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The SXI: CCD camera onboard the NeXT mission

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ABSTRACT

The Soft X-ray Imager (SXI) is the X-ray CCD camera on board the NeXT mission that is to be launched around 2013. We are going to employ the CCD chips developed at Hamamatsu Photonics, K.K. We have been developing two types of the CCD: an N-channel chip and a P-channel chip. The effective area of the detector system will be 5-6 cm square with a depletion layer of 100-200 $\mu$m. The P-channel chip will have thicker depletion layer that makes it easy to develop it to back-illuminated type CCD. It will need a year or so for us to reach the final conclusion which type will be available. Based on the Suzaku experience, we will incorporate the charge injection gate so that we can reduce the proton damage. Furthermore, we will employ a mechanical cooler to keep the CCD working temperature down to -120$^{\circ}$C in spite that NeXT will be in the low earth orbit. We can expect the radiation damage on our system very small. The CCD will have an Al coat on the chip to prevent optical photons from entering. This also eliminates the vacuum-tight chamber and the door-opening mechanism. We are planning to employ a custom-made analog ASIC that will reduce the power consumption and the size. The ASIC may speed up the frame-time if we can use a multi-node CCD. With using the focal length of 6 m, the SXI will fully function with the optics around 20$^{\prime\prime}$ resolution. We will report the current plan of the SXI in detail.

Keywords: X-ray CCD, Back-illumination, Charge injection, NeXT

1. INTRODUCTION

X-ray astronomy satellites widely employ charge-coupled devices (CCDs) for imaging as well as for spectroscopy. Combining them with optics, they have good spatial resolution and moderate energy resolution. There are some less desirable characteristics in X-ray CCDs, namely size, time resolution, pile-up and detection efficiency at high energy. What is required for X-ray use is a low-noise read-out, a thick depletion layer, thin absorption layer and large format. The ASCA satellite\textsuperscript{1} employed X-ray photon counting CCDs (SIS) for the first time. The CCD chip was about half inch square. They employed 4 chips in a camera. Chandra\textsuperscript{2} and Suzaku\textsuperscript{3} employed a CCD chip of one inch square. The CCD camera on Chandra employed 4 chips in the imaging camera. XMM-Newton also employed 7 chips in the MOS camera\textsuperscript{4} and one large chip of the pn-CCD.\textsuperscript{5} The CCD for X-ray use is fabricated in a buttable form so that they can obtain a large effective area by using many chips.

ASCA and SUZAKU are put into the low earth orbit (LEO) where we need an active cooling system. We employed a peltier cooler and reached -60$^{\circ}$C in ASCA and -90$^{\circ}$C in SUZAKU.\textsuperscript{6} Chandra and Newton are put into deep eccentric orbit where they can passively cool down to -120$^{\circ}$ or less. Judging from the CCD performance against the radiation damage, we find that the working temperature of -120$^{\circ}$ is desirable. However, judging from the CCD performance against the non-X-ray background, we find that the LEO is much better. Therefore, we have to look for a system to cool down the CCD to the desirable temperature at the LEO.
Since the CCD is made of Si, it has poor detection efficiency at high energy, particularly above 10 keV. All the CCD cameras onboard satellites function below 10 keV. When the CCD chip is built in a large format, either in a single chip or in multiple chips, the number of pixels increases, resulting in a reduction of the time resolution. Since a low noise read-out requires a relatively slow read-out speed, we have to increase the number of analog electronics channels in order to improve the time resolution or to avoid the pile-up. Due to the limited mass, space and power, we have to develop an ASIC for the CCD data process that fits the space use.

After the ASCA and the SUZAKU satellites, we are planning to have the NeXT mission\(^7\) that will be launched around 2013. We will have a CCD camera, the Solid X-ray Imager (SXI), on it. So far, we are developing a buttable X-ray CCD with large imaging area and good time resolution in Japan in a collaboration between NAOJ (National Astronomical Observatory Japan) and Hamamatsu photonics.\(^8\) We will summarize the SXI for NeXT.

