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Thermal experiment of silicon PIN detector *

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Abstract The experiment of this paper is the thermal test of the leakage current of silicon PIN detector. Raising temperature may cause the detector to increase leakage current, decrease depletion and increase noise. Three samples are used in the experiment. One (called ΔE) is the sample of 100 μm in thickness. The other two (called E_1 and E_2) are stacks of five detectors of 1000 μm in thickness. All of them are 12 mm in diameter. The experiment has been done for 21 hours and with power on continuously. The samples have undergone more than 60 ℃ for about one hour. They are not degenerated when back to the room temperature. The depletion rate is temperature and bias voltage related. With the circuit of the experiment and temperature at 35 ℃, ΔE is still depleted while E_1 and E_2 are 94.9% and 99.7% depleted respectively. The noises of the samples can be derived from the values at room temperature and the thermal dependence of the leakage currents. With the addition of the noise of the pre-amplifier, the noises of E_1, E_2 and ΔE at 24 ℃ are 16.4, 16.3, and 10.5 keV (FWHM) respectively while at 35 ℃ are about 33.6, 33.1, and 20.6 keV (FWHM) respectively.

Key words thermal effects, PIN detector, radiation detection, energetic particle, space environment

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1 Introduction

The silicon PIN detector is a kind of diode by using boron and phosphorus ions implanted respectively on the two sides of inherent silicon to form P-I-N junction[1]. Institute of microelectronics of Peking University developed the PIN detector by using Micro-Electro-Mechanical Systems (MEMS)[2]. Since MEMS can cut the sensitive area with arbitrary shapes, this planer technique can produce position-sensitive detector to measure the angle distribution of particles[3, 4]. The PIN detector also has good performances[5]. Its leakage current is small, it is about 10 nA order compared with 100 nA of the barrier detector and 1000 nA of the Si-Li drift detector.

Due to its good characteristics and good environment adaptability, the PIN detector is used in the detection of energetic particles in the space. However, the space application requires that the payloads suffer the hard mechanical and hot environments. Mechanical requirement means that the payload can stand against the vibration and impact during the launch. The detector needs to be well designed in mechanics of its structure and package.

The thermal dispersion of satellite in the vacuum of the space is much different from it on the ground. The bad thermal dispersion may cause the temperature too high or too low. Generally, the energetic particle detection can be performed in room temperature, which can be maintained by the thermal control system of the satellite[6]. But, under special conditions, the payload may suffer abnormal temperature. Therefore, the components of the payload should be adapted to the large temperature span. The scheme model and the flight model of the payload will undergo thermal test on the ground.

The solid detector has good adaptability in low temperature. Some special instruments such as X-ray detector should work in low temperature to reduce the noise. The PIN detector works well at −25 ℃[7].

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Our experiment is to investigate the thermal tolerance of Si-PIN detector, and answer questions: How is its performance in high temperature? Can it recover when back to room temperature? And can its precision be certifiable at certain temperature?

Peking University developed the Particle Radiation Detector (PRD) to detect the energetic particle inside the satellites of CBERS-1 and CBERS-2[8]. The Si-Li drift detector was used in PRD to detect high energy electrons. Since the Si-Li drift detector is less stable than the PIN detector, a stack of PIN detectors can be used instead of the Si-Li dectector[9]. The thermal experiment in this paper uses three samples of such instrument. One is the front detector to identify the electrons, say as to ΔE. It is 12 mm in diameter and 100 μm in thickness. The other two are to measure the energy of energetic electrons, say as to E_1 and E_2. Each of E_1 and E_2 is a stack of five detectors with a diameter of 12 mm and a thickness of 1000 μm, which are combined to form 5000 μm to measure the 0.5—2 MeV electrons.

The properties of the samples have been measured in room temperature (24 ℃). The depleted voltage of ΔE is 8 V and the noise is 10.5 keV in Full Width at Half Maximum (FWHM). E_1 and E_2 are combined with five 1000 μm detectors that are chosen with almost the same depleted voltage bellow 120 V. And the noises of E_1 and E_2 are 16.4 and 16.3 keV in FWHM respectively.

