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Measurements of charge transfer efficiency in a proton-irradiated swept charge device*

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Abstract: Charged Coupled Devices (CCDs) have been successfully used in several low energy X-ray astronomical satellites over the past two decades. Their high energy resolution and high spatial resolution make them a perfect tool for low energy astronomy, such as observing the formation of galaxy clusters and the environment around black holes. The Low Energy X-ray Telescope (LE) group is developing a Swept Charge Device (SCD) for the Hard X-ray Modulation Telescope (HXMT) satellite. A SCD is a special low energy X-ray CCD, which can be read out a thousand times faster than traditional CCDs, simultaneously keeping excellent energy resolution. A test method for measuring the charge transfer efficiency (CTE) of a prototype SCD has been set up. Studies of the charge transfer inefficiency (CTI) with a proton-irradiated SCD have been performed at a range of operating temperatures. The SCD is irradiated by $3\times10^{8}\text{cm}^{-2}$ 10 MeV protons.

Key words: CCD, SCD, HXMT, LE, CTE, CTI, proton-irradiated

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1 Introduction

The Low Energy X-ray Instrument (LE) on the Hard X-ray Modulation Telescope (HXMT) satellite [1] is China's first low energy (1.0–15 keV) X-ray observation attempt. The HXMT mission is scheduled to be launched in early 2015, with a planned mission duration of four years, and will have a 550 km circular orbit around the earth. A major part of the HXMT, the LE is an X-ray spectrometer with good energy resolution (full width at half maximum (FWHM) better than 450 eV at 5.9 keV), high time resolution (no more than one microsecond), and large detection area (384 cm^2).

Because satellites are subject to a harsh radiation environment that is filled with protons, neutrons and γ-rays, the study of radiation hardness is important for the application of CCD detectors in astronomy satellites [2]. The LE group has been developing and testing several CCDs for about six years. Previous experimental results on neutron irradiation were reported in Ref. [3]. This work focuses on an effective experimental measurement method to determine the charge transfer efficiency (CTE) of a Swept Charge Device (SCD), performed with a proton-irradiated SCD on a test stand in the Institute of High Energy Physics, Chinese Academy of Sciences, Beijing.

The particles to which the satellite will be exposed in orbit will cause damage to the SCD materials, leading to defects acting as charge traps in the silicon; in particular, the protons in the South Atlantic Anomaly (SAA) can have serious consequences for the SCD. The mechanism by which these traps are created has been discussed in the literature [4]. In phosphorus-doped devices, like SCDs, two types of traps can be created [5]. A trap can capture about one electron per microsecond, increasing dark current, thus causing apparent fluctuation in the electron cloud signal. The result is a charge transfer inefficiency and degradation of energy resolution in the SCD.

The LE is in development and undergoing a series of

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space environment tests. The LE's SCD unit runs at a readout frequency of 100 kHz. In this paper, we demonstrate a simple and effective method to determine the CTE with a proton-irradiated SCD. This method is crucial for checking the performance of the SCD in environment tests like thermal cycle, proton irradiation and γ irradiation tests.

2 SCD test stand and work modes

A test stand, as shown in Fig. 1, has been set up with a collimator and cooling unit. The temperature range of the cooling unit is from room temperature down to −100 ℃. This temperature has been achieved with cold nitrogen gas by boiling liquid nitrogen. The very low operating temperature is required to suppress the dark current and keep the SCD sensitive to very low energy signals. The collimator attached to the cooling unit restricts the incoming X-rays so that they fire as few pixels as possible. The collimator is machined from a whole aluminium block by line-cutting. The minimal grid of the collimator is about 1.47 mm, which is much longer than the size of a pixel, 0.1 mm. We, therefore, attach a copper film of thickness 0.5 mm to the top of the collimator, with a 0.5 mm diameter hole punched in the copper film. The hole further reduces the number of pixels with which the X-ray reacts. A 0.5 mCi $^{55}_{26}$Fe radioactive source is attached to the top of the copper film using black 3 M tape. The $^{55}_{26}$Fe is uniformly distributed over a copper disk by electroplating. The whole test stand is enclosed in a low temperature vacuum tank.

