Design and performance study of the LEPD silicon tracker onboard the CSES satellite*

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Abstract: The low energy particle detector (LEPD) is one of the main payloads onboard the China seismic electromagnetic satellite (CSES). The detector is designed to ascertain space electrons (0.1–10 MeV) and protons (2–50 MeV). It has the capability of identifying the electrons and protons, to measure the energy spectrum and the incident angle of the particles. The LEPD is made up of a silicon tracker system, a CsI (Tl) mini-calorimeter, an anti-coincidence system made by plastic scintillator, as well as electronics and a data acquisition system (DAQ). The tracker is also a kind of ΔE-E telescope; it consists of two layers of double-sided silicon strip detectors (DSSD). The signals emerging from the silicon tracker can be read out by two pieces of application specific integrated circuit (ASIC), which also can generate an event trigger for the LEPD. The functions of the DSSD system in the LEPD for charged particles were tested by ^{241}Am @5.486 MeV α particles. The results show that the DSSD system works well, and has high performance to detect charged particles and measure the position of incident particles.

Key words: silicon detector, ΔE-E, particles identification, electrons detector, protons detector, position of incident particles

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1 Introduction

The China Seismic Electromagnetic Satellite (CSES) is designed to study the electromagnetic waves linked to human activities and natural phenomena, such as artificial VLF(very low frequency) electromagnetic waves, volcano eruptions, earthquakes, atmospheric and magnetic storms; it also can detect charged particles to study the related ionospheric changes and the precipitation of the radiation belts? particles [1–4].

The low energy particle detector (LEPD) is one of the two particle detectors, which is designed to detect the electrons in the energy range from 0.1 MeV to 10 MeV and the protons in the energy range from 2 MeV to 50 MeV. The other one, the high energy particle detector (HEPD), is aimed at measuring electrons in the energy range from 8 MeV to about 50 MeV and protons in the energy range from 40 MeV to about 200 MeV.

The schematic diagram of the LEPD is shown in Fig. 1. It mainly consists of three parts.

1) A silicon tracker is constructed by two layers of 50 mm×50 mm double-sided silicon strip detectors (DSSD), which can be used for the measurement of the directions and deposit energies of the incident particles, as well as identification of the particles by ΔE-E technique [5]. The first silicon is 142 μm in thickness, and the second one is 300 μm.

2) A CsI(Tl) mini-calorimeter is devoted to measuring the residual energies of the charged particles passing through the two DSSDs.

3) An anti-coincidence detector made up of the segmented plastic scintillator is used to reject charged particles outside the observation field of view.

The electronics are designed individually to process their output signals. The most complicated part is the silicon tracker, which contains the front-end electronics

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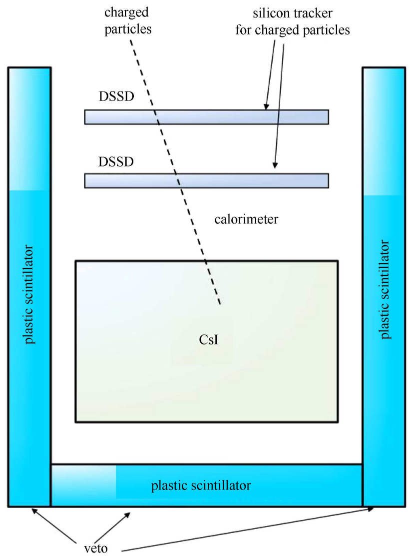

Fig. 1. The description and working principle of the LEPD.

and the data acquisition part. The function of the two parts is to readout the signals from two DSSDs, provide the event triggers, transfer the signals from parallel to serial, convert the analog signal to the digital, select the desired signal, and then transfer the scientific data to the processing unit or computer. Two pieces of front-end ASIC VA64TA2 are used in the front-end electronics part, which are the key components of the readout electronics. Field programmable gate array (FPGA) is adapted to the digital circuit as a controller of two pieces of VA64TA2; it is also a managing center of the data acquisition (DAQ) system, it processes the data from ADC, controls the USB interface, sends and receives data with the computer. The function system diagram of the LEPD's silicon tracker is shown in Fig. 2.

