Low temperature testing and neutron irradiation of a swept charge device on board the HXMT satellite*

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Abstract: We present the low temperature testing of an SCD detector, investigating its performance such as readout noise, energy resolution at 5.9 keV and dark current. The SCD's performance is closely related to temperature, and the temperature range of −80 ℃ to −50 ℃ is the best choice, where the FWHM at 5.9 keV is about 130 eV. The influence of the neutron irradiation from an electrostatic accelerator with fluence up to 1×10^9 cm^{-2} has been examined. We find the SCD is not vulnerable to neutron irradiation. The detailed operations of the SCD and the test results of low temperature are reported, and the results of neutron irradiation are discussed.

Key words: SCD, HXMT, energy resolution, readout noise, neutron irradiation

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1 Introduction

The Low Energy X-ray Instrument (LE) to be flown on the Hard X-ray Modulation Telescope (HXMT) satellite [1] is the first low energy X-ray observation (1.0–15 keV) attempt of China. The HXMT mission is scheduled to be launched in 2014, with a planned mission duration of 4 years in a 550 km circular orbit around the earth. The LE is an X-ray spectrometer requiring good energy resolution of FWHM less than 450 eV@5.9 keV, high time resolution of no more than 1ms and large detection area. The CCD detectors are capable of yielding high resolution spectroscopy whose FWHM could be 140 eV at 5.9 keV. In addition to the high detection efficiency and high energy resolution, the CCD also has better position resolution than traditional solid state X-ray spectrometers. After comparing several detectors,the Swept Charge Device (SCD), a new type of Charge Coupled Device (CCD) is selected for the LE. The SCD can process high energy resolution like a traditional CCD, and has a quick readout of one frame (time response). However, there are several disadvantages of the SCD. The SCD's dark current integrated in the charge transfer period could contribute to the overall system readout noise. The CCD's performance is also susceptible to space radiation such as protons, neutrons, heavy ions and so on. The dark current is usually reduced to an insignificant level by cooling the CCD to below −50 ℃. The radiation

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damage of the CCD usually makes the dark current increase to a significant level, where a lower temperature of less than −50 ℃ is necessary.

To ensure that the LE will remain operable for 4 years, it is important to know the SCD's principle and learn the SCD's characterization. Through many kinds of tests of the SCD, we have understood the SCD fully and got optimum parameters for long time stable working. It is also important to learn the space environment the LE will be exposed to, and understand the degree of radiation damage on the given fluence of space radiation. For CCD devices working on the low earth orbit, the main kinds of radiation damage of concern are protons in the earth's radiation belts and solar protons. These protons could cause hot pixels from displacement damage and dark current increase from ionization damage [2]. The low energy neutrons on the low earth orbit could lead to the increase of dark current too [3]. The total proton and neutron fluences are obtained from the space radiation report of the HXMT satellite. The total proton and neutron fluences at the end of life of the LE are 1×10^{8} cm^{-2} and 1.2×10^{8} cm^{-2}, respectively. The structure and un-irradiated performance are described in the second section of this paper. The neutron irradiation experiment and simple results of proton irradiation are introduced in the third section. Finally, un-irradiation and post-irradiation characterization of the SCD is then described to get a limit radiation fluences on the SCD.

2 Swept charge device and its characterization

The SCD has been created by E2V (English Electric Valve Company Ltd.) and is a relatively large area four-quadrants detector having a 400 mm^2 active area. The active area of one quadrant is covered with 100 "L" electrodes, and the other quadrants have the same structure, as shown in Fig. 1. The "L" electrodes are depicted as the dashed lines without arrow in the figure, the arrow lines stand for the direction of charge transfer. The charge just needs to be transferred along one dimension because of the "L" electrodes, so its time for reading one frame is less than that of the normal X-ray CCDs by a great extent. The SCD needs 200 two phase clocks to read out the whole active area, meaning 1ms when the working frequency is 120 kHz (1s for traditional two dimension image CCD). The capacity of readout could be reset per sample or reset per several samples. The method of reset per sample is a normal readout sequence for shaping spectrum. The method of reset per several samples could make the split charge accumulate in the capacity, reducing the split events [4] to a certain extent. In addition to the above methods of charge transfer, the charge packet could be stored at the pixel for many periods, then the whole active area is read out by the method of reset per sample, called "long exposure sequence". Through this kind of charge transfer, we can learn the dark current of every electrode and check whether some electrodes are hot pixel or generate dark current over the normal level.

