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Performance of large-area avalanche photodiode for low-energy X-rays and γ-rays scintillation detection

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Abstract

We report on the performance of large-area ($5 \times 5\ mm^2$) avalanche photodiodes (APD) produced by Hamamatsu Photonics, as a low-energy X-rays and γ-rays scintillation detector. Hamamatsu APD has a reverse structure and works at relatively low bias voltage of 300–350 V. The leakage current is 1.2 nA at room temperature (25°C) and decreases to 10 pA at −20°C for an avalanche gain of 50. The best FWHM energy resolutions of $9.4 \pm 0.3\%$ and $7.4 \pm 0.3\%$ were obtained for 59.5 keV γ-rays from ^{241}Am and 122 keV γ-rays from ^{57}Co sources, respectively, as measured with a $5 \times 5 \times 5\ mm^3$ cubic CsI(Tl) crystal. We show that the minimum detectable energy for the scintillation light is remarkably low; 4.6 keV at room temperature (20°C) and 1.1 keV at −20°C. 5.9 keV X-rays from ^{55}Fe were clearly resolved at −20°C with an FWHM resolution of $32.9 \pm 0.3\%$. These results suggest that Hamamatsu APD can be a promising device for future applications in low-energy scintillation detection.

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Keywords: Avalanche photodiode; Low-signal scintillation detector; Minimum detectable energy

1. Introduction

Photo diodes (PDs) have an excellent quantum efficiency (close to 100%) in the visible and near infrared. PDs work very stably with low bias voltage and provide compact and rugged structures. A drawback is that they provide no internal gain and in most cases require use of an amplifier to provide a large enough signal. Most of its use is limited in any background-limited applications. In the field of experimental physics, however, background may dominate over the signal in a number of situations. Signal carriers can be more than 10 times *smaller* in number than those of the noise charge, which can be either due to the dark current in the detector and/or the noise in the read-out

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electronics. In such low-signal applications, photomultiplier tube (PMT) is generally used because internal gain is very high and sufficient signal-to-noise ratio is available. Several disadvantages of using PMTs are that it is sensitive to magnetic field, has relatively low quantum efficiency for input light signal (20–30%), and power consumption is rather high.

The good features of both PDs and PMTs are shared by avalanche photodiodes, (hereafter APD). The basic properties of APDs and their advantages are reviewed in Refs. [1,2]. The quantum efficiency of APD is close to 100% in the visible and near infrared. They can be very compact and less affected by magnetic field. The APD produces an internal gain of 10–100 or more, though it is much less than typical gain of PMTs. Thus the basic properties of APD may be well suited to read out small numbers of photons, so long as it has large detection area and is operated under stable conditions. For a long time, however, APDs were limited to very small surfaces, had a large dark current, and were very expensive. It had been mainly used as a digital device for light communications (e.g., a receiver for optical fibers). During the past decade, the technology to produce APDs has improved significantly. A large area APDs operating as a linear detector has also been available.

Such a new type of APDs have been extensively studied in literature. For example, Moszyński et al. [3–5] have studied the performance of APDs produced by different industries in scintillation detection. Thanks to an excellent quantum efficiency of APDs, a better or comparable energy resolution to those observed with a photomultiplier were obtained with a number of different scintillators. The best result of $4.8 \pm 0.14\%$ (FWHM) was obtained for 662 keV γ-rays using CsI(Tl) crystal coupled to a 16-mm-diameter APD produced by Advanced Photonix. Even better energy resolution of $4.3 \pm 0.2\%$ was measured with YAP:Ce crystal. Note that, these results are better than those obtained with a PMT using the same crystal ($6.5 \pm 0.19\%$ for CsI(Tl) and $4.38 \pm 0.11\%$ for YAP:Ce), and one of the best ever observed with scintillation detectors.

