Study of the charge carrier properties GaAs:Cr with Timepix3

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Introduction

- High resistivity (HR) GaAs:Cr has become an interesting material for X- and gamma- ray imaging detectors.
- But, it can be also used for particle tracking:
  - higher electron mobility -> faster device;
  - higher stopping power -> more particle species can be separated in mixed radiation fields.
- The GaAs:Cr charge carrier transport properties were studied experimentally (by means of 125 MeV protons irradiation):
  - the parameters of Ruch model [1] for electrons drift velocity were founded for GaAs:Cr;
  - based on the simulation and testbeam data the mobility μ_h and lifetime τ_h of holes were estimated;
  - charge carrier space spread was measured as a function of interaction depth;
  - obtained parameters were used to simulate the GaAs:Cr-Timepix3 response to gammas of 10 – 60 keV.

Why do we need proper knowledge of transport properties of charge carriers?

- In pixel detectors the small pixel effect plays the significant role.
- The dependence of Charge Collection Efficiency (CCE) on interaction depth is almost flat, electrons give main contribution, but in close to pixel region the contribution of holes is significant -> for proper simulation of events which occur close to pixels it is important to know lifetime and mobility of both charge carriers – electrons e^- and holes h^+.
- Transport properties of electrons in HR GaAs:Cr were measured and recently reported multiple times [2, 3], but for holes such information was not found updated.

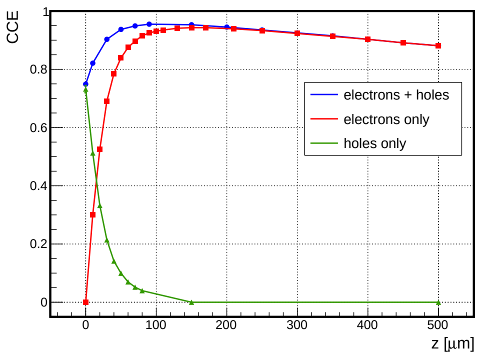


Figure: CCE versus interaction depth z for 500 μm thick GaAs:Cr-Timepix3 detector. $z = 0$ μm are pixels plane.

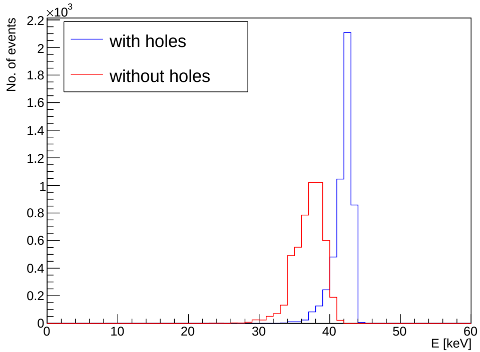


Figure: Simulated energy spectrum of 10 ke^- charge placed at 50 μm from pixel.

Detector based on Timepix3 chip and HR GaAs:Cr sensor

Timepix3:

- Matrix of 256x256 pixels with pitch 55 μm.
- Simultaneous measurements of deposited energy (ToT) and time of interaction (ToA with binning of 1.5625 ns) in each pixel.
- Data driven readout.
- Maximum hit rate: 40 Mhits/cm^2/s.

High resistivity GaAs:Cr:

- Technology of chromium compensation is developed by Tomsk State University.
- $\rho \sim 10^9$ Ohm·cm.
- e$^-$ are main charge carriers: $\tau_e \in [10, 100]$ ns.
- Transport properties of h$^+$ are very pure.
- Sensor thickness 500 μm.

Figure: HR GaAs:Cr-Timepix3 detector with readout interface Katherine.

Measurements with charge particles at grazing angles

- Protons of 125 MeV and pions of 120 GeV/c at impact angles of **30 − 75** deg.
- Timepix3 chip operated in hole/electron collection mode.
- Electron collection mode: verify Ruch et al. electron drift velocity model.
- Hole collection mode: estimate lifetime and mobility of holes.

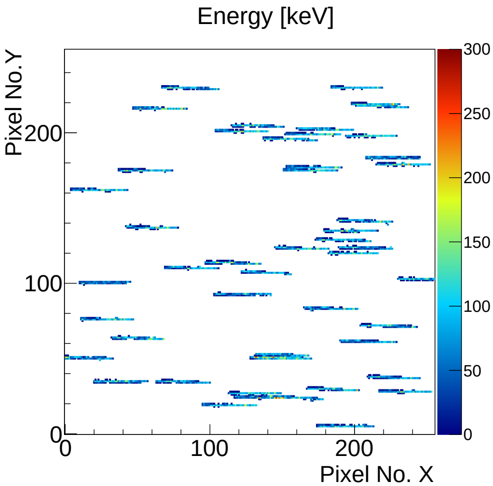


Figure: Typical protons tracks in electron collection mode at 75 deg.

