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Study of Large Area Avalanche Photodiode as a Fast Photon and a Soft X-Ray Detector

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Abstract

We have studied the fundamental properties of a large area avalanche photodiode(APD) of a 16mm diameter as a low signal detector. The dependences of the gain on the bias-voltage and temperature are presented. In particular, the timing property was investigated as a function of the detection area. Moderate timing property was obtained from a 16mm ϕ APD. Especially a small 0.5mm ϕ APD provided an excellent small timing jitter of less than 200ps, which is close to that of PMTs.

The performance of an APD as a photon counter for the scintillation light of a CsI(Tl) crystal was also studied. The resolution (RMS) obtained for 662keV photons from ^{137}Cs is 4% for a small scintillator block and 12% for a large scintillator block, respectively. The performance of the APD was found not to degrade down to a short shaping time of 200 ns.

Our study was extended to the possibility of an APD in detecting soft X-rays of less than 1 keV. By cooling it down to $\sim -20^\circ\text{C}$, it is shown that a 16mm ϕ large area APD can detect $\sim 400\text{eV}$ X-rays above its noise level.

1 Introduction

It was well known that an Avalanche Photodiodes (APD) would be an excellent device for detecting small number of photons or X-rays due to its distinct features such as the internal-multiplication, high-quantum efficiency and fast timing, if it has a stable operation and a large detection area. APDs have been developed since more than thirty years ago as digital devices for light communications [1]. In those days, they did not have such good properties as to operate as linear detectors for precise analog measurements since APDs developed early had some weak points such as low (only 10 $\sim$ 20) gain, instability, and small light receiving area(few mm 2). However, APDs have been intensively improved to operate stably and to enlarge its detection

area. At present, APDs having enough gain of $10^2 \sim 10^3$ and large photo sensitive area of more than 2cm 2 are commercially available [2].

As a photon detector, a PIN-photodiode (hereafter, we call it PIN-PD to distinguish it from an APD) is now generally used because of its high quantum efficiency and very simple and thin structure. Its operation in the strong magnetic field is also very attractive. Nevertheless, non-multiplication in a PIN-PD still does not allow us to use it as a photodetector replacing a photo-multiplier tube (PMT), since more than thousands photons are needed to get enough signal to noise ratio. In fact, PMTs are still widely used in detecting small number of photons.

The structure of an APD is originally similar to that of a PIN-PD, although it has internal gain. Application of high bias-voltage to an APD creates a strong electric field in the depression layer. Near the cathode, an electron-hole pair is created by an incident photon, and photoelectrons are accelerated into the depression layer by the high gradient electric field, which is high enough to accelerate electrons to make more electron-hole pairs, and these secondary electrons cascade successively in the depression layer. A lot of electrons, that is an avalanche, are consequently created in an APD from one photon, by which the signal to noise ratio is dramatically improved. Although a multiplication factor of a few hundred is typically possible, it strongly depends on the bias voltage.

The types of noises of an APD are classified mainly into two sources. One is dark current, and the other is shot noise. Dark current consists of surface current and bulk current. Surface current is independent of the gain of an APD. On the other hand, bulk dark current rises as the gain is increased. Then small signals, which cannot be seen in the dominant surface current noise and shot noise when an APD is operated at low gain, gradually exceed the noise as gain is increased. However, bulk dark current grows exponentially above the critical bias voltage, and eventually overwhelms the signal. Thus, a suitable gain has to be chosen in order to achieve a good signal to noise ratio.