An internal gain of APD reduce the noise contribution of electronic system and photodiode, enabling that they can be used for detecting the weak scintillation light from a low-energy γ-rays. It has been reported that the device dark noise contribution significantly affects energy resolution only for γ-rays with energy below 50 keV [6]. The best FWHM energy resolutions of $11.3 \pm 0.3\%$ and $8.4 \pm 0.3\%$ have been obtained so far for 59.5 keV γ-rays from ^{241}Am and 122 keV γ-rays from ^{57}Co sources, respectively, as measured with a 10 mm diameter $\times 10$ mm high NaI(Tl) crystal [7]. In the case of using CsI(Tl) scintillator, the best energy resolutions of $12.7 \pm 0.4\%$ and $8.9 \pm 0.3\%$ have been reported. Performance of APDs operating at liquid nitrogen temperatures are reported in Refs. [6,8,9]. Operations at low temperature has an advantage of reducing the dark current noise dramatically, down to 1 pA level. The detection of low-intensity light pulses, producing only a few primary electron–hole pairs, are reported.

In this paper, we report the performance of 5×5 mm^2 APD recently developed by Hamamatsu Photonics K.K to determine its suitability as a low-energy X- and γ-rays scintillation detector. After recalling APD structures, we summarize parameters, gain, characteristics and an excess noise factor of Hamamatsu APD in Section 2. In Section 3, we present the energy spectrum of ^{241}Am (59.5 keV) and ^{57}Co (122 keV) obtained with a CsI(Tl) crystal coupled to Hamamatsu APD. We show that the minimum detectable energy is as low as 1 keV at -20°C, and 5.9 keV X-rays from ^{55}Fe source can be clearly resolved. Finally, we summarize our results in Section 4. Throughout this paper, the temperature was controlled in a thermostat within 0.1°C. Corresponding variations of gain is less than 0.3% (see Section 2.2).

2. Hamamatsu APDs

2.1. APD structures and parameters

Three different types of APDs are now commercially available: (a) ‘‘beveled edge’’, (b) ‘‘reach through’’, and (c) ‘‘reverse-type’’ diode. Structure (a), the ‘‘beveled edge’’ diode is a p$^+$n junction in which the n-type resistivity is chosen so as to make the breakdown voltage very high, typically 2000 V. APDs developed by Advanced Photonix Inc (hereafter, API) belongs to this type and extensively studied in literature [3–8,10]. This type of APDs yields a wide depletion layer and high avalanche gain ($\geqslant 100$). APDs produced by API allowed getting the best energy resolutions measured ever with different scintillators (see Section 1). Furthermore, thanks to its wide depletion layer of $\geqslant 50$ μm depth, it can be used in direct detection of soft X-rays in the device [4,5,9,10]. An energy resolution of 9.3% (FWHM) was obtained for 5.9 keV X-rays.

Structure (b), ''reach through'' type, applies to a diode in which the depletion, layer comprises both a relatively wide drift region of fairly low field (~ 2 V/μm) and a relatively narrow region of field sufficient for impact ionization ($25-30$ V/μm). The advantage of such a structure is that only relatively low voltages (typically less than 500 V) are required to full depleting the devices. For example, SPL2625 developed by Hamamatsu has a depletion region of 130 μm thickness, and operates below 500 V. Kishimoto et al. [11,12] used this APDs for diffraction experiments with synchrotron radiation. The FWHM energy resolution of 11% and 9.4% were obtained for 8.05 keV X-rays at 1×10^6 s^{-1} and for 16.53 keV X-rays at 2×10^6 s^{-1}, respectively. Traditional reach-through APDs have a wide low-field drift region at the front of the device, with the multiplying region at the back. A disadvantage of this structure is that most of the dark current generated within the device undergoes full multiplications, so that large-area devices tend to be somewhat noisy.

The ''reverse type (c)'' or ''buried junction'' is a reach-through APD developed recently for use specifically with scintillators [13,14]. In this device the narrow high-field multiplying region has been moved to the front end of the device, with the peak field only about ~ 5 μm from the surface of the device. Since most scintillators emit at wavelength of 500 nm or less, most of the light from scintillators is absorbed within the first 1–3 μm of the depletion layer and generates electrons which undergo full multiplication. Whereas most of the dark current undergoes only hole multiplication, and so its contribution to the noise is reduced significantly. An APD measured in this paper (Hamamatsu S8664-55) is the improved version of SPL 2560 recently studied by Moszyński et al. ([4], see also Refs. [15,16] for other products by Hamamatsu). An additional layer of n-type material is introduced to decrease the capacitance and to improve stability with respect to changes in bias voltage, which is closely related to the capacitance.

