Signal Simulation and Test of Cadmium Zinc Telluride Nuclear Radiation Detector

Yunfei Chen¹, Jijun Zhang¹,*, Linjun Wang¹, Shulei Wang¹ and Yang Yang¹
¹School of Materials Science and Engineering, Shanghai University, Shanghai, China

*Corresponding author e-mail: zhangjijun222@shu.edu.cn

Abstract. In the research and development of nuclear instruments, the simulation and shaping of nuclear pulse signals are very important. Since the output signal of nuclear detectors is very weak and has noise interference, it cannot be processed well by the data acquisition system, so it is necessary to filter and shape the nuclear pulse signals. Using MATLAB 2019a simulation software to superimpose random noise to simulate the output signal of the CdZnTe nuclear radiation detector, the output signal of the preamplifier and the output signal of the main amplifier. The final result is basically the same as the actual signal, which is a simulated nuclear pulse signal, laying the foundation for the nuclear-simulated pulse signal generator.

1. Introduction

In the field of nuclear radiation detection technology, the research on analog nuclear signal generating devices has important practical significance. In order to test the performance of nuclear radiation detection instruments, it is necessary to obtain nuclear signals with different parameters. Directly using radioactive sources to obtain nuclear signals will cause radiological hazards and damage the health of scientific researchers[1]. Therefore, it is particularly necessary to simulate real nuclear signals. Moreover, nuclear detectors are expensive and easily damaged. At the same time, the existing nuclear imitating pulse signal generator is still in the early stage of research, and the corresponding products are few. The development of nuclear-simulating signal generators is mainly divided into two types: analog and digital. In the early days, due to technical limitations, they generally built their own analog circuits to meet the testing requirements, which met a certain random distribution law, and could not guarantee better reliability and flexibility. With the development of electronic technology and computer technology, digital nuclear-simulating signal generators began to appear gradually. As early as 1969, Attwenger[2] and others used analog circuits to directly build them to realize the output pulse to meet the exponential distribution in time. The hardware circuit of this design was complicated, the cost was high, and the flexibility was poor. In 1996, Byung[3] realized the output spectrum based on the single-chip microcomputer. The line satisfies the Gaussian distribution in amplitude. The pulse signal obtained by this scheme has a low count rate, which cannot meet the high count rate use occasions. In 2014, researchers from the School of Nuclear Technology and Automation Engineering of Chengdu University of Technology designed a nuclear pulse signal generator based on random sampling[4]. In 2017, researchers from the School of Mathematics and Physics of the University of Ljubljana designed an FPGA-based nuclear pulse generator with a certain amplitude distribution[5]. In addition, Wang Lijun[6] and others have used FPGA to realize that the nuclear pulse signal meets the exponential distribution in time and in amplitude. A nuclear pulse signal generator that satisfies the Gaussian distribution. However, traditional signal generators cannot make
the output pulse signal be distributed according to the probability density of any given reference spectrum data, and at the same time, the accuracy of the time distribution is poor, and it cannot meet the test needs in high-demand occasions. Therefore, this article uses MATLAB programming to achieve Gaussian pulse signal generation and trapezoidal filter shaping, cleverly avoiding complex algorithms. Using Matlab, the digital simulation of nuclear signals can be realized portable, and the time characteristics, amplitude characteristics and pulse shape characteristics of nuclear pulse signals can be guaranteed. A random Gaussian pulse whose amplitude is distributed according to the characteristic spectral line is obtained, which improves the operating efficiency.

