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

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Abstract. Hybrid pixel semiconductor detectors find more and more applications in modern experimental physical setups. In particular, pixelated detectors based on GaAs:Cr sensor and Timepix3 chip are used in R&D for a state-of-the-art Transition Radiation Detector prototype at CERN. Motivation and usage aspects for GaAs:Cr-Timepix3 device in the experiment are covered in the talk. Authors’ contribution to the work of the research group is a study of charge collection and transportation processes in the sensor including fluorescence and so-called charge sharing effect. These are able to significantly affect both spatial and energy resolution of the system. Estimates for the effects are obtained via numerical modelling and then used to analyze the impact on the detector performance.

1. Introduction

Hybrid semiconductor pixel detectors with Timepix3 readout chip\textsuperscript{[1]} offer a unique ability of position-sensitive single-photon counting using array of independent sensitive pixels sized 55 × 55 \( \mu \)m\textsuperscript{2} each. Moreover, each pixel is able to simultaneously measure time of arrival and photon energy (using time-over-threshold technique) and also has noise suppression capability by using energy threshold. This allows to use such detectors in experimental setups for tasks which require precise photon counting with measuring both coordinates and energy, e.g. transition radiation tracking\textsuperscript{[2,3]}.

The working principle of the detector is shown on figure\textsuperscript{[1]}. A photon is absorbed through photoelectric effect and electron-hole \( e^{-}h^{+} \) pairs are created in the semiconductor sensor. Charge carriers then drift under the influence of bias voltage applied to the sensor. Due to charge diffusion in semiconductor material, the charge carrier cloud increases as it drifts to sensitive pixels. As a result, after passing distance \( z \) the cloud has effective size of \( \sigma \) and the charge could be split among adjacent sensitive pixels. This phenomenon is commonly referred to as ”charge sharing”\textsuperscript{[4]}. It affects the energy resolution of the detector if the pixel charge is below the energy threshold. Another phenomenon that persists in the sensor is fluorescence which is basically production of another photon during photoelectric absorption. These secondary photons have fixed energy determined by semiconductor material and are able to travel a certain distance in the sensor. Fluorescent yield significantly increases spread of deposited charge between pixels, which may lead to loss of some charge under threshold and/or triggering more than one pixel\textsuperscript{[4]}

\textsuperscript{1} In some cases, however, it is possible to overcome this by using proper cluster merging techniques.
in a single event. This negatively affects energy and spatial resolution of the chip.

Fluorescent properties of common types of semiconductors are given in table 1 [4]. Silicon sensors have the lowest fluorescent yield but they are inefficient [5] for detection of X-rays >25 keV due to relatively low $Z$, whereas expected energy band for transition radiation is approx. 10–60 keV. CdTe sensors, in opposite, show the best absorption efficiency but the fluorescence in CdTe is relatively strong and fluorescence photons have very long travel also. So, GaAs is the most suitable choice for X-ray detection at the given band of several dozens keV as it has sufficient gamma absorption and moderate fluorescent yield.

Table 1. Fluorescent properties of semiconductors, namely, energy of fluorescent photons $K$, mean free path $d$ and yield $\eta$.

| Material | $Z$ | $K_{\alpha 1}$ [keV] | $K_{\alpha 2}$ [keV] | $d_{\alpha 1}$ [\(\mu\)m] | $d_{\alpha 2}$ [\(\mu\)m] | $\eta$ [%] |
|----------|-----|---------------------|---------------------|-------------------|-------------------|--------|
| Si       | 14  | 1.74                | 1.74                | 11.86             | 11.86             | 4.1    |
| Ga       | 31  | 9.25                | 9.22                | 40.62             | 40.28             | 50.5   |
| As       | 33  | 10.54               | 10.50               | 15.62             | 15.47             | 56.6   |
| Cd       | 48  | 23.17               | 22.98               | 113.20            | 110.75            | 83.6   |
| Te       | 52  | 27.47               | 27.20               | 59.32             | 57.85             | 87.3   |

Charge sharing and fluorescence may significantly affect both spatial and energy resolution of Timepix3 semiconductor detectors. This should be thoroughly estimated as this is crucial for mentioned above transition radiation tracking which relies much on accurate measurement of both photon position and energy. Estimates of impact on detector resolution are obtained via Monte-Carlo modelling. Firstly, charge diffusion is found numerically as $\sigma(z)$ – dependency of charge carriers cloud size on its drift distance. Obtained diffusion data is then used to build detector response in several model cases in order to calculate resolution.

Figure 1. Semiconductor hybrid detector working principle.
2. Charge diffusion simulation

This chapter is devoted to numerical simulation of charge diffusion process in the 500 \( \mu \)m thick GaAs:Cr sensor, as it used in the TRD prototype. The simulation is performed with MESI framework \(^6\) which is mostly based on Geant4. The framework is capable of modelling of photon absorption in the sensor and drift processes\(^2\), including charge diffusion and also so-called small pixel effect (charge induction on pixels due to weighting potential in the semiconductor).