2. CCD DEVELOPMENT

We have developed CCDs for X-ray use in Japan. Our research was carried out in order to have a large format and a thick depletion layer. The conventional type of the CCD, N-channel CCD, is developed for the MAXI mission. A new type of the CCD, P-channel CCD, is introduced by a group at Lawrence Berkeley National Laboratory (LBNL) to obtain about 300 \(\mu\)m-thick depletion layer.\(^9\) CCDs with thick depletion layer are also important for X-ray astronomy, because they can provide high detection efficiency in the energy band higher than 10 keV. Furthermore, the thicker the depletion layer of the CCD, the easier it is to make it a back-illuminated CCD (BICCD). Stimulated by the LBNL development and realizing the scientific importance of both optical and X-ray astronomy, the National Astronomical Observatory Japan, Osaka University and Kyoto University formed a consortium to fabricate P-channel CCDs in collaboration with Hamamatsu Photonics K.K. Japan. We have developed prototypes of P-channel CCDs and have achieved depletion layers of 200 \(\mu\)m thickness in optical measurement\(^11\) and confirmed in X-ray measurement.\(^12\)

2.1. CCD camera for the MAXI mission

We are developing the CCD camera (SSC) for the Monitor of X-ray Image (MAXI) to be onboard the International Space Station (ISS) in 2009. The SSC consists of two cameras, each containing 16 CCDs shown in Fig.1. The SSC is a slit camera having a field of view of 1\(^\circ\) \(\times\) 90\(^\circ\). It can scan the sky along the large circle of the ISS orbit. Two cameras are placed almost perpendicular to each other. The CCD chip is an N-channel CCD of 25 mm square, fabricated by Hamamatsu Photonics K.K., having a depletion depth of about 70 \(\mu\)m.\(^13\) There are 1024\(\times\)1024 pixels with 24 \(\mu\)m square. Since we will use CCD as one-dimensional detector, we will run it in a on-chip sum mode along the vertical line. It has an Al coating of 2000\(\AA\) on its surface to prevent optical photons from entering. The effective energy range is from 0.5 keV to 10 keV. Each CCD chip is directly glued to the top of the thermo-electric cooler to be cooled down to the working temperature of about -60\(^\circ\)C.

The CCD chip is three-side buttable so that we can obtain a large effective area. Each SSC camera contains 16 chips side by side in two rows as shown in Fig.1. The gap between chips is about 0.5 mm. Since they are installed behind a simple one dimensional slit instead of in the focal plane of an X-ray mirror, we selected the gap between chips to optimize the ease and safety of the assembly. We can reduce the gap to 200 \(\mu\)m or less, if needed. The analog electronics is working at a pixel clock of 125 kHz. We can run the CCD in an on-chip sum mode, up to 1\(\times\)64 pixels. This enables us to obtain sufficient time resolution with a reduction of spatial resolution. The number of electronics channels is limited both by the weight and by the power consumption.

2.2. X-ray CCD for balloon experiment

We have developed a P-channel CCD having thick depletion layer. This enables us to make it as a BI-CCD. Due to the low detection efficiency of the CCD above 10 keV, the SDCCD was introduced. It has a scintillator directly attached to the CCD of the BI side. High energy X-ray photons passing through the depletion layer can be easily detected in the scintillator where visible photons are produced. The visible photons are also detected by the CCD, which increases the detection efficiency up to 100 keV. The energy resolution of X-rays detected by the scintillator is limited by the scintillator while that of detected by the CCD depletion layer is as good as that of the conventional CCD.
A super mirror is being developed at Nagoya University that can collect X-rays up to 80 keV. Therefore, it is a good combination of the super mirror and the SDCCD. We performed a balloon experiment, SUMIT, to observe X-ray of 20-80 keV. Fig.1 shows the SDCCD employed in the SUMIT experiment. The P-channel CCD used is the BICCD of 3×6 cm², half of which is a storage area. Although the balloon was lost in the Atlantic Ocean in 2006, we confirmed that it functioned properly at the balloon altitude.

3. NEW TYPE OF CCD FOR NEXT

3.1. N-CHANNEL CCD, NEXT2

After the development of the MAXI CCD, we have improved it as ‘NeXT2’ so that it has a storage area to be a frame transfer type CCD. The imaging area is 25×25 mm² with 24 μm square pixel. There are 1 M pixels that can be read out by using two output nodes. We can select which readout node is used; one of them or both. As shown in Fig.2 left, we can fabricate multi-chips on one wafer so that there is very little gaps between the chips. This is intended to employ in the NeXT mission by using 4 CCDs. The effective area in the focal plane is 50 mm square. This is the front-illuminated CCD (FICCD) that is similar in function to those employed in the SUZAKU satellite.

Since this is the FICCD, the low energy efficiency is similar to those of other FICCDs. In the production of NeXT2, we have employed a high registivity wafer to obtain thick depletion layer. Fig.2 right shows the response of X-rays from ¹⁰⁹Cd. In this measurement, we employed 4×4 binning mode and grade method in the analysis. We find that about 10% of events are single-pixel events while about 50% are grade-7 events. The spectrum is calculated by using all grades (0-7). We confirmed that the depletion layer is about 100 μm that corresponds to 7.1% detection efficiency at 22.1 keV.