2 DSSD detector and its front-end ASIC

2.1 The DSSD of the LEPD's silicon tracker

The silicon tracker of the LEPD is devoted to measuring the energy and the direction of incident particles. As the primary ionization in semiconductors is proportional to the energy loss of the incident radiation or particle, the detectors may provide the possibility of energy measurement. Position sensitivity may be obtained by creating a situation in which the charged particle coming from the magnetic field above earth can fire the DSSD silicon strips amongst more than two readout electrodes depending on the position [6].

The DSSD used in the LEPD is a kind of new silicon semiconductor detector made by Micron Semiconductor Ltd., UK. The type of DSSD is W1 (DS)-300 2 M on a standard ceramic transmission package (Fig. 3). It is composed of 16 strips on the Junction side of a 64 um thick n-type silicon wafer; and 16 orthogonal strips of the same dimensions are on the Ohmic side. Every strip is 50 mm long and 3 mm wide separated by 0.1 mm. The chip of the DSSD is 52.25 mm×52.25 mm.

Two methods can be used to readout DSSD. Charge division readout reduces the number of readout channels as only a fraction of the strips are connected to a readout amplifier. Charge collected at the other strips is divided between the two neighboring readout channels according to the relative position. This can be accomplished by resistive or capacitive division (Fig. 4) [6].

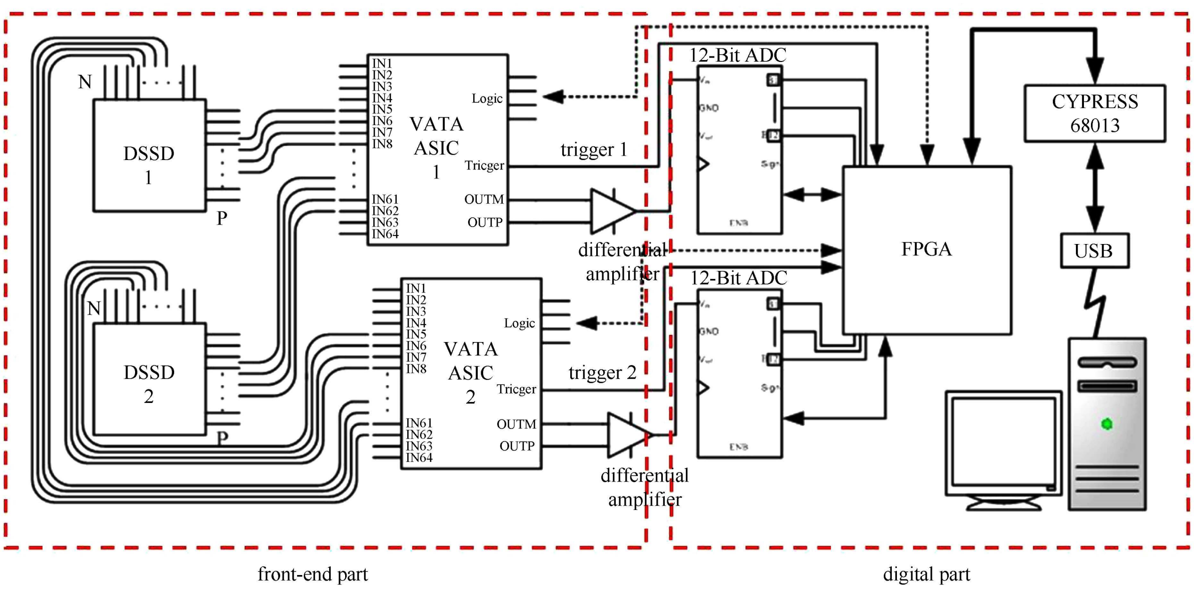

Fig. 2. The function diagram of the LEPD's silicon tracker system.

