Picosecond Avalanche Detector working principle and gain measurement with a proof-of-concept prototype

LORENZO PAOLOZZI

XVI Workshop on Resistive Plate Chambers and Related Detectors

Precise timing measurement with silicon detectors

What are the main parameters that determine the time resolution of semiconductor detectors?

Induced current from the Shockley-Ramo's theorem:

$$I_{ind} = \sum_i q_i \bar{v}_{drift,i} \cdot \bar{E}_{w,i}$$

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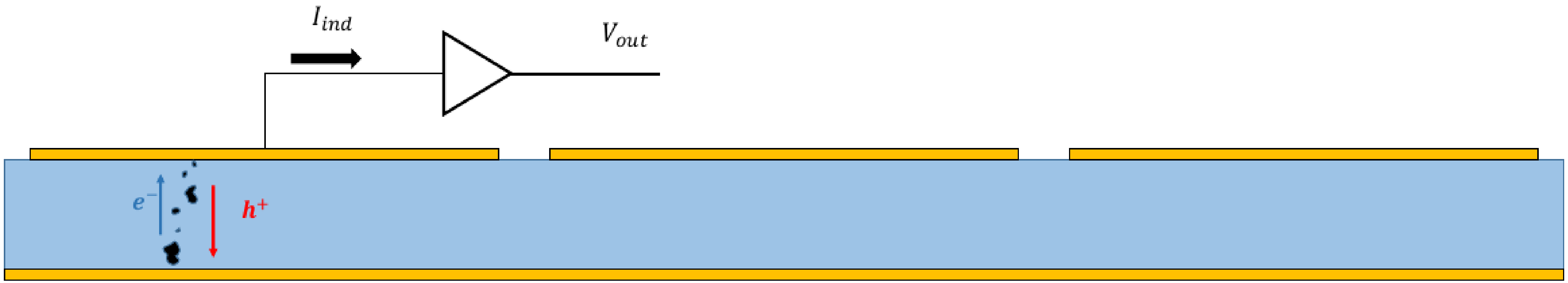

Precise timing measurement with silicon detectors

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- Geometry and fields
- Charge collection noise
- Electronic noise

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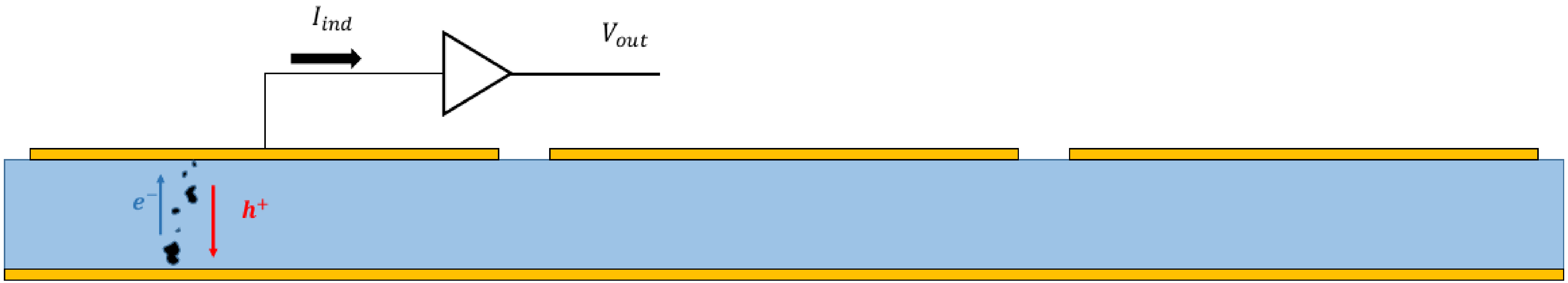
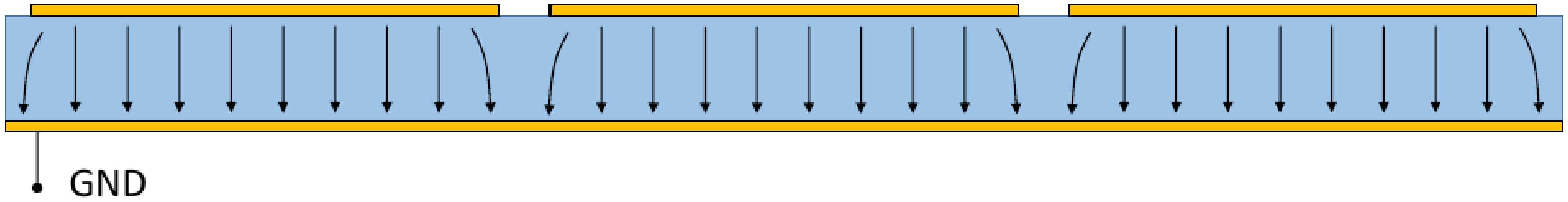


1. Geometry and fields

Sensor optimization for time measurement means:
Sensor time response **independent** from the particle trajectory



→ "Parallel plate" read out: wide pixels w.r.t. depletion region

$$I_{ind} = \sum_i q_i \bar{v}_{drift,i} \cdot \bar{E}_{w,i} \cong v_{drift} \frac{1}{D} \sum_i q_i$$

Scalar, saturated

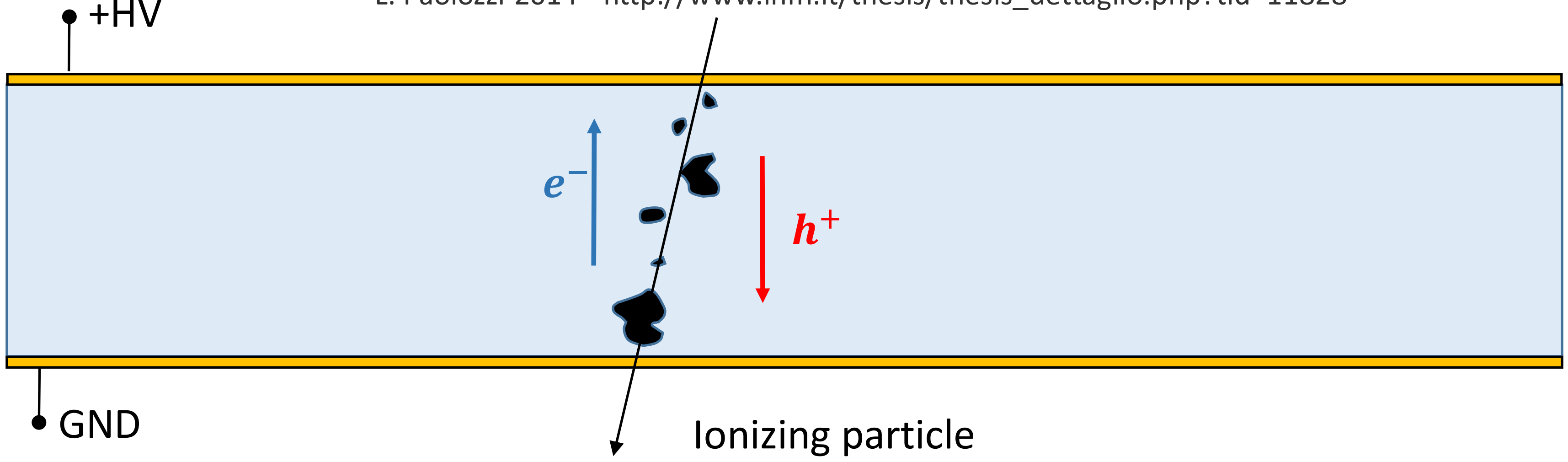
Scalar, uniform

Desired features:

- Uniform **weighting field** (signal induction)
- Uniform **electric field** (charge transport)
- Saturated charge **drift velocity** (signal speed)

2. Charge-collection noise

L. Paolozzi 2014 - http://www.infn.it/thesis/thesis_dettaglio.php?tid=11828

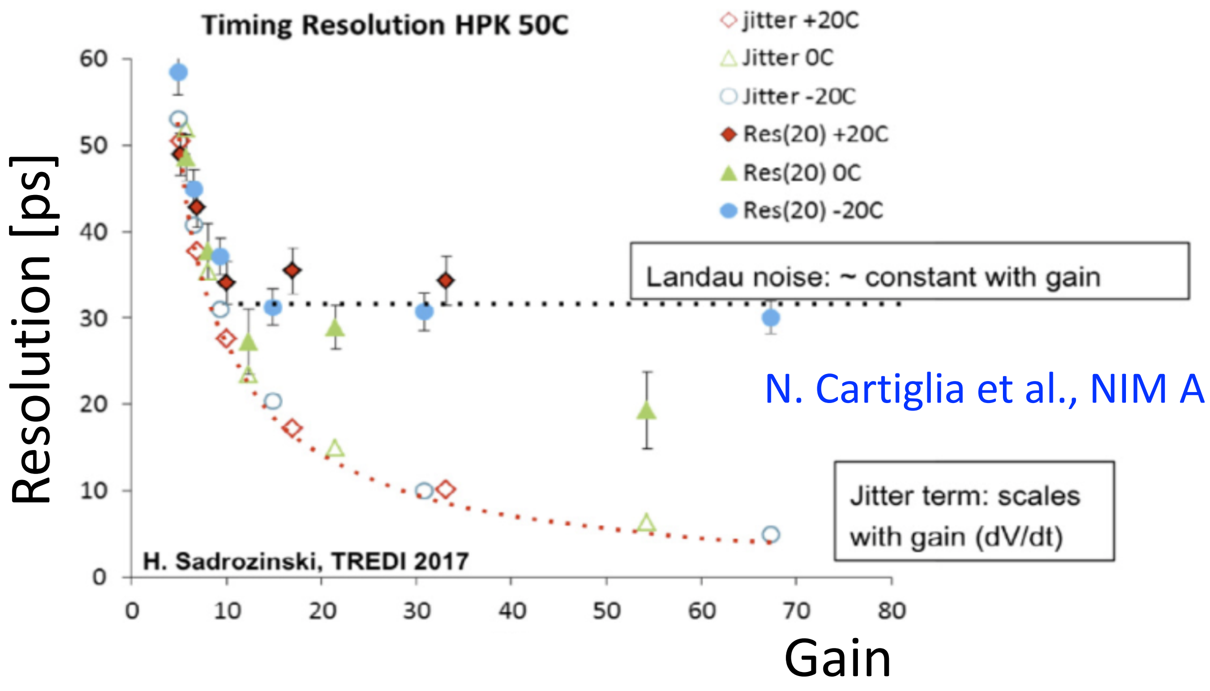


is produced by the **non uniformity of the charge deposition** in the sensor:

$$I_{ind} \cong v_{drift} \frac{1}{D} \sum_i q_i$$

When **large clusters** are absorbed at the electrodes, their contribution is removed from the induced current. The **statistical origin** of this variability of I_{ind} makes this effect irreducible in PN-junction sensors.

2. Charge-collection noise



N. Cartiglia et al., NIM A 924 (2019) 350-354

Charge collection noise represents an intrinsic limit to the time resolution for a semiconductor PN-junction detector.