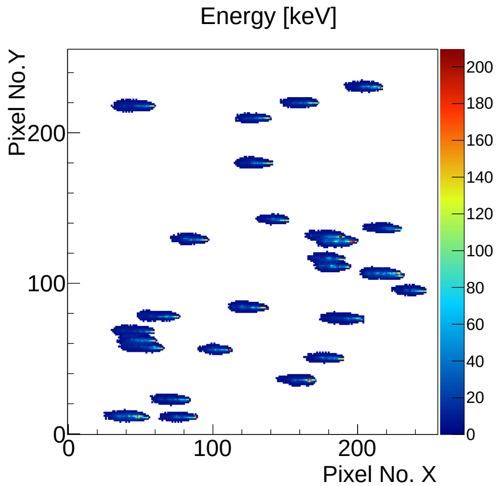


Figure: Typical protons tracks in hole collection mode at 75 deg.

Modes of detector operation

Simplified schemas of preamplifier output

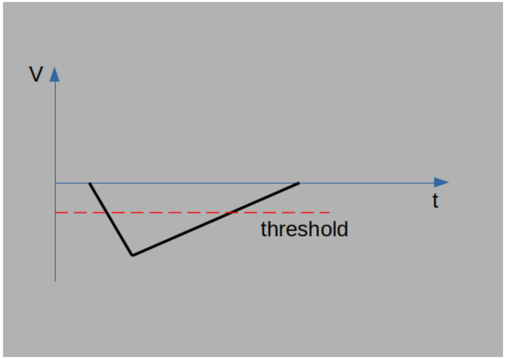


Figure: Electron collection mode

- Negative bias applied to common electrode (electrons drift towards pixels), discriminator polarity "-".
- Typical "GaAs"/"CdTe" mode of operation.

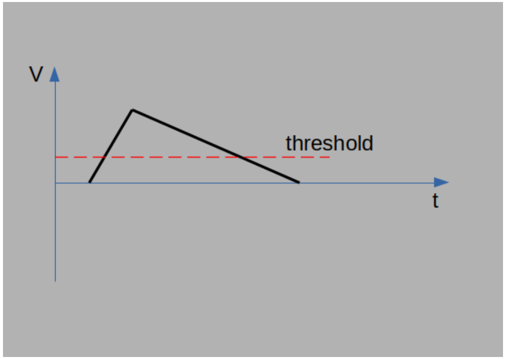
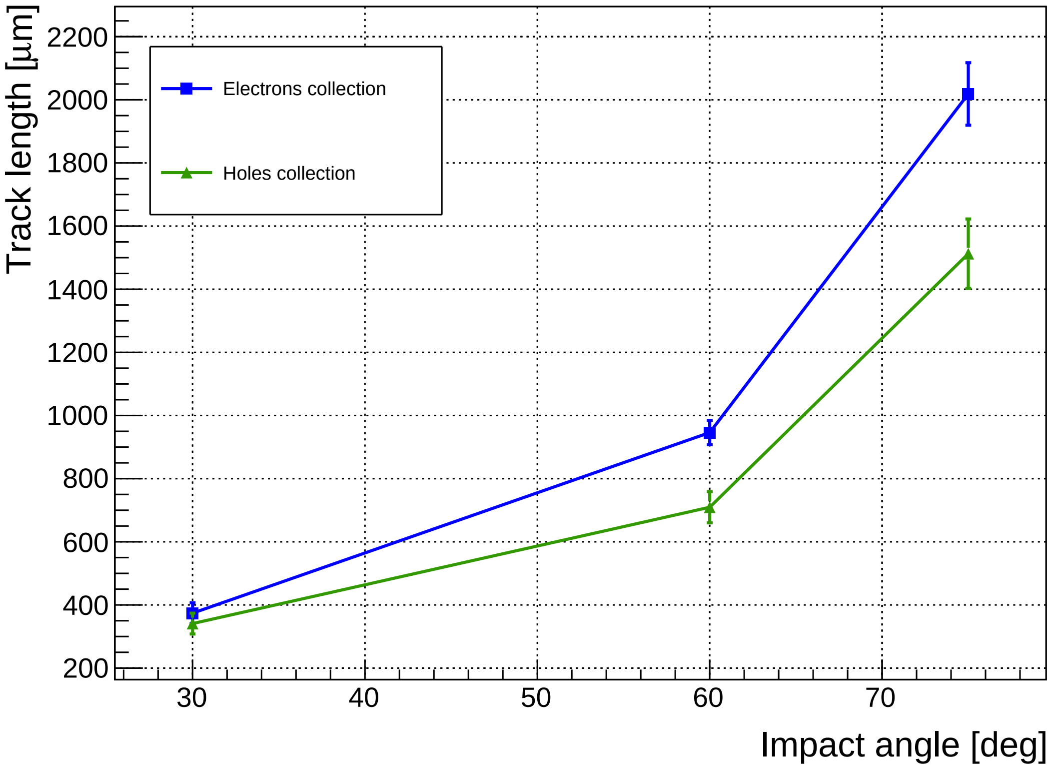