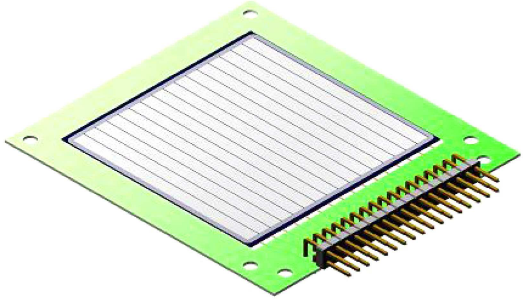

Fig. 3. The design of W1 (DS)-300 2 M on a standard ceramic transmission package.

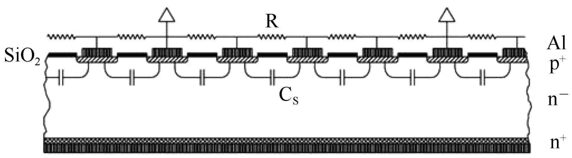

Fig. 4. The structure of capacitive charge division readout.

The analog readout of every channel may lead to a substantial improvement of energy and position measurement precision, as shown in Fig. 5. The silicon tracker of the LEPD is constructed by two DSSDs, 64 channels in total. So 64 channels of readout electronics are needed at least. However, the weight, volume, and especially the power supply are limited onboard the satellite. It is impossible to design the front-end electronics and sampling hold circuits with separated components. Thus, the analog-digital, low noise, self-triggering and sampling hold ASIC VA64TA2 is adapted to solve the problems.

2.2 The front-end ASIC VA64TA2

The signals emerging from two DSSDs of the LEPD are read out by two ASICs. The ASIC VA64TA2 is designed by IDEAS Co, and produced with Analog Mixed-Signal (AMS) 0.35 μm N-well CMOS, double-poly, triple metal with epitaxial layer, that is measured to be radiation hard to a few Mrad or more [7]. It is a low power radiation hard chip with 64 channels of low-noise charge sensitive preamplifier-shaper circuits, with simultaneous sample and hold, as well as multiplexed analogue readout and calibration facilities. Each channel consists of a folded cascade charge sensitive preamplifier, a CR-RC shaper, a sample and hold circuit, a level sensitive discriminator and trigger logic, as shown in Fig. 6. All channels share a common wire-or'ed trigger output. There is a 4-bit trim DAC in each channel to reduce the threshold spread. The flip-flops are implemented with error correction in order to improve SEU (single event upset) tolerance. Occurrence of SEU will be signaled on an external pad.

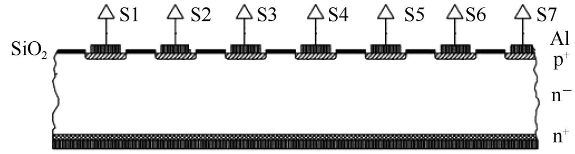

Fig. 5. The structure of analog readout.

The readout is a multiplexed analog readout with a maximum readout clock frequency of ten MHz. The ASIC readout clock in this system is one MHz for reliability. The power consumption of each channel is around 3 mW. Using VA64TA2 to construct the front-end electronics of the LEPD silicon tracker will reduce the total power and also compact the whole electronics system including the trigger circuit of the LEPD.

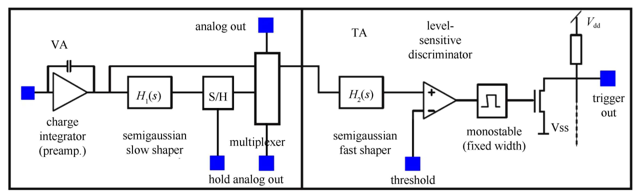

Fig. 6. Diagram of LEPD silicon tracker system.

3 Properties of the silicon tracker and its electronics

The silicon tracker of the LEPD is not only to detect the direction and deposit energy of incident particles, but also to identify the particles by ΔE-E technique. When the incident particles with kinetic energy E_0 pass through the first detector and are stopped in the second one, the ΔE-E technique is applicable. The partition of E_0 between the two detectors is different for different incident particles [8]. If higher energies of charged particles are expected, the CsI(Tl) mini-calorimeter is used as a third element of large stopping power.