3.2. P-CHANNEL CCD, 2K4K

We have developed a P-channel CCD where holes are major carriers instead of electrons. Since it can have a thick depletion layer, it can be a fully depleted CCD. This is initially intended for the optical application. It is designed to be a back-illuminated CCD so that they can improve the short wavelength efficiency. We have modified it to fit the X-ray detection. Fig.3 left shows a P-channel CCD named 2K4K. It has a format of 2K×4K pixels with 15 μm square pixel. It can function either in the full frame mode or in the frame transfer mode.

Since this device is a BICCD having a relatively thick depletion layer, we find that X-rays at 6 keV generate relatively a large charge spread. We find that most X-ray events form spread events. Single-pixel events is less than 0.01%. The pixel size of 15 μm square is too small to efficiently collect charges. Therefore, we run the CCD in 4×4 binning mode where 4×4 pixel signals are summed up on-chip. The effective pixel size is 60 μm square. In this mode, 25% of X-ray events form single-pixel events and almost all events are within 3×3 pixels, which...
Figure 2. Left: photo of the NeXT2 CCD. There are two CCDs each is 25×50 mm$^2$. Right: X-ray spectrum of Ag-K$_\alpha$ and Ag-K$_\beta$ is shown. The depletion layer is 100$\mu$m thickness.

Figure 3. Left: photo of the 2K4K CCD. The imaging area is 30×30 mm$^2$. The storage area is equal to that of the imaging area. Right: X-ray spectrum of Mn-K is shown.
makes us possible to analyze the data in conventional method (ASCA grade). Fig.3 right shows the histogram of $^{55}$Fe using single-pixel events showing the energy resolution of 136 eV.

We used $^{109}$Cd to measure the detection efficiency. Fig.4 left shows the X-ray image of the calibration beam that is the sum of 1600 frames. Fig.4 right shows the detection efficiency at Ag-K X-rays as well as that of 213 $\mu$m thick Si. With taking into account the statistical uncertainties, this is consistent with the physical dimension of the thickness of 200 $\mu$m.

4. CHARGE INJECTION

X-ray CCDs are gradually degraded in orbit due to the charged particle damage. When the charged particle leaves damage near the charge transfer channel inside the CCD, it reduces a lot on the charge transfer efficiency. Since the charge transfer channel is formed just below the gate structure, it is in shallow region of the FICCD

Figure 5. Degradation of the CCD performance as a function of time. The top panel shows the gain history while the bottom panel shows the history of the energy resolution. In late 2006, we introduced the charge injection that improved the CCD performance.
while it is in deep region of the BICCD. With taking into account the energy spectrum of protons near the satellite orbit, the FICCD is more sensitive to the radiation damage than that of the BICCD.

When CCDs are damaged by charged particles, we can partially compensate the damage by using a spaced-row charge injection (SCI) method. Gendreau et al. reported the effect of a sacrificed charge by using the ASCA CCD through the laboratory experiment. In Suzaku, they have introduced the SCI method in orbit.

In the SCI method, we usually inject charge into one row at every 55 rows. These rows compensate the electron traps generated by charged particles as the frame data are transferred. Since the traps leave electron in a finite time, we have to periodically inject charges. The interval is selected by referring to the trapping time. Fig.5 shows the performance history of the CCDs on board SUZAKU. In the first year, we can see a rapid degradation of the CCD while it recovers to the initial condition by employing the SCI. We see that the degradation rate is reduced by a factor of about ten. In this way, we can extend the CCD performance in orbit.

5. SOFT X-RAY IMAGER

5.1. ASIC AND MECHANICAL COOLER

Since the CCD is an integrated type detector, it has a relatively poor time resolution, resulting a pile-up problem. There is a tight constraint on the increase of electronics if they are made of discrete electronic parts. The first ASIC for space use CCD is developed for the pn-CCD on board Newton. We have been developing a readout ASIC for X-ray CCDs. We fabricated the MD01 employing a 0.35 µm CMOS process provided by Taiwan Semiconductor Manufacturing Company (TSMC), with 2 poly-silicon layers, 5 metal layers and a deep N-well. We employed a ∆Σ modulator to obtain moderate speed and moderate accuracy. The size of the bare chip is 3mm x 3mm where there are four analog circuits. The noise level is about 34µV that is comparable with the analog circuits employing discrete components. We have evaluated the radiation hardness of this ASIC. Then we have improved the design and fabricated the MD02 ASIC that properly functions as we expected. The noise level is 30~40 µV and the pixel rate is up to about 1 MHz. The power consumption is less than 100 mW/chip. Using this type of ASIC, we can reduce the power consumption and the mass of the electronics for the future satellite mission.

