Proton Irradiation Experiment for X-ray Charge-Coupled Devices of the Monitor of All-Sky X-ray Image Mission Onboard the International Space Station: I. Experimental Setup and Measurement of the Charge Transfer Inefficiency

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We have investigated the radiation damage effects on a charge-coupled device (CCD) to be employed in the Japanese X-ray astronomy mission including the monitor of all-sky X-ray image (MAXI) onboard the international space station (ISS). Since low-energy protons release their energy mainly at the charge transfer channel, resulting in a decrease of the charge transfer efficiency, we focused on low-energy protons in our experiments. A 171 keV to 3.91 MeV proton beam was irradiated onto a given device. We measured the degradation of the charge transfer inefficiency (CTI) as a function of incremental fluence. A 292 keV proton beam degraded the CTI critically. Taking into account the proton energy dependence of the CTI, we confirmed that the charge transfer channel has the lowest radiation tolerance. We have also developed different device architectures to reduce the radiation damage in orbit. Among them, the “notch” CCD, in which the buried channel implant concentration is increased, resulting in a potential well deeper than outside, has a three times higher radiation tolerance than that of the normal CCD. We then estimated the CTI of the CCD in the orbit of the ISS, considering the proton energy spectrum. The CTI value is estimated to be 1.1 × 10⁻⁵ per transfer after two years of mission life in the worst case analysis if the highest radiation tolerant device is employed. This value is well within the acceptable limit and we have confirmed the high radiation-tolerance of CCDs for the MAXI mission. [DOI: 10.1143/JJAP.41.7542]

KEYWORDS: charge-coupled device, radiation damage, displacement, international space station, radiation belt

1. Introduction

Charge-coupled devices (CCDs) have emerged as the preferred detectors on all new X-ray astronomy missions in recent years. This is because they simultaneously possess a high spatial resolution and a moderate energy resolution.\(^1\) The dead layer above the CCD must be sufficiently thin to attain a high quantum efficiency at soft X-ray regions. As a result, devices cannot be protected against high-energy particles in space in the incident direction of X-rays.

Soon after the launch of the X-ray astronomy satellite, Chandra, all of the front-illuminated CCDs of the X-ray CCD camera (ACIS) suffered the degradation of the charge transfer inefficiency (CTI).\(^2\) The CTI is defined as an average fraction of charge packet lost at each transfer. Devices similar in type to ACIS CCDs have been tested by us by low-energy protons (10 MeV and 40 MeV) but not by the low-energy protons before launch. The low-energy protons having energy of 150 keV release a major part of their energy at the transfer channel of the ACIS CCDs, which is located roughly 1 μm below the electrodes. This causes the displacement damages in Si, leading to the formation of trapping sites for the charge packet. Since the flux of low-energy protons at the orbit of Chandra is much higher than that at the low earth orbit such as in the case of ASCA\(^3\) and low-energy protons reflecting through the X-ray mirror assembly (HRMA) can reach the focal plane,\(^4\) a significant degradation of the CTI has occurred.

The monitor of all-sky X-ray image (MAXI) has been selected as an early payload of the Japanese experimental module (so called KIBO) exposed facility on the international space station (ISS).\(^5\) The MAXI has slit scanning cameras which consist of two kinds of X-ray detectors; one-dimensional position-sensitive proportional counters with a total area of ~5000 cm² named GSC and the X-ray CCD camera with a total area of ~200 cm² named SSC. The SSC carries 32 CCDs which are three-side buttable with full-frame transfer and have 1024 × 1024 pixels of 24 μm × 24 μm size with two-phase gate structures. The CCD chips are fabricated by Hamamatsu Photonics K.K. (HPK). In order to perform useful X-ray spectroscopy over the whole device, the CTI must be less than roughly 2 × 10⁻⁵ per transfer where the shift of the peak energy is close to that of the Fano-limited noise of 120 eV at 5.9 keV.

Previous studies of the radiation hardness for HPK CCDs also focused on high-energy protons above 1 MeV\(^6\) and no data are available for low-energy protons. We thus performed the irradiation test focusing on the low-energy protons. In this paper, we describe the device architecture, irradiation experiment, and the measurement of the CTI at −100 °C.