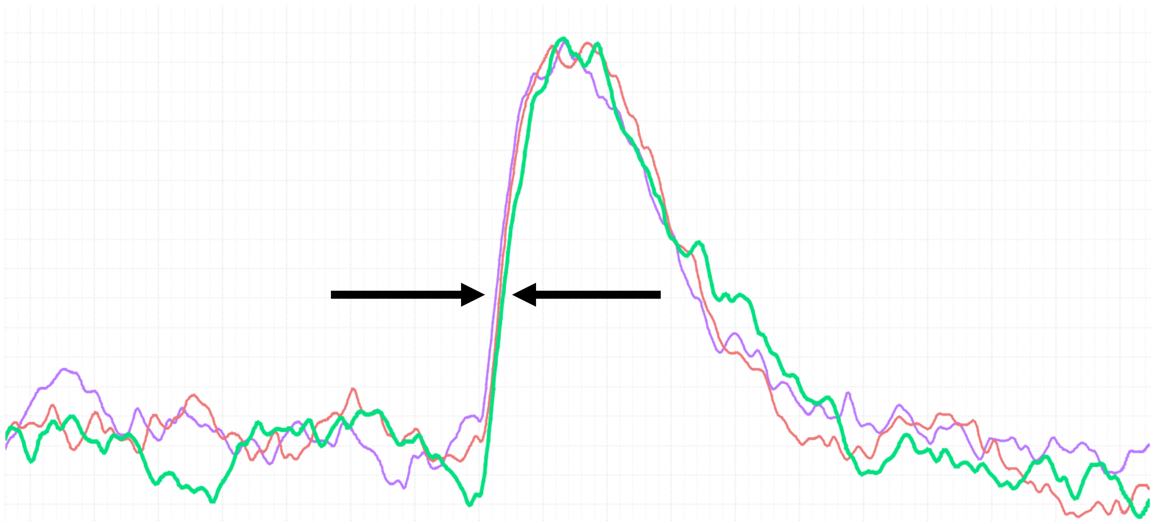
~30 ps reached by present LGAD sensors.

Lower contribution from sensors without internal gain

3. Electronic noise

Once the geometry has been fixed, the time resolution depends mostly on the **amplifier performance**.

Time jitter

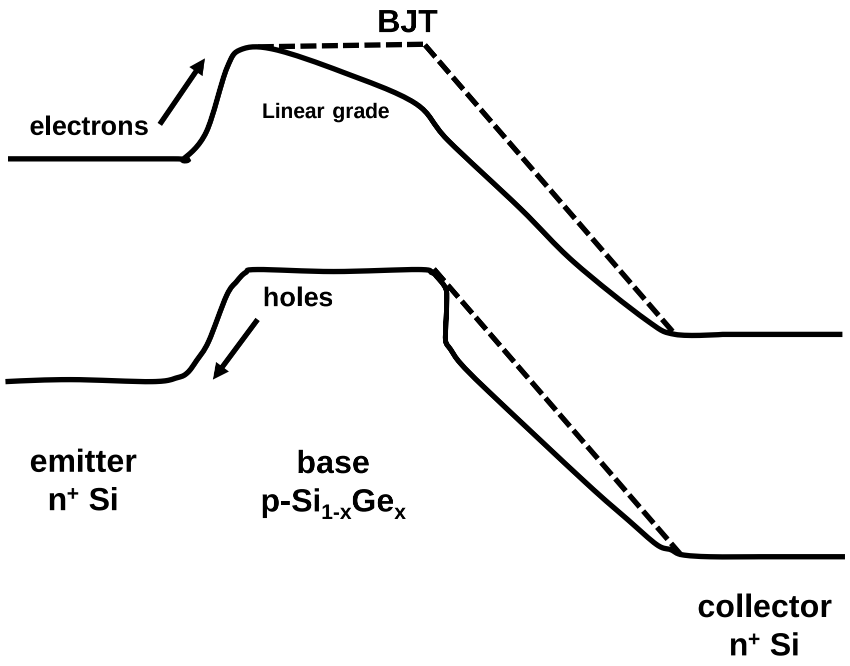


Fast integration

$$\sigma_t = \frac{\sigma_V}{dV/dt} \cong \frac{ENC}{I_{Ind}}$$

SiGe HBT technology for low-noise, fast amplifiers

In SiGe Heterojunction Bipolar Transistors (HBT) the **grading** of the bandgap in the Base changes the **charge-transport mechanism** in the Base from **diffusion** to **drift**:



Grading of germanium in the base:
field-assisted charge transport in the Base,
equivalent to introducing an electric field in the Base

$\Longrightarrow$ short e$^-$ transit time in Base $\Longrightarrow$ very high β

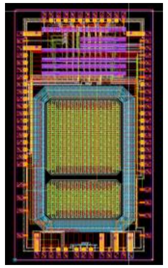
$\Longrightarrow$ smaller size $\Longrightarrow$ reduction of R_b and very high f_t

Hundreds of GHz

Monolithic silicon pixel sensors in 130nm SiGe BiCMOS **with no internal gain**

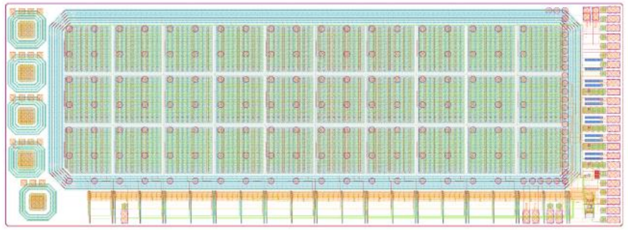
UNIVERSITÉ DE GENÈVE

innovations for high performance microelectronics
Leibniz-Institut für innovative Mikroelektronik



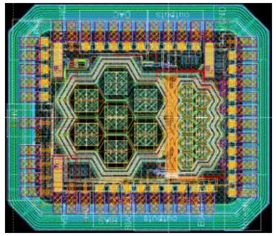
200 ps

2016



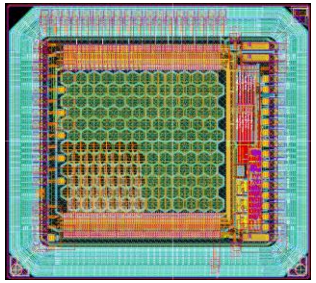
100 ps

2017



50 ps

2018



ATTRACT
36 ps

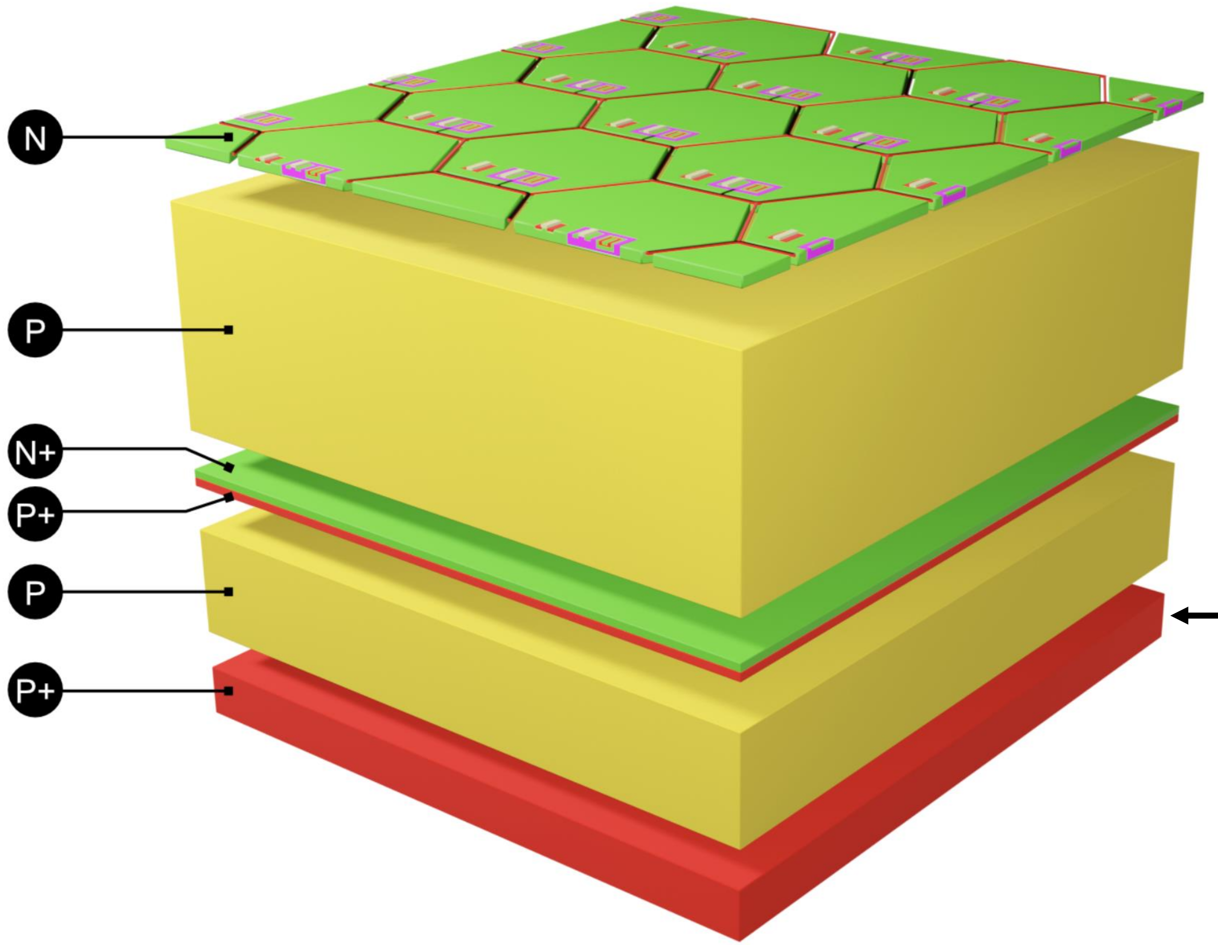
2019

Picosecond time resolution?

