Design and characterization of Low-Gain Avalanche MAPS in 110nm CMOS

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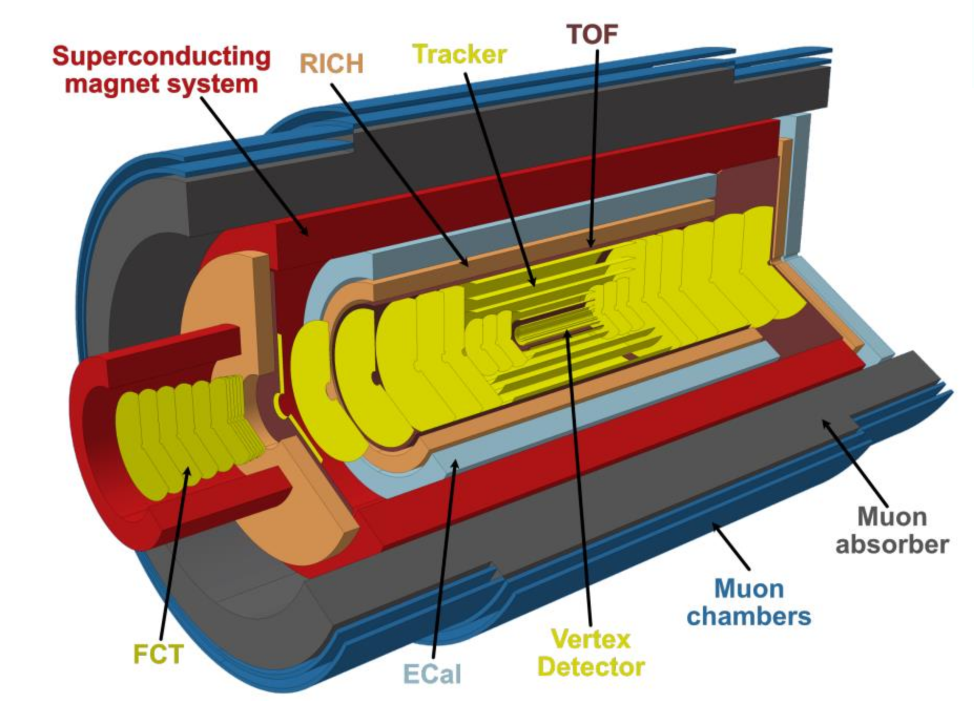
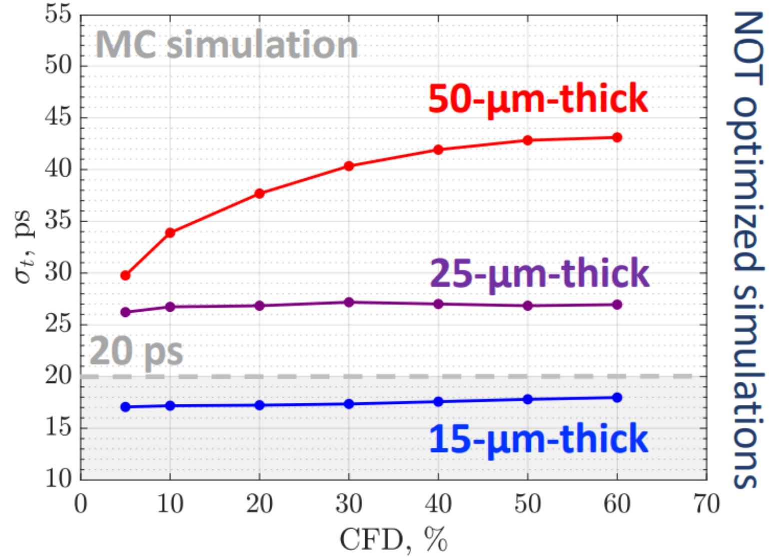
Outline

- Introduction
- CMOS LGADs in 110nm CMOS: summary of test devices
- Simulations and experimental results
- Work in progress

Motivation

- Main driver: **ALICE 3 ToF layers**
- Timing layers resolution: 20ps
- Constraints:
  - Power consumption
  - Material budget
  - Cost
- Monolithic timing detectors are considered as a possibile option
- Other fields: 4D tracking, very low power pixel sensors, medical applications



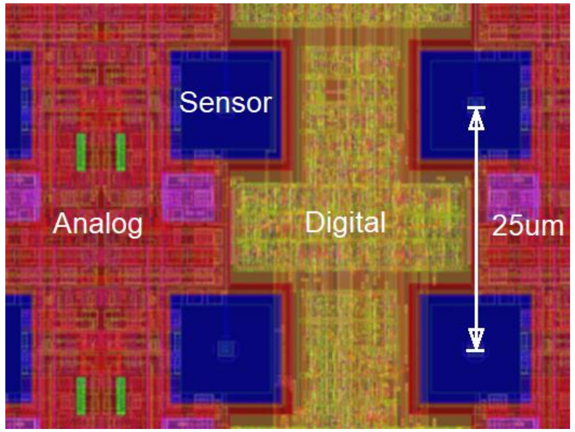


Starting point: ARCADIA monolithic sensors

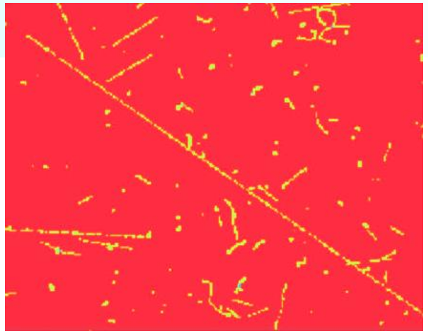
- Fully depleted MAPS in 110nm CMOS
- Different **thickness** options: **48µm, 100µm, 200µm** (full depletion demonstrated up to **400µm**)
- Target applications:
  - medical imaging (PCT)
  - space applications
  - HEP experiments
  - X-ray imaging
- Main Demonstrator (MD) with sensor array made of 512x512 pixels with **25µm pixel pitch**
- **Binary pixels** with **event-driven** readout
- 3 engineering runs: 1st (mid 2021), 2nd (beginning of 2022), 3rd (beginning 2023)

Includes monolithic LGADs

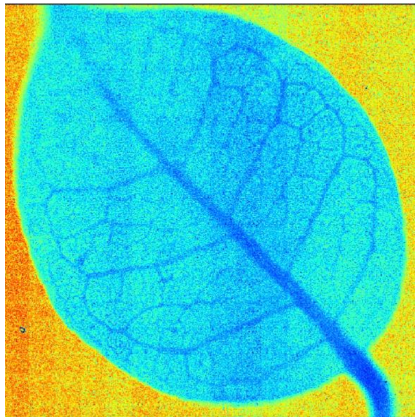
Andrea Paternò, Vertex 2021
ARCADIA Main Demonstrator chip



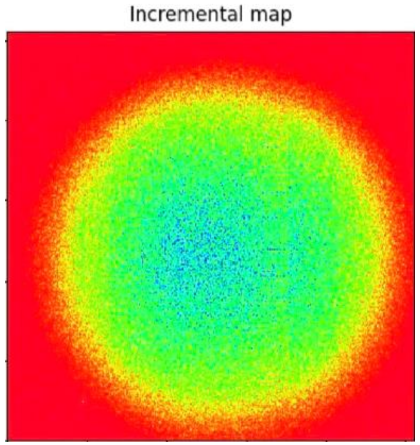
M. Rolo, **Pixel layout**



Cosmic rays

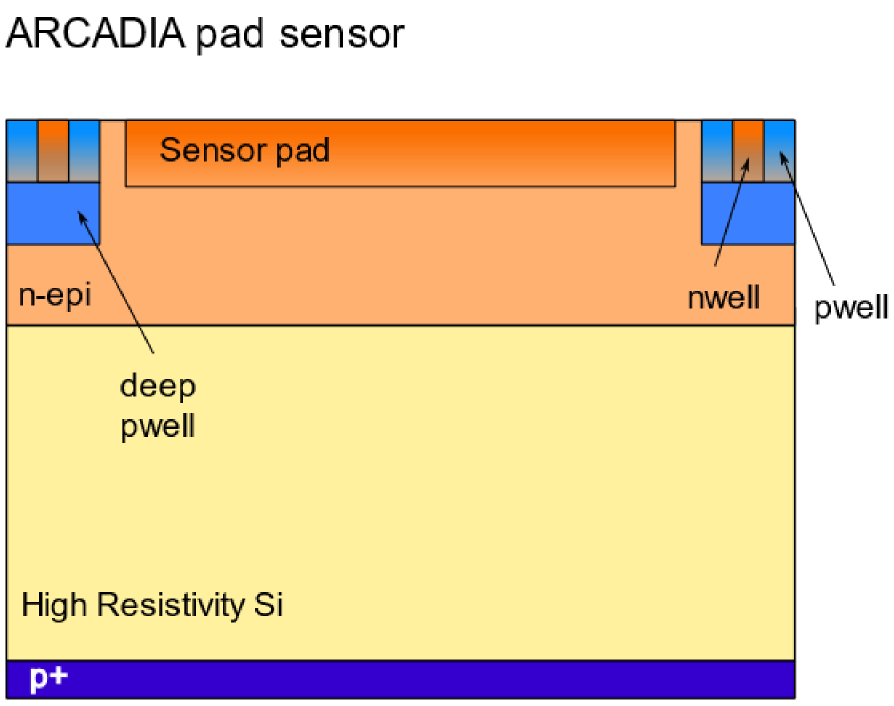


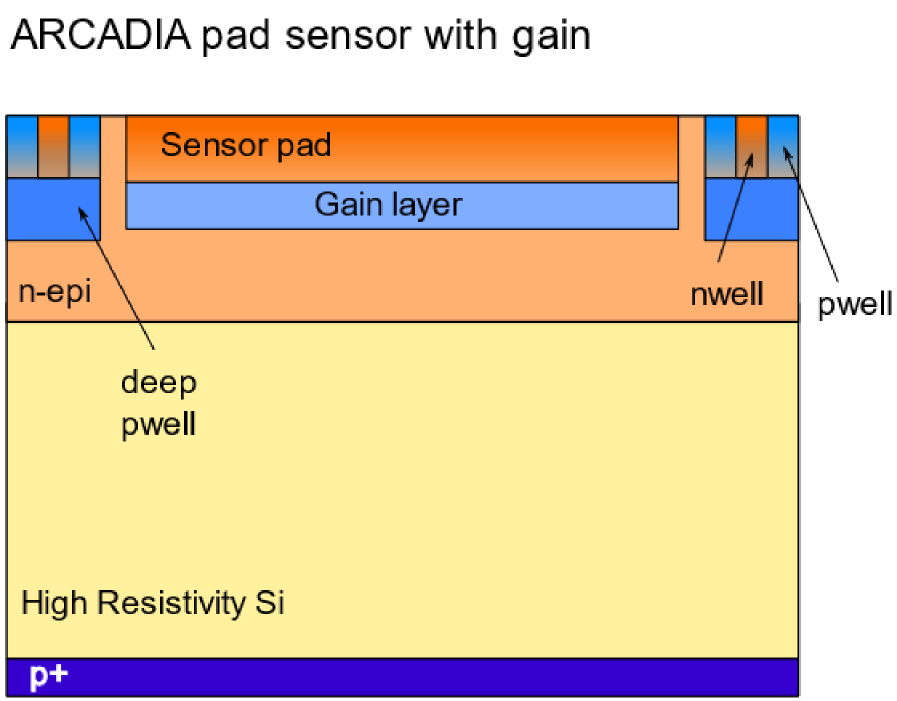
X-ray Image (photon counting mode)



