Readout electronics for a prototype high resolution soft X-ray spectrometer based on silicon drift detector

Er-Lei Chen 1, 2 Chang-Qing Feng 1, 2 Shu-Bin Liu 1, 2 Chun-Feng Ye 3

Dong-Dong Jin 4 Jian Lian 4 Hui-Jun Hu 4

*1 State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, 230026, China.*

*2 Department of Modern Physics, University of Science and Technology of China, Hefei, 230026, China.*

*3 705 Research Division, Electronic Engineering Institute, Hefei, 230037, China.*

*4 Shandong Aerospace Electro-technology Institute, Yantai, 264670, China.*

Corresponding author: Chang-Qing Feng, E-mail: [fengcq@ustc.edu.cn](mailto:fengcq@ustc.edu.cn)

**Abstract** The readout electronics for a prototype soft X-ray spectrometer based on Silicon Drift Detector (SDD), for precisely measuring the energy and arrival time of X-ray photons, is presented in this paper. The system mainly consists of two parts, i.e., an analog electronics section (including a Pre-Amplifier, a signal shaper and filter, a Constant Fraction Timing circuit, and a peak-hold circuit) and a digital electronics section (including an Analog-to-Digital Converter and a Time-to-Digital Converter). Test results with X-ray sources show that an energy dynamic range from about 1 keV to 10 keV with an Integral Non-Linearity (INL) less than 0.1% can be achieved, and the energy resolution is better than 160 eV @ 5.9 keV FWHM (Full Width at Half Maximum). Using a waveform generator, test results also indicate that time resolution of the electronics system is about 3.7 ns, which is much less than the transit time spread of SDD (< 100 ns) and satisfies the requirements of future applications.

**Keywords** Energy and time measurement · Soft X-ray detection · Silicon drift detector · Readout electronics

# Introduction

The X-rays emitted by galaxy clusters, black holes and neutron stars play key roles in revealing the extraordinary gravitational [1], electromagnetic, and nuclear-physics of the universe. Moreover, observation of X-rays from neutron stars will explore the exotic states of matter, of which the density and pressure are higher than in atomic nuclei, confronting theory with unique observational constraints [2]. It has been widely shown that the X-rays of pulsars are attractive in autonomous navigation due to their properties of stable, periodic and predictable signatures [3].

In recent years, therefore, a lot of projects involving soft X-ray detection in space have been carried out or planned, such as Suzaku [5], NICER [2] and LOFT [6]. The X-ray Imaging Spectrometer of Suzaku employs charge-coupled devices (CCD) for observations of celestial X-ray sources in the soft X-ray band from 0.2 keV to 12 keV. NICER adopts SDD for X-ray timing and spectroscopy of neutron stars in the soft X-ray band. While LOFT also adopts SDD for exploiting the diagnostics of rapid X-ray flux and spectral of neutron stars and black holes in the energy range of 2 keV ~ 50 keV.

Among the application of soft X-ray detection, Silicon Drift Detector (SDD), which can operate smoothly at close to room temperature with a Peltier cooler, is considered as an appropriate choice because of the advantages of high energy resolution and count rate capabilities. As for the SDD, an incoming photon can generate a number of electrons and holes, the holes drift towards the back side of the detector, while the electrons drift towards the anode electrode with a proper bias of a set of cathodes [7]. The accumulated charge at the anode is connected to the gate of a Field Effect Transistor (FET), which forms the first stage of a Charge Sensitive Amplifier (CSA).

A prototype high resolution soft X-ray spectrometer is under development, which is aimed at conducting astrophysical studies and also pushing forward X-ray based navigation as well as X-ray communication in space [8]. The adopted detector, i.e., SDD H30 [9] made by KETEK GmbH in Germany, has a maximum input count rate of 1000 kcps, and very good energy resolution performance. Its efficiency of X-ray is about 80% at 1 keV and 98% at 10 keV with an active area of 30 mm2. The readout electronics is described in the following text in detail.

# Architecture of the readout electronics

High-resolution time and charge measurement are widely used in nuclear physics [10-12]. Fig. 1 shows the block diagram of the Soft X-ray Detection (SXD) readout electronics for time and energy measurement, which is mainly composed of an analog electronics section and a digital electronics section.