The path towards picosecond time resolution

PicoAD - sensor design concept

Picosecond Avalanche Detector (PicoAD): EU Patent EP18207008.6

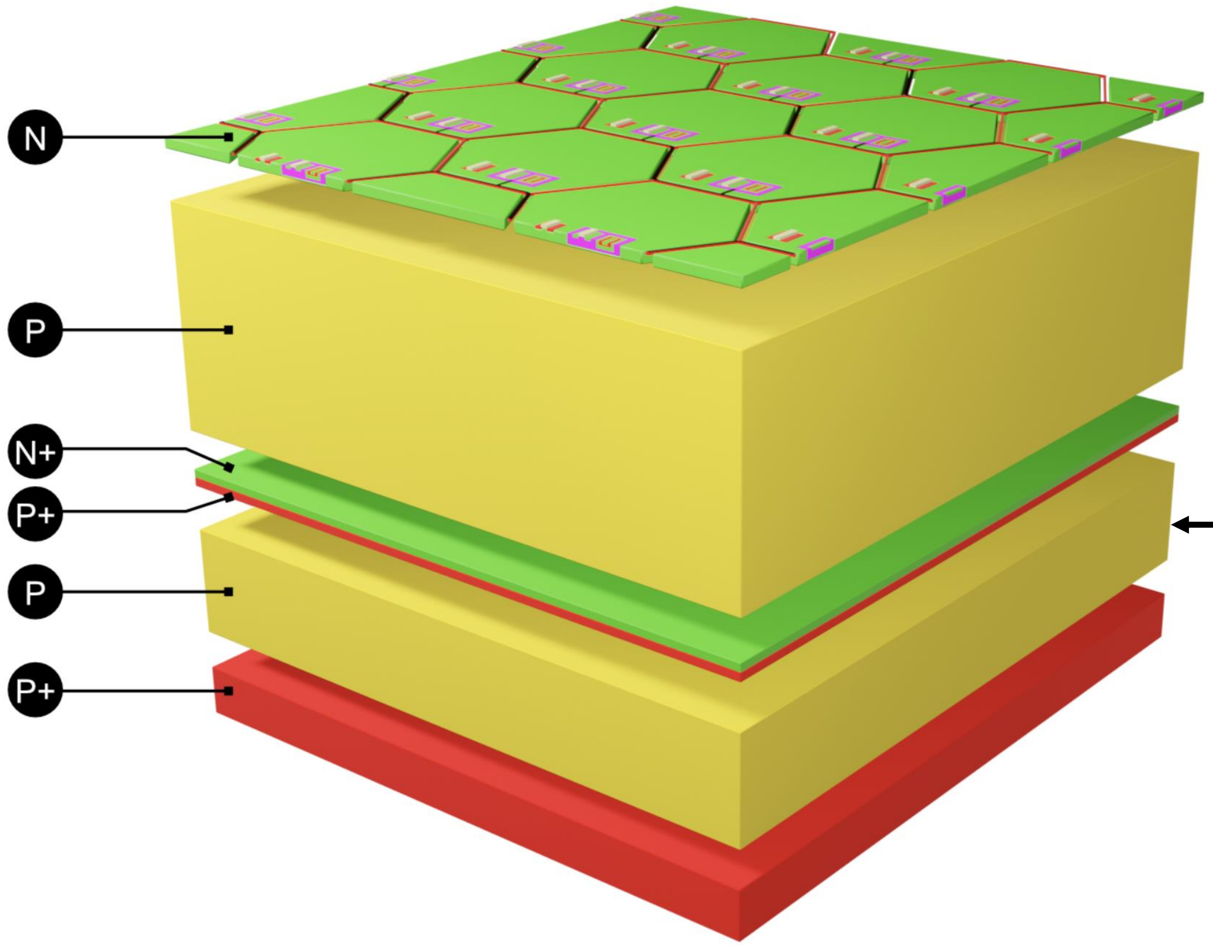


Sensor growth on low resistivity wafers:

1. **No dedicated backside processing** needed
2. Low resistivity important to end depleted active region of sensor and minimise coupling to FE integrated in pixel

PicoAD - sensor design concept

Picosecond Avalanche Detector (PicoAD): EU Patent EP18207008.6



Thin 'absorbtion region', 1st epitaxial layer:

1. Region where primary charge charge drifting towards topside gets amplified is produced
2. Thin layer (~5µm) to **minimise charge collection noise**

PicoAD - sensor design concept

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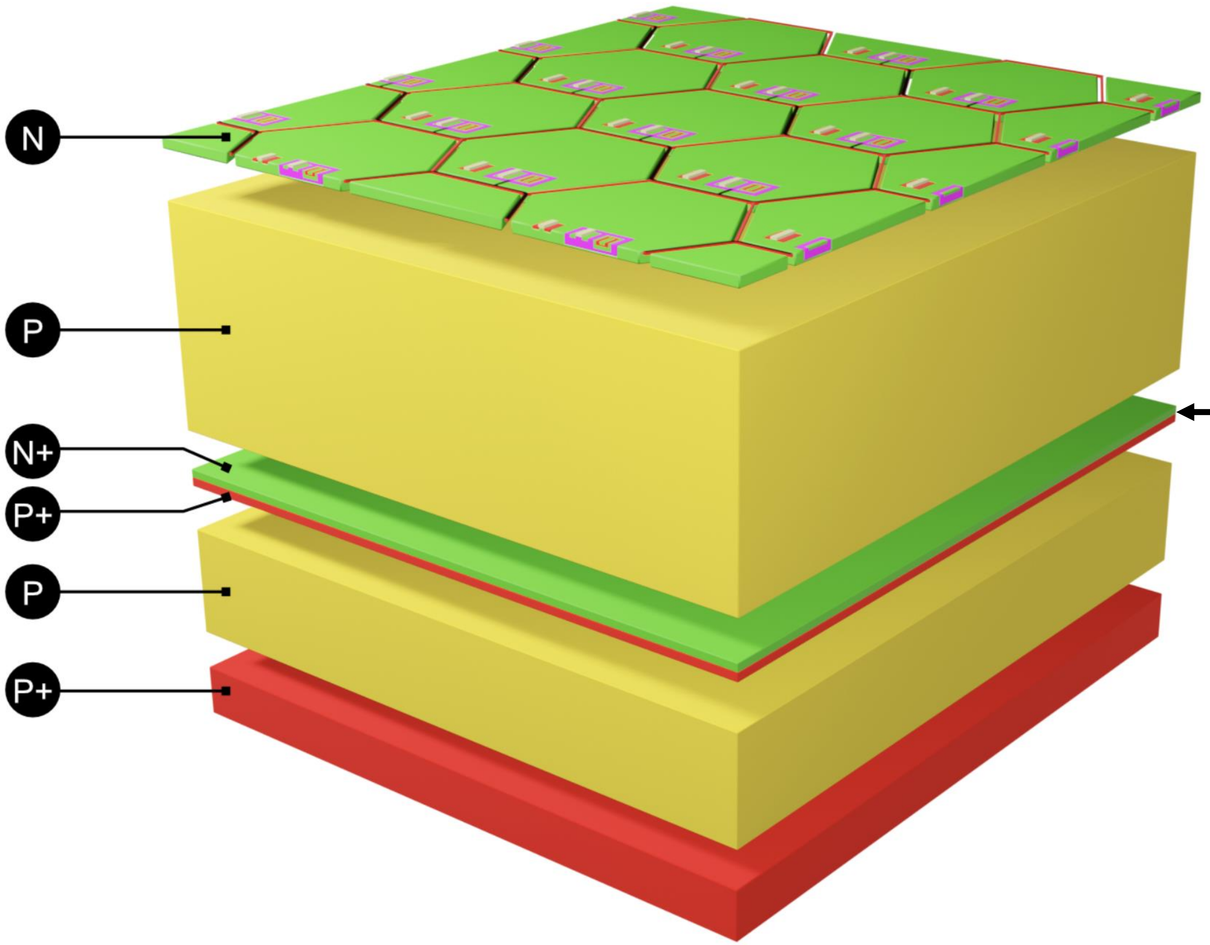

Thin and uniform deep gain layer:

- Same doping of gain layer over full pixel cell (full ‘fill-factor’):
  - ➢ **Uniform gain** and minimisation of pixel edge effects
- Gain layer physically seperated from pixel implant:
  - ➢ Can decrease absorbtion region to minimise charge collection noise without increasing sensor capacitance (coupling to backside substarte p+)
  - ➢ Can integrate FE electronics inside pixel implant (**fully monolithic CMOS**)

PicoAD - sensor design concept

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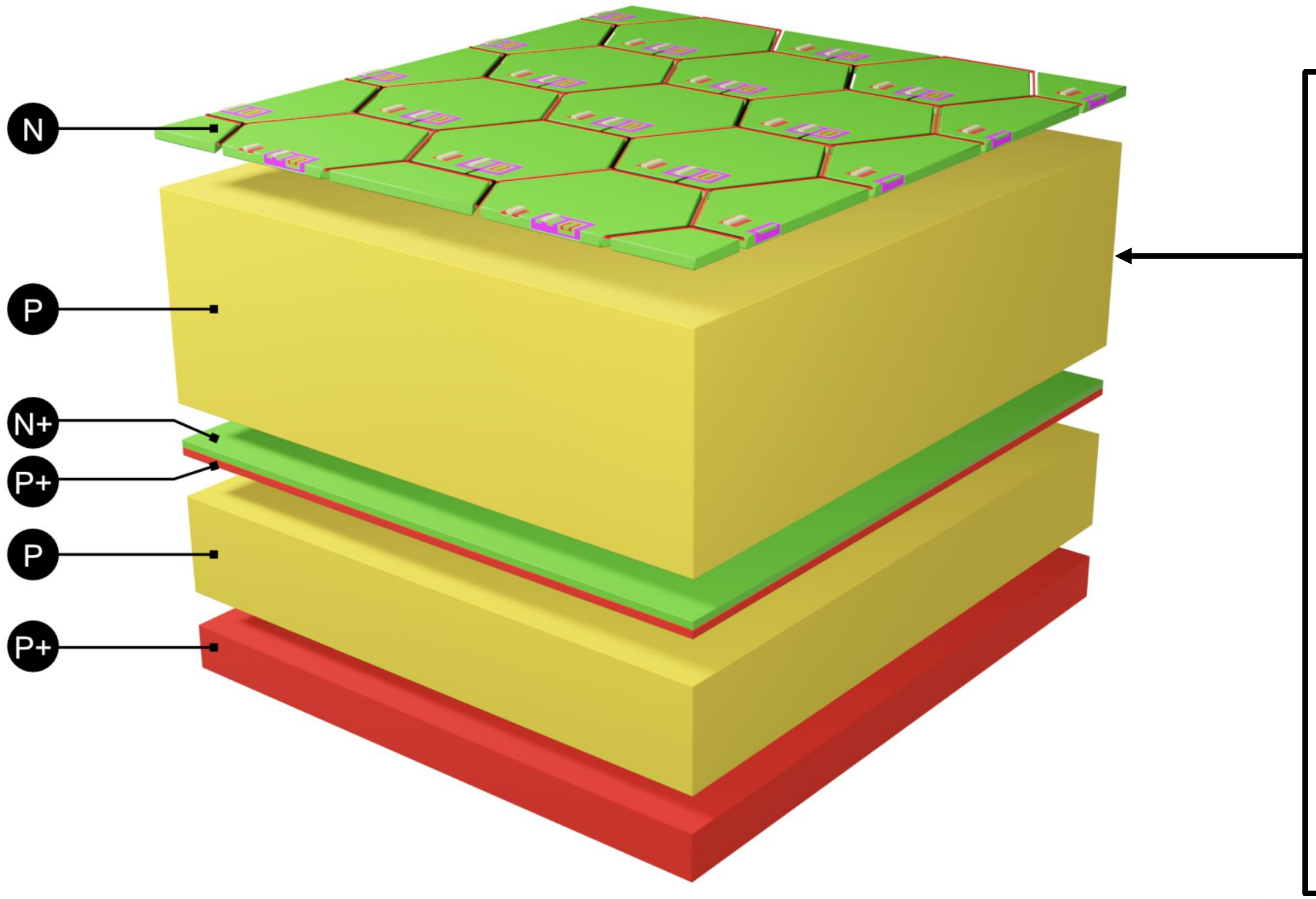