Figure: Hole collection mode

- Positive bias applied to common electrode (holes drift towards pixels), discriminator polarity "+".
- Typical "Si" mode of operation.

Tracks length comparison in two collection modes

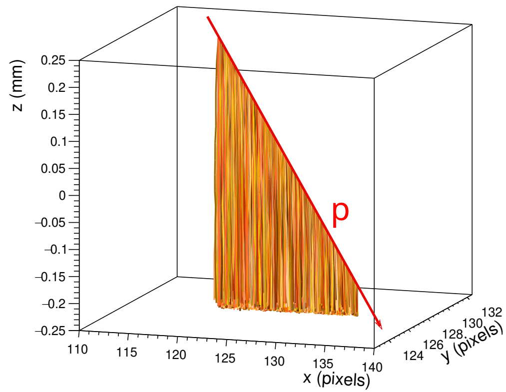
- Proton tracks in hole collection mode are shorter than in electron collection mode for all impact angles.



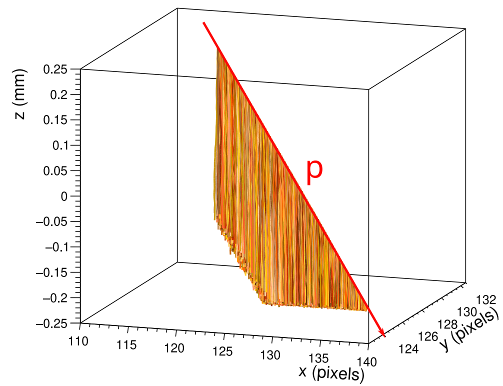
Simulation with Allpix^2 framework

- Several modules of Allpix^2 framework were modified in order to add:
  - GaAs as physical material;
  - drift velocity models and charge carrier lifetime.
- TransientPropagation module was used in order to obtain the evolution in time of induced charge on pixel electrodes according to Shokley-Ramo theorem.
- Constant electric field model was chosen as appropriate for GaAs:Cr [2].
- ToA information was calculated as time when induced on pixel charge crossed the threshold ($\neq$ drift time) + smeared according to $\sigma_{timewalk}$ [5].

Visualization of electrons drifted to pixels from 125 MeV proton track path.



Visualization of holes drifted to pixels from 125 MeV proton track path.



Drift time(z) & CCE(z) in electron collection mode

- Used mobility and lifetime values: $\mu_e = 3227$ cm^2/V/s and $\tau_e = 30$ ns give typical many times reported value of $\mu_e \times \tau_e \sim 10^{-4}$ cm^2/V.
- Drift time is ∼3 ns for 500 μm thick detector with U_{bias}=-300 V, what is already good enough to fully utilize the time resolution of Timepix3.

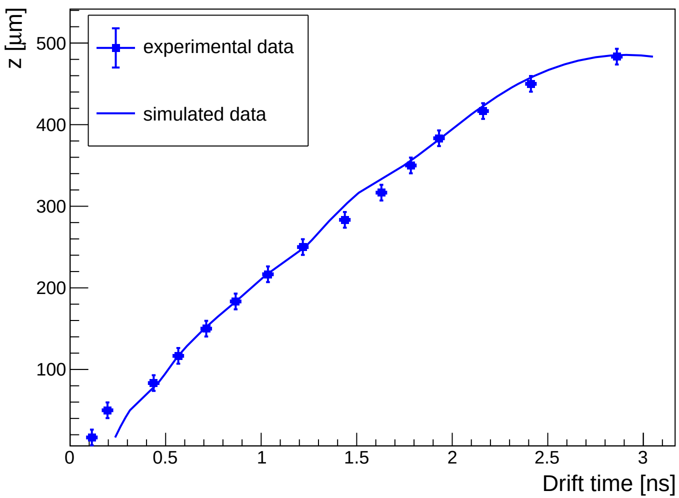


Figure: Drift time(z) for electrons.

