3D silicon sensors as timing detectors

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Introduction

• Future hadron colliders challenge the tracking and reconstruction with high rates and huge pile-up

• ATLAS and CMS already aim for 30-40ps timing resolution, future trackers like FCC will demand timing of 5ps while still providing position resolution below 10 µm in high density environments

• Silicon sensors are proven to be very radiation hard and have a short charge collection time – current and future choice for tracking detectors

• Many collaborations working on improving time resolution, e.g.
  ➡ Ultra Fast Silicon Detectors (UFSDs - LGADs)
    • Working on improving radiation hardness (gain layer degradation)
  ➡ 3D pixel sensors dedicated for timing: RD50 project
    • Potential alternative: proven radiation hardness, gain increase
3D sensors

(a) IBL schematics
(b) ATLAS schematics

Insertable B-Layer production
- Double-sided
- 235 $\mu m$ active thickness
- $50 \times 50$ $\mu m^2$ unit cell size
- $100 \times 100$ $\mu m^2$ active area
- Depletion voltage: 5-10 V

ATLAS Inner Tracker pre-production
- Single-sided
- 150 $\mu m$ active thickness, 270 $\mu m$ total thickness
- Unit cell size: $50 \times 50$ $\mu m^2$ or $25 \times 100$ $\mu m^2$
- Active area: $100 \times 100$ $\mu m^2$ or $50 \times 200$ $\mu m^2$
- Depletion voltage: 5-10 V
Experimental Setups

- Single pulses recorded of both reference and tested sensor
- About 3000 events with DUT signature for appropriate statistics
- Measurements with MIP-like particles and laser source
- If possible, only external triggers

- $^{90}$Sr-source
- LGAD reference, $\sigma_{Ref} = 25.18 \pm 0.35\ ps$
- PMT yes/no trigger
- Top-TCT, infrared laser (1060nm)
- 2 pulses recorded (fiber splitter)
- Intensity tunable
Time Resolution: Unirradiated 3D Pixel Sensors

- Low laser intensity – MPV around 80-110 mV, low compared to beta set-up (145 mV)
- Cell structure not as clear as for time resolution, but still fits the expectations
- Rise time between 340 and 420 ps, higher than measured in the beta set-up
Time Resolution: Unirradiated 3D Pixel Sensors

- Time resolution measured at 60 V for a 10x40 \( \mu \text{m} \) area in 5 \( \mu \text{m} \) steps and interpolated
- Two sensors measured: Similar cell structure recognisable:
  - Better resolution closer to the readout column
  - Worse resolution closer to the other junction columns
  - Range from 23-43 ps/25-47 ps
- Differences: Uncertainties in position, laser focus, laser intensity

\[ \text{Time Resolution} \]

\[ \text{Range from 23-43 ps/25-47 ps} \]
Before irradiation, sensors reach about 30-31 ps time resolution at room temperature.

Quadratic geometry performs better.

ATLAS and IBL sensors perform very similar, slightly better rise time (240ps) for ATLAS sensor.
Time Resolution: 3D vs other sensors

- Planar: Strips sensors - 300 μm thickness (ATLAS, Hamamatsu) and 150 μm thickness (CMOS, LFoundry)
- LGADs – Pad diodes: 50 μm thickness, high gain layer doping and 35 μm thickness, lower gain layer doping
- As expected, 3D strip sensors show better time resolutions than planar strip sensors, but only pixel sensors are competitive with LGADs
- Benefit: Lower voltage necessary for 3Ds than for LGADs
Time Resolution: Irradiated 3D sensors

- Signal decreases with fluence
- Rise time drop after irradiation
- No significant fluence dependence for rise time
Time Resolution: Irradiated 3D sensors

- Slightly higher bias voltages necessary
- No clear voltage dependence for highest fluences
- Time resolution seems to be slightly improving with fluence

* measured with different trigger setup
Time Resolution vs Fluence

- Measured at 80V
- Time resolution improves with increasing fluence
- Higher electric field between columns improves timing
Comparison - LGAD vs 3D Pixel after irradiation

- Significantly lower rise time
- For these 3D pixel and LGAD types: 3D sensors perform better in timing measurements
- Note: This are not the latest/ fastest generation of LGADs – but the 3D sensors prove to be competitive
New Timing 3D sensors

- 3D doublesided technology
- Hexagonal geometry, quadratic for comparison
- 285 μm active thickness
- 10 μm column diameter

Designed and produced by CNM

RD50 common fast timing project:
CNM, Uni Freiburg, JSI (Ljubljana), IFAE (Barcelona), NIKHEF (Amsterdam), UZH (Zurich)
New Timing 3D sensors: Simulations

N-column

P-columns

Electric field at 10V

No zero field spots

Electric potential

N-column

P-columns

Waveforms @10V, f = 5e15 cm⁻²
New Timing 3D sensors

2-x: SC, hexagonal, 50 $\mu m$ rad

4-x: 5x5 array, Hexagonal, 30 $\mu m$ rad

7-x: 10x10 array, Hexagonal, 30 $\mu m$ rad

1-x: Single channel, orthogonal, 55 $\mu m$
New Timing 3D sensors: IVs

- 7 different sensor types measured: Depletion voltages between 5-20V
- Several devices per type available: All functional, timing measurement campaign to be started
Conclusion and Outlook

- Time resolution of silicon sensors is an important research area for upcoming and future colliders.