Thicker 'drift region', 2nd epiaxial layer:

- Constrains:
  - ➢ Needs to be as thin as possible to:
    - ➢ Maximise weighting field ($\propto$ 1/depletion)
    - ➢ Maximise drift field
  - ➢ Needs to be as thick as possible to:
    - ➢ Sufficantly minimise capacitance
    - ➢ Sufficantly minimise impact of pixel implants on gain layer uniformity

PicoAD - sensor design concept

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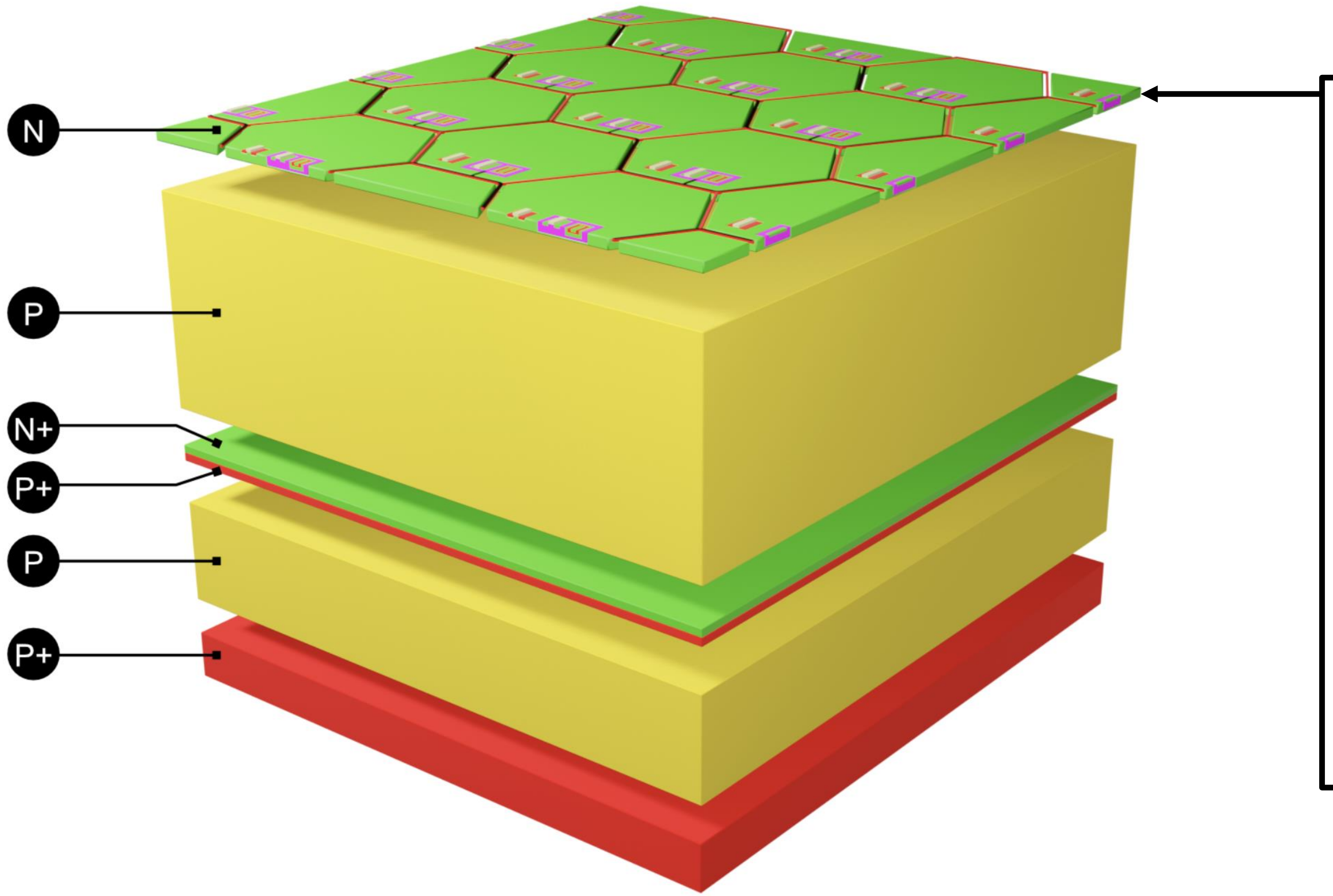

Fully monolithic CMOS processing:

- Implemented in **large collection electrode design to maximise weighting** field over full pixel cell
- **Pixel implant size can be minimised** while maintaining gain layer uniformity!
- **Hexagonal design to minimise edge effects** (impact on gain layer + high field breakdown between pixels)

PicoAD - sensor design concept

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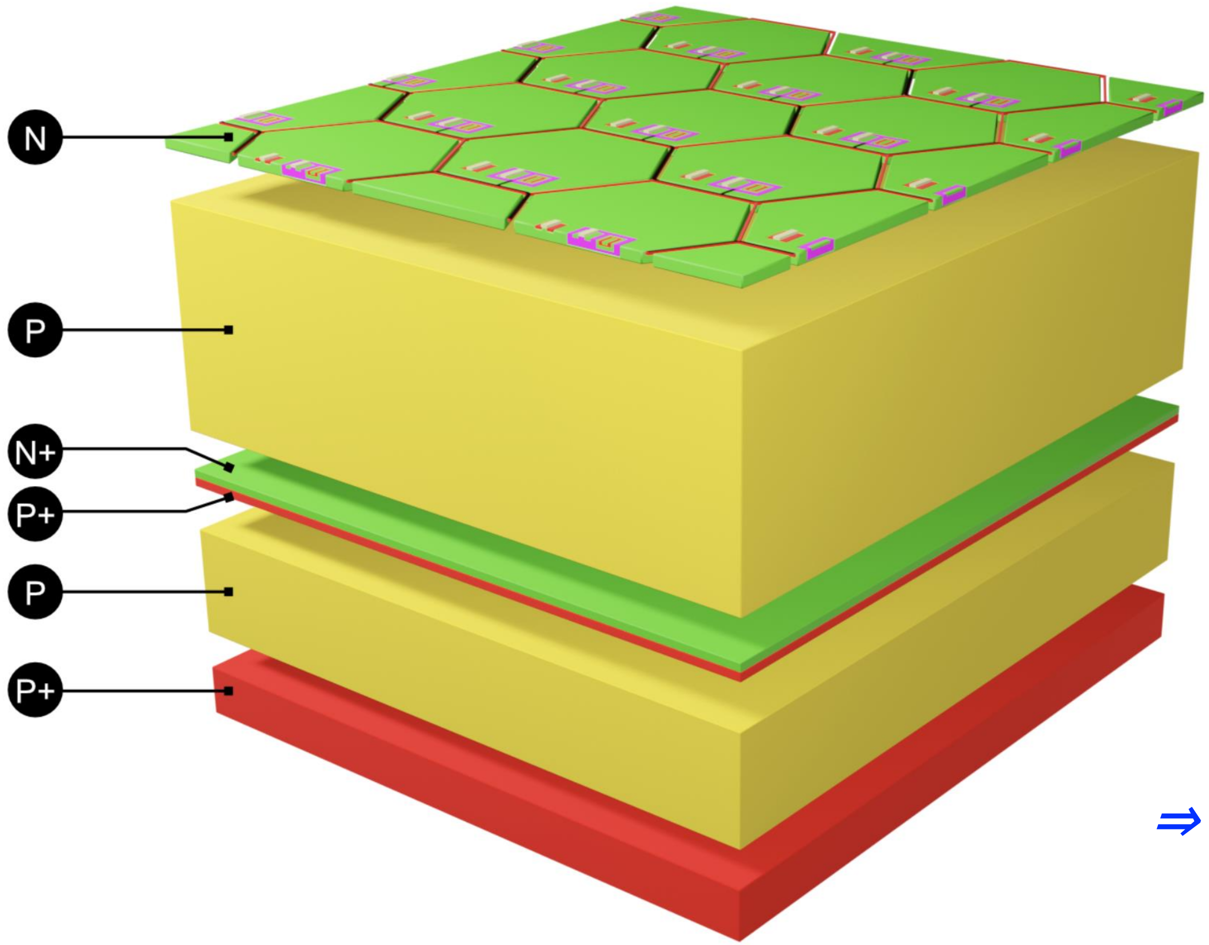

⇒ PicoAD concept provides **simultaneusly**:

- Reduced charge collection noise
- Reduced sensor capacitance
- Improved weighting field
- Small pixel size
- Fully monolithic CMOS design

