Development Status of Scintillator-directory-coupled CCD onboard FFAST

Ryo Nagino\textsuperscript{1}, Hiroshi Nakajima\textsuperscript{1}, Masaaki Sadamoto\textsuperscript{1}, Masayuki Sasaki\textsuperscript{1}, Hiroshi Tsunemi\textsuperscript{1}, Kiyoshi Hayashida\textsuperscript{1}, Naohisa Anabuki\textsuperscript{1}, Hisashi Kitamura\textsuperscript{2}, Yukio Uchihori\textsuperscript{2} and FFAST/SDCCD team

\textsuperscript{1} Osaka University, Machikaneyama-cho 1-1, Toyonaka-shi, Osaka, Japan
\textsuperscript{2} National Institute of Radiological Science (NIRS), Anagawa 4-9-1, Inage-ku, Chiba-shi, Chiba, Japan

\textit{E-mail(RN): nagino@ess.sci.osaka-u.ac.jp}

\section*{Abstract}
We have developed Scintillator-directry-coupled CCD (SDCCD) for FFAST. SDCCD is the imaging device that realizes sensitivity to 100 keV by pasting up a scintillator on CCD directly. To verify the proper function in space, we irradiated 100 MeV proton with SDCCD. As a result, we confirmed the CCD recovering effect both for Dark Current and CTI. After we leave the device at room temperature for 150 hours, the derived CTIs are similar or lower than those of ASTRO-H/SXI and Suzaku/XIS. The spread of the visible light generated in CsI is much bigger than that of the soft X-rays detected in the CCD. It is neccessary to establish new algorithm for spread events to convert the signal output into the incident X-ray energy. We have successfully detected the events originated from the CsI. We will also report the progress of the analysis for CsI spread events in new algorithm.

\textbf{Key words:} X-ray, FFAST, SDCCD

\section{1. FFAST mission and SDCCD}
FFAST is a large area sky survey mission at hard X-ray region with formation flying two satellites (Tsunemi et al. 2012; Tsunemi 2012, 2014). Two small satellites, a telescope satellite and a detector satellite, are put into the low earth orbit (LEO), and form an X-ray optics. The X-ray telescope satellite carries a multilayer super mirror which can focus hard X-ray up to 80 keV. On the other hand, the detector satellite carries SDCCDs. The distance between two satellites is kept constant to be 20m±5cm. The observation direction is scanning the sky and pointing to a fixed direction.

We have developed SDCCD for employing on FFAST (Tsunemi 2005). The CCD chip in the SDCCD is fully deplated which can be a back-illuminated CCD. The scintillator, its thickness is ∼ 300 μm, is directly attached to the CCD at back side so that it has high detection efficiency for visible photons generated inside the scintillator. Soft X-ray events are directly detected in the depletion layer of the CCD. On the other hand, Hard X-rays reach to the scintillator after penetrating the CCD. Then, they are converted to optical photons by the scintillator and detected by the CCD with high efficiency.

\section{2. Operating condition}
The same electronics as that of ASTRO-H/SXI is used to operate the SDCCD, which succeses at first time. In this experiment, we could drive the SDCCD as a full frame transfer (FFT) mode only due to hardware limitation. The event data are read out in a 4-seconds cycle after on-chip 8×8 binning. The device was cooled downed to -70 °C. In order to identify a proton beam irradiation position in spite of FFT mode, the all electric charges have to been swept out at the beginning of each read out cycle. The read-out of data is performed after that. There are four read out nodes, and we nominally use two of them. Thoughout this experiment, X-rays from $^{55}$Fe and/or $^{109}$Cd radio isotope source was irradiated to SDCCD.

\section{3. Proton irradiation test to SDCCD}
In order to verify the proper function of SDCCD in space, we have to understand the long-term performance degradation of SDCCD in the severe radiation environments. In addition, in the case of SDCCD, we must also investigate the influence of radio-activation of a scintillator.

Thus, we performed experiment of proton irradiation to verify the radiation tolerance of our device. We irradiated the SDCCD with 100MeV proton at HIMAC, corresponding to about 0.3, 1.0 and 3.0 years in orbit. Then, We have assumed that the CCD is surrounded by the aluminum shield with the thickness of 20 mm and the LEO of ASTRO-H. In this case, the deposited energy spectrum the CCD has calculated by Mori et al.
According to their result, we obtained a dose rate of 260 rad year$^{-1}$.

As a result, we confirmed the CCD recovering effect also in the time profile of the dark current as well as CTI. The effect of recovering can be seen immediately after the irradiation, and dark current recovered to the same level as that before proton irradiation after 150 hr. The degradation of the dark current and CTI seems to be originated to the damage in CCD, rather than CsI activation.

After 150 hr leaving at room temperature, the derived ∆CTI is $1.7 \times 10^{-6}$ for 1.0 year in LEO and $9.4 \times 10^{-6}$ for 3.0 years. This result is almost equal or even better CTI than those of the Suzaku/XIS and ASTRO-H/SXI (Fig. 1). By applying the temperature cycle up to $+20$ °C, SDCCD at least satisfies the mission requirement.

4. Analysis of the CsI events

The spread of the visible light generated in CsI is much bigger than that of the soft X-rays detected in the CCD. We can distinguish the events detected in the depletion layer from those detected in the scintillator by looking at the charge spread size. Therefore, we can properly convert the signal output into the incident X-ray energy. We have obtained the spectrum with $^{109}$Cd and successfully detected the CsI events (Fig. 2).

For CsI events spreading than 3×3 pixel, we are trying to analyze with new algorithm named Fitting Method. In this method, the grade method is once performed, and the detected events are fitted with a two-dimensional Gaussian function in the range of 5×5 pixels. Next, we integrates the central values of each pixel in the range of 7×7 pixels by using fitted Gaussian function.

The spectrum derived by Fitting Method is shown in Fig. 3. The derived peak is expected as 22 keV event of the CsI origin. But, in order to support this expectation, a number ratio with a CCD events is required.

5. Summary and Future works

We irradiated a SDCCD with 100 MeV proton to verify the radiation tolerance of the chip. The effects of recovering both for Dark Current and ∆CTI are confirmed. After 150 hr leaving at room temperature, the derived ∆CTIs is similar or lower than those of ASTRO-H/SXI and Suzaku/XIS.

We have successfully detected the events which can be expected as ones originated from CsI. But, a number ratio with a CCD events is required to support this expectation. In order to establish the optimal technique for the detection of CsI events, we will progress the analysis with fitting method.

References
Mori et al. 2013 NIMA, 731, 160
Tsunemi et al. 2012 Proc. of SPIE, 8443
Tsunemi 2014 Proc. of COSPAR Meeting, 39
Tsunemi 2012 Proc. of AIP Conference, 1427, 237–238
Tsunemi 2005 NIMA, 541 (1–2), 295–303