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Basic study of PPD for the next generation of IACTs

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Now, the VHE γ-ray astronomy is moved from the detection era into the detailed physics era. Imaging Atmospheric Cherenkov Telescopes (IACTs) are demanded a higher sensitivity and a lower energy threshold, for discussions of astrophysics and astroparticle physics. For these purposes, we focus on the PPD which is a novel photon detector made up of multiple APD pixels operated in Geiger mode. We started the research for the possibility of applying PPDs to the next generation of IACTs. As a first step, we measure the response of 1mm$\times$1mm size and 3mm$\times$3mm size samples of PPD, and study the basic characteristics such as the gain, noise rate, cross talk probability and cross talk + after pulse probability. We confirmed these characteristics of 1mm$\times$1mm size PPD are consistent with reported results by the other groups, and we verified the gain characteristics of 3mm$\times$3mm size PPD are the same as those expected from 1mm$\times$1mm size PPDs.

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1. Introduction

Now, the number of discovered VHE γ-ray objects exceeds 80, which means the VHE γ-ray astronomy is moved from the detection era into the detailed physics era. Imaging Atmospheric Cherenkov Telescopes (IACTs) are demanded a higher sensitivity and a lower energy threshold, for discussions of astrophysics and astroparticle physics[1][2]. For existing IACTs, the photomultiplier tube (PMT) is used most commonly as a photon detector. However, PMTs require high operation voltage and have low quantum efficiency.

The PPD is a photon detector consisting of multiple Geiger mode APD pixels. It has a signal output, and when it detects photons, the signal from the PPD is proportional to the number of hit APD pixels. The most remarkable features of the PPD are fine photon-counting capability and higher photodetection efficiency. However, its size is too small for the astroparticle experiments, and there are problems that the dark counts, the optical cross talk, and the after pulses. Furthermore, the gain is very sensitive to the operating conditions such as bias voltage and temperature. These disadvantages should be improved for future astroparticle experiments.

The Multi-Pixel Photon Counter (MPPC) is one of such PPDs manufactured by Hamamatsu Photonics K.K. in Japan [3][4]. Here we studied the basic properties of the 1mm$\times$1mm and 3mm$\times$3mm size MPPCs. The geometries of the tested MPPCs are summarized in Table 1. The results of our measurements are presented in this paper.

Table 1: Specifications of measured MPPCs

Serial ID	Type	Photosensitive area	Number of pixels	Pixel pitch [μm]
602	S10362-11-050C	1mm$\times$1mm	400	50
441	S10362-11-100C	1mm$\times$1mm	100	100
455	S10362-33-050C	3mm$\times$3mm	3600	50
464	S10362-33-100C	3mm$\times$3mm	900	100

2. Measurement setup

The measurements discussed here are gain and noise rate which depend on bias voltage and temperature. The MPPC is set in the light-tight constant-temperature unit where the temperature is controlled with accuracy of $\pm 1^\circ$C between -10°C and 25°C. Bias voltage is controlled by a stabilized power supply with an accuracy of ± 0.1V around 70V. When we get the ADC spectrum for measurement of the gain of the MPPC, it is illuminated with blue LED light controlled by a pulse mode function generator. The pulse duration per pulse is 8ns and the repetition frequency is 3kHz. The MPPC signal is amplified for $\sim$ 100 times using an amplifier, and is digitized by a CAMAC ADC. The synchronized signal from the function generator is used to generate the trigger of ADC, and the gate width is set between 80ns and 180ns depending on the number of pixels. When we measure the dark count rate, a self-trigger signal is used.

3. Results of Gain measurements

Fig. 1 shows an example of ADC counts distribution of dark current with a tiny LED illumination. The first peak is pedestal, and the following peaks indicate the number of hit cells during gate width, which correspond to the number of photons as long as it is significantly smaller than the number of cells. The ADC spectrum is fitted by a multi-Gaussian function to find positions of peaks and to use the following analyses.

