Study of charge sharing effect in a GaAs:Cr-based Timepix3 detector

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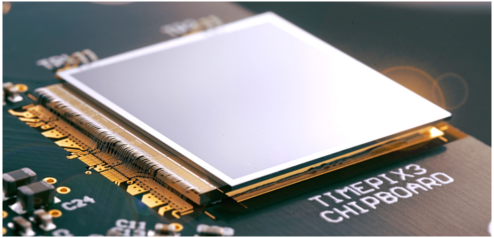
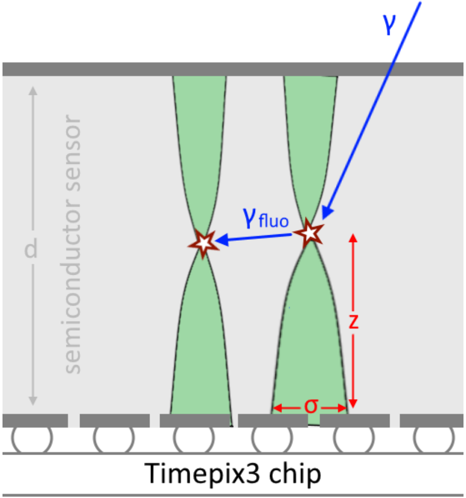
Timepix3 pixel detectors

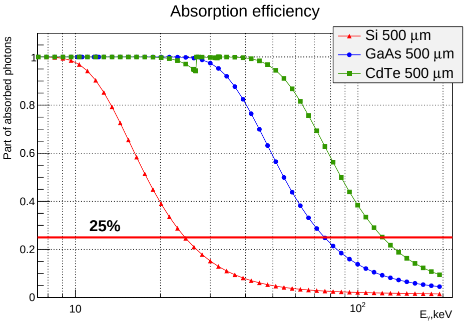


- 256 × 256 pixels, 55 μm pitch
- Simultaneous energy and time measurement in each pixel
- Various sensor materials: Si, GaAs, CdTe
- Up to 80 Mhits/s/cm^2



Hybrid pixel detector Timepix3

Some thoughts about semiconductor sensor materials for X-rays detection



Material	N	$K_{\alpha 1}$ [keV]	$K_{\alpha 2}$ [keV]	$d_{\alpha 1}$ [μm]	$d_{\alpha 2}$ [μm]	η[%]
Si	14	1.74	1.74	11.86	11.86	4.1
GaAs						
Ga, 48.20%	31	9.25	9.22	40.62	40.28	50.5
As, 51.80%	33	10.54	10.50	15.62	15.47	56.6
CdTe						
Cd, 46.84%	48	23.17	22.98	113.20	110.75	83.6
Te, 53.16%	52	27.47	27.20	59.32	57.85	87.3

Fluorescent yield

Si

Is very technological to work with and has low fluorescent yield,
BUT is quite transparent for X-rays >25 keV

CdTe

Has very good X-rays absorption efficiency and can be up to 2 mm thick, **BUT** has strong fluorescence (and fluo photons can go far)

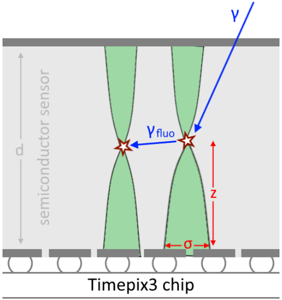
GaAs

Has good balance between efficiency and fluorescence. Can be up to 1 mm thick.
Is an optimal choice for X-rays of 10–60 keV

Motivation and goal

Response of GaAs–Timepix3 detector is affected by various effects which emerge in the semiconductor as the deposited charge drifts through the sensor layer:

- Charge sharing = deposited charge spread among pixels due to charge carriers diffusion
- Fluorescent yield in the sensor



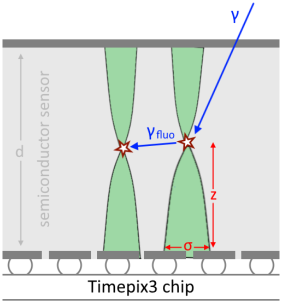
The goal

The goal is to study charge diffusion and related effects in the GaAs sensor and its influence on detector energy and spatial resolution since this could be crucial for certain use cases.