2. Characteristics of cadmium zinc telluride semiconductor materials

Cadmium zinc telluride (CdZnTe, CZT) is a new type II-VI compound semiconductor material with an average atomic number of 49.1 and a density of 5.78 g/cm³. It has good blocking power against gamma rays. The band gap of cadmium zinc telluride is 1.57 eV. The larger bandwidth suppresses the number of electron-hole pairs generated by thermal excitation and ensures that the crystal has a high resistivity. This makes the cadmium zinc telluride detector can be at room temperature the work. Its basic working principle is: after rays are incident, interaction processes such as photoelectric effect, Compton scattering, positive-negative electron pair effect and other interactions occur with the cadmium-zinc-telluride material, and freely moving charges q are generated inside it. Under the action of an external electric field, these The charge carriers are collected by the electrode of the detector, and an induced charge Q is generated on the electrode, and then the collected induced electricity Q is converted into a voltage pulse signal for detection through an amplifying circuit. There is a unique correspondence between the energy deposition generated by radiation and the mobile charge q generated inside the detector, and there is also a unique correspondence between the induced charge Q on the collecting electrode and the output signal, so the pulse amplitude of the output signal can reflect the incident photon deposition energy the size of. Figure 1 shows the principle diagram of the detector.

![Figure 1. Schematic diagram of nuclear radiation detector.](image)

Cadmium zinc telluride (CZT) has the advantages of high atomic number, good intrinsic energy resolution, high detection efficiency per unit volume, large band gap, long carrier mobility life product, high resistivity, and can work in a greenhouse. Table 1 is a comparison of the physical characteristics of some commonly used semiconductor detectors. It can be seen that CZT is the nuclear radiation detection material with the best comprehensive performance [7]. The γ-ray detector prepared from it has high detection efficiency and energy resolution. High, small size, easy to use and can work at room temperature advantages [8,9], can be widely used in industrial non-destructive testing, nuclear safety inspection, nuclear medicine imaging, nuclear weapons penetration, astrophysics and high energy physics and other fields. It is of great significance to carry out research on the cadmium zinc telluride detector and master its related core technologies.
Table 1. Physical characteristics of commonly used semiconductor detectors (temperature=25℃)

|                  | Si | Ge | GaAs | CdTe | CdZnTe | HgI |
|------------------|----|----|------|------|--------|-----|
| Lattice structure| Cubic | Cubic | Cubic(ZB) | Cubic(ZB) | Cubic(ZB) | Tetragonal |
| Growth method    | C  | C  | CVD  | THM  | HPB,THM | VAM |
| Atomic number    | 14 | 32 | 31.33 | 48.52 | 48,30,52 | 80,53 |
| Density/(g·cm⁻³) | 2.33 | 5.33 | 5.32 | 6.20 | 6.58 | 6.4 |
| Bandgap/eV       | 1.12 | 0.67 | 1.43 | 1.44 | 1.57 | 2.13 |
| Average ionization energy/eV | 3.62 | 2.96 | 4.2 | 4.43 | 4.6 | 4.2 |
| Resistivity/(Ω·cm) | 10⁴ | 50 | 10⁴ | 10⁻⁹ | 10⁻¹⁰ | 10⁻¹³ |
| Electron mobility/(cm²·(V·s)⁻¹) | >1 | >1 | 10⁻⁸ | 10⁻⁸ | 10⁻³ | 10⁻⁴ |
| Hole mobility/(cm²·(V·s)⁻¹) | ~1 | >1 | 10⁻⁸ | 10⁻⁴ | 10⁻⁵ | 10⁻³ |

3. Simulation and testing of nuclear radiation signal

The original output signal of the detector is the instantaneous pulse charge Q collected by the anode. For the CZT detector, this charge is too small, so that it is impractical to process the pulse signal without intermediate amplification measures.

Therefore, it is necessary to use a preamplifier as the interface between the detector and the subsequent pulse processing and analysis electronics. During the measurement process, the parameters of the preamplifier generally rarely change, and the subsequent main amplifier adjusts the amplification factor and the shaping time constant [10], so the main problem of studying the signal output falls on the preamplifier and On the main amplifier[11,12,13].

3.1. Simulation of the output signal of nuclear radio detector

When the signal delay time is much smaller than the time constant of the output circuit, it can be considered that the nuclear radiation detector signal mainly appears in the form of pulses. When the charge collection time is short, it can be considered as a very short current shock pulse[14].