The distance between the pedestal peak and the first peak corresponds to the gain of MPPC. Then, the MPPC gain G_{MPPC} can be expressed as

$$G_{MPPC} = \frac{ADC_{dis} \times Conv}{e \times G_{amp}} \tag{3.1}$$

where ADC_{dis} is the average distance between adjacent peaks, $Conv = 0.244$ pC/count is a conversion factor from ADC counts to charge, $G_{amp} \simeq 93.2$ is the amplifier gain, and e is the electron charge. The determined gain for Serial ID = 602 is plotted in Fig. 2 as a function of the bias voltage V_{bias}, where each fitted line corresponds to a given value of temperature.

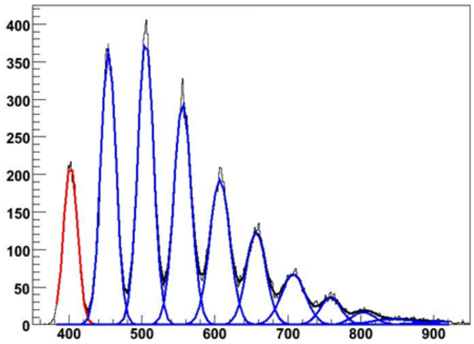

Figure 1: ADC spectrum of the 1mm×1mm size MPPC (S10362-11-050C) with 10°C and 69.5V triggered by pulsed light that fitted by multi-Gaussian convolved function. In this case, ten gaussians were used in the fitting.

The breakdown voltage V_{break} is determined by extrapolating the fitted line in Fig. 2 to the gain equal to zero. Fig. 3 shows the breakdown voltage V_{break} which linearly increase as the temperature becomes higher. The slope is $(5.4 \sim 6.0) \times 10^{-2}$V°C^{-1}.

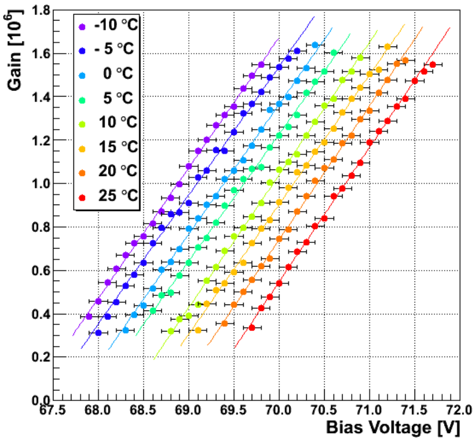

Figure 2: Bias voltage characteristic of gain of S10362-11-050C with temperature from −10°C to 25°C.

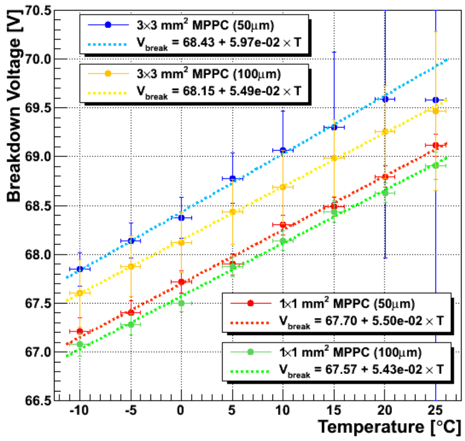

Figure 3: Temperature characteristics of breakdown voltage of four MPPCs.

From Fig. 2 and 3, the gain can be plotted as a function of over voltage $\Delta V = V_{bias} - V_{break}(T)$. The results including the other samples show that the over voltage dependence of the gain is linear,

Table 2: Gain slopes of over voltage characteristics and cell capacitances

Serial ID	Gain slope [V^{-1}]	Cell capacitance [fC]	Terminal capacitance [pC]
602	5.97×10^5	95.5 ± 0.04	38.2 ± 0.02
441	2.53×10^6	405.3 ± 0.15	40.5 ± 0.02
455	5.57×10^5	89.1 ± 0.08	320.7 ± 0.30
464	2.26×10^6	365.4 ± 0.48	328.9 ± 0.43

and does not depend on the temperature. It depends on the pixel size, which corresponds to the capacitance of each pixel, because the gain is proportional to the capacitance, $G_{MPPC} = C_{pix}\Delta V$, where C_{pix} is a pixel capacitance. The slopes and capacitances are summarized in Table 2.