} Pico-second sensor timing

⇒ Sensor optimised for picosecond timing in fully monolithic small pixel design

PicoAD - sensor design concept

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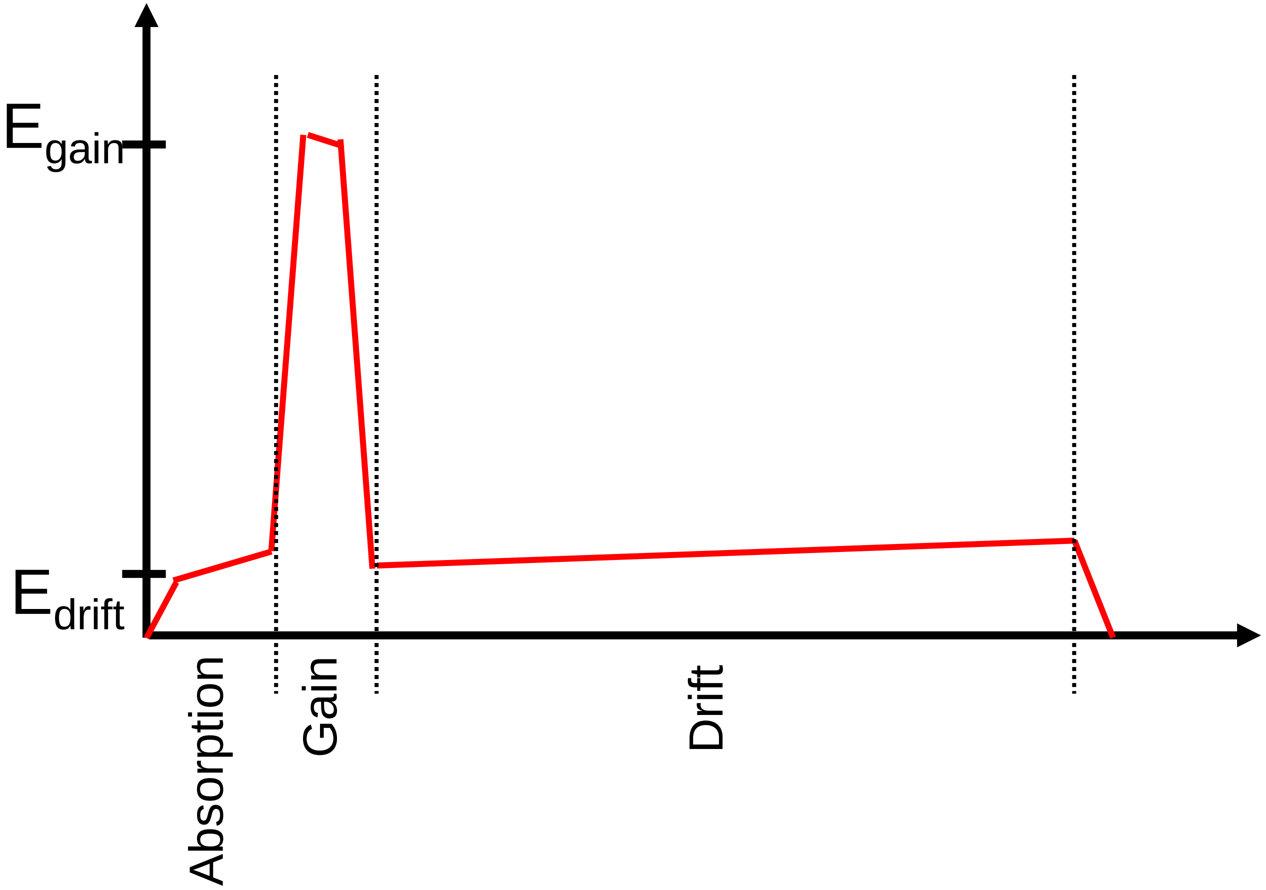
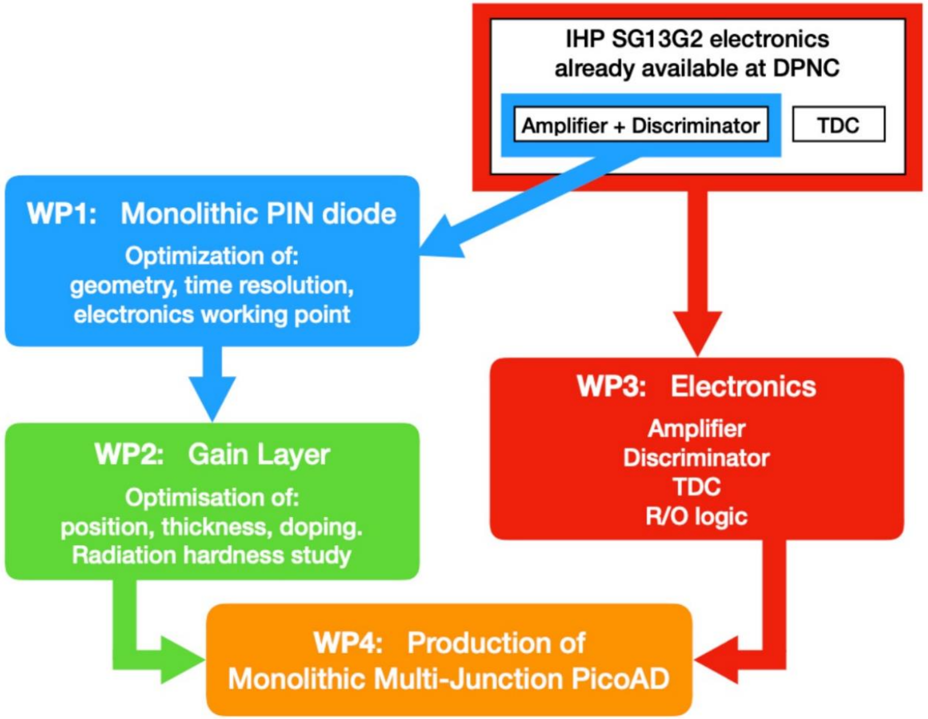


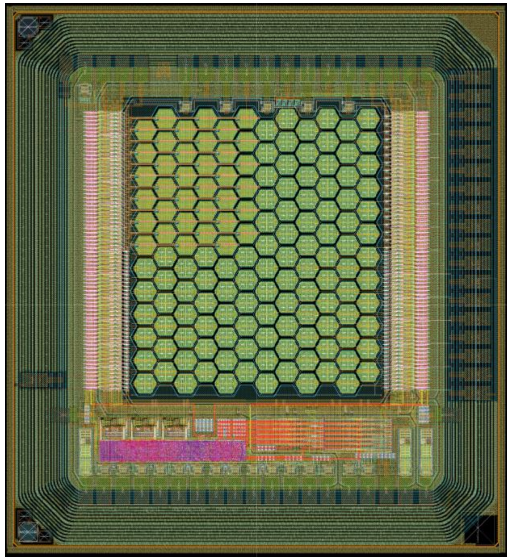
- The introduction of fully-depleted multi-pn junctions allows to **engineer the electric field**.
- New device with unique timing and reliability performance.
- Gain with 100% fill-factor.
- Geant4 + Cadence simulations estimate ~**2ps time resolution** contribution from the sensor.
- Requires low-noise, ultra fast electronics to be fully exploited.

MONOLITH ERC project

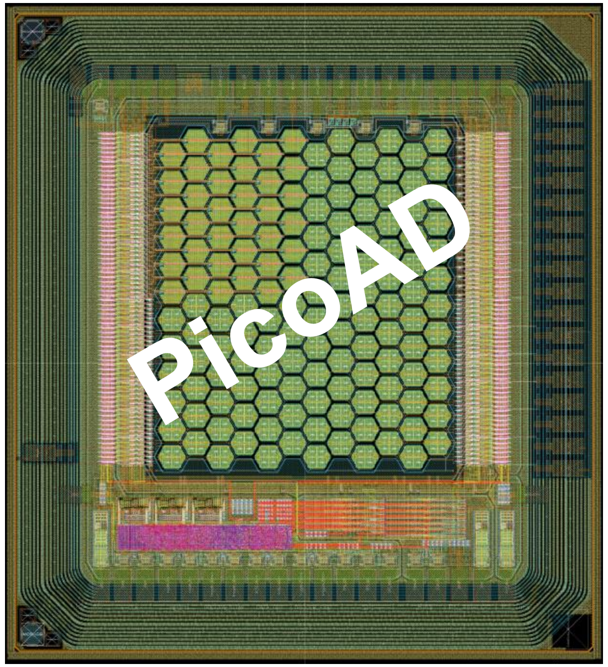
A monolithic silicon sensor able to measure precisely the 3D spatial position of charged particles while providing at the same **picosecond time resolution** using the novel **Picosecond Avalanche Detector (PicoAD)** concept**.**



PicoAD +



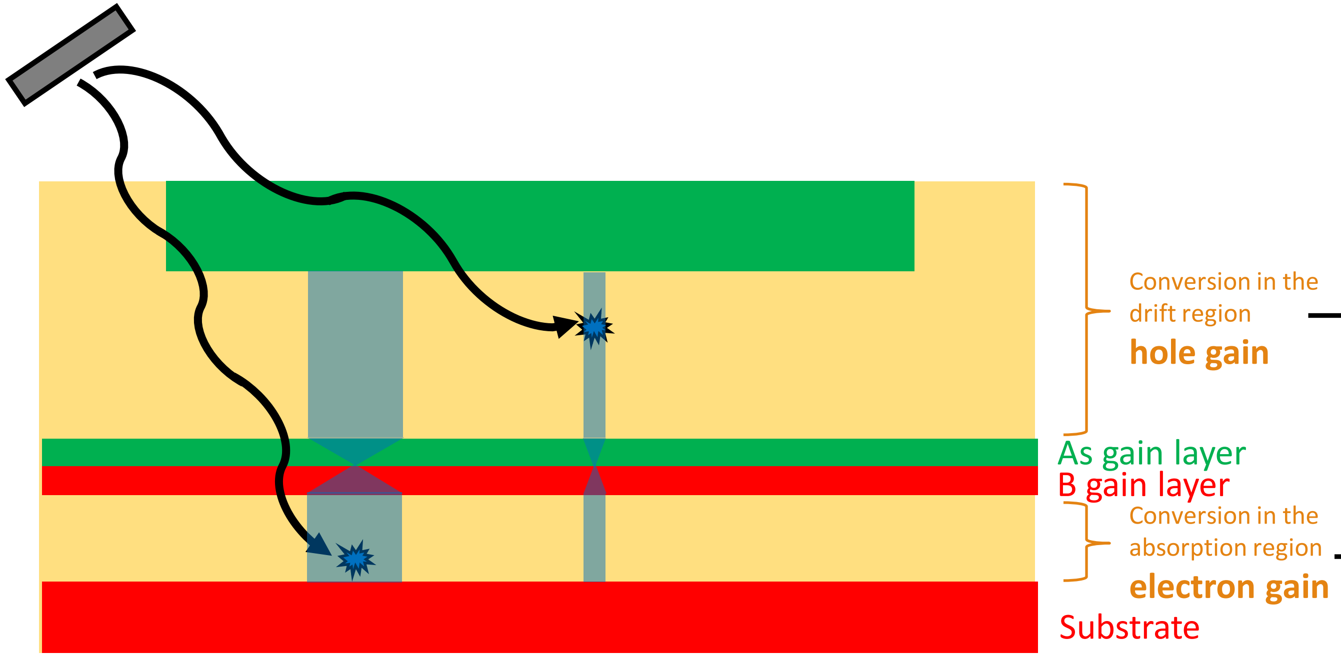
PicoAD proof-of-concept prototypes

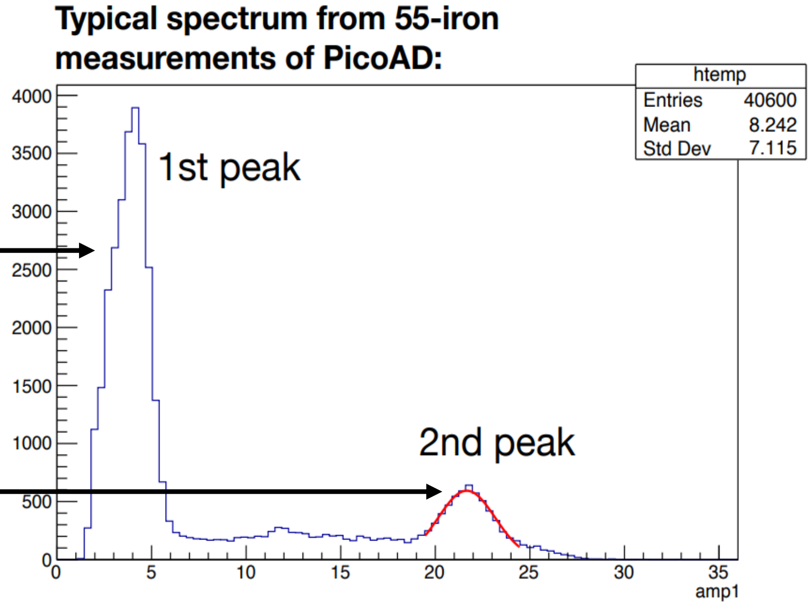


- Integrated in a special wafer for the ATTRACT prototype.
- Process design in collaboration with IHP.
- 15 µm total epi layer.