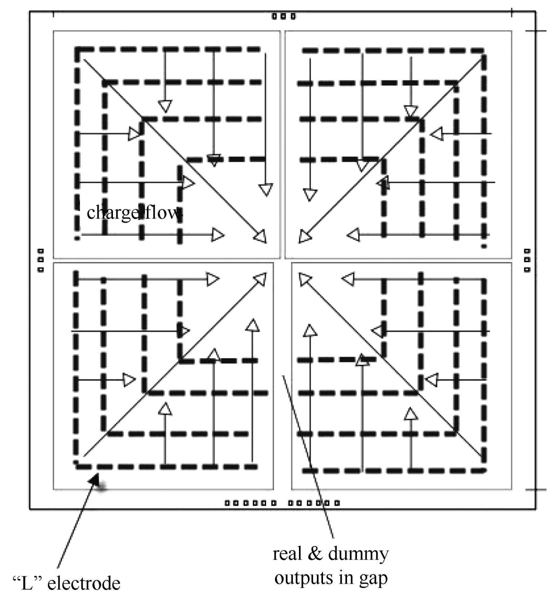

Fig. 1. Schematic diagram of the SCD.

The gap between the two down quadrants in Fig. 1 are the two output integrated circuits: the real output and the dummy output, which are useful for reducing common mode noise (CM). The voltage of the substrate is 9 V, higher than that of the electrodes (6 V), which is called "dither mode". Under dither mode clocking, the holes which occur on the SCD surface are suppressed because the silicon surface is inverted.

The SCD has been tested under a special instrument. It is cooled by liquid nitrogen and evacuated by complex vacuum pumps, which could maintain pressure less than 1×10^{-4} Pa and temperature no more than −100 ℃. The special instrument for the SCD is shown in Fig. 2. The performance of the SCD has been tested in the special instrument many times, to understand the SCD's operation and test electronic circuits.

Through multiple tests, we get the optimum working parameters of the SCD, as shown in Table 1.

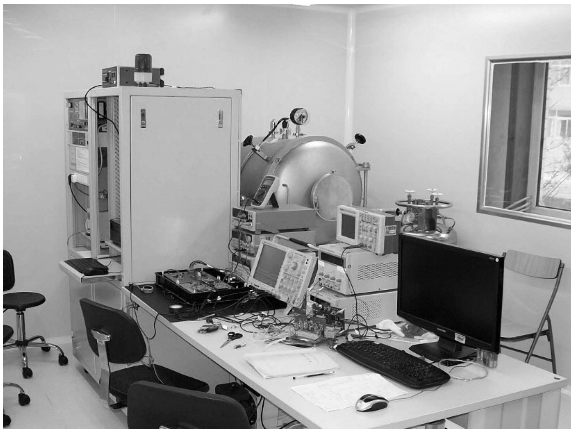

Fig. 2. A special instrument for the SCD.

Table 1. Optimum working parameters of the SCD.

reset gate2/V	17.0
clock phase1/V	6.0
clock phase2/V	6.0
substrate/V	9.0
barrier/V	2.5
output gate/V	2.5
frequency/kHz	50

We also detect that the energy resolution is best in the temperature range of −80 ℃ to −50 ℃, as shown in Fig. 3. When the temperature is more than −50 ℃, the dark current increases with increasing temperature obviously. Although it is normal that the lower temperature, the better the performance of the silicon device, all the events are split events when the temperature is less than −80 ℃, which is called “full split events”.