The simulation technique \(^7\) involves the following steps:

- Center of a certain pixel in the detector is hit with point-collimated monochromatic photon beam.
- The data on total charge deposit in this pixel is collected.
- The procedures above are repeated but the beam now hits a different spot in the pixel (the beam is moved parallel to the pixel side).
- Cuts on interaction depth \( z \) are applied.
- For a selected \( z \) band, total charge \( Q \) is plotted vs beam offset \( x \).
- The data is fitted with function\(^3\)
  \[
  Q(x) = Q_0 \ast (1 + \text{erf} \left( \frac{27.5-x}{\sigma \sqrt{2}} \right) \),
  \]
  where \( Q_0 \) and \( \sigma \) are fit parameters and beam offset \( x \) and cloud width \( \sigma \) are given in \( \mu \)m (see figure 2).
- \( \sigma \) is extracted from the fit for each \( z \) to obtain the required \( \sigma(z) \) dependency.

![Figure 2. Total charge in pixel vs. beam offset for a selected \( z \) region.](image)

![Figure 3. \( \sigma(z) \) for \( E_\gamma = 30 \) keV, \( U_{\text{bias}} = 400 \) V.](image)

An example charge cloud size dependency on drift path is shown on figure \(^2\). Such diffusion simulations were performed for different beam energies and also different sensor bias voltages. It was found that \( \sigma \) does not depend on photon energy for the given energy range of 10–60 keV, but decreases significantly with bias voltage increase. This allows to use a single \( \sigma(z) \) curve since the chip usually operates at fixed bias voltage (from now on this is assumed to be 400 V, as it is used in the TRD prototype). A second degree polynomial fit is applied in order to use the curve in further analysis. For the figure 2 it goes as \( \sigma = 2.96 + 0.02z - 0.000014z^2 \) with all parameters given in \( \mu \)m.

\(^2\) Fluorescence is turned off in the simulation in order to estimate \( \sigma \) for events with single photon only.

\(^3\) This could be derived assuming that initial charge carrier density on the pixel plane has Gaussian form

\[
q(x, y) = \frac{Q_{\text{total}}}{2\pi\sigma^2} \exp \left( -\frac{x^2 + y^2}{2\sigma^2} \right).
\]
3. Energy resolution simulation

As charge sharing caused by diffusion and fluorescence persists in the sensor, the total charge deposited during absorption of a single photon could be split between several pixels. Since each pixel utilizes an energy threshold, in some events a fraction of energy may be lost if some charge goes to adjacent pixels but does not surpass energy thresholds in these pixels. So, an additional term which corresponds to charge loss under threshold is added to detector energy resolution.

To estimate the energy resolution, the detector response on monochromatic gamma radiation is built with Monte-Carlo simulation. The process goes as follows:

- A single pixel is chosen in the detector.
- Hit parameters are generated. $x$ and $y$ are spread uniformly around the pixel and $z$ generation is based on semiconductor properties and photon energy. Effective charge cloud size $\sigma$ is gotten from previously obtained $\sigma(z)$ dependency.
- A fluorescent photon may be generated, depending on fluorescent yield statistics for the material. The spatial distribution is assumed spherically symmetrical.
- Charge deposit smearing is applied, limited by Fano factor, in order to account for intrinsic charge deposit fluctuations.
- Assuming 2D Gaussian form of charge distribution at the pixel plane, total charge deposits are calculated for the given pixel and the adjacent ones by integration.
- Readout circuits noise (80 $e^-$) and threshold (4.2 keV) are applied in each pixel and the results are summed over all the non-zero pixels to get a measured energy value.

A model case of detector response on 60 keV monochromatic beam is shown on figure 4. A peak at expected energy of 60 keV represents events with negligible energy losses under threshold, so its width is mostly determined by chip noise and deposit fluctuations in semiconductor. The left hand side of the spectrum, though, represents events with significant energy loss. This picture reproduces also for lower beam energies, and the standard deviation of such energy resolution seems to be independent from the photon energy. Consequently, the energy resolution in terms of relative error has form $\delta E / E \sim 1 / E$ (see figure 5).

![Measured spectrum for 60 keV monochromatic source](image1)

**Figure 4.** Simulated energy spectrum for $E_\gamma = 60$ keV.

![Energy resolution](image2)

**Figure 5.** Dependence of the detector energy resolution obtained with the simulation on the photon energy.

\footnote{Though $1 / \sqrt{E}$ term also persists due to charge deposit fluctuations, $1 / E$ is prevailing at the given energy region.}
4. Fluorescence and spatial resolution
Spatial resolution of the detector could also be affected as well by charge sharing and fluorescence. Since fluorescent photons travel a certain distance in the semiconductor, they may deposit its energy not in the pixel where the primary hit occurred (such pixel is called "central"). At beam energies of 10–20 keV this may lead to a situation when a primary photon is undetected due to insufficient energy deposit which becomes lower than chip’s energy threshold. As the primary hit is undetected, the information about its coordinates is lost because a central pixel is basically zero.

To estimate the effect, cluster shape (non-zero pixels pattern in each event) data is gathered. The simulation also allows to select events where the only one pixel is non-zero but that pixel is not the one where a primary photon was absorbed. Such events are referred to as "off-center side" and "off-center corner", depending on a position of that non-zero pixel in relation to the central pixel.

Fraction of spatial resolution affecting clusters is shown on figure 4. It could be observed that at lower energies more than 10 percent of all events have either "off-center side" or "off-center corner" signature which means that coordinate uncertainty increases to 2 pixels. Although, the effect quickly goes down as energy increases to 20 keV.

5. Conclusion
The dependencies of the charge cloud size on the drift distance $\sigma(z)$ were obtained for different energies of photons and the bias voltages 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. The results are to be used in Monte-Carlo simulations of the TRD prototype.

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