PicoAD: First prototype test with Fe-55 source

Fe-55 X-ray source: point-like charge deposition inside the sensor

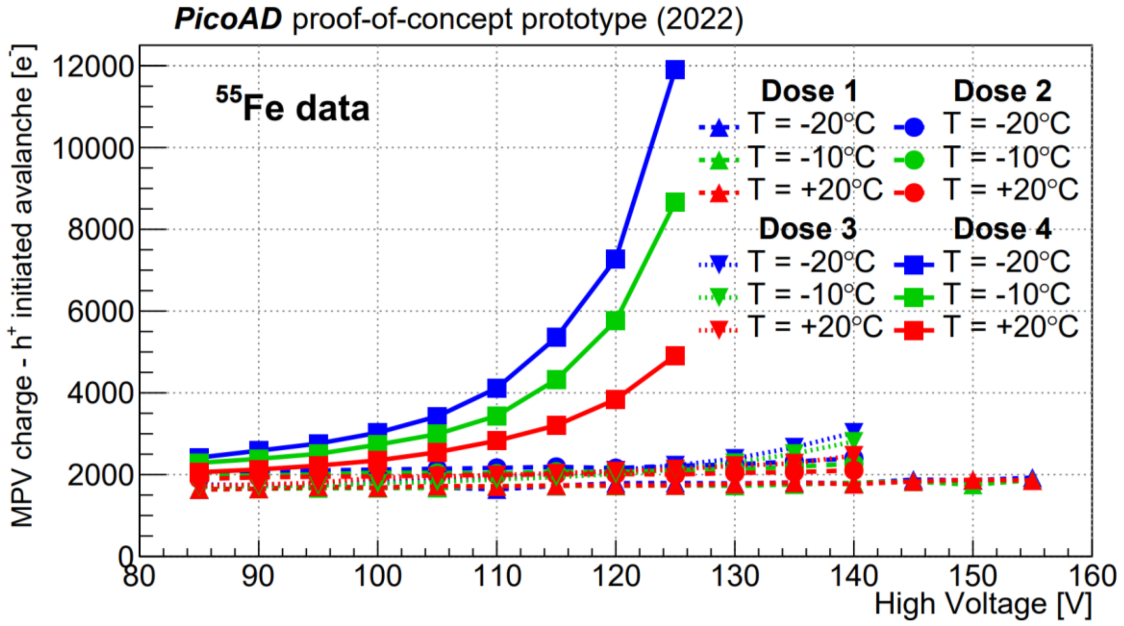




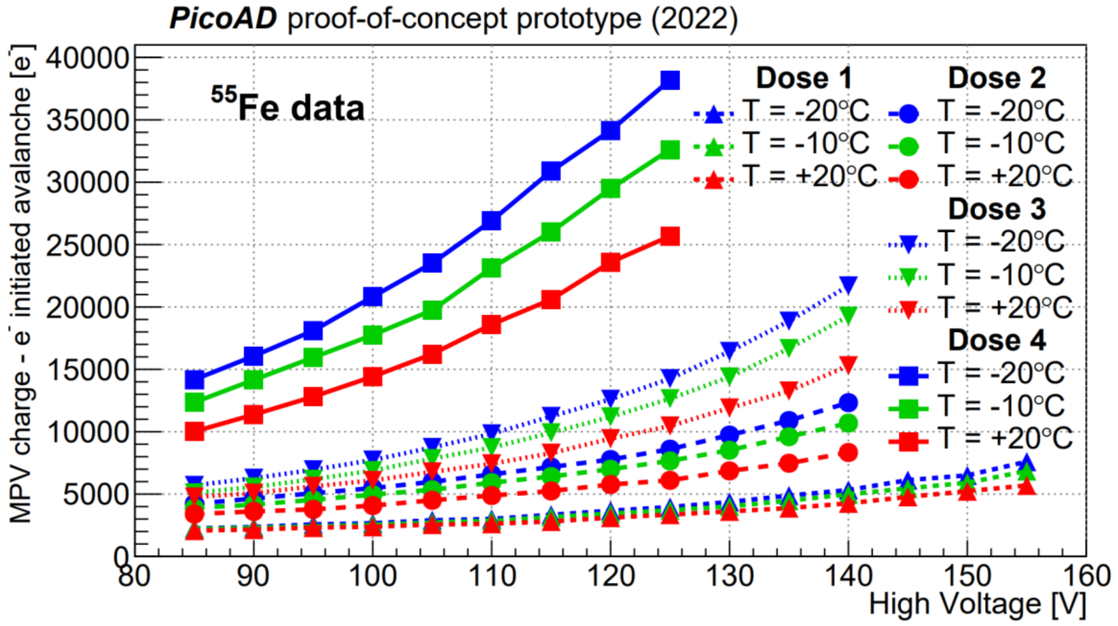
PicoAD: First prototype test with Fe-55 source

Picosecond Avalanche Detector - working principle and gain measurement with a proof-of-concept prototype, L. Paolozzi et.al, arXiv:2206.07952, submitted to JINST

Hole gain, measured with 55Fe:



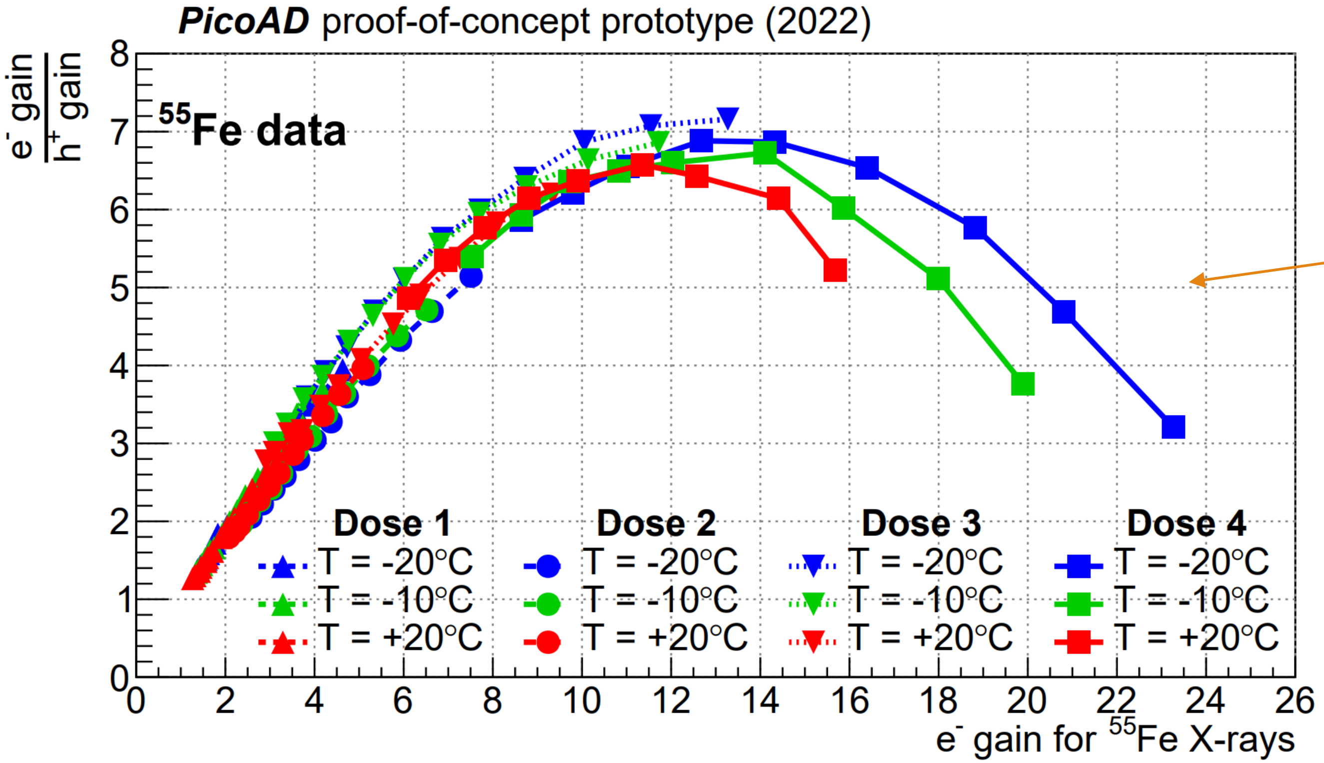
Electron gain, measured with 55Fe:



- A gain for 55Fe X-rays of ~20 is reached at HV = 120V and T=-20°C
- Evidence for gain suppression due to space charge effects

PicoAD: First prototype test with Fe-55 source

Ratio of e/h-gain, measured with 55Fe:



Decreasing trend is an indication of space charge effects

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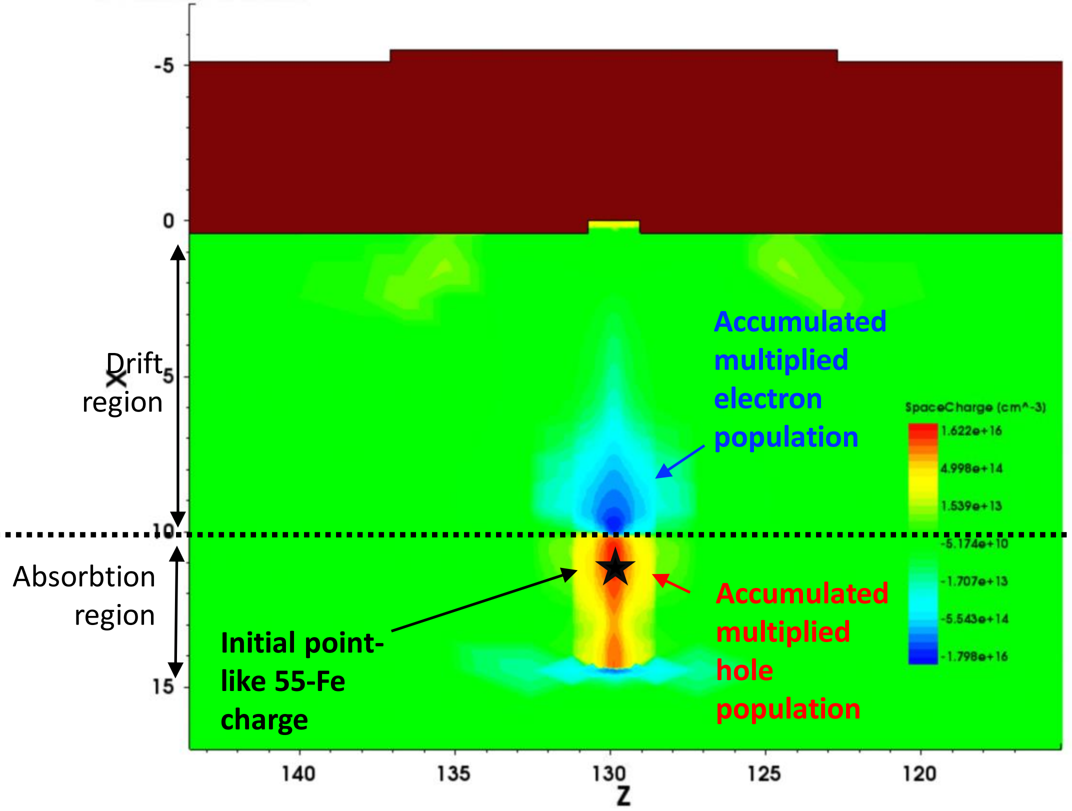
- Evidence for gain suppression due to space charge effects

