Study of radiation damage caused by 23MeV protons on Multi-Pixel Photon Counter (MPPC)

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Abstract

The automatic gain control system (AGC) is designed to continuously monitor and automatically control the gain of the phoswich detectors of the Hard X-ray Modulation Telescope (HXMT). It consists of a ^{241}Am radioactive source distributed within a plastic scintillator (BC408) viewed by Multi-Pixel Photon Counter (MPPC). To verify the feasibility of application in space experiments, four MPPCs (S10362-33-050C) from Hamamatsu were irradiated using a beam of 23 MeV protons with flux 1.0×10^{8}pcm^{-2}, 2.0×10^{8}pcm^{-2}, 4.0×10^{8}pcm^{-2} and 1.0×10^{10}pcm^{-2}. The leakage current of irradiated MPPC samples is found to increase linearly with total dose due to radiation damage. The device has completely lost its photon-counting capability when irradiated up to 13.6Gy. The pulse-height resolution has deteriorated hardly after irradiation and couldn't work with more than 450Gy, where the measured sample has been illuminated with a few hundred photons by the ^{241}Am radioactive source.

1. Introduction

The Hard X-ray Modulation Telescope (HXMT) is an X-ray satellite working in 1-250 keV band, consisting of three collimated instruments: the High Energy X-ray telescope (HE, 20-250 keV), the Medium Energy X-ray telescope (ME, 5-30keV) and the Low Energy X-ray telescope (LE, 1-15keV) [1,2]. HXMT will perform an all-sky scan survey with high sensitivity and high angular resolution in 20-250keV by using the Direct Demodulation (DD) image reconstruction method [3,4]. It will also carry out pointing observations to investigate the temporal and spectral properties of compact objects such as black hole and neutron star binaries.

HE is composed of 18 modules. Each module has a collimator, a phoswich scintillation detector, and readout electronics. The gain of the detectors are continuously monitored and automatically controlled by the automatic gain control system (AGC). The AGC placed in front of the detection plane of phoswich detector consists of a ^{241}Am radioactive source distributed within a plastic scintillator (BC408) viewed by a MPPCs (Hamamatsu S10362-33-050C).

The Multi-Pixel Photon Counter (MPPC), developed by Hamamatsu, consists of an array of Avalanche Photodiodes (APDs) working in the Geiger mode which biased above the breakdown voltage (V_{BD}) with quenching resistor in serial and connected in parallel. Their insensitivity to magnetic field and low operating voltage (<100 V) and sensitivity to a small number of photo-electrons make them good light detectors for the plastic scintillators of AGC. AGC will be operated in harsh radiation environments such as cosmic protons, electrons which produce damage in silicon detectors. As shown by many investigators, parameters of MPPC such as leakage current, dark count rate, gain, and photon detection efficiency may change during irradiation [5-8]. How these parameters change during irradiation when operating in orbit becomes one of the most important questions for the application of the MPPC on board the HXMT satellite. The total dose for one HXMT lifetime in the proximity of the AGC photo-detector is expected to be approximately 3.4 Gy. To verify the feasibility of application in space experiments, four MPPCs (S10362-33-050C) with 3×3 mm^{2} active area from Hamamatsu were irradiated using a beam of 23MeV protons.

2. Experiment setup

The radiation studies were carried out at China Institute of Atomic Energy (CIAE) using the HI-I3 accelerator. The fluence delivered on target was measured directly during irradiation using CsI detector which calibrated by an Au-Si surface barrier detector. The four MPPCs were mounted on printed circuit board as an 2×2 array in a vacuum dark box. The MPPCs were biased at 72V during radiation with a Keithley 6487 picometer. The current delivered to the MPPCs were monitored during irradiation.

The performances of the MPPC samples were checked before irradiation, such as current-voltage (I-V) curve and dark noise pulse height spectrum and the alpha spectrum of a ^{241}Am radioactive source distributed within the plastic scintillator. These performances are to be compared with that after irradiation. And the leakage current was monitored from the moment that the beam was switched on to about 10 minutes after the proton beam off. The proton beam flux irradiated (φ_p) was 4.0×10^{4}pcm^{-2}s^{-1} for Sample 4847, 1.0×10^{5}pcm^{-2}s^{-1} for Sample 4848 and 4849 and 1.0×10^{7}pcm^{-2}s^{-1} for Sample 4851. For Sample 4849, it was irradiated twice, thereby the estimated proton fluence (Ψ_p) is 4.0×10^{8}pcm^{-2} in total. The beam flux and total fluence for each sample are summarized in