^{90}Sr source

ARCADIA MAPS: gain add-on option

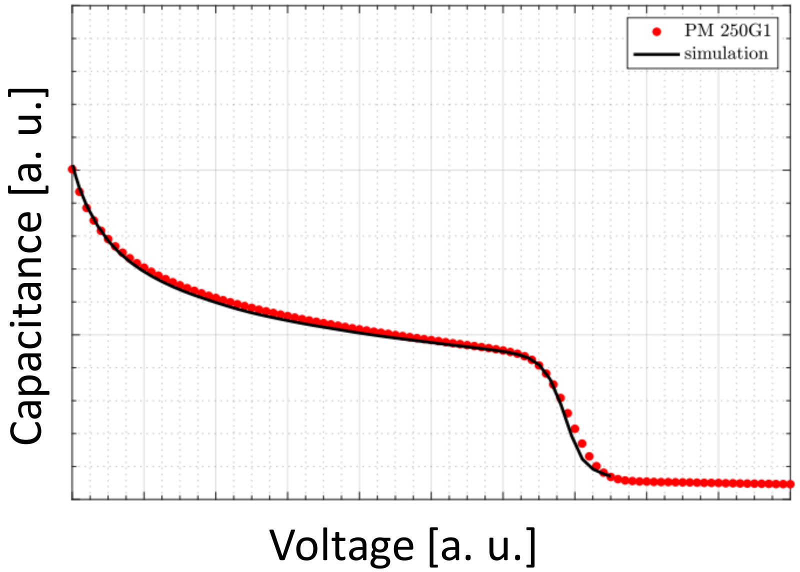


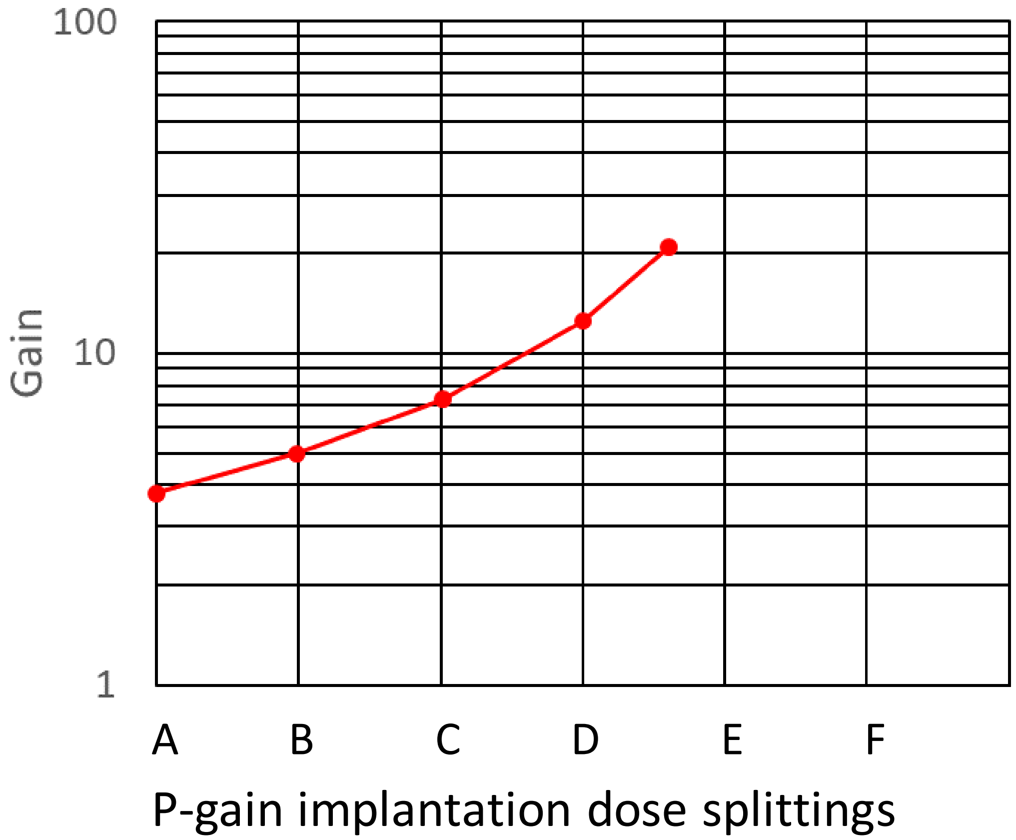


- ARCADIA engineering run (LFoundry **CMOS 110nm with 48µm active thickness**) used to integrate passive and active test structures with gain, starting from 3rd run.
- Process add-on: **gain layer implantation**
- Requires negative voltage applied at the backside, positive voltage at the sensor pad and **AC coupling** of readout electronics.

Gain dose splitting

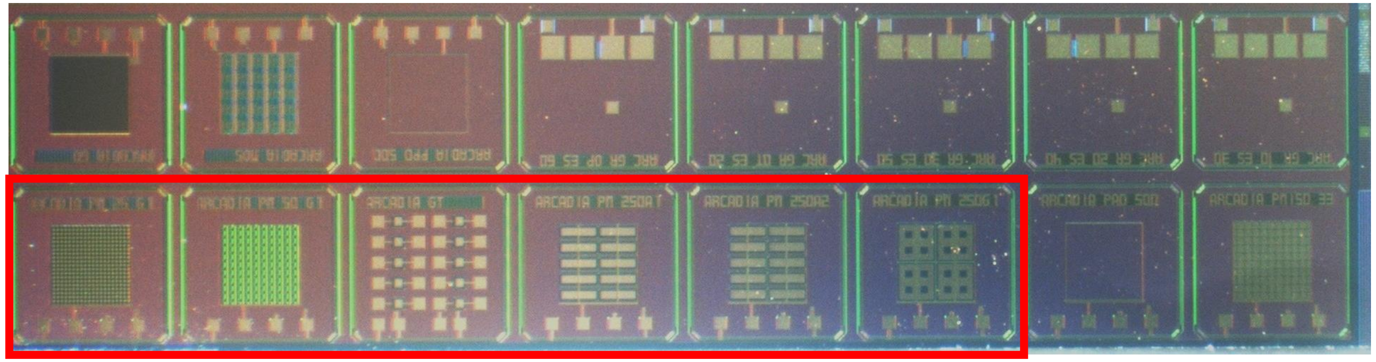
- Last fabrication run: **short loop** (using ARCADIA 3rd run mask set). Devices available early september 2024
- **6 dose splittings** (to cope with uncertainties and variability) + a split with no gain
- **Nominal gain** estimated using profiles extracted from CV curves in a previous production run

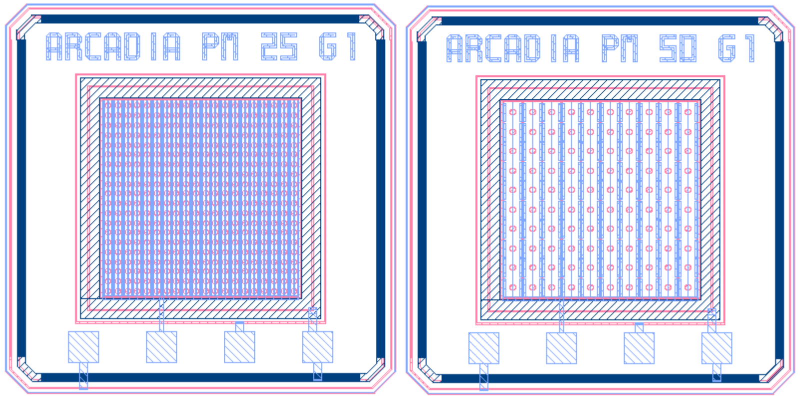




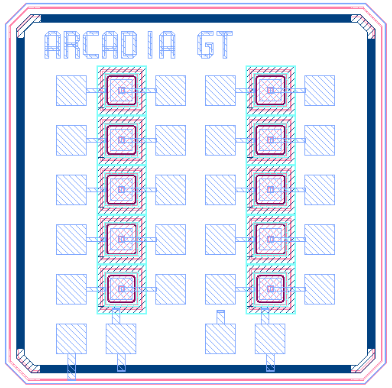
Passive test structures layout

Designed for test at the probe station and with external amplifiers

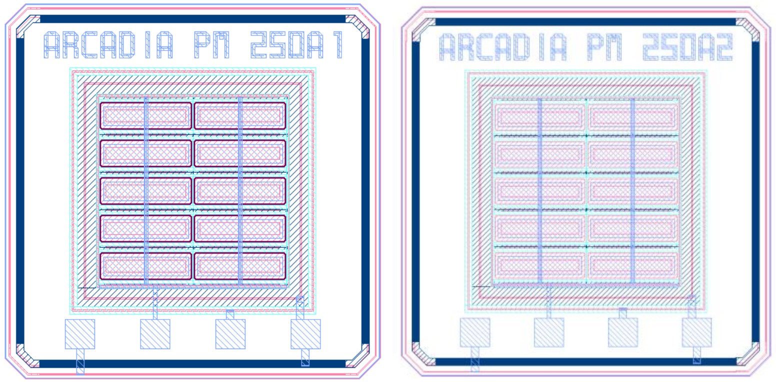




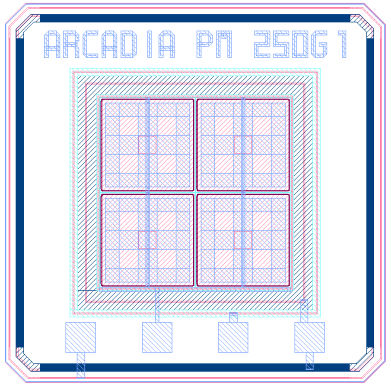
Small passive pixels with **25µm x 25µm** and **50µm x 50µm** Pixel size



