Study of the basic characteristics of PPD (SiPM) for the next generation of IACTs

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***Abstract*. The PPD (formerly called SiPM) is a novel photon-counting device made up of multiple avalanche photodiode pixels operated in Geiger mode. It has many advantages, such as single photon counting capability, high detection efficiency, and high gain at low bias voltage. However, the size is small for astroparticle physics experiments, and some other features, such as dark counts, can be a problem. MPPC is one of the PPDs manufactured by Hamamatsu. We measure the response of some samples, and study the basic characteristics of MPPC, such as the gain, noise rate, cross-talk, etc., particularly in consideration of the improvement for the next generation of IACTs.**

***Keywords*: Air Cherenkov, photodetector, SiPMs**

I. INTRODUCTION

Today detectors efficient for low light level detection and single photon counting are required in a large variety of fields including astroparticle physics. The next generation plans of the Imaging Atmospheric Cherenkov Telescopes (IACTs) are not an exception. For existing IACTs, the photon detector most commonly used is the photomultiplier tube (PMT). However, PMTs have low quantum efficiency limited by the photocathode materials and require high operation voltages.

In the 1990s, a new type of photon sensor based on the Metal-Registor-Semiconductor (MRS) avalanche photodiodes (APDs) were invented in Russia [1]. Since then, intense development has been made in many institutes and by many manufacturers (*e.g.*, [2], [3],[4],[5]). These devices consist of multiple APD pixels and are operated in the limited Geiger mode, *i.e.*, with the bias voltage above the breakdown point. All pixels are connected in parallel to a single output, which is proportional to the number of hit pixels. These novel photon detectors were formerly called silicon photomultipliers (SiPMs), and are recently referred to as pixelized photon detectors (PPDs) [6].

The most remarkable features of the PPD are excellent photon-counting capability and higher photodetection efficiency. Furthermore it also possesses great advantages such as low operation voltage, low power consumption, insensitivity to magnetic fields and so on. However, for the field of astroparticle physics, its size is too small, and there are some major problems: the dark counts due to thermally generated free carriers, the optical cross talk due to photon travelling to a neighboring cell which trigger a breakdown, and the afterpulse due to carrier trapping and delayed release. Furthermore, the gain is very sensitive to the main operating conditions such as bias voltage and temperature. These disadvantages should be improved for the future astroparticle experiments.

The Multi-Pixel Photon Counter (MPPC) is one of such PPDs manufactured by Hamamatsu Photonics K.K. in Japan. There are some preceding studies of MPPC (*e.g.*, [7], [8], [9], [10]) . Here, we studied the basic properties of the MPPCs which have 1 mm×1 mm and 3 mm×3 mm photosensitive surfaces consisting 100, 400 or 3600 pixels for each device. The results of our measurements are presented in this paper.

II. MEASUREMENT SETUP

Five samples of MPPCs have been studied. The geometrical size of the tested MPPCs are summarized in Table I.

The measurements discussed here are gain and noise which depend on bias voltage and temperature. The MPPC is set in the light-tight constant-temperature unit where the temperature is controlled with an accuracy of ±1°C between -10°C and 25°C. Bias voltage is controlled by a stabilized power supply between 67.9 V and 71.7 V. When we measure the gain of the MPPC, it is illuminated with light from a blue LED powered by a function generator in a pulse mode. The pulse repetition frequency is 3 kHz and the duration per pulse is 8 ns. The MPPC signal is amplified for ~ 100 times using a commercial amplifier, and is fed into a CAMAC ADC to be digitized. The trigger was generated by the synchronized signal from the function generator, and the gate width is set between 80 ns and 180 ns depending on the number of pixels. When we measure the dark count rate, a self-trigger signal is used.

III. PROPERTIES OF A 1 MM×1 MM MPPC

Fig. 1 shows an example of ADC counts distribution of dark current with a tyny 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.

TABLE I
SPECIFICATIONS OF MEASURED MPPCS

Sample id	Type	Photosensitive area	Number of pixels	Pixel pitch [μm]
602	S10362-11-050C	1 mm×1 mm	400	50
603	S10362-11-050C	1 mm×1 mm	400	50
440	S10362-11-100C	1 mm×1 mm	100	100
441	S10362-11-100C	1 mm×1 mm	100	100
08J001455	S10362-33-050C	3 mm×3 mm	3600	50