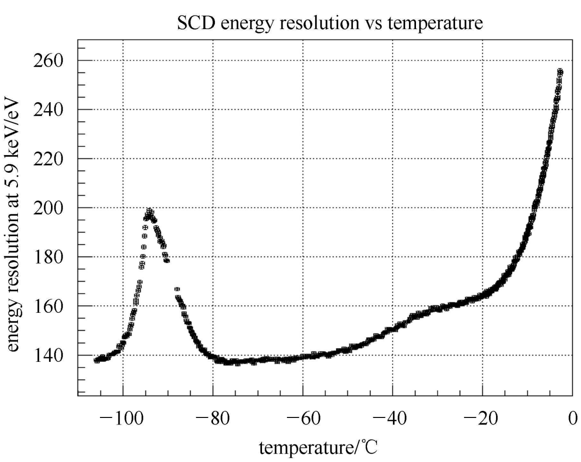

Fig. 3. The SCD’s energy resolution at 5.9 keV with change of temperature.

Therefore, we select the range of −80 ℃ to −50 ℃ as the future operational temperature on the basis of the test result. On the normal sequence of reset per sample, there are also some split events, which is called “normal split events” [5]. About 10 percent of all the events are split events at the future operational temperature, which make the energy resolution worse and the signal amplitude lower. We select the normal split events through the time interval between two events. When the interval is less than 80 μs, the two events are considered to be split events, if not, to be isolated events. As shown in Fig. 4, the energy resolution of the isolated spectrum is obviously better than that of raw spectrum. On the accumulating sequence of reset per several samples, most split events are accumulated to be isolated events, thus avoiding the post-data analysis [6].

The long exposure sequence of learning dark current is for checking the status of the “L” type electrodes. Because the length of the “L” type electrodes are different, the long electrodes away from the

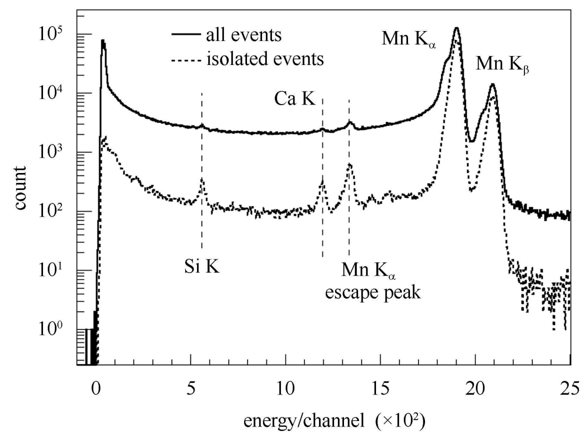

Fig. 4. The SCD’s raw spectrum and the corresponding isolated spectrum obtained using ^{55}Fe at −70 ℃. The number of split events are the difference of all and isolated events, which is about 20% of all events. (The ^{55}Fe peak is the main part of spectrum)

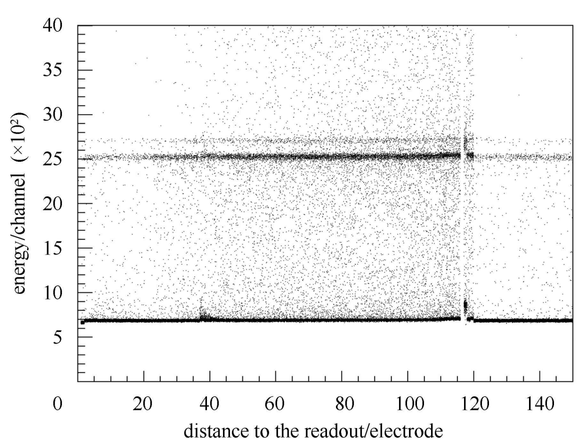

Fig. 5. The SCD’s dark current of every pixel using long exposure sequence (introduced in Section 2).

readout are more likely to have a defect. We detect a problematic pixel with over dark current on one of the SCDs, as shown in Fig. 5. Dark current of the next to last electrode is greatly over the average level of the other.

