Optimization of a Silicon Drift Detector Module for a Gamma Camera

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The aim of this study was to optimize the design parameters of a silicon drift detector (SDD) module for a gamma camera. The examined design parameters were the reflection coefficients, the crystal size, the energy threshold effect, the light guide thickness and the sensor packing fill factor. The silicon drift detector module proposed in this study was composed of hexagonally packed 72 SDDs and a single-slab NaI(Tl) crystal with a light guide that was optically coupled to the SDD sensors. Monte Carlo simulations using DETECT2000 were performed to generate necessary data for the optimization. The Poisson noise was calculated analytically and was applied to the simulation. The effects of the reflection coefficients (RC) of the crystal’s side surfaces and of the crystal size were examined. A Cramer-Rao (CR) lower bound analysis was conducted to determine the light guide thickness and the energy thresholds providing best spatial resolutions were estimated. A white reflector (RC = 0.9) on the side surface improved the light collection efficiency (LCE) versus black paint (RC = 0.1) while the spatial resolution was less sensitive to the reflection coefficient. We found that crystal size should be smaller (about 4 mm) than the SDD size to prevent event overlapping. Though a thinner light guide provided a better CR lower bound, a 2-mm light guide was suggested for the mechanical support and for NaI(Tl) crystal encapsulation. The intrinsic spatial resolution was best at a 2 % energy threshold regardless of the noise level. An inter-SDD gap of 2-mm was chosen to obtain a fill factor of 95 % without any technical problems in the SDD manufacturing. The results of this study will be useful in the development of a compact high-resolution gamma camera based on an array of SDDs coupled to a single-slab scintillator.

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I. INTRODUCTION

Silicon drift detectors (SDDs) have the primary advantages of high quantum efficiency, compact physical size, low output capacitance and good energy resolution, which make them attractive for gamma camera applications [1–10]; hence, they could potentially replace photomultiplier tubes (PMTs) in high-resolution gamma cameras [11–16]. Our group developed a 7-channel SDD detector module with a high spatial resolution of 0.74-mm full width at half maximum (FWHM) [17]. The detector module consists of an array of hexagonally-packed SDDs (hexagon shaped with about 1 cm in diameter) which is optically coupled to a single-slab scintillator.

Since a compact and high-resolution gamma camera detector module employing 72 SDDs is being developed, an investigation of the design parameters that sustain the advantage of the high spatial resolution of the SDD module was required.

The design parameters of the scintillation crystals utilized in conventional PMT-based gamma cameras are well known [18–20]. However, these parameters may be unsuitable for SDD gamma cameras because of the drawbacks of SDD sensors, which require optics optimization. The drawbacks of the SDDs are a low signal-to-noise ratio (SNR) and gain fluctuations due to changes in the bias voltage and the temperature. In addition, their lower intrinsic SNR means that a fast low-noise preamplifier is required at each SDD output [21]. High-intrinsic-spatial-resolution SDD sensors could promote the introduction of an improved scintillation crystal design unsuitable for conventional PMT. Additionally, since gamma cameras based on PMT detector modules have

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very high SNRs, all PMT signals from a detector module are used to calculate the gamma-ray event localization and the energy resolution. For SDD gamma camera detector modules, however, each SDD sensor has a relatively high electronic noise, which may be altered by bias voltage, shaping time and temperature. Furthermore, a suitable restriction on the use of SDD signals is necessary to minimize the serial (voltage) and the parallel (current) noise. For the above reasons, a new design is needed to obtain the best performance when SDD array modules are used.

The aim of this study was to optimize the design parameters for a gamma camera detector module consisting of 72 channel SDD detectors coupled to a NaI(Tl) crystal via a light guide. The reflectivity of the scintillation crystal’s side surfaces, crystal size, effect of the energy threshold on the spatial resolution, the light guide thickness and the sensor packing fill factor were investigated using Monte Carlo simulation studies.

II. MATERIALS AND METHODS

1. Simulation Geometry

The silicon drift detector (SDD) module proposed in this study consisted of a 72 hexagonal SDD array (Figure 1) coupled to a 10-mm-thick NaI(Tl) crystal. The sensitive area of the SDD array was 114 mm × 120.6 mm. The crystal light guide thicknesses were changed from 1 to 6 mm. A Monte Carlo simulation using DETECT2000 [22, 23] was conducted to investigate the effect of side surface reflectivity and crystal size on the spatial and the energy resolution. The thickness of the optical grease between the NaI(Tl) crystal and the light guide was fixed at 0.1 mm and its refractive index was 1.79. Light sources were generated at a 2.9-mm depth from the top surface of the crystal, which was the mean interaction depth that provided a 50% detection probability.