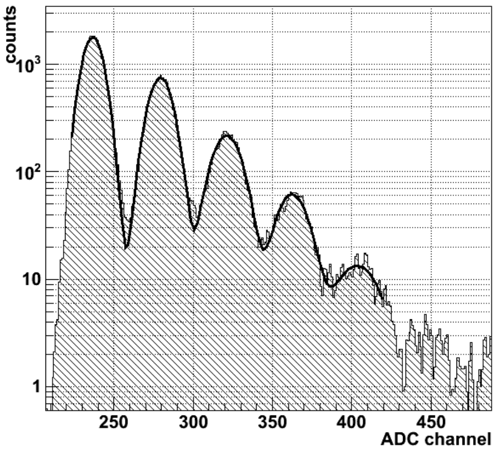

Fig. 1. ADC spectrum of the 1mm^2 MPPC (S10362-11-050C) triggered by the low-intensity pulsed light that fitted by multi-gaussian convolved function. In this case, five gaussians were used in the fitting.

A. Gain

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

$$G_{\mathrm{MPPC}} = \frac{ADC_{\mathrm{dis}} \times Conv}{e \times G_{\mathrm{amp}}}, \qquad (1)$$

where ADC_{dis} is the average distance between adjacent peaks, $Conv = 0.244$ pC/count is a conversion factor from ADC counts to charge, $G_{\mathrm{amp}} \simeq 93.2$ is the amplifier gain, and e is the electron charge.

The determined gain for sample 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.

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} for S10362-11-050C and S10362-11-100C which linearly increase as the temperature becomes higher. The slope is $(5.2 \sim 5.4) \times 10^{-2}\mathrm{V}°\mathrm{C}^{-1}$.

From Fig. 2 and 3, the gain can be plotted as a function of over voltage $\Delta V = V_{\mathrm{bias}} - V_{\mathrm{break}}(T)$. The results are shown in Fig. 4. From this figure, it is seen that the over voltage dependence of the gain is linear, 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 of the cell multiplied by the over voltage, $G_{rmMPPC} = C\Delta V$, where C is a pixel capacitance. The slopes for S10362-11-050C and S10362-11-100C are $(6.0 \pm 0.2) \times 10^5 V^{-1}$ and $(2.6 \pm 0.2) \times 10^6 V^{-1}$, respectively.

For a given bias voltage value, the gain linearly decreases with the temperature. The examples are shown in Fig. 5. The temperature coefficients of the gain for 400 pixels and 100 pixels are -3.3×10^4 °C^{-1} and -1.4×10^5 °C^{-1}, respectively.

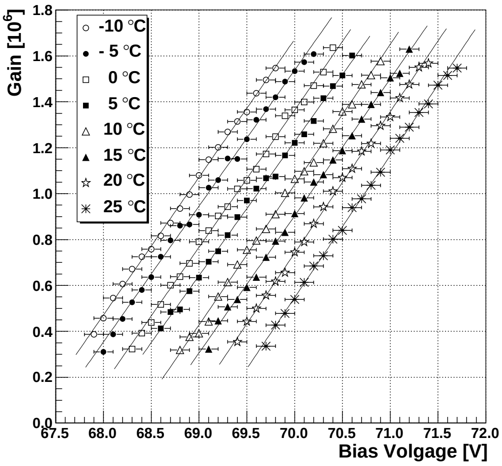

Fig. 2. Bias voltage characteristic of gain of S10362-11-050C with temperature from -10°C to 25°C.

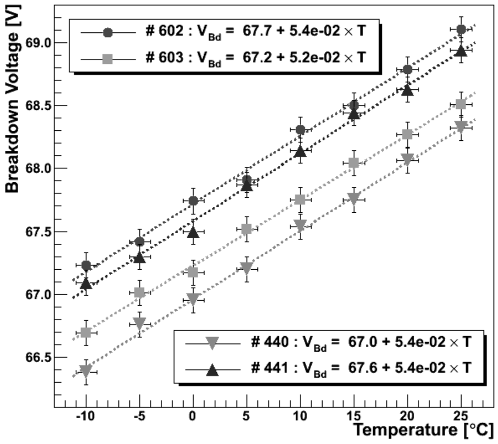

Fig. 3. Temperature characteristics of breakdown voltage of four 1mm^2 size MPPCs.

B. Dark count rate

Dark count rates as a function of bias voltage, which are taken at four fixed temperature of -5°C, 5°C, 15°C,

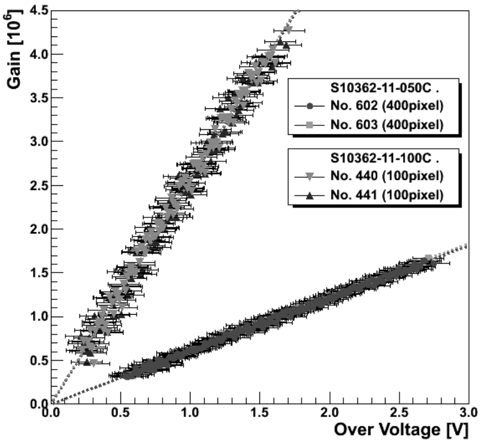

Fig. 4. Over voltage characteristics of gain of four 1mm^2 size MPPCs. Steep fitted line is for S10362-11-100C, and flatter one is for S10362-11-050C.