For a given bias voltage, the gain linearly decreases with the temperature. The examples are shown in Fig. 4. The temperature coefficients of gain of 1mm×1mm size MPPC are $-3.21 \times 10^4[°C^{-1}]$ for 50μm pitch and $-1.33 \times 10^5[°C^{-1}]$ for 100μm pitch, and the same coefficients of 3mm×3mm size are $-3.13 \times 10^4[°C^{-1}]$, $-1.26 \times 10^5[°C^{-1}]$, respectively. This means, in 10^6 gain operation, 3°C variation affects to the gain by ∼10% and ∼40% for 50μm and 100μm pitch devices, respectively.

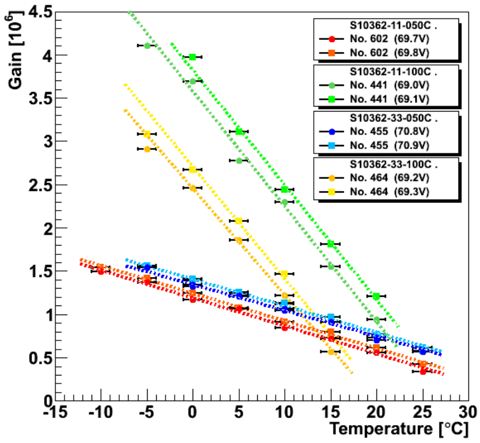

Figure 4: Temperature characteristics of gain with fixed bias voltage.

4. Results of Noise measurements

Dark count rates as a function of over voltage, which are taken at four fixed temperature of −5°C, 5°C, 15°C and 25°C, for two levels of threshold, are shown in Fig. 5 and 6, for the 1mm×1mm and the 3mm×3mm size samples, respectively. From these figures, we can see that the dark count rate increases at higher over voltage which corresponds to higher gain.

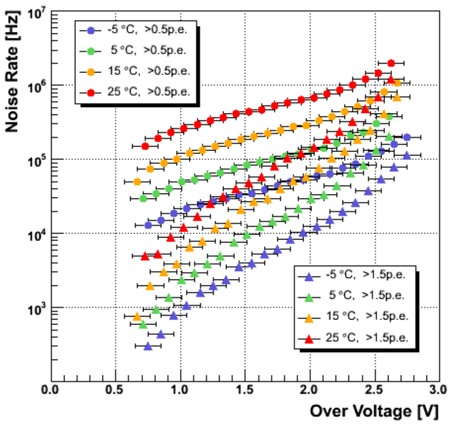

Figure 5: Over voltage characteristics of noise rate of S10362-11-050C with 0.5p.e. threshold level and 1.5p.e. threshold level, respectively.

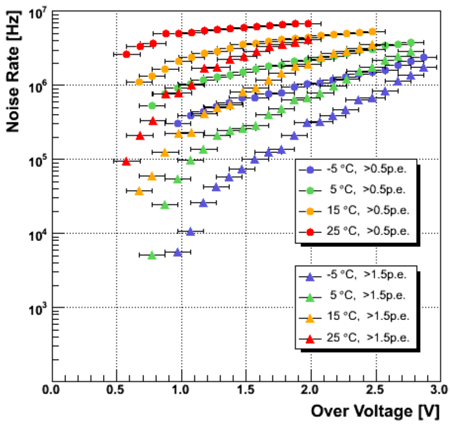

Figure 6: Over voltage characteristics of noise rate of S10362-33-050C with two levels of threshold, but here including the pile up effect.

Assuming the dark noise corresponding to the 2-pixel or more hits are dominantly produced by the cross talk effect, the ratio of dark count rates above 1.5 p.e. threshold and above 0.5 p.e. threshold gives an estimate of the cross talk probability. Fig. 7 shows the cross talk probability as a function of over voltage for two kinds of samples of 1mm^2 size MPPCs (green;100μm pitch, red;50μm pitch). The data points measured at four different temperatures between −5°C and 25°C are plotted by the same symbol. As you can see, the over voltage dependences of the cross talk probability for the different temperature are identical, and the cross talk probability increases as the over voltage increases. At the fixed over voltage, the probability does not depend on the temperature. The over voltage characteristics of the cross talk probability is well fitted by the combination of the linear function and the exponential function.