How To

The simulation comprises two rather independent parts:

- **Charge diffusion simulation.** Gamma ray absorption and charge diffusion in the detector under given conditions are simulated with our framework based on Geant4 to obtain dependency of the effective charge cloud size on its drift distance – $\sigma(z)$
- **Detector response building.** The obtained $\sigma(z)$ dependency is then used to simulate detector response governed by charge diffusion and fluorescence



Part 1. Diffusion simulation technique and features

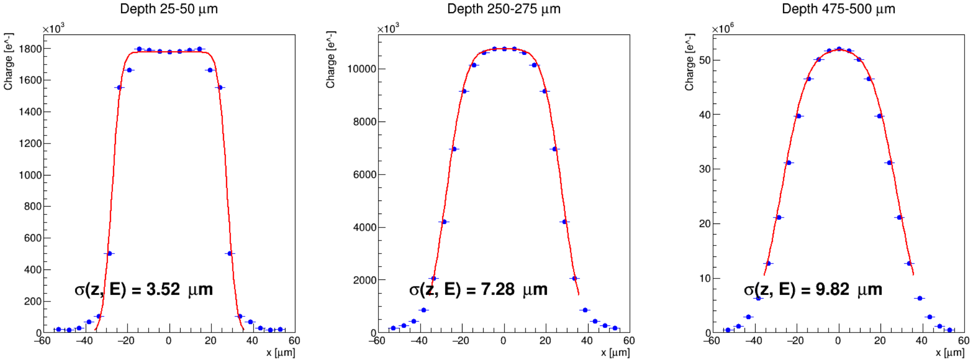
The technique implies simulation of response of the given pixel on a collimated monochromatic photon beam. Data is taken for different beam positions in relation to the pixel center. Thus, dependency of counts in the given pixel for the given drift length on the beam position is obtained to extract $\sigma(z)$ dependency. The simulation takes into account the following effects:

- Charge diffusion
- Charge losses
- Small pixel effect (weighting potential)

Charge diffusion simulation

Obtained dependence is fitted with this function and σ is extracted:

$$Q(x) = Q_0 * (1 + Erf(\frac{27.5 - x}{\sigma\sqrt{2}}))$$



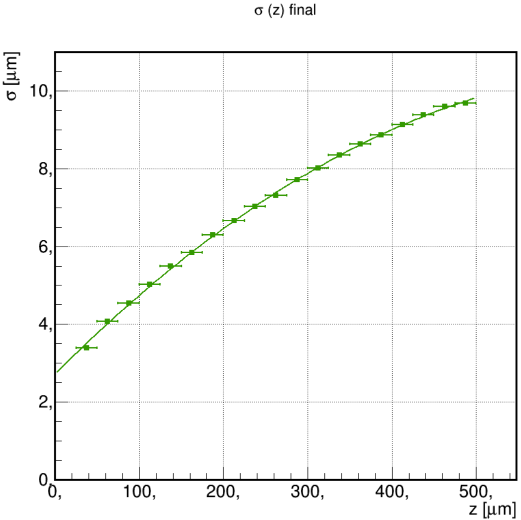
Counts vs. beam position dependencies (E_γ = 30 KeV, U_{bias} = 400 V)

Part 1 results: $\sigma(z)$

This plot shows dependency of the effective charge cloud size on pixel plane on charge cloud travel distance ($E_\gamma = 30$ keV, $U_{bias} = 400$ V)

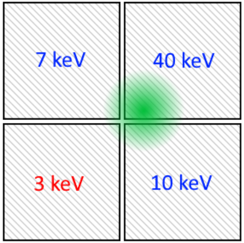
Features:

- Energy dependency can be neglected, so we may use one $\sigma(z)$ curve for each fixed bias voltage
- Charge diffusion decreases significantly with bias voltage increase
- `pol2` fit is applied in order to use this dependency in further simulations



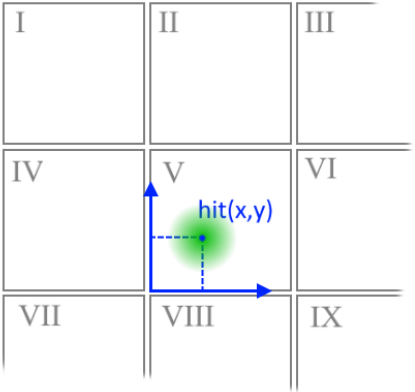
Part 2a: Energy losses under threshold

- As the deposited charge distributes among adjacent pixels, some charge may be lost if the amount collected in a single pixel is below the energy threshold
- Due to this effect, total measured energy (after cluster processing) may be less than the initial energy deposit.