We have tested four pieces of S8664-55 in this paper. The basic parameters are quite uniform between these four pieces, as summarized in Table 1. An avalanche gain of 50 is achieved for a bias voltage of 346 V at room temperature, and the break down takes place at 390 V. These parameters are similar to those of SPL 2560 [4], but improvements have been made to have a lower capacitance and lower leakage current. In fact, detector capacitance reduced from 110–120 (SPL 2560) to 80–90 pF in the development phase of S8664-55. Also note that the leakage current is 1.2–1.3 nA at room temperature (25°C) and decreases to 10–15 pA at -20°C, which is about an order of magnitude smaller than those reported for SPL 2560 [4].

2.2. Gain characteristics

Avalanche gain and its stability are important parameters describing the performance of APD. The gain characteristic can be measured under constant illumination of monochromatic light source and recording the photocurrent of the APD as a function of bias voltage. We use a light-emitting diode (LED) producing light signals of 525 ± 5 nm. This wavelength is particularly

Table 1
Parameters of Hamamatsu APD (S8664-55; four units)

Surface area	5×5 mm^2
Window	Epoxy resin
Dark current: I_D(gain = 50, 25°C)	1.2–1.3 nA
Dark current: I_D(gain = 50, -20°C)	10–15 pA
Break-down voltage: V_{brk}(25°C)	390 V
Bias: $V_{G=50}$ (gain = 50, 25°C)	346 V
Capacitance: C_{det}(gain = 50, 25°C)	85 pF
Quantum efficiency	$\geqslant 80\%$ (500–830 nm) $\geqslant 60\%$ (390–930 nm)

important to mimic the scintillation light from CsI(Tl) crystal (550 nm), as we will see in Section 3. At voltages lower than 50 V, the APD gain can be regarded as unity since the photocurrent remained constant. Fig. 1 shows variations of APD gain as a function of bias voltage for several temperatures (from -20°C to $+20^\circ$C). At $+20^\circ$C, gain reaches to 10 at 280 V, and 50 at 340–350 V. At a gain of 50, the gain variations on bias voltage is approximated by

$$\frac{1}{M}\frac{\mathrm{d}M}{\mathrm{d}V} \simeq +3.4\%/\mathrm{V}. \quad (1)$$

Note that this is only 2 times the voltage coefficient of typical PMTs ($\sim 2\%/\mathrm{V}$).

When the APD device is cooled down, bias voltage required to achieve a certain gain is significantly reduced. This is due to the much smaller probability of electron energy loss in interactions with photons as compared with that at room temperature [6]. Such characteristics, however, cause significant gain variations of APDs on temperature. At a gain of 50, the gain variation is approximated by

$$\frac{1}{M}\frac{\mathrm{d}M}{\mathrm{d}T} \simeq -2.6\%/^\circ\mathrm{C}. \quad (2)$$

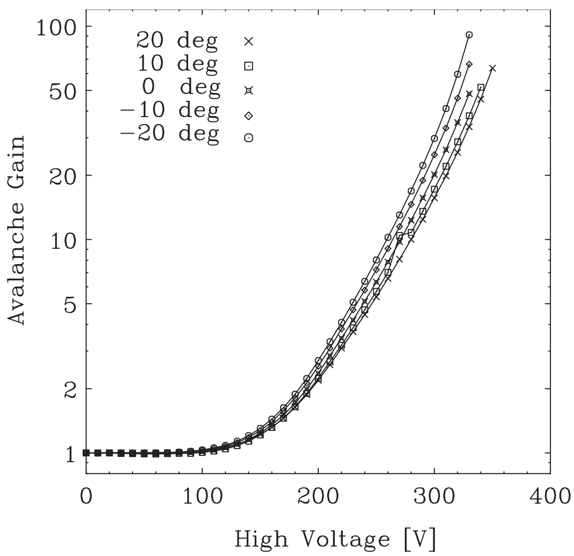

Fig. 1. Gain variations of APD measured at various temperatures from -20°C to $+20^\circ$C.

Since the temperature coefficient of PMTs is typically $-0.3\%/^\circ$C, variations of gain could be a more critical problem for APDs. In order to stabilize gain at 1% level, temperature must be controlled within $\Delta T = 0.4^\circ$C. Note that, these gain characteristics measured for S8664-55, are similar to those reported in literature [4,16] measured with prototypal reverse-type APD provided by Hamamatsu.