2 Leakage current test

The samples of E_1, E_2, and ΔE are put into a thermal chamber and applied bias voltages to ensure them to be depleted. A nA meter is inserted in each circuit of the detector to record the leakage current as Fig. 1 shows. Similar to the working situation, three resistances (R_1, R_2, and R_3) are connected in series to E_1, E_2, and ΔE as bias resistances. They are equal to 100 MΩ. The bias voltage V_1 and V_2 for E_1 and E_2 are 160 V while V_3 for ΔE is 20 V. The voltages should be enough to ensure the detectors to be depleted, but not too high. The high bias voltage may cause large noise[10].

Table 1 is the records of the leakage currents of E_1, E_2, and ΔE while heating and cooling. Two temperature sensors were used to monitor the thermal status. One was put in the thermal box while the other was put on the structure that contained the detectors. The thermal balance was roughly confirmed when the two sensors indicated the same temperature. Even so, it requires time for thermal balance inside the detectors since the detectors have certain thermal capacity. As we know, the leakage current of PIN detector is very sensitive with temperature. The data of Table 1 were recorded when the nA meter was stable. It indicates that the thermal balance was taken inside the detectors.

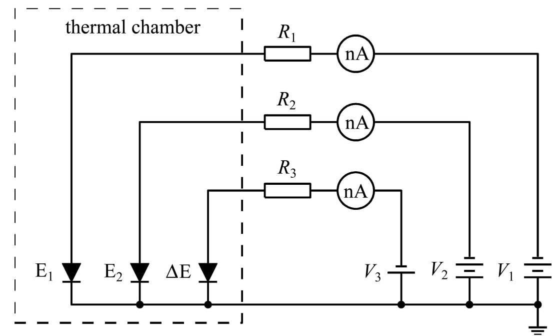

Fig. 1. Configuration of the leakage current measurement.

Table 1. Record of the leakage current measurement.

time/h	temperature/℃	leakage current/nA			description
		E_1	E_2	ΔE	
0	15	39	25	4	start
3.25	20	90	64	8	heating
4.92	35	466	334	35	
5.08	34	469	334	35	
6.00	46	1162	922	89	
6.13	45	1150	914	87	
6.75	50	1400	1228	124	
6.80	50	1400	1228	124	
8.00	71	1571	1549	181	
8.17	71	1571	1549	181	cooling
8.37	64	1571	1549	181	
8.42	64	1571	1549	181	
8.50	64	1571	1549	181	
21.58	21	112	81	10	post-check

Table 1 shows that the leakage currents of the three samples increase as the temperature rises. The temperature rose step by step. After eight hours it got to the top temperature 71 ℃, kept for 10 minutes and cooled to 64 ℃. After then, the measurement stopped and let the chamber cool to room temperature naturally. 21 hours later, a post measurement was taken to check if the detectors recovered.

Two results are obtained from the experiment. Firstly, all samples can recover to normal after being heated to 71 ℃ for 10 minutes and more then 60 ℃ for about one hour. Secondly, the relationship between the leakage currents and temperature has been obtained. And it can be used to discuss the thermal property of the PIN detectors.

3 Discussion of leakage current

The circles in Figs. 2, 3, and 4 are the measurement data for E_1, E_2, and ΔE respectively from Table 1. The leakage currents are controlled by the thermal effects of the detectors and the bias resistances as Fig. 1 shows. Let R_b represent R_1, R_2, and R_3 while V_b represents V_1, V_2 and V_3 in Fig. 1. R_e represents the resistance equivalent to the effect of the leakage current. Each circuit of the samples in Fig. 1 follows the Ohm's law, that

$$I_L = \frac{V_b}{R_b + R_e} \ , \tag{1}$$

where I_L is the leakage current. In the case of R_b omitted or neglectable, I_L is determined by the properties of the detector. It may increase with temperature exponentially. R_e may decrease exponentially with temperature as $R_e = \alpha\exp(-\beta T)$. Therefore, in our experiment case,

$$I_L = \frac{V_b}{R_b + \alpha\exp(-\beta T)} \ . \tag{2}$$

The solid curves in Figs. 2, 3, and 4, for E_1, E_2, and ΔE respectively, are relationships between the leakage currents and temperature fitted by Eq. (2). Table 2 lists the parameters of the fitting curves.

