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

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ABSTRACT

A automatic gain control system (AGC) is designed to continuously monitor and automatically control the gain of the phoswich detectors onboard the Hard X-ray Modulation Telescope (HXMT). It consists of a Am^{241} radioactive source and a photo-detector. The Am^{241} radioactive source is tagged within a plastic scintillator (BC440M). The scintillating photons produced by the decayed alpha particles from the radioactive source is readout by the photo-detector. The Multi-Pixel Photon Counter (MPPC) produced by Hamamatsu is used as the photo-detector for AGC. To verify the feasibility of its application in space environment, four MPPCs (S10362-33-050C) were irradiated by a beam of 23 MeV protons. The integrated proton fluence that exposed to the four MPPC samples are 1.0×10^8 p cm^{-2}, 2.0×10^8 p cm^{-2}, 4.0×10^8 p cm^{-2} and 1.0×10^{10} p cm^{-2} respectively. It is found that the increment leakage current of the MPPC samples caused by irradiation damage increase linearly with the integrated fluence. The pulse-height resolution of the MPPC has deteriorated hardly after irradiation. When irradiated up to 1.1×10^9 cm^{-2} 1 MeV equivalent neutrons, the MPPC completely lost its photon-counting capability but could still work as a photo-detector for AGC. The MPPC fails as a photo-detector for the AGC when the irradiated 1 MeV neutron equivalent fluences is up to 2.7×10^{10} cm^{-2}.

1. Introduction

The Silicon Photomultiplier (SiPM) becomes a promising device for applications in medical imaging, high energy particle physics and particle astrophysics with high Photon Detection Efficiency (PDE), high gain (up to 10^6), low cost, low operating voltage (<100 V), excellent timing resolution (~ 120 ps) and insensitivity to magnetic field [1–3]. It consists of an array of Avalanche Photodiodes (APDs) working in the Geiger mode. The APDs are biased above the breakdown voltage (V_{BD}) with quenching resistor in serial and connected in parallel. The bias voltage (V_{bias}) above the breakdown voltage is called over-voltage ($\Delta V = V_{bias} - V_{BD}$).

The SiPM is also referred as SSPM, AMPD, MPPC, MRSAPD. Their insensitivity to magnetic field, low operating voltage (< 100 V), compact size and sensitivity to a small number of photo-electrons make them good light detectors for the plastic scintillators in space telescopes. The Chinese space telescope, the Hard X-ray Modulation Telescope (HXMT) is an X-ray satellite working in the 1–250 keV band. It will perform an all-sky scan survey with high sensitivity and high angular resolution by using the Direct Demodulation (DD) image reconstruction method [4–7]. A automatic gain control system (AGC) for continuously monitoring and controlling the gain of the NaI/CsI phoswich detectors on board the HXMT is under construction. The AGC consists of a Am^{241} radioactive source and a photon-detector. The radioactive source is tagged within a plastic scintillator (BC448M). The decayed alpha particles from the Am^{241} radioactive source produce scintillating photons when deposit its total energy in the plastic scintillator. And the MPPC (one kind of SiPM produced by Hamamatsu) is used as the photon-detector to read out the scintillating photons.

The AGC will be operated in harsh radiation environments with cosmic charged particles, including high energy protons and electrons [8]. These charged particles will produce damage in MPPC especially displacement damage. As shown by many investigators, this displacement damage will effect the performance of MPPC, such as leakage current and dark count rate [9–18]. Deterioration of the MPPC performance caused by the radiation hardness when operating in orbit becomes one of the most important questions for the application of MPPC on board the HXMT

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satellite. The 1 MeV neutron equivalent fluence in the proximity of the AGC is expected to be approximately $3.2\times10^{6}\ cm^{-2}$ for one HXMT lifetime. To verify the feasibility of its application onboard HXMT, the displacement damage for the MPPC was studied by irradiating four MPPC samples (S10362-33-050C) with a 23 MeV proton beam. The irradiated MPPC samples are produced by Hamamatsu with an $3\times3\ mm^2$ active area and 3600 pixels.

2. Experimental setup

The radiation studies were carried out at China Institute of Atomic Energy (CIAE) by using the HI-I3 accelerator. The 23 MeV protons from the HI-I3 accelerator were exposed to the MPPC samples. A CsI detector was used to measure the proton fluence that delivered on the MPPC. The CsI detector was calibrated by an Au-Si surface barrier detector before the experiment. Four pieces of MPPC were mounted on a printed circuit board as an 2×2 array in a vacuum dark box. These samples are referred as "Sample 4847", "Sample 4848", "Sample 4849" and "Sample 4851". The biased voltage at 25 °C when works with a gain of 7.5×10^{5}, is 72.32 V for Sample 4847, 72.33 V for Sample 4848, 72.32 V for Sample 4849 and 72.35 V for Sample 4851. The four pieces of MPPC were biased at 72.0 V during irradiation. A Keithley 6487 picoameter/voltage source was used as the bias voltage source for the MPPC samples. And the dark current that flew through the MPPC samples during irradiation were simultaneously monitored by the Keithley 6487.