3.1 Simulation of the ΔE-E telescope

Geant4 program is applied to simulate the energies deposited in the two detectors. To be closer to the real environment, several restricted conditions were considered in the simulation, such as the satellite orbit, particle flux, and energy conversion factor.

The particle flux has diverse distributions in earth orbit, it is also much more than that of X-rays and gamma rays. The energy deposition of X-rays and gamma rays is very low in the DSSD, most of which could be ruled out by the ASIC threshold. Even if some of those are treated as an effective event, because the deposited energy in the three detectors (two DSSDs and the CsI(Tl) mini-calorimeter) has different characteristics, the X-ray and gamma ray events should also be eliminated in the post-processing. For this reason, only the flux

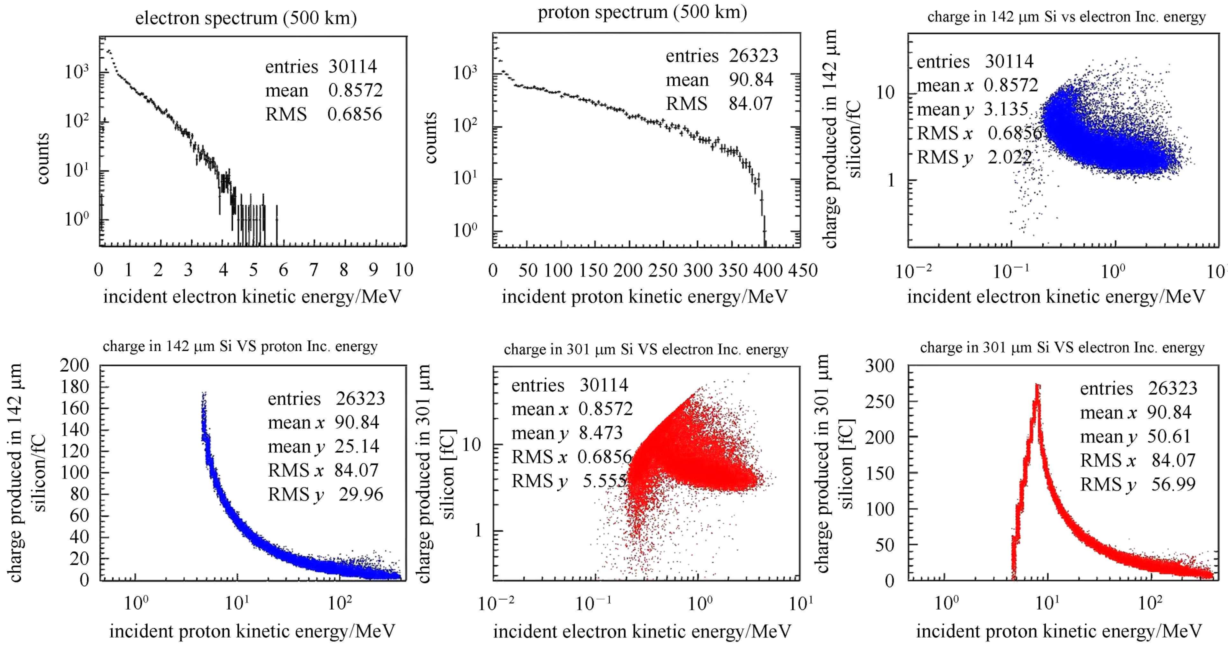

Fig. 7. Particles flux and charge vs. incident energy of electrons and protons in the ΔE-E telescope.

