ARTICLE

The Optimization of CsI(Tl)-PIN Photodiode for High-Energy Gamma-Ray Detection

Jin Hyoung Bai[1], Joo Ho Whang[1*]

[1]*Department of Nuclear Engineering, Kyunghee University, Gyunggi-Do, 446-701, Korea*

A Monte Carlo simulation was performed to induce optimized parameters for CsI(Tl) crystals and large area PIN phohtodiode detectors for applications in high energy gamma ray spectroscopy. In order to derive the optimum parameters we used a Trade-Off procedure between the deposition energy and light transmission efficiency, while varying the detector thickness. Moreover, it was found that the surface treatment of the crystal in the photodiode is also an important factor for good light transmission. The tests were performed using a low noise charge-sensitive preamplifier and a pulse shape amplifier. Concerning the operating condition of the system, it is necessary to shape the time and reverse the bias voltage in order to provide another minimization of noise for the system. In order to maximize the light output from the crystal, the crystal geometry, crystal wrapping, optical bonding and matching to the PIN photodiode were all optimized. With a fixed crystal height of 5 cm, it was best to grind the sides and the top surface of the crystal on the front facing sides of the external reflectors, resulting in about a 14.5% enhancement compared with polishing all the sides and top.

KEYWORDS: Monte Carlo simulation, PIN photodiode, CsI(Tl) crystals, optical wrapping, light output

I. Introduction

Fast neutron and gamma-ray radiography (FNGR) systems are useful for scanning cargo containers for contraband. In particular, FNGR can provide good images of a broad range of enclosed materials as well as densities.[1–2] Two parallel detector modules are used to detect neutrons and gamma-rays. One is a CsI(Tl) coupled to photodiode (PD) detectors that has been used to detect high energy gamma-rays.[3–5] The CsI(Tl)-PD detectors are more suitable because of their high stopping power, relatively low cost, and easy ability to be fabricated.

In this paper, the discussion will be focused upon the light yield of CsI(Tl) coupled to photodiode detectors. The light yield is very dependent upon so many factors, such as crystal size, geometry, surface treatment, type of adhesive, and type and thickness of wrapping material. We proposed an idea to maximize the light output of the CsI(Tl) detector for a high gamma-ray source of ^{60}Co. In our system we used Monte Carlo simulation code, MCNPX[6], to optimize the crystal thickness, and to evaluate factors affecting light collection efficiency we used DETECT-97[7] Code. We present results of a study on the different polishing, and the adopted wrapping treatments of crystal surfaces, for CsI(Tl)-PD detectors. The experiment and the result are reported in section 2 and 3. Section 4 gives a summary of the conclusions.

II. Experiments

1. Gamma-ray detector simulations

When used in conjunction with a photodiode 1×1 cm^2 in size, the appropriate thickness was determined to be 5 cm

using MCNPX. The main physical properties of the crystal scintillator were collected as shown in **Table 1**. Tests were performed using cubic CsI(Tl) crystals, $1\times1\times5$ cm^3, with a PIN photodiode (S3590-01 from Hamamatsu). In addition, the two PIN photodiodes were fabricated on an oriented n-type wafer (100) with a high-resistivity of 1.5k ohm·cm and 5k ohm·cm. For our n-type photodiode design, the total thickness was 380 μm. It is a PIN diode where N+ doping was formed in the entire rear face and P+ doping was formed in the front face. Si$_3$N$_4$ of ~700 Å, which is optimal at a wavelength of 550 nm, was used as an anti-reflection coating film. A junction depth of P+ doping was prepared to be as thin as possible. The parameters of recent used PIN photodiodes are depicted in **Table 2.** For the PIN photodiode, the terminal capacitance, dark current, and spectral response were all measured.

As shown in **Fig. 1**, the amount of light (%) generated in the crystal that reaches the Si photodiode coupled face depends upon whether there is any optical bonding, the wrapping materials and the diffusing effects of the reflector in the basic structure of the CsI(Tl) and Si sensor. To evaluate factors affecting light collection efficiency, a simulation using DETECT-97 Code was performed. As a result of calculating electron-hole pairs generated in the Si sensor, the large area CsI(Tl) crystal for high-energy gamma rays was calculated to have the best performance. The results are shown in **Fig. 2**.

The surface treatment of the crystal is important. For good light output from the crystal into the photodiode, it is necessary to also decide the crystal surface conditions. The Monte Carlo simulation results indicate that in perfectly polished crystals, much of the scintillation light is internally trapped and cannot escape. Adding an external reflector therefore only results in a modest improvement in light collection.