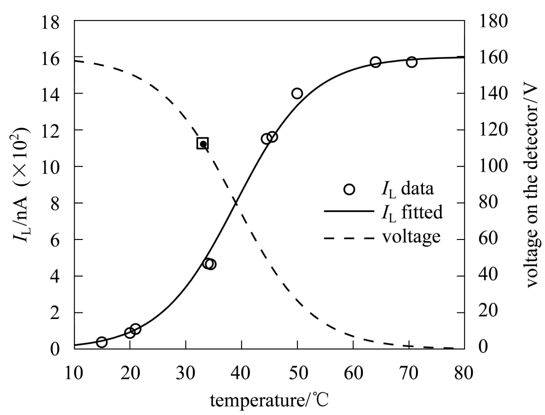

Fig. 2. Leakage current vs. temperature for E_1.

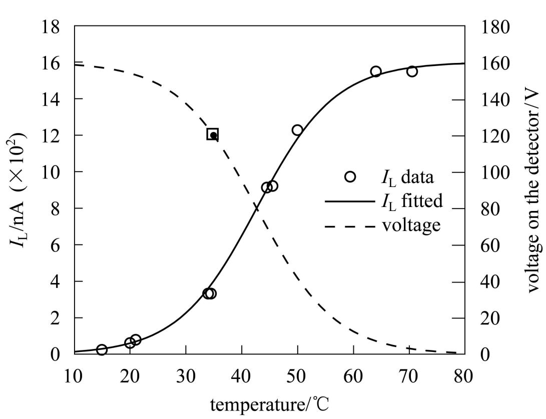

Fig. 3. Leakage current vs. temperature for E_2.

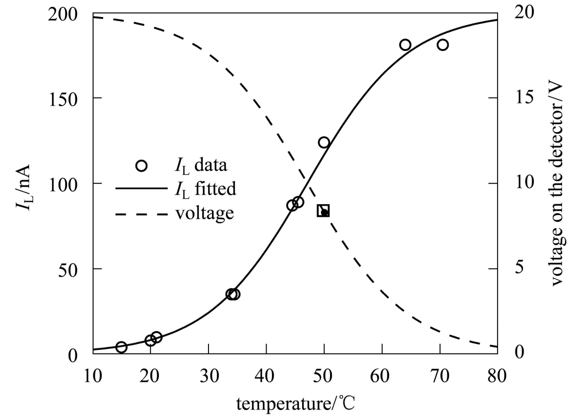

Fig. 4. Leakage current vs. temperature for ΔE.

Table 2. The parameters of fitting data to Eq. (2).

samples	α/Ω	$\beta/(1/\mathrm{K})$
E_1	5.664×10^{27}	0.146
E_2	2.603×10^{27}	0.141
ΔE	1.158×10^{24}	0.115

As the temperature rises, the leakage current increases while the voltage on the detector decreases. The dashed lines in Figs. 2, 3, and 4 are the voltages on E_1, E_2, and ΔE respectively according to Eqs. (3)—(5).

$$V_{E_1} = V_1 - R_1 \cdot I_{E_1}, \tag{3}$$
$$V_{E_2} = V_2 - R_2 \cdot I_{E_2}, \tag{4}$$
$$V_{\Delta E} = V_3 - R_3 \cdot I_{\Delta E}. \tag{5}$$

Decreasing of the voltage on the detector with temperature may cause the detector not to be depleted. According to the principle of the solid state detector[11], the depletion thickness (X) is related to the voltage on the detector (V) as

$$X = \sqrt{2\varepsilon\mu\rho V} \ , \tag{6}$$

where ε is the dielectric coefficient of silicon; μ is the mobility of the carriers; ρ is the resistivity of the material of the detector. The carriers can be electrons or holes. The mobility is carriers dependent and also temperature dependent. For silicon at temperatures higher than 150 K, Ludwig and Watters (1956) have found that (refer in Ref. [12]).

$$\mu = 2.1\times10^9 T^{-2.5} \quad \text{electrons}, \tag{7}$$
$$\mu = 2.3\times10^9 T^{-2.7} \quad \text{holes}, \tag{8}$$

where the units of μ and T are $\mathrm{cm^2/Vs}$ and K respectively.