2.3. Performance as a soft X-ray detector

As we have reviewed in Section 1, APD can also work as a soft X-ray detector, and have been used in a number of applications. We first tested the performance of Hamamatsu APD (S8664-55) by direct illumination with 5.9 keV X-rays from a ^{55}Fe source and the LED pulses. The high voltage supply (REPIC RPH 0022) was connected to the APD via the resistance of 1 GΩ. Signals were read out from the anode of the APD, cutting the DC component by the coupling condenser of 2.2 μF. The signals of APD were amplified by charge sensitive preamplifier (CSA: CP5102) provided by Clearpulse Co., and fed to the shaping amplifier (ORTEC 570). Charge conversion factor of CSA is 5 V/pC, and noise equivalent charge is 205 electrons at 0 pF (Si), and 748 electrons at 107 pF (Si). The pulse height of the shaping amplifier was digitized by the 18 bit analog to digital converter (Clearpulse 1114A), and recorded by computer.

Fig. 2 presents the energy spectra featuring 5.9 keV X-rays, as recorded with S8664-55 at room temperature (+20°C). The FWHM width of the 5.9 keV peak was 835 eV (14.1%). A 525 nm light pulser peak and the test pulser peak are also given in the same panel. The energies of light peak and charge peak were calibrated against the X-ray peak energy. This assumption, however, is controversial since discrepancy between the gains for X-rays and light pulsers have been reported for certain kinds of APDs (e.g., Refs. [2,4]). We therefore compared the ratio of device gain for X-rays and light measured for Hamamatsu S8664-55 in Fig. 3. We find that the gain for X-rays is reduced by 10% at a gain of 20, and 30% at a gain of 100. Similar effect has been reported for

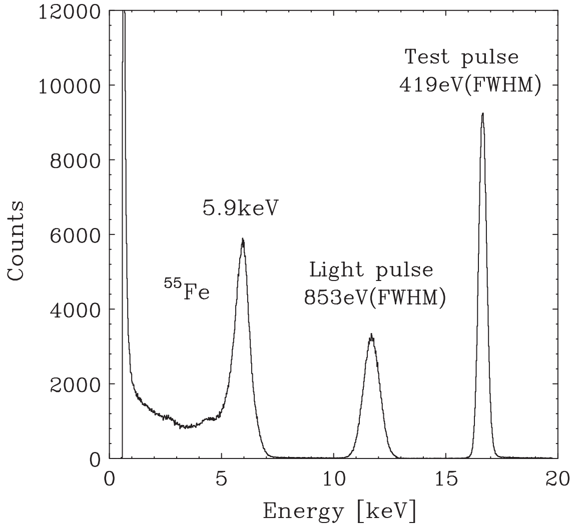

Fig. 2. The energy spectra showing 5.9 keV X-rays and light and test pulser peaks measured with Hamamatsu S8664-55.

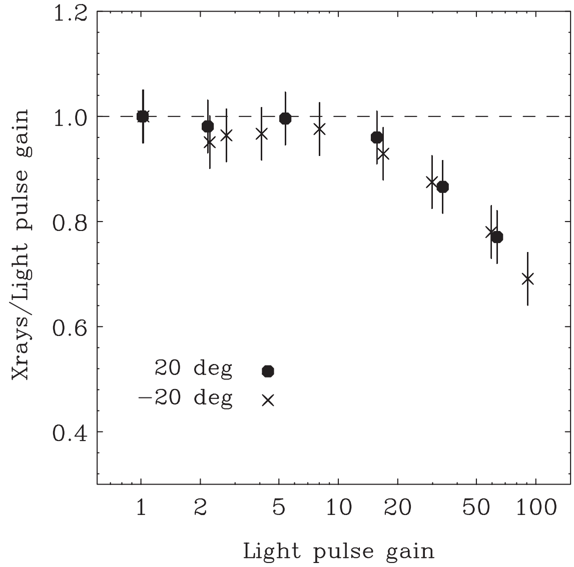

Fig. 3. The ratio of the APD gain for 5.9 keV X-rays and light pulses measured for Hamamatsu S8664-55.

SPL2560 produced by Hamamatsu [4]. Apparently, this is closely related with the internal structure of reverse-type APD, where the thin high-field multiplying region has been moved to the front end of the device surface (see below).

