Optimization of silicon detector layout and associated front-end electronics for timing performance of a silicon PET through simulation

Andrej Studen, Neal H. Clinthorne, Harris Kagan, Marko Mikuž

Abstract—There are indications that PET imaging may profit by incorporating position sensitive silicon detectors with intrinsic excellent spatial resolution into the scanner setup [1]. However, poor timing performance of detectors can compromise mentioned benefits.

Our group is developing a PET probe with silicon detectors. Our detectors come in two varieties, both with square pads and a thickness of 1 mm, but the pads are either 1 mm or 1.4 mm in size. The signals are amplified through VATAGP brand ASICs. For the timing signal, the ASIC provides a charge-sensitive pre-amplifier with a fast (75-150 ns shaping time) CR-RC$^2$ shaper, and a fixed-level discriminator to generate a trigger signal.

There are three contributions to timing resolution: the time-walk, the jitter and the broadening related to depth of interaction. The paper concentrates on the last contribution, assuming a viable time-walk compensation [2] and negligible jitter for signals large compared to the discriminator threshold. The interaction of photons causes local depositions of ionization. The shape of the signals vary with impact position. Through simulation, we estimated the impact of variation on timing resolution. We evaluated the present systems and estimated improvement for alternative detector and electronics designs.

The simulation consists of four major steps. First, a particle tracking tool (GEANT4 [3]) is employed to track the interactions of a 511 keV photon in a silicon detector. A TCAD suite is used to determine the electric and the weighting field in a detector for a given electrode and doped implant arrangement. Next, a charge propagation model [4] using TCAD calculated fields is employed to determine the paths of secondary ionization and the resulting charge induced on electrodes, and finally, a model of the first stage of the signal amplification - the pre-amplifier, the shaper and the discriminator - is used to generate the timing signal.

Index Terms—silicon pad detectors, timing resolution, medical imaging.

I. INTRODUCTION

Silicon is a promising detecting material for a PET application. It offers great energy and spatial resolution, insensitivity to magnetic fields, robustness and compactness needed for dense probes. However, the stopping power is only 2% of 511 keV photons in a mm of silicon, with most of those undergoing Compton scattering rather than photoabsorbtion. The obvious remedy is an increase in sensor thickness. The ionization caused by (mostly) Compton electrons will be local in nature – the range of recoil electron with a kinetic energy of 300 keV is only about 300 μm – so the signals induced on (surface) electrodes in thick(1 mm) detectors will vary depending on the depth of interaction$^1$. This variation will be reflected in an additional depth-related broadening of the timing resolution.

This paper reports the results of the simulation of the signals in a 1 mm thick p$^+\text{n}^+$ detector in a pad geometry. The following section describes the steps taken for realistic calculation of signal shapes in a silicon detector - first the simulation of the recoil electron track, then the simulation of the signal current pulse at each point along the track (and in the detector) and finally, the virtual electronics applied to the raw current pulse. Next section shows the results: agreement of simulation with the data, simulated variation with bias voltage, shaping time, pad size, shaper order, secondary threshold and readout strategy. We also introduce an alternative detector design with segmented readout of the backplane and compare results to conventional detectors.

II. THE SIMULATION

The simulation was realized in three very distinct steps which are explained in the following subsections:

A. Recoil electron track

Geant 4 [3] with low-energy scattering extension [8] was used to generate tracks of recoil electrons for interactions of 511 keV photons from a point source placed 5 cm in front of the 1 mm thick detector. Secondary particles generation threshold of Geant 4 was set to its minimum at 1 keV. The Figure 1 shows a typical track in a sensor. Each sphere represents a (measureable) charge deposit by the track of the recoil electron in a 1 mm$^3$ cube. This illustrates the locality of the photon interaction and the resulting diversity of induced signal currents.

B. Induced signal

The energy deposition of the recoil electron is converted to pairs of electrons and holes. Each pad is essentially a diode, and the electric field caused by the applied reverse bias splits the electrons and holes. Holes drift towards the top (p-type) pad electrode which is connected to the electronics and held at ground potential. The electrons drift to the backplane, held

$^1$This fact is often used to deconvolute the signal depth based on signal shape [5]–[7]
at positive potential. Both types of carriers induce signal on the top electrode. The simulation is split in two parts - drift and induction.