Table I.
Table III Summary of proton irradiation for MPPCs

Irradiation	φ_p (cm^{-2}s^{-1})	Ψ_p(cm^{-2})	D(Gy)
Sample 4847	4.0×10^4	1.0×10^8	4.5
Sample 4848	1.0×10^5	2.0×10^8	9.1
Sample 4849	1.0×10^5	3.0×10^8	13.6
Smaple 4851	1.0×10^7	1.0×10^{10}	450

The total dose (D) due to the proton irradiation can be estimated from the proton fluence Ψ_p by taking the stopping power of 23 MeV protons in silicon into account. The estimated total dose was 4.5 Gy for Sample 4847, 9.1Gy for Sample 4848, 13.6Gy for Sample 4849 and 450Gy for Sample 4851 respectively.

3. Result

3.1Variations of the leakage current

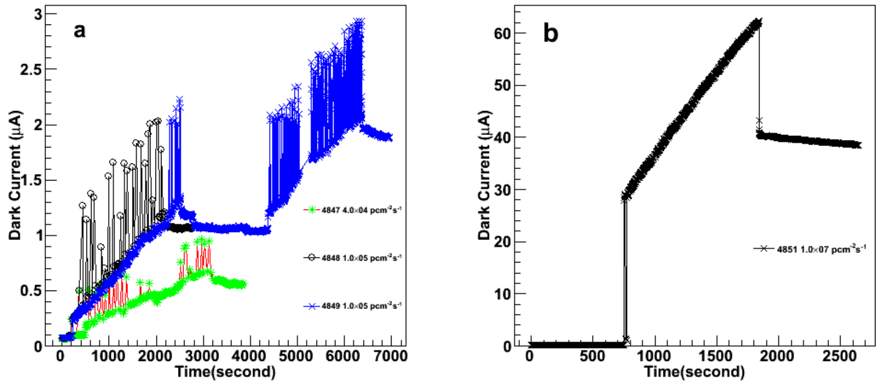

Fig. 1 Variations of the leak current for the four Samples. The fixed operating voltages, 72.0V for the samples, were applied to the samples with the voltage source during irradiation. (a) Sample 4847, 4848, 4849 (b) Sample 4851

Fig. 1 shows the variations of leakage current of Sample 4847, 4848, 4849 and 4851. The measurement of the leakage current was started before the irradiation. The current sometimes increased largely and then decreased in a short time during radiation as shown in Fig.1 (a). This is caused by the beam spot uniformity which worked in scan mode with average intensities uniform in a long time. To avoid this, the Sample 4851 was irradiated in the spread mode which the beam was pointed to Sample 4851 with 4.5×4.5cm^2 beam spot and was located in the center of the beam spot. The step-like changes during the irradiation as in the case of Sample 4848 disappeared as shown in Fig.1 (b). Step-like changes of leakage current at the beginning and ending of the irradiation would be caused by free carriers generated due to the ionizing processes of the beam protons traversing in silicon. And the offset change of leakage current of Sample 4851 is about 30μA. Considering the uniformity of the beam, the leakage current almost linearly increased with time due to radiation damage. The increasing rate of Sample 4848 and 4849 during irradiation was the same as the same irradiation intensity. Compared with the Sample 4848, the increasing rate of Sample 4851 was high because of higher irradiation intensity. After the beam stopped, the leakage current gradually decreased with time. This indicates recovery phenomenon from the radiation damage, although the recovery was not completed to the original conditions.

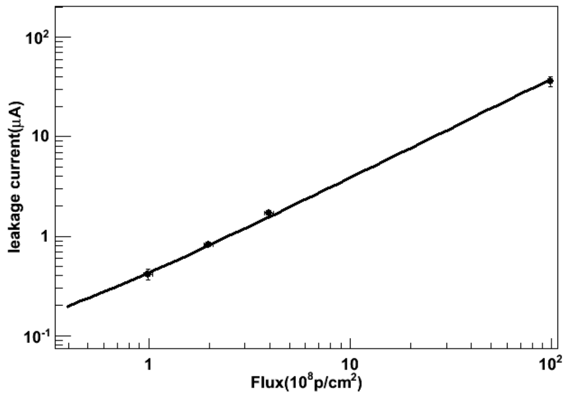

Fig. 2 Plots of the leakage current under the operating voltage measured for 5 days after irradiation as a function of 23MeV proton fluence, the black line shows the linear

Five days after the irradiation, the leakage current of the four MPPCs at operating voltage was measured and compared with the leakage current before the irradiation. Fig. 2 shows the increased leakage current of the four samples as a function of the 23MeV proton fluence Ψ_p. The leakage current increases linearly with the fluence as shown in Fig. 2. The black line in the figure shows the linear function fitted to the data of four samples, which indicates the relation between the leakage current and the irradiation fluence with a slop parameter a=0.38×10^{-8}[μA /pcm^{-2}].