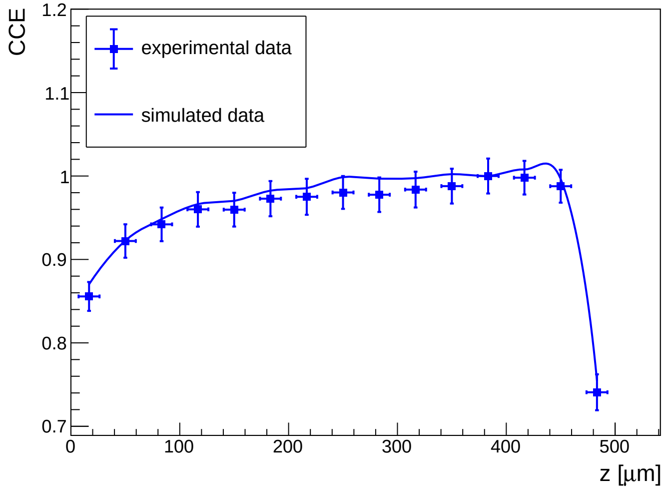


Figure: CCE(z) for electrons.

Drift time(z) in hole collection mode

- Iterative simulation with different values of μ_h and τ_h with step on mobility of 10 cm^2/V/s and lifetime – 0.5 ns.
- The best agreement is achieved for $\mu_h = 320 \pm 10$ cm^2/V/s and $\tau_h = 4.5 \pm 0.5$ ns.

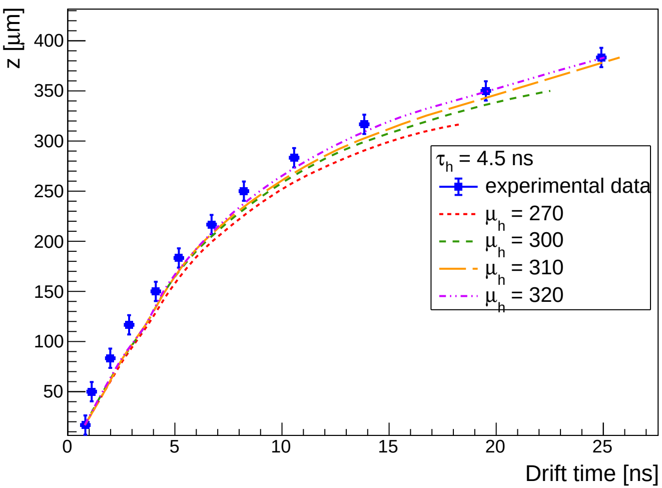


Figure: Fixed $\tau_h = 4.5$ ns, various mobilities.

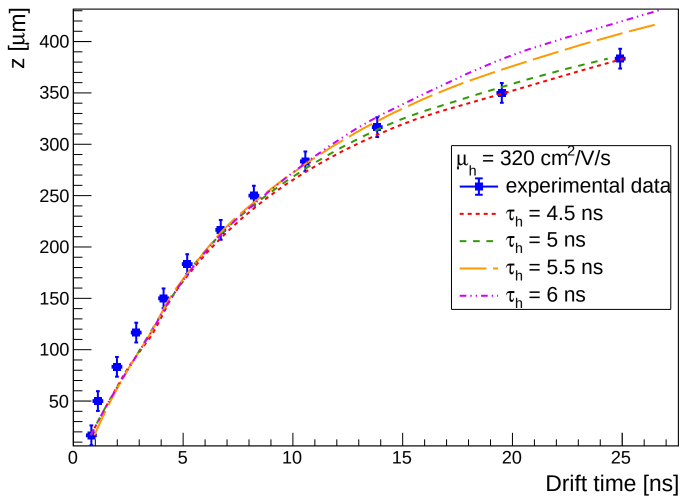


Figure: Fixed $\mu_h = 320$ cm^2/V/s, various lifetimes.

HR GaAs:Cr charge transport models

Electrons drift velocity dependence on electric field – from Ruch et al.:

- if E < E_0: $V^e_{drift} = \mu_e \cdot E$.
- if E ≥ E_0: $V^e_{drift} = \mu_e \cdot E/\sqrt{1 + (E - E_0)^2/E_c^2}$.
- Saturation electric field is $E_0 = 3517$ V/cm.
- Verified with previous measurements [4].

For holes:

- Simple approach: $V^h_{drift} = \mu_h \cdot E$.
- Estimation of μ_h and τ_h based on comparison of data and simulation.