The energy resolution of the light pulse detected by an APD is limited mainly by the statistics related to avalanche multiplication, statistics of primary e–h pairs, and dark noise contribution of the APD-preamplifier system. Assuming a Gaussian shapes of the detected peak, the energy resolution ΔE of the LED light pulser peak (expressed in keV) can be described by

$$\Delta E^2 = (2.355)^2 FE\varepsilon + \Delta^2_{\text{noise}} \quad (3)$$

where E is the energy, of the light peak in keV, F is the excess noise factor, ε is the energy per e–h pair creation (3.65 eV for Si), and Δ_{noise} is the dark noise contribution of APD-preamplifier system (e.g., Refs. [6,7]). Difference of a gain between the X-rays and light signals (Fig. 3) were taken into account in the calculation. We obtain an excess noise factor of $F = 2.0 \pm 0.1$ for S8664-55. More exactly, an excess noise depends on both the avalanche gain and the light wavelength of input light pulse (e.g., Ref. [4]). Fig. 4 shows the dependency of the excess noise factor versus gain for the tested APD, provided by the manufacturer.

These result is consistent with our measurement at a specific light wavelength of 525 nm and a gain of 34.

We comment that 5.9 keV X-ray peak is much broader than those reported for other APDs studied previously ($\sim$550 eV; e.g., Ref. [4]). The broadening of the peak is mostly due to the gain non-uniformity of S8664-55 since multiplying region is very close to the surface (7 μm for S8664-55), and considerable fraction of X-rays ($\sim$90%) should penetrate through, or be absorbed in the avalanche region. This produce gain non-uniformity according to where the X-rays are absorbed, resulting in a broad X-ray peak as we have seen in Fig. 2. These results suggest that "reverse-type" APD may not be suitable for direct detection of X-rays in the device, though it can be an excellent light sensor for use with scintillators (see the next section).

3. Performance as a scintillation photon detector

3.1. Comparison between APD and PIN-PD

The low leakage current of S8664-55 should have an excellent advantage for a weak scintilla-

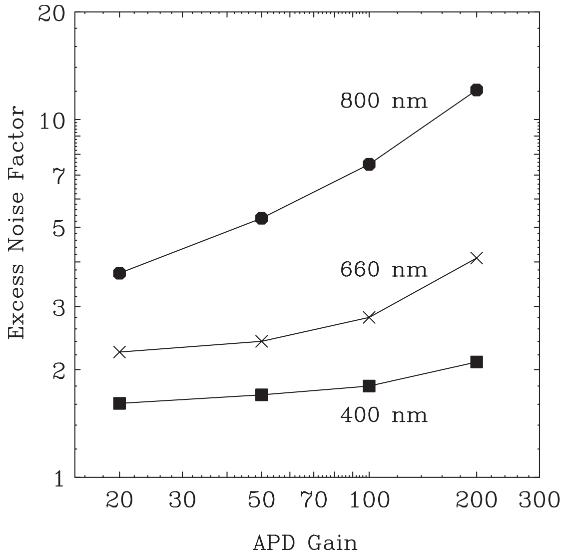

Fig. 4. Excess noise factor versus APD gain for the S8664-55 provided by Hamamatsu.

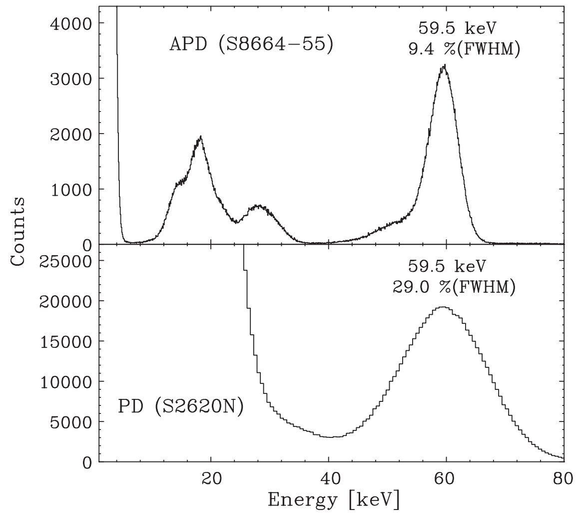

Fig. 5. Upper: Energy spectra of 59.5 keV γ-rays from a ^{241}Am source measured with a $5 \times 5 \times 5\,mm^3$ cubic CsI(Tl) crystal coupled to the APD (S8664-55). Lower: Energy spectra of a $5 \times 5 \times 5\,mm^3$ cubic CsI(Tl) crystal measured with the PIN diode (Hamamatsu S2620N). Energy resolutions are 9.4% (59.5 keV; FWHM) and 29.0% (59.5 keV; FWHM), respectively.

