Construction of an X-ray detecting module and its application to relative-sensitivity measurement using a silicon PIN diode in conjunction with short-decay-time scintillators

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ABSTRACT

To detect low-dose-rate X-rays, we have developed an X-ray-detecting module for semiconductor diodes. The module consists of a current-voltage (I-V) amplifier, a voltage-voltage (V-V) amplifier, and an alternating-current adopter with a smoothing circuit. The photocurrents flowing through a diode are converted into voltages and amplified using the I-V and V-V amplifiers. To measure relative sensitivities, we used

three silicon PIN diodes (Si-PIN), a cerium-doped yttrium aluminum perovskite [YAP(Ce)] crystal, and a $\text{Lu}_2(\text{SiO}_4)\text{O}$ [LSO] crystal. Three detectors are as follows: an Si-PIN, a YAP(Ce)-Si-PIN, and an LSO-Si-PIN. Using the three detectors, the amplifier output voltages were in proportion to the tube current at a constant tube voltage of 70 kV. Using a multichannel analyzer, the event-pulse-height spectra were measured to analyze X-ray-electric conversion effect in the three detectors. The output voltage of the Si-PIN was approximately twice as high as those obtained using the YAP(Ce)-Si-PIN and the LSO-Si-PIN at the measurement conditions.

41

42 **1. Introduction**

43 First, enhanced iodine (I) K-edge imaging [1,2] has been performed using extremely
44 clean monochromatic parallel X-ray beams with photon energies of approximately 35
45 keV. Utilizing this imaging, fine coronary arteries can be observed at high contrast,
46 since X-rays with energies just beyond I K-edge 33.2 keV are absorbed effectively by I
47 atoms. On the other hand, monochromatic K-edge imaging can be carried out utilizing
48 energy-dispersion of X-ray photons using high-energy-resolution detectors.

49 We usually use a cooled cadmium telluride (CdTe) detector to measure X-ray spectra,
50 and the photon energy resolution has been improved to 1.0% at 122 keV. Using this
51 detector, we have developed several energy-dispersive X-ray CT (ED-CT) systems [3-5]
52 to perform enhanced K-edge imaging using I and gadolinium (Gd) contrast media.
53 Subsequently, a CdTe detector array driven at room temperature has been developed to
54 construct preclinical ED-CT systems [6,7].

55 One pixel of the X-ray detector array in a conventional CT system consists of a
56 silicon photodiode and a scintillator crystal. However, we found a readymade high-
57 sensitivity silicon diode [8] and a silicon PIN diode (Si-PIN) for directly detecting X-
58 rays. In particular, the Gd-K-edge ED-CT was easily performed using a readily
59 available 100 MHz Si-PIN [9] with an energy resolutions of 3% at 59.5 keV using X-
60 ray photons with energies ranging from 50 to 90 keV. Therefore, the relative
61 sensitivities among the Si-PIN and scintillator-Si-PIN detectors should be measured
62 using a developed low-noise amplifier module.

63 In conjunction with a multipixel photon counter (MPPC) [10] and a small

64 photomultiplier tube (SPMT) [11], short-decay-time and high-light-yield scintillators
65 are quite useful for carrying out high-speed photon counting [10] and energy dispersion
66 [11]. Therefore, the measurement of event-pulse-height (EPH) spectra from the
67 scintillator-Si-PIN detectors are important. In this case, the EPH spectra as a function of
68 photon energy consists of the directly-measured and scintillation-converted X-ray
69 photons.

70 In our research, the major objectives are as follows: to develop a low-priced
71 semiconductor dosimeter, to measure the relative X-ray sensitivities among the Si-PIN
72 and scintillator-Si-PIN detectors, and to measure the EPH spectra to evaluate
73 scintillation effects. Therefore, we developed a low-dose-rate low-noise X-ray detecting
74 module and measured the relative sensitivities using the three detectors.

75

76 2. Experimental Setup

77 2.1. X-ray detecting module

78 We have developed a high-sensitivity amplifier system to detect X-ray beams with
79 dose rates of approximately 100 $\mu\text{Gy/s}$. Therefore, steady-state output voltages are
80 obtained when the X-rays with a constant dose rate are detected.