Good features of a PIN-PD (quantum efficiency, structure, and resistance to magnetic field) are also shared by an APD. In contrast, the response time of an APD is much faster than that of a PIN-PD, and is close to that of a PMT. Obviously an APD has advantages of both a PMT and a PIN-PD, and expected to be a most promising device in replacing the traditional PMTs. Then several types of APDs have been studied for application in many fields. Recently, a new APD has been developed by Advanced Photonix Inc., which has both large effective area of a

16mm diameter and relatively high gain of ~ 500 . In particular, the photon-collection capability of this APD is similar to that of 2-inch photo-multiplier, when the high quantum efficiency of the APD is taken into account. This APD appears to have enough quality to replace a PMT, and thus an investigation of its fundamental properties is very much desired. Here we have measured the properties of this APD as a photon detector for scintillation light. Also, an APD has a potential as a good soft X-ray detector. A silicon device with no multiplication does not have enough signal to noise ratio to distinguish small signal of 1-10 keV X-rays from its noise without a cooling system. An APD can however easily give good signal to noise ratio in the room temperature due to its multiplication. Therefore, our investigation is extended to measure the properties as a soft X-ray detector.

2 Measurement as a photon detector

2.1 Measurement of basic property of APD

The dependences of the gain on the bias voltage and the temperature were measured. In addition, timing property was studied as a function of the detection area, because the rise-time of an APD signal strongly depends on its own capacitance. The relatively large capacitances of silicon devices indeed make the timing properties worse, which sometimes restricts their application as a readout device of scintillator. The 16mm ϕ APD produced by Advance Photonix was mainly used for this measurement. For the measurement of timing properties, APDs with smaller diameters produced by this company were used for comparison. The specifications of those APDs are summarized in Table 1.

Figure 1 shows the block diagram of the system for this measurement. A high voltage power supply was connected to an APD via a ripple filter, and signals from the APD were read out from the anode by cutting DC component with a capacitor. In particular, the ripple filter consisting of capacitances and resistances was carefully designed, because in this system dominant noises were from the high voltage supply. The signals of the APD were amplified by a charge integrating pre-amplifier, and were fed to a shaping amplifier. The pulse height of the output from the shaping amplifier was digitized by an analog to digital converter, and then recorded by a computer. As a fast photon source, high luminescence Orange Light emitting diode(LED) was driven by very fast rise-time and narrow pulse (1 μ s rise-time and 10ns width).

and we obtained fast photons with 10ns rise-time and 20ns pulse width. The amount of photons was controlled by optical filters located between the LED and the APD.

The gain of APDs strongly depends on the bias voltage. Figure 2 shows the gain of the 16mm ϕ APD in the room temperature as a function of bias voltage, where we used the gain at the bias voltage of 500V as the standard, to which data are normalized. The gain increases exponentially, and then, near the breakdown voltage (2460V for this device), the gain reaches up to ~ 1000 . However, the noise also rises up suddenly and exceeds signals just around the breakdown voltage more than 2420V. In the following measurements, therefore, we used bias voltage of 2400V at which the gain is estimated to be about 300.

Next, the dependence of the gain on the temperature was measured. In this measurement, a ^{55}Fe source was used instead of LED to avoid the temperature dependence of LED. The dependences of the output pulse height and the resolution on the temperature are shown in Fig.3. The gain variation of the APD was observed to be $-3\%/^{\circ}\text{C}$. This result shows that the gain fluctuation caused by the temperature dependence of APDs is much larger than that of PIN-PDs or PMTs, and thus we have to keep the temperature stable when using them.

Fast timing property is another excellent feature of APDs. The capacitance of a semiconductor device is inversely proportional to the depth of the depression region which is expanded by increasing the bias voltage of APDs. The mobility of electrons in APDs is also faster than other semiconductor devices due to the high electric field in the depression region. Then, APDs can provide an excellent fast rise-time signal. Also, the simple structure of APDs in principle gives rise to much less jitter, in contrast to PMTs where the structure of electrodes is more complex. From these points of view, APDs are supposed to provide good timing information. Indeed, it is reported that a small detection area APD with 1mm $^2\phi$ provides timing resolution of a few tens ps [3]. However, the rise-time of signals from the APD is dulled by the capacitance of APDs which is in proportion to its size. The rising slope of the dulled signal is in general more affected by the electrical noise than that of the faster rising signal, and thus fluctuates. This fluctuation appears as a timing jitter when the signal is discriminated. This timing jitter is different from that by time walk effect or by the fluctuation of photon statistics in PMTs. This type of timing jitter is considered to be negligibly small in the case of PMTs due to its fast rise-time. However, it becomes the dominant source for APDs. Even for a very stable, bright and fast light pulse, this timing jitter principally generates and deteriorates the timing measurement with APDs.