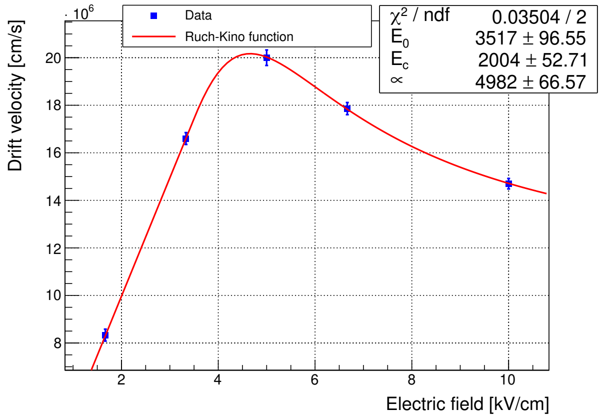
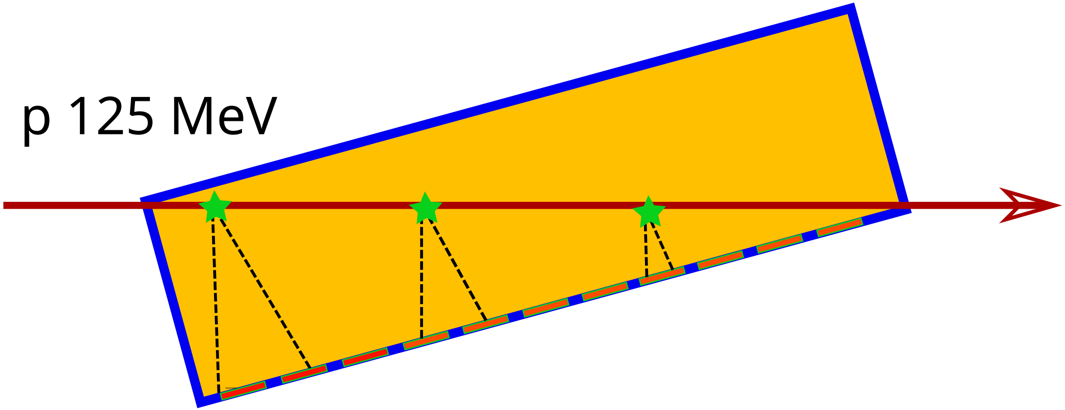


Figure: Dependence of electrons drift velocity on electric field.

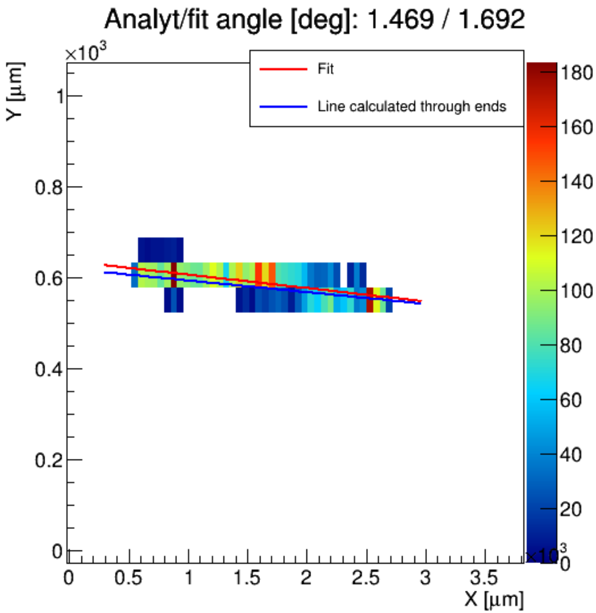
Charge carrier space spread – charge sharing

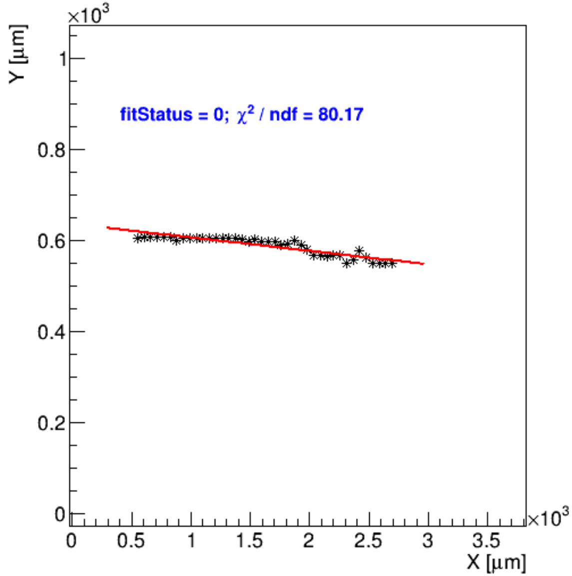
- Main influencing factors: initial charge cloud size, diffusion, repulsion, weighting field, capacitive coupling.
- All these contributions can be measured simultaneously with energetic protons impacted to the detector at grazing angle.



