Effects of radiation damage caused by proton irradiation on Multi-Pixel Photon Counters (MPPCs)

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Abstract

We have investigated the effects caused by proton-induced radiation damage on Multi-Pixel Photon Counter (MPPC), a pixelized photon detector developed by Hamamatsu Photonics. The leakage current of irradiated MPPC samples linearly increases with total irradiated doses due to radiation damage, which is not completely recovered even after a year from the irradiation. No significant change has been observed in the gains at least up to 8.0 Gy (9.1×10\textsuperscript{7} n/mm\textsuperscript{2} in 1 MeV neutron equivalent fluence, $\Phi_{\text{eq}}$). The device has completely lost its photon-counting capability due to baseline fluctuations and noise pile-up after 21 Gy irradiation (2.4×10\textsuperscript{8} n/mm\textsuperscript{2} in $\Phi_{\text{eq}}$), which might be problematic for some applications, such as ring-imaging Cherenkov detectors. We have found that the pulse-height resolution has been slightly deteriorated after 42 Gy irradiation (4.8×10\textsuperscript{8} n/mm\textsuperscript{2} in $\Phi_{\text{eq}}$), where the measured sample has been illuminated with a few hundred photons. This effect should be considered in the case of energy-measurement applications.

Key words: Radiation damage, MPPC, SiPM, PPD, Photon detector
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1 Introduction

Pixelized Photon Detector (PPD), a generic name of multi-pixel Geiger-mode avalanche photodiodes, is a high-sensitivity photon detector developed recently. This device has attracted much attention since a PPD has great advantages over photo-multipliers, such as insensitivity to magnetic fields, compactness, low bias voltage and low power consumption, although the active area of the device is limited to be $1 \sim 10 \text{ mm}^2$ at present. Therefore a PPD device is very useful for high-energy and astrophysics experiments and medical science applications, especially for a readout device with scintillating fibers, wavelength shifting fibers, and fine granulated scintillating crystals, etc. A review about PPD has been prepared by D. Renker [1], for example.

The Multi-Pixel Photon Counter (MPPC) is one of such PPD devices which has been developed by Hamamatsu Photonics [2]. Three types of MPPCs (100, 400, and 1600-pixels type) with an active area of $1 \times 1 \text{ mm}^2$, and some other larger devices, are commercially available at present. Experimental groups, such as T2K, ILC, Belle, TREK and KOTO, are planning to adopt the MPPC in their detector systems for scintillating fibers and/or wavelength-shifting fibers readout, and for ring imaging Cherenkov detectors [3,4,5,6,7]. Experimental studies of the basic performance of the MPPC have been carried out by those groups (see e.g. [8]).

For practical use of the MPPC, radiation hardness is one of the important issues to be made clear for applications in a high radiation environment. In general, an indication of radiation damage on silicon devices is an increase of the leakage current, which is caused by lattice defects created due to radiation damage. An experimental study with a positron beam has been reported for radiation hardness of old types of MPPCs, showing an increase of the leakage current and the dark-count rates but no significant change in the gain and the photon-detection efficiency [9]. For $\gamma$-ray irradiation, high dark pulses generated at the outer regions of individual pixels have been observed after 240 Gy irradiation in addition to increases of the leakage current and the noise rates [10]. To investigate hadron-induced radiation damage, which is important in high-energy physics experiments, we performed an irradiation experiment with a 53.3 MeV proton beam.

In the following part of this report, at first, we describe the setup and the procedure for the irradiation experiment. Then, characteristic changes, such as the leakage current, gains, dark counts, pulse-height distributions, are presented. Finally, we discuss issues to be concerned with the effects caused by proton-induced radiation damage from a practical standpoint.
Fig. 1. Illustration of the print substrate prepared for the experiment. A proton beam hit the MPPC sample mounted on the substrate from the direction perpendicular to the entrance face of the sample. The substrate has a $20 \times 25 \text{ mm}^2$ hole around the sample to avoid radio-activation. A voltage source was connected to the connector $B_{in}$ to apply a negative reverse voltage to the sample. Signals from the sample were read out from the connector $S_{out}$. Capacitances ($C_1:0.047 \mu F$, $C_2:0.1 \mu F$) and resistors ($R_1:10 \text{ k}\Omega$, $R_2:1 \text{ k}\Omega$) were used for noise-filter circuits. A blue LED mounted on the substrate was employed as a light source for measurement of pulse-height distributions.