This cannot be corrected in the same way as timing walk effect, and restricts the use of APDs as a fast timing device. Therefore, we investigated this type of timing jitter as a function of the size of APDs.

In the measurement, all of measured APDs were illuminated by bright photon pulses of LED (5 ns rise time and 10 ns pulse width) for which pulse heights of the APD were kept constant pulse by pulse within less than 5%. The pre-amplifier used had a 5 ns rise-time, and the gains of each APD are adjusted to 50. The rise-time and jitter were measured for the large area APD with 16mm ϕ , and for another smaller size APDs in comparison. Figure 4 shows the measured rise-time and timing jitter. There is a strong correlation between the diameter of APDs and both its rise-time and timing jitter. In order to estimate the intrinsic timing jitter of the system including the fluctuation of the light source LED, the timing jitter was also measured with a 2-inch PMT of fast timing type, and was found to be less than 100 ps. The measured timing jitters of APDs are considered to be mostly due to the electrical noises mentioned above.

It is found from this study that APDs have a relatively good timing property of a few hundred ps timing jitter.

2.2 Readout of CsI(Tl) scintillator with APD

Figure 5 shows the dependences of the quantum efficiency on the wavelength of photons for APDs, PIN-PDs, and PMTs [4]. There one sees that the quantum efficiency of APDs and PIN-PDs are much higher than that of PMTs in the region of visible light. In particular, APDs and PIN-PDs provide more than 80% quantum efficiency for red or infra-red region where quantum efficiency of PMTs steeply decreases. Furthermore, APDs or PIN-PDs in which phosphorus is doped extend its sensitive region down to 300 nm. It enables to use relatively small size APDs in replacement of PMTs of which quantum efficiency is less than a half of APDs even in the blue region. The spectrum of emitted light from CsI(Tl) scintillator is superimposed in Fig.5 with arbitrary scale, which matches well with the region of high quantum efficiency of APDs and PIN-PDs.

Recently CsI(Tl) scintillators have been used in collider experiments as γ -ray calorimeters because of their good energy resolution. Since a PIN-PD has distinct features for the readout of a CsI(Tl) scintillator as mentioned above, it has been adopted as a photon device of a CsI calorimeter by some collider experiments [5]. However it is easily supposed that an APD will

provide much better performance by means of its internal gain and timing property. Already a good performance of small size APDs in that application was reported in Ref.[6].

Here we have investigated the possibility of using APDs as a scintillation readout device of the BELLE end cap calorimeter [7]. BELLE is the detector of KEK-B project to study B-meson physics. Most characteristic features of this experiment are the asymmetric energies of electron and positron beams (8.0 and 3.5 GeV), and the high luminosity of $\sim 10^{34}/(\text{cm}^2\text{s})$. Under such a high intensity beam, it is easily noted that the end-cap calorimeter has to operate in a high counting rate condition, and at the same time to keep good energy resolution similar to that in the barrel part. In particular, backgrounds due to spent electrons (positrons) will hit the detector continuously. These high rate noises deteriorate the energy resolution by the pile-up effect. The influence of this effect to the energy resolution is estimated to be 3.2MeV (RMS) with 1.0 μs shaping time at normal condition [8]. It can be improved by changing the parameters of the electronic circuit when the photon yield in a calorimeter is enough to ignore the photon statistics for the energy resolution. One method is to shorten the timing constant of the shaping amplifier, which makes it possible to differentiate the piled-up effects from signals. The output signal of APDs is larger than PIN-PDs for its internal multiplication, and APDs have fast rise-time of less than 100ns. These features allow fast processing of signals ($< 100\text{ns}$). Therefore, an APD with fast pre-amplifier and short shaping time is one of solutions for the reduction of pile-up noises.