Table 1. Charge produced in DSSD.

incident particle	energy range of power-law spectrum/MeV	thickness of DSSD/μm	main distribution of charge/fC	maximum value of charge/fC	average value of charge/fC
electron	0.04–10	142	1–10	30	3
		301	1–10	70	8
proton	0.1–400	142	0–175	175	25
		301	0–280	280	51

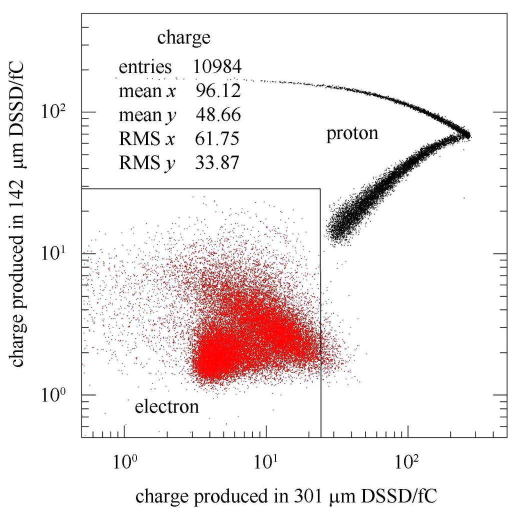

Fig. 8. Energy deposition of different energies of electrons and protons in the ΔE-E telescope.

of electrons and protons in CSES orbit (500 km) is used for the simulation, as shown in Fig. 7. In this figure, it also shows charge vs. incident energy of electrons and protons in two DSSD detectors. The charge from two DSSD detectors is the sole physical quantity that could be measured directly, and also the reference condition to design the electronics of the detector. The charge is shown in Table 1.

The ΔE-E technique is based on the accurate measurement of the deposit energies in the two DSSDs. Fig. 8 shows the Geant4 simulation of how to identify electrons and protons using ΔE-E technique. The result shows that the ΔE-E telescope can suffice for the identification of electrons and protons.

3.2 Structures of silicon tracker's electronics

3.2.1 The front-end part

The front-end part is the key component of the silicon tracker readout electronics. The signal emerging from the DSSD is very weak, as shown in Table 1, so the front-end board should be low noise, ground well and have little interference. To reduce the interference of the front-end board, the quantity and type of components on the board should be kept to a minimum.

Matching the DSSD with the front-end chip VA64TA2 will affect the quality of signals. The matching circuit is made up of the biasing circuit and coupling capacitance (Fig. 9). R1-C1, R2-C2 and R3-C3 form the filtering network for the negative high voltage. The resistance of R1, R2 and R3 is about ten million ohms. R4 and R5 are used to reduce the leakage current of the DSSD, so the resistance must be several hundred million ohms. CC1 and CC2 are the coupling capacitances between the DSSD and the front-end chip VA64TA2. The coupling capacitance is affected by the distributed capacitance of the DSSD and the input capacitance of front-end electronics. After many tests, we select the 160pF high voltage capacitor as the coupling capacitance.

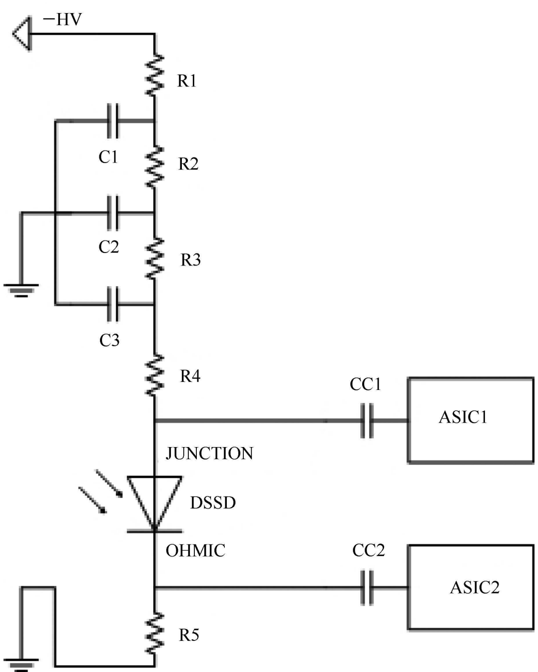

Fig. 9. The matching circuit of one channel of the DSSD.