2. Silicon Drift Detector Electrical Noise

The leakage current of each SDD, as simulated in this study, was about 3 nA/cm² with a total capacitance of 2 pF at room temperature. The Poisson distribution noise was calculated as the equivalent noise charge (ENC) by using the leakage current and the capacitance information as shown in Eq. (1) [24–26] and this was applied to simulation results:

\[
\text{ENC}^2 = A_1 \frac{KT}{g_m} \alpha C_T^2 \frac{1}{\tau} + A_2 \left(2\pi \alpha f C_T^2 + \frac{b_f}{2\pi}\right) + A_3 q I_L \tau,
\]

where \(A\) is the coefficient of the CR-shaper, \(K\) is Boltzmann’s constant, \(T\) is the temperature (Kelvin), \(g_m\) is the transconductance, \(\alpha\) is the excess noise factor, \(C_T\) is the total capacitance, \(a_f\) and \(b_f\) are frequency noise factors, \(q\) is the unit charge, \(I_L\) is the leakage current and \(\tau\) is the shaping time. The effect of temperature on the electronic noise was estimated analytically.

3. Reflectivity of the Scintillation Crystal’s Side Surfaces

Five locations, shown in Figure 2, were selected to study the effect of the crystal’s side surface reflectivity on the spatial resolution and on the light collection efficiency (LCE). A total of 2,000 gamma-ray interactions...
Fig. 3. Monte Carlo simulation geometry to determine the crystal size. Case 1 illustrates an overhanging type and the scintillation crystal size was decreased to Case 4.

were generated at five gamma detection positions 4-mm apart. The LCE is defined by

\[ LCE = \frac{\text{Collected Photons}}{\text{Generated Photons}} \times 100\% \]  

(2)

Black absorber, half reflector and white reflector on the side surfaces were simulated using reflection coefficients (RC) of 0.1, 0.5 and 0.9, respectively. The effects of side surface reflectivity on the LCE and the gamma-ray event overlapping were investigated.

4. Determination of the Crystal Size

The effect of crystal size was investigated by changing the size from an overhanging type (Case 1) to a flush type (Case 4), as demonstrated in Figure 3. The side surface simulated as a white reflector (RC = 0.9) provided the best results (Section III. 1). The overlap of gamma ray events in the crystal edges was examined and the spatial resolutions of Case 1 to Case 4 were compared.

5. Light Guide Thickness

A Cramer-Rao (CR) lower bound analysis [27] using Eq. (3) was applied to determine optimum light guide thickness:

\[ \sigma_{\theta_i}^2(x) \geq \left( \sum_{i=1}^{n} \left( \frac{\partial S_i(x)}{\partial x} \right)^2 \right)^{-1}, \]  

where \( S_i(x) \) is the mean output of the \( i \)-th SDD as a function of the scintillation position \( x \), which is known as a light response function. The \( S_i(x) \) function was smoothed to avoid excessive noise in its derivative. The light response function, an input of the CR lower bound calculation, was obtained when light guide thicknesses were changed from 1 to 6 mm.

6. Energy Thresholds

The total sum of all SDD signals in one detector module was defined as an energy signal. The cut-off value of an energy signal was defined as the energy threshold that excluded SDD signals lower than the reference value. The energy threshold values providing the best spatial resolution were determined using a line profile analysis. Since the SDD sensor had a relatively high electronic noise when the bias voltage and the temperature were changed, two different noise levels of 50 and 100 electrons were added to each threshold image.

7. Fill Factor

The SDD array has a dead space due to inter-SDD gaps (Figure 1) and this dead space affects the light collection efficiency. The LCE was estimated when the inter-SDD gap was changed from 0 mm to 3 mm. The acceptable fill factor was selected to be 95 % in this study.

III. RESULTS AND DISCUSSION

1. Reflectivity of the Scintillation Crystal’s Side Surfaces

A white reflector (RC = 0.9) on the side surface markedly improves the light collection efficiency (LCE).
which affects the energy resolution (Table 1). For example, the LCE improved from 60 % to 84 % by changing the RC from 0.1 to 0.9 at position 5 (Figure 4).