Methodology: charge cloud σ dependence on depth

- Protons of 125 MeV at 75 deg. to the detector normal.
- Select only clusters at small angle (1-2 deg.) to rows.
- Fit by line to obtain sub-pixel position of the track -> extract sub-pixel $y_{subpixel}$ position for each x position of track.
- Calculate depth z coordinate of the track from geometry.
- Fit by Gaus + Landau the energy spectrum for each (z, Δy = y - $y_{subpixel}$) position.
- Create pixel "sensitivity map" MPV(Δy) for each depth position, fit by function below and extract σ.





Pixel sensitivity maps for different depths

- Fit MPV(Δy) dependence for each depth bin by function [6]:

$$MPV(\Delta y) = MPV_0 * (1 + Erf(\frac{27.5 - y}{\sqrt{2}\sigma}))$$

- Flatter top – lower charge sharing.

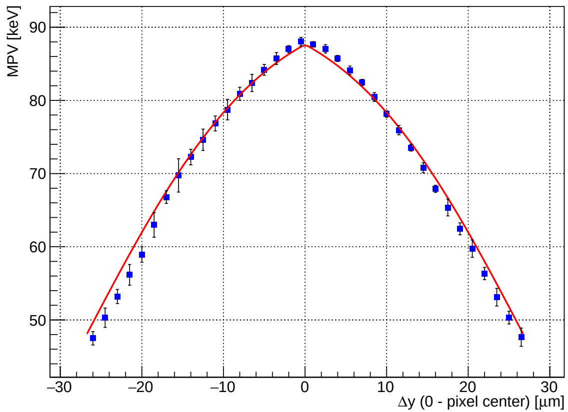


Figure: Interaction close to the common electrode: $\sigma = \sim 16\ \mu$m.

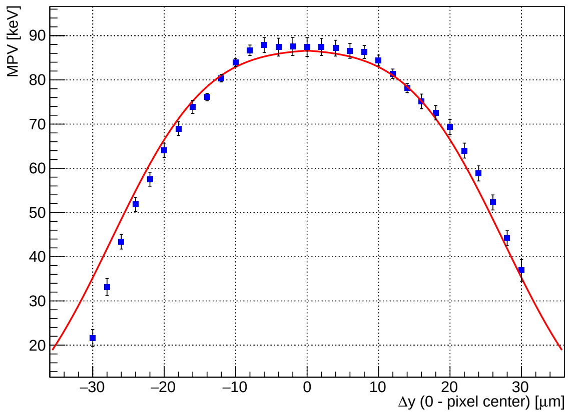
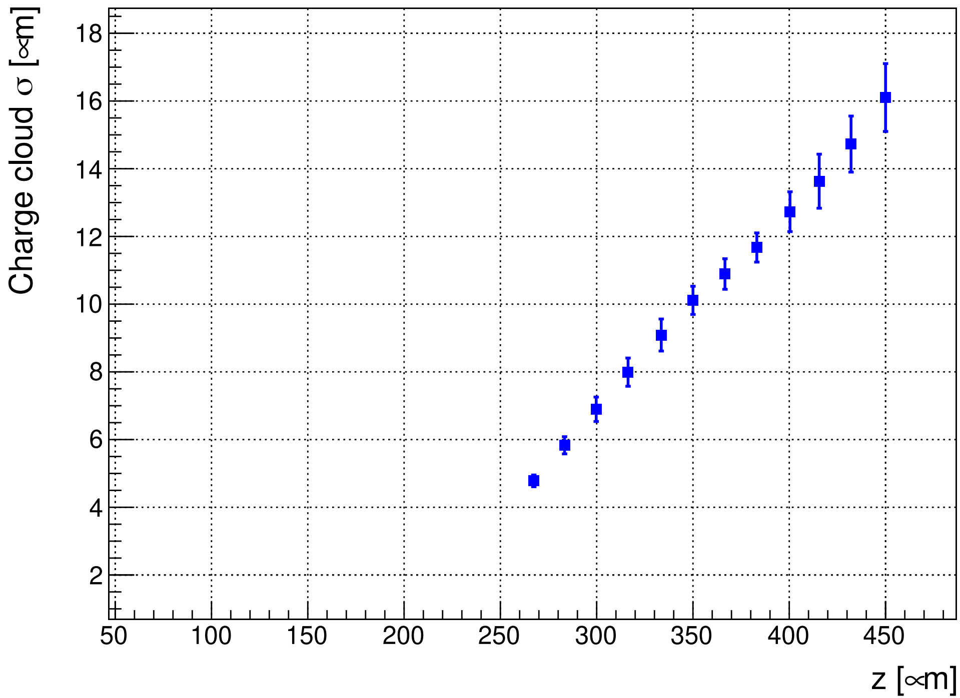


Figure: Interaction in the middle of the sensor: $\sigma = \sim 5\ \mu$m.