3.2.2 The digital part

The digital part is shown as Fig. 2. The USB chip CY7C68013 is a communication chip between the digital board and PC. An AD9220 chip, which is a 10 MSPS, single 5V supply, 250 mW, 12-bit ADC with a differential input structure, is used to A/D convert the differential analog output signals of front-end ASIC VA64TA2. A Xilinx Spantan-XC3S200 FPGA is the core of the digital board. It is used to control the ASIC VA64TA2, AD9220 and USB chip, and also to process scientific data. In total, the digital part has three functions:

1) To configure the 360 bits serial shift register of front-end ASIC VA64TA2 and achieve logic control.

2) To receive the analog signal from front-end chip VA64TA2, convert analog to digital and select the interested signal.

3) To communicate with the PC, receive control command from PC and transfer the scientific data to PC.

3.3 The logic of the silicon tracker readout system

3.3.1 Overview of the logic of FPGA

All the logic of the silicon tracker readout system is accomplished by the FPGA. The logic of the readout system mainly includes five parts, as shown in Fig. 10. The main-module is the central control module, used to control the four sub modules which realize different functions, and some of them have their own second order sub modules.

3.3.2 The logic of ASIC Module

As shown in Fig. 10, the logic of ASIC module consists of two second order sub modules. After power on, the ASIC VA64TA2 on the front-end board cannot work until configuration. The configuration of VA64TA2 is realized by the CONFG module; 360 bits are shifted in the serial shift register. When all bits are shifted to the correct place, a pulse should be applied to open the latches, and to store the value of the DFF in the three parallel latches. In this way, an SEU occurring in one of the three latches or in the DFF will not be visible to the chip logic because of the TMR (triple module redundancy) technology.

After configuration, the front-end ASIC VA64TA2 is in working condition, and the logic is in READOUT module. The normal mode of operation is that the 64 inputs are connected to a detector from which the charge signal comes. After the physics event, each channel will integrate its eventual signal for 1 μs. See Fig. 11 for an example of the timing in VA64TA2 readout mode.

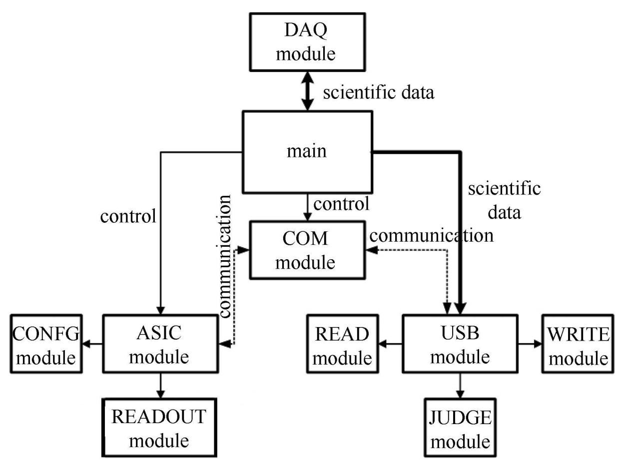

Fig. 10. Logic diagram of LEPD silicon tracker readout system.

3.3.3 The logic of other sub modules of FPGA

Except for the ASIC module, there are another three sub modules: USB module, COM module and DAQ module. The USB module is used to control the USB chip CY7C68013, receive modules and communicate with each other by the COM module. When the USB module receives the command from the PC, the COM module judges the type of command, and then sends it to relevant modules.

The DAQ module is another important part of the readout system, all the scientific data are processed in it. That will be discussed in more detail in the next section.

3.4 Digital signal processing

In a satellite, the resources, such as the memory space and the transmission rate, are very limited, so the DAQ module is designed to keep the scientific data in an appropriate size.

The data flow of the LEPD silicon tracker is shown in Fig. 12. The analog signals emerging from two sides of the DSSD are different, one is positive and the other is negative. The input signal of VA64TA2 is unipolar, either positive or negative. So two pieces of VA64TA2 are needed to process the analog signals from the DSSD. One processes positive signals, and the other processes negative signals. When any DSSD is hit, both of the two pieces of VA64TA2 will generate a trigger signal. Only when two trigger signals are produced, it is considered to be an effective case of the silicon tracker readout system. Though the two pieces of VA64TA2 are independent, the control logic of them is synchronous.