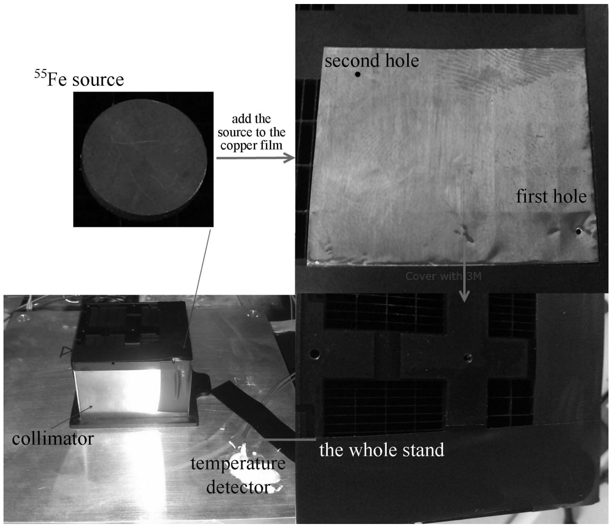

Fig. 1. SCD test stand.

Using this test stand, we can obtain different responses from different pixels by changing the work mode of the SCD. The SCD was produced by E2V (English Electric Valve Company Ltd.) and is a relatively large area four-quadrant detector with an active area of 400 mm^2. The active area of the four quadrants is covered by a total of 100 "L" electrodes, as shown in Fig. 2. The "L" electrodes are depicted as dashed lines without arrows in the figure, and the arrow lines stand for the direction of charge transfer. The charge only needs to be transferred along one dimension because of the "L" electrodes, so the time to transfer one frame is about 1 ms, which is much less than that of normal X-ray CCDs. The pixel and electrode are almost the same in this SCD, but they are different from two-dimensional CCDs. One pixel is an "L" electrode while the first pixel is only one point, and the last pixel is a 10+10 mm long "L" electrode [6].

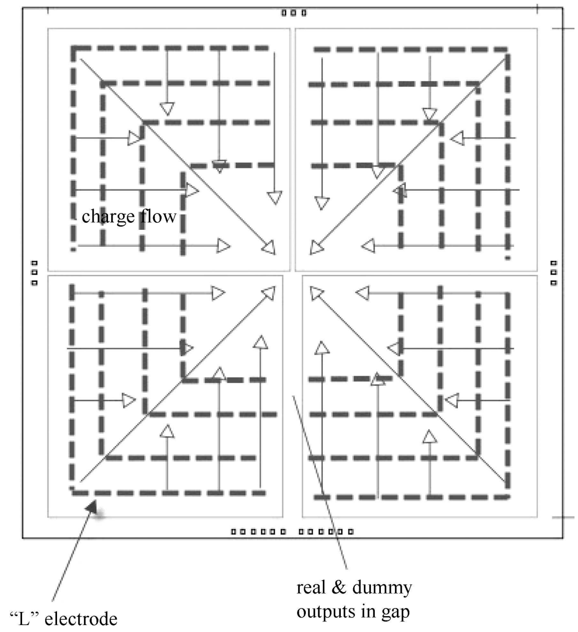

Fig. 2. Schematic diagram of SCD.

Because of the one-dimensional readout, there are only two work modes for the SCD: the spectrum mode and the long exposure mode. The spectrum mode is a normal readout sequence for shaping spectra, under which the readout is reset for each sequence clock. The spectrum mode is usually adopted in tests in order to obtain high energy and time resolution X-ray spectra. In addition to the spectrum mode, the charge packet can be stored at the pixel for many sequence clocks. The whole active area is then read out by 100 continuous clocks. This mode is called the "long exposure mode". Through this operation of charge transfer, we can learn the dark current for every electrode and check whether any of the electrodes is a "hot pixel" which generates a dark current above the normal level. More importantly, the long exposure mode can show the one-dimensional position distribution of the SCD with accurate pixel position information.