Test pads with variations of termination geometry

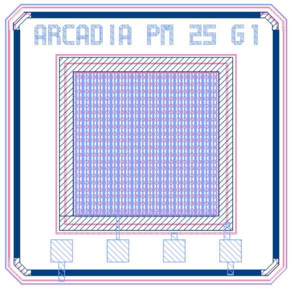


A1 and A2: Rectangular passive pads active area **250µm x 80µm**

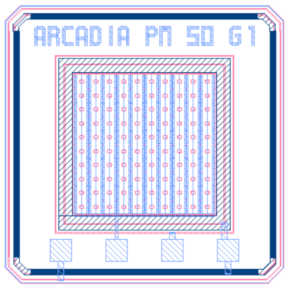


Square passive pads with large fill factor: **250µm x 250µm**

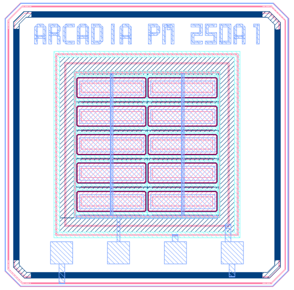
Test devices: junction termination



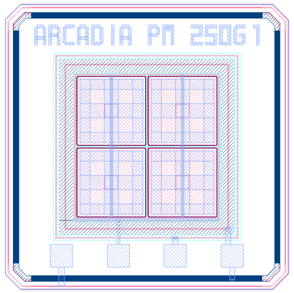
25µm x 25µm



50µm x 50µm

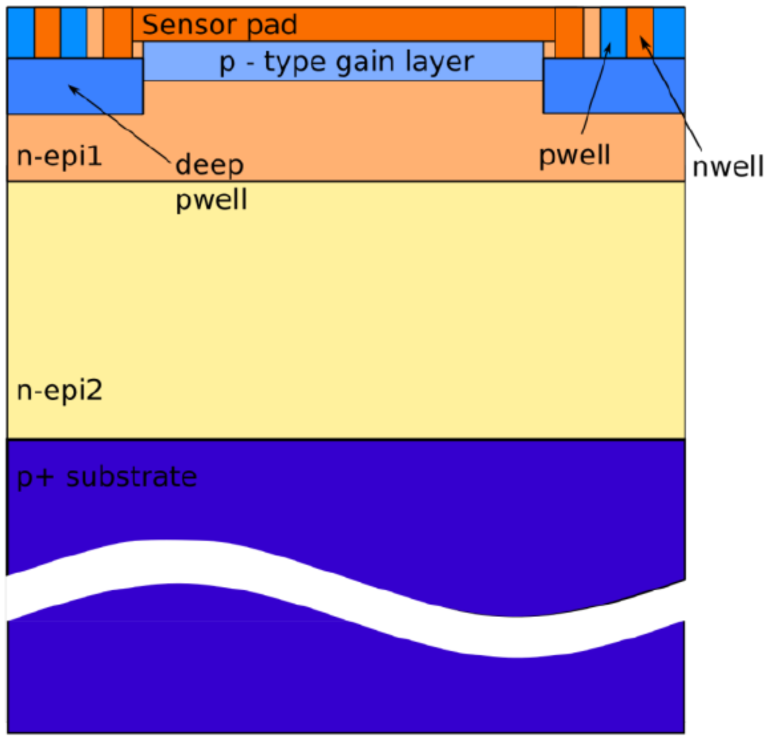


250µm x 80µm

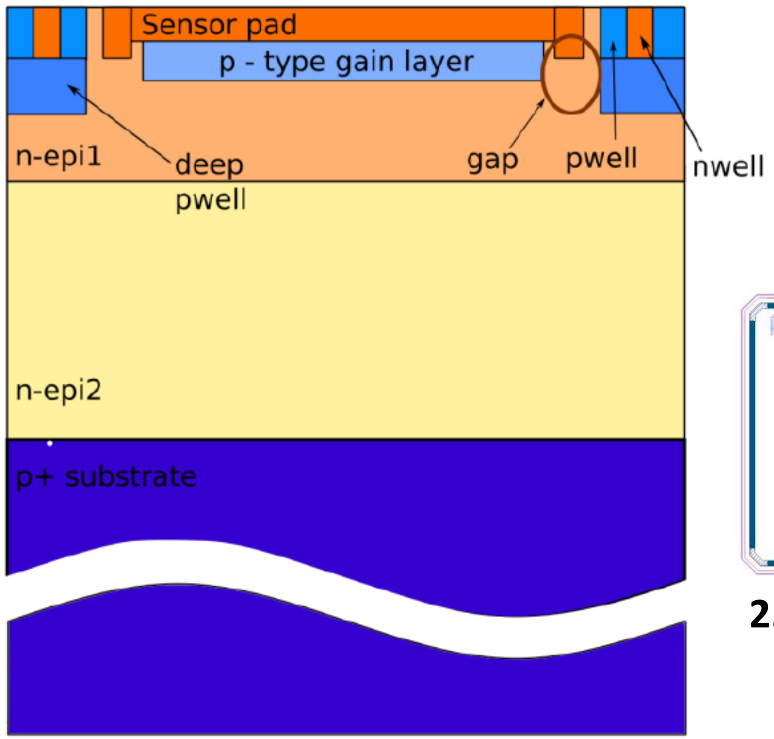


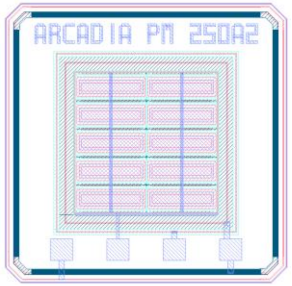
250µm x 250µm

Termination layouts A1-G1



Termination layout A2





250µm x 80µm

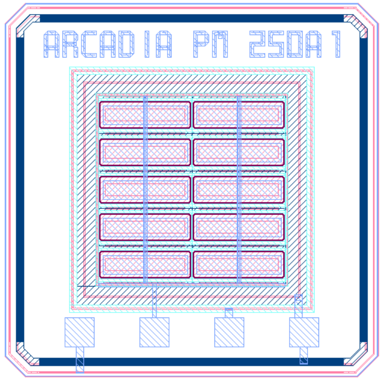
deep pwell below the junction termination: electrons generated below the deep pwell reach the gain layer

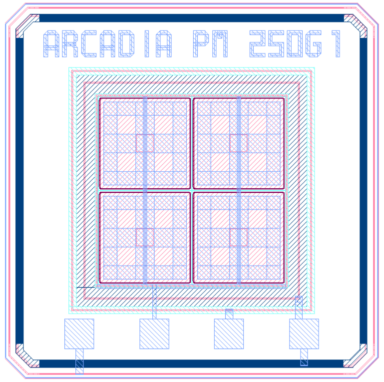
Termination directly facing the active region: electrons generated below termination can be collected without gain (same as «standard» LGADs)

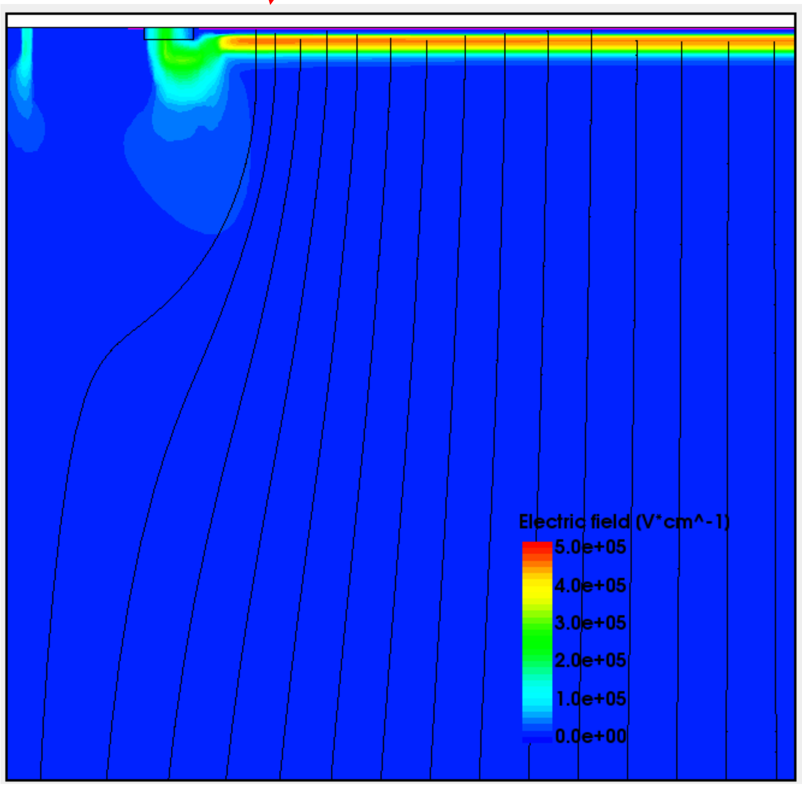
Test devices: electric field lines

All the field lines cross the gain region:
- **100% fill factor**
- non-uniform gain and timing