2 Experiment

2.1 MPPC samples

Two pieces of MPPC samples, Hamamatsu S10362-11-050C delivered in February 2007, were irradiated with a proton beam in the experiment. We refer to these samples as “Sample #1” and “Sample #2”. The samples have an active area of $1 \times 1 \text{ mm}^2$ and consist of 400 pixels of Geiger-mode avalanche photodiodes whose individual pixel-size is $50 \times 50 \mu \text{m}^2$. The operating voltage, which is the voltage giving a gain of $7.5 \times 10^5$ at $25 \degree \text{C}$, is $69.75 \text{ V}$ for Sample #1, and $69.58 \text{ V}$ for Sample #2, respectively.

One of the MPPC samples was mounted on a print substrate as illustrated in Fig. 1. Protons were directed onto the sample from the direction perpendicular to the entrance face of the sample. To avoid radio-activation of materials other than MPPC caused by proton irradiation, a $20 \times 25 \text{ mm}^2$ hole was made in the substrate. A blue LED (NICHIA NSPB320BS, $\lambda = 470 \text{ nm}$) on the substrate was used as a light source for measurements of pulse-height distributions. A voltage source, KEITHLEY model 2400, was employed in order to apply a negative reverse voltage to the MPPC sample. The leakage current of the sample was measured with the voltage source and recorded by the laptop computer connected to the voltage source via GP-IB communications. Signals from the MPPC sample were sent to a readout circuit, consisting of NIM and CAMAC modules, to measure pulse-height spectra and dark-noise rates. The resistors and capacitors on the substrate were used as noise-filter circuits.
2.2 Proton beam

The experiment was carried out at the Research Center for Nuclear Physics, Osaka University by using the 53.3 MeV proton beam from the AVF cyclotron. Protons were extracted from a vacuum beam pipe of the H-course beamline through a thin aluminum window to the experimental area. The beam size was set to be a rectangular shape of $6 \times 8 \text{ mm}^2$ by adjusting the several beamline slits, which was enough to cover the active area of MPPC, $1 \times 1 \text{ mm}^2$. The beam current was first tuned to be 2 nA at the beam stopper placed downstream of the final slit. Then the beam intensity was further reduced and controlled by inserting several mesh-type attenuators in the beamline located between the ion source and AVF cyclotron, so that the proper proton beam flux was obtained for the irradiation experiment ($10^4$-$10^5 \text{ p/mm/s}$). The uniformity of the beam intensity near the beam center was measured with a copper collimator and plastic scintillators. From this measurement, we confirmed that the position dependence of the beam intensity varied by less than 5% in the region of $4 \times 4 \text{ mm}^2$ around the beam center.

2.3 Experimental setup

Fig. 2 shows the experimental setup for this proton irradiation. A MPPC sample mounted on the substrate was placed just after the vacuum window of the beam pipe. The sample was covered with a black sheet (200 µm thickness) for light shielding. We set a platinum thermometer near the MPPC sample in order to monitor variations of the temperature inside of the black sheet during the experiment. The proton beam emerging from the beam pipe passed through the MPPC sample, and then it was trimmed with a copper collimator.
to be 3.5 mmφ. Two plastic scintillators placed downstream of the collimator were used to monitor the number of protons contained in the collimated beam. The proton beam was dumped in the beam stopper placed at the end of the beamline.