The I-V curves were measured before and after the irradiation. The results are shown in Fig. 3. 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 dose. As shown in these plots, the breakdown voltage (V_{BD}) of the four samples keeps unchanged after irradiation.

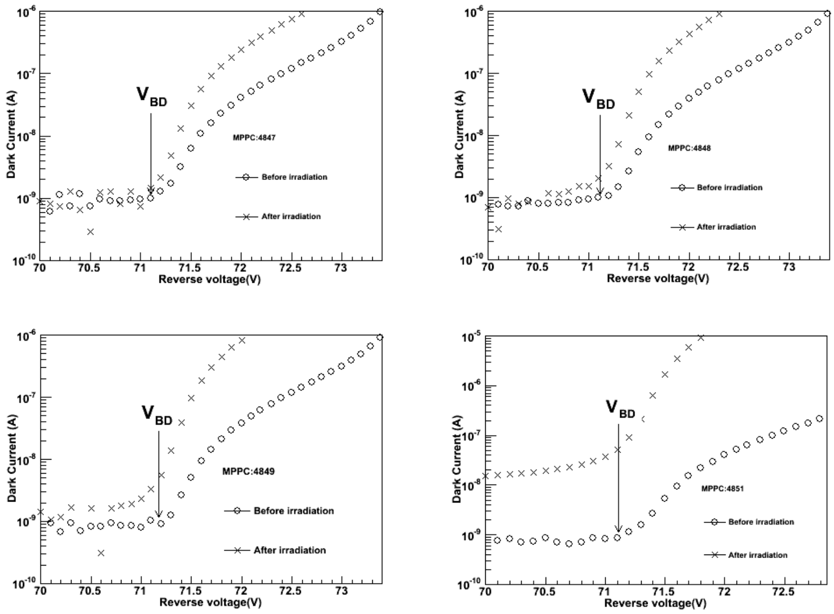

Fig. 3 I-V curves of samples for different radiation doses. The symbol V_{BD} denotes the breakdown voltage of each sample measured before the irradiation.

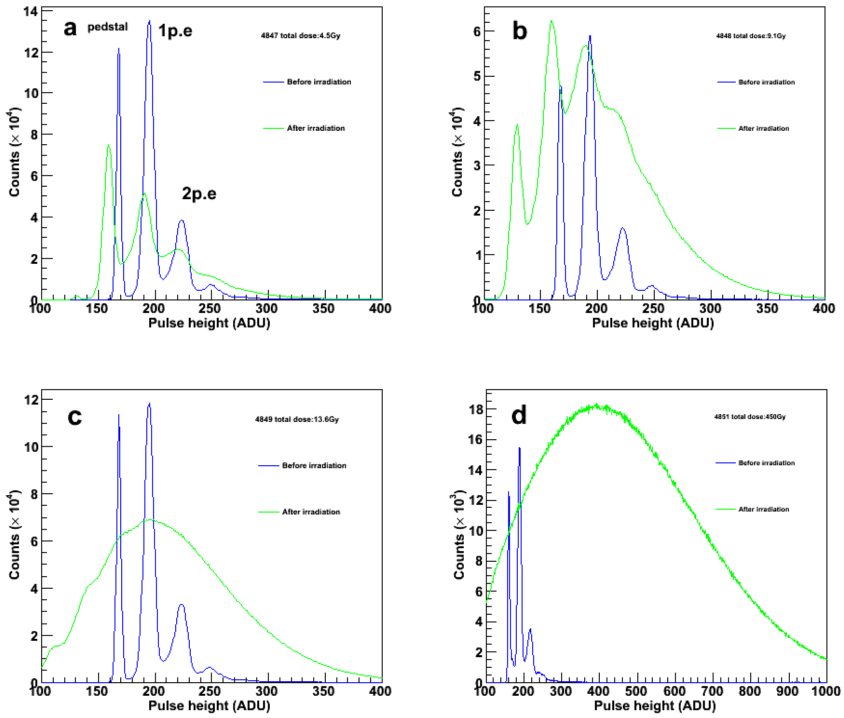

Fig. 4 Noise distributions for four MPPCs with different total dose before and after irradiation, integrated with the same time. (a) 4847 with 4.5Gy (b) 4848 with 9.1Gy (c) 4849 with 13.6Gy (d) 4851 with 450Gy