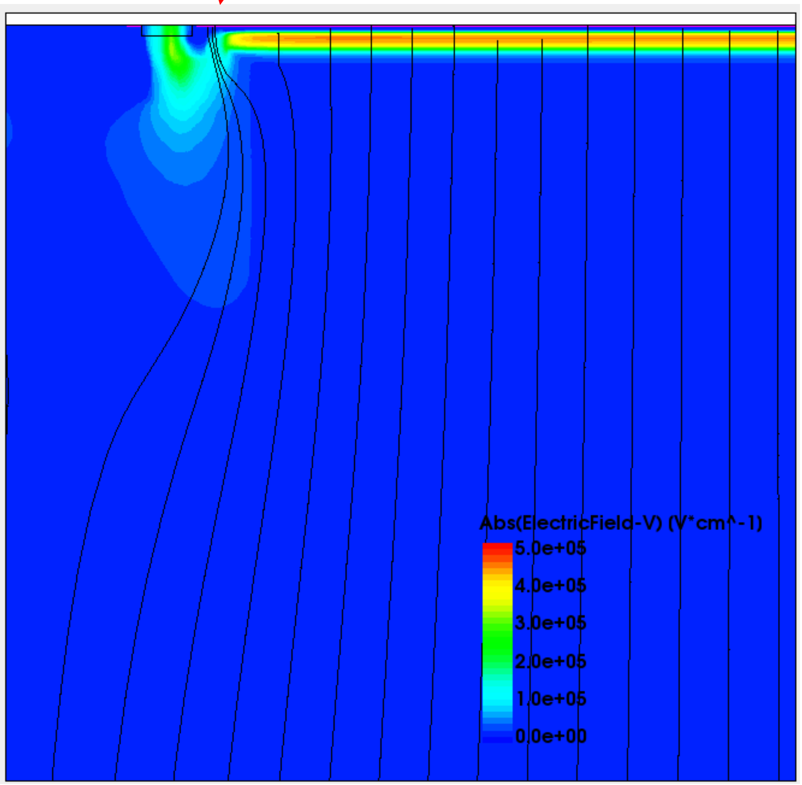
Peripheral field lines don't cross the gain region:
- «dead area» at the borders with gain 1
- **better for timing** uniformity



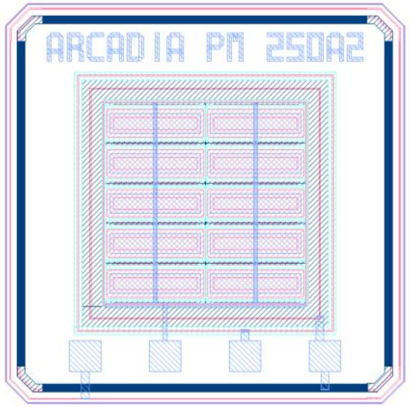




Layout A1 and G1



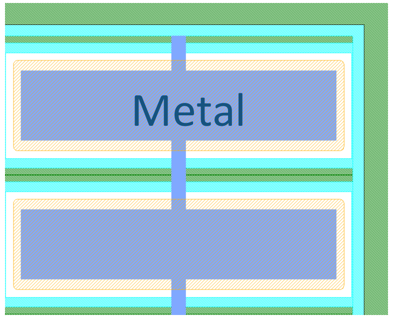
Layout A2



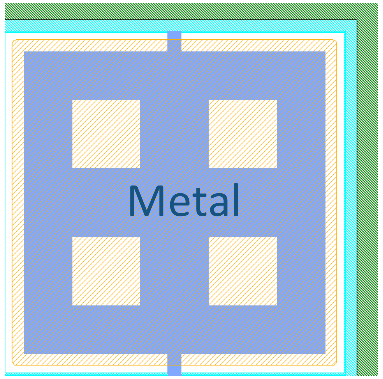
Quasi-static characterization: experimental gain with top illumination

Gain measured with **DC NIR light** (850nm) flood illumination from top surface:

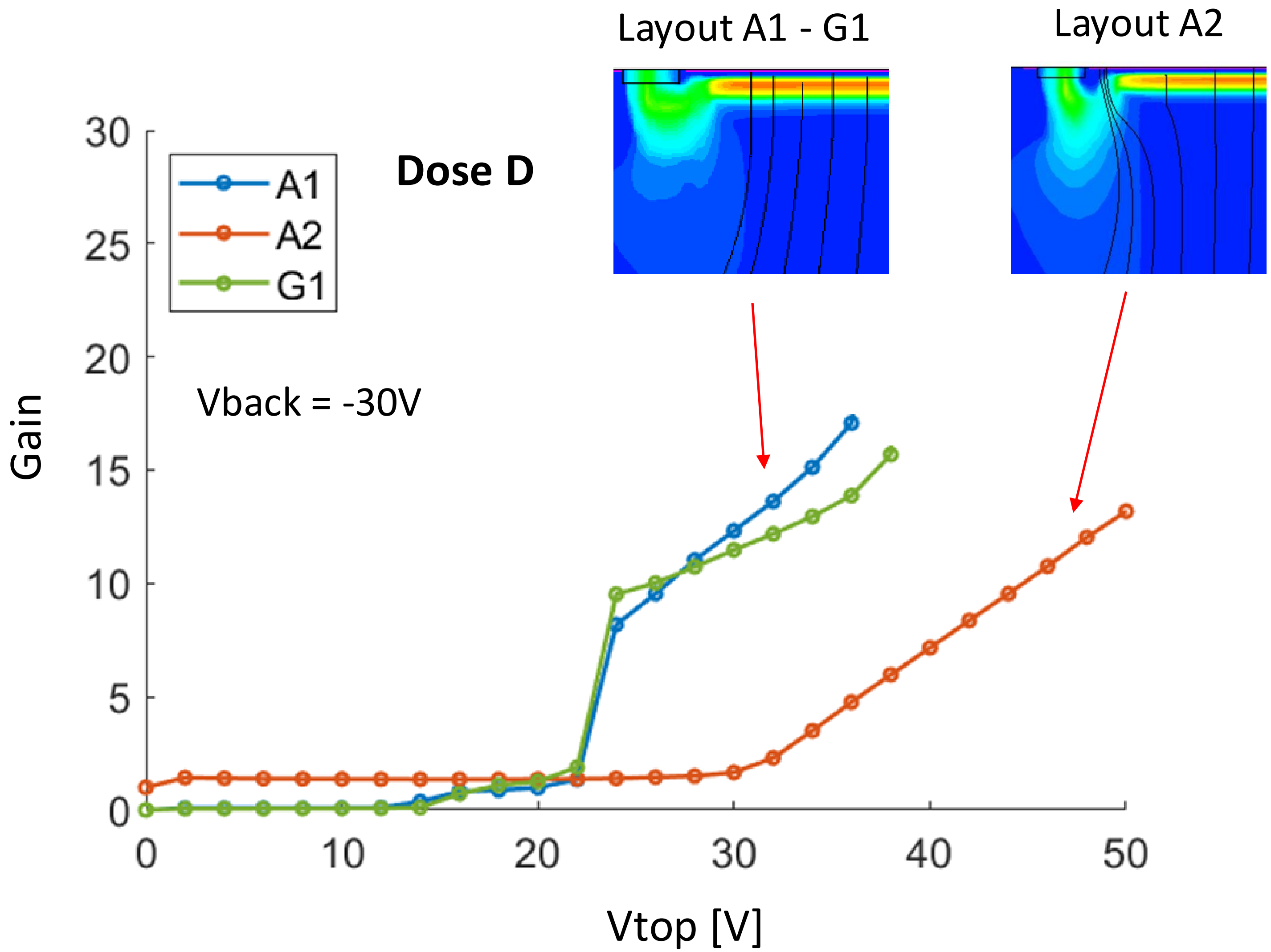
- A1 and A2: edge only
- G1: contribution from the device center