81 Using the detector module, it is very important to measure the relative sensitivity of
82 the Si-PIN detector and to compare it with those of the scintillator-Si-PIN detectors,
83 since most X-ray CT systems use detectors consisting of scintillators and photodiodes.
84 Fig. 1 shows a block diagram of an X-ray detecting module and the relationships
85 between the light-receiving surface of an Si-PIN (S5971, Hamamatsu) and the
86 scintillator crystals of cerium-doped yttrium aluminum perovskite [YAP(Ce)] and
87 $\text{Lu}_2(\text{SiO}_4)\text{O}$ [LSO]. Using the Si-PIN detector, X-ray photons are detected directly by
88 the light receiving surface of 1.2 mm in diameter. A $1.0 \times 1.0 \times 1.0 \text{ mm}^3$ scintillator crystal
89 is positioned on the light receiving surface of the Si-PIN using epoxy resin in the
90 scintillator-Si-PIN detector; the 1.0-mm-cube crystals had been made for the MPPC
91 detector [10] with a $1.0 \times 1.0 \text{ mm}^2$ light-receiving surface. Therefore, four portions of the
92 surface which are not covered with the crystal can detect X-ray photons directly. On the
93 other hand, a portion covered with the crystal can detect both the penetrating X-ray and
94 scintillation photons. Each detector is shielded using an aluminum (Al) case with a 25-

95 μm -thick Al window and a BNC connector.

96 In the module, the photocurrents flowing through the Si-PIN are converted into
97 voltages and amplified using current-voltage (I-V) and voltage-voltage (V-V) amplifiers,
98 and the output from a small connector (ERA.00.250.CTL, Lemo) is measured using a
99 digital voltage meter. To construct low-noise high-sensitivity amplifiers, a low-ripple
100 smoothing circuit for an alternating current (AC) adopter is necessary.

101 The main circuit diagrams of the X-ray detecting module are shown in Fig. 2. The
102 photocurrents are converted into voltages using the inverse I-V amplifier with a 2-fA-
103 bias 2-channel operational amplifier (LMC662, National Semiconductor). The V-V
104 amplifier utilizes the second channel of LMC662 with a non-inverse amplifying circuit.
105 Although the gain of the V-V amplifier increases with increasing resistance in a 50 k Ω
106 variable resistor, the resistance was set to 0 Ω . In the smoothing circuit for the two
107 amplifiers, the output voltage from the AC adopter is input to a common-mode inductor
108 of 2.0 mH $\times$ 2 with a 4.7-mF condenser. The ripple of the output voltage decreases with
109 increasing electric capacity.

110

111 2.2. Measurement of EPH spectra

112 Fig. 3 shows a block diagram for measuring EPH spectra. The X-ray photons from an
113 X-ray generator ((RXG-0152, R-tec)) are detected using the Si-PIN, and the electric
114 charges produced in the Si-PIN are converted into voltages using a charge-sensitive
115 amplifier (580, Clear Pulse). The output voltages from the charge amplifier are
116 amplified by a shaping amplifier (4419, Clear Pulse), and event pulses from the shaping
117 amplifier are sent to multichannel analyzer (MCA; MCA4000, γ PGT) to measure the
118 EPH spectra using a personal computer (PC). The two readily available amplifiers are
119 used to produce event pulses corresponding to photons.

120 Without scintillation crystals, X-ray photons are detected directly by the Si-PIN
121 detector. Using the scintillator-Si-PIN detectors, 16% of the light-receiving surface can
122 detect X-ray photons directly, and 84% of the surface can detect both the penetrating X-
123 ray photons through the crystal and the converted X-ray photons by the scintillation
124 method. In the scintillation method, the scintillation photons are detected by the Si-PIN,
125 and the electric charges produced in the Si-PIN are integrated using the charge amplifier.

126 In the EPH spectra, the electric charge produced by the absorption of an X-ray photon
127 is proportional to the photon energy. Therefore, the X-ray sensitivity increases in
128 proportion to the photon energy using the X-ray detecting module.