- DRIFT. A series of steps move the charge from point of creation (Geant4 energy deposit) to the top or bottom electrode. Each step is a time shift $\Delta t$, during which the carrier moves for a $\Delta x$ equal to the sum of electric field $E(x)$ related drift and diffusion:

$$\Delta x = \mu E(x) \Delta t + \Delta x_D,$$

where $\Delta x_D$ is drawn from a 3D gaussian distribution with a mean of 0 and a variance of $D \Delta t$ in all three dimensions. $D$ is the diffusion coefficient and $\mu$ is the carrier mobility, and both are related through Einstein equation. The mobility is parametrized as in [9] to account for velocity saturation at high electric fields.

For a pad detector, the electric field $E$ depends on depth only and is linear for voltages above $V_{FD}$. For detector with backplane divided into strips, a 2D field was calculated on a finite grid (2.5 $\mu$m step) with direct matrix inversion.

- INDUCTION. Given a series of steps, the carrier velocities $v(x) = \Delta x / \Delta t$ are obtained for each step from (1). The pulse shape is determined by the Shockley-Ramo theorem:

$$I = qv(x) \cdot W(x),$$

assuming a known weighting field $W(x)$. The calculation of the later requires a 3D calculation in a pad sensor, which was realized through TCAD [10] simulation tool.

For a strip shaped electrode, a finite grid method was used and a 7 strip detector was modelled.

- SIGNAL MATRIX. There is a randomness in calculation of carrier track (1) due to diffusion. Since there are approximately 300 carriers generated per 1 keV of the energy deposit, we tracked 100 drifts per packet for a realistic signal. As that would consume a lot of CPU time, a signal matrix of pre-calculated signals was prepared. A 3D grid was mapped onto the sensor and the signals were calculated at grid interstitions, with grid spacing between 50 and 70 $\mu$m (depending on the pad size). Interpolation was used for intermediate points.

C. Electronics

Due to expected high count of channels in a silicon detector for a PET application, we concentrated on a simple electronic circuits, such as the one present in VATAGP series by IDEAS [11]. Each electronic channel was equipped with a charge-sensitive preamplifier and a CR-RC$^n$ shaper. The shape was determined with a convolution, using Simpson method for integrating the product:

$$S(T) = \int_0^T s(t) K(T-t) dt,$$

with $s(t)$ electronics input, $K(t)$ the kernel of the electronics and $S(t)$ the output signal. A leading edge discriminator was used as a trigger signal generator, the threshold was set to 15 keV. There was only a weak dependence of the timing performance when threshold was varied between 10 and 20 keV.

D. CPU usage

The grid infrastructure [12] was used for signal computation. The heavy part, the matrix calculation took about 8000 CPU minutes for a single voltage/detector pair, using $\Delta t$ of 200 ps, 100 drifts per interstition and 80k interstitions.

III. RESULTS AND COMPARISONS

A. The weighting field

Figure 2 shows profiles of the weighting field in a pad detector for different pad sizes. The red curves correspond to the 1 mm pads and the black to pad size of 1.4 mm. A constant weighting field (equal to that of the backplane electrode) is shown for comparison.

B. Signal shape

Figure 3 shows pulse shapes obtained in a pad detector. Extreme casses are shown at a low voltage – 200 V compared to 150 V full depletion voltage. For events near the backplane (depth=1 mm) the holes have to drift through the whole detector before they reach the high weighting field (Figure 2 hence their collection time is long. Increasing the reverse bias does not remove the effect completely (blue curve on the Figure 3 for a 500 V reverse bias).
C. Comparison to measurement

The simulated results were compared to the data [13]. The data were taken with a 1.4 by 1.4 mm\(^2\) silicon detector, 1 mm thick, with a VATAGP3 ASIC used at the detector’s front end. In VATAGP3, the trigger is performed as a leading edge of a CR-RC\(^2\) shaped output of the charge-sensitive preamplifier, the shaping time is approximately 200 ns. The threshold in measurement and simulation was set to 30 keV. A positron source (giving back-to-back 511 keV photons) was used and a fast LYSO/PMT assembly gave a timing reference signal. Figure 4 shows (appropriately delayed) trigger time versus measured energy of the recoil electron. In red, the graph is shown for the simulated events with the bias voltage of 200 V (V\(_{FD}\)=150 V), the leading edge threshold set to 30 keV, a CR-RC\(^2\) shaper and a shaping time of 200 ns, approximately matching the conditions set to the measured data (black) at 200 V and a single channel of the VATAGP3. An appropriate constant delay was set to the measured data to match them to the simulation.