2. Experiments and Results

2.1 Architecture of CCD

We employed CCDs packaged to a half-inch size which is different from that of the MAXI CCD, however, the device was fabricated from the same type of wafer as the MAXI CCD. The devices irradiated possess 512 × 512 pixels of 24 μm square size. Figure 1(a) shows a schematic view of the CCD. The cross sections of a CCD pixel in the horizontal and the vertical directions are shown in Fig. 1(b) (we call this type of device normal CCD which has no counter-measure for radiation hardness). Since the CCD employed is a buried-channel type, there is a thin (≈ 1 μm) doped n-type...
Nitridation of the oxide layer enables us to reduce the ionization damage, resulting in a flat-band shift smaller than those of devices having only oxides.\textsuperscript{9,10} This technique would reduce the dark current for damaged devices. It might not be efficient to improve the CTI since the nitride CCD possesses a structure similar to that of the depletion layer for the normal CCD. However, the degradation of the CTI must be of a similar level for normal devices.

We have developed CCDs from various Si wafers. Details about newly developed devices have been described in Miyata \textit{et al.}\textsuperscript{11} Devices fabricated from epitaxial wafers and from bulk wafers were tested. We have decided to employ devices from epitaxial wafers in order to achieve high energy resolution, high quantum efficiency for hard X-rays and low dark current. Among them, we employed the epitaxial-2 (hereafter referred to as epi-2) and epitaxial-3 (referred to as epi-3) devices for comparison. The resistivity of the epi-3 wafer is roughly one order of magnitude higher than that of the epi-2 wafer.

We then fabricated the following four types of devices to compare their radiation tolerance: epi-3 with and without notch, epi-2 with notch, and epi-2 without notch but having the nitride oxide.

### 2.2 Experimental setup and beam calibration

The 570 keV to 4.0 MeV proton beam shown in Table I was provided by the Van de Graaff accelerator at the Laboratory for Nuclear Studies, Osaka University. We employed an Al degrader with a thickness of 5 μm to reduce the energy to 171 keV (Table I). Pulsed beams were used to control the irradiation fluence. The proton beam was over-defocussed by a quadrupole magnet to obtain a weak and uniform beam at the CCD.

Figure 2 shows the experimental setup of the CCD chamber. We employed four diaphragm plates made of Al between the degrader and the CCD in order to reduce scattered protons or secondary electrons generated by the inside wall of the duct. Inside the CCD chamber, the collimator made of Al with a thickness of 3 mm having a hole of 21 mm was set to both collimate the proton beam and monitor the intensity of the incident proton beam to the CCD. Two 55Fe sources were located behind the collimator. This enabled us to investigate the \textit{in-situ} performance of the CCD.

Roughly half the area of each CCD was shielded against protons to obtain data for the non-irradiated region and compare the results with those from the irradiated region. Since the amount of scattering protons is not small, the vertical boundary between the shielded and the irradiated

| Energiy of protons irradiated. | Upstream of the degrader | Downstream of the degrader |
|---|---|---|
| proton energy (keV) | proton energy (keV) | width (keV)\textsuperscript{a} |
| 570 | 171 | 13 |
| 650 | 292 | 12 |
| 720 | 391 | 11 |
| 820 | 522 | 11 |
| 2200 | 2061 | 10 |
| 4000 | 3911 | 9 |

\textsuperscript{a} Width is shown in units of standard deviation.
regions was not clear. It renders the calculation of the CTI in the horizontal transfer direction uncertain. We thus focused on the vertical CTI only.

We drove CCDs with our newly developed system, the E-NA system. The CCD analog data were processed by an integration-type circuit and digital data were acquired with a VME system. The readout noise of our system including the device is less than $10^{-8}$ cm$^{-2}$s$^{-1}$.

The spatial uniformity of the beam intensity was measured with 650 keV protons. The proton energy downstream of the degrader was 292 keV (details will be described in the next section). A 292 keV proton generates a 294 eV X-ray. We thus measured the number of events generated by protons in a 24 mm square area and found the spatial uniformity to be better than 10%.

