Design of a Preamplifier for Silicon Detector Redout Experiment

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Abstract

An experimental circuit design method of charge sensitive preamplifier for signal readout of silicon detector is introduced. Firstly, the circuit principle simulation and circuit parameter optimization are realized based on Multisim software. Secondly, the circuit is designed with junction field effect transistors (JFETs) as input stage, constant current source as load and integrated operational amplifier as amplifier stage. Finally, the circuit is applied to match silicon semiconductor detector to measure the energy spectrum of low energy γ-rays. The circuit has the advantages of large open-loop gain, high stability of charge voltage conversion gain, simple circuit structure and good energy resolution.

Subject Areas

Electric Engineering, Nuclear Engineering

Keywords

Charge-Sensitive Preamplifier, Silicon Detector, Multisim Simulation, Energy Spectrum

1. Introduction

In the traditional high-resolution energy spectrum measurement system, the charge-sensitive preamplifier circuit mostly uses the junction field effect transistor as the input stage, the cascaded transistor as the intermediate amplification stage and the output stage [1]. The structure circuit takes discrete components as the core, and each stage circuit needs to design a suitable bias circuit to ensure a stable static operating point and a wide dynamic range. This increases the difficulty of circuit design, while each stage of the circuit needs to design a suitable bias circuit to ensure a stable static operating point and a wide dynamic range,

there is a magnification is not high and complex circuit structure and other shortcomings [2] [3] [4]. This circuit in size and performance are difficult to meet the current experimental and application requirements. Aiming at this problem, this paper proposes a circuit structure based on constant current source bias circuit and integrated operational amplifier. The circuit has the advantages of simple operation, easy debugging and stable performance. During the experiment, Multisim software is used to simulate the principle of the circuit, optimize the parameters, and then complete the circuit production [5] [6]. Finally, the core performance parameters of the circuit are measured [7] [8] [9] [10]. Compared with the traditional charge sensitive preamplifier circuit, the circuit significantly reduces the system noise and improves the signal-to-noise ratio.

2. Working Principle of Circuit

The schematic diagram of a resistive-capacitive feedback charge-sensitive preamplifier is shown in **Figure 1**, where DET is the detector, $+HV$ is the detector bias power supply, R_D is the bias resistance, C is the input coupling capacitance, C_i is the total input capacitance, A_O is the open-loop gain of the amplifier circuit, R_f is the feedback resistance, and C_f is the feedback capacitance. According to the reference [11], the output voltage signal $V_o(t)$ of the amplifier and the charge Q collected by the detector satisfy the following relationship:

$$V_O(t) = -A_O V_i(t) = \frac{A_o Q}{C_i + (1 + A_O) C_f} \tag{1}$$

When A_O is large enough, $A_o C_f \gg C_i + C_f$, which can be reduced to:

$$V_o(t) \approx \frac{Q}{C_f} \tag{2}$$

At this time, as long as C_f remains unchanged, the output voltage amplitude is only proportional to the input charge Q, almost independent of other parameters in the circuit. Therefore, the circuit has a very stable gain and is suitable for high-resolution energy spectrum measurement.

3. Circuit Simulation and Parameter Optimization

The experimental circuit is designed with junction field effect transistor (JFET)
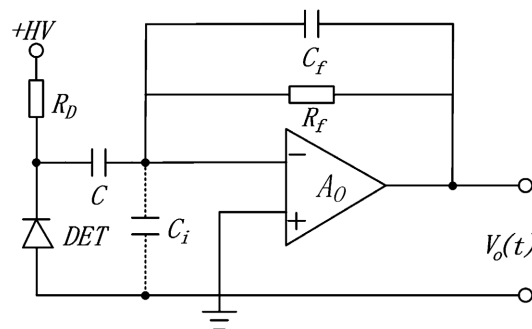

Figure 1. Charge sensitive preamplifier schematic diagram.

as input stage, constant current source as bias circuit and integrated operational amplifier as main amplifier. The simulation circuit is drawn by Multisim software, as shown in Figure 2. Since the input stage noise is the main source of system noise, the N-channel JFET with high input impedance and low noise is selected. In order to overcome the problem that the static operating point of the traditional amplifier circuit based on discrete components is not easy to set and the open-loop gain is small, a constant current source bias circuit based on triode and a main amplifier stage circuit based on integrated operational amplifier are designed [12] [13]. The following will explain the working principle of the circuit, circuit simulation analysis and parameter optimization process in detail.