The intensity of the beam impinging on the active area of the MPPC sample was estimated from the total counts of the coincidence signals of the plastic scintillators and the measurement times. Since the beam intensity was almost flat in the region of 4 × 4 mm² around the beam center, we obtained the intensity from the coincidence rate by taking the ratio between the active area of the MPPC sample and the area of the collimator hole, \( R_A = 0.1040 \pm 0.0015 \), into account, where we assumed the machining accuracy of the collimator hole to be 50 µm. The following corrections were also taken into account: beam loss due to the scattering at the ceramic package of the MPPC sample and the black sheet \( (C_s) \), and the beam divergence induced difference of the beam density at the sample position and at the collimator position \( (C_d) \). The factor \( C_s \) was obtained by the coincidence rate change between with and without the MPPC sample wrapped by the black sheet. \( C_d \) was also determined by comparing the coincidence rates at different collimator positions. We estimated \( C_s \) and \( C_d \) to be 2.71 and 1.18, respectively. The considered uncertainties of the product of \( C_s \cdot C_d \) are the coincidence rate fluctuation during the irradiation (3.4 %) and accuracy of the detector and collimator positioning (0.9 %). As the result, we obtained the correction factor, \( R_A \cdot C_s \cdot C_d = 0.333 \pm 0.013 \), to multiply to the coincidence rates. The proton beam-flux during irradiation was monitored in this way.

A readout circuit consisting of NIM and CAMAC modules was prepared for the measurements of pulse-height distributions and dark-noise rates of the MPPCs as illustrated in Fig. 3. The blue LED was driven with TTL signals coming from a 100 Hz clock generator. Signals from the MPPC sample were sent to an amplifier (Phillips Model 777) where the gain was set to be 56.4. Then, these signals were integrated with a 12-bit charge-sensitive ADC of a CAMAC module (REPIC RPC-022). Gate signals from the clock generator were input to the ADC module. The gate width, 55 ns, was determined so that entire pulse signals coming from the MPPC were integrated, where the typical fall time of the signals was 40 ns. The intensity of the LED light was adjusted in such a way that the average number of photo-electrons (µ) was about 1.3. This value can be calculated from the null probability of the Poisson statistics \( P_0 (= e^{-\mu}) \), which was obtained from the ratio of the number of pedestal events to the total events in an ADC distribution. A discriminator (Phillips Model 705) and a visual scaler (Kaizu Works KN1860) were used for the measurement of dark-noise rates.
Fig. 3. Readout circuit for measurement of pulse height distributions and dark noise. The LED was driven with a 100 Hz clock generator. To digitize the signals from the MPPC on the substrate, we used a CAMAC ADC, which is connected to the amplifier with a gain of 56.4. A discriminator and a scaler were used for the measurement of dark-noise rates.

Table 1
Summary of proton irradiation for Sample #1 and Sample #2. The symbols represent as follows: $\phi_p$ (flux of the proton beam), $t$ (irradiation time), $\Phi_p$ (total fluence of the proton beam), $\Phi_{eq}$ (1 MeV neutron equivalent fluence), $D$ (accumulated absorption dose), and $T$ (temperature during each measurement).

| Sample #1 | \begin{tabular}{lcccc} \hline \text{irradiation} & $\phi_p$ (mm$^{-2}$s$^{-1}$) & $t$ (min.) & $\Phi_p$ (mm$^{-2}$) & $\Phi_{eq}$ (mm$^{-2}$) & $D$ (Gy) & $T$ (°C) \\ \hline \text{before} & -- & -- & -- & -- & -- & 27.6±0.1 \\ \text{1st} & $2.3 \times 10^5$ & 10 & $1.4 \times 10^8$ & $2.4 \times 10^8$ & 21 & 28.0±0.1 \\ \text{2nd} & $2.4 \times 10^5$ & 10 & $2.8 \times 10^8$ & $4.8 \times 10^8$ & 42 & 28.0±0.1 \\ \hline \end{tabular} |
| Sample #2 | \begin{tabular}{lcccc} \hline \text{irradiation} & $\phi_p$ (mm$^{-2}$s$^{-1}$) & $t$ (min.) & $\Phi_p$ (mm$^{-2}$) & $\Phi_{eq}$ (mm$^{-2}$) & $D$ (Gy) & $T$ (°C) \\ \hline \text{before} & -- & -- & -- & -- & -- & 27.6±0.1 \\ \text{1st} & $3.1 \times 10^4$ & 10 & $1.9 \times 10^7$ & $3.1 \times 10^7$ & 2.8 & 27.4±0.1 \\ \text{2nd} & $3.0 \times 10^4$ & 10 & $3.7 \times 10^7$ & $6.2 \times 10^7$ & 5.5 & 27.2±0.1 \\ \text{3rd} & $2.8 \times 10^4$ & 10 & $5.3 \times 10^7$ & $9.1 \times 10^7$ & 8.0 & 27.0±0.1 \\ \hline \end{tabular} |