### 2.3 Performance degradation of mono-energetic protons

We performed the incremental irradiations at a given energy on a given device. All devices were operated (biased) during this experiment and were fabricated from the same wafer (epi-3 wafer). Table I shows the energy of protons irradiated. The center energy and width of the proton spectrum downstream of the degrader were calculated with the Geant4. We employed the low-energy extension with the Geant4. In order to simulate the physical process of low-energy less than 2 MeV. In the subsequent section, we only refer to the proton energy downstream of the degrader.

Figure 3(a) shows the spectrum of $^{55}$Fe extracted from single-pixel events before proton irradiation. The energy resolution of Mn K$_\alpha$ has a full-width at half maximum (FWHM) of 146 eV. After an irradiation of 292 keV protons with a fluence of $1.04 \times 10^7$ cm$^{-2}$, the degradation of the detector performance was significant and the energy resolution became 294 eV. The peak positions of Mn K$_\alpha$ and K$_\beta$ were shifted, suggesting the incomplete collection of the charge packet. We then incremented fluence up to $1.11 \times 10^8$ cm$^{-2}$ and the resultant spectrum is shown in Fig. 3(c). Mn K$_\alpha$ and K$_\beta$ X-rays could not be resolved and the energy resolution was degraded to 614 eV.

The device irradiated with 292 keV protons suffered the most serious damage in terms of the energy resolution compared with those irradiated by protons of other energies.

Figure 4 shows the readout noise as a function of proton fluence for 292 keV and 3.91 MeV protons. Since the readout noise was evaluated from the histogram of the horizontal over-clocked area, it included the noise of the CCD as well as that of the electronics. Before the proton irradiation, the readout noise of both CCDs was ~7.8 e$^-$. Therefore, there was no influence of proton irradiations on the readout noise.
In this way, we confirmed there was no degradation of the readout noise for irradiations with protons of all energies employed. The degradation of energy resolution shown in Fig. 3 was not caused by the degradation of the readout noise.

Figure 5 shows the pulse heights of $^{55}$Fe events as a function of the number of transfers. Each dot in these figures corresponds to an individual X-ray event. The histogram shown in Fig. 3 can be obtained if one makes a projection of these plots to the Y-axis (pulse height axis). Before irradiation, two horizontal lines are clearly seen, corresponding to Mn Kα at $\sim 710$ channel and Kβ at $\sim 790$ channel [Fig. 5(a)]. After irradiating with 292 keV protons with fluence of $1.04 \times 10^7 \text{ cm}^{-2}$, the pulse height of X-ray events decreases with increasing transfer number, suggesting the loss of the charge packet during the transfer [Fig. 5(b)]. We should note that the widths of the two lines were broadened as the transfer number became larger. Figure 5(c) shows the same plot after irradiating with protons of $1.11 \times 10^8 \text{ cm}^{-2}$. A significant loss of charge packets is found and the pulse height at the transfer number of 500 is less than half of that before irradiation. The pulse height at the transfer number of zero is still less than that before irradiation, suggesting the loss of charge packets in the serial register of the device.

In order to characterize the loss of charge packet, we calculated the values of the CTI for all proton energies based on Fig. 5. Figure 6 shows the CTI as a function of proton fluence for various proton energies. Protons having energy of 150 keV have seriously degraded the detector performance in the case of ACIS. On the other hand, 171 keV protons affected the CTI for HPK CCDs less severely. Instead, HPK CCDs suffered serious damage caused by protons with energies of 292 and 391 keV. The degradation of the CTI caused by proton energies above 500 keV is again less than those caused by protons of 292 and 391 keV.

Since values of the CTI shown in Fig. 6 depend on the initial value of the CTI, we calculated the increase rate of the CTI ($\Delta \text{CTI}$) as a function of proton fluence at each incremental irradiation as shown in Fig. 7.

### 2.4 Dependence of CTI on biased and unbiased devices

On the satellite orbit including the ISS, the distribution of high-energy particles is far from uniform and it is concentrated in a very small area on the Earth. The densest region of the high-energy particles is so-called the South Atlantic Anomaly (SAA). During the passage of the SAA, the quality of data is poor because of high background.
Therefore, if the performance degradation of CCDs depends on the biased (in operation) or unbiased (out of operation) condition, we could turn off CCDs during the passage of the SAA.