3.1. Signal Source

The circuit designed in this experiment is mainly suitable for silicon detectors. The equivalent circuit of the detector is shown in part A of Figure 2, where I_1 is the leakage current of the detector under the bias voltage V_6, R_{10} is the forward on-resistance of the detector, V_7 is the pulse voltage source, C_4 is the junction capacitance of the detector, and the total charge collected by the detector Q is:
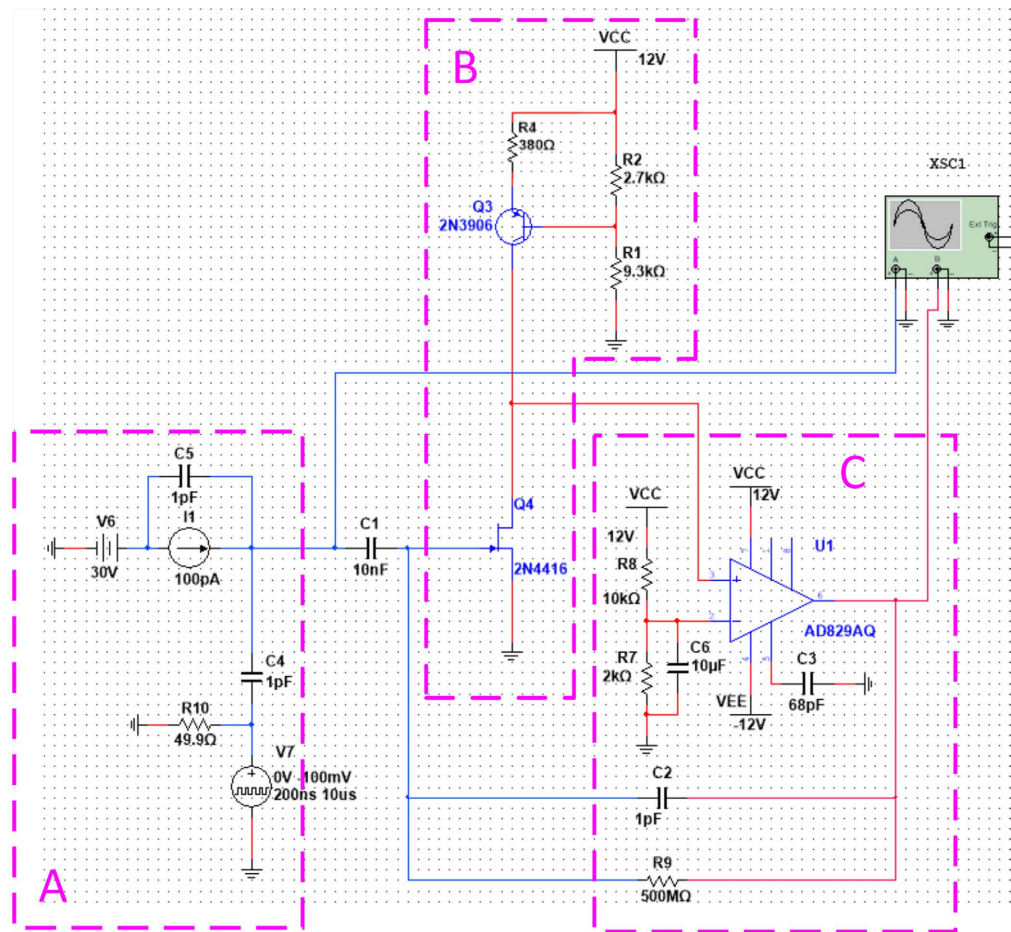
$$Q = V_7 \times C_4 \tag{3}$$

Figure 2. Simulation of charge sensitive preamplifier.

Therefore, the designed constant current source should be 5 mA. Using Multisim software to optimize the bias circuit parameters, When the power supply is ±12 V, in order to simplify the parameter design, so that $R_1 + R_2 = 12$ kΩ, while $R_1 + 0.7$ V $= 10$ V, select $R_1 = 9.3$ kΩ, $R_2 = 2.7$ kΩ, to ensure that the constant current source is 5 mA, that is $R_4 = 380$ Ω. Using Multisim software to verify the bias circuit parameters, the circuit meets the requirement of constant current source for 5 mA output. Therefore, when using Multisim software simulation, the total amount of charge collected can be simulated by setting the amplitude of the pulse voltage source, and the time of collecting charge can be simulated by setting the pulse width of the pulse voltage source.