2.4 Experimental procedure

First, we checked basic performance of the MPPC samples, such as gain, current-voltage ($I$-$V$) curve and noise rate, before the proton irradiation. This performance is to be compared with that after the irradiation. For the next step, one of the MPPC samples with normal operating voltage was irradiated with the proton beam. After the irradiation, in order to check recovery effects on radiation damage, the leakage current was monitored for about 1 hour under the condition without the beam. Then we measured the basic performances after the irradiation. This process was repeated several times.

We used two different beam intensities for the irradiation. One of the MPPC samples, Sample #1, was irradiated with a proton beam flux ($\phi_p$) of $2.3 \times$
The second MPPC, Sample #2, was irradiated with a lower flux, $\phi_p = 3.0 \times 10^4$ p/mm$^2$/s. One irradiation took 10 minutes for both the samples. For Sample #1, we repeated the proton irradiation twice, thereby estimated the proton fluence ($\Phi_p$) is $2.8 \times 10^8$ p/mm$^2$ in total. On the other hand, three times irradiation were made for Sample #2, thus the total fluence is $5.3 \times 10^7$ p/mm$^2$. The beam flux and total fluence in each irradiation are summarized in Table 1.

Instead of the proton fluence $\Phi_p$, it may be useful to represent a total fluence with 1 MeV neutron equivalent fluence ($\Phi_{eq}$). This quantity is commonly used in order to evaluate damage levels caused by different radiation sources and different energies based on the NIEL scaling hypothesis, which is the assumption that damage level in silicon bulk is related to the cross-section of processes with Non-Ionization Energy Loss [11]. The $\Phi_{eq}$ can be obtained with a hardness factor $\kappa$ as $\Phi_{eq} = \kappa \cdot \Phi_p$, where the value of the $\kappa$ for 53.3 MeV protons is about 1.7 obtained from the displacement damage function described in the reference [11]. Hence, we estimated the $\Phi_{eq}$ for Sample #1 to be $4.8 \times 10^8$ n/mm$^2$, and $9.1 \times 10^7$ n/mm$^2$ for Sample #2, respectively.

The absorption dose ($D$) due to the proton irradiation can be estimated from the proton fluence $\Phi_p$ by taking the mass stopping power of 53.3 MeV protons in silicon, 9.38 MeV·cm$^2$/g, into account. The estimated dose rates for both Sample #1 and Sample #2 were 130 Gy/h and 16 Gy/h, respectively. Thus, the total radiation dose was 42 Gy for Sample #1, and 8.0 Gy for Sample #2.

The temperature in the experimental area was controlled to be stable. During the experiment the temperature near the MPPC samples ($T$) was in the range 27.0 - 28.0 °C. Note that we estimated the maximum temperature increment caused by the proton beam in the MPPC volume to be 0.03 °C in the case of 10 minutes irradiation, which was calculated from the beam energy deposition in the MPPC and the specific heats of the device materials. Thus, we concluded that the temperature increase due to the irradiation was negligible compared with the temperature fluctuation in the experimental area. The temperatures in each measurement are also summarized in Table 1.

