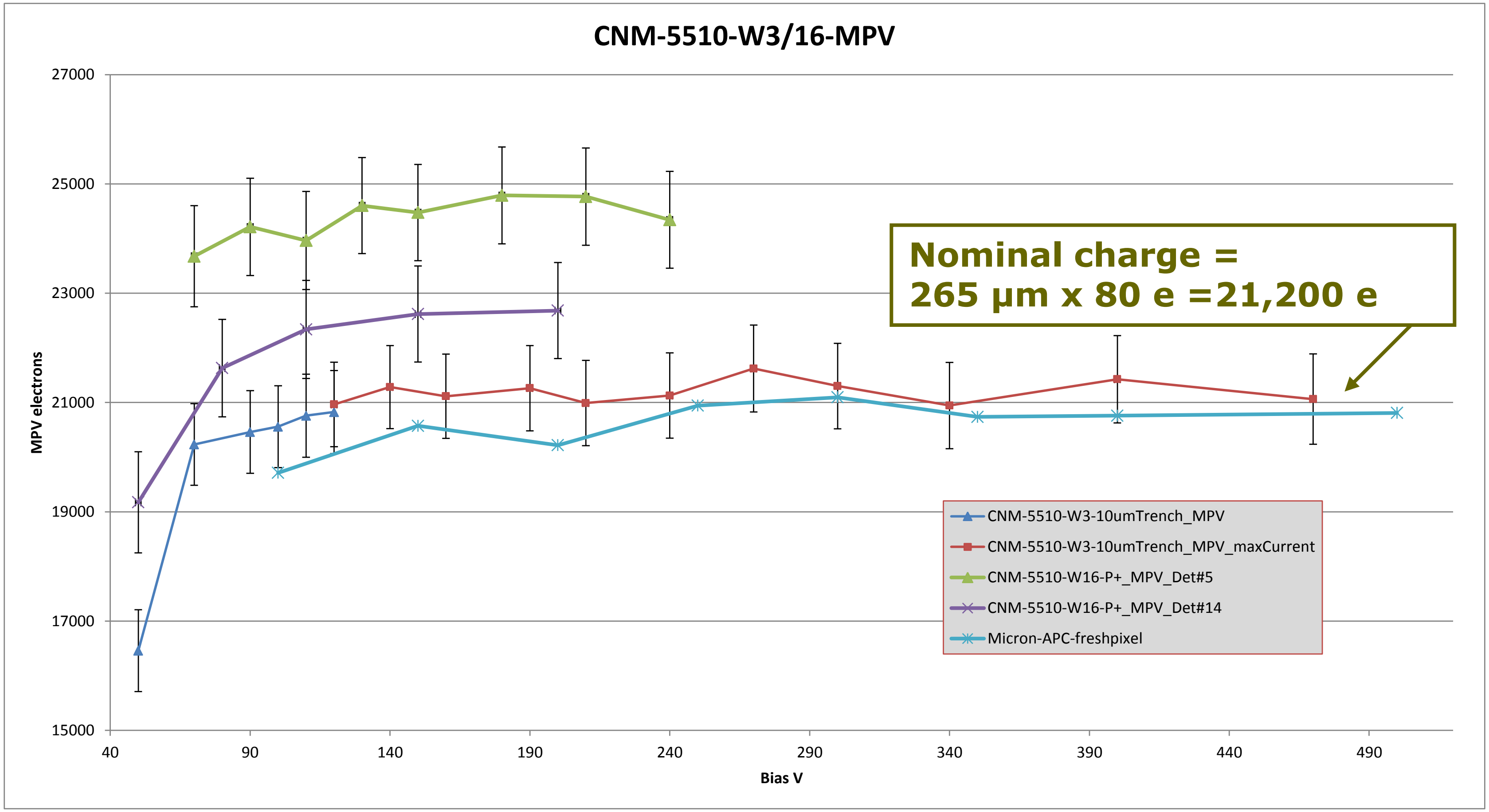
- **Conventional Strip Detectors**
- **Poly Trench structures with different trench depths:**
  - **5 µm**
  - **10 µm**
  - **50 µm**
- **Structures with small P layer along the center of the strip**
- **Devices with large P layer along the center of the strip**
- **Oxide filled trench structures with a P layer implanted through the trench:**
  - **5 µm**
  - **10 µm**
  - **50 µm**



Preliminary results: Strip Diodes

Now measuring in Liverpool (G. Casse)

In the framework of CERN RD50



Nominal charge =
265 µm x 80 e =21,200 e