The reverse current–voltage (*I–V*) curve and dark noise pulse height spectrum of the MPPC samples were measured before and after irradiation to study the irradiation hardness. The MPPC is used as a photo-detector for AGC to detect the alpha particles from the dotted Am^{241} radioactive source. So a qualified model of the radioactive source was used as the photon source to study the pulse height distribution of the MPPC. The pulse height distribution for the dotted Am^{241} radioactive source was measured before and after irradiation for comparison. The leakage current of the MPPC samples were monitored during irradiation. The irradiated differential proton beam flux (ϕ_p) and total integrated fluence (Φ_p) for each sample are summarized in Table 1.

The displacement damage caused by different charged particles to the semi-conductor is quite different. In order to study the displacement damage produced by different charged particles, the irradiated particles flux will be translated into 1 MeV neutron equivalent fluence (Φ_{eq}). Based on the Non Ionizing Energy Loss (NIEL) scaling hypothesis, the Φ_{eq} can be obtained with a hardness factor κ as $\Phi_{eq}=\kappa\cdot\Phi_p$. The value of parameter κ for 23 MeV protons is about 2.7, which is obtained from the displacement damage function described in [19]. The AGC is to work in space for more than 4 years, and irradiated by the comic rays mainly protons and electrons. The calculated differential spectral distribution for the proton and electron in the proximity of AGC are shown in the left panel of Fig. 1. The equivalent fluence of 1 MeV neutron is obtained by integrating NIEL(E) with the differential fluence $d\Phi/dE$, as shown in the right panel of Fig. 1. Finally, the 1 MeV neutron equivalent fluence during the flight of HXMT for MPPC is $3.2\times10^{6}\ cm^{-2}$.

The total dose (D) due to the proton irradiation can be estimated from the proton fluence Φ_p by taking the stopping power into account. The stopping power of the 23 MeV protons in the depleted region of MPPC is 44.5 MeV/cm. The estimated total dose for the four MPPC samples are shown in Table 1.

Table 1
Summary of proton irradiation for the four MPPC samples.

Sample	ϕ_p ($cm^{-2}\cdot s^{-1}$)	Φ_p (cm^{-2})	Φ_{eq} (1 MeV)	D(Gy)
4847	4×10^{4}	1×10^{8}	2.7×10^{8}	0.31
4848	1×10^{5}	2×10^{8}	5.4×10^{8}	0.62
4849	1×10^{5}	4×10^{8}	1.1×10^{9}	1.2
4851	1×10^{7}	1×10^{10}	2.7×10^{10}	31

3. Result

3.1. Variations of the leakage current

Fig. 2 shows the variations of leakage current for the four samples as functions of time during irradiation. From Fig. 2, it is found that the leakage current of the sample 4847 increased a large amount and then decreased in a short time at some moment during irradiation. This step-like change of leakage current were also observed when irradiating the sample 4848 and 4849. This indicates that the proton beam which exposed to the MPPC sample was nonuniform in a short time scale. The proton beam was working in a scan mode when exposed to the sample 4847,4848 and 4849. The sudden increase and decrease of the leakage current was caused by the proton beam spot scanned on/off the MPPC. When the beam spot was scanning onto the MPPC, the leakage current increased immediately. And then the leakage current decreased once the beam spot scanning off the MPPC. While the differential beam flux in average is uniform as the leakage was gradually increase during irradiation. To avoid the step-like change of the leakage current, the Sample 4851 was irradiated in the spread mode. In the spread mode, the proton beam was pointed directly to the center of Sample 4851 with a 4.5 cm × 4.5 cm beam spot size. As a result, the step-like change of leakage current during the irradiation disappeared, just as shown in the right panel of Fig. 2.

The step-like changes of leakage current were also observed when the proton beam was switched on/off. This is due to the free carriers generated by the ionizing processes when the incident beam protons traverse in silicon of MPPC. Taking the uniformity of the beam into account, the leakage current gradually increased with time due to radiation damage produced by the proton beam. The sample 4948 and 4849 were irradiated with the same differential proton beam flux. As a result, it can be found that the leakage current increasing rate of these two samples equal with each other, just as shown in Fig. 2. Compared with the sample 4848 and 4849, the increasing rate of Sample 4851 was higher because of higher irradiated differential beam flux. After the proton beam switched off, the leakage current gradually decreased with time. This indicates the recovery phenomenon from the radiation damage. And the leakage current could not recover to the original conditions after irradiation.

The leakage current at operating voltage for the four MPPCs were measured before and after irradiation. In order to study the annealing effect, the leakage current were measured with four different annealing time (one day, three days, four days and 18 months). The measured leakage current after irradiation were subtracted by the leakage current measured before irradiation to get the increased leakage current ΔI. Fig. 3 shows the measured leakage current increment with different irradiation fluences. The increase in the leakage current ΔI is due to defects produced by the irradiated proton beams and can be expressed as [11]

$$\Delta I=\alpha(\Delta V)\cdot\Phi_p=\beta\cdot G(\Delta V)\cdot\Phi_p \tag{1}$$

where $\alpha(\Delta V)=\beta\cdot G(\Delta V)$ is the damage parameter, $G(\Delta V)$ is the gain of MPPC, and Φ_p is the integrated proton beam flux.