### Result

#### 3.1 Variations of the leakage current

Fig. 4(a) shows the variations of the leakage current of Sample #1 during the experiment. The measurement of the leakage current was started 10 minutes before the first irradiation, where the leakage current was about 0.05 $\mu$A at
Fig. 4. Variations of the leakage current for (a) Sample #1 and (b) Sample #2. The fixed operating voltages, 69.75 V for Sample #1 and 69.58 V for Sample #2, were applied to the samples with the voltage source. The proton irradiation was performed during the times represented as the hatched regions. In the times shown as the shaded regions, no data was recorded since measurements for gains, current-voltage ($I$-$V$) curves and noise rates, were carried out, taking typically 1-2 hours. Note that the actual voltages applied to the samples changed during the measurement because of a voltage drop at the resistors in the filter circuit (see text).

The operating voltage. We irradiated the sample with the proton beam for 10 minutes (see the leftmost hatched region in the figure). During the first irradiation, the current almost linearly increased with time due to radiation damage. Step-like changes at the beginning and ending of the irradiation, \(\sim 1.0 \ \mu\text{A}\), would be caused by free carriers generated due to the ionizing processes of the beam protons traversing in silicon. After the beam stops, the leakage current gradually decreased with time. This indicates recovery phenomenon from the radiation damage, although the recovery was not completed to the original condition within hours. The second irradiation was performed after the measurements of pulse-height distributions, $I$-$V$ curves and dark noise. Again the leakage current increased linearly with time, and a similar recovery effect is also seen in the second irradiation. Note that we applied the fixed operating voltage with the voltage source during the measurement; thus, the increase of the leakage current due to the radiation damage caused a gain reduction due to a voltage drop at the resistors $R_1$ and $R_2$ in the filter circuit (see Fig. 1). Such effect should be corrected for performance studies and this will be discussed later. The result of leakage-current variations for Sample #2, which was irradiated with a lower beam flux, is shown in Fig. 4(b). Although the increasing rate during the irradiation was low compared to that for the Sample #1 irradiation because of the lower beam flux, we have found a similar tendency as in the Sample #1 irradiation, that is, the linear increase of the leakage current and the recovery effect. The offset of the leakage current due to the ionizing processes of protons in silicon was about 0.3 $\mu\text{A}$ in this case.
As we mentioned, the effect of the voltage drop at the resistors $R_1$ and $R_2$ should be corrected. Since the leakage current ($I_{\text{leak}}$) flows the resistors arranged in series, the voltage drop is expressed as $I_{\text{leak}}(R_1 + R_2)$. Hence, actual reverse voltages of the MPPC ($V_{\text{MPPC}}$) is given by

$$V_{\text{MPPC}} = V_{\text{source}} - I_{\text{leak}}(R_1 + R_2),$$

(1)

where $V_{\text{source}}$ denotes the voltage applied by the voltage source. In the following part of this paper, we will express reverse voltages as $V_{\text{MPPC}}$ in place of $V_{\text{source}}$.

Fig. 5 shows the leakage current of both samples under the operating voltages ($V_{\text{MPPC}} = 69.75$ V for Sample #1 and $V_{\text{MPPC}} = 69.58$ V for Sample #2) as a function of the 1 MeV neutron equivalent fluence $\Phi_{\text{eq}}$, where the data has been taken after 1 hour from each end of irradiation. From these plots we have found that the leakage current increases linearly with the fluence. The rates of increase for the both samples are almost the same although the beam flux for Sample #1 is about eight times higher than for Sample #2. The straight line in the figure shows the linear function fitted to the data of Sample #1, which gives us the relation between the leakage current and the irradiation dose,

$$I_{\text{leak}}[\mu\text{A}] = 3.2 \times 10^{-8} \cdot \Phi_{\text{eq}}[\text{n/mm}^2].$$

(2)

This information would be useful to compare radiation hardness of other PPD devices with that of MPPC.