At first, the properties of APDs as a photon detector were examined. The low-energy γ rays of 662keV and 1173keV emanating from ^{137}Cs and ^{60}Co sources respectively were measured using a CsI(Tl) crystal on whose back face the APD was attached. Two crystals of different size were used for this measurement; the small one has the size of 25mm $\times$ 25mm $\times$ 55mm, and the other large one has a truncated pyramidal shape of 300mm length with 55mm $\times$ 55mm front face and 65mm $\times$ 65mm back face. The large one is approximately the same size as a block in BELLE barrel calorimeter. Figure 6 shows the energy spectra of the small crystal measured by the APD with a 16mm diameter for the γ rays from ^{137}Cs and ^{60}Co . The comparison of energy resolutions between APDs and PIN-PDs is also tabulated in Table 2. In this table, the resolutions of the PIN-PD are cited from Ref.[9] in which the same sizes of crystals and the PIN-PD with little a larger sensitive area than that of our APD were used. Obviously APDs are superior to PIN-PDs. In particular, figure 7, which is the energy spectrum of the large crystal

measured by the APD for γ ray of ^{137}Cs , ensures us the advantage of APDs, since such a clear peak cannot be obtained for similar crystal by PIN-PDs.

The dependence of energy resolution on the shaping time was also examined. The γ rays from ^{137}Cs were measured by changing the shaping time. Figure 8 shows the energy resolution for each shaping time, where the circle points are RMS energy resolution with the small size crystal, and the square ones are that with the large crystal. In the measurement of the small crystal, there is little variation of the energy resolution by changing the shaping time from $2\mu\text{s}$ to 100 ns. In the measurement of the large crystal, however, there is a deterioration of the energy resolution by shortening the shaping time less than 200 ns. In this measurement, the best shaping time is between 500ns and $1\mu\text{s}$, which is consistent with the decay-time of CsI(Tl) , and the best resolution obtained with $1\mu\text{s}$ shaping time is 12% (80keV) RMS. However, it should be noted that the energy resolution with 100ns short shaping time is still at 15% (100keV) RMS in such a low energy region.

It means that the photon statistics of a large BELLE CsI crystal is still enough for even low energy photons of less than 1 MeV, and the electrical noises arising from the photon detectors are the dominant component of the energy fluctuation. Therefore, in order to reduce this kind of noises by the integration of signals, the shaping time is preferred to be longer than the rise time of the photon devices such as this large-area APDs of which rise times are typically 100ns. Because of that, the good energy resolution of APDs is considered to sustain down to the short shaping time of 100ns.

The requirement of the energy resolution for the BELLE calorimeter is better than $1.3\%/\sqrt{E(\text{GeV})}$ ($\sim 330\text{keV}$) RMS, which corresponds to $\sim 130\%$ (RMS) at 100keV [7]. According to this result, APDs with short shaping time of 100ns is possibly used for the application, satisfying the requirements of both energy resolution and the pile-up problem.

3 Measurement as a Soft X-ray detector

Semiconductor devices such as lithium doped silicon or germanium have been so far used as detectors for the energy measurement of soft X-rays (1keV $\sim$ 10keV). An incident X-ray interacts with semiconductor, and deposits its energy by creating electron-hole pairs. In silicon, $h\nu/3.6\text{eV}$ pairs are produced, where $h\nu$ is the energy of X-ray and 3.6 eV is the work function for creating a hole. Since the number of electrons in silicon created by 5 keV X-ray is ~ 1300 which is

about 6 times of those in the gas counter, semiconductor devices can provide very good energy resolution for X-rays. However, semiconductor detectors for soft X-ray (1 $\sim$ 10keV) have to be operated under very low temperature such as the boiling point of liquid nitrogen, in order to reduce the thermal noise below a signal of a few hundred electrons. The size of the detector is also restricted to small area of a few ten mm^2 in the same reason. These restrictions of semiconductor devices have limited their application. Recently PIN-PDs have been used for this purpose. Their capacitances are relatively smaller than those of other semiconductors, because of which the thermal noise is reduced significantly. Then, PIN-PDs cooled using an electric-cooling device have been applied for measurements of X-rays, while its available size is still restricted due to the thermal noise and the cooling power.