129

130 **3. Results**

131 3.1. X-ray dose rate

132 The measurement of X-ray dose rate is very important because the relative
133 sensitivities of the three detectors are roughly proportional to the dose rate. The X-ray
134 dose rate from the X-ray generator was measured using an ionization chamber
135 (RAMTEC 1000 plus, Toyo Medic) without filtering (Fig. 4). The chamber was placed
136 1.0 m from the X-ray source. At a constant tube current of 1.0 mA, the X-ray dose rate
137 increased with increasing tube voltage [Fig. 4(a)]. On the other hand, the dose rate was
138 proportional to the tube current at a constant tube voltage of 70 kV [Fig. 4(b)]. At a tube
139 voltage of 70 kV and a current of 1.0 mA, the X-ray dose rate was 57.0 $\mu\text{Gy/s}$.

140

141 3.2. X-ray spectra

142 First, it is important to measure X-ray spectra correctly using a standard CdTe
143 detector (XR-100T, Amptek) with an energy resolution of 1% at 122 keV. Variations in
144 the X-ray spectra at a tube voltage of 70 kV are shown in Fig. 5. Without filtration, the
145 peak and maximum energies of the bremsstrahlung X-rays were 32 and 70 keV,
146 respectively. Using 1.0-mm-thick YAP(Ce) and LSO crystals, most X-ray photons were
147 absorbed by the two crystals, and the lutetium (Lu) K-edge was confirmed using the
148 LSO crystal.

149

150 3.3. Relative sensitivities

151 Fig. 6 shows the output voltages from the Si-PIN, YAP(Ce)-Si-PIN, and LSO-Si-PIN
152 detectors measured using the X-ray detecting module. At a tube current of 1.0 mA, the
153 outputs increased with increasing tube voltage [Fig. 6(a)]. As shown in Fig. 6(b), the
154 output voltages were in proportion to the tube current at a tube voltage of 70 kV.
155 Compared with the YAP(Ce)-Si-PIN and LSO-Si-PIN, the Si-PIN detector had
156 approximately 2-times output at tube voltages below 85 kV.

157

158 3.4. EPH spectra

159 The EPH spectra at a tube voltage of 70 kV are shown in Fig. 7. When the Si-PIN
160 was used, only X-ray spectra can be measured. Although the photon count substantially
161 decreased at a region beyond 50 keV, the maximum energy corresponded to the tube
162 voltage. When the two scintillation detectors were used, the total photon counts
163 substantially decreased, and these results corresponded qualitatively to those of the
164 relative sensitivities. According to insertion of the Al filter, we observed silver (Ag) $K\alpha$
165 photons from the wiring materials behind the Si substrate. The scintillation detectors can
166 detect X-ray photons directly using 16% of the Si-PIN, and the EPH spectra showed the
167 similar distributions. In addition, the yttrium (Y) $K\alpha$ photons were also observed using
168 the YAP(Ce)-Si-PIN detector. From the results concerning the EPH spectra, it was
169 difficult to increase the X-ray sensitivities using these two scintillators.

170

171 4. Discussion and conclusions

172 We constructed a low-dose-rate low-noise X-ray detecting module for semiconductor
173 diodes, and this module with an ADC and a tablet personal computer will be applied
174 soon to a compact X-ray dosimeter. The detectors for this module are as follows: the Si-
175 PIN, ceramic-substrate Si, and CdTe detectors. In the former experiment using the three
176 detectors without scintillators, it was very easy to detect high-dose-rate short-pulse X-
177 rays for medical diagnosis at a tube current of 0.2 A by the decreases in the amplifier
178 gain.

179 Using the module, we measured the relative sensitivities of the Si-PIN, YAP(Ce)-Si-
180 PIN, and LSO-Si-PIN detectors, and the sensitivity of the Si-PIN was approximately
181 twice as high as those of the two scintillation detectors. Although this general-purpose
182 Si-PIN can detect scintillation photons with wavelength ranging from 320 to 1080 nm,
183 the sensitivities of the two scintillation detectors substantially decreased by the crystals.

