Proton Radiation Damage Experiment for X-Ray SOI Pixel Detectors

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Abstract

In low earth orbit, there are many cosmic rays composed primarily of high energy protons. These cosmic rays cause surface and bulk radiation effects, resulting in degradation of detector performance. Quantitative evaluation of radiation hardness is essential in development of X-ray detectors for astronomical satellites. We performed proton irradiation experiments on newly developed X-ray detectors called XRPIX based on silicon-on-insulator technology at HIMAC in National Institute of Radiological Sciences. We irradiated 6 MeV protons with a total dose of 0.5 krad, equivalent to 6 years irradiation in orbit. As a result, the gain increases by 0.2% and the energy resolution degrades by 0.5%. Finally we irradiated protons up to 20 krad and found that detector performance degraded significantly at 5 krad. With 5 krad irradiation corresponding to 60 years in orbit, the gain increases by 0.7% and the energy resolution worsens by 10%. By decomposing into noise components, we found that the increase of the circuit noise is dominant in the degradation of the energy resolution.

Keywords: X-ray, SOI, CMOS camera

1. Introduction

Radiation damage of semiconductor detectors is an important issue in high energy particle and nuclear physics experiments, in which the detectors are exposed to high radiation environments. The radiation damage is mainly due to two mechanisms: bulk effect and surface effect. The bulk effect is caused by lattice defects created by nuclear interactions between high energy particles and the detector. The defects trap carriers, and increase leakage current of the detector. The surface effect, which is often referred to as total ionizing dose (TID) effect, significantly affects MOS devices. It is due to charge accumulation in the SiO\textsubscript{2} layer induced by incident X-rays or charged particles, resulting in a shift of threshold voltages. The semiconductor detectors onboard X-ray astronomy satellites also suffer the radiation damage effect. When semiconductor detectors are used in low earth orbit at several hundred kilometers above the Earth, detector performances degrade over time. It is mainly due to cosmic-ray protons in the south atlantic anomaly (SAA) located at the altitude of ~300 km. In fact, the energy resolution of X-ray CCD onboard the Suzaku satellite degraded from 130 eV to 190 eV during the 1 year following launch [1]. Hence, quantitative evaluation of the radiation hardness is essential in development of X-ray detectors for astronomical satellites.

We have been developing silicon on insulator (SOI) CMOS image sensor XRPIX (X-Ray PIXel) [2, 3]. Fig. 1 shows cross-sectional view of XRPIX. XRPIX is a monolithic detector composed of low-resistivity circuit layer, SiO\textsubscript{2} insulator layer and high-resistivity sensor layer. X-rays are photoelectrically absorbed by the sensor layer and charges are created. These charges are collected to sense node and are converted to signals in circuit layer. We equip the XRPIX with a function to output trigger signals and the corresponding hit-pixel addresses, with which it achieves a high time-resolution of better than ~10 \textmu s. Furthermore, the high time resolution enables the anti-coincidence method with surrounding active shields, which would effectively reduce the in-orbit background.

The main effort for development of XRPIX was poured so far into improving the energy resolution and implementing the trigger function. However in order to operate XRPIX in the space radiation environment, the effect on the performance of XRPIX by radiation damage must be understood. Therefore, a quantitative evaluation of the radiation hardness of XRPIX is necessary before the launch. Although a few studies of radiation hardness have been conducted for SOI pixel detectors [3], nothing has been done for XRPIX.

In this paper, we report on the result of the proton radiation damage.
Figure 1: Cross-sectional view of XRPIX. A thin oxide film (BOX: buried oxide) was sandwiched between sensor layer and circuit layer. This picture shows example of n-type silicon sensor layer. Holes generated by X-ray are collected to sense node. The size varies depending on series: the pixel size is 30 – 36 µm square and the thickness of sensor layer is 60 – 500 µm.

Table 1: The chip design of XRPIX2b used in this experiment.

| parameter          | value        |
|--------------------|--------------|
| Pixel size         | 30 µm sq.    |
| BPW size           | 12 µm sq.    |
| Type of sensor layer | Floating zine n type Si |
| Thickness of the sensor | 500 µm      |
| Sensor resistivity | 5 kΩ·cm      |

damage experiment on XRPIX. The degradation of the energy resolution and the change of the gain are shown, and the reasons of the performance degradation are discussed.

