Integrated CMOS sensor technologies for the CLIC tracker

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Possible **multi-TeV linear e^+e^- collider** in the post LHC phase at CERN:

CLIC layout:

<table>
<thead>
<tr>
<th>3 TeV stage:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch separation [ns]</td>
</tr>
<tr>
<td># bunches / train</td>
</tr>
<tr>
<td>Train duration [ns]</td>
</tr>
<tr>
<td>Repetition rate [Hz]</td>
</tr>
<tr>
<td>Bunch size $\sigma_x / \sigma_y$ [nm]</td>
</tr>
<tr>
<td>$\sigma_z$ [µm]</td>
</tr>
</tbody>
</table>

- High centre of mass energies **up to 3 TeV**
- Dense bunches to achieve high luminosity
- High background rates ➔ **time-stamping of ~ 10 ns needed to reject background hits**
- Note: significantly lower radiation levels of $\sim 10^{11}$ neq/cm²/y compared to hadron colliders

See talk by E. Sicking: “Detector challenges for future high-energy e^+e^- colliders”
# Integrated technologies for the CLIC tracker

## Physics needs & environment:

- Momentum resolution: \( \sigma_{p_T} / p_T^2 = 2 \cdot 10^{-5} / \text{GeV} \)
- Suppression of high beam beam background occupancies

## Tracker requirements:

- 7 µm single point resolution
- \(~1\%\) radiation length per layer
- 10 ns time stamping

## Technology choice:

1. Highly granular / fine pitch
2. Thin / low material budget
3. Fast signal

### Challenge to meet requirements simultaneously:

**Benefit from integrated CMOS technologies:**
- No separate ASIC material: \(\rightarrow\) Lower material budget
- No sensor-ASIC interconnect: \(\rightarrow\) Large scale production (100m² CLIC tracker)
- Finer pitch

**Crucial for integrated CMOS technologies:**
- Full depletion for fast and fully efficient operation

\(\rightarrow\) **Achievable with CMOS circuitry on High Resistivity HR epitaxial layer (epi)?**

See talk by A. Nurnberg:

“A vertex and tracking detector system for CLIC”
The Investigator Chip (W. Snoeys, J. W. van Hoorne et. al.)

HR-CMOS process:
180 nm High Resistivity (HR) CMOS process, 15-40 µm thick epitaxial layer (1-8 kΩcm):
• Developed as part of ALPIDE development for ALICE ITS upgrade
• Fully monolithic ALPIDE chip developed in this process

Test-chip:
Various mini-matrices with different pixel layouts:
• Optimisation of pixel layout:
  • Minimising size of collection diode
    ➔ Minimise capacitance (~ fF)
  • Large signal/noise ➔ fast timing (~ ns)

External readout board (designed by K. M. Sielewicz):
• 64 ADCs to read out full analogue waveform of 8 x 8 active pixel matrix
• 65 MHz sampling clock limits achievable timing resolution

Two different submissions:
Changes in modified process to achieve full depletion:
• Better timing performance
• Radiation hardness
Test-beam studies

Test-beam setup:
CLICdp Timepix3 telescope at SPS beam line:

- **Timepix3 telescope:**
  - *Excellent timing resolution ~ 1 ns:*
  - Benefit for studies of fast Investigator timing
  - *Excellent track prediction resolution ~ 2 µm:*
  - Benefit for sub-pixel performance studies for small pixel sizes of Investigator

Investigator data-taking & reconstruction:
If at least one pixel crosses a seed threshold:
- **Full analogue waveform of all 8 x 8 active pixels read out**
- Timestamp send to telescope planes for offline synchronisation

![Example of single pixel waveform](image)

- **Waveform reconstructed by exponential fit:**
  \[
  f(t) = \begin{cases} 
  \text{Pedestal} & t \leq t(\text{hit}) \\
  \text{Pedestal} + \text{Signal} \times \left( e^{\frac{t-t(\text{hit})}{\text{t(rise)}}} - 1 \right) & t > t(\text{hit}) 
  \end{cases}
  \]
Efficiency over pixel matrix / modified process

Efficiency over pixel matrix:
Pitch = 28 µm, bias voltage = 6 V,
epi thickness = 25 µm, modified process:

- Analysis of efficiency of standard process currently ongoing

**Efficiency > 99 % over fiducial region** *(masking half of edge pixels to account for limited track precision)*
Cluster size & resolution / standard & modified process

Standard process:
- Pitch = 28 µm
- Bias voltage = 6 V
- Epi thickness = 18 µm
- Neighbour threshold ~ 70 e⁻

Modified process:
- Pitch = 28 µm
- Bias voltage = 6 V
- Epi thickness = 25 µm
- Neighbour threshold = 50 e⁻

Despite thinner epi and larger threshold for standard process:
- Larger cluster size and better resolution, as expected from more diffusion

\[ \mu \sim 1.5 \quad \text{for standard process} \]
\[ \mu \sim 1.3 \quad \text{for modified process} \]

\[ \sigma \sim 5 \mu m \quad \text{Gauss fit} \quad \text{for standard process} \]
\[ \sigma \sim 6 \mu m \quad \text{Gauss fit} \quad \text{for modified process} \]

→ Position resolution matching well requirement of 7 µm for CLIC tracker (t.b.c. with fully integrated chip).
Timing / standard & modified process