184 Table 1 shows the typical scintillation characteristics among the NaI(Tl), YAP(Ce),
185 and LSO crystals, and the relative light yield of the YAP(Ce) and LSO crystals are 40
186 and 72, respectively. However, the sensitivity of the YAP(Ce)-Si-PIN was higher than
187 that of the LSO-Si-PIN because most X-ray photons were absorbed by the 1.0-mm-thick

188 LSO crystal.

189 Using these three detectors, the output voltages were proportional to the tube current
190 at a constant tube voltage. However, the output voltages were not in proportion to the
191 tube voltage at a constant tube current because the bremsstrahlung X-ray dose was
192 proportional to the second power of the tube voltage.

193 Using these scintillation detectors, because 16% of the light-receiving surface can
194 detect X-rays directly, the EPH spectra from 84% surfaces covered with the two crystals
195 should be calculated. The calibrated EPH spectra from the three detectors are shown in
196 Fig. 8; 16% of the counts from the Si-PIN as a function of photon energy are subtracted
197 from the spectra in Fig. 7(a). Compared with the Si-PIN, the detection efficiencies of the
198 two scintillation detectors still decreased by the calibration. Of course, the spectra in Fig.
199 7(b) showed the same characteristics utilizing the calibration. Therefore, it is difficult to
200 increase the relative sensitivities using these two scintillator crystals in conjunction with
201 the Si-PIN.

202 Compared with a CdTe detector, although the X-ray-electric conversion efficiency of
203 the Si-PIN and ceramic-substrate Si detectors are low, a low-priced dosimeter for
204 detecting X-rays with a wide-range dose rate will be manufactured soon.

205

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213 References

- 214 [1] H. Mori, K. Hyodo, E. Tanaka, M. U. Mohammed, A. Yamakawa, Y. Shinozaki, H.
215 Nakazawa, Y. Tanaka, T. Sekka, Y. Iwata, S. Honda, K. Umetani, H. Ueki, T. Yokoyama,
216 K. Tanioka, M. Kubota, H. Hosaka, N. Ishizawa, M. Ando, Radiology 201 (1996) 173-
217 177.
- 218 [2] K. Hyodo, M. Ando, Y. Oku, S. Yamamoto, T. Takeda, Y. Itai, S. Ohtsuka, Y.

219 Sugishita, J. Tada, J. Synchrotron Rad. 5 (1998) 1123-1126.

220 [3] H. Matsukiyo, M. Watanabe, E. Sato, A. Osawa, T. Enomoto, J. Nagao, P. Abderyim,
 221 K. Aizawa, K. Hitomi, E. Tanaka, H. Mori, T. Kawai, A. Ogawa, K. Takahashi, S. Sato,
 222 J. Onagawa, Jpn. J. Appl. Phys. 49 (2010) 027001-1-6.

223 [4] H. Matsukiyo, E. Sato, O. Hagiwara, A. Abudurexiti, A. Osawa, T. Enomoto, M.
 224 Watanabe, J. Nagao, S. Sato, A. Ogawa, J. Onagawa, Nucl. Instrum. Methods A 632
 225 (2011) 142-146.

226 [5] H. Chiba, Y. Sato, E. Sato, T. Maeda, R. Matsushita, Y. Yanbe, O. Hagiwara, H.
 227 Matsukiyo, A. Osawa, T. Enomoto, M. Watanabe, S. Kusachi, S. Sato, A. Ogawa, J.
 228 Onagawa, Jpn. J. Appl. Phys. 51 (2012) 102402-1-5.

229 [6] S. Feuerlein, E. Roessl, R. Proksa, G. Martens, O. Klass, M. Jeltsch, V. Rasche, H. J.
 230 Brambs, M. H. K. Hoffmann, J. P. Schlomka, Radiology 249 (2008) 1010-1016.

231 [7] X. Wang, K. Taguchi, E. C. Frey, D. Meier, D. J. Wagenaar, B. E. Patt, Med. Phys.
 232 38 (2011) 1534-1541.

233 [8] R. Matsushita, E. Sato, Y. Yanbe, H. Chiba, T. Maeda, O. Hagiwara, H. Matsukiyo,
 234 A. Osawa, T. Enomoto, M. Watanabe, S. Kusachi, S. Sato, A. Ogawa, J. Onagawa, Jpn.
 235 J. Appl. Phys. 52 (2013) 032202-1-5.