Fig. 1 Block diagram of the SXD readout electronics.

In the analog electronics section, a Pre-Amplifier (PA) module, a High Voltage (HV) module and a Temperature Control (TC) module are specially designed by the Original Equipment Manufacturer (OEM) of the SDD. All the other modules following the PA are developed by the present authors. The output of PA is split into two channels. The one marked as ‘Q\_out’ from a slow shaper (Fig. 1) is for energy measurement, the other marked as ‘T\_out’ from a fast shaper (Fig. 1) is for time measurement.

In the digital electronics section, the ‘Q\_out’ is fed into an analog peak hold module, and then sampled by an Analog-to-Digital-Converter (ADC), while the ‘T\_out’ is converted into a hit signal by a Constant Fraction Timing (CFT) circuit, and then sent to a Time-to-Digital-Converter (TDC) for digitization. All the ADC and TDC results are buffered and fed into a Data Processor (DP) for processing. Simultaneously, the system can be monitored and controlled by the DP according to the standard Controller Area Network (CAN) protocol. The external power supplies of the whole electronics are ±6 V, +5 V and +12 V.

# Design of the readout electronics

## Pre-amplifier

As shown in Fig. 2, a matched PA [13] for SDD is used to amplify the output current pulse of the detector, which offers an ultra-low noise, and a ramped reset type CSA with high gain (4.5 mV/keV ±15%). The amplitude of the ramped output signal is between ± 2 V with a reset duration of below 5 µs, and the period of the reset ranges from a few milliseconds to a few hundred milliseconds, which depends on the frequency of the incoming photons and the temperature of the detector.



Fig. 2 Block diagram of PA connecting with SDD.

The output of PA is a voltage step when the signal produced by individual X-ray photon appears. The rise time (from about 10 ns to 100 ns [14]) mainly depends on the location where X-rays interact with the SDD, while the voltage amplitude depends on the energy deposition of the incoming photon.

## Energy measurement circuit

For energy measurement, the amplitude of the signal should be efficiently detected, which is in the current work achieved via the analog peak detection and ADC method. As shown in Fig. 3, the PA is followed by a slow shaping circuit consisting of a CR-RC2 filter, which is employed to form a quasi-Gaussian signal. The peak value of the quasi-Gaussian signal is held by a peak hold module (PH300 from Amp-Tek) and then digitalized by a 14-bit ADC (AD9243) with 3 MHz sampling clock. The pole zero cancellation circuit is not necessary in case that being the signal form PA a step voltage [15].



Fig. 3 Block diagram of the energy measurement circuit.

An analysis of the noise has been carried out to determine the noise contribution of the detector and readout electronics, and thus to find the factor limiting the performance of the system.

The energy resolution of the detector, staged in the datasheet, is about 126.9 eV @ 5.9 keV [16] (at temperatures below -60 °C using a Peltier cooler, peaking time of 16 µs). For the slow shaping circuit, a Pspice simulation shows that the RMS of the noise is about 3.4 mV, which is equivalent to 44 eV @ 5.9 keV. A 14-bit ADC with a quantization error of about 0.12 mV (1.5 eV @ 5.9 keV) is selected, which is regarded to play a minor role in affecting the total energy resolution.

In addition, the rise time of the real signal will cause extra loss of the shaped signal height, which is termed as the Ballistic Deficit. Although increasing the peaking time (i.e. the time constant of CR and RC) can decrease the Ballistic Deficit, however it will increase the dead time of the energy measurement. A peaking time of 2 µs is determined finally to guarantee a proper counting rate as well as the energy resolution. Test results with a signal generator show that the actual electronic noise (i.e. *FWHMelectronic*) of the energy measurement circuit is equivalent to about 68 eV @ 5.9 keV as a constant in the dynamic range with a peaking time of 2 µs.