The CCD requires the working temperature low so that we can reduce the thermal noise. So far, we employed the thermo-electric cooler to reach the required working temperature. However, it is difficult to gain a big temperature difference by using the peltier device. The temperature difference is practically attainable at most 50°C. If we assume the satellite to be put into a LEO, we can reach -90°C by using the peltier device. Since we require the working temperature of the CCD to be -120°C from the CCD performance, we have to employ

![Figure 6. The mechanical cooler (SR2110) developed for space use. A similar type of the cooler is functioning properly on the SUZAKU satellite for more than 3 years.](image-url)
a mechanical cooler. The Sterling coolers shown in Fig.6 are employed in Suzaku where the cooler is properly working in orbit for more than 3 years. We will employ a similar type of the cooler (SR2110: fabricated by SHI) for the NeXT CCD camera. It is working with higher efficiency than that of the thermo-electric cooler, we will reach the temperature to be -120° with the hot side to room temperature. Based on the camera design, this temperature condition can be easily achieved by the mechanical cooler. We will use two mechanical coolers for redundancy.

5.2. SXI AND ITS PERFORMANCE

Fig.7 left shows the block diagram of the SXI. We will use either NeXT2 CCDs or 2K4K CCDs. Fig.8 shows the expected efficiencies for the SXI. SUZAKU CCDs are also plotted for comparison. The P-channel CCD is expected to have higher efficiency at all energy range than the N-channel CCD. The first target is to employ 2K4K CCDs that are BICCD with thick depletion layer. These CCDs will have an Al coat so that we can eliminate the optical blocking filter. If we employ the BICCD, we have to add an thin plastic layer on the CCD to prevent EUV photons from entering into the CCD. The thin plastic layer will be also directly attached to the CCD. This enables us to launch the camera in non-vacuum condition that may eliminate the door opening mechanism used both in ASCA and in SUZAKU.

We will employ the mechanical cooler instead of the thermo-electric cooler. Fig.7 right shows the mechanical structure of the CCD camera where there are two sets of cooler: each consists of a compressor and a cold head. The camera body will be a heat path and thermally connected to the satellite base. Therefore, the camera body will be around +20°C while the CCD chips inside are around -120°C. We will have a heater so that we can evaporate the possible contaminants from the CCD surface.

We will employ the analog ASIC that can be placed near the CCDs. All the ASIC outputs are digital signal (LVDS) that will be taken care by the space wire.

6. SUMMARY

We have reported here the current plan of the SXI for the NeXT mission. The overall performance is tightly connected with the optics. The optics for the SXI is 6 m focal length and moderate imaging quality. Table 1 shows the fact sheet for the SXI. Since we want to employ the BICCD with relatively thick depletion layer and with a pixel size of 24μm square (the current pixel size for BICCD is 15μm square), the low energy X-rays usually form spread event. Therefore, we may have to run the system with on-chip binning mode either of 2×2 pixels or...
Figure 8. The expected efficiency of the SXI is plotted as a function of incident X-ray energy. Efficiencies of SUZAKU CCDs are also plotted for comparison.

Table 1. Fact sheets for the SXI (expectation)

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<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Energy range</td>
<td>0.2~20 keV</td>
</tr>
<tr>
<td>Imaging area</td>
<td>31 mm × 31 mm / chip</td>
</tr>
<tr>
<td>Total imaging area</td>
<td>62 mm × 62 mm</td>
</tr>
<tr>
<td>Field of view</td>
<td>35′.5 × 35′.5</td>
</tr>
<tr>
<td>Pixel size</td>
<td>24 μm × 24 μm</td>
</tr>
<tr>
<td># of pixels</td>
<td>1280 × 1280 / chip</td>
</tr>
<tr>
<td># of read-out node</td>
<td>4/chip (use 2 out of 4)</td>
</tr>
<tr>
<td># of video chain</td>
<td>8</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>≤ 140 eV @ 6 keV</td>
</tr>
<tr>
<td>Depletion layer depth</td>
<td>≥ 200 μm</td>
</tr>
<tr>
<td>Read-out speed</td>
<td>≥ 100 kHz / node</td>
</tr>
<tr>
<td>Working temperature</td>
<td>≥ -120°C</td>
</tr>
<tr>
<td># of chips</td>
<td>4</td>
</tr>
<tr>
<td>Performance life</td>
<td>≥ 5 years</td>
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3×3 pixels. Even in 3×3 pixels, the effective pixel size is less than 2′.5. If we have to set the over-sample rate with the PDF of the optics to be 8, our system will fully function with the 20′ optics.

There are many items we have to carefully measure or solve. We can perform most of them based on our experience of previous satellite missions. Since this is the first time to employ a thick depletion layer, we have to study how we can analyze the data whether or not the grade method is acceptable or the fitting method is
needed. We will study the system both in the actual calibration and in the usage of the simulator like GEANT4.

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