3.2. Input Stage Circuit

The circuit designed in this experiment selects 2N4416 N-JFET with large transconductance, low input capacitance, high input impedance and small gate leakage current. In order to ensure its normal operation, the PNP transistor 2N3906 is used to form a constant current source bias circuit, and a stable static working point is set for the input stage. In addition, using a constant current source as the active load of the input stage field effect transistor can further improve the gain and linearity of the circuit. The bias circuit structure is shown in part B of Figure 2. Its working principle is as follows: R_1 and R_2 are the bias resistors that set the Q_3 base voltage, and R_4 is the current limiting resistor that sets the constant current source current. According to the data manual of 2N4416, when the drain current is about 5mA, the gate and source are in reverse bias state and have high transconductance gain.

3.3. Main Amplifier Circuit

In order to reduce the design difficulty of this experiment, the integrated operational amplifier is selected as the main amplifier. The circuit structure is shown in part C of Figure 2. Compared with the amplifier circuit composed of triode cascade, this structure has the advantages of stable charge voltage conversion gain, simple structure, high reliability and low design difficulty [4]. According to the requirements of the amplifier circuit for bandwidth, noise, and power supply range, the AD829 operational amplifier is selected. The front-end signal is input into the same-direction end of the operational amplifier, and the reverse end uses resistors R_7 and R_8 to provide bias voltage. According to the virtual short principle of the operational amplifier, the voltage value of the reverse input is approximately equal to the voltage value of the same-direction input, and is equal to the Q_4 drain voltage value. When the power supply is ±12 V, in order to provide 2 V bias voltage to the reverse end of the AD824, select the resistance combination of $R_8 = 10$ kΩ, $R_7 = 2$ kΩ. The output of the operational amplifier is reintroduced into the input stage of the amplifier circuit through the resistance-capacitance parallel feedback network. The feedback capacitance is used to collect the charge signal, and its value affects the charge-voltage conversion sen-

sitivity. The feedback resistor provides a DC feedback path, and its resistance affects the static operating point and low frequency characteristics of the circuit. In addition, the resistor can discharge the charge in the capacitor. High resistance will lead to pulse accumulation effect, while low resistance will lead to incomplete charge collection and affect the amplitude of output signal. The experimental results show that the circuit performance is excellent when the feedback resistance $R_9 = 500$ MΩ and the feedback capacitance $C_2 = 1$ pF.

4. Circuit Performance Simulation

4.1. Charge Sensitivity Simulation

Charge sensitivity characterizes the relationship between the output voltage amplitude V_O and the input charge quantity Q of the charge sensitive preamplifier, which can be measured by the charge conversion gain A_{CQ}. The calculation formula is:

$$A_{CQ} = \frac{V_O}{Q} \tag{4}$$

Q can be obtained by formula 4, and V_o can be measured by oscilloscope in Multisim simulation software [14]. In the simulation process, different pulse voltage source amplitudes are set, and the corresponding output voltage values are measured in turn. Finally, the results of the charge conversion gain are shown in Table 1. The simulation results show that the charge conversion gain of the circuit remains stable, and the measured average value is about 0.979 *mV/fC*, which is in good agreement with the theoretical calculation value.

4.2. Rise Time Simulation

The rise time of the output pulse of the charge sensitive preamplifier is mainly determined by the charge collection time of the detector, the junction capacitance of the detector and the input capacitance of the amplifier circuit [15]. In order to study the influence of the input capacitance of the amplifier circuit

Table 1. Simulation results of charge sensitivity.

Pulsating voltage Sourece (mV)	Input Charge Quantity (fC)	Output Voltage (mV)	Charge Conversion Gain (mV/fC)
1	1	0.992	0.992
2	2	1.961	0.981
5	5	4.893	0.979
10	10	9.781	0.978
20	20	19.519	0.976
50	50	48.764	0.975
100	100	97.441	0.974
1000	1000	978.118	0.978

designed in this experiment on the rise time, in Multisim software, the signal rise time of the pulse voltage source is set to 10 ns, the signal width is 200 ns, and the signal amplitude is 100 mV. The input port of the amplifier circuit is added to the capacitance in parallel with the ground as the input capacitance of the amplifier circuit, and the rise time of the output signal under different capacitance conditions is simulated. The results are shown in Table 2.