We thus investigated the difference of device performance depending on whether the device was biased or not during irradiation of 292 keV protons. Figure 8 shows the $\Delta$CTI as a function of proton fluence. We found no significant difference between them. Therefore, the devices need not be turned off during the SAA only in terms of the degradation of the CTI.

2.5 CTI for various devices and for various processes

As mentioned in §2.1, we fabricated four types of devices to compare the difference of radiation hardness. All devices were unbiased during the proton irradiation. The values of $\Delta$CTI obtained for these devices are shown in Fig. 9. We found that the $\Delta$CTI value obtained by epi-3 with a notch is a factor of 3–5 times lower than that by epi-3 without a notch. A significant improvement is obtained although this value is slightly smaller than that of the geometrical ratio of the notched area and other area. We thus decided to employ the notch structure for flight devices.

There is no significant difference between epi-2 with a notch and epi-3 with a notch, suggesting there are no differences in $\Delta$CTI for low and high resistivity wafers. We can therefore investigate the effect of the nitride oxide by comparing epi-3 without a notch and epi-2 without a notch, both having the nitride oxide. There were very little differences between them. Therefore, if the degradation of the dark current in the device having the nitride oxide is smaller than that without the nitride oxide, we will employ the nitride oxide for flight devices. The experimental results concerning the dark current are described in the subsequent paper.

3. Discussion

3.1 Proton Bragg curve

We found that protons having energies of 292 and 391 keV seriously damaged HPK CCDs in terms of the CTI performance. The degradation of the CTI obtained with protons having lower and higher energies is much less than those with 292 and 391 keV protons. This strongly suggests that the low radiation-tolerant region inside the HPK CCD is located in a relatively narrow region.

We calculated the Bragg curves of protons in Si. We employed Geant4 with the G4EMLOW0.3 data and considered the energy straggling due to the Al degrader of 5 μm thickness. Figure 10 (upper) shows the energy loss of protons as a function of depth of Si. The dashed line represents the minimum energy required to displace Si atoms ($\simeq 6$ eV Å$^{-1}$). The energy deposition due to 292 and 391 keV protons is concentrated at the depth of 2–4 μm inside Si. At this depth, the energy deposition of protons with other energies is less than those with 292 and 391 keV. Therefore, the radiation tolerance at a depth of 2–4 μm is much lower than those in other regions inside the HPK CCD.

Figure 10 (lower) shows the schematic view of the cross section of the HPK CCD employed. Since the HPK CCD is a
buried-channel type, the charge packet is transferred in a narrow region along the depth of the CCD. This transfer channel well coincides with the Bragg peak region of 292 keV protons. This result is consistent with the ACIS result but the most serious proton energy is slightly different from our value. Prigozhin et al.\textsuperscript{25} estimated the minimum proton energy required to reach the buried channel to be somewhat higher than 50–70 keV in order to penetrate the optical blocking filter, covering layer, and electrodes. Therefore, the covering material is much thinner than that in our case, resulting in that lower energy protons seriously affected the ACIS CCDs.

As described in §2.5, there is no difference in CTI values between CCDs fabricated from a high resistivity wafer and those fabricated from a low resistivity wafer. The acceptor doping concentration of our device is only on the order of $10^{13} \text{cm}^{-3}$ and the difference between the epi-2 wafer and the epi-3 wafer is roughly one order of magnitude.\textsuperscript{11} At this doping concentration level, the probability that protons encounter Si atoms is essentially the same for both of these devices. Since the thickness of the $n$-type layer is the same for both of them, their difference lies in the thickness of the depletion layer. This means that the transfer channel is located at the same depth for both of them. Our results are, therefore, expected if the radiation tolerance depends not on the depletion depth but on the transfer channel. This is consistent with previous work.\textsuperscript{8)} We are now developing CCDs from newly obtained epitaxial wafers having a much higher resistivity than that of epi-3. Since, however, the transfer channel of new type of CCDs is located at the same depth as current devices, we are convinced that we can apply these results to new type of CCDs.