The $I$-$V$ curves were measured before and after the irradiation without the
LED light. The results are shown in Fig. 6. The symbols $V_{bd}$ in the figure denote the breakdown voltages measured before the irradiation; they are 68.57±0.01 V for Sample #1 and 68.34±0.01 V for Sample #2 at 27.6 °C. From these plots, the leakage currents have rapidly increased with reverse voltages after the irradiation in comparison with that before the irradiation. This tendency is more significant for higher doses.

### 3.2 Photon-counting capability

Next we discuss the effects on photon-counting capability, which is one of the features of MPPCs. The pulse-height distributions of the irradiated samples were measured by flushing the blue LED. Fig. 7 shows the distributions for
different irradiated doses. Before the irradiation the distributions for both samples show the structure with clear discrete peaks, which includes a pedestal peak, a single photon peak and so on, and those peaks are well separated each other. In contrast, the situation changes after the irradiation. First, the position of the pedestal peak shifts slightly toward lower channels because of the baseline shift coming from high dark counting rates. Note that the dark counting rate of MPPC increases after the irradiation, which is the main reason for the increase of the leakage current. This is because production of the lattice defects due to radiation damage gives higher probability of thermal carrier generation and delayed pulse coming from trapped carriers in the defects (afterpulsing). Actually, the measurement of the counting rates without the LED showed that the counting rates drastically increased from 270 kHz to 6.8 MHz after the 2.8 Gy irradiation (Although we could not measure the counting rates for higher doses due to limitation of the scaler performance, the counting rates would be expected to be more than 10 MHz). Another thing is that the distributions are contaminated with accidental backgrounds coming from dark noise and afterpulsing as the dose increases. This effect smears the separation of the peaks in the pulse-height distributions as seen in Fig. 7 since some of noise pulses are not integrated over the entire charge. Gain uniformity among the individual APD pixels may also be deteriorated by radiation damage because if the extent of the damage differs among the pixels, average leakage current through each quenching resistor varies. This results in gain variations among the pixels because of the different voltage drops at the quenching resistors, and thus the peaks could be broadened. For these reasons, the peak structure has completely disappeared for the distributions of more than 21 Gy in the case of 55 ns gate width. This means that the capability of the photon-counting by measuring pulse-height spectra was lost due to the radiation damage.

### 3.3 Gain

The gain variations were evaluated before and after the irradiation. We define the gain of the MPPCs as the ratio of the collected charge \( Q \) and the electron charge \( e \), \( Q/e \). The reason is that a single carrier generated by an incident photon is multiplied due to Geiger discharge, and then the collected charge in a single pixel is extracted as a output signal. In the data analysis the charge \( Q \) was estimated from the gain of the amplifier, 56.4, and the charge corresponding to single-photon signals. The charge of single-photon signals was obtained by the fit to the pulse-height distributions with a multi-Gaussian function.

Fig. 8 shows the gains as a function of reverse voltages for different radiation doses. Note that only the gains for Sample #2 was obtained since we observed
Fig. 7. Pulse height distributions measured with a blue LED for different irradiated doses. The operating voltages were applied to both of the samples. The position of peaks located at the lowest level in each histogram, except for the 21 Gy and 42 Gy spectra, correspond to the pedestals.

no peak structure in the distributions of Sample #1 after the irradiation. The gain before the irradiation shows a linear dependence with the reverse voltage \( (V) \) since the gain of a single pixel \( (G) \) increases with \( V \) as

\[
G = Q/e = C(V - V_{bd})/e \tag{3}
\]

where \( C \) denotes the average capacitance of a single pixel, and \( V_{bd} \) is the breakdown voltage. The capacitance \( C \) was estimated to be 0.096 pF from the result of a linear fitting, which is shown as the dotted line in Fig. 8. After the irradiation, the data points slightly deviate from a linear relation at higher voltages, where the simple fitting with a multi-Gaussian function may be inadequate because of significant accidental backgrounds coming from dark noise and afterpulsing. However, at the operating voltage where those backgrounds would be less affected, gain change is not significant (within 3% level). The result shows that the effect to the gain due to radiation damage is small at least up to 8.0 Gy irradiation. Note that there is no data point at higher voltages after the irradiation because of the disappearance of the peak structure in the pulse-height distributions.
Fig. 8. Gains of Sample #2 as a function of reverse voltage for different radiation doses. Dotted line shows the function (3) fitted to the data before the irradiation. The symbol \( V_{op} \) denotes the operating voltage.