With a fixed crystal thickness of 5 cm, it was best to grind

---

*Corresponding Author, E-mail: xray10@korea.com

the sides and top surface of the crystal adding sides of diffuse reflectors, resulting in about 70% efficiency compared with polishing all sides and the top which resulted in about 40% efficiency.

Table 1 Properties of the proposed crystals.

	CsI(Tl)
Density [g/cm^3]	4.53
Light yield [ph/MeV]	59000
Peak of max. emissions [nm]	550
Refractive index	1.78
Decay time [ns]	1000
Size [cm]	1×1×5
Manufacturer	SICCAS Co. [8]

Table 2 Properties of Silicon PIN photodiodes.

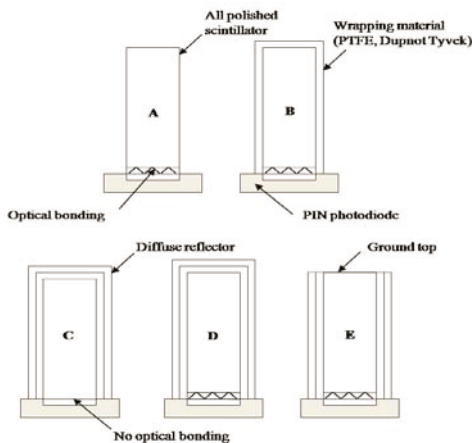| Manufacturer	Hamamatsu	RadTek	RadTek
Type	S3590-01	RT/PD-1.5	RT/PD-5
Active area [mm]	10×10	10×10	10×10
Responsivity [A/W] (@550 nm)	0.31	0.51	0.50
Dark current [nA] (@V_R=5 V)	0.44	0.59	1.34
Terminal capacitance [pF] (@V_R=5 V)	100	200	100
NEC [rms] (@V_R=5 V)	500	900	1200
Window	Epoxy resin	Epoxy resin	No window
Reference	9)	10)	11)

Fig. 1 Various combinations of CsI(Tl) coupled photodiode with or without the optical bonding and wrapping materials

Additionally, CsI(Tl)-photodiode optical bonding is modeled by the refractive index of the optical interfaces, the

results of which are shown in **Fig. 3**. The photodiode has an outer anti-reflective coating with an index of refraction of 2.02 while the refractive index of the CsI(Tl) is 1.78. A bonding optical adhesive was chosen to fill the space between the CsI(Tl) and photodiode. In order to optimize light transmission, a grease with an index equal to the geometric mean of the two adjoining materials is ideal, or mathematically, [12]

$$n_{optimum} = \frac{(1.78 \times 2.02)}{2} = 1.82 \tag{1}$$

The highest light collection efficiency was achieved with the Bicron BC 600 adhesive. The optical adhesives listed have broadly similar optical indices and, as calculated, there was no optical matching material. So the choice of material is likely to be as a result of practical considerations, which in turn was coupled with the corresponding adhesive to the crystal.
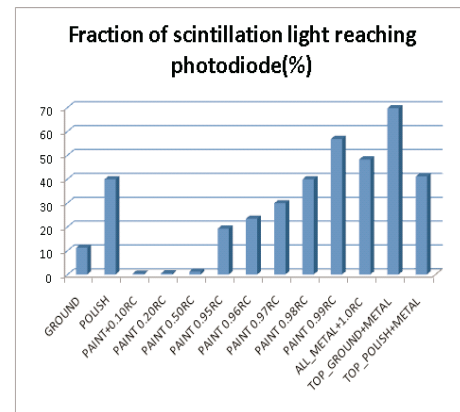

Fig. 2 Simulation showing fraction of scintillation light reaching photodiode for different conditions
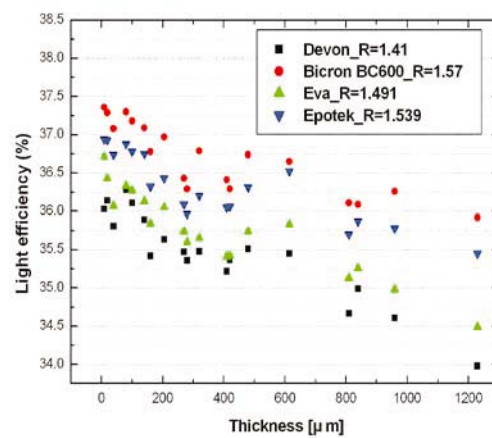

Fig. 3 Light collection efficiency CsI(Tl)-photodiode optical bonding as a function of the refractive index