## Time measurement circuit

Compared with leading edge timing, CFT essentially eliminates the amplitude-dependent time walk for signals and has better timing resolution [17]. Fig. 4 explains the CFT principle briefly, and a delay time ‘*∆t*’ of 8 ns as well as an attenuation coefficient ‘*q*’ of 0.5 are chosen, leading to a fixed delay ‘*t*’ of 16 ns.



Fig. 4 A brief explanation of the CFT principle. The delay ‘*t*’ is constant and independent from the slope of the input signal.

As shown in Fig. 5, the PA is followed by a fast shaping circuit, which consists of an AC coupled circuit (CR with a time constant of 0.5 µs) and an amplifier, to condition the signals for time measurement. The fast shaper also drives three branches of the CFT circuits: the first branch is delayed by a time of ‘*td*’ (8 ns), the second one is attenuated by a coefficient of ‘*q*’ (0.5) and the third one is compared with an adjustable threshold for noise canceling. The output of both comparators is fed into an ‘AND’ gate for coincidence and then digitized by an FPGA based TDC.



Fig. 5 Block diagram of the time measurement circuit.

Since accuracy of time measurement is highly sensitive to CFT circuit, stringent hardware design is considered. One 100 Ω impedance fixed Delay Line (1919-20B from Data Delay Device) is used to achieve high precision delay and impedance matching. An Ultra-High-Speed comparator (MAX9601 from MAXIM Inc.), which has 30 ps propagation delay dispersion and differential PECL outputs is selected. A programmable delay line (NB6L295 from ON semiconductor) configured at 5 ns, is used to delay the CFT branch to guarantee the timing constrain. The AND gate (MC100LVEL05 form ON semiconductor) has 2 differential ECL input with a propagation delay of 340 ps.

## TDC integrated in FPGA

To digitize the output signals from the CFT module, a TDC is implemented in a XILINX FPGA (XC5VLX110), which reduces the system complexity and provides good flexibility [18, 19]. Fig. 6 shows the block diagram of the TDC, where the arrival time of the ‘hit in’ signal is digitized by both a 3-bit ‘fine time’ and a 29-bit ‘coarse counter’ modules, and then encoded to a final 32-bit time measurement result, which is finally read out by a FIFO.

A 50 MHz external clock is fed into the FPGA, and then used by an internal Phase Lock Loop (PLL) to generate four 100 MHz clock outputs with 90° phase interval (0°, 90°, 180°, 270°), which is equivalent to 2.5 ns Least Significant Bit (LSB) and much less than the transit time spread of SDD.



Fig. 6 TDC integrated in the FPGA. 3-bit ‘fine time’ and 29-bit ‘coarse counter’ constitutes a final 32-bit time measurement result (with the bin size of 2.5 ns and dynamic range of 10.74 second).

# Test results

A test platform has been set up to evaluate the performance of the system, which mainly consists of a power supply (KEITHLEY 2230-30-1), a signal source (Tektronix AFG3252), an oscilloscope (Tektronix DPO5104), a 55Fe X-ray radiation source, and the aforementioned analog electronics module and the digital electronics module. Then a series of tests are conducted to evaluate the performance of the SXD readout electronics.

## Energy measurement results

After SXD is assembled, firstly, using a radioisotope 55Fe X-ray source, the test result of energy measurement is about 153.4 eV @ 5.9 keV FWHM (Full Width at Half Maximum) as shown in Fig. 7 (a). Simultaneously, statistical distribution of time intervals of two photons is depicted in Fig. 7 (b), where the counts have the characteristic of Poisson distribution and behave in accordance with the theoretical property of radioisotope.



Fig. 7 Energy spectra (a) and time interval distribution (b) of a 55Fe using the SXD system.

After that, we measure the energy resolution and linearity (including both the detector and electronics properties) utilizing the X-rays lines listed in Table 1. These lines are fluorescence lines produced by interaction specific specimen (such as Cu, Fe, Cr and Ti) with high-energy electron beam [20]. The energy performance test results of the SXD are also listed in Table 1. The linearity of one representative SDD indicates that the Integral Non-Linearity (INL) is less than 0.1% can be achieved. It is worth noticing that the minor INL can be corrected by off-line analysis.