Fig. 9. Setup for the measurement of the pulse-height resolution. Collimated LED light was illuminated one of the MPPC samples, which was mounted on a movable X-Y stage. The filters on the collimator were used to control the light intensity. Absolute number of photons entering onto the active area of the samples was obtained with a photo-multiplier tube (PMT) prior to the measurement. Note that the size is not to scale.

### 3.4 Pulse-height resolution after more than a year from the irradiation

The pulse-height resolution of photo-sensors is one of the most important properties in the case of measurements for the incident-particle’s energy. In order to check whether the radiation damage could affect to the pulse-height resolution of the MPPCs, we measured the pulse-height distributions of the
irradiated samples by illuminating with a LED light (∼200 photons/mm²). Spectral changes due to the damage can be found by comparing to the distribution taken with a non-irradiated reference sample. This measurement has been performed after 430 days from the irradiation experiment. The irradiated samples, which have been kept in a desiccator at room temperature, have partially recovered from the radiation damage because the leakage current at the operating voltage decreased from 12.0 µA to 7.1 µA for Sample #1, and from 3.3 µA to 1.6 µA for Sample #2, respectively.

Fig. 9 shows the setup for the measurement. The entire setup was placed in a thermostat oven to ensure temperature stability (25 °C) and light-tightness. The LED light was collimated with a collimator having the hole size of 3 mmφ and illuminated one of the MPPC samples. We aligned the sample with the center of the light spot by using a X-Y stage moving with an accuracy of 5 µm. The intensity of incident light was controlled with filters placed on the collimator.

Prior to the measurement, we estimated the absolute number of the photons entering to the active area of the MPPC (N_ph) with a green-extended photomultiplier tube (PMT), Hamamatsu H3178-61. The entrance window of the PMT was masked with black slits having the area of 1.0×1.0 mm² so as to meet the requirement for the same active area of the MPPC. The quantum efficiency of the PMT at the wavelength of 470 nm, which corresponds to the peak wavelength of the LED, was measured to be 26.0 % by the manufacturer. Two different intensities of light, N_ph = 11.2 ± 0.2 photons/mm² and N_ph = 193 ± 4 photons/mm², were illuminated in the measurement.

The result is shown in Fig. 10, where pedestal-subtracted ADC distributions of the three samples (reference sample, Sample #2, and Sample #1) are presented for the different light intensities. In the low-intensity case, the peak structure in the distribution of the irradiated samples was smeared due to the radiation damage as discussed in the section 3.2, although more than a year have elapsed from the irradiation and the recovery effect in the leakage current was observed. In the high-intensity case, the distributions show a Gaussian shape having the mean values of about 1760 channels, where the repeatability of the mean-value measurement was evaluated to be about 2%. Thus, we found that there was no significant change in the mean value of the pulse height-distribution among the three samples, suggesting that the irradiated samples work well as a photo-sensor even after photon-counting capability was lost. In contrast, the relative width of the distribution slightly widened for Sample #1 whose irradiated dose was 42 Gy in total. The measured widths were 14.60 ± 0.03 % for the reference sample, 14.57 ± 0.03 % for Sample #2, and 17.37 ± 0.04 % for Sample #1, respectively, where the errors were estimated from Gaussian fittings. Assuming that the fluctuation caused by radiation damage contributed to the width in quadratic sum, the contribu-
Fig. 10. Pedestal subtracted ADC distributions for the reference sample (a), Sample #2 (b) and Sample #1 (c). Histograms in the left column show the distributions measured with low-intensity light (11.2 ± 0.2 photons/mm²), and in the right column the distributions obtained with high-intensity light (193 ± 4 photons/mm²) are presented. The mean values and the relative widths of the distributions obtained by Gaussian fittings are shown in the right figures, where the errors of the relative widths were estimated from the fittings.