The side surface reflectivity of the NaI(Tl) scintillation crystal did not affect event overlapping at the crystal edges, as demonstrated in Figure 4. The white reflector treatment on the side surface of the scintillation crystal provided slightly better spatial resolution than treatment with a black absorber. The intrinsic spatial resolution for a white reflector was slightly better than that for a black absorber with values of 0.72 and 0.75 mm full width at half maximum (FWHM), respectively, at position 5. Hence, the side surfaces of the scintillation crystals should be coated with a white reflector to improve the spatial resolution and the LCE.

2. Determination of the Crystal Size

The effect of the crystal size on the spatial resolution is demonstrated in Figure 5. The figure shows that test points 1 to 3 (Figure 3) overlap each other and cannot be resolved. Half of the SDD size (~8 mm) from the detector edge could not be used for event localization due to limitations of the Anger-logic positioning algorithm. The line profiles illustrate that oversized scintillation crystals cause event overlapping and an edge blurring effect. Furthermore, light positions 1 and 2 intruded upon light position 3 in Cases 1 and 2. However, light position 3 in Case 3 was not overlapped because there was no outer light contamination.

This result indicates that the crystal size should not be larger than the SDD area and, in fact, that it needs to be little smaller. Smaller sized (about 4 mm from the SDD edge) scintillation crystals were favorable in preventing unwanted event overlapping and edge blurring. Furthermore, smaller crystal sizes reduce manufacturing costs.

3. Light Guide Thickness

Figure 6 shows the Cramer-Rao (CR) lower bound as a function of the light guide thickness between a crystal and the SDD array. The result suggests that the light guide, located between the crystal and the SDD, needs to be as thin as possible.

Although the scintillation light must be spread for the Anger-logic positioning algorithm, excessive spread...
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**Fig. 6.** Cramer-Rao (CR) lower bound as a function of the light guide thickness.

**Fig. 8.** The effect of inter-SDD gap on the light collection efficiency.

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Fig. 7. The effect of the energy threshold. The energy threshold value was changed from 0 % to 5 %. The 2 % energy threshold of total light collection provided the most accurate positional information.

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4. Energy Threshold

An accurate positioning estimate is an important consideration for a high-resolution gamma camera. If all the SDD signal outputs contribute to the position determination, the spatial resolution could be deteriorated due to the low signal-to-noise ratio (SNR) of the SDDs. Therefore, an energy threshold was employed to eliminate some of the noisy SDD signal from the positioning computation.

The accuracy of event localization was improved by applying an energy threshold of up to 2 %, as shown in Figure 7. At higher energy thresholds, however, the positioning algorithm suffered from event localization error due to a lack of light-sharing information. An energy threshold value of 2 % provided the best intrinsic spatial resolution with electrical noise when a 100-mm$^2$ SDD and a 10-mm thick scintillation crystal were used. The intrinsic spatial resolution at the center field-of-view (FOV) at a 2 % energy threshold was 0.79-mm in FWHM.

5. Fill Factor

Figure 8 shows the effect of the inter-SDD gap on the relative light collection efficiency. The fill factor was 99 % with a 1-mm inter-SDD gap and 94 % with a 2-mm gap.

The inter-SDD gap was investigated to provide a reference value for a SDD manufacturer. Although a smaller inter-SDD gap results in a higher fill factor, it is technically difficult to minimize the gap. An inter-SDD gap of 2 mm is feasible without SDD performance degradation and allows a fill factor of about 95 % to be obtained.
IV. CONCLUSION

The purpose of this study was to optimize the design parameters of a silicon drift detector (SDD) module by using a Monte Carlo simulation. The SDD module could be utilized to develop a high-performance gamma camera and single photon emission computed tomography (SPECT), which are widely used to obtain functional and molecular images in experimental small animals and humans. Scintillation crystal reflection coefficients, sizes, light guide thicknesses, energy threshold effects and sensor packing fill factors were investigated. The results of this study indicate that the devised scintillation crystal design was optimum with a white reflector on the side surface, a 2-mm light guide thickness and a 4-mm smaller size from the edge of the SDD. The energy threshold should be 2% for best event localization and the dead space between SDD sensors should be less than 2-mm in order to obtain a fill factor of over 95%. The results of this study will be useful in the development of a gamma camera using a high-resolution photosensor, for example, a SDD detector coupled to a single-slab scintillator.

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