2. Proton radiation damage experiment for XRPIX at HIMAC

We performed proton radiation damage experiment at "Heavy Ion Medical Accelerator in Chiba (HIMAC)" in National Institute of Radiological Sciences. In this experiment, we irradiated 6 MeV proton beam to XRPIX2b which was one of the XRPIX series [3][6]. The design of XRPIX2b is summarized in Table 1.

2.1. Radiation dose by proton beam in this experiment

In order to carry out the radiation damage experiment at the experimental facility on the ground, it is necessary to estimate the dose rate considering the space radiation environment and to convert the exposed dose in this experiment to equivalent time in space. Firstly, we calculated the radiation dose using ESA’s SPace ENVironment Information System (SPENVIS) [7], to estimate the dose rate on XRPIX assuming that XRPIX would be mounted on the future X-ray satellite in low earth orbit such as Hitomi satellite [8]. In this calculation, we supposed the altitude and the inclination angle of the satellite were 550 km and 31°, respectively [9][10]. We also assumed that the depletion layer thickness of XRPIX was 500 µm and XRPIX was surrounded by a 20 mm thick aluminum camera body. Secondary, we calculated the energy deposition in XRPIX by protons using stopping power value calculated by PSTAR of NIST (National Institute of Standards and Technology) [11]. Fig. 2 shows the calculated energy deposition by protons in XRPIX in orbit. From this result, we found 4–20 MeV protons have the largest impact on XRPIX.

Then, we calculated total proton dose by integrating the energy deposition over 0.05–400 MeV and derived the dose rate to be 1.6 × 10^6 MeV/cm^2/day, or 82.3 rad/year. From this calculation, 0.5 krad was equivalent to 6 years operation in orbit which was the typical required lifetime for X-ray astronomical satellites. In this experiment, at first we irradiated protons up to 0.1 krad, then increased the dose little by little, and finally the total dose reached 20 krad. Eventually, we evaluated performances of XRPIX at 0.1, 0.5, 1, 5, 8, 10 and 20 krad.

2.2. Experimental setup

Fig. 3 shows a schematic top view of experimental setup at the medium energy irradiation beamline in HIMAC. The proton beam intensity is so strong that large current induced by the
protons might damage the read-out circuit on XRPIX. Therefore we set 2.5 μm thick Au film as a scatterer in front of XRPIX to reduce the proton beam intensity. XRPIX was located at 30 degree direction from the downstream and set in the vacuum chamber where the degree of vacuum was 5.0 \times 10^{-4} hPa. From the result of simulation by Geant4 [12], the proton intensity scattered to 30° was 6 \times 10^{-6} of the original beam intensity and the proton energy became \sim 5.9 MeV. XRPIX was cooled down to \sim 60°C to reproduce the radiation damage in orbit precisely.

XRPIX2b was operated with a bias voltage (V_{BB}) of 150 V and with the integration time of 100 μs. We also evaluated the performance while changing V_{BB} of 5, 50, 150, 250 and 290 V. However, we evaluated at 8 krad only with (V_{BB}) = 150 V.

2.3. Estimation of proton flux with APD

Before the proton irradiation experiment for XRPIX, we irradiated protons to avalanche photodiode (APD). This APD was located at the same position as XRPIX. As shown in Fig. 3 a Faraday cup was also installed along the beam direction. It measured un-scattered protons, and tracked fluctuation of the beam intensity during the proton irradiation experiment. By comparing count rates from APD and the Faraday cup, correlation between scattered and un-scattered protons were known. Fig. 4 shows the correlation of the count rate between APD and Faraday cup. The count rates from APD and the Faraday cup were not proportional because of dead time mainly due to a charge-sensitive amplifier for the APD, which behaves as a paralyzable detector. Hence, we fitted the correlation with the paralyzed dead time model expressed as

\[ y = x e^{-x/\tau} \]  

where \( y \) is count rate with APD, \( x \) is count rate with Faraday cup and \( \tau \) is dead time [16]. The best fit model and the dead time corrected correlation between APD count rate \( r_{APD} \) and Faraday cup count rate \( r_{FC} \), \( r_{APD} = (6.56 \pm 0.01) \times 10^{-7} r_{FC} \) are shown in Fig. 3. From this correlation and counts from the Faraday cup, we estimated the number of protons irradiated on XRPIX.