Under these sequences and selected temperature range, the performance of the SCD satisfies the need of the LE. The performance of the SCD after irradiation of protons and neutrons is measured under these sequences and temperature range, just for comparing the changes.

3 Neutron irradiation

3.1 The neutron irradiation facility

The neutron source at Peking University, Beijing has a beam line dedicated to low energy neutron damage testing, and is selected to evaluate the effect of low energy neutron damage on the SCDs used in the LE (see Fig. 6). This facility could generate two different energy neutrons, 14 MeV and 4.5 MeV.

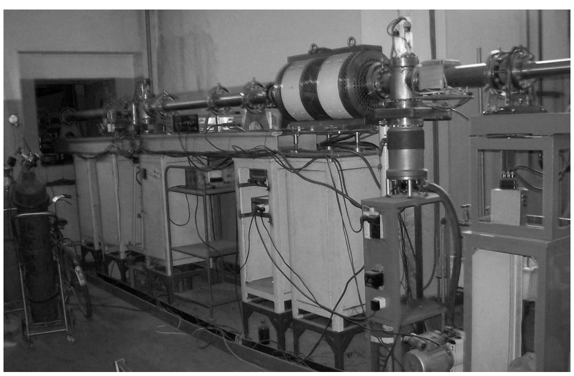

Fig. 6. The neutron source at Peking University, Beijing.

The 14 MeV neutrons are produced by the $T(d,n)^4He$ reaction using atomic deuterons bombarding a water-cooled titanium-tritide target. The 4.5 MeV neutrons are produced by the $D(d,n)^3He$ reaction using atomic deuterons bombarding a water-cooled titanium-deuteride target [7]. The neutrons from the reaction are diffused nearly equally in the directions. There is a neutron calibration device near the SCD and its test circuits. We obtain the number of neutrons which pass through the SCD from the neutron calibration device. Due to the need for low temperature and vacuum of the SCD, the SCD is packed in an aluminium vacuum tank with electric refrigeration, which can keep the SCD working under about −30 ℃ for rather a long time. Therefore, it is not convincing to test the on-line performance of the SCD. The effect of neutron damage is compared between performances of un-irradiation and post-irradiation.

3.2 The neutron spectra of the SCD

The SCD's response to the neutrons is helpful to check the neutron signal, which could be used to reduce the particle background of the LE. The SCD is irradiated by the 4.5 MeV neutrons, first. The SCD's response to 4.5MeV neutrons is shown in Fig. 7. Most of the events are low energy split events without obvious peak structure like ^{55}Fe. Then the 14 MeV neutrons are applied to the SCD the same as the 4.5 MeV neutrons. The two kinds of neutron spectrums shown in Fig. 7 and Fig. 8 are nearly the same, including low energy concentration, wide energy band response and many events whose energy is out of range of the circuit design ("events out of channel").

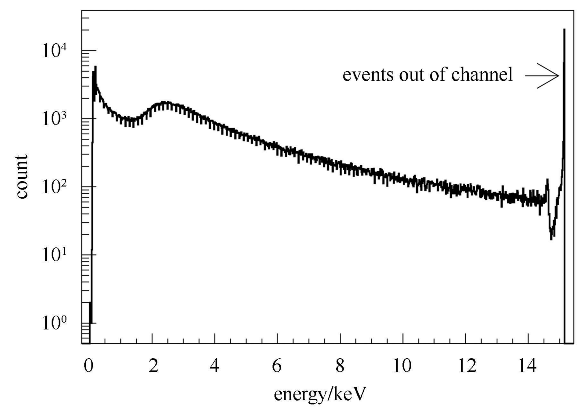

Fig. 7. The SCD's response to 2×10^8–2×10^9 4.5 MeV neutrons.

