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# Spatial resolution and detection efficiency of algorithms for charge sharing compensation in single photon counting hybrid pixel detectors

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ABSTRACT

This paper presents a new method for charge sharing compensation in hybrid pixel semiconductor detectors. The presented solution is based on pattern recognition and allows to significantly reduce circuit complexity, while maintaining allocation accuracy of other, more complex algorithms. The proposed method is evaluated and compared to the existing solutions in terms of missed/false hit probability and allocation accuracy, based on simulation results of a pixel readout circuit model.



## 1. Introduction

Various X-ray imaging techniques to convert incident photons into electrical signals used in physics, biology and medicine include indirect (i.e. scintillators) and direct detectors. In applications requiring high spatial resolution, hybrid pixel detectors are commonly used [1], where the readout circuit and the sensor are developed separately. Depending on a readout concept, such systems can be categorized as integrating or Single Photon Counting (SPC). This paper focuses on SPC systems. They advantage over integrating detectors (e.g. Charge-Coupled Devices) is very high dynamic range and possibility of noiseless imaging, assuming that a discrimination threshold is set above the noise floor and pulse amplitude is sufficiently high [2].

The next step in SPC pixel detectors is to not only count pulses, but also determine the amplitude of each input pulse, what is equivalent to finding the energy of each photon. X-ray absorption in matter has a strong spectral dependence, as it essentially depends on the element's $Z$-number. Therefore, through the examination of the absorbed or transmitted spectrum, it is possible to deduce information on the relative concentration of the elements in the examined sample.

When a single X-ray photon of energy $E_P$ is absorbed in the semiconductor detector, it generates the average number electron–hole pairs given by $N = E_P/E_{eh}$, where $E_{eh}$ is energy needed for ionization (energy required to create an e–h pair—in CdTe $E_{eh} = 4.4$ eV). Electric field in the detector allows to collect the generated charge on pixel electrodes. However, due to diffusion, the charge cloud can spread into neighboring pixels. This effect becomes significant with decreasing pixel sizes, in order to improve spatial resolution, and is commonly referred as charge sharing [3]. The charge spread influences strongly the energy measurement of the incoming photon and also it may result in duplicated registration or not detecting a photon at all.

The pioneering implementation of the electronics to eliminate the spectral distortion produced by the charge sharing in highly segmented pixel detector was proposed by Medipix3 collaboration [4], but nowadays also other groups have made a considerable progress in this direction [5–7].

However, the problem of charge sharing in pixel detector still requires new algorithms, which can be implemented in integrated readout circuits, providing short allocation times in the presence of noise and mismatch effects. This paper presents a new method for charge sharing compensation in hybrid pixel semiconductor detectors, which can be effectively implemented in modern CMOS nanometer process. The proposed method is evaluated and compared to the existing solutions in terms of missed/false hit probability and allocation accuracy, based on simulation results of a pixel readout circuit model.

## 2. Simulation overview

### 2.1. Simulation model

In order to analyze and compare various charge sharing compensation algorithms, a pixel readout circuit model has been implemented in the LabVIEW environment [8]. The model composes of components typically found in a readout circuit, such as an input charge sensitive amplifier (CSA) and a discriminator. Additionally, it contains circuitry

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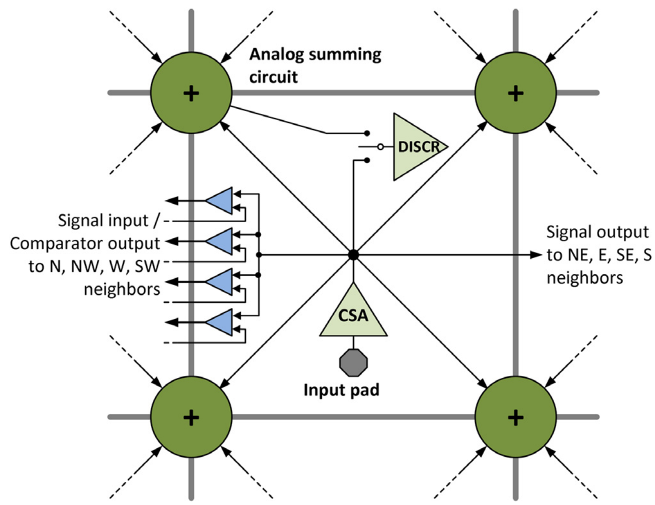


**Fig. 1.** Diagram of a single pixel in the simulation model – discriminator can be connected to CSA output or analog summing circuit's output.