5. Circuit Performance Test

5.1. Charge Sensitivity and Rise Time Test

The DG1200 signal generator is used to generate a square wave signal with an amplitude of 100 mV, a frequency of 10 Hz, a duty cycle of 50%, and a rise time of 35 ns, and input it to the test port of the preamplifier. The output signal after amplification is measured as shown in Figure 3: The output signal amplitude is about 99 mV and the rise time is about 60 ns. The above test results show that the circuit has excellent charge sensitivity and frequency response characteristics.

5.2. Ray Response Test

First Sensor's X5-γ Si-PIN detector is connected to the preamplifier designed in this experiment to measure the response of the ^{241}Am radioactive source to γ-rays. The output signal of the preamplifier is shaped by a differential circuit with a time constant of 1 μs. The measured waveform is shown in Figure 4: The signal amplitude is about 13 mV, the baseline noise peak-to-peak value is about 2 mV, and the signal rise time is about 65 ns.

Table 2. Rise time (10% - 90%) simulation results.

Input Capacitance (pF)	0	1	5	10	20	50
Rise Time (ns)	10	15	20	30	50	80

(a) Amplitude of test _output   (b) Risetime of test_output
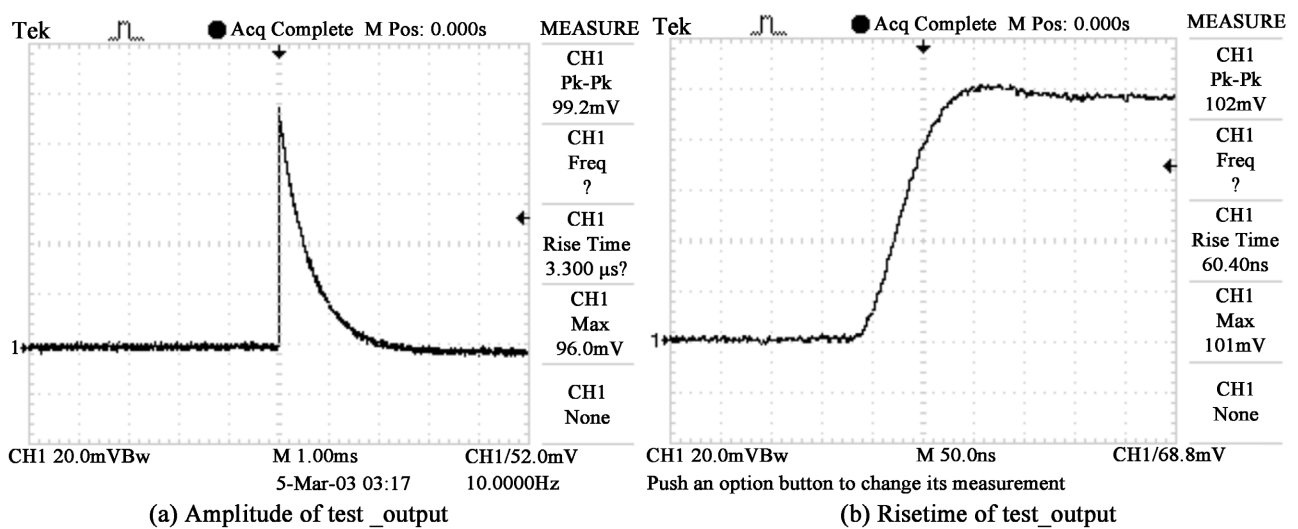