A1 and A2 layout

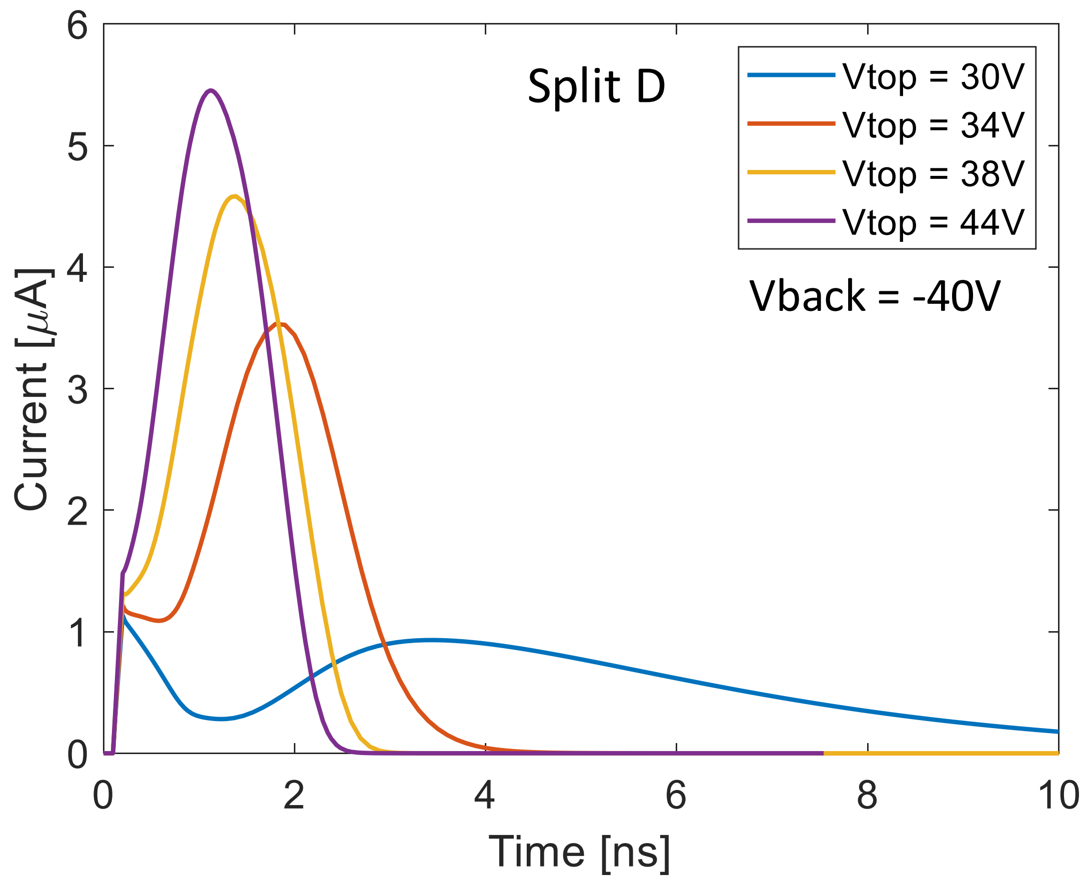


G1 layout

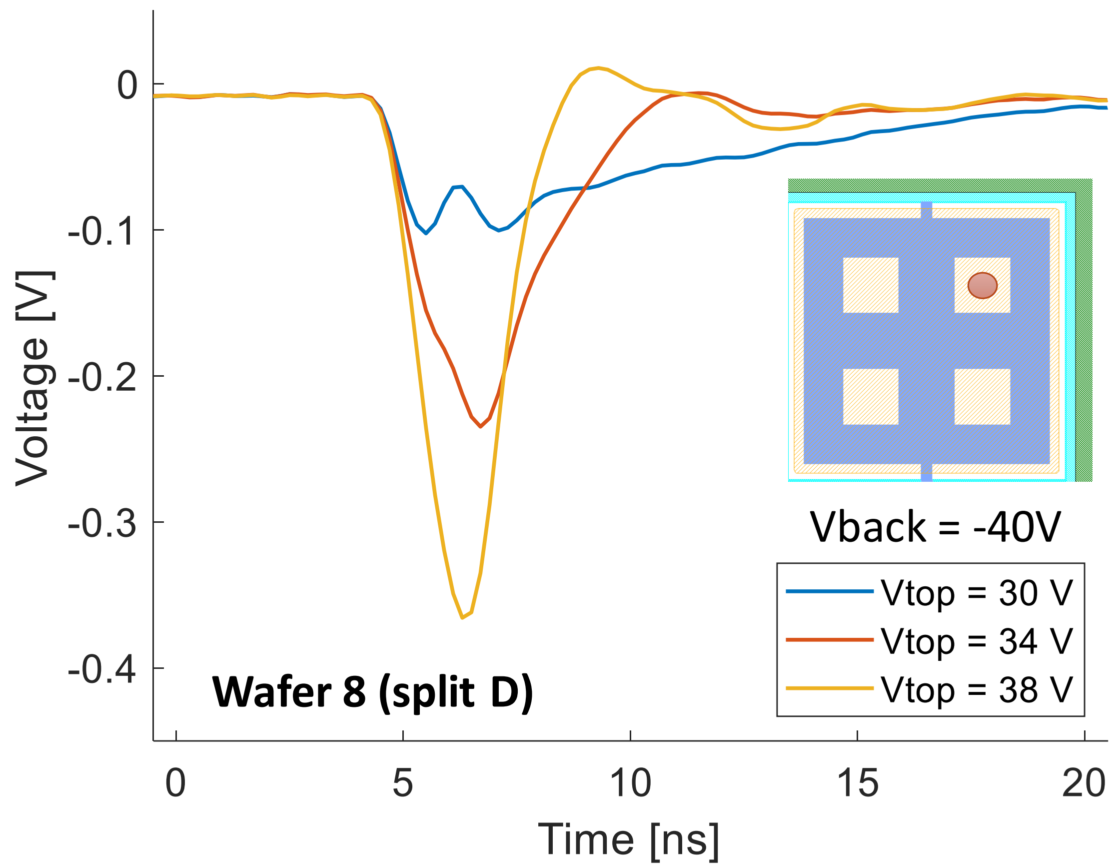


Signal shape – TCAD simulation vs. experimental data

- **TCAD** simulations with MIP-like signal (80 e-h pairs per µm)



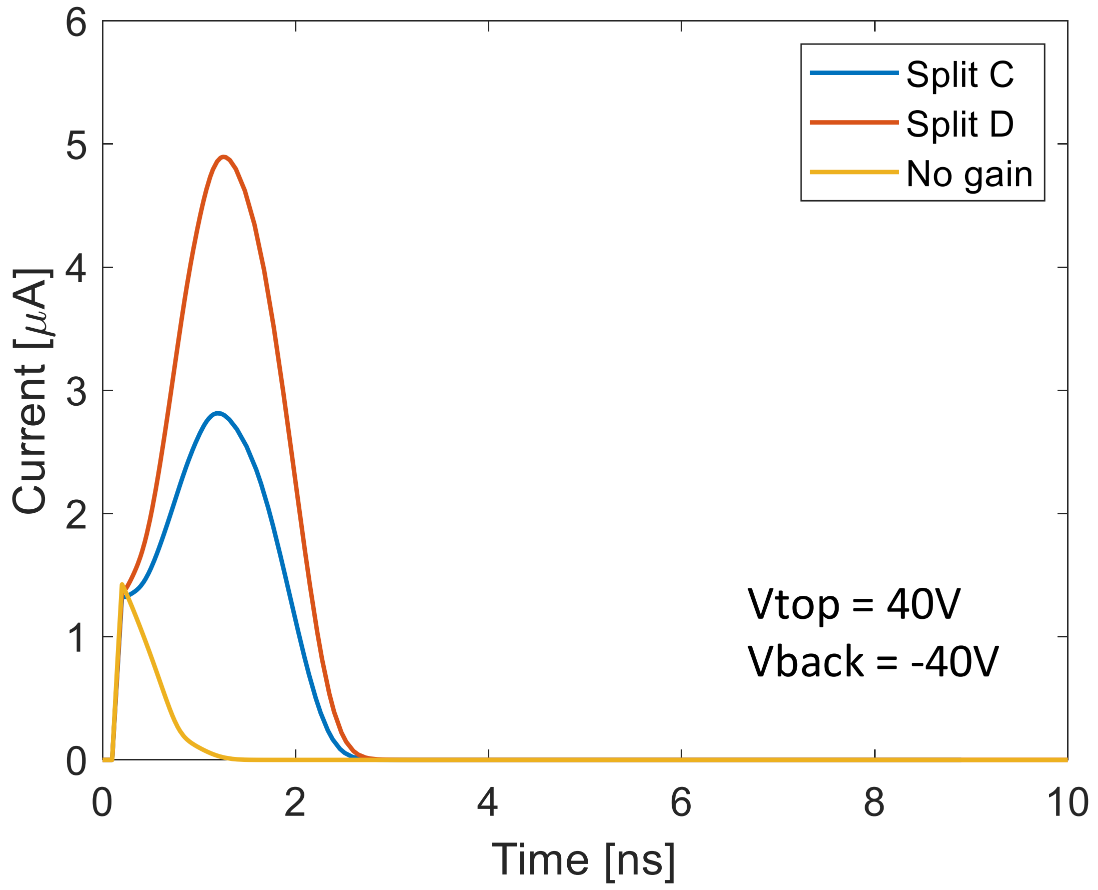
- Front side illumination with a **focused picosecond pulsed IR laser** (1060nm)
- Sensors connected with broadband amplifier (Cividec, 2GHz)

