Performance of a newly developed SDCCD for X-ray use

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Abstract
A Scintillator Deposited CCD (SDCCD) is a wide-band X-ray detector consisting of a CCD and a scintillator directly attached to each other. We assembled the newly developed SDCCD that the scintillator CsI(Tl) is below the fully depleted CCD. The incident X-rays enter the CCD depletion layer first. Then, X-rays passing through the depletion layer are absorbed in the scintillator. The contact surface of the CCD is a back-illuminated side so that we can have good light collection efficiency. In our experimental setup, we confirmed good performance of our SDCCD detecting many emission lines up to 88 keV that comes from \textsuperscript{109}Cd.

Keywords: Charge-coupled device, Photon counting, Scintillator, Hard X-ray imaging

1. Introduction
A new type of X-ray detector, SDCCD (Scintillator Deposited CCD) was proposed (Miyata and Tamura, 2003). It consists of a CCD and a scintillator that are directly attached to each other. The CCD detects X-rays absorbed in the depletion layer. Since the CCD is made of silicon wafer, it is difficult to extend the effective energy range above 20 keV. The SDCCD employs a fully depleted CCD and is fabricated such that X-rays passing through the depletion layer are absorbed in a scintillator, which extends the CCD energy range up to 100 keV.

When X-rays are photo-absorbed in the scintillator, they produce some amount of visible photons whose number is proportional to the incident X-ray energy. Then visible photons are absorbed in the CCD to form an electron cloud. The conversion gain of the configuration. Furthermore, the light collecting efficiency of visible photons.

The bottom side of the scintillator has an Al coat so that visible lights are efficiently collected. This is a columnar shape scintillator with a column size about a few \(\mu\)m in diameter that was already employed in the previous SDCCD. The bottom side of the scintillator has an Al coat so that visible lights are efficiently collected. This is a columnar shape scintillator with a column size about a few \(\mu\)m in diameter that was already employed in the previous SDCCD. The bottom side of the scintillator has an Al coat so that visible lights are efficiently collected. This is a columnar shape scintillator with a column size about a few \(\mu\)m in diameter that was already employed in the previous SDCCD. The bottom side of the scintillator has an Al coat so that visible lights are efficiently collected. This is a columnar shape scintillator with a column size about a few \(\mu\)m in diameter that was already employed in the previous SDCCD.
We developed the method of obtaining a good optical contact between the CCD and the CsI(Tl). Before assembling the SDCCD, we tested the method by using a flat glass instead of the CCD. The scintillator was about 3cm×6cm and the glass was a little bigger than that. We visually inspected that our method left no visible bubbles inside the optical cement. Then, we assembled the SDCCD by using this method. We have to limit the working temperature of the SDCCD to be –55°C that is limited by the temperature allowance of the optical cement.

The CCD employed is called 2K4KCCD that is fabricated in the Hamamatsu photonics K.K. It is a fully depleted p-channel type CCD and has a depletion layer of 200 µm. The pixel size is 15 µm square and the chip size is 3cm×6cm. When we use it as a frame-transfer mode, the imaging area is 3cm×3cm. This device is developed with a collaboration of the NAOJ \cite{Kamata2004, Kamata2006}. It is primarily used as a BI CCD that there is no gate structure in the entrance of X-rays (back side). There is an AR coat for optical use or an Al coat for X-ray use. In our case, no gate side is attached to the scintillator and the gate side (front side) is the entrance of X-rays.

Figure 2 shows the detection efficiency of our SDCCD. After passing the gate structure, X-rays below 15 keV are mainly absorbed in the depletion layer of 200 µm Si of which the detection efficiency is shown in red line. X-rays above 15 keV, passing through the depletion layer and the optical cement, are absorbed in the 300 µm CsI(Tl) scintillator of which the detection efficiency is shown in green. Sum of them is also shown in blue. Since our CCD is fully depleted, the X-ray absorbed in the CCD forms a primary charge cloud as that in the general X-ray CCD (CCD event). The charge cloud size is quite small, resulting to be a single pixel event or two-pixel split event. When it enters into the pixel corner, it may form a four-pixel split. The X-ray absorbed in the scintillator generates visible lights that enter into the CCD (scintillator event). Although visible lights form a charge cloud, it is much bigger size than that absorbed in the CCD. We can expect that the CCD event forms a compact charge size with relatively a large signal while the scintillator event forms a wide-spread charge size with relatively a small signal. Therefore, we can expect to distinguish them with a signal shape.

3. Experiment and results

3.1. Data taking in 16×16 binning mode

We mainly employ $^{109}$Cd as a calibration source. We run the CCD in a various binning mode in which n pixel × n pixel data are on-chip sum. In no-binning mode, we can detect CCD events while scintillator events are difficult to be seen. Then, we increase the number of binning. In figure 3, we show a part of the frame image in 16×16 binning mode. We can see two types of events. One is a single pixel event and the other is a split pixel event. In this mode, the practical pixel size is 240 µm square. Therefore, almost all the CCD events form single pixel events. Split pixel events (up to 2×2 pixels) by CCD events are expected to be about a few %. However, we see many split pixel events, splitting into 3×3 pixels.

Scintillator events are generated in the CsI(Tl) with a thickness of 300 µm. The spread of the scintillation lights will be an order of its thickness. Therefore, when we observe them
in practical pixel size of 240 µm square, they will confine in a 3x3 pixels. If the spread of signal is within 3x3 pixels, we can easily apply the standard X-ray analysis tools, a grade method, that are developed for the X-ray satellites, ASCA (Tanaka et al., 1994) and SUZAKU (Mitsuda et al., 2007). The grade method is widely employed in the data analysis in X-ray astronomy. It analyzes the data of 3x3 pixels for each X-ray event and sorts pixels whether or not they exceed the threshold. There is another method, a fitting method. The fitting method is to fit the data of 5x5 pixels by a Gaussian profile (Tsuru et al., 2001) that requires more data and analysis time than those of the grade method.