\begin{table}
\centering
\begin{tabular}{lll}
Proton energy (keV) & Slope & CTI$_0$ \\
\hline
171 & $(1.63 \pm 0.04) \times 10^{-13}$ & $(5.3 \pm 0.9) \times 10^{-6}$ \\
292 & $(1.35 \pm 0.05) \times 10^{-11}$ & $<8 \times 10^{-6}$ \\
391 & $(3.34 \pm 0.03) \times 10^{-12}$ & $(6.3 \pm 0.2) \times 10^{-5}$ \\
522 & $(1.10 \pm 0.01) \times 10^{-12}$ & $(6.70 \pm 0.08) \times 10^{-5}$ \\
2061 & $(3.43 \pm 0.06) \times 10^{-13}$ & $(5.7 \pm 0.9) \times 10^{-6}$ \\
3911 & $(2.26 \pm 0.07) \times 10^{-13}$ & $<2 \times 10^{-6}$ \\
\end{tabular}
\caption{Result of linear fit for $\Delta$CTI as a function of proton energy.}
\end{table}

3.2 Modeling the CTI degradation

As shown in Fig. 7, the degradations of $\Delta$CTI are expressed as a linear function of the proton fluence. Since $\Delta$CTI is expressed as a linear function of the electron trap density,\textsuperscript{16)} the formation of electron traps proportionally increases, the electron traps ratio.\textsuperscript{17)} The electron trap concentration is expressed as a linear function of the electron trap density. The best fit parameters, a slope, and an intercept ($\Delta$CTI$_0$), are shown in Table II. Figure 11 shows the slope obtained as a function of proton energy. Since the obtained values of slope correspond to an efficiency required to create the electron trap, Fig. 11 shows that 292 keV protons most seriously affect the CTI degradation.

As shown in Fig. 10, low-energy protons deposit a major part of their energy within a confined depth. The peak of the Bragg curve corresponds to the depth of 2.3 $\mu$m in Si in the case of 292 keV protons. We thus assume that there is a thin radiation-sensitive area within the CCD at a depth of 2.3 $\mu$m with a thickness of 0.05 $\mu$m. We should note that 0.05 $\mu$m is the shortest unit we can simulate. Ignoring the $\Delta$CTI degradation at other depths, we can calculate the energy deposition using protons that affect the CTI. The results are plotted in Fig. 11 with filled circles normalized by the value at 292 keV. For all proton energies, calculated values are much larger than those obtained. As shown in Fig. 10, if the thickness of the radiation-sensitive region increases, the energy deposit of 391 or 522 keV protons becomes relatively

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Fig10.png}
\caption{Bragg curves for various proton energies (upper) and the schematic view of the cross section of the HPK CCD employed (lower). The dashed line in the upper figure shows the minimum energy required to displace Si atoms.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Fig11.png}
\caption{Slope of $\Delta$CTI as a function of proton energy. Model calculations with and without taking into account the nonlinear effect due to NIEL are also plotted by filled squares and filled circles, respectively. Solid lines represent the empirical relations.}
\end{figure}
larger than that of 292 keV protons. This drives the calculated values for 391 and 522 keV to be increased to values much larger than current values, resulting in the deviation from data to be more significant. In this calculation, we assumed that the probability for creating an electron trap is linearly proportional to the proton energy loss. This assumption leads to large discrepancies between the data and the calculations. Therefore, there may be some nonlinear effects in their probabilities.

There are two types of processes for proton energy loss; ionization energy loss (IEL) and nonionization energy loss (NIEL). These two different forms of energy dissipation are translated into two major damage mechanisms for CCDs: ionization damage and bulk damage. The ionization damage leads to a flat-band shift which causes the operating voltage to be shifted. This damage is caused by all types of charged particles. On the other hand, energetic charged particles undergo Rutherford-scattering-type Coulombic interactions with the Si lattice structure. The energy deposited by the interacting ion is sufficient to pull a Si atom out of its lattice position, forming an interstitial Si atom and a vacancy. The displaced atom, called the primary knock-on atom (PKA), may have sufficient energy to undergo collisions with lattice atoms, producing more vacancies. The NIEL is partly responsible for the energy producing the initial vacancy-interstitial pairs and phonons.