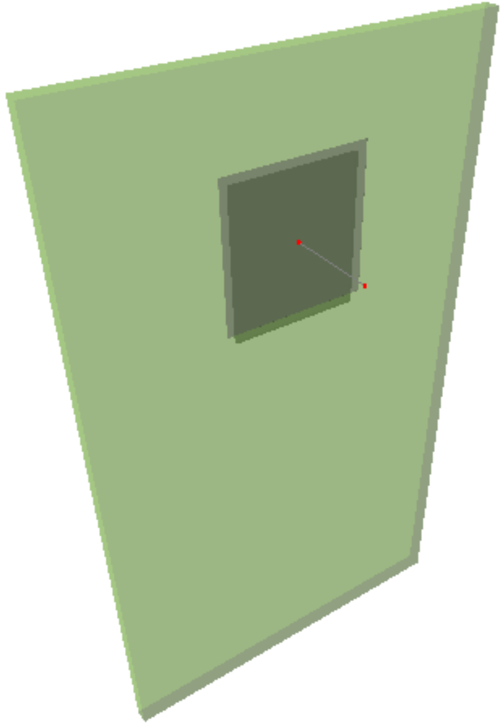
Preliminary results

- The obtained dependence can be used for quick detector response simulation.
- More experimental data is needed to obtain dependence σ (z, U_{bias}): bias voltage scan.



Simulation of the response to gammas

- Obtained charge transport parameters were applied in the simulation of the detector response to γ-s.
- Standard geometrical model of the Timepix detector in Allpix^2 was used.
- It includes PCB, bump-bonds, chip and sensor covered by Al.
- Surrounding safety box was not taken into account (scattering).
- Experimental dataset: ^{241}Am source with 59.6 keV γ-line was placed in front of the detector + several X-ray fluorescence lines were used.



Simulated/measured energy spectra

- GP - GenericPropagation [no Shokley-Ramo theorem, artificial charge smearing]
- TP - TransientPropagation [Shokley-Ramo theorem, proper simulation of Timepix3 electronics]
- Relative energy resolution $\sigma/E \sim 6$ % @ 60 keV.

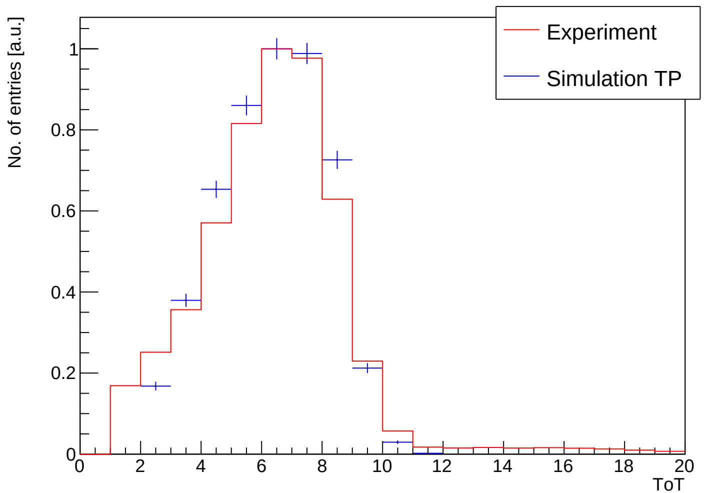


Figure: 8 keV photons spectra.