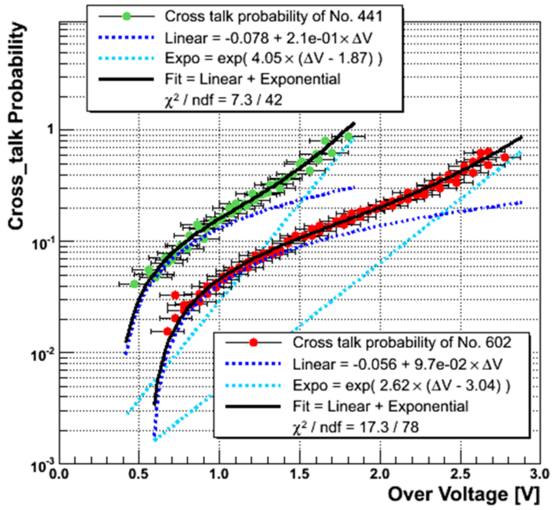

Figure 7: Over voltage characteristics of cross talk of 1mm×1mm size MPPCs with -5°C, 5°C, 15°C and 25°C, which can be fitted by combination of linear and exponential.

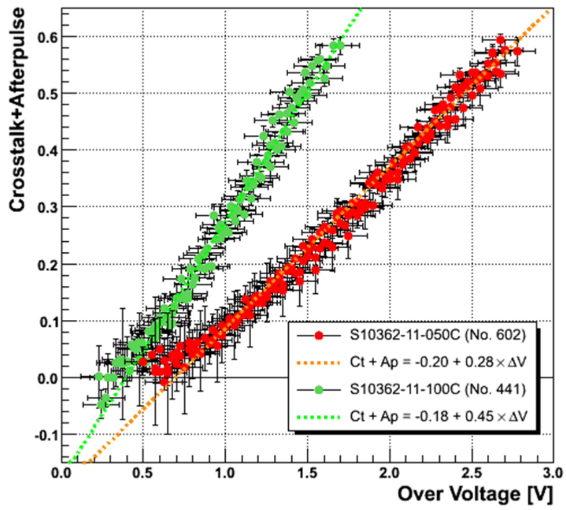

Figure 8: Over voltage characteristics of cross talk + after pulse probability of 1mm×1mm size MPPCs with -5°C, 5°C, 15°C and 25°C, and each device followed single line, respectively.

When low level light is illuminated on the MPPC, ADC counts distribution follows the Poisson distribution. Since the number of entry in the pedestal peak N_0 is not affected by the cross talk or after pulse, then the Poisson mean value λ is expressed by N_0 and the number of all entry N, $\lambda = -\ln \frac{N_0}{N}$. If there is no cross talk and no after pulse, the expected number of entry at 1p.e. peak $N_{1,expected}$ is $N_{1,expected} = N\lambda e^{-\lambda} = N_0 \ln \frac{N}{N_0}$. If the contamination due to cross talk and after pulse is in the measured entry of 1p.e. peak $N_{1,measured}$, the probability of cross talk and after pulse $P_{C\&A}$ is estimated as $P_{C\&A} = 1 - \frac{N_{1,expected}}{N_{1,measured}}$. Estimated results of $P_{C\&A}$ of 1mm size MPPCs are shown in Fig. 8. The probability linearly increases with over voltage, and does not depend on the temperature, where the data measured at four different temperatures are plotted by the same symbol in this figure. So, at the fixed over voltage, the probability does not depend on the temperature as the cross talk probability does not.

5. Summary

We measured basic properties of PPDs that the voltage and temperature characteristics of gain, total noise rate, cross talk probability and cross talk + after pulse probability. We confirmed that the gain at fixed bias voltage strongly depends on the temperature. So we may have to use temperature compensation circuit for the future application. We found the cross talk probability as a function of over voltage is well fitted by the combination of the linear function and the exponential one. Also, we confirmed the characteristics of the gain of 3mm×3mm size MPPC is the same as those expected from 1mm×1mm size MPPC.

References

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[4] D. Renker et al., 2009, Journal of Instrumentation, 4, P04004