Table 1 X-ray fluorescence used for the calibration of the SXD.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| X-ray | Cu-K*β* | Cu-Kα | Fe-Kβ | Fe-Kα | Cr-Kβ | Cr-Kα | Ti-Kβ | Ti-Kα |
| Energy (keV) | 8.91 | 8.04 | 7.06 | 6.40 | 5.95 | 5.41 | 4.93 | 4.51 |
| *Mean*a (code) | 5583 | 5072 | 4479 | 4091 | 3821 | 3503 | 3212 | 2960 |
| *INL* (%) | -0.05 | 0.07 | 0.06 | 0.03 | 0.01 | 0.07 | -0.02 | -0.04 |
| *FWHMall* (eV) | 163.2 | 162.1 | 149.1 | 148.0 | 138.8 | 137.6 | 127.7 | 126.8 |
| *FWHMFano*b (eV) | 148.4 | 147.2 | 132.7 | 131.5 | 121.0 | 119.6 | 108.1 | 107.0 |

a *Mean* is the peak position expressed in ADC channels.

b *FWHMFano = (FWHMall2-*FWHMelectronic*2)1/2*. FWHMelectronic is about 68 eV as a constant.

## Time measurement results

The RMS of time measurement basically contributed by two factors: the noise of the circuits and the quantization error. A 10 kHz pulse (30 ns rise time, 50 mV amplitude, generated by a Tektronix AFG3252) is utilized to drive the fast shaper module directly, and then to evaluate the performance of time measurement. Test results of the SXD (including contribution of both analog and digital electronics) are shown in Fig. 8. It can be seen that the Standard Deviation (STD) is 3.7 ns, which is much less than the transit time spread of SDD.



Fig. 8 Performance of time precision test with 10 kHz (period of 100 µs) pulse input.

As mentioned in sub-section 3.3, CFT essentially eliminates the amplitude-dependent time walk for signals. As shown in Fig. 9 (a), we conduct a series of tests to observe the performance of the CFT circuit. The first channel (‘CH1’) is the reference signal with a frequency of 10 kHz and 2.5 ns rise time; while the other (‘CH2’) is created based on the waveform of the fast shaper, which has different amplitude (from 0.4 V to 4 V) with 10 ns rise time. Fig. 9 (b) shows the performance of CFT circuit, it can be clearly observed that the propagation delay of CFT circuit is about 20 ns with the time walk less than 3 ns.



Fig. 9 (a) Test method of CFT circuit. (b) Test results of CFT circuit. Delay is the skew of the ‘reference’ and the output of ‘CFT’.

# Conclusion

The readout electronics system for a prototype soft X-ray spectrometer with SDD has been successfully implemented, and achieves good time and energy measurement performance. A time measurement resolution below 5 ns is obtained. The energy resolution is about 153 eV FWHM @ 5.9 keV with analog peak detection and ADC method. Tests with X-ray fluorescence indicates that the INL is less than 0.1% with a dynamic range of 1 keV to 10 keV. It has been shown that the current SXD system has broad potential for X-ray timing and observation missions in space.

**Acknowledgments** This work was financially supported by the National Natural Science Foundation of China (Grant No. 11205154), which is gratefully acknowledged.