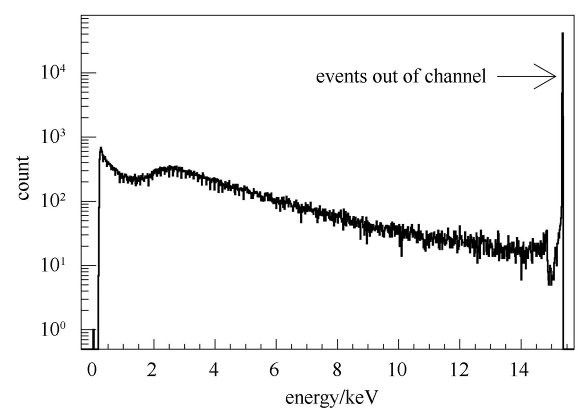

Fig. 8. The SCD's response to 3×10^8–3×10^9 14 MeV neutrons.

The total fluence of the SCD is 2×10^8–2×10^9 4.5 MeV neutrons and 3×10^8–3×10^9 14 MeV neutrons, respectively. The performances of un-irradiation and post-irradiation are compared. Unlike what is expected, the energy resolution and readout noise are almost unchanged, as shown in Fig. 9 and Fig. 10, respectively.

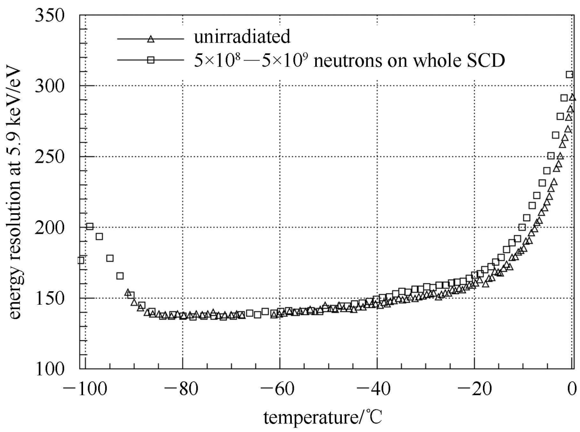

Fig. 9. The SCD's energy resolution(FWHM at 5.9 keV) as a function of temperature.

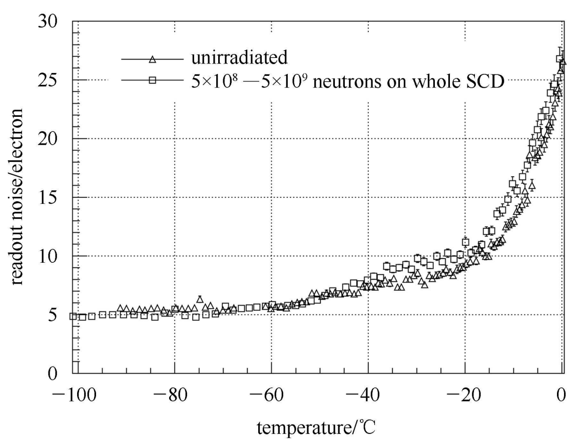

Fig. 10. The SCD's readout noise as a function of temperature.

The SCD's energy resolution and readout noise keep an ideal level after neutron irradiation, which can confirm that the SCD could work for 4 years on orbit without concern of neutron irradiation. The SCD is not vulnerable to neutron irradiation. It may be caused by a small cross section of nuclear reaction and little volume of the SCD. Additionally, the proton damage on the SCD is serious unlike that of the neutron. The energy resolution of the SCD has degraded from 140 eV to 450 eV in the temperature range of −80 ℃ to −50 ℃, which is the limit of the LE's performance.

4 Conclusion

In this paper, we investigate the performance of the SCD at low temperature and obtain several optimized voltages for low time operation. It is also discovered that the suitable temperature of the SCD is from −80 ℃ to −50 ℃, which can maintain the performance of the SCD best. On the other hand, we introduce our neutron irradiation experiment at Peking University. Through the neutron irradiation with fluence up to 5×10^8–5×10^9 on the whole SCD, we find that the SCD's performance has not been degraded unlike under proton irradiation. Therefore, neutrons could be confidently excluded from the concerned threats of the LE.

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