tion detection, where the device dark noise significantly affect the energy resolution [7,9]. Therefore in this paper, we focus on the detection of low energy X-rays and γ-rays ($\leqslant$100 keV) using a crystal coupled to S8664-55. Since the quantum efficiency of an APD and PIN-photodiode (PIN-PD) peaks at visible and near infrared (500−830 nm), we particularly use a CsI(Tl) crystal (peak emission at 550 nm) provided by Bicron (Saint-Gobain). A size of the CsI(Tl) crystal was $5 \times 5 \times 5\,mm^3$, and can fully match the sensitive area of the APD. The crystals were wrapped with several layers of white Teflon tape, and were coupled with Si rubber sheet (500 μm thickness) directly to the entrance window of S8664-55.

Fig. 5 shows the pulse height spectrum of 59.6 keV γ-rays from an ^{241}Am source, measured at room temperature (+20°C). The pulse height spectra, using the same CsI(Tl) scintillator coupled to the PIN-photodiode (Hamamatsu S2620N-1771: $5 \times 5\,mm^2$ surface) is also shown for comparison. Significant difference can be seen in the low-energy part of the spectra. A combination of 14–21 keV lines of Np (L_α, L_β and L_γ) is clearly resolved for APD whereas noise dominates for PIN-PD. Energy resolutions of 59.5 keV γ-rays are 9.4$\pm$0.3% for the APD and 29.0$\pm$0.2% for the PIN-PD, respectively. Similarly, Fig. 6 shows the pulse height spectra of 122 keV γ-rays from a ^{57}Co source measured with APD (S8664-55: *upper*) and PIN-PD (S2620N-1771: *lower*). Energy resolutions of 7.4$\pm$0.3% are obtained for the APD, whereas 16.1$\pm$0.2% for the PIN-PD. More strikingly, a 14.4 keV peak is clearly resolved for the APD with an energy resolution of 26.9$\pm$0.3%. The energy resolutions we have achieved with APD for low-energy γ-rays, are one of the best records ever reported for scintillation detectors.

3.2. Minimum detectable-energy with CsI+APD

As we have shown above, Hamamatsu APD (S8664-55) can read out CsI(Tl) scintillation photons well below 14.4 keV (^{57}Co) even at a room temperature. Our next concern is to quantify the minimum detectable energy (energy threshold) as a function of bias voltage and temperature. Fig. 7 shows the variations of energy spectrum below 80 keV for various bias voltages, irradiated by ^{241}Am source. When the bias voltage is very

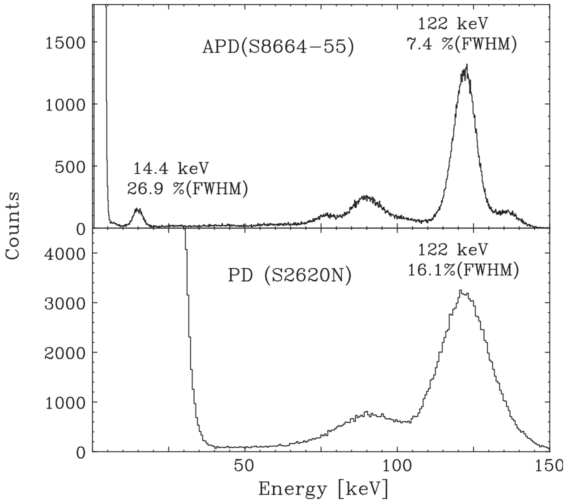

Fig. 6. Upper: Energy spectra of 122 keV γ-rays from a ^{57}Co source measured with a $5 \times 5 \times 5\ mm^3$ cubic CsI(Tl) crystal coupled to the APD (S8664-55). Lower: Energy spectra of a $5 \times 5 \times 5\ mm^3$ cubic CsI(Tl) crystal measured with the PIN diode (Hamamatsu S2620N). Energy resolutions are 7.4% (122 keV; FWHM) and 16.1% (122 keV; FWHM), respectively.