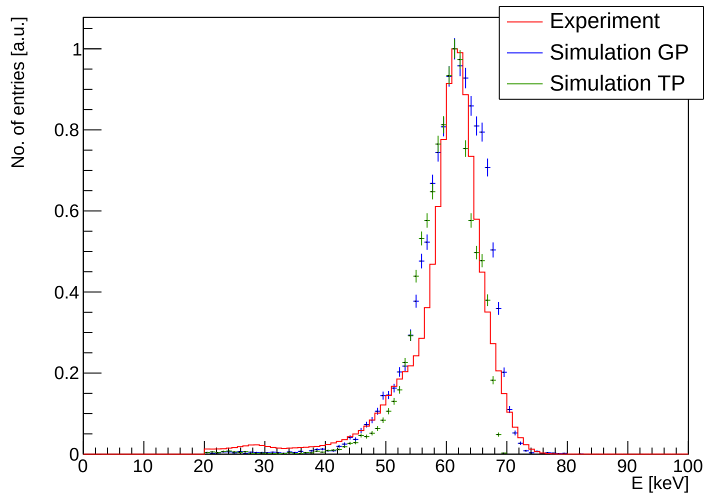


Figure: of ^{241}Am source spectra.

Simulated spectra of 10÷60 keV gammas

- The energy resolution of simulated spectra is very close to experimental ones, especially in case of Transient current simulation.

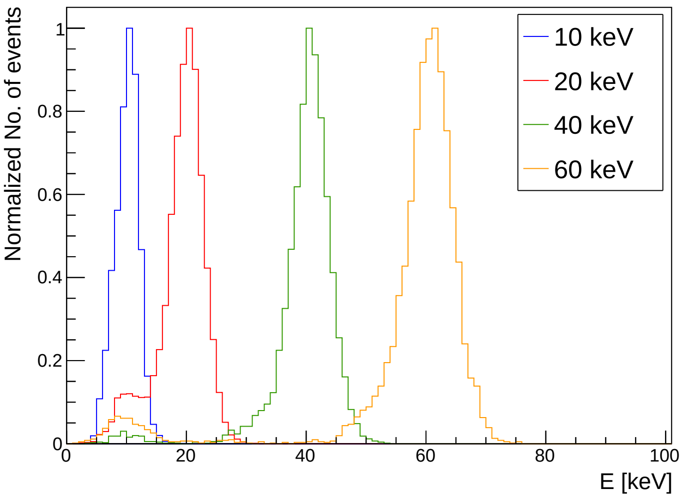


Figure: Simulated spectra.

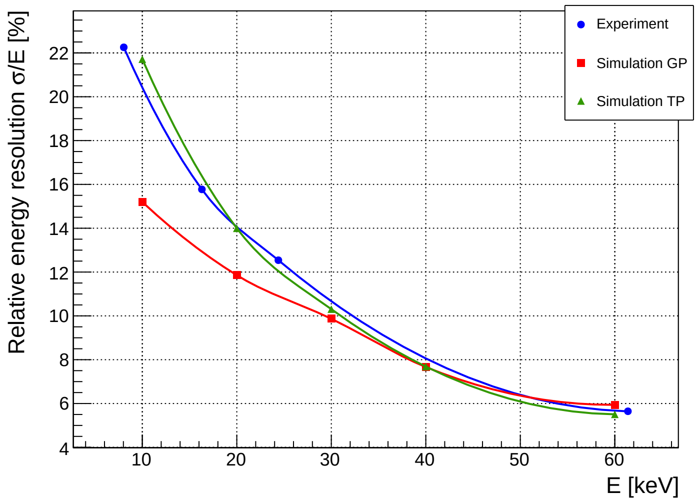


Figure: Relative energy resolution versus energy.

Conclusions

- Timepix3 is a useful tool for sensors charge transport study.
- Charge transport models for HR GaAs:Cr were verified with experimental data and the reasonable agreement was demonstrated.
- Mobility and lifetime of holes in HR GaAs:Cr were estimated using the simulation and experimental data.
- The spread of charge cloud was measured in dependence on interaction depth.

Thank you very much for your attention!

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Links

1. J. G. Ruch and G. S. Kino. Transport Properties of GaAs. Phys. Rev. 174, 921 https://doi.org/10.1103/PhysRev.174.921
2. A.V. Tyazhev et al. GaAs radiation imaging detectors with an active layer thickness up to 1 mm. NIM A 509 (2003) 34–39
3. T. Billoud et al., Homogeneity study of a GaAs:Cr pixelated sensor by means of X-rays, 2018 JINST 13 P04002.
4. B. Bergmann et al., Detector response and performance of a 500 um thick GaAs attached to Timepix3 in relativistic particle beams, 2020 JINST 15 C03013
5. P. Smolyanskiy et al., Tracking and separation of relativistic ions using Timepix3 with a 300 um thick silicon sensor, 2021 JINST 16 P01022
6. E. J. Schioppa et al., Study of Charge Diffusion in a Silicon Detector Using an Energy Sensitive Pixel Readout Chip, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 62, NO. 5, OCTOBER 2015

Weighting potential for central and non-central pixels