The digital data from two ADCs transfers to the FPGA at the same time, which will be selected by the 'Select1 Threshold' module first. The 'Select1 Threshold' module is used to wipe off the un-hit channel and the noise of the DSSD. Only the biggest data and the data of both channels will be reserved. After this step, most of the useless data are wiped off. The size of data is decreased to 9.4% of the original data's. It is the primary treatment of the digital signal. The deposit energy of high-energy particles and low-energy particles is very little, and also it is hard to differentiate. Accordingly, the 'Select2 Threshold' module will be contrived to solve the problem.

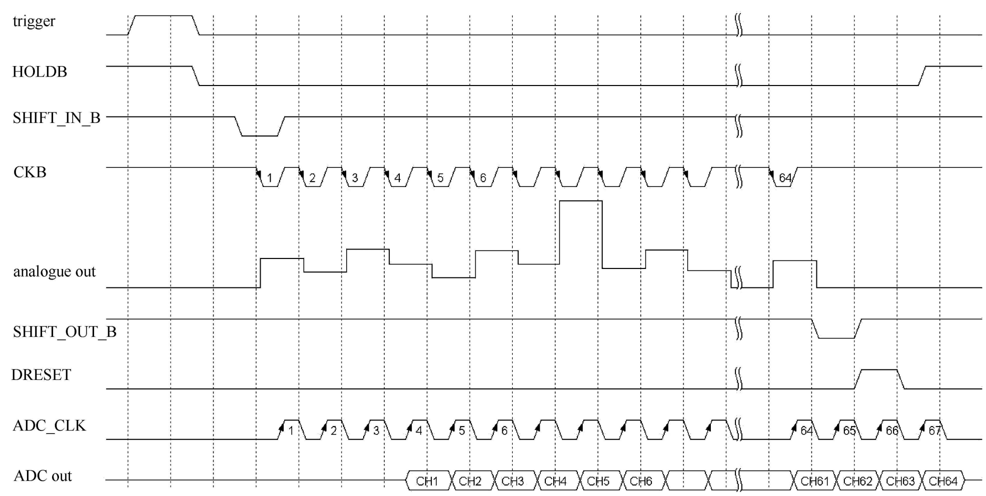

Fig. 11. Timing of readout of the VA64TA2.

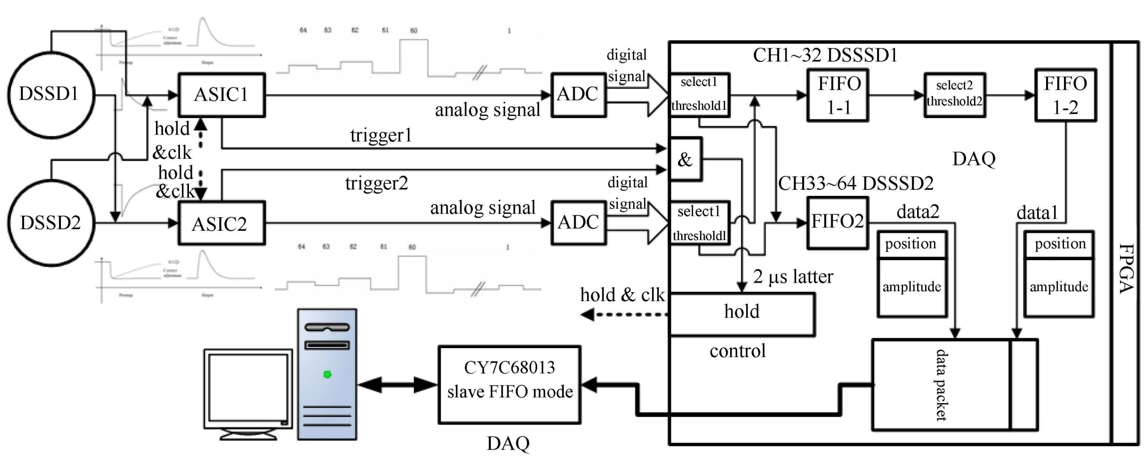

Fig. 12. The diagram of LEPD silicon tracker data flow.