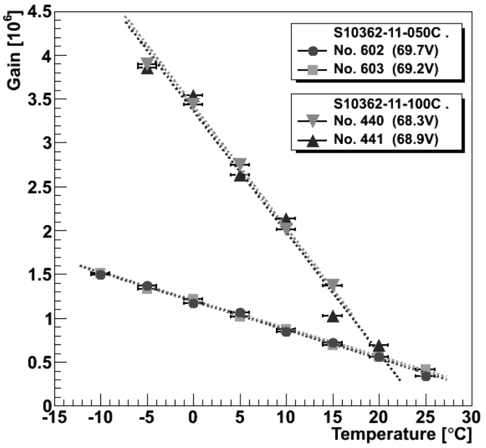

Fig. 5. Temperature characteristics of gain of four 1mm^2 size MPPCs with fixed bias voltage.

and 25°C, for two levels of threshold, are shown in Fig. 6. From this figure, we can see that the dark count rate increases at higher bias voltage which corresponds to higher gain.

C. *Cross talk probability*

Taking the dark noise corresponding to the 2-pixel hit is 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 crosstalk probability for 400 pixels 1mm^2 size MPPC as a function of over voltage. The cross talk probability increases as the over voltage increases, *i.e.*, as the gain increases, and it does not depend on the temperature at the fixed value of over voltage. The over voltage dependence of the cross talk probability is well fitted by the combination of the linear function and the exponential one between V_{over} =0.7 V and 2.7 V.

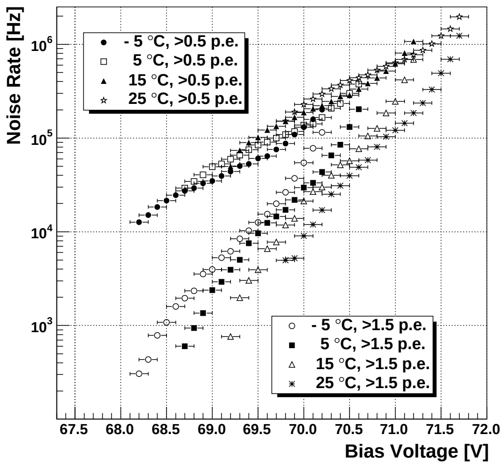

Fig. 6. Bias voltage characteristics of noise rate of S10362-11-050C with 0.5p.e. threshold level and 1.5p.e. threshold level, respectively.

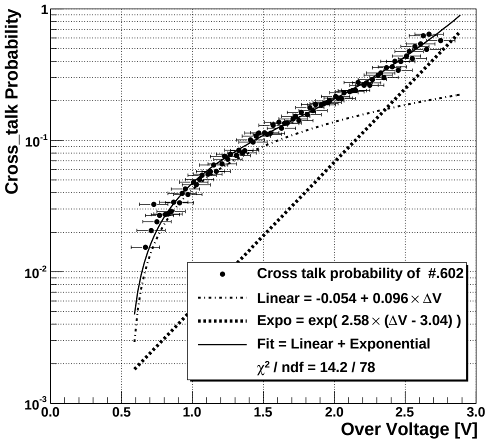

Fig. 7. Over voltage characteristics of crosstalk probability of S10362-11-050C, which can be fitted by linear function + exponential function.

D. *Cross talk and after pulse probability*

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:

$$\lambda = -\ln\frac{N_0}{N}. \tag{2}$$

If there is no cross talk or an after pulse, the expected number of entry at 1 p.e. peak $N_{1,expected}$ is expressed as

$$N_{1,expected} = N\lambda e^{-\lambda} = N_0 \ln\frac{N}{N_0}. \tag{3}$$

If the contamination due to cross talk and after pulse is in the measured entry of 1 p.e. peak $N_{1,measured}$, the probability of crosstalk and after pulse $P_{C\&A}$ is estimated as follows:

$$P_{C\&A} = 1 - \frac{N_{1,expected}}{N_{1,measured}}. \quad (4)$$

One example of the estimated results is shown in Fig. 8. The probability linearly increases with over voltage, and does not depend on the temperature.