The settings are the same as in Figure 4. Observe the good matching between data and the simulation. The variation of the trigger time for a subset of events where energy of the recoil electron exceeded the secondary threshold of 100 keV; the secondary threshold was set to compensate for the time-walk of the trigger. The agreement between the measured data (red) and the measurement (black) is good. The discrepancy can be attributed to the limited accuracy of some of the parameters of the simulation – most notably the full depletion voltage and the shaping time of the shaper. Also shown on the Figure 5 is the distribution for an ideal detector signal – a current pulse in the form of a \(\delta(t=0)\) function. This illustrates the contribution of time-walk only, without depth or jitter related broadening.
D. Time window studies

As a figure of merit we chose the time window required to collect half of the interactions in silicon. This correlates nicely with the requirements of a PET detector, since the time window limits the activity of the source the detector can be exposed to.

We assumed the pads of the detector to be connected to an electronics with a leading edge trigger on the output of a CR-RC\textsuperscript{sh} shaper. A secondary threshold was set to compensate for time-walk, obtained by looking at an ideal detector response (δ()).

Figure 8 shows the dependence of the timing window when voltage, shaping time and pad size are varied. The voltage increase from 200 to 500 V reduces the required window for about 40 %. Halving the shaping time reduces the timing window for 30 \% only for selected portion of events. And finally, the pad size reduction of 30 \% increases the time window, but only for about 20 \%. The above numbers are given in Table I and vary very little among the eight possible pairs in the figure. So a 1 mm pad detector with a 75 ns shaping time will perform approximately 10 \% better than a 1.4 mm pad detector with 150 ns shaping time for all voltages, a fact that can be seen in the figure. Time-walk, obtained by looking at an ideal detector response – δ() is comparably small, giving window width of 1.2 ns for 75 ns shaping and 2.3 ns for 150 ns shaping.

Figure 9 shows the time-window dependency on the secondary threshold, shaper order and readout strategy. For this study, the pad size of 1 mm was chosen, the bias voltage of 500 V and the shaping time of 75 ns\textsuperscript{2}. A word on the readout strategy – it is advantageous to make the Ramo field as constant as possible to remove depth of interaction dependency [2]. This is achieved by summing the central and all 8 adjacent

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
parameter & value A & value B & window (A)/window (B) \\
\hline
bias voltage & 500 V & 200 V & 0.59-0.62 \\
shaping time & 75 ns & 150 ns & 0.69-0.72 \\
pad size & 1.4 mm & 1 mm & 0.79-0.84 \\
\hline
\end{tabular}
\caption{The relative change achieved by variation in listed parameter. The remaining parameters were set as in Figure 8. The range shown in window (A)/window (B) column is covered by data points shown in the graphs in Figure 8.}
\end{table}

\textsuperscript{2}Using the results from Table I the approximate values at different parameter settings can be estimated.
pads, making the Ramo field (only approximately in a real detector) constant.

### Table II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value A</th>
<th>Value B</th>
<th>Window (A)/Window (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaper</td>
<td>CR-RC</td>
<td>CR-RC²</td>
<td>0.72-0.77</td>
</tr>
<tr>
<td>Secondary threshold</td>
<td>100 keV</td>
<td>50 keV</td>
<td>0.81-0.83</td>
</tr>
<tr>
<td>Readout strategy</td>
<td>9-pad</td>
<td>single pad</td>
<td>0.55-0.58</td>
</tr>
</tbody>
</table>

The most dramatic improvement is achieved by summing the pads, reducing the window size to approximately half its size (exact values in Table II). However, one must consider the jitter trade-off; assuming that the input capacitance dominates, the jitter would increase three-fold for such an arrangement, possibly dominating the timing resolution. Where jitter is considered, the higher order shaping is more efficient in noise filtering (reduction rate of 174/190 for CR-RC² versus CR-RC [14]). However, Figure 9 and Table II show that this gain is overwhelmed by the depth related broadening, with CR-RC² shaper requiring a 30% larger time window. The time-walk contribution is not as pronounced - only 20% is gained when the secondary threshold is increased from 50 to 100 keV.