As mentioned in the previous section, APDs have good features superior to PIN-PDs, and may enable us to detect soft X-rays in the room temperature [10] or using a simple cooling system. From this point of view, we have studied the possibility of APDs as soft X-ray detectors for energy measurement. The timing property of APDs for X-rays was already described in detail in Ref.[11, 12]. Here we examined the APD which has the largest sensitive area of $16\text{mm}\phi$. For large area APDs, some problems for the energy measurement of X-ray should be taken into account. Dark-current of APDs, which increases in proportion to its size, blurs the energy resolution and limits the lower bound of detectable X-ray energy. Dark current of APDs can be however reduced by a simple cooling system such as a small electrical-cooling device. It is reported that the dark current at 0°C is reduced by one tenth of that in the room temperature [13]. The existence of the non-uniformity of the gain in the sensitive area is also another critical problem. Recently an APD array has been developed, in which each cell can be connect to each amplifier independently [14]. Amplifiers do not have to be of an ultimate low level type like that for traditional semiconductor detectors due to the internal gain of the APD. Amplifiers having such performance are already available in a monolithic IC. The combination of an APD array and IC amplifiers may make it possible to correct its non-uniformity.

The measurements were made using an electrically controlled cooling box in which temperature can be cooled down to -10°C . In order to cool down to -30°C , a small Peltier-device was used in addition, of which one face was directly attached to the metal case of the APD, and the other was attached to the aluminium plate in the cooling box. The temperature of the APD was always monitored by an electrical thermo-sensor. During the measurements, the temperature of

the APD was controlled within $\pm 0.2^\circ\text{C}$, and only one APD and X-ray source were placed in the cooling box, and connected to the preamplifier outside of the cooling box. Its shaping time was $0.1\mu\text{s}$, and the gain of the APD was always fixed at about 300. Here, we used the APD having no-window in the front of the detection surface so as to be transparent to soft X-rays.

Figure 9 shows the pulse height distribution of the APD irradiated directly by a ^{55}Fe source (5.9keV X-ray) in the room temperature. There is a clear peak corresponding to the 5.9keV X-ray, which cannot be observed with a PIN-PD in the room temperature. The resolution of this peak is 8.3% RMS, and equivalent noise charge (ENC) is estimated to be 160. The noise level rises up below $\sim 1\text{keV}$. The same distributions at lower temperature are drawn in Figure 10 where the bias voltage of the APD was fixed during the measurement. At a glimpse, one notes that the gain of the APD increases as the temperature is cooled down, while the noise level gradually decreases as pointed out in previous section. Since the gain of the APD varies considerably with the temperature, we measured dependences of the dark current and the lower boundary of the detectable energy on the temperature by fixing the gain at 300. The results are presented in Figs.11 and 12, where both quantities are dramatically improved by decreasing the temperature down to less than 0°C . In particular, it surely indicates that even APDs with large detection area can be used as a good soft X-ray detector by cooling it down to less than -10°C . However, the energy resolution cannot be improved by cooling as indicated in Fig.13, where X-rays were irradiated to the whole area of the APD uniformly. In order to estimate the intrinsic energy resolution of the APD for the same deposited energy, we illuminated the APD by the LED which was adjusted to provide the similar number of photoelectrons to the 5.9 keV X-rays, and obtained obviously better energy resolution of $\sim 5.6\%$ for LED than that of $\sim 8.3\%$ for 5.9 keV X-rays.