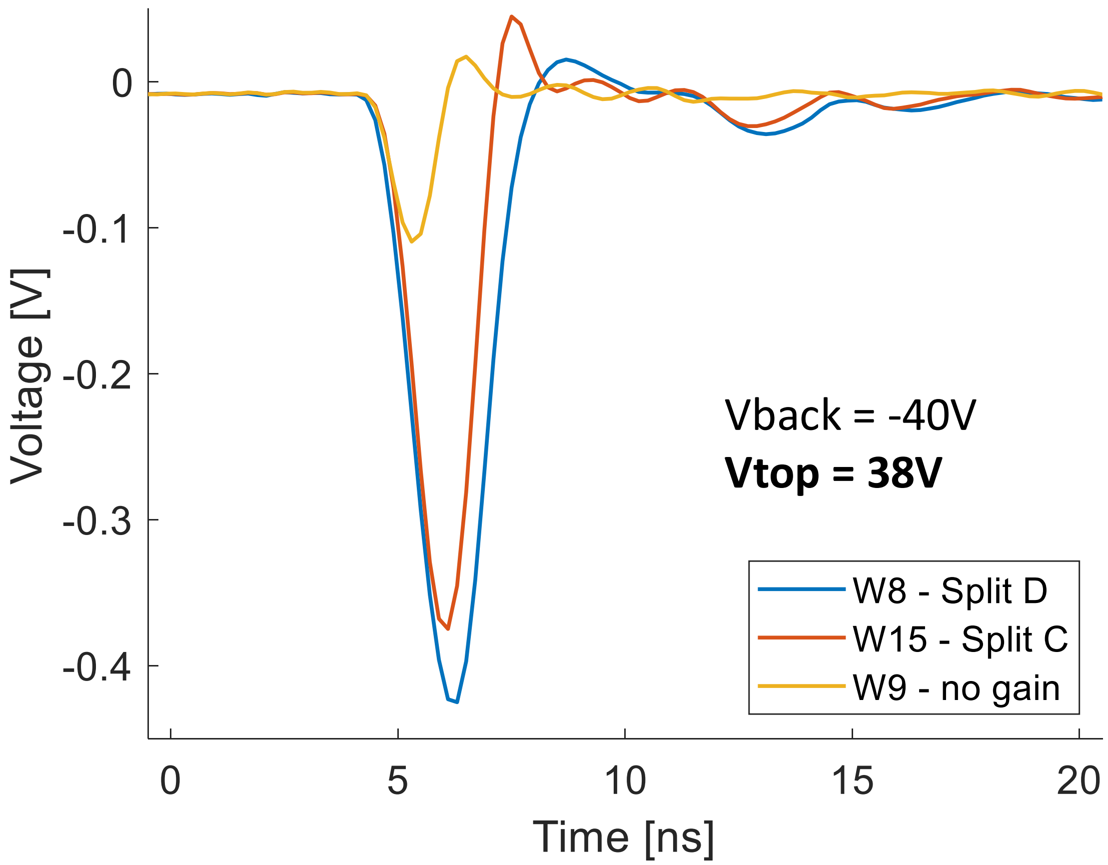


Signal shape – TCAD simulation vs. experimental data

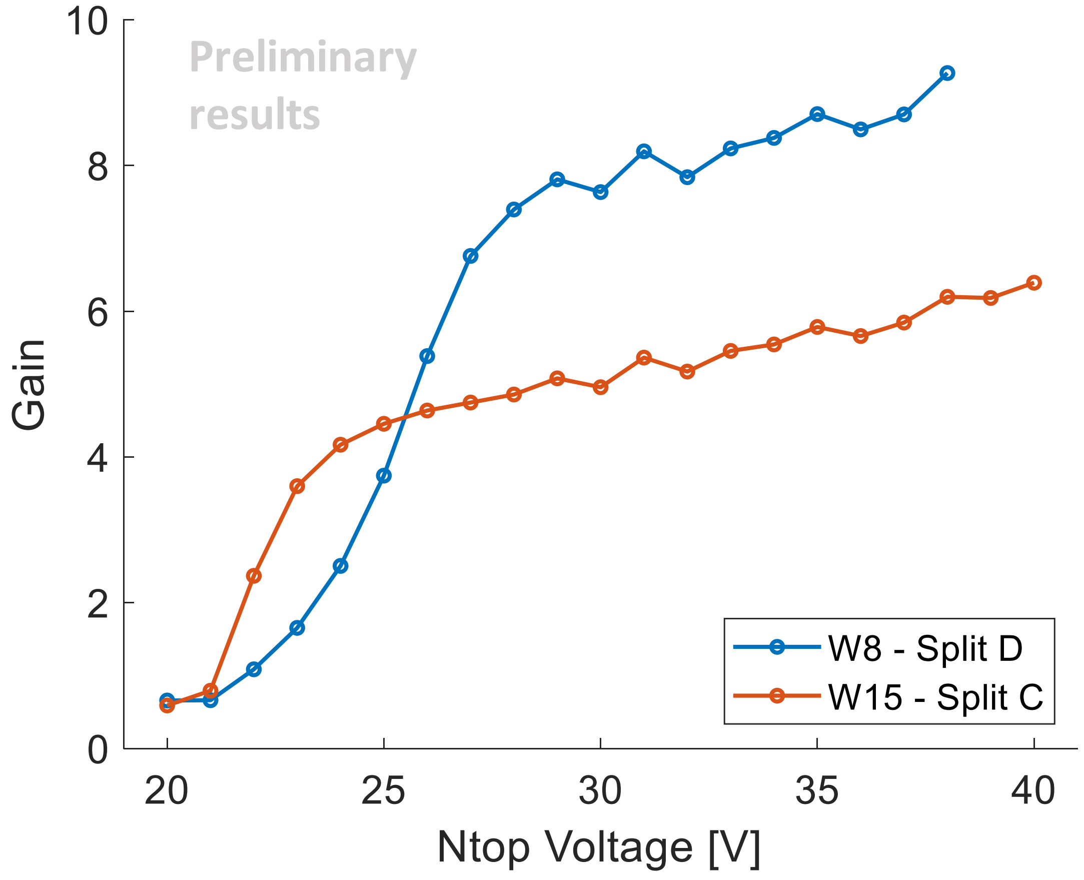
Effect of **gain layer dose**

Device from split D: as expected, gain is larger than in split C but signal is slower (at the same bias voltage)





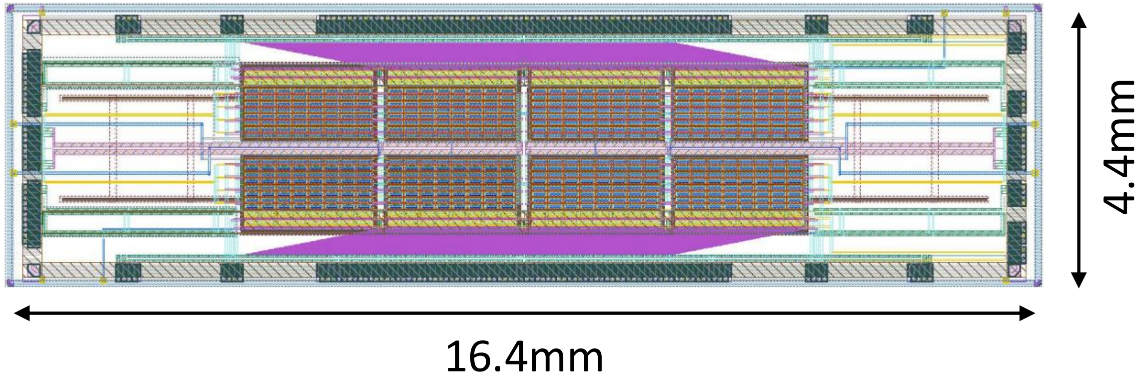
Avalanche gain: IR laser - pulsed mode



- Maximum top voltage limited by **edge breakdown**
- Results may be affected by **space charge effects** (to be investigated)
- Higher voltages can be applied on A2 devices, but the device center cannot be illuminated on front side
- **Planned:** TCT characterization with IR laser with back-side illumination and radiation sources

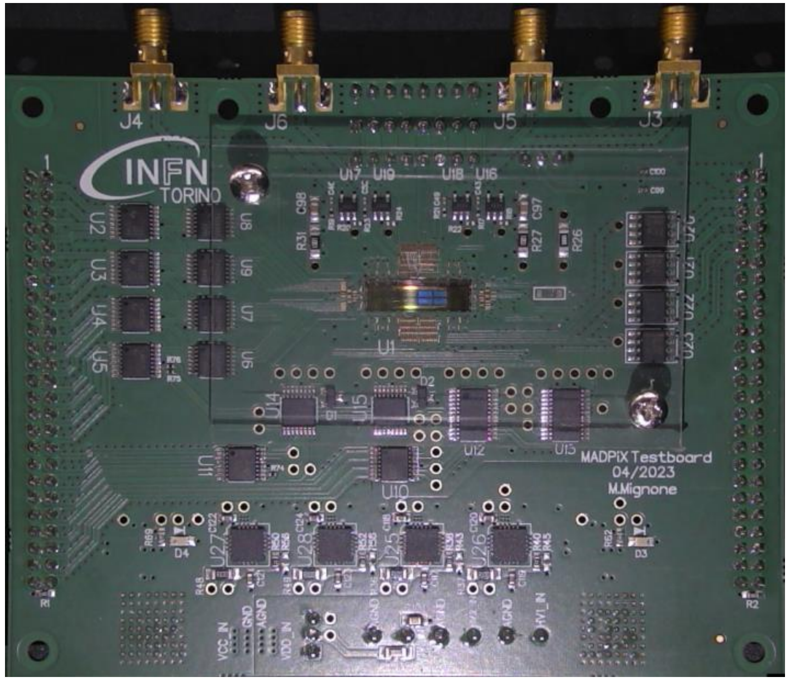
Sensors with integrated electronics: MadPIX chip

- Pixel array with integrated pre-amplifiers and buffers
- Sensors size: **250µm x 80µm** (A1 and A2)
- Power: 0.18mW/channel (pre-amplifier)

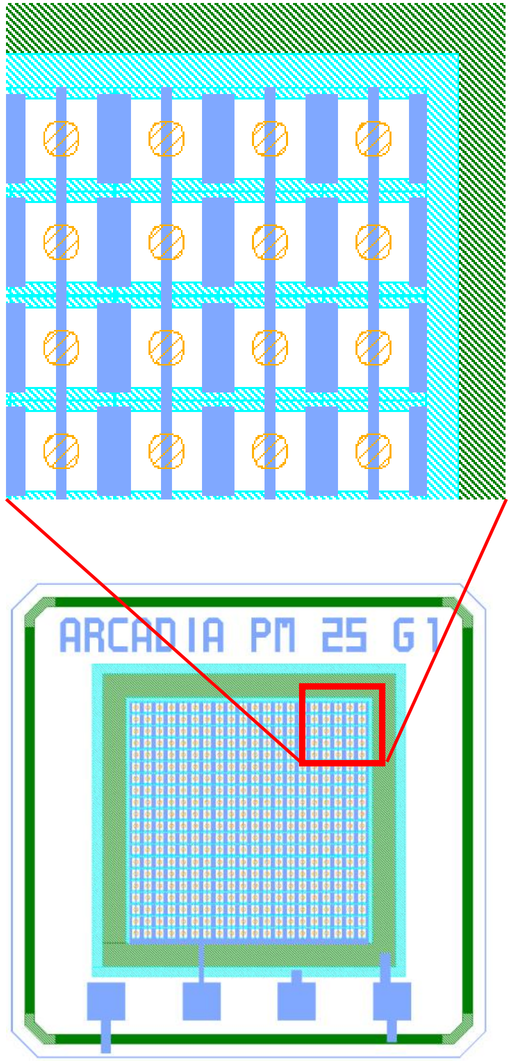


Timing resolution with MIPs: **74ps** with **gain = 13** (preliminary analysis from October test beam)

To be improved:
- Reduced sensor thickness
- Sensor geometry (width/thickness)
- Optimize front-end electronics