2. Gamma-ray energy measurements

To verify the linearity of the detection systems (**Fig. 4**), five different isotopes were used: ^{57}Co, ^{133}Ba, ^{137}Cs, ^{54}Mn, and ^{60}Co, having a dominant gamma emission at roughly 122 keV, 356 keV, 662 keV, 835 keV, 1173 keV, and 1332 keV, respectively. Along with the RT/PD-1.5 photodiode, the eV 5093 (produced by eV products and known to have a low noise level among the commercialized charge sensitive preamplifiers) operated in pulse counting mode with a shaping time of 6 μs. The spectroscopic shaping amplifier chosen was the Canberra AFT 2025. The gain is the same for each isotope so that the photopeak channel number will be proportional to the gamma energy if the CsI(Tl) crystal has a linear energy response. The peak channel numbers of the fitted peak centroids were plotted, the results of which are shown in **Fig. 5**. Hereby, superimposed over the data points, is a least-squares fit to the data which show that the gain of the detection systems is linear with CsI(Tl) crystal across the full energy range.
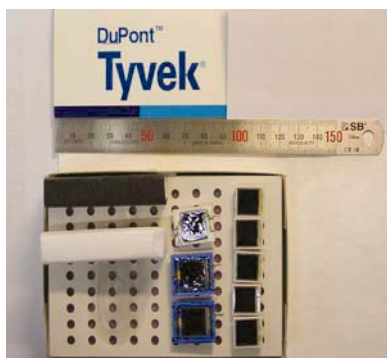

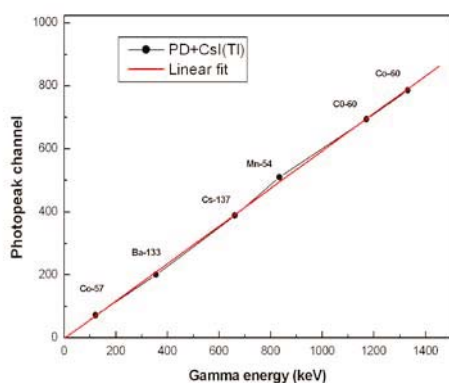**Fig. 4** The tested sets of CsI(Tl) and PIN photodiode

Fig. 5 Measured gamma response linearity as a function of gamma-ray energy

3. Optical wrapping and coupling

In this study the influence of type, quality, and thickness of the wrapping material on CsI(Tl) crystal light output is described. Conventionally, PTFE tape used CsI(Tl) crystal as

a wrapping material, however this is essentially non-uniform as light output is dependent upon the number of layers used, thus requiring a considerable thickness to ensure maximum light output. **Table 3** summarizes the comparison of the PTFE tape with a combination of various wrapping materials and the reflectors prepared in this experiment.

To enhance light output, numerous combinations of different surface conditions (polished, painted, ground) for the sides and top face were tested to find the best solution. In addition, as predicted in **Fig. 3,** the choice of optical adhesive is likely to be as a result of practical considerations. Hereby, two combinations of photodetector were tested with or without the optical bonding in the case of E (see **Fig. 1**). In order to compare the experimental results we chose the number of photoelectrons generated from the CsI(Tl) photodetector. This was determined by comparing the position of the 0.511 keV gamma-ray source of ^{22}Na to the position of a single photoelectron peak. The ^{22}Na spectrum acquired with CsI(Tl) crystals are shown in **Fig. 6**. Even for a proper one-to-one match of crystal and photodiode, losses into the photodiode window caused a reduction in light output of around 20% for the Bicron BC 600 adhessive.
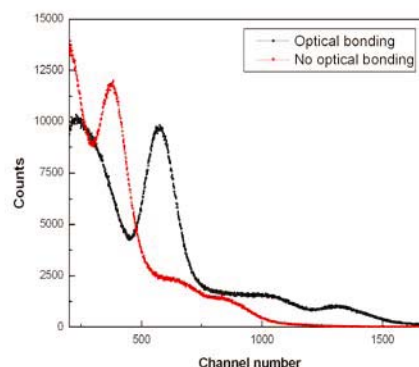

Fig. 6 Measured ^{22}Na spectrum using CsI(Tl)-photodetector
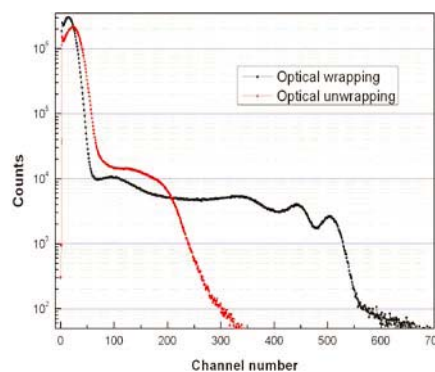

Fig. 7 Measured ^{60}Co spectrum using CsI(Tl)-photodetector

Fig. 7 shows the measured ^{60}Co spectrum using a CsI(Tl)-photodetector. However, the ^{60}Co spectra acquired

with no optical bonding of CsI(Tl) crystal is not shown in **Fig. 7** for the 1173 keV and 1332 keV gamma-ray source to the position of a double photoelectron peak due to compton scattering. In this study, because we focused on the application of FNGR using ^{60}Co, the effect of the optical bonding is important in our case.