- Pixel energy threshold = 4.2 keV
- Initial energy = 60 keV
- Measured energy = 57 keV

Measured energy calculation



- Due to ratio *pixelsize* $\approx 5\sigma$ it's sufficient to account for one neighboring pixel from each side
- As charge distribution at the pixel plane is gaussian $q(x,y) = \frac{Q_{total}}{2\pi\sigma}\exp\left(-\frac{-x^2-y^2}{2\sigma^2}\right)$, one may explicitly integrate charge density over a given pixel to get the total charge deposit in this pixel
- For example, for pixel No.II we may derive $E_2 = \frac{E_{total}}{4}(\mathrm{erf}\,\frac{x}{\sigma\sqrt{2}} + \mathrm{erf}\,\frac{55-x}{\sigma\sqrt{2}})(1 - \mathrm{erf}\,\frac{55-y}{\sigma\sqrt{2}})$
- We generate hits which are uniformly spread around the pixels and calculate fractions of charge deposited in adjacent pixels
- Then threshold is applied for each pixel

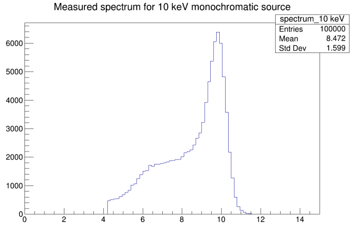
Energy response simulation

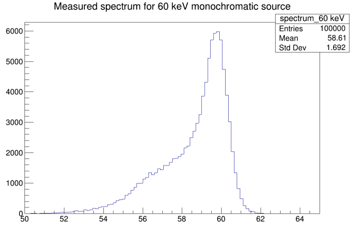
Now with the given $\sigma(z)$ dependency we're able to simulate detector energy response on gamma radiation of given spectrum (which governs interaction depth distribution and, subsequently, charge diffusion distribution).
Model cases of detector response on monochromatic radiation are presented.
Chip threshold is set to 4.2 keV.
Each pixel is assumed to have noise with standard deviation of 80 e^-

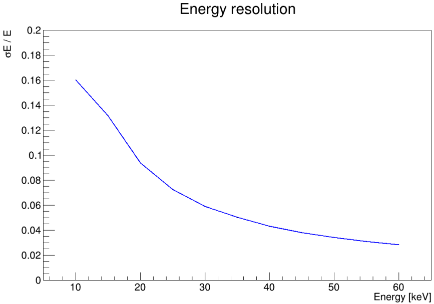
NB!

Even though incident radiation is monochromatic, the initial charge deposit varies due to pair number fluctuation during photoelectric effect. Pair number distribution is assumed to be normal with $\sigma(N_{pairs}) = \sqrt{F * N_{pairs}}$. Fano factor F equals approximately 0.14 for GaAs.

Part 2a results: Measured energy plots



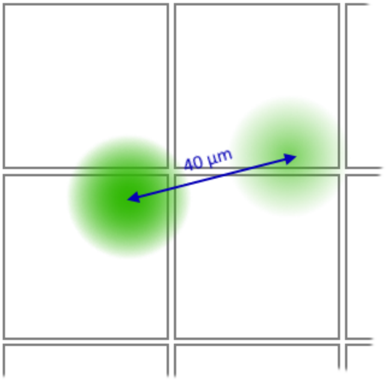




Standard deviation governed by both charge sharing and properties of the detector itself seems to be independent from photon energy. Thus, $\frac{\sigma E}{E} \propto \frac{1}{E}$

Part 2b: Fluorescence and spatial resolution

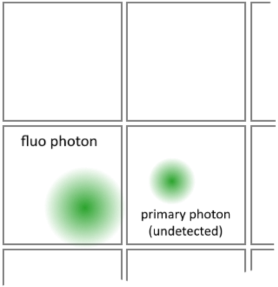
- As the deposited charge distributes among adjacent pixels, some charge may be lost if the amount collected in a single pixel is below the energy threshold
- Spatial resolution could be affected as well if charge deposit of the primary photon is unregistered but a fluorescence photon is detected in the adjacent pixel



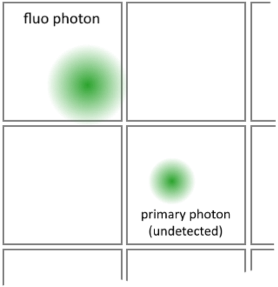
Energy deposit (Ga K-line)

Cluster recognition

Cluster shape analysis is implemented in the simulation. Several cluster types are recognized.