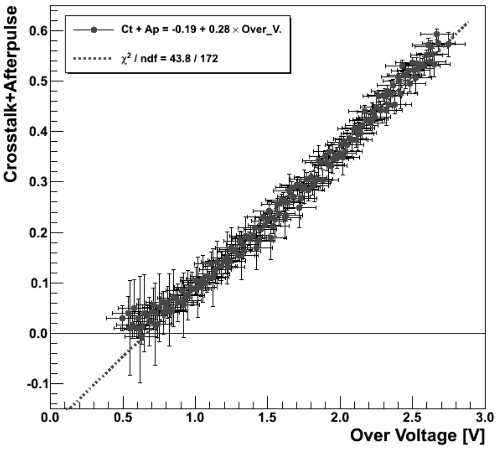

Fig. 8. Over voltage characteristics of crosstalk+afterpulse probability of S10362-11-050C with various temperatures.

IV. PROPERTIES OF A 3 MM×3 MM MPPC

We have just started the measurement of 3 mm×3 mm MPPC samples. Here we show the gain as a function of bias voltage and as a function of over voltage in Fig. 9 and Fig. 11, respectively. The temperature dependence of the breakdown voltage is also shown in Fig. 10.

Temperature dependence of 3 mm×3 mm size MPPC breakdown voltage is a little stronger, and oppositely over voltage dependence of gain is a little weaker than 1 mm×1 mm size MPPC with same pixel pitch. Difference of over voltage dependence of gain suggests 3 mm×3 mm MPPC have differ pixel capacitance compare to 1 mm×1 mm MPPC with same pixel pitch.

V. SUMMARY

We have measured some basic properties of MPPC and it is confirmed that MPPC is a possible candidate for replacing PMT for the future applications. However, it is true that the present properties must be improved particularly for the astroparticle experiments.

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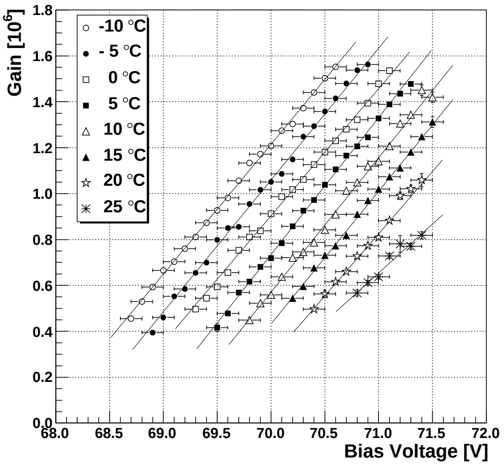

Fig. 9. Bias voltage characteristics of gain of S10362-33-050C with temperature from -10°C to 25°C. But we can not find the pedestal peak in noisy data (In 20°C, the pedestal peak was not found in lower voltage that under 70.7V. In 25°C, the pedestal peak was not found in all data. So, we have no confidece in 25°C data.)

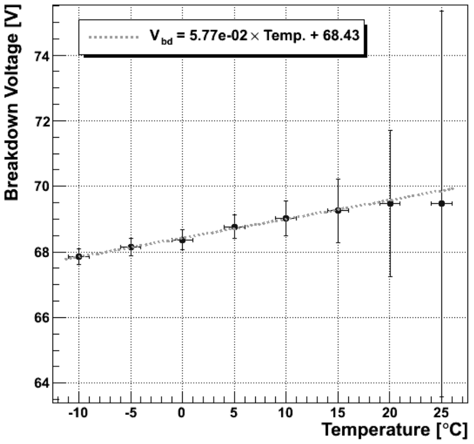

Fig. 10. Temperature characteristics of breakdown voltage of 9mm^2 size MPPC (S10362-33-050C).

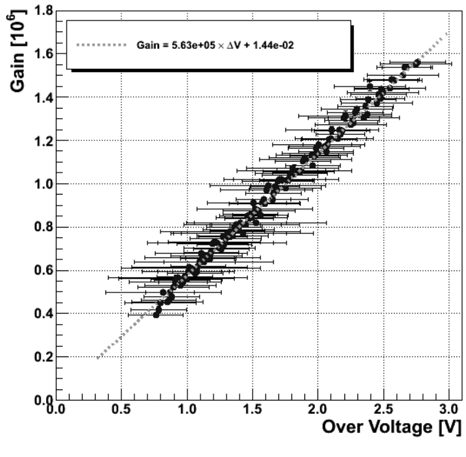

Fig. 11. Over voltage characteristics of Gain of 9mm^2 size MPPC(S10362-33-050C).