As pointed out previously, it can be inferred that the whole energy resolution for X-rays was deteriorated by the non-uniformity of the gain over the detection area. X-ray deposits its total energy just at the hit point of the APD, while the photons emanating from LED illuminate the whole detection area simultaneously. Therefore, the energy resolution for X-rays is deteriorated by the non-uniformity of the gain. Actually, collimated X-ray by $1\text{mm}\phi$ pin-hole was irradiated to the APD, and the energy resolution was improved to 7.0% in the room temperature. The gain variation on the detection area was further measured by scanning the gain of the APD using the collimated X-ray beam. The resulted gain fluctuation on the whole detection area is shown

in figure 14, and it indicates that energy resolution of the APD for the whole detection area was almost due to the non-uniformity of the gain. This result is consistent with the non-improvement of the energy resolution by cooling down. APDs with large detection area can however provide a moderate energy resolution similar to that of proportional counters. Furthermore this result presents the promising capability of segmented APDs as detectors having good energy resolution for soft-X rays in the room temperature.

In order to evaluate the actual performance of the APD for soft X-rays, characteristic X-rays of chlorine, silicon, and aluminium were measured by the APD cooled down to -30°C . Those characteristic X-rays were generated by irradiating ^{55}Fe 5.9keV X-ray to the corresponding materials. Observed peaks shown in Fig.15 are characteristic X-ray peaks of Al(1.49keV), Si(1.74keV) and Cl(2.62keV), respectively. The peak of ^{55}Fe 5.9keV X-rays is also seen because the incident ^{55}Fe X-rays were not collimated. The RMS resolution of the peaks are 554eV for Fe, 605eV for Cl, 313eV for Si and 302eV for Al. In spite of the gain non-uniformity of this APD, we obtained an excellent energy resolution of less than 2keV which is usually achieved only by a very cooled and small PIN-PD with a special low noise amplifier. From this figure, one sees that more than 400eV X-ray can be detected exceeding the noise level. The linearity of pulse height was also examined as shown in Fig.16, and found to be good over the studied energy region.

4 Summary

This work presents the promising future of an APD as a photon counting device. APDs are superior not only to the PMTs from the viewpoints of the quantum efficiency and the use under strong magnetic field, but also to the PIN-PD due to its internal gain and fast signal processing. We investigated in particular a recently developed APD having large gain of more 300 and the detection area of $16\text{mm}\phi$ which gives similar number of photoelectrons as that by a 2-inch PMT. The APD was stably operated with the gain of more than 300 during the long time of the measurement, when the temperature and the bias voltage was controlled within 0.3°C and 1 volt respectively. Fast rise-time is another excellent feature of APDs. It is clarified from this measurement that an APD having relatively small detection area is endowed with similar fast timing property as that with the fast PMTs, and even those having large effective area can provide moderate timing jitter of $\sim 500\text{ps}$. Due to its fast timing resolution and fast rise-time,

APDs will replace PMTs in some applications.

In order to study the ability of an APD as a photon counting device, we investigated the application of APDs to measure the photons of a CsI(Tl) crystal. The energy resolution measured using an APD was greatly improved from that using a PIN-PD, which can be easily inferred from the internal gain of APDs. In particular, even the low energy γ -ray of ^{137}Cs could be distinguished from the noise, even when using a large CsI(Tl) crystal block in which such γ -rays cannot be observed as a peak by PIN-PD. In addition, we shortened the shaping time for this large CsI calorimeter block, because those, which will be used in the end cap of the BELLE detector, should be operated under high counting rate condition. The shortest shaping time to which the good energy resolution can be maintained was obtained to be $\sim 200\text{ns}$, which is about five times shorter than that using a PIN-PD. This result shows that this calorimeter can be operated well in the BELLE end cap calorimeter.