Ziegler et al.\(^\text{[15]}\) and Burke\(^\text{[16]}\) calculated the IEL and the NIEL, respectively. Based on their calculations, it is determined that more than 98% of incident proton energy \([E_p \text{ (keV)}]\) is released as the IEL for \(E_p \geq 100\text{ keV}\). For a proton of relativistic energy, the NIEL in Si is almost constant whereas for lower energies the NIEL has a \(1/E_p\) dependence. This suggests that the probability of displacement creation is not linearly proportional to the total energy loss but is proportional to \(E_p^{-\gamma}\). We then fitted the function \(E_p^{-\gamma}\) to the results of NIEL calculated by Burke. We found that \(\gamma = 0.76\) in the energy range of 100 keV \(\leq E_p \leq 4\text{ MeV}\).

In order to take into account the nonlinear effect of creating traps due to the NIEL, we need to employ not the incident proton energy but the energy at the depth of 2.3 \(\mu\text{m}\). We calculated the energy reduction of \(E_p\) during the passage of 2.3 \(\mu\text{m}\) in Si with Geant4. We then calculated the fraction of the NIEL among the total energy losses taking into account the energy dependence of the NIEL for each reduced \(E_p\). We normalized the fraction of the NIEL for each proton energy by that of 292 keV and took them into account for the previous calculations. Results are shown by filled squares in Fig. 11. Our calculations considering the NIEL represent the data obtained. However, measured values of the slope suddenly decreased as \(E_p\) increased whereas they could not be reproduced by our calculations. In our model, we only consider the NIEL which represents the energy deposition as the initial vacancy-interstitial pairs and phonons. If the energy of PKA is large enough to undergo collisions with Si atoms, the number of vacancies increases. Therefore, taking into account the spectrum of PKA and collisions between PKA and Si atoms is important for future modeling.

Empirical relations between the slope of \(\Delta\text{CTI}\) versus the proton energy are described as:

\[
\text{slope } [E_p \text{ (keV)}] = 1.2 \times 10^{-10} \times E_p - 2.0 \times 10^{-11} \quad \text{for } E_p \leq 292\text{ keV} \quad (3.1)
\]

\[
\text{slope } [E_p \text{ (keV)}] = 1.2 \times 10^{-9} \times \exp(-E_p/6.6 \times 10^{-2}) + 3.0 \times 10^{-13} \quad \text{for } E_p \geq 292\text{ keV} \quad (3.2)
\]

Solid lines in Fig. 11 represent the above empirical relations. For a given proton spectrum in orbit, we can calculate the \(\Delta\text{CTI}\) value by summing contributions from all proton energies.

### 3.3 Estimation of the CTI for the MAXI mission

We found that low-energy protons with energies of 290–400 keV seriously damaged the spectroscopic performance of MAXI CCDs. The degradation of the CTI as a function of mission life for the MAXI based on our experiments has been estimated. There is a slit at the top of the SSC camera with a size of 5 \(\times\) 0.3 mm\(^2\) and slat collimators just above the CCDs.\(^\text{[19]}\) The thickness of the slat collimator is \(\sim 100\mu\text{m}\), which is aligned by \(\sim 3\text{ mm}\) pitch, indicating that the field of view of each CCD is \(\sim 1.5^\circ\) square. Within the field of view, no shield protects the devices whereas the column density in other directions on the camera is \(\sim 2.5\text{ g cm}^{-2}\), suggesting that the number of protons passing through the camera is negligibly small. We thus calculate the proton flux passing through the 1.5\(^\circ\) \(\times\) 1.5\(^\circ\) area.

We employed the proton flux described in the literature,\(^\text{[20]}\) in which the attitude of the ISS is 500 km and solar activity is the maximum. The proton flux at 500 km is the largest among attitudes expected for the ISS\(^\text{[20]}\) and we therefore use it for the worst case analysis. The number of protons at the solar minimum is a factor of \(\sim 2\) larger than that at the solar maximum. We thus increase the proton flux by a factor of 1.5 as the average value. Figure 12 shows the CTI estimated for the MAXI as a function of its mission life. The dashed line shows the acceptable limit for the MAXI. Since the mission life of the MAXI is two years, the degradation of the CTI is well below the acceptable limit even for the worst case analysis. We therefore confirm the high radiation tolerance of MAXI CCDs.

![Fig. 12. CTI estimated for the MAXI CCDs. The dashed line indicates the acceptable limit for the MAXI.](image-url)
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