236 [9] H. Kodama, M. Watanabe, E. Sato, Y. Oda, O. Hagiwara, H. Matsukiyo, A. Osawa, T.
 237 Enomoto, S. Kusachi, S. Sato, A. Ogawa, Jpn. J. Appl. Phys. 52 (2013) 072202-1-6.

238 [10] E. Sato, Y. Oda, H. Kodama, O. Hagiwara, H. Matsukiyo, A. Osawa, T. Enomoto,
 239 M. Watanabe, S. Kusachi, S. Sato, A. Ogawa, Jpn. J. Appl. Phys. 52 (2013) 092401-1-6.

240 [11] S. Yamaguchi, E. Sato, Y. Oda, R. Nakamura, H. Oikawa, T. Yabuushi, H. Ariga, S.
 241 Ehara, Jpn. J. Appl. Phys. 53 (2014) 040304-1-4.

242 [12] E. Sato, E. Tanaka, H. Mori, T. Kawai, T. Inoue, A. Ogawa, A. Yamadera, S. Sato, F.
 243 Ito, K. Takayama, J. Onagawa, H. Ido, Jpn. J. Appl. Phys. 44, (2005) 8204-8209.

244 **Figure captions**

245 Fig. 1. Block diagram for detecting low-dose-rate X-rays using a diode. The
246 photocurrents flowing through the Si-PIN are converted into voltages and amplified
247 using the I-V and V-V amplifiers. Structures of the Si-PIN, YAP(Ce)-Si-PIN, and LSO-
248 Si-PIN detectors are shown in the same figure. A 1.0-mm-cube scintillator crystal is
249 positioned on the light-receiving-surface of the Si-PIN.

250 Fig. 2. Circuit diagrams of two amplifiers and a smoothing circuit for an AC adopter. (a)
251 An inverse I-V amplifier with a 2-fA-bias two-channel LMC662 chip, (b) a non-inverse
252 V-V amplifier with the LMC662, and (c) a smoothing circuit with a common-mode
253 inductor and a large-capacity condenser.

254 Fig. 3. Block diagram for measuring EPH spectra. The electric charges produced in the
255 Si-PIN are converted into voltages using a charge-sensitive amplifier, and the voltages
256 are amplified using a shaping amplifier. The event pulses from the shaping amplifier are
257 sent to an MCA to measure EPH spectra.

258 Fig. 4. X-ray dose rate measured at 1.0 m from the X-ray source. (a) Variations with
259 changes in the tube voltage at a tube current of 1.0 mA and (b) variations with changes
260 in the tube current at a tube voltage of 70 kV.

261 Fig. 5. X-ray spectra measured using a CdTe detector at a tube voltage of 70 kV. The
262 spectra after penetrating two scintillators are also measured to confirm the absorption
263 effect by the two scintillator crystals, and the measurement method using a scintillator
264 crystal is shown in the same figure for reference.

265 Fig. 6. Output voltages from the module using the Si-PIN, YAP(Ce)-Si-PIN, and LSO-
266 Si-PIN detectors. (a) Variations with changes in the tube voltage at a tube current of 1.0
267 mA and (b) variations with changes in the tube current at a tube voltage of 70 kV.

268 Fig. 7. EPH spectra using the three detectors (a) without filtration and (b) using a 3.0-
269 mm-thick Al filter. Low-energy photons are absorbed effectively by the filtration.

270 Fig. 8. Calibrated EPH spectra from 84% of Si-PIN portions covered with scintillator
271 crystals. 16% of photon counts from the Si-PIN are subtracted from the three spectra in
272 Fig. 7(a).

273

274 Table 1. Typical characteristics of the three scintillator crystals of NaI(Tl), YAP(Ce),
275 and LSO.

Fig. 1

Fig. 2

Fig. 3

a

b

Fig. 4

Fig. 5

a

b

Fig. 6

a

b

Fig. 7

a

b

Fig. 8

Table 1

	NaI(Tl)	YAP(Ce)	LSO
Density (g/cm ³)	3.67	5.35	7.35
Effective atomic number	51	31	66
Relative light yield	100	40	72
Decay time (ns)	230	30	40
Peak wave length (nm)	410	360	420