The absorbed dose described hereafter is calculated based on counts from the Faraday cup.

3. Result of radiation damage experiment

The leakage current was estimated by the derivative of the pedestal level with respect to the integration time, because the output signal contains the charges due to the leakage current summed during the integration time. Fig. 5 shows the dependence of the leakage current on the total dose. Leakage current showed a tendency to increase with total dose. At 0.5 krad which is equivalent to 6 years in orbit, the leakage current increases by 1.2 times from 0 krad, and at 5 krad it rapidly increases up to 4.2 times of that at 0 krad. At 20 krad, the V_{BB} was applied up to only 5 V because the ADC output were saturated above 5 V.

The dependence of bad pixel fractions on total dose is shown in Fig. 6. The bad pixel is defined by using distribution of read out noise as shown in Fig. 7. Standard deviation \( \sigma \) of the distribution was evaluated by fitting the distribution with Gaussian function. Then, pixels outside of 3\( \sigma \) are defined as the bad
Figure 7: Histogram of read-out noise for each pixel. Noise level of all pixels was increased as total dose increased. The definition of bad pixels at 5 krad is shown by $V_{BB}$ shade.

Figure 8: $^{109}$Cd energy spectrum at 0 krad and 5 krad. 5 krad spectrum was scaled so that the peak has about the same counts of 0 krad peak. At 5 krad, output became higher than output at 0 krad and sigma of peak got slightly thicker.

4. Discussion

4.1. The influence of bulk effect and surface effect

As described in section 1, the detector performance degrades with proton irradiation via two different processes, namely surface and bulk effects. Whereas the surface effect strongly depends on the detector configuration, the bulk effect is roughly determined by only the particle fluence. Thus, we estimated the influence of the bulk effect by protons in orbit. According to [15], by the bulk effect, an increase of leakage current per unit volume $\Delta I$ at a temperature of 25°C is written as

$$I_{\text{increase}} = 3.0 \times 10^{-8} \times F \text{nA/cm}^2/\text{year},$$

where $I_{\text{increase}}$ is the increase of leakage current, $F$ is the particle fluence in $\text{nA/cm}^2/\text{year}$.
Thus, the energy resolution is expressed as
\[ \sigma^2 = \sigma_{\text{Fano}}^2 + \sigma_{\text{RO}}^2. \]

\[ \sigma_{\text{Fano}}^2 \] is Fano noise, and \( \sigma_{\text{RO}}^2 \) is read-out noise. The read-out noise consists of CMOS circuit noise \( \sigma_{\text{cir}}^2 \) and shot noise of leakage current \( \sigma_{\text{leak}}^2 \).

\[ \sigma_{\text{RO}}^2 = \sigma_{\text{cir}}^2 + \sigma_{\text{leak}}^2. \]

Thus, the energy resolution is expressed as
\[ \sigma^2 = \sigma_{\text{Fano}}^2 + \sigma_{\text{cir}}^2 + \sigma_{\text{leak}}^2 + \sigma_{\text{other}}^2. \]

where the last term \( \sigma_{\text{other}}^2 \) is introduced to reproduce the energy resolution.

By using this expression, we decomposed the energy resolutions into each noise component as shown in Fig. 11. The shot noise of the leakage current is not shown in Fig. 11 because it is so small as \( \sim 1 \) eV. From this result, only circuit noise increases as the total dose increases. In other words, degradation of energy resolution were caused by increase of circuit noise.

5. Summary

We irradiated 6 MeV proton beam to XRPIX2b. The detectors performance was almost unchanged at 0.5 krad which is equivalent to 6 years in orbit. At 5 krad, the energy resolution was increased significantly and the leakage current was increased by 5 times from 0 krad, but increase of gain was only 0.7%. By decomposing the energy resolution into noise components, we found that CMOS circuit increased the noise.
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