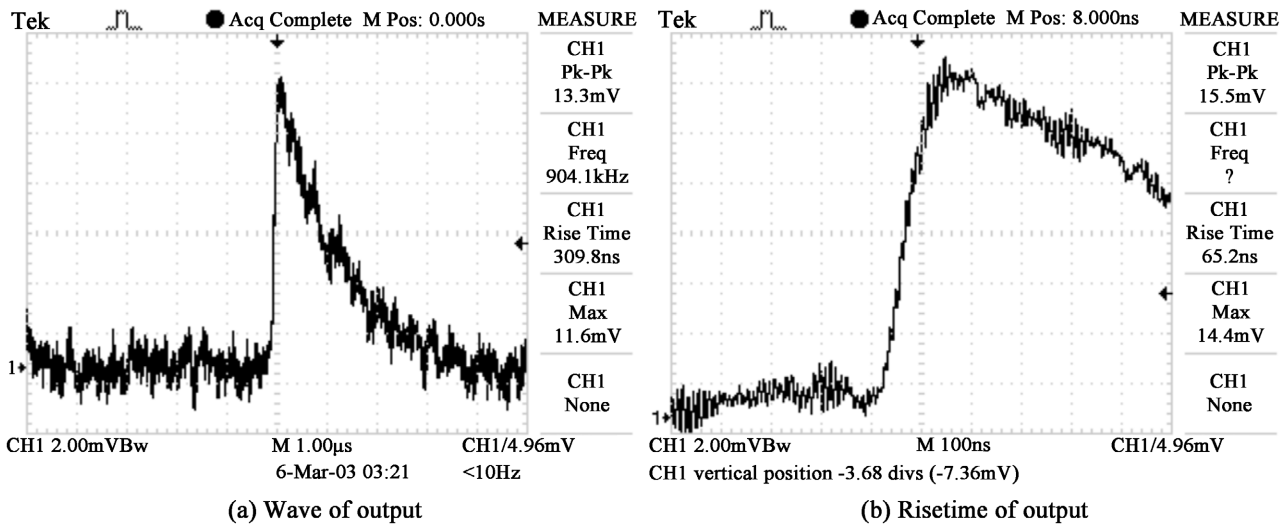**Figure 3.** Test signal output.
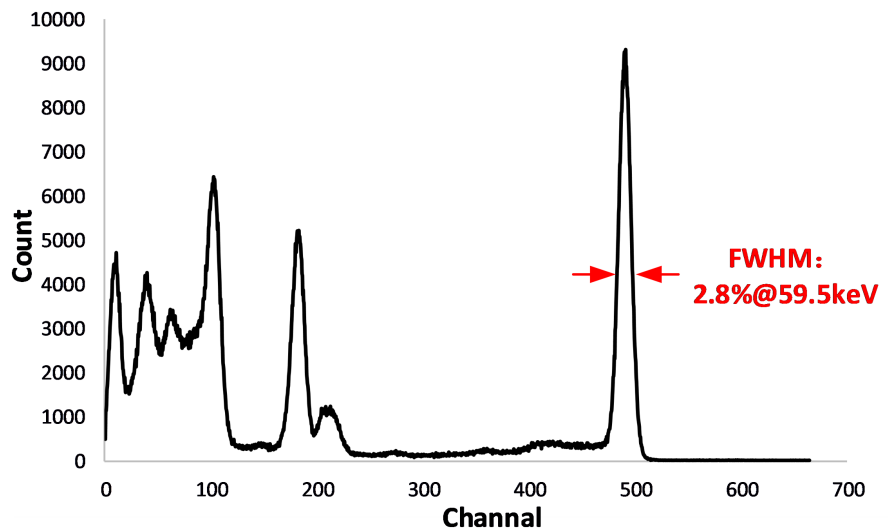
Figure 4. ²⁴¹Am ray output signal diagram.

Figure 5. ²⁴¹Am energy spectrum measurement results.

5.3. Energy Spectrum Test

The output signal after coupling the preamplifier to the Si-PIN detector is connected to a multichannel pulse amplitude analyzer for energy spectrum measurement. The measured spectral lines are shown in **Figure 5**: The energy resolution is approximately 2.8% @ 59.5 keV.

6. Experimental Analysis

Using the experimental method introduced in this paper, the working principle of the charge sensitive preamplifier circuit is analyzed firstly, and then the circuit simulation and parameter optimization design are carried out by Multisim software, and a practical circuit is completed. Finally, the charge sensitivity, frequency response, output waveform response, energy spectrum response and other indicators of the circuit are tested, this energy resolution of ²⁴¹Am is as high as 2.8%

@ 59.5 keV, which proves that it has excellent performance and can be applied to the field of high-resolution energy spectrum measurement.

Acknowledgements

Conflicts of Interest

The authors declare no conflicts of interest.

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