# References

1. D. H. Wen, Y. Zhou., Gravitational waves from the axial oscillation of neutron star considering non-Newtonian gravity. Nucl Sci Tech, 24 (2013) 050508. doi: 10.13538/j.1001-8042/nst.2013.05.008
2. K. C. Gendreau, Z. Arzoumanian, T Okajima., The Neutron star Interior Composition ExploreR (NICER): an Explorer mission of opportunity for soft X-ray timing spectroscopy. SPIE, Space Telescopes and Instrumentation 2012. doi: [10.1117/12.926396](http://dx.doi.org/10.1117/12.926396)
3. S. I. Sheikh, D. J Pines., Recursive Estimation of Spacecraft Position Using X-ray Pulsar Time of Arrival Measurements. ION 61st Annual Meeting, 2005. doi: [10.1002/j.2161-4296.2006.tb00380.x](http://onlinelibrary.wiley.com/doi/10.1002/j.2161-4296.2006.tb00380.x/abstract)
4. P. S. Ray, K. S. Wood, B. F. Philips., Spacecraft Navigation Using X-ray Pulsars. NRL Review. 2006.
5. K. Mitsuda, M. Bautz, H. Inoue et al., The X-ray Observatory Suzaku. Astronomical Society of Japan, 2007. doi: [10.1093/pasj/59.sp1.S1](http://dx.doi.org/10.1093/pasj/59.sp1.S1)
6. M. Feroci, J. W. Herder, E Bozzo et al., LOFT-the Large Observatory For X-ray Timing. Proceeding of SPIE, Vol. 8443, 2012. doi: [10.1117/12.926310](http://arxiv.org/ct?url=http%3A%2F%2Fdx.doi.org%2F10%252E1117%2F12%252E926310&v=02f99ab2)
7. G. Bertuccio, M. Ahangarianabhari, C. Graziani et al., X-ray Silicon Drift Detector-CMOS Front-End System with High Energy Resolution at Room Temperature. IEEE T Nucl Sci. doi: [10.1109/TNS.2015.2513602](http://dx.doi.org/10.1109/TNS.2015.2513602)
8. L. M. B Winternitz, K. C. Gendreau, M. A. Hassouneh et al., The Role of X-rays in Future Space Navigation and Communication. 36th Annual AAS Guidance and Control Conference, 2013.
9. KETEK GmbH. VITUS Silicon Drift Detectors. [User’s Manual.](http://www.ketek.net/downloads/vitus-sdd/?eID=dam_frontend_push&docID=2148) 2013.
10. L. Zhao, L. F. Kang, J. W. Zhou et al., A 16-Channel high-resolution time and charge measurement module for the external target experiment in the CSR of HIRFL. Nucl Sci Tech, 25, 010401(2014). doi: 10.13538/j.1001-8042/nst.25.010401
11. X. J. Hao, Sh. B. Liu, L. Zhao et al. A digitalizing board for the prototype array of LHAASO WCDA. Nucl Sci Tech, 22(2011) 178-148. doi: 10.13538/j.1001-8042/nst.22.178-184
12. Q. B. Zheng, Ch. Q. Feng. Y. Q. Huang et al., Design and Implementation of a High Resolution DAQ System for an (e, 2e+ion) Electron Momentum Spectrometer. IEEE T Nucl Sci, 2015, Vol. 62, No. 6. doi: [10.1109/TNS.2015.2497282](http://dx.doi.org/10.1109/TNS.2015.2497282)
13. KETEK GmbH. VITUS VICO PA. [Product Information.](http://www.ketek.net/products/vico/vico-pa/)
14. G. Prigozhin, K. Gendreau, R. Foster et al., Characterization of the silicon drift detector for NICER instrument. Proc. SPIE 8453. doi: [10.1117/12.926667](http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=1363333)
15. J. B. Zhou, X. Hong, B. R. Wang et al., Study of recursive model for pole-zero cancellation circuit. Nucl Sci Tech, 25, 010403(2014). doi: 10.13538/j.1001-8042/nst.25.010403
16. KETEK GmbH. VITUS H30 SDD. [Product Information.](http://www.ketek.net/products/vico/vico-pa/)
17. ORTEC. Fast-Timing Discriminator Introduction. [AMP-TEK advanced measurement technology.](http://www.ortec-online.com/download/Fast-Timing-Discriminator-Introduction.pdf)
18. K. Chen, Sh. B. Liu, Q. An., A high precision time-to-digital converter based on multi-phase clock implemented within Field-Programmable-Gate-Array. Nucl Sci Tech, 21(2010)123-128. doi: 10.13538/j.1001-8042/nst.21.123-128
19. C. F. Ye, L. Zhao, Z. Y. Zhou et al., A field-programmable-gate-array based time digitizer for the time-of-flight mass spectrometry. Rev Sci Instrum, [85, 045115(2014).](http://scitation.aip.org/content/aip/journal/rsi/85/4/10.1063/1.4870922) doi: 10.1063/1.4870922
20. W. Middleton. Energy Dispersive X-ray Microanalysis. NORAN Instruments, 1999.