Detector response and performance of a 500 μm thick GaAs attached to Timepix3 in relativistic particle beams

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Outline

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Motivation

Main driver for development of high-Z compound semiconductor materials is X-rays imaging and γ-detection

Imaging applications profit from the higher stopping power (higher efficiency of photoeffect)

Why to use it for particle tracking?

- High charge carrier mobility → increased speed of operation
- Higher stopping power
- Expected higher radiation tolerance
- Particle identification using a combination of X-ray detection and tracking (Transition radiation detector)*

Disadvantages: Thermal stability, higher leakage current, sensor inhomogeneity, charge carrier lifetime ...

Timepix3 detector and GaAs:Cr

**Timepix3**
- 256 x 256 pixels with 55 µm pitch (1.98 cm² sensitive area)
- Minimal detection threshold in each pixel is 500 e⁻
- Each pixel measures energy deposit (ToT) and time of interaction (ToA, precision 1.5625 ns)
- Data driven-readout (data are send on an event-by-event base)

**Sensor layer:**
- Chromium compensated GaAs from Tomsk State University
- Thickness 500 µm
- Ohmic contacting scheme

**Readout:**
- AdvaDAQ (pion measurement)
- Katherine readout (characterization, mixed ion beam)
Basic sensor characterization: I-V curve and count rate homogeneity

I-V curve measurement:
- Measurement of the leakage current as function of the applied bias
- Line fit used to determine the sensor resistivity

\[ \rho = \frac{U}{I} \times \frac{A}{d} \]

Count rate homogeneity:
- Sensor irradiated by 59.6 keV γ-rays from an $^{241}\text{Am}$ source
- Good homogeneity

T ~ 30°C

Amercium (59.6 keV)
Basic sensor characterization: Determination of the $\mu \tau_e$-product

- Irradiation of the GaAs:Cr sensor with K-line photons of zirconium (15.77 keV)
- Determine the peak position of single pixel clusters $E_{\text{peak}}$ as a function of the applied bias $U_{\text{bias}}$

Induced charge is defined as $E_{\text{peak}}/E_{\text{K-line}}$

Sensor temperature: $T_{\text{sensor}} \sim 50^\circ$C

$$\mu \tau_e = (0.673 \pm 0.0214) \times 10^{-4} \text{ cm}^2 \text{ V}^{-1}$$
$$\mu \tau_e = (0.882 \pm 0.059) \times 10^{-4} \text{ cm}^2 \text{ V}^{-1}$$

* Fit function by Billoud et al.
** Fit function by Hamann, used in Greiffenberg et al.

Measurements in a 40 GeV/c pion beam

- Super-proton-synchrotron at CERN
- Irradiation at 60° wrt the sensor normal
- Sensor used in electron collection (negative polarity)
- Bias varied in the range from -25 V to -500 V
- Study of the sensor material properties (drift time, charge collection efficiency)
40 GeV/c pion beam: 60 deg – Typical tracks

Collection of 100 tracks measured at 60 deg irradiation at bias -25 V
- Energy deposition (left)
- Relative time difference within a track (right)
40 GeV/c pion beam: 60 deg – Single event analysis

- Increase of the time with increasing distance to the pixel electrodes
- Overall decrease of energy with increasing distance to the pixel electrodes
  → Study drift time ($\Delta$ToA) and charge collection efficiency (ToT) as a function of $z$

Bias: -25 V
40 GeV/c pion beam: 60 degrees - Drift time analysis

Slope of the presented curves is \( \frac{1}{v_{\text{drift}}} \) (determined by fitting)
Electric field:

\[ E = \frac{U_{\text{Bias}}}{d} \]

\( U_{\text{bias}} \): Bias voltage

\( d \): Thickness

\( v_{\text{drift}} \) saturates and decreases above the electric field \( E_0 \)

\[ E < E_0: \quad v(E) = \mu_e E \]

\[ E \geq E_0: \quad v(E) = \frac{\mu_e E}{\sqrt{1 + (E - E_0)^2 / E_c^2}} \]


40 GeV/c pion beam: 60 degrees – Drift velocity and electron mobility

\( \mu_e = 8000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \)