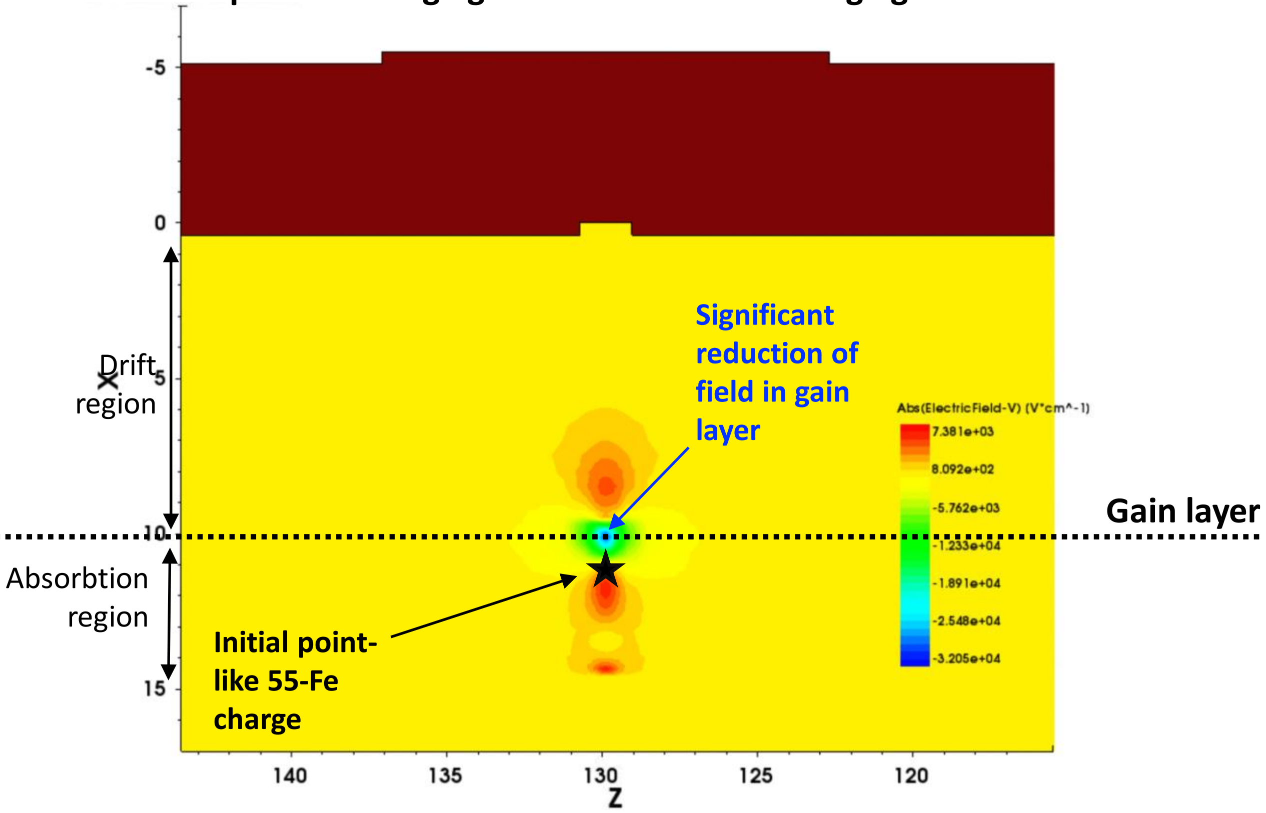
Transient space charge effect

Transient 3D TCAD simulation of point like 55-Fe charge deposition in absorption layer:

Space charge:
10ps after charge generation – before charge generation:

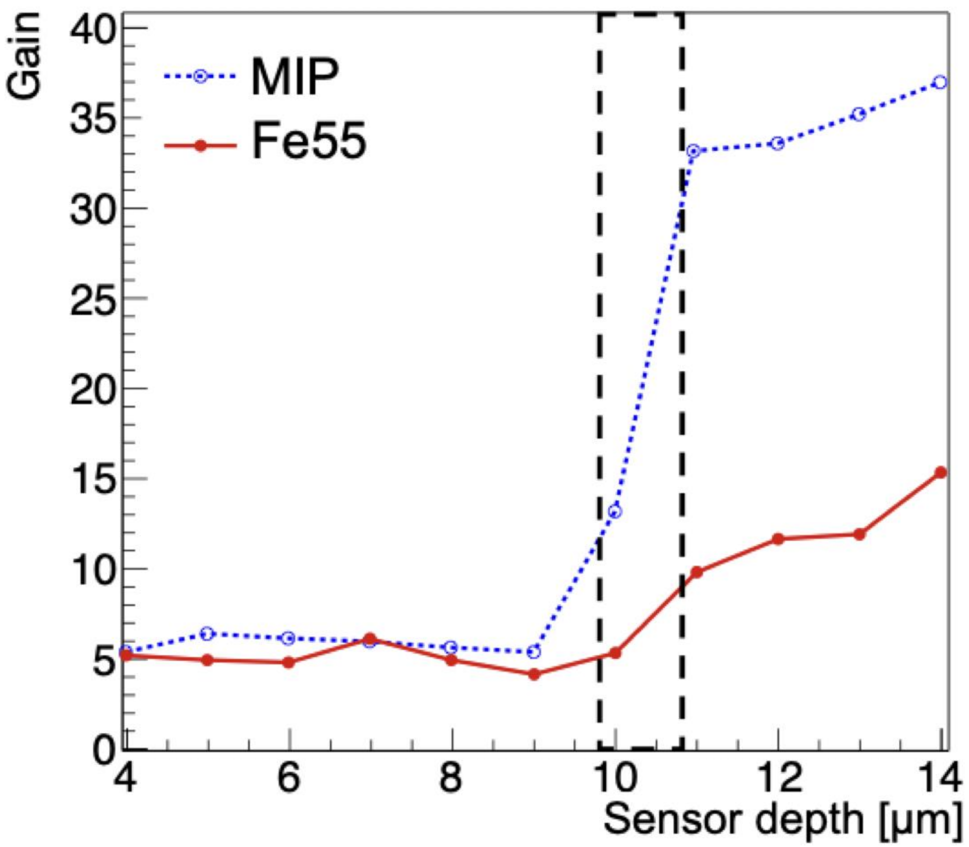


Electric field:
10ps after charge generation – before charge generation



Transient space charge effect

Gain as function of sensor depth for different primary charge carrier densities:



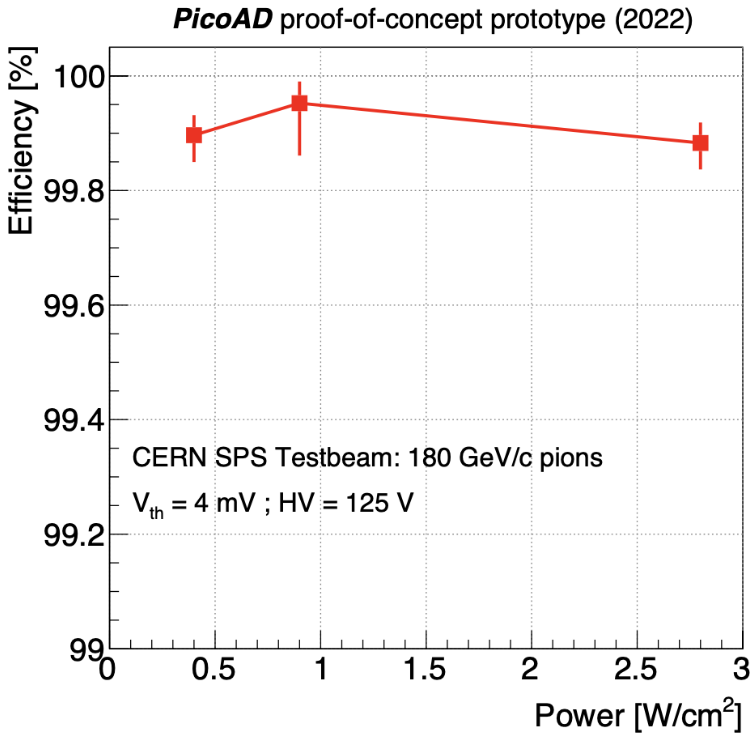
- For high charge carrier densities (Fe55) the gain is suppressed compared to lower charge carrier densities (MIPs).
- Simulated suppression factor of Fe55 w.r.t. MIP charge compatible to calculation of compression factor from test-beam and Fe55 measurements.

→ Measured gain for Fe55 significantly supressed by transient space charge effect.

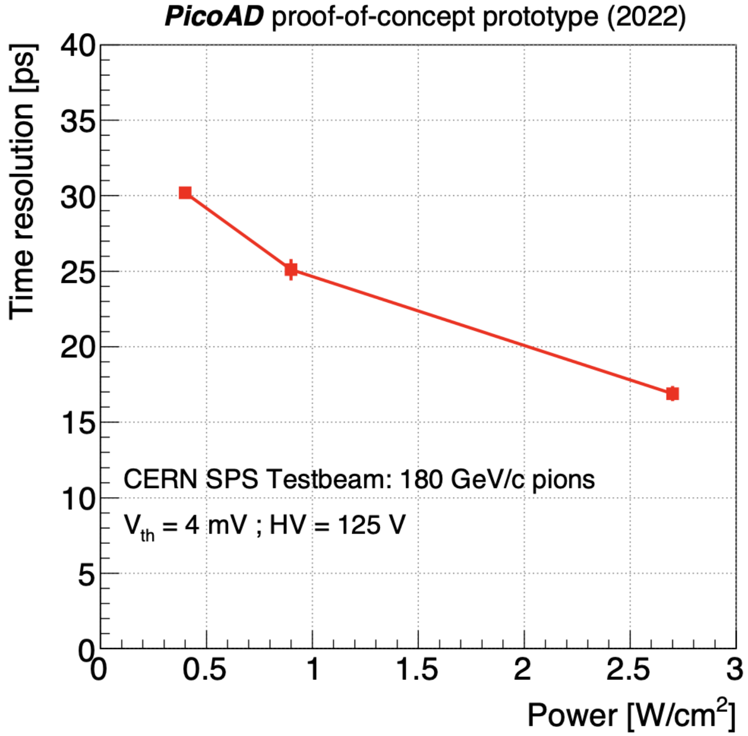
→ Need of fully self consistent transient TCAD simulations.

PicoAD – test-beam results

Efficiency vs. Front-end power:



Time resolution vs. power:



Testbeam Results of the Picosecond Avalanche Detector Proof-Of-Concept Prototype, G. Iacobucci et.al, arXiv:2208.11019v1, submitted to JINST

→ **Efficiency > 99.8%** for all power consumptions.