Therefore, the output signal of the nuclear detector is a series of randomly distributed current pulses with different amplitudes and uneven intervals between the front and back, which can usually be equivalent to a current source I(t).

Figure 2. MATLAB simulation of current source (unit shock function).
3.2. Simulation and test of output signal of preamplifier

The output signal of a nuclear radiation detector is a series of random current pulse signals with a specific shape, which are generally converted into voltage signals for signal transmission and subsequent information analysis. From the perspective of a nuclear radiation detection system, the circuit that converts the detector output current signal into a voltage signal is usually called a front-end electronic circuit (preamplifier).

After the nuclear pulse signal is output by the preamplifier, a lot of noise is usually superimposed, because the waveform of the nuclear pulse signal is known, but the superimposed noise is complex and diverse. The rising edge of the preamplifier waveform is similar to a step signal, and the falling edge is an exponentially decaying signal, forming a sharp top at the maximum amplitude. When directly sampling the rising edge and the maximum amplitude, an ultra-high-speed sampling frequency is required [15]. The maximum value of the pulse amplitude corresponds to the energy information of the radiation. When performing energy spectrum measurement, it is necessary to obtain the maximum value of the pulse amplitude as much as possible. The single-nuclear pulse signal of this simulation is the exponential signal that conforms to the output of the nuclear detector. The standard index signal is realized by the following formula. In this design, in order to obtain the ideal nuclear pulse signal, the following exponential signal formula is obtained:

\[ y = Ae^{-\frac{t}{\tau}} \]  \hspace{1cm} (1)

In this design, in order to obtain the ideal nuclear pulse signal, the following exponential signal formula is obtained, where \( u(t) \) is the step signal.

\[ f(t) = A_1u(t) + A_2e^{-\frac{t}{\tau}} \]  \hspace{1cm} (2)

\[ u(t) = \begin{cases} 0, & t < 0 \\ 1, & t \geq 0 \end{cases} \]  \hspace{1cm} (3)

In the formula (2), \( A_1 \) and \( A_2 \) are the amplitude of the analog signal, and \( \tau \) represents the attenuation constant of the analog signal (that is, the forming time of the pulse signal). According to (2) and (3), the ideal mononuclear pulse signal can be obtained.

![MATLAB simulation of the preamplifier signal](image1)

Figure 3. (a) MATLAB simulation of the preamplifier signal  \hspace{1cm} (b) Actual preamplifier signal

Figure 3(b) shows the output response of the preamplifier corresponding to the CdZnTe nuclear radiation detector measuring 137Cs gamma rays. The applied bias voltage is 1000V, and the gamma rays are incident from the anode direction. The output response voltage is 100 mV, the duration is 0.2 ms, the equivalent noise root mean square voltage is about 6 mV, and the signal-to-noise ratio is 22:1.
Compared with the simulation results in Figure 3, it is basically the same. It shows that using MATLAB can well realize the simulation of nuclear pulse signal.

3.3. Simulation of the output signal of the main amplifier

The final purpose of the filter shaping circuit in the main amplifier is to shape the step pulse output by the charge-sensitive preamplifier into a quasi-Gaussian pulse, which can obtain a better signal-to-noise ratio, and maintain a certain width at the top, which can satisfy subsequent analysis and measurement. Circuit requirements. According to the current theoretical research, the commonly used pulse forming methods mainly include: trapezoid, triangle and Gaussian forming[16].

There are two ways to achieve Gaussian forming. One is to realize the Gaussian shaping method based on the filter designed by discrete components. The module designed by this method has a single function and is not convenient for system upgrade. The second is the digital Gaussian forming method. Compared with the trapezoidal forming method, the falling edge is slower, the forming time is longer, and the amount of calculation is large, which is not suitable for use in high count rate occasions. In comparison, the trapezoidal filter shaping algorithm has the following advantages:

(1) The algorithm is simple and fast. After forming, the pulse front and back edge time are equal, the pulse is narrow, the pulse back edge falls fast, and the pulse rise time and flat top can be adjusted independently. Compared with Gaussian forming, when the energy resolution is the same, the forming time of trapezoid forming is shorter, which is beneficial to improve the pulse pass rate and facilitate real-time processing.