The backplane offers a very good timing signal, because of the truly constant weighting field. However, it also has a very large capacitance and hence, plenty of jitter. We looked at an intermediate solution where the backplane is fragmented into smaller electrodes with bearable capacitance. We simulated a 1 mm thick silicon detector with the top side fragmented into 1 mm pads (p⁺ implants on an n-material), and the bottom side segmented into 0.4 mm wide strips at a pitch of 0.5 mm (n⁺ implants, p-stops implicitly assumed), as schematically shown in Figure 10. The bottom electrodes were set to +500 V potential relative to the top electrodes and the electronics used was the same as for the top readout - charge sensitive preamplifier with a CR-RC shaping and a shaping time of 75 ns. The electronics used for all signals was a charge-sensitive preamplifier with a CR-RC shaping and a shaping time of 75 ns, the secondary threshold was set to 100 keV. The δ() corresponds to an ideal current pulse and shows contribution of time-walk only.

![Fig. 10. Schematic drawing of the replacement of the solid backplane (left) with a strip-shaped electrodes (right) for a bottom timing readout.](image)

![Fig. 11. The optimal 50% time window (Q₂-Q₀) for two detector geometries. Top readout and solid backplane correspond to a normal pad detector (left-hand side of Figure 10), while the bottom strip and bottom 3-strip readout correspond to the strip readout of a modified detector with the backplane segmented into 0.4 mm wide strip electrode on a 0.5 mm pitch. The bottom electrodes were at +500 V potential relative to the top electrodes. The electronics used for all signals was a charge-sensitive preamplifier with a CR-RC shaping and a shaping time of 75 ns, the secondary threshold was set to 100 keV. The δ() corresponds to an ideal current pulse and shows contribution of time-walk only.](image)
of 75 and 150 ns, shaper orders n=1 and n=2. As a time-walk compensation, a secondary threshold on the recoil electron energy was used and varied between 50 and 100 keV. As a figure of merit, the time window necessary to collect half of the events was chosen. Results were compared to collected data and reasonable agreement was found.

The results can be grouped by the parameter which was varied:

- **Voltage**: Increasing the sensor voltage always helps, with reduction to half the original time window as voltage is increased from 200 V to 500 V, at a full depletion voltage of 150 V.

- **Shaping Time**: The reduction in shaping time from 150 ns to 75 ns still helps, but its effect is far less than one half. In most simulated cases, the charge collection time is already appreciable, giving a reduction of approximately 30%.

- **Pad Size**: Smaller pad sizes compromise the timing resolution, since the weighting field is contained closer to a smaller pad and the depth related signal variation is more pronounced. The effect adds about 20% to the timing window when pad size is reduced from 1.4 to 1 mm.

- **Shaper Order**: Using high order shapers is misleading. Although the electronic noise is reduced, the additional broadening due to a weaker slope of the shaper output overcomes the apparent benefits.

- **Secondary Threshold**: The effect is not pronounced. A 20% reduction when going from 50 to 100 keV.

An additional study was made in adjusting detector geometry and readout strategy. However, in those cases one must consider additional circumstances, e.g. the effects of the jitter as the capacitance of the readout channel is changed. The following results are more of a trade-offs which have to be considered at specific total detector dimensions and involved complexities:

- **9-Pad Readout**: To improve the timing performance, sum of central and 8 adjacent pads was compared to a single pad readout. The reduction of depth related broadening is a solid 50%, but increase in jitter is (naively) 3-fold.

- **Bottom Strips**: Producing a detector where strips on the bottom side are used for the timing information one can gain another factor of 2 on the timing window. However, the detector size will determine the amplifier input capacitance and the resulting jitter, which may compromise the benefits. Also, there is an additional level of complexity involved since: a) the bottom side of the detector has to be processed and b) an AC coupled electronics over 500 V potential has to be used.

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**References**