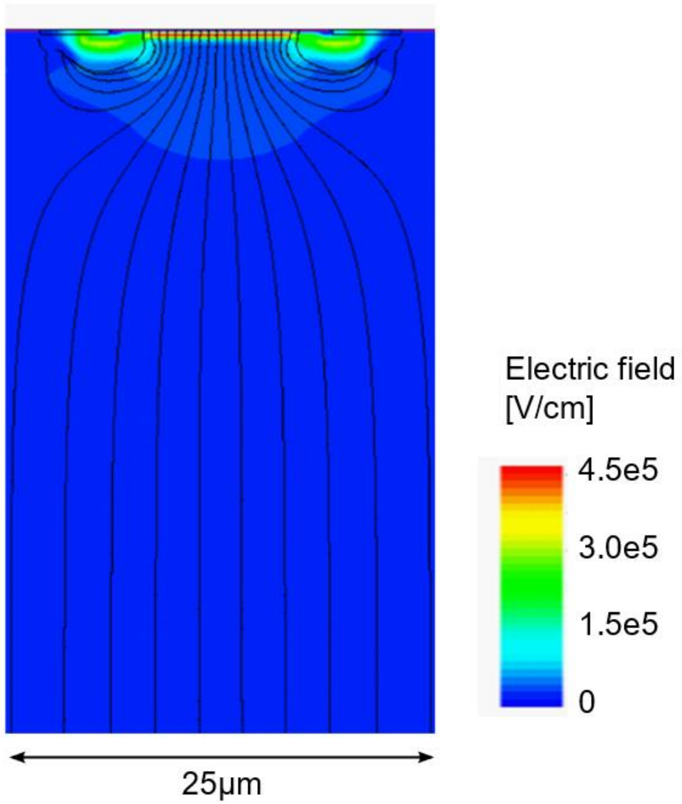
Small pixels – 25μm pitch



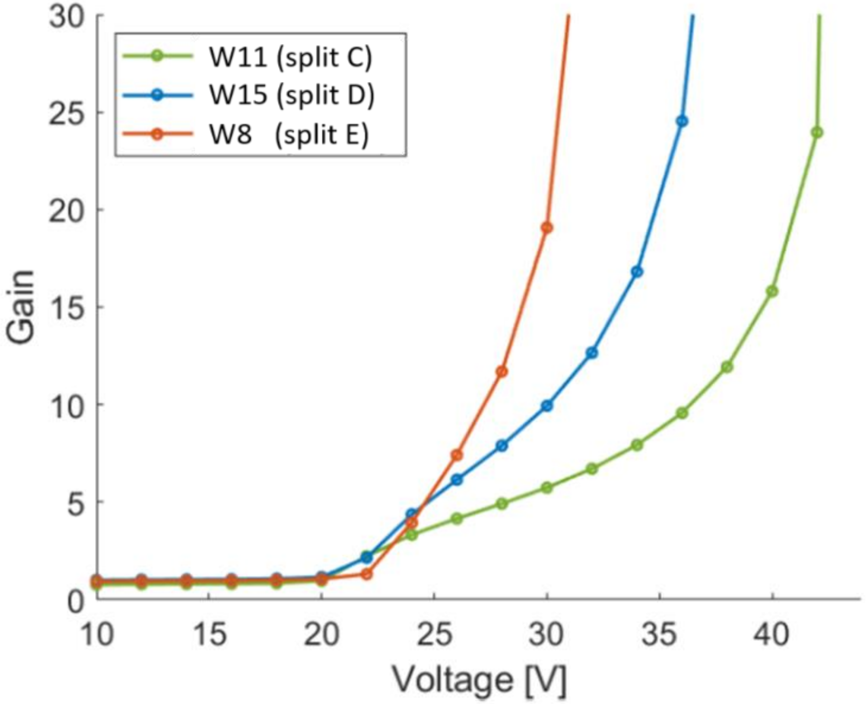
Test structure layout – zoomed detail

Termination: the electric field lines converge into the gain region: all the generated electrons undergo avalanche multiplication

TCAD-simulated electric field



DC gain measured on 3 pixel arrays with NIR Light (850nm) flood illumination

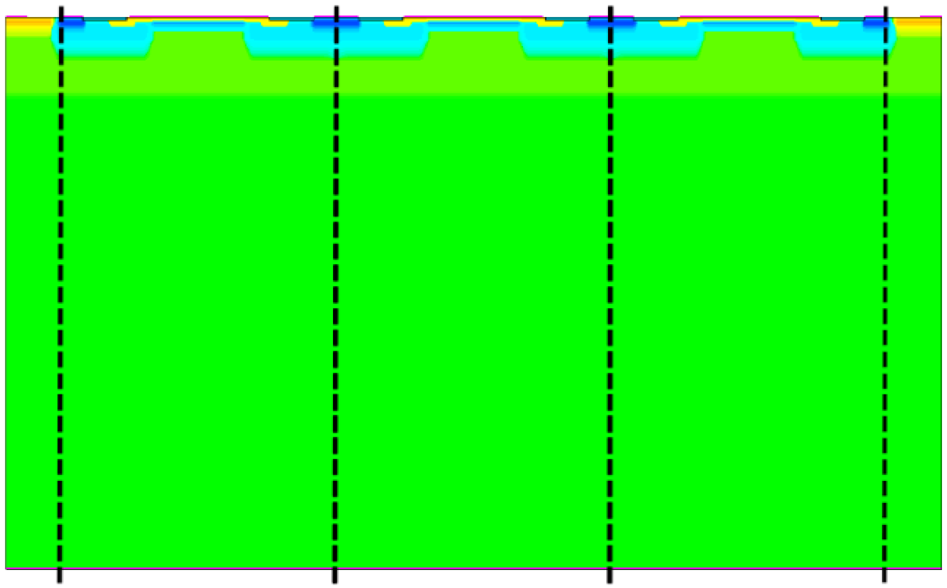


Small pixels – gain non-uniformity

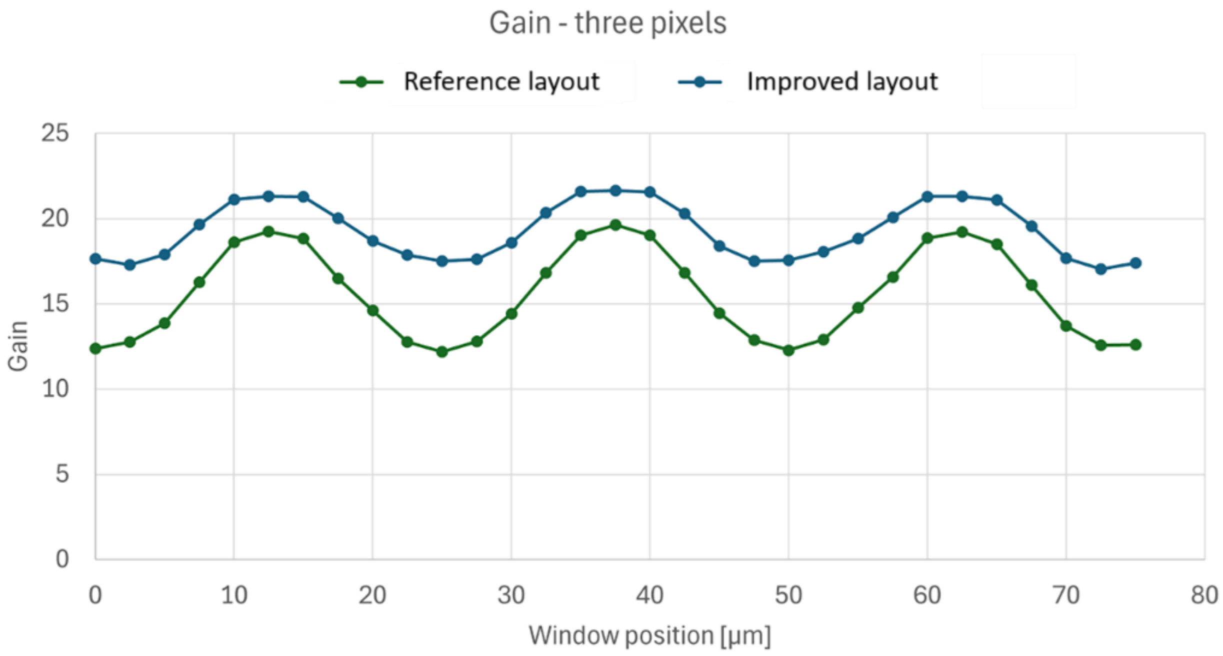
The electric field is non-uniform across the gain window: gain is larger in the pixel center

Work in progress:

- Gain non-uniformity experimental characterization (TCT)
- Layout parameters tuning for improved uniformity (TCAD)



3-pixel TCAD simulation domain



Simulated gain vs. radiation incidence position

Work in progress

- **Analysis**
  - Complete analysis of **test beam** data
  - Compare MC prediction with test beam results
  - Tune simulator parameters on experimental results

- **Sensors design (TCAD + Monte Carlo)**
  - Simulation of thinner (15 – 25µm) and larger (200 – 300µm) devices for improved timing resolution
  - Optimize sensor **termination**

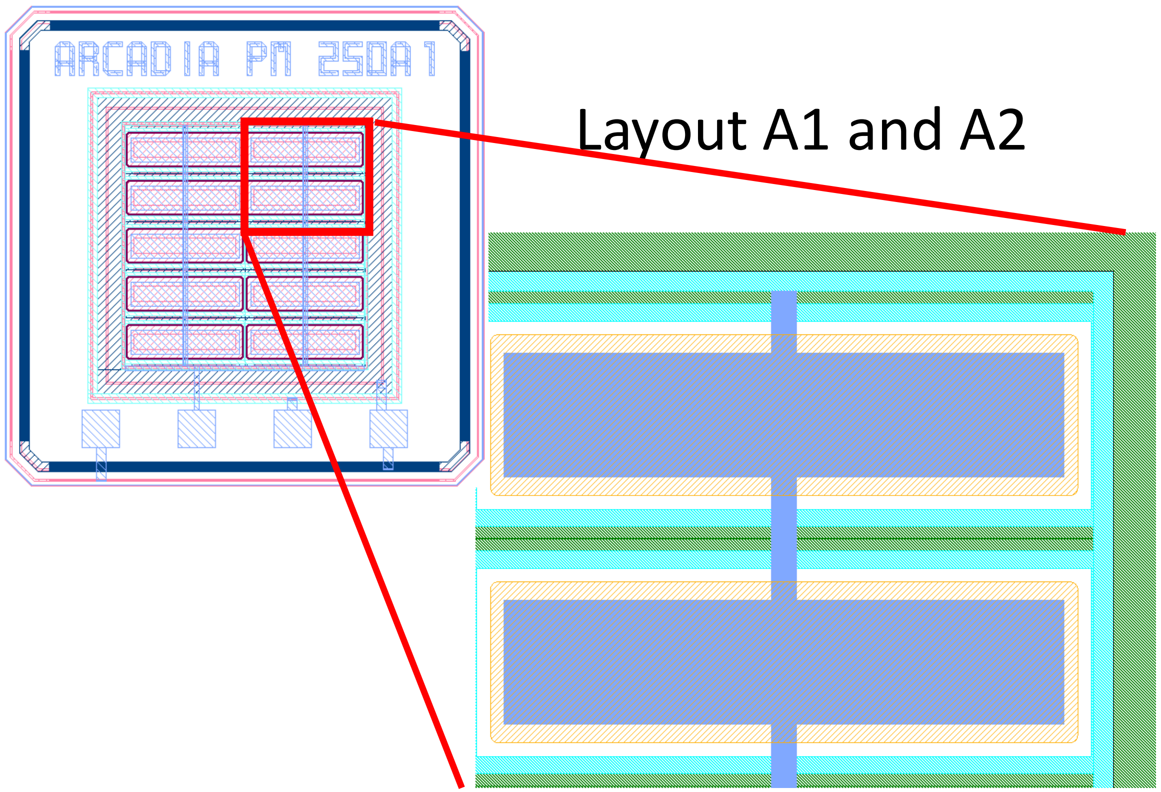
- **Electronics:**
  - design of integrated electronics for **new engineering run**