When the $^{55}_{26}$Fe radioactive source is fixed on the copper film with the hole, the $^{55}_{26}$Fe can irradiate several pixels (electrodes) of the SCD through the hole. Under the SCD's long exposure mode, the position distribution of X-rays on the 100 electrodes can be revealed, as shown in Fig. 3.

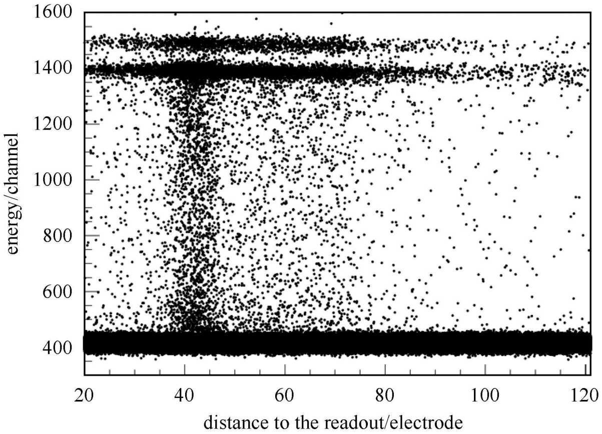

Fig. 3. The position distribution of X-rays under long exposure mode. The position of the hole is at about the 22nd pixel.

The lower part of the scatter diagram (about channel 400) consists of noise events, while the middle and top part of the scatter diagram are the Mn kα (about channel 1400) and Mn kβ (about channel 1500) events. Through this operation the hole position correspondence to the pixels is confirmed, giving the reaction area of X-rays in the SCD. We then change the SCD to spectrum mode and acquire sufficient events to fit the performance parameters at different temperatures. After these operations in the two modes, the response for one hole is obtained. When we change the $^{55}_{26}$Fe radioactive source to the other hole in the copper film and perform the same operations as for the first hole, the other hole position's correspondence to pixels and the performance parameters at different temperatures can be confirmed. Since the CTE is used to represent the efficiency of charge transfer from one electrode to another, it can be reasonably determined from the responses of the two holes.

3 Proton irradiation

The irradiation was performed successfully at the China Institute of Atomic Energy (CIAE). The beam energy was measured to be 10 MeV at the SCD, irradiating the whole active area of the SCD. The 10 MeV proton fluence delivered to the SCD was 3×10^{8} cm^{-2} protons over a period of 110 minutes, and the beam flux was about 4.6×10^{4} cm$^{-2}\cdot$s^{-1}. The field uniformity was measured by CIAE, and was found to be less than 80%.

4 Signal measurement at different positions

The signal measurement with two holes is designed to determine the CTE of different pixels. The measurement procedure for the first hole is as follows. First, we put the $^{55}_{26}$Fe radioactive source on the first hole above the 88th pixel from the readout. We then acquire the events under long exposure mode and plot the scatter diagram of the first hole. Through Gaussian fitting in ROOT, the mean position of the first hole as read by the SCD is confirmed, as shown in Fig. 4.

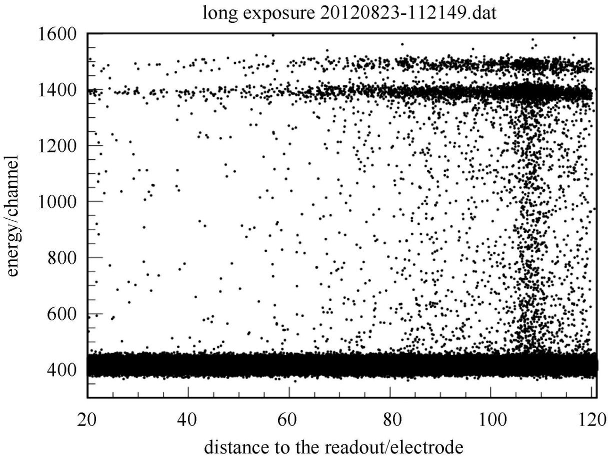

Fig. 4. The X-ray position distribution of the first hole in a proton-irradiated SCD. The position of the hole is at about the 88th pixel.