- Before irradiation, both 3D sensors reach time resolutions of 30-35 ps, comparable to LGADs.

- 3D pixel sensors improve resolution after irradiation while the bias voltage range stays almost the same.

- 3D pixels withstand $5 \times 10^{16} n_{eq}/cm^2$ while keeping their timing performance.

- The position dependent time resolution measured correlates very well with the electric field distribution.

- Dedicated timing sensors: Hexagonal geometry, IV measurements completed - timing measurements to be started soon.

- Irradiation campaign to high fluences planned.
Thank you for your attention!
BACKUP
LGAD Readout Board

1. Bonded LGAD
2. Amplifier
3. High voltage connector
4. Readout connector
5. Low voltage connector
6. PT100 connector
7. Lid
Time Resolution - Components

• Main components: Jitter and time walk: \( \sigma_t^2 = \sigma_j^2 + \sigma_{TW}^2 \)

• Jitter component \( \sigma_j \): Determined by the rise time at the amplifier output \( \frac{dV}{dt} \) and the noise level \( \sigma_n \):
  \[
  \sigma_j = \frac{\sigma_n}{|\frac{dV}{dt}|} \approx \frac{\sigma_n}{S/\tau_p} = \frac{\tau_p}{S/N}
  \]

• Time walk component includes:
  - Weighting field/el. Field contribution
  - Landau fluctuations in signal shape
  - Landau fluctuation in the amount of deposited charge (correctable)

• Time Walk component depends strongly on the sensor design
TCT area scans: 3D Pixel Sensors

- TCT scans show very small measurable area for Timing-TCT
- Outer columns connected – indefinite electric field outside the cell

Leena Diehl - 3D silicon sensors as timing detectors
Time Resolution: 3D Strip Sensor

- 3D strip sensor: 235 µm thickness, 80x80µm$^2$ cell size, 6 channels connected to readout
- Measured with TCT and Timing Set-Up
- For high voltages: Time resolution of about 75 ps reached
Position dependent measurement of the time resolution with the TCT, measured at 150 V

- Clear cell structure
- Worse resolution between junction columns
- Worse resolution around ohmic columns
- Resolution correlates to the expected el. Field
- Resolution between 65 and 83 ps
Time Resolution: 3D Strip Sensor

- Clear cell structure
- Similar patterns for jitter and rise time
- Both correlate to the expected el. Field
- Rise Time between 810 and 855 ps
- Jitter higher than in Beta Set-Up, 52-62 ps
Time Resolution: 3D Strip Sensor 2

5936-4 Strip Sensor: 285 μm thick, high leakage current (sensor broken in half), measured at 40 V

- Clear cell structure
- Worse resolution between junction columns
- Worse resolution around ohmic columns
- Resolution correlates to the expected el. Field
- Resolution between 85 and 115 ps -> lower voltage, higher noise
- Correlation also to MPV
TCT Set-Up for Timing

- **Transient Current Technique**: Charge created by a short laser pulse
- The current arising from the created e/h-pairs is amplified and then recorded with an oscilloscope
- **Top-TCT**: Laser on sensor surface, laser wavelength 1060 nm (infrared)
- First: Scanning the sensor area to determine the position of the columns
- For each specific position on the sensor: 3000 single events recorded
- Two pulses recorded per event: Using a fiber splitter and a cable (25 ns delay)
Time Resolution: Analysis

- Maximum amplitude for each event filled into histogram – MPV of the sensor is extracted with a Landau-Gauss-Fit

- If the maximum signal is above a threshold, events used for further analysis

- Time of Arrival determined with Constant Fraction Discrimination

- Linear fit around this point to extract the slope

- Determination of the rise time for each event by diving the maximum amplitude by the slope – mean of the distribution defines rise time
Time Resolution: Analysis

- Noise level: Determined in a time span in the recorded waveform before the pulse

- Jitter: Sigma of a Gauss fit to the distribution of noise divided by slope

- Time Spread: Sigma of a Gauss fit to the distribution of the time difference between the two signals

- Time resolution can then be calculated

\[
\sigma_{DUT} = \sqrt{\sigma_{TS}^2 - \sigma_{Ref}^2}
\]

\[
\sigma_{Ref} = 25.18 \pm 0.35 \text{ ps}
\]

\[
\sigma_{DUT} = \frac{\sigma_{TS}^2}{\sqrt{2}}
\]

Beta Set-Up:

TCT Set-Up:
Time Resolution: 3D Pixel sensors

- Sanity Check: Comparison with/without additional PMT trigger
- With PMT: Very low rate – pick-up noise problems
- Without PMT: overestimation of MPV
- Otherwise: Very comparable results

➢ All further measurements without PMT – improved statistics and measurement time, while time resolution characteristics are maintained
3D Pixel sensors

Expected voltage dependence

- Position along x-axis [μm]
- Position along y-axis [μm]
- Time Resolution [ps]

- 5306-4, Position 1
- 5737-7, Position 1
- 5737-7b, Position 1
- 5306-4, Position 2
- 7b, Position 2

Voltages [V]

30 40 50 60 70 80 90 100

Time Resolution [ps]

35 40 45 50