\( E_0 = 3.5 \text{ kV/cm} \)

\( E_c = 1.5 \text{ kV/cm} \)

\( v_{\text{drift}} \) (10^7 cm/s)

Measurement

Model*)
40 GeV/c pion beam – 60 degrees - Charge Collection Efficiency

CCE extracted from the energy deposition profile of the track
- Higher charge collection efficiency as expected from simulation
- Behavior of the charge collection efficiency cannot be explained
Measurements in mixed ion beam after 330 GeV/c Pb impact on target

- Super-Proton-Synchrotron at CERN
- Sensor used in electron collection (neg. polarity)
- Results at bias -200 V are shown
- Data at angles 0°, 25°, 50° and 75° (wrt the sensor normal)
- Study the detection and separation capability of multiply charged particles
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330 GeV/c Pb impact on target: Stopping power spectra at different angles

Per-pixel saturation level ~450 keV and higher per-pixel energy deposit reduces capability of ion species separation at low angles.

Peaks correspond to multiply charged projectiles: \( E_{\text{dep}} \sim Z^2 \)
330 GeV/c Pb impact on target: Impact at 75 degree – Landau fitting and track shapes

Energy deposition spectra described by Landau functions.

A halo becomes pronounced from the 3rd peak.

Halo starts to grow from the side, where the track is close to the pixels.
Conclusion

- The detector response of a 500 µm thick GaAs:Cr was studied in relativistic particle beams.
- Measurement in a 40 GeV/c was used to study drift times of electrons and the charge collection efficiency as functions of interaction depth at different bias voltages.
  - The drift time measurement was consistent with $\mu_e = 8000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$
  - Drift velocity saturation was found at electric fields above $E_0 = 3.5 \text{ kV/cm}$
- The particle species separation capability was studied in a mixed relativistic ion beam at different angles.
  - The higher the impact angle the more species could be identified by stopping power.
  - For low angles saturation of pixel electronics ($\sim 500 \text{ keV}$) reduces particle species separation capability.
  - For heavier ions a halo becomes visible. It is delayed by $\sim \mu$s.

Thank you for your attention!
Back-up
Electric field GaAs:Cr sensors


Fig. 8. The spatial distribution of function $F$ through the detector thickness for various bias voltages (GaAs:Cr).
40 GeV/c pion beam: 60 deg – Energy spectra

Energy deposition spectra are fitted by a Landau-distribution (physics of interaction in the medium) convoluted with a Gaussian (energy resolution)
40 GeV/c pion beam: 60 degrees –
Most probable value vs. bias voltage

Most probable value increases with increasing bias

\[ E_{MPV} \text{ (keV)} \]

\[ \begin{array}{c}
\text{Absolute bias (V)} \\
0 & 100 & 200 & 300 & 400 & 500 \\
\end{array} \]

\[ \begin{array}{c}
\text{500} & 550 & 600 & 650 \\
\end{array} \]
330 GeV/c Pb impact on target: Impact at 75 degree – Typical tracks

• Example tracks:

Events measured at an impact angle of 75 degrees
Pixel-saturation level

Per pixel energy saturation level $\sim 500$ keV independent of impact angle and bias

Mixed ion beam: 0 deg

Mixed ion beam: 25 deg

Mixed ion beam: 50 deg

Mixed ion beam: 75 deg
Measured energy vs. expected energy

Per-pixel energy saturation kicks in
Halo vs. energy

Relative amount of energy in the halo increases with increasing energy deposition.

Relative amount of energy in the halo increases with increasing bias voltage.
330 GeV/c Pb impact on target: Single heavy ion event – Features

- Initial track (core) with outgoing $\delta$-rays surrounded by a halo of pixels with lower energy measurements

Halo pixels are seen with a delay in the order of $\mu$s

- Time structure can be used to easily separate core and halo

- Halo delay decreases with increasing bias voltage

- Halo pixels' timestamp decreases with increasing distance to the core

- Number of halo pixels and energy in the halo increases with increasing bias

- Energy in the halo increases with energy deposition