Figure 4 shows a spectrum of X-rays from Cd. We employed the grade method in the data analysis. We took events of G0,2,3,4,6 that is the standard criteria in the X-ray spectrum analysis. Ag-Kα/β are clearly seen. Furthermore, we see a peak around 3.5 keV that is seen only in the SDCCD. Therefore, the scintillator events yield charge signals that are approximately 1/6th as big as those derived from CCD events.

CCD events can be easily distinguished the Ag-Kα from the Ag-Kβ. The apparent intensity of Ag-Kα is about 6.7 times larger than that of Ag-Kβ. In the scintillator events, these two X-rays form a single peak due to the poor energy resolution of the CsI(Tl). We can calculate the number of scintillator events expected. If we set the thickness of the depletion layer to be 200 µm and that of the scintillator to be 300 µm, we expect that the number of the scintillator event is 7 times more than that of Ag-Kα. Our data show the intensity ratio to be 6.9 that is consistent with our expectation.

The scintillation light yield of the CsI(Tl) scintillator (Valentine et al., 1993) depends on the working temperature, peaking about 60 visible photons/keV at –30°C. It reduces to about 80% of its peak value at –55°C. The scintillation light from CsI(Tl) shows a peak value around 550 nm. The quantum efficiency of the 2K4K CCD is about 85% at this wave length. With taking into account these conditions, the expected number of electrons generated inside the CCD is 20–40 electrons/keV, depending on the reflection efficiency of the Al coat on the back surface of the scintillator. We obtain the peak of the scintillator events to be 3.5 keV, which shows that we detected about 40 electrons/keV. Therefore, we confirm that the Al coat on the bottom of the CsI(Tl) functions properly.

In the 16x16 binning mode, we can employ the grade method that is well established in the X-ray Astronomy. However, there is a problem in covering a wide energy range. Our electronics (12-bit ADC) is saturated around 30 keV/pixel. If we find a pixel saturated in 3x3 pixels, we will discard the event. Since the effective pixel size is 240 µm, almost all the CCD events generate single-pixel event. Therefore, the CCD events above 30 keV cannot be properly analyzed. Furthermore, the CCD operation of 16x16 binning mode will increase the noise level, particularly at the working temperature of –55°C.

3.2. Data taking in no binning mode

SDCCD can detect high energy X-rays while the energy resolution is poor which is limited by the scintillator. If we can detect X-rays as CCD events, we can achieve a good energy resolution. Therefore, it is quite useful to detect high energy X-rays as CCD events although the detection efficiency for such a case is low. In this context, we set up the experimental configuration such that X-rays from Cd source enter into the CCD in a grazing angle. Furthermore, we restricted the X-ray path by using a metal guide so that we could expect many fluorescence lines. Figure 5 shows the setup of the SDCCD in which we run it in a frame-transfer mode.

We ran the CCD in no binning mode by irradiating X-rays from Cd. The pixel size is only 15 µm square. We analyzed the data by using a fitting method that can take care of both the compact events and spread events. Figure 6 shows the spectrum. There are many strong emission lines most of which are originated from CCD events. X-rays of Ag-Kα (22.1 keV) and Ag-Kβ (24.9 keV) come from the electron capture of Cd. Emission lines of Cr-K (5.4 keV), Fe-
K (6.4 keV), Cu-K (8.04 keV), Zn-K (8.6 keV) come from the metal guide excited by Ag-K X-rays. We notice that there is a CCD event at 88 keV that are nuclear metal guide excited by Ag-K X-rays. We notice that there is a peak around 1.7 keV that is not detected in 16×16 binning mode. Half of the visible signals are well below the detection threshold. If this peak comes from Ag-K X-rays, the intensity is about 1% of the expected value in the previous section. Therefore, almost all the signals are missing due to a large spread of signal. Furthermore, the peak is only half that is detected in 16×16 binning mode. Half of the visible signals generated in the CsI(Tl) directly enters into the CCD while the other half transfers to the opposite direction of the CCD and reflects at the Al coat. The reflected light will widely spread on the CCD and be missing. Only when the scintillation lights are generated very close to the CCD, direct lights will form relatively compact events that are detected. This is consistent with that the no-binning data form a peak that is just half that formed in 16×16 binning data.

3.3. Summary

We have fabricated a new type of SDCCD. The incident X-rays enter into a fully depleted F1 CCD. Soft X-rays (below 15 keV) are photo-absorbed in the depletion layer and form CCD events. Hard X-rays (above 15 keV) penetrate the CCD and are photo-absorbed in the CsI(Tl). Scintillation lights enter into the CCD where they form extended event.

There are two methods of analyzing data: a grade method and a fitting method. The grade method is well established in the X-ray astronomy. We have to run the SDCCD in 16×16 binning mode to obtain both the CCD events and the scintillator events where we can apply the grade method. However, it shows an energy limit for CCD events. We ran the CCD in no binning mode so that we can apply the fitting method. This method shows good results for CCD events while it does not work well for scintillator events. We show that the CCD events has a good linearity up to 88 keV between the incident X-ray energy and the charge generated in the CCD. We need to develop an analysis method of taking care of both CCD events and scintillator events simultaneously.

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