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

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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:

\[ I_{\text{ind}} = \sum_i q_i \bar{v}_{\text{drift},i} \cdot \bar{E}_{w,i} \]
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Induced current from the Shockley-Ramo's theorem:

![Diagram showing induced current and drift velocities](image)
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- 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

\[ I_{\text{ind}} = \sum_i q_i \vec{v}_{\text{drift},i} \cdot \vec{E}_{w,i} \approx \frac{1}{D} \sum_i q_i \]

Desired features:
- Uniform weighting field (signal induction)
- Uniform electric field (charge transport)
- Saturated charge drift velocity (signal speed)
2. Charge-collection noise

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

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

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

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

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

\[ \sigma_t = \frac{\sigma_v}{\frac{dV}{dt}} \approx \frac{ENC}{I_{Ind}} \]
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

⇒ short e⁻ transit time in Base ⇒ very high $\beta$

⇒ smaller size ⇒ reduction of $R_b$ and very high $f_t$

Hundreds of GHz
Monolithic silicon pixel sensors in 130nm SiGe BiCMOS with no internal gain

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
Thin ‘absorption region’, 1st epitaxial layer:

1. Region where primary charge drifting towards topside gets amplified is produced

2. Thin layer (~5µm) to minimise charge collection noise
PicoAD - sensor design concept

Pico-second Avalanche Detector (PicoAD): EU Patent EP18207008.6

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 separated from pixel implant:
  - Can decrease absorption region to minimise charge collection noise without increasing sensor capacitance (coupling to backside substrate p+)
  - Can integrate FE electronics inside pixel implant (**fully monolithic CMOS**)

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

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

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:
    -Sufficiently minimise capacitance
    -Sufficiently minimise impact of pixel implants on gain layer uniformity
PicoAD - sensor design concept

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

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

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

⇒ PicoAD concept provides simultaneously:

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

⇒ Sensor optimised for picosecond timing in fully monolithic small pixel design
PicoAD - sensor design concept

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

• 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.
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 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

Conversion in the drift region
hole gain

As gain layer
B gain layer
Conversion in the absorption region
electron gain

Substrate

Typical spectrum from 55-iron measurements of PicoAD:

1st peak

2nd peak

Entries: 40600
Mean: 8.242
Std Dev: 7.115
PicoAD: First prototype test with Fe-55 source

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

• 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

Decreasing trend is an indication of space charge effects

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

Initial point-like 55-Fe charge

Accumulated multiplied electron population

Accumulated multiplied hole population

Significant reduction of field in gain layer
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 suppressed by transient space charge effect.
  - Need of fully self consistent transient TCAD simulations.
"PicoAD – test-beam results"

→ 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

- 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 $13.2 \pm 0.8$ 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 \( \sim 99\% \) at sensor bias voltage of \(-105\) V

Time resolution vs. sensor bias:

- Timing resolution is \( \leq 30 \) 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, G. Iacobucci et.al, arXiv:2208.11019v1, submitted to JINST
PicoAD prototype: Time resolution

CERN SPS Testbeam with 180 GeV/c pions
- No gain, 24 µm depletion, HV = 120V
- PicoAD, 15 µm depletion, HV = 125V, Preliminary
- PicoAD, 15 µm depletion, HV = 125V, double threshold Preliminary

Time resolution [ps] vs. \( I_{\text{preamp}} \) [µA]