(2) The influence of unfavorable factors can be reduced. It can reduce the influence of electronic noise, ballistic loss and pulse accumulation on energy and time resolution, and also takes into account the optimization of energy resolution and pulse pass rate, which improves the flexibility and adaptability of the system, within the signal width, the capacitor is charged and discharged through R at the same time, so the charge can reach a magnitude less than Q/C.

(3) Improve energy resolution. The trapezoid shape reduces the requirements for differential nonlinearity and improves the energy resolution of the system. Ballistic loss means that the current pulse output by the detector has a certain width. Due to the presence of R and C in the preamplifier[17].

Assuming that the output of the preamplifier is an ideal exponential signal, the time domain expression is

\[ V_i(t) = V_{\text{max}} e^{t/\tau} \mu(t) \]  

(4)

\( V_{\text{max}} \) is the pulse amplitude, \( \tau \) is the time constant of the front-end amplifier, \( \mu(t) \) is the standard unit step function, and the input signal is sampled with \( T_s \) as the period, and the pulse sequence expression can be obtained:

\[ V_i(t) = V_{\text{max}} e^{-nT_s/\tau} \mu(t) \]  

(5)

let \( e^{-nT_s/\tau} = q \), apply Z transformation to the above formula to get:

\[ V_i(z) = V_{\text{max}} z / (z-d) \]  

(6)

the piecewise function of the ideal trapezoidal function can be expressed as:

\[ V_o(z) = V_{\text{max}}(1-z^{-a}z^{-b}z^{-c})(1-2z^{-1}+z^{-2}) \]  

(7)

thus the transfer function of the trapezoidal algorithm can be obtained:

\[ H(z) = V_o(z)/V_i(z) = [z(1-z^{-a})(1-z^{-b})(1-q^*z^{-1})]/[na*(1-z^{-1})^2] \]  

(8)

As shown in Figure 4 set the sampling period to 0.05; take the quantization time of the rising edge of the trapezoidal pulse as 20; take the quantization time of the top width of the trapezoidal pulse as 100; quantize the trapezoidal pulse forming time as 140; the maximum amplitude of the trapezoidal pulse is 5; the decay time constant Is 1, to get a single exponential decay input signal and a shaped trapezoidal pulse signal.
Gaussian pulse shaping formula is

\[ y_n = \frac{(k+2k^2)y_{n-1}+k^2y_{n-2}+2x_n}{1+k+k^2} \]  \hspace{1cm} (9)

In formula (9), \( k \) is a shaping parameter, and the width of the Gaussian pulse waveform can be adjusted by changing the value of \( k \). As shown in Figure 5(a), by setting the value of \( k \) to 50, 60, 70, the Gaussian shaped signals with different pulse widths can be simulated, and it is found that as the value of \( k \) increases, the width of the output signal becomes wider and the amplitude becomes smaller. Figure 5(b) is the actual output signal of the main amplifier. It can be seen that the actual signal is roughly the same as the simulated signal.

4. Conclusion

This paper uses MATLAB 2019a to simulate the nuclear pulse signal waveform and compare it with the nuclear pulse signal output by the actual CdZnTe nuclear radiation detector. The results show that the output signal obtained by the simulation has the same waveform characteristics as the output signal of the actual circuit. The method can be applied to the analysis of nuclear electronics filter circuits, and lays the foundation for the realization of pulse amplitude conforming to Gaussian distribution, exponential distribution, uniform distribution, and pulse time interval obeying exponential distribution, providing theoretical basis for the design and realization of nuclear-simulated pulse signal generator.
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