III. Results

Simulations predicted (see **Fig. 2**) and the measurements proved that two combinations are especially good: all these optical interfaces are considered as polished surfaces. (E-1) front face polished, (E-2) front face ground.

Light output as a function of the crystal wrapping and surface treatment was calculated and the results summarized in **Table 3**. On the basis of case D, recent light output achieved by ^{60}Co is 5.7% and 14.5% for CsI(Tl) crystal with E-1 and E-2, respectively. The ground surface on the front face breaks up internal trapping and   preferentially directs light down towards the photodiode. The results show the excellent agreement between the experiments and simulations. This table also illustrates how more material wrapping significantly reduces the light output of B-2, and how important light collection efficiency is where the crystal will have a large area (as with this study).

Table 3 Light output for different wrapping materials with ^{60}Co.

	Wrapping material	1 layer counts	2 layer counts
A	Bare	-	-
	Black tape	-	-
	Al foil [0.015 mm]	-	-
B-1	PTFE [0.05 mm]	-	-
	PTFE [0.1 mm]	-	2547±26
B-2	Dupont Tyvek		
	L-1025D [0.14 mm]	2764±21	2244±26
	L-1056D [0.16 mm]	2603±34	1713±30
	L-1070D [0.2 mm]	1809±24	1625±25
	L-1082D [0.27 mm]	2168±29	1835±27
C	L-1025D+Al+Tape		
	/No optical bonding	-	-
D	/Covered all side	2668±15	
E-1	/Polished open top	2819±10	
E-2	/Grounded open top	3054±26	

IV. Conclusion

In this study we optimized a number of issues related to maximizing the light output yield from CsI(Tl) crystal coupled to a PIN photodiode detector designed for high energy gamma-ray applications. The optimization of our photodetectors was identified as being a ground surface on the front face with wrapping material and optical bonding provides the best results regarding light output and can provide a 14.5% enhancement. An improvement in performance may be achieved by the above route. A significantly large area scintillator coupled to photodiodes can be exploited in FNGR

References

1) J. Eberhardt, S. Rainey, R. Stevens, B. Sowerby, J. Tickner, "Fast neutron radiography scanner for the detection of contraband in air cargo containers," Applied Radiation and Isotopes, 63, 179–188 (2005).
2) J. Rynes, J. Bendahan, T. Gozani, R. Loveman, J. Stevenson, C. Bell, "Gamma-ray and neutron radiography as part of a fast neutron analysis system," Nucl. Instr. and Meth. A 422, 859-899 (1999).
3) J. Brose, G. Dahlinger, K. R. Schubert, "Properties of CsI(Tl) crystals and their optimization for calorimetry of high energy photons," Nucl. Instr. and Meth. A 417, 311-324 (1998).
4) V. Prat, H. Simon, A. Kazandjian, "Performance of large volume CsI(Tl) scintillators coupled to silicon photodiodes in gamma-ray spectroscopy," Nucl. Instr. and Meth. A 369, 617-621 (1996).
5) D. Bederede, E. Bougamont, P. Bourgeois, et al., "Performances of the CsI(Tl) detector element of the GLAST calorimeter," Nucl. Instr. and Meth. A 518, 15-18 (2004).
6) J. S. Hendricks, G. W. McKinney, L. S. Waters et al., MCNPX extensions version 2.5.0, LA-UR-04-0570, Los Alamos National Laboratory, (2004).
7) G. F. Knoll, T. F. Knoll, and T. M. Henderson, "Light collection in scintillation detector composites for neutron detection," IEEE trans. Nucl. Sci., 35, 872-875 (1988).
8) SICCAS, http://www.siccas.com/.
9) HAMAMATSU photonics, http://jp.hamamatsu.com/.
10) J. H. Bai, J. H. Whang, Y. S. Kim, et al., "New method of increasing detector sensitivity for high energy radiation," Proc. SCINT, Jeju, Korea, June 8-12, 2009, p.2-38 (2009).
11) K. H. Kim, Y. S. Kim, J. S. Kim, "Signal and noise performance of large-area PIN photodiodes and charge-sensitive preamplifiers for gamma radiography," Nucl. Instr. and Meth. A 591, 63–66 (2008).
12) J. B. Birks, The theory and practice of scintillation counting, Pergamon press, Oxford, 96-103 (1964).