4 The experiment and results

4.1 The performances of the DSSD system

The electrons (0.1–10 MeV) and protons (2–50 MeV) are the best choice to test the LEPD silicon tracker. However, the appropriate radioactive source is nonexistent in nature. In order to make the experiment more convenient, and also contrast with the rated performance of the DSSD, the ^{241}Am@5.486 MeV alpha particles are used for testing the detector.

In this experiment, how to regulate the working condition of the VA64TA2 will influence the resolution. Almost every function of the VA64TA2 can be adjusted by the internal serial shift register, and also could be adjusted by the external pads. Fig. 13 shows the analog signal output of the VA64TA2, which contains position information and energy information.

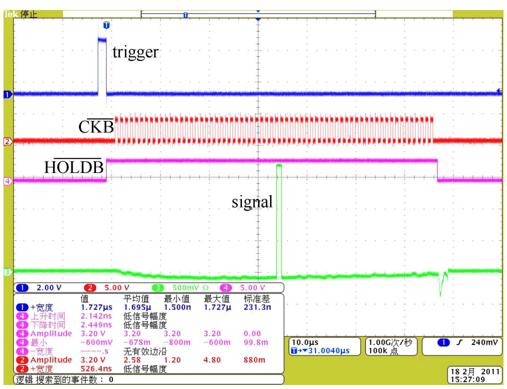

Fig. 13. The analog signal output of ^{241}Am experiment.

4.2 Results

The α particles? spectra of ^{241}Am @5.486 MeV are shown in Fig. 14. On the left is the spectrum measured by the Ohmic side of the DSSD in the air, and the right is the Junction side. It can be seen from Fig. 14 that the energy resolution of the Junction side is better than that of the Ohmic side. The energy resolution of the Junction side is about 1%–2%; and the energy resolution of the Ohmic side is about 3%–4%. The results from our test generally meet the rated performance of the DSSD.

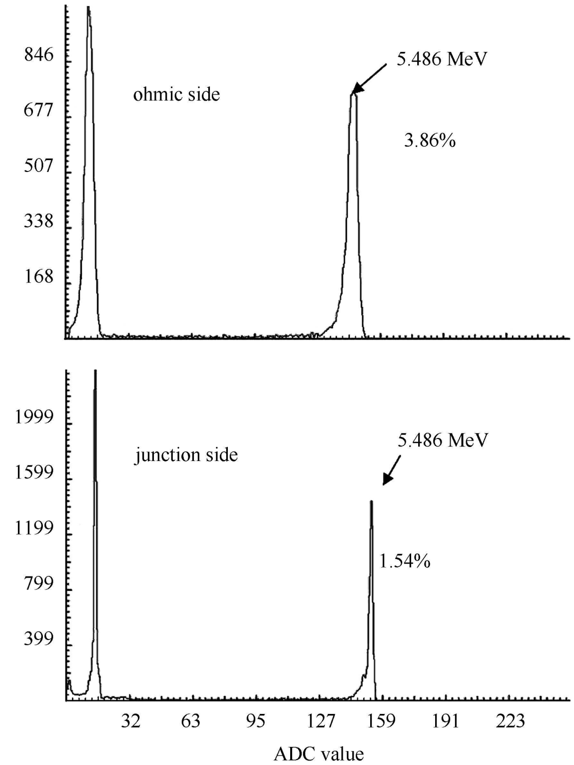

Fig. 14. The ^{241}Am@5.486 MeV α particles spectra measured by the DSSD in the air

5 Conclusion

The LEPD silicon tracker readout system works well and has high performance in detecting the charged particles, such as the 5.486 MeV α particles of ^{241}Am. All strips of the DSSD can be read out respectively. The connection between the DSSD and VA64TA2 should be further optimized; and the SNR (signal to noise ratio) and the DAQ system should continuously be improved. After completing the prototype LEPD, more beam tests for electrons and protons should be done. An appropriate threshold value of an event trigger will be defined.

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