OFF_CENTER_SIDE type 1px cluster



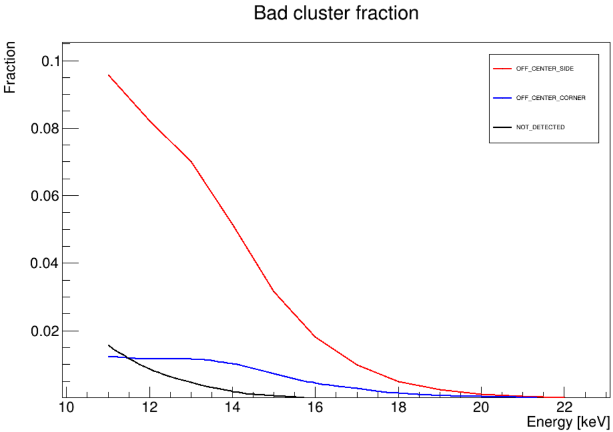
OFF_CENTER_CORNER type 1px cluster

These two types affect detector spatial resolution as the position of the primary interaction is lost

Part 2b results: Cluster stats

Example cluster type statistics
1 million photon hits

```
16 keV
1PX CENTER: 670621
1PX OFF_CENTER_SIDE: 18791
1PX OFF_CENTER_CORNER: 4573
2PX SIDES: 293475
2PX CORNERS: 9734
3PX: 2664
4PX: 2
NOT_DETECTED: 140
```



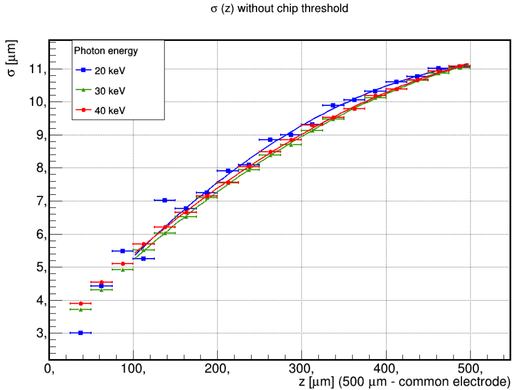
Fraction of spatial resolution affecting clusters

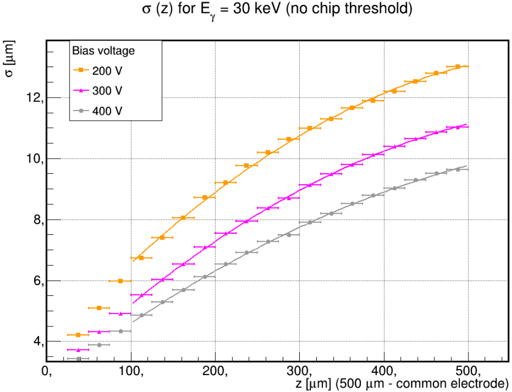
Conclusion

- $\sigma(z)$ dependency is obtained as a measure of charge carrier diffusion in GaAs sensor. This could be used as a lookup table for future research.
- Obtained data is then used to estimate charge sharing impact on detector energy and spatial resolution.

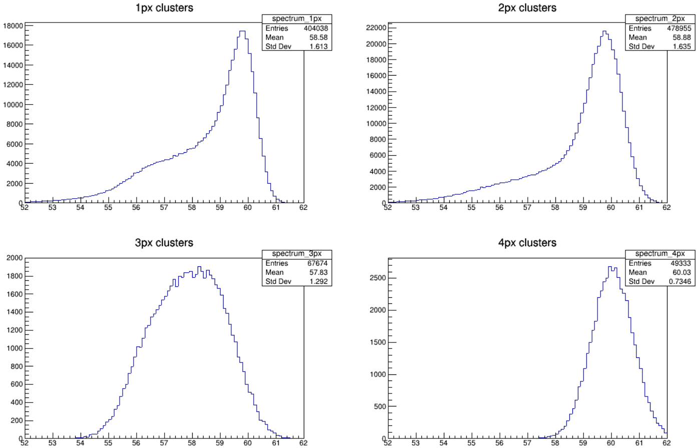
Thank you for the attention!

Appendix 1: $\sigma(z)$ dependency on beam energy and bias





Appendix 2: Cluster types and energy resolution



Measured energy spectra for the selected cluster sizes
60 keV monochromatic source, no fluorescence

- **1px**: Central area
- **2px**: Near the edge
- **3px**: Near the corner
- **4px**: Near the corner