3.2 Pulse height resolution

The pulse-height resolution of MPPC as photo-detector is one of the most important properties in the case of measuring the incident alpha particles of AGC. In order to check whether the radiation damage could affect the pulse-height distributions of the MPPC, we measured the pulse-height distributions of the irradiated samples in a dark box without light sources. Fig. 4 shows the distributions for different irradiated dose. Before the irradiation the distributions for different samples all show the structure with clear discrete peaks, which includes a pedestal peak, single equivalent photon peaks, and those peaks are well separated with each other. The position of the pedestal peak shifts slightly toward lower channels because of the baseline shift coming from high dark counting rates after irradiation. The dark counting rate of MPPC increases after the irradiation, which is the main reason for the increase in the leakage current. This is because production of the lattice defects duo to radiation damage with higher probability of thermal carrier generation [9]. As the radiation damage on individual microcell pixels is different, the gain uniformity of MPPCs deteriorated after irradiation. The single equivalent photon electron peaks of dark noise pulse-height distribution would be broadened result from this uniformity [9], as shown in Fig.4. For these reasons, the discrete peak structure has completely disappeared for the total dose of more than 13.6 Gy. This means that the MPPC has completely lost its capacity of the photon-counting by measuring pulse-height spectra due to the radiation damage.

And then Another pulse-height distribution of the 4849 and 4851 were taken by illuminating them by the ^{241}Am radioactive source dotted in the plastic scintillator, as shown in Fig. 5. Compared to that of the Sample 4849 and Sample 4851 before irradiation, it could tell whether the MPPCs should also be able to detect the alpha particles as a photo-detector of the AGC when the MPPC lost its capacity of single photon-counting. It was found that the Sample 4851 with 450Gy could not detect the alpha particles by measuring pulse-height spectra while the Sample 4849 could still work with high dark count rate. In the pulse-height distribution of Sample 4851, there was only one peak including the dark noise and the alpha signals, shown in Fig. 5 (b). And the dark count rate is much higher than that before irradiation. This would deteriorate the performance of the AGC by causing much more dead time of the associated electronics.

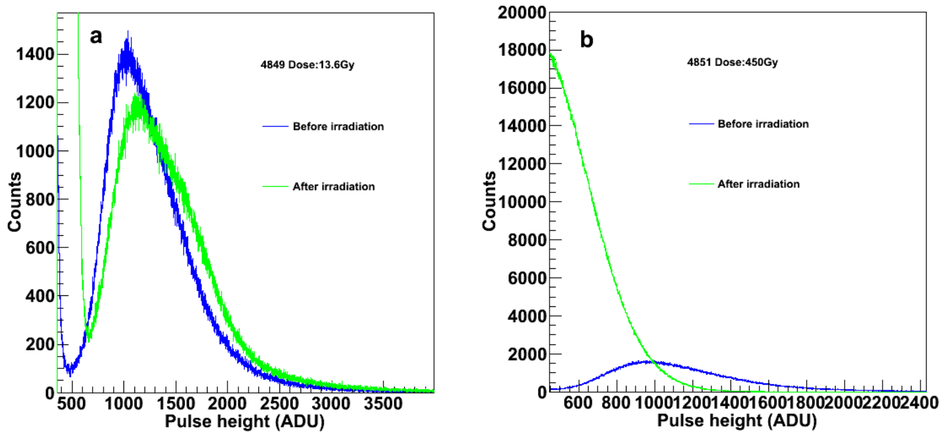

Fig. 5 Alpha pulse spectrums which integrated in the same time before and after irradiation (a) 4849 13.6Gy (b) 4851 450Gy

4. Summary

The effects on the performance of the MPPCs mainly leakage current and pulse-height resolution, caused by proton irradiation, has been discussed as a photo-detector in space environment. The four MPPC samples were irradiated by 23MeV protons with different fluence to investigate the effects of radiation damage. It is found that the leakage current increase linearly with time during irradiation. And the increment in leakage current is increase with the total beam fluence. From the measurement of pulse-height distribution in a dark box without any light sources, it indicates that the MPPCs completely lost its capacity of single photon-counting after more than 13.6Gy absorption dose. But the MPPCs as a photo-detector to detect the alpha particles from the ^{241}Am radioactive source by measuring pulse-height spectra still works, until irradiated by more than 13.6Gy.

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