**Fig. 2.** Distance between an actual hit position and its allocating pixel.

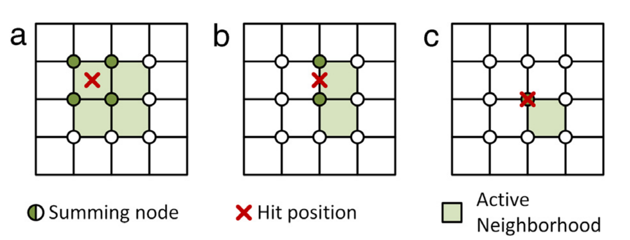


**Fig. 3.** Examples of active neighborhoods of PR algorithm for different hit locations.

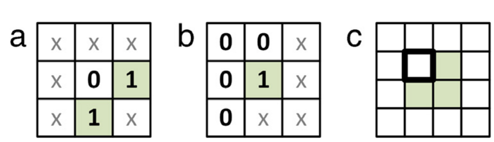


**Fig. 4.** Pattern Recognition bitmasks: (a) first step — directional closing of the neighborhood, (b) second step — selecting the pixels at the top-left corner, (c) example of a neighborhood with the chosen pixel marked.

dedicated for charge reconstruction, namely the analog summing circuits [9] and inter-pixel comparators. Summing circuits evaluate the sum of CSA output signals coming from four adjacent pixels, arranged in the array of 2 × 2, and are placed schematically at pixels' corners. The output of each summing circuit is connected to the discriminator located in the lower-right corner of the array. The comparators compare the CSA output signals among the neighboring pixels (each pixel has 8 neighbors). The diagram of a single pixel is presented in Fig. 1.

The model simulates effects related to the readout circuit such as noise, dispersion of CSAs' gains and spread of discriminator's and comparator's offset voltages. Gaussian distributions for all parameters is assumed. The simulation model neglects effects associated with the sensor itself, e.g. Compton scattering, fluorescence etc. and assumes that each event produces the same amount of charge.

**Table 1**
Detector and readout circuit simulation parameters.

| Parameter | Value |
|---|---|
| Detector thickness | 1 mm |
| Detector bias voltage | 500 V |
| Charge cloud radius | 10 μm |
| Photon's energy | 20 keV |
| Input referred noise | 96 e⁻ |
| Matrix size | 8 × 8 pixels |

The model is based on the analysis of a pixel array at a sampled time instant, after the charge has been collected and the CSA output has reached its peak value. The pixels are assigned values, which represent their maximum signal amplitudes. The outputs of analog summing circuits, discriminators and comparators are evaluated according to these values.

### 2.2. Simulation model parameters

The simulation model parameters were chosen to closely reproduce an actual readout circuit. In order to pronounce the charge sharing effect, a system with 1 mm thick CdTe detector has been chosen as a Ref. [10]. The one-$\sigma$-radius of the charge cloud was computed according to the equation [11]:

$$\sigma = d\sqrt{\frac{2kT}{qV_B}},$$

where $k$ is the Boltzmann constant, $T$ — the absolute temperature, $q$ — the elementary charge, $V_B$ — the detector bias voltage and $d$ — the drift distance to collecting electrodes. The simulation model parameters are summarized in Table 1.

### 2.3. Simulation methodology

The simulations were performed on an array of 8 × 8 pixels. To estimate and compare the performance of the presented algorithms, a simulation resembling a threshold scan under flood-fill exposure, which is typically performed in single photon counting systems [12], was conducted. For every discriminator's threshold value, several events (100 000) were generated over the array to gather sufficient statistical data. Each event was processed separately, in five steps:

- An input hit was generated at a random position in the array, the charge was shared between the nearest pixels.
- Gaussian noise was applied to the obtained signal values.
- The summing circuits', discriminators' and comparators' outputs were calculated, based on the obtained pixel signals' values.
- An algorithm's response was evaluated and hits were allocated to pixels.
- An event was appropriately categorized, according to the computed result and knowing the input hit position.

The number of detected hits was counted for each event. If no hits were detected, an event was treated as missed. If more than 1 hits were counted, they were treated as false hits. The results of the simulation are presented as two plots – separately for a number of missed and false hits as a function of discriminator's threshold.

Additionally, in order to evaluate the spatial resolution of an allocation algorithm for each event, where at least a single hit was detected, the distance $D$, between an actual hit position and the allocated pixel's center, as shown in Fig. 2, has been computed. If more than one pixel has been allocated a hit, the one with the shortest distance is chosen as valid.