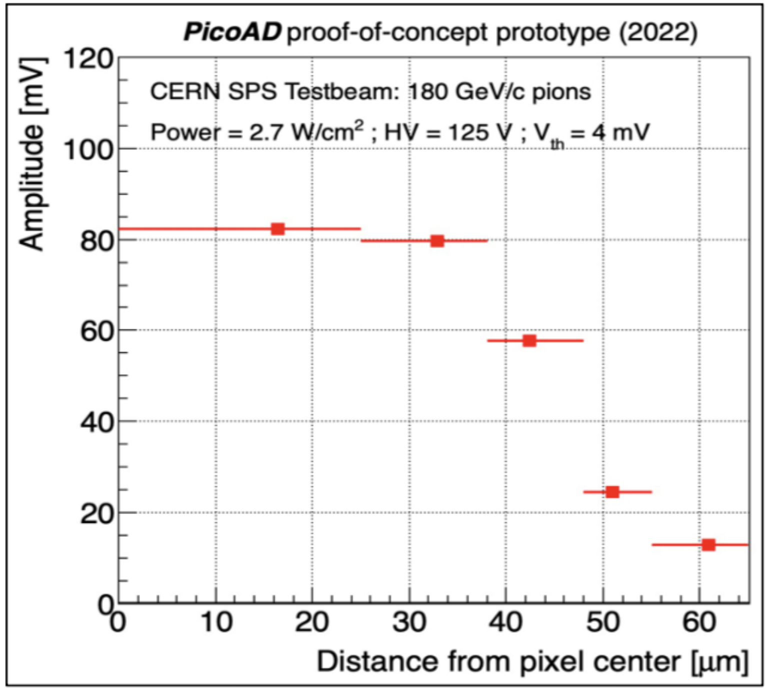
→ Timing resolution is ≲30 ps, even for the **lowest power consumption.**

→ **Best timing resolution of 17 ps.**

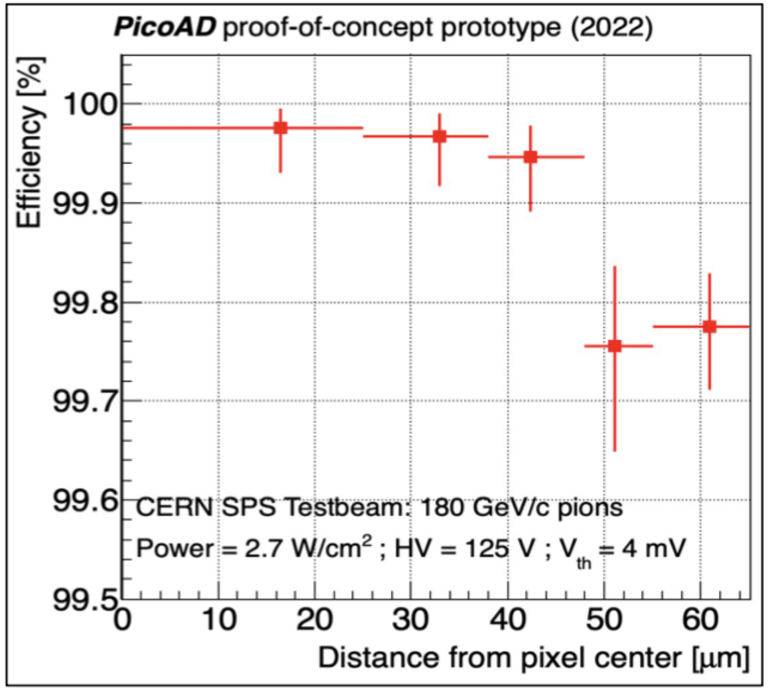
PicoAD – test-beam results

Testbeam Results of the Picosecond Avalanche Detector Proof-Of-Concept Prototype, G. Iacobucci et.al, arXiv:2208.11019v1, submitted to JINST

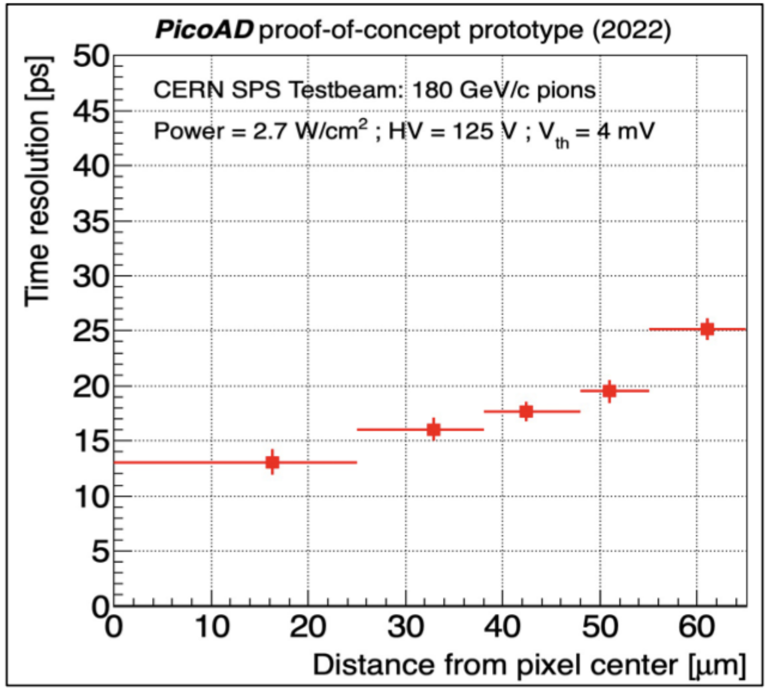
Amplitude vs. distance pixel center:



Efficiency vs. distance pixel center:



Time resolution vs. distance pixel center:



- Small degradation of the performance towards the edge of the pixel
- Effect of the finite resolution of the telescope convoluted with the real degradation
- The best timing resolution is $\mathbf{13.2 \pm 0.8}$ ps within 25 μm from the pixel center

CONCLUSIONS

- SiGe BiCMOS proved the feasibility of a monolithic integration of silicon pixel sensors for ionizing radiation for **large area detectors with state-of-the-art space-time resolution**.

- The development of the PicoAD, a **4D detector with picosecond time resolution,** is in progress with the MONOLITH project.

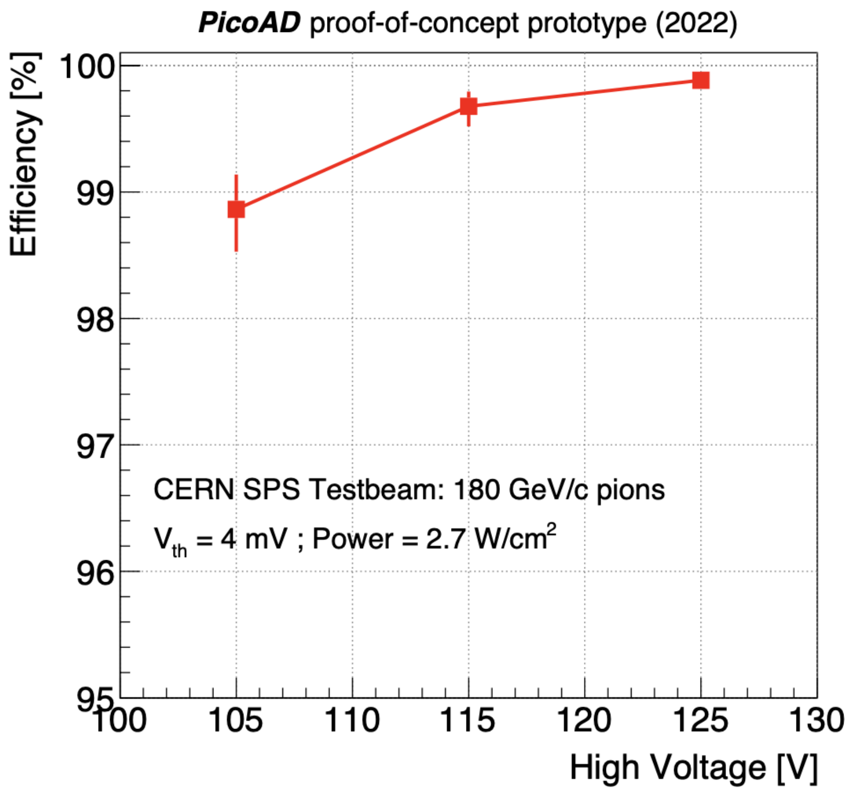
- Test with a Fe-55 source show transient space charge effects, but these are not expected to impact gain with MIPs.

- The first test beam shows that a time resolution of 17ps is possible. Better performance are achieved at the pixel center, possibly due to a drop of gain in the interpixel region.

Extra Material

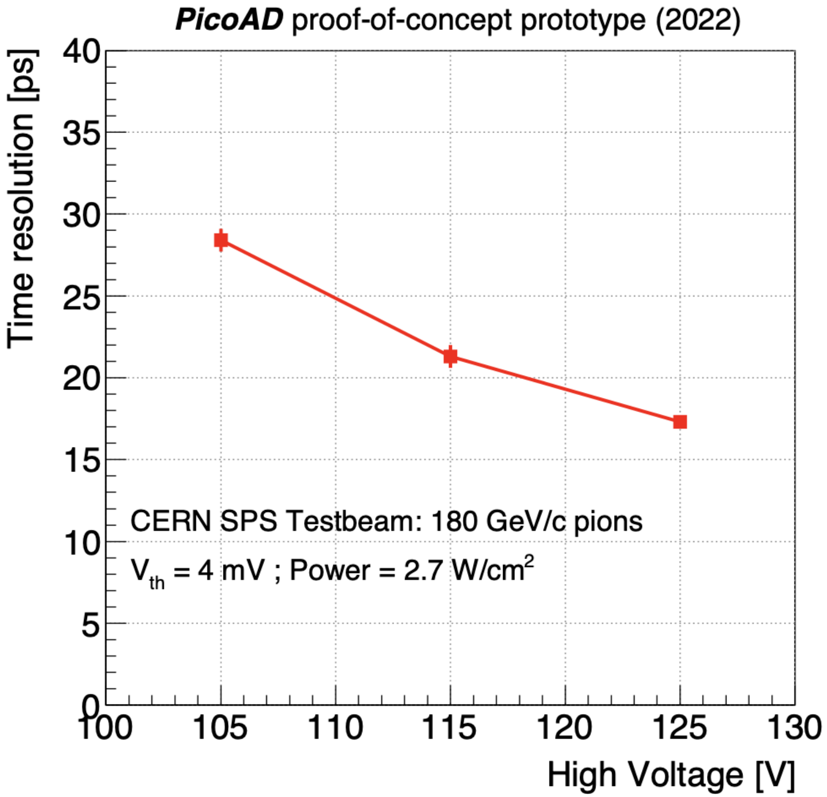
PicoAD – test-beam results

Efficiency vs. sensor bias voltage:



→ **Efficiency drops to ~ 99%** at sensor bias voltage of -105V

Time resolution vs. sensor bias:



→ Timing resolution is $\lesssim$30 ps, even for the **lowest sensor bias voltage**

→ **Best timing resolution of 17 ps**

Testbeam Results of the Picosecond Avalanche Detector Proof-Of-Concept Prototype,
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PicoAD prototype: Time resolution