tion was estimated to be about 9 %, where the effect of the broadened baseline fluctuation was negligible based on a comparison of the pedestal widths of the reference sample and Sample #1. In principal, the relative width, which arises because of fluctuations in the number of fired APD-pixels, is given by Poisson statistics. Thus, the difference of the relative width would be not due to the variability of individual devices, but given due to the radiation damage. Some details about the pulse-height resolution will be discussed later.
4 Discussions

The leakage current of the MPPC increased with total irradiated dose as shown in Fig. 5. This behavior can be interpreted as an increase of thermal excitations of carriers via intermediate states in the forbidden gap created due to radiation damage. Such effect is known to be categorized into bulk damage and surface damage, where the bulk damage is caused by defects in the Si bulk and the surface damage is created at the Si-SiO$_2$ interface. In the case of proton irradiation, both of them can contribute to the increase of the leakage current. In order to understand the mechanism of proton-induced damage, studies of neutron irradiation would be helpful since the surface damage does not contribute to neutron-induced radiation damage [12].

Photon-counting capability, which is one of the features of MPPCs, was gradually deteriorated with the irradiation dose and completely lost after 21 Gy irradiation due to baseline fluctuations and noise pileup as a result of increasing dark counting rates. This effect would be problematic for some applications in high-energy physics experiments. For example, when one uses the MPPC as a photon-counting device for a ring-imaging Cherenkov detector (RICH), which detects weak light generated from Aerogel radiators, the reconstruction of ring images becomes more difficult due to the increase of fake hits. This point should be carefully considered. On the other hand, for the detectors which is expected to yield more light ($\geq 10$ photo-electrons), such as scintillators with wavelength-shifting (WLS) fiber readout, the damage effect might be acceptable at least up to 8.0 Gy because no significant change was observed in the gain and the pulse-height distribution.

We have found an indication of the deterioration of the pulse-height resolution for the sample irradiated with 42 Gy. Although we have not understood the mechanism of the deterioration, there are two possible explanations: (1) change of gain uniformity among the individual pixels and (2) increase of afterpulsing. The afterpulsing effect would be expected to increase after the irradiation because of radiation damage. Hence, increase of afterpulsing could affect to the pulse height distributions. The deterioration of the pulse-height resolution is an issue to be concerned in the case of energy-measurement applications.

5 Summary

The effects on MPPCs caused by proton irradiation has been discussed from a view point of applications in high radiation environment. In order to investigate the effects of radiation damage, we have performed an irradiation experiment by using a 53.3 MeV proton beam. The linear increase of the
leakage current has been observed due to radiation damage during the irradiation. We found recovery effects from the radiation damage, however it has not completed even after a year from the irradiation. The result of the gain measurement shows no significant change in the gain at least up to 8.0 Gy ($9.1 \times 10^7$ n/mm$^2$ in $\Phi_{eq}$). From the measurement of pulse height distribution, we found the photon-counting capability was completely lost due to baseline fluctuations and noise pile-up after 21 Gy irradiation ($2.4 \times 10^8$ n/mm$^2$ in $\Phi_{eq}$). This effect might be problematic in the case of applications for low light-yield detectors such as RICH counter. We found that the pulse-height resolution was slightly deteriorated after 42 Gy irradiation ($4.8 \times 10^8$ n/mm$^2$ in $\Phi_{eq}$), where the measurement has been performed after 430 days from the irradiation experiment with slightly intense LED light ($\sim 200$ photons/mm$^2$). This effect should be considered in the case of energy-measurement applications.

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