Another ability of an APD as a soft X-ray detector was investigated. Even the APD having large detection area was able to measure the 5.9keV Iron X-ray with 8.3% RMS energy resolution, and the observed noise level was only 1keV in the room temperature. However, this energy resolution was found to be dominated by the non-uniformity of the gain in the detection area, since our measurements indicated that small area irradiation improved the energy resolution to 7.0% RMS. Furthermore, those features of the APD was dramatically improved by cooling using a simple electrical thermo-device. As cooling the APD down to 0 °C, the dark current was particularly decreased by one order of that in the room temperature, which extended the detectable region down to 400 eV at -20°C for the APD having large detection area. In conclusion, we have shown that APDs have excellent properties for detections of both scintillation light and soft X-rays.

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Diameter	Breakdown voltage	Maximam gain
0.3 mm	~ 175 V	~ 250
1.5 mm	~ 150 V	~ 100
5 mm	~ 2500 V	~ 1000
16 mm	~ 2500 V	~ 1000

Table 1: The specification of APDs using for measurement of timing properties.

Source	Size of scintillator	resolution(RMS)	
		APD	PIN-PD [9]
^{60}Co (1173keV)	small	3.0% (35keV)	5.6% (65keV)
^{137}Cs (662keV)	small	4.0% (26keV)	6.3% (42keV)
	large	12% (79keV)	cannot evaluate

Table 2: Comparison of the peak resolution with APD and PIN-PD

Figure captions

- Figure 1.** Block diagram of the measurement setup. This read-out electronics chain from APD to ADC was also used for a scintillator or a soft X-ray test.
- Figure 2.** Gain variation of the 16mm ϕ APD by changing its bias voltage, where the gain at the bias voltage of 500V is used as the standard, to which data are normalized.
- Figure 3.** Dependences of the output pulse height (a) and the resolution (b) on the temperature.
- Figure 4.** Plot of the measured (a) rise-time and (b) timing jitter of APDs by changing APD's size.
- Figure 5.** Quantum efficiency for APD, PIN-PD, and PMT. In addition, emission spectrum of CsI(Tl) are drawn.
- Figure 6.** Energy spectra of the small CsI(Tl) crystal measured by the 16mm ϕ APD for (γ rays of (a) ^{137}Cs and (b) ^{60}Co respectively.)
- Figure 7.** Energy spectrum of the large CsI(Tl) crystal measured by the APD for γ ray of ^{137}Cs .
- Figure 8.** Dependence of energy resolution on pulse shaping time, where the circle points are for small crystal, and the square ones are for large crystal.
- Figure 9.** Pulse height distribution of the 16mm ϕ APD irradiated directly by ^{55}Fe source (5.9keV X-ray) in the room temperature. The operating voltage is 2400V, and the gain is ~ 300 .
- Figure 10.** Pulse height distribution of the APD with 16mm ϕ irradiated directly by ^{55}Fe source in (a) the room temperature, (b) 0°C and (c) -30°C . In this measurements, same bias voltage is supplied.
- Figure 11.** Dependence of dark current on the temperature where gain of the APD was fixed at 300 during this measurement.
- Figure 12.** Dependence of lower boundary of the detectable energy on the temperature where gain of the APD was fixed at 300 during this measurement.
- Figure 13.** Dependence of energy resolution on the temperature where gain of the APD was fixed at 300 during this measurement.

- Figure 14.** Plot of the relative gains measured along the axes of arbitrary diameter on the 16mm ϕ detection area of the APD, where each gain was measured using the collimated X-ray beam within 1mm ϕ , and normalized to the averaged value.
- Figure 15.** Pulse height distributions of the 16mm ϕ APD irradiated directly by characteristic X-rays. Observed peaks are of Al(1.49keV) in (a) and Si(1.74keV) in (b) characteristic X-ray peaks respectively. The peaks of ^{55}Fe 5.9keV and Cl 2.62keV X-rays are also seen because the incident ^{55}Fe X-rays were not collimated, and hit APD directly or Cl included in plastics around the APD.
- Figure 16.** Relation between X-ray energy and the pulse heights of the peaks of characteristic X-rays.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16