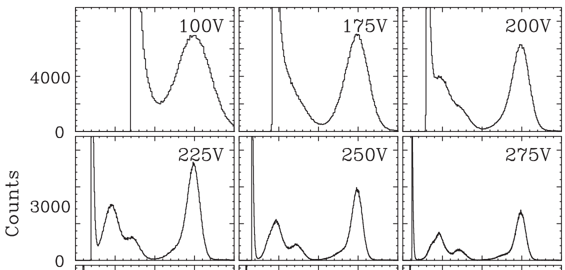

Fig. 7. Variations of energy spectra of ^{241}Am for various bias voltages. Combined peaks at 14–21 keV ($N_p - L_{\alpha,\beta,\gamma}$) are clearly resolved for bias voltage of $\geqslant$250 V.

low, avalanche process does not take place (Gain ~ 1; see Fig. 1) meaning that APD is working at *quasi* "PD mode". In fact 59.5 keV peak is very broad and similar to that obtained with PD for a bias voltages of 100 V. By increasing the bias, avalanche occurs and the noise and signals are clearly separated. Above 300 V, no apparent difference can be seen in the spectra.

For more quantitative comparison, we remove the γ-ray source ^{241}Am and measured the noise spectra at various bias voltage. Minimum detectable energy (E_{th}) was determined by fitting the noise spectra with an exponential function, and defined as an energy where the noise reaches a certain flux level (1 counts/s for our case). We show the variations of E_{th} in Fig. 7 measured at room temperature (+20°C). E_{th} is 47.6 keV for a bias of 100 V (similar to PD; Fig. 5), decreasing significantly by increasing the bias, and reaches to a constant level of 4.6 keV. Fig. 8 shows the temperature dependence of E_{th} for bias voltages of 300 and 330 V. Energy threshold improves significantly as decreasing temperature. At −20°C, E_{th} reaches to 1.1 keV. Figs. 9 and 10 shows the ^{55}Fe spectra measured at −20°C, with APD (S8664-55) coupled to Csl scintillator ($5 \times 5 \times 5\ mm^3$). A 5.9 keV peak is clearly resolved with the energy resolution of $32.9 \pm 0.3\%$ (FWHM). Note that, the energy resolution is better or comparable to those obtained with cleaved Nal(Tl) crystal coupled to photomultipliers (typically 35–50% for 5.9 keV X-rays).

We finally consider the number of e–h pairs produced in the APD for scintillation detection. Comparison of the gain observed with APD in direct detection of soft X-rays and light pulses provides a good reference to measure number of e–h pairs in the APD. For our experiments, bias voltage of 330 V corresponds to the avalanche gain of 34 from Fig. 1. By comparing the peak position of 59.5 keV γ-ray peak detected in the scintillator to that of 5.9 keV X-rays detected directly with the APD, we infer that $31,900 \pm 1600$ e–h pairs are primarily produced in the APD per 1 MeV at room temperature. Note that, the difference of a gain between the X-rays and light pulses (Fig. 3) were taken into account for this calculation. The result is consistent with a light collection of CsI(Tl) scintillator measured in literature (e.g., Refs. [4,5]), and corresponds to 60% of scintillation light yield reported by manufacture (54,000 photons/MeV for typical CsI(Tl) crystal; private communication

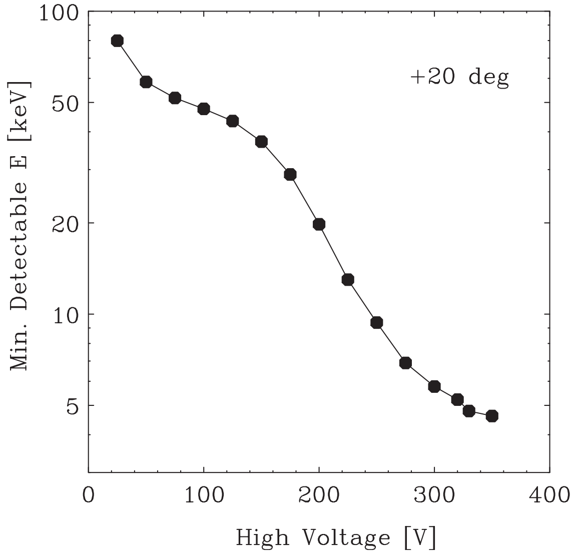

Fig. 8. Dependence of minimum detectable energy on bias voltages.