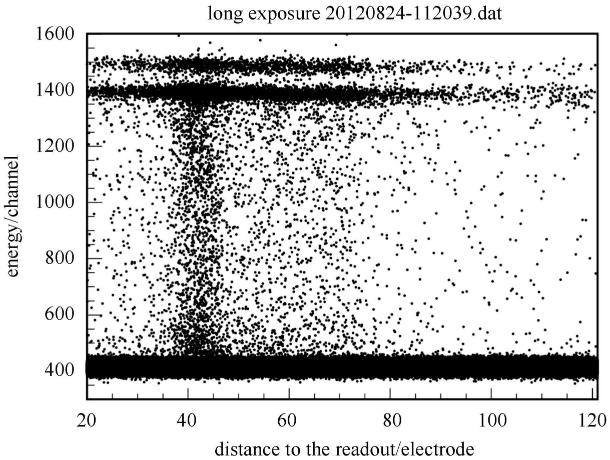

Fig. 5. The X-ray position distribution of the second hole in a proton-irradiated SCD. The position of the hole is at about the 22nd pixel.

For the third step, large numbers of X-ray events were acquired under the spectrum mode as the temperature of the SCD rose. Since the SCD was in continuous operation while the temperature rose slowly, the signals corresponding to different temperatures were obtained at the end through Gaussian fitting. The measurements were taken in a low temperature vacuum tank with a minimum temperature of −100 ℃ and a vacuum pressure of 10^{-5} Pa. For the second hole the measurement procedure is the same, simply moving the $^{55}_{26}$Fe radioactive source to the second position above the 22th pixel from the readout. The second hole position as read by the SCD is confirmed in Fig. 5, and the signal-temperature curves for the two holes are shown in Fig. 6.

The signal amplitude of the pixels nearer to the readout is obviously higher than that of the far pixels. The signal-temperature curve of the far pixels is non-linear, with a sharp decrease over the temperature range from −70 ℃ to −40 ℃. This indicates that low temperatures are helpful in charge transfer in SCDs irradiated by protons. In addition, the measurement of signal amplitude needs to meet the requirements of high stability and repeatability. In our test, we keep the test stand almost unchanged, only moving the $^{55}_{26}$Fe radioactive source slightly. Therefore, the two noise peaks in the measurement shown in Fig. 7 are almost identical.

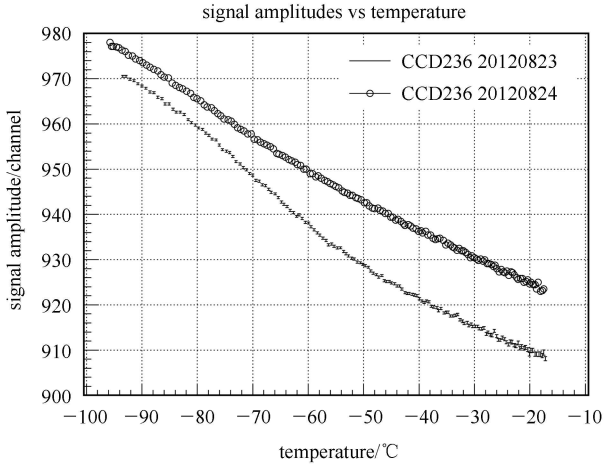

Fig. 6. The signal-temperature curves of the two holes. The blue line is the signal amplitude of the second hole, which is nearer to the readout than the first hole.

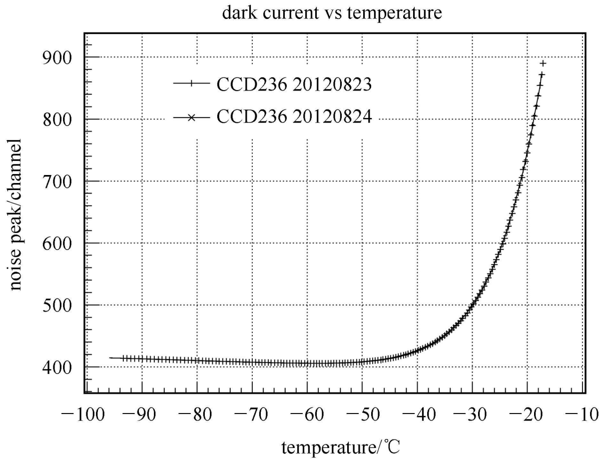

Fig. 7. The noise peaks for the two holes in CTE measurements.