Standard process:
- Pitch = 28 µm
- Bias voltage = 6 V
- Epi thickness = 18 µm
- Neighbour threshold ~ 70 e⁻
- Seed threshold ~ 200 e⁻

\[ \sigma \sim 7 \text{ ns} \]

Modified process:
- Pitch = 28 µm
- Bias voltage = 6 V
- Epi thickness = 25 µm
- Neighbour threshold = 50 e⁻
- Seed threshold ~ 150 e⁻

\[ \sigma \sim 5 \text{ ns} \]

- Faster timing for modified process, as expected from full depletion
- Measured timing resolution limited by readout sampling frequency of 65 MHz

→ Timing resolution matching well requirement of 10 ns for CLIC tracker (t.b.c. with fully integrated chip).
Sub pixel studies / modified process

- Results shown for modified process:
  ▶ Pitch = 28 µm, epi thickness = 25 µm, bias voltage = 6V, neighbour threshold ~ 50 e⁻

- More charge sharing in pixel edges and corners
  ▶ Higher cluster size and Lower seed signal in pixel edges and corners

- Low seed threshold of ~ 150 e⁻ during data taking:
  ▶ No significant efficiency loss in pixel corners

→ Sub-pixel performance in qualitative agreement with expectations.
Simulation

Simulation chain:

**GEANT4 simulation:**
- Energy that particle deposits while traversing the sensor.

**2-dimensional TCAD simulation:**
- Simulate sensor geometry, doping and bias voltage application
- Transient simulation using particle with energy deposit from GEANT4

**Fast parametric model:**
- Energy fluctuations
- Threshold application
- Telescope resolution
- Reconstruction

TCAD simulation of standard & modified process:

Electrostatic potential for standard process:

![Depletion](image1)

Electrostatic potential for modified process:

![Depletion](image2)

CLICdp work in progress
Comparison data - simulation / standard process

Mean X cluster size in pixel cell:

- Simulation
- Data

CLICdp work in progress

Mean X cluster size

Mean X cluster size in pixel cell:

- Simulation
- Data

CLICdp work in progress

Mean X cluster size

Residual in X-dimension:

- Simulation
- Data

CLICdp work in progress

Residual in X-dimension

- Simulation
- Data

• $^{55}$Fe- calibration applied to define threshold in simulation

  ➔ Excellent agreement between simulation and data on sub-pixel level.
Comparison data - simulation / modified process

Cluster size distributions for different thresholds:

Residual distributions for different thresholds:

Mean cluster size & resolution for different thresholds:

- $^{55}$Fe-calibration applied to define threshold in simulation
- Expected trend of lower cluster size and worse resolution visible in data & simulation

$\Rightarrow$ Good agreement of data and simulation for different thresholds within a few percent.
Summary

Study of Investigator HR-CMOS test-chip with respect to requirements for the CLIC tracker:

- Test-beam study of two different submissions standard & modified process
- Spatial and timing resolution matching requirements of 7 µm single point resolution & 10 ns time stamping for CLIC tracker:
  - Single point resolution ~ 6 µm
  - Time resolution < 5 ns
  - Efficiency > 99%

→ Studies used as input for design of fully monolithic tracker chip for CLIC (see talk by A. Nurnberg: “A vertex and tracking detector system for CLIC”)

Explore Investigator HR-CMOS technology:

- Detailed understanding of charge sharing on sub-pixel level
- Simulation of standard and modified process show agreement between simulation and data within a few percent showing a good understanding of the studied technology
The CLIC detector

CLIC detector for **high precision measurements**:

### Physic aims

- E.g. Higgs recoil mass, Smuon endpoint
- W/Z/H seperation
- E.g. Higgs couplings (b/c-tagging)

### Detector needs

- Momentum resolution
  \[ \sigma_{p_T} / p_T^2 = 2 \cdot 10^{-5} / \text{GeV} \]
- Jet energy resolution
  \[ \sigma_E / E = 3.5\% - 5\% \]
- Impact parameter resolution
  \[ \sigma_r \sim 5 \times 15 / p \cdot \sin^{3/2} \Theta \mu m \]

### Tracker requirements:

- Momentum resolution at high \( p_T \)
- Momentum resolution at low \( p_T \)
- Reduce occupancies from beam-beam interactions

- 7 \( \mu m \) single point resolution
- \(~1\%\) radiation length per layer
- 10 ns time stamping

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**CLIC detector model:**

Large area (~100m\(^2\)) silicon tracker
Analysis & definition of observables

Investigator event reconstruction:

- Signal defined as magnitude of amplitude drop
- Noise defined as RMS of fluctuation around pedestal
- Analysis cut on Signal/Noise > 5 for each single pixel
  (Note: higher data taking threshold corresponds to cut on seed signal while lower analysis cut corresponds to cut on neighbour pixel signal)
- Fit exponential function $f(t)$ to waveform of each pixel to extract exact timing and signal:

$$f(t) = \begin{cases} 
\text{Pedestal} & \text{if } t \leq t_{\text{Hit}} \\
\text{Pedestal} + \text{Signal} \cdot (e^{-(t - t_{\text{Hit}})/t_{\text{rise}}} - 1) & \text{if } t > t_{\text{Hit}} 
\end{cases}$$

Further analysis cuts:

- Event size of 10 µs
- Distance track-Investigator hit position < 2 x pixel pitch
- Masking of half of edge pixels to avoid bias by edge effects due to limited tracking resolution and/or charge sharing