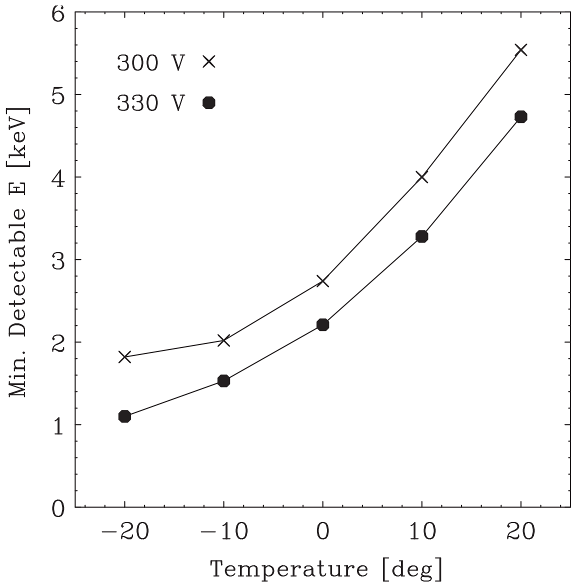

Fig. 9. Dependence of minimum detectable energy on temperature.

with Bicron). Similarly, minimum detectable energy of 1.1 keV measured at -20°C corresponds to only 35 e–h pairs primary produced in the APD device. Such a low-light-level detection has only been reported at a liquid nitrogen temperature in

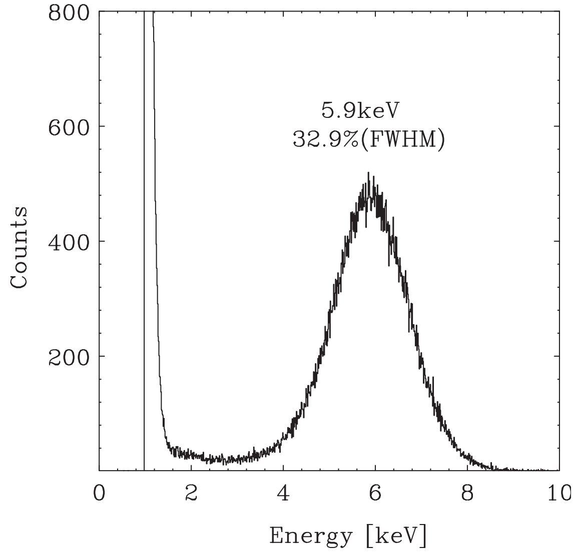

Fig. 10. ^{55}Fe spectrum measured at -20°C with Csl scintillator ($5 \times 5 \times 5$ mm^3 cubic). A 5.9 keV peak is clearly resolved with an energy resolution of 32.9% (FWHM).

literature, and promise the future applications of Hamamatsu APD at a "lightly cooled (e.g., -20°C)" environment, which is easily accessible in both the ground and space experiments.

4. Conclusion

We have studied the performance of a large area, reverse-type APD developed by Hamamatsu Photonics K.K, as a low-energy X-rays and γ-rays detector. Important properties of this APD are as follows: (1) sufficient gain(~ 50) can be obtained with a relatively low-bias voltage of ~ 350 V, (2) low leakage current of 1 nA at room temperature, and (3) gain stability of 3.4%/V, and $-2.6\%/^\circ$C. The best FWHM energy resolutions of $9.4 \pm 0.3\%$ and $7.4 \pm 0.3\%$ were obtained for 59.5 keV γ-rays from ^{241}Am and 122 keV γ-rays from ^{57}Co sources, respectively, as measured with a $5 \times 5 \times 5$ mm^2 cubic Csl(Tl) crystal. We showed that the minimum detectable energy for scintillation detection is 4.6 keV at room temperature (20°C) and 1.1 keV at -20°C. A 5.9 keV X-ray from ^{55}Fe was clearly resolved at -20°C with an FWHM resolution of $32.9 \pm 0.3\%$. These results suggest that APD could be a promising devices for replacing traditional PMT usage in low-energy scintillation detection, as long as temperature and bias voltages are stable and satisfy the required condition.

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