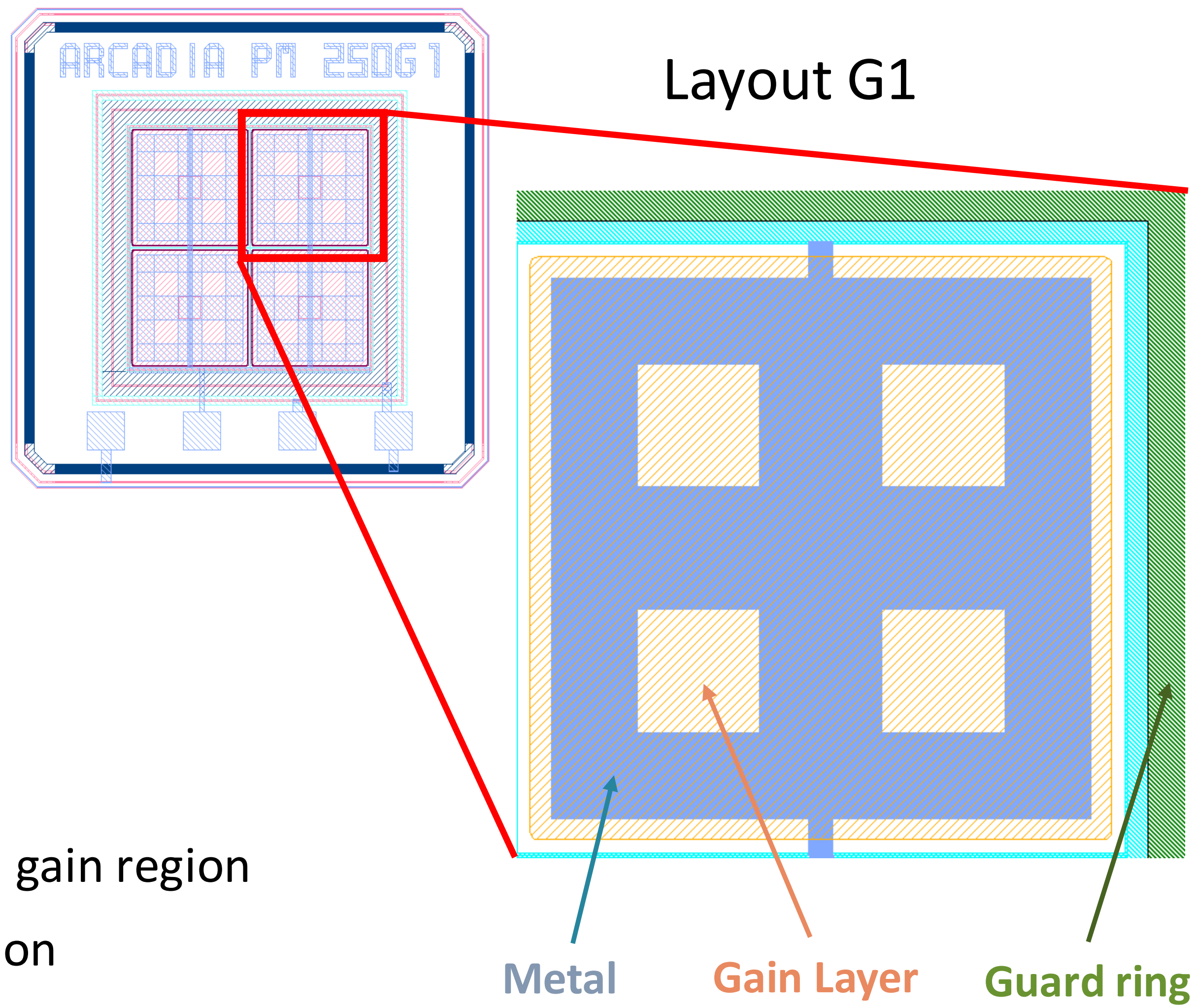
Thank you

Questions are welcome

Backup slides

Test structures layout: detail of surface metals

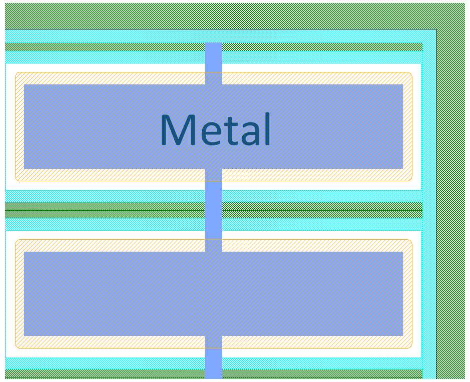




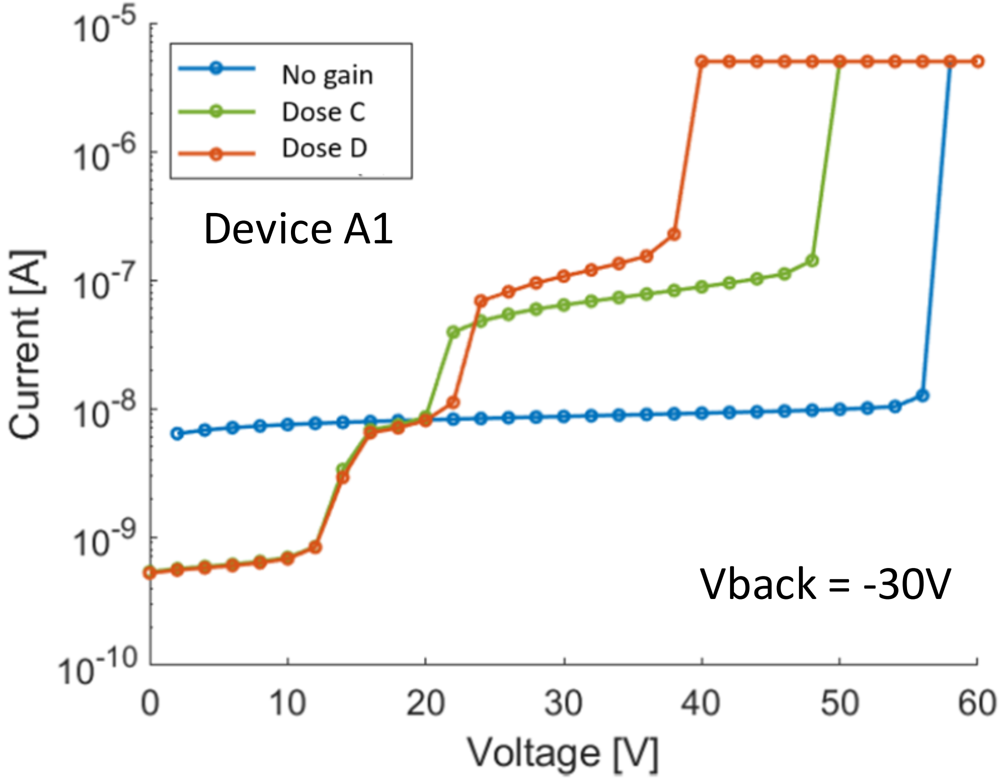
- A1 and A2: top-side illumination at the edges of the gain region
- G1: can be illuminated at the center of the gain region
- Backside illumination (only available for bonded devices)

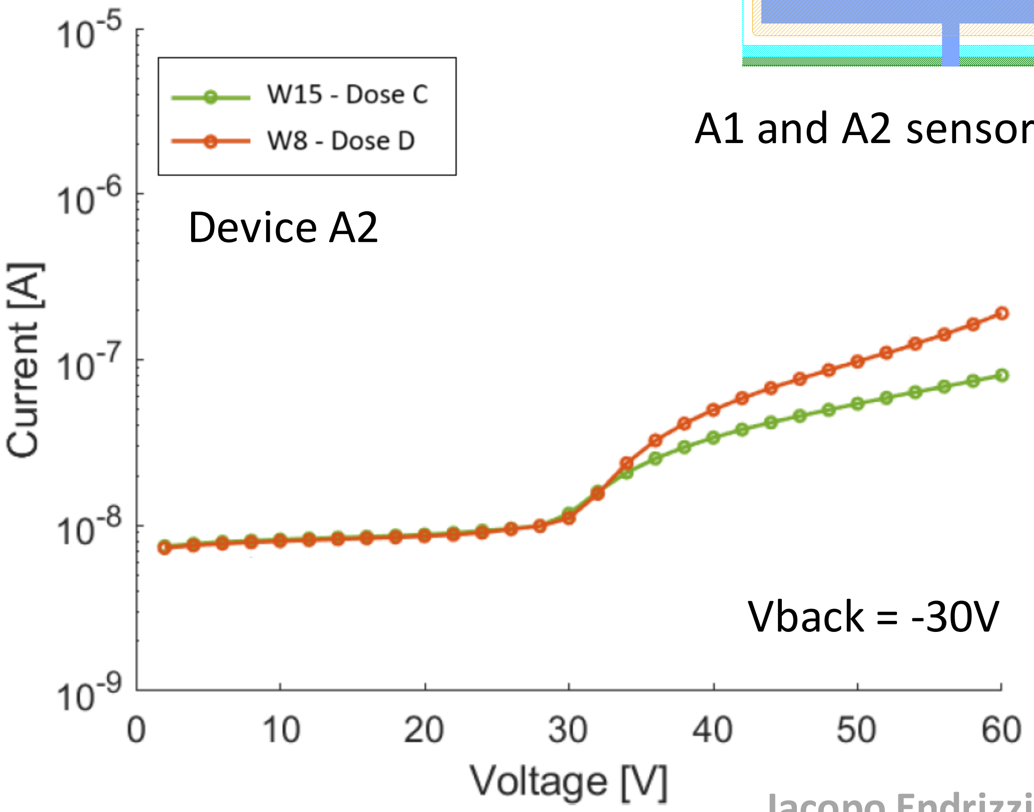
Quasi-static characterization: I-V curves with NIR LED illumination

- **Experimental data** obtained on devices with layout A1 and A2
- Flood illumination at the top side: LED light **wavelength: 850nm**
- **Edge breakdown in A1**



A1 and A2 sensors layout





Jacopo Endrizzi

Quasi-static characterization: A2 gain with NIR LED illumination

- In **device A2** the high-field region expands laterally with voltage: onset of gain at larger Voltage.
- High voltage: 55 – 60V → Gain is similar to central value