The noise peak is the background for the signal and is eliminated in calculating the final signal amplitude, which can confirm the credibility of the signal amplitude.

5 Calculation of the CTE

In the above test, the two signal amplitudes corresponding to the two holes are determined for a temperature range from about −90 ℃ to −20 ℃. If the CTE of every pixel is assumed to be the same, then the CTE can be reasonably calculated using Eq. (1).

$$\text{Amplitude1}=\text{Amplitude2}\times\text{CTE}^{\text{Pixel2}-\text{Pixel1}},\qquad(1)$$

where Pixel1 and Pixel2 are the electrode order numbers from the readout for the first and second hole, respectively. Similarly, Amplitude1 and Amplitude2 stand for the signal amplitudes of the two holes. Fitting of the data shows that Pixel1 is about 88, and Pixel2 is about 22. Amplitude1 and Amplitude2 can be obtained from the events acquired under spectrum mode. By calculating from Eq. (1), the CTE is found to be as shown in Fig. 8.

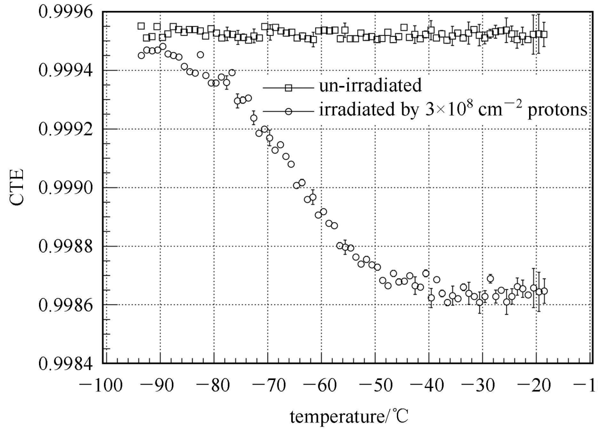

Fig. 8. The CTE of a proton-irradiated SCD (CCD236).

As shown in Fig. 8, the CTE is sensitive to temperature. Low temperature is helpful to achieve low CTI (Charge Transfer Inefficiency) for proton-irradiated SCDs. This result affirms the importance of thermal control of the LE, which can also suppress the dark current in the instrument [7].

6 Conclusion and outlook

A proton-irradiated SCD is operated at a range of temperatures from −70 ℃ to −40 ℃ with different operation modes. The spectrum and energy distribution of a $^{55}_{26}$Fe radioactive source are acquired with the SCD. The CTE is calculated from the comparison of the two signal amplitudes corresponding to the two holes. The noise peaks are almost the same, which shows that the method of CTE measurement is reliable. The CTE value is sensitive to high temperature, indicating the necessity of low temperature. Further CTE measurements with a γ-irradiated SCD are planned. We will also try to measure the CTE of SCDs using a more convenient and effective method based on the integration of dark current under the long exposure mode.

References

1 LI T P. Nuclear Physics B, 2007, **166**(Proceedings Supplements): 131–139

2 Smith D R, Gow J, Holland A D. Nuclear Instruments and Methods In Physics Research A, 2007, **583**: 270–277

3 WANG Y S et al. Chinses Physics C (HEP & NP), 2012, **36**(10): 991–995

4 Ambrosi R M, Smith D R et al. Nuclear Instruments and Methods in Physics Research B, 2003, **207**: 175–185

5 Sopczak A et al. IEEE Nuclear Science Symposium Conference Record, 2008, **N30-482**: 2639–2644

6 Gow J, Holland A D, Pool P. UV, X-ray, and Gamma-Ray Space Instrumention for Astronomy XVI, 2009, **743**: 74350V-1–74350V-9

7 WANG Y S et al. Chinses Physics C (HEP & NP), 2010, **34**(12): 1812–1817