While the temperature rises, the voltages on R_1 to R_3 increase as the leakage currents increase; and the voltages on the detectors decrease. On the other hand, the mobility of the carriers decreases while the temperature rises. It causes the depletion voltage to rise according to Eq. (6). Both of the two effects may cause the detectors to be non-depleted at high temperature. Non-depletion of detector may cause errors in the measurement of the particle energy.

The depletion voltages of the samples with temperature can be extrapolated by Eqs. (6)—(8) from their measurements in room temperature. As mentioned in Section 1, the bias voltages at 24 ℃ for depletion E_1, E_2, and ΔE are 120 V, 120 V, and 8 V respectively. The voltages on the detectors can be calculated by Eqs. (3)—(5). So, the critical properties for depletion E_1, E_2, and ΔE in the experiment can be evaluated as Table 3 lists. The square and dot markers drawn in Figs. 2 to 4 represent the critical properties for carriers as electrons and holes respectively.

Table 3. The critical depleting status.

sample	carrier	temp./℃	voltage on detector/V	I_L/nA	depletion on 35 ℃(%)
E_1	electrons	33.2	112.3	476.6	95.2
	holes	33.1	112.9	470.8	94.9
E_2	electrons	35.0	120.0	399.5	100.0
	holes	34.9	120.8	392.5	99.7
ΔE	electrons	50.2	8.3	116.9	100.0
	holes	50.0	8.4	115.7	100.0

The critical depletion temperatures are higher for the carriers of electrons than for those of holes. But the differences are not significant; and the latter is preferred safely. The depletion rates of E_1, E_2, and ΔE will be 94.9%, 99.7%, and 100% respectively at 35 ℃. It supposes to be the up limit of the working environment.

4 Noise analysis

Figure 5 shows the equivalent circuit for the noise analysis. The parallel resistance (R_p) of the PIN detector is much larger than the bias resistance (R_b), so it is neglectable. The connection resistance (R_s) is much small to be neglectable. The pre-amplifier is so perfect that the input resistance is much larger than R_b. C_d is the capacity of the detector addition with the capacities of the pre-amplifier, frame of the detector, and connection cable.

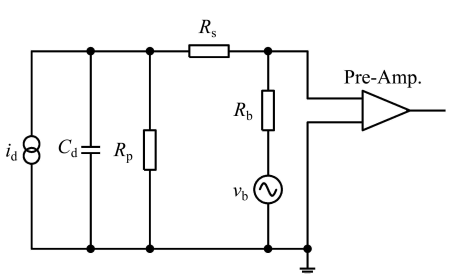

Fig. 5. Equivalent circuit for the noise analysis.

The noise sources of the circuit of Fig. 5 attribute to the leakage current and R_b. These two sources can be evaluated by Eqs. (9) and (10)[13].

$$\overline{(v_L)^2} = \overline{(i_L R_b)^2} = 2I_L e R_b^2 \Delta f \ , \tag{9}$$

where v_L and i_L are respectively the voltage noise and current noise due to the leakage current. e is the electron charge. And Δf is the frequency bandwidth of the system.

$$\overline{(v_R)^2} = 4kTR_b\Delta f \ , \tag{10}$$

where v_R is the noise voltage due to the bias resistance. T is the temperature in units of Kelvin. k is the Boltzmann constant.

The noise amount is equal to the noise signals charged on C_d. Supposing that 80% of C_d attributes to the detector while 20% attributes to other parts, $C_d = C_{d0}(0.2+0.8/r)$, where r is the depletion rate of the detector. r is equal to one if the temperature is bellow the critical value of Table 3. If the temperature is above the critical value, r can be evaluated by the voltage on the detector. Combining Eqs. (9) and (10), Eq. (11) gives the noise relation to the leakage current and temperature.

$$S_d = C\cdot(0.2+0.8/r)\sqrt{2I_L e R_b^2 + 4kTR_b} \ , \tag{11}$$

where S_d is the noise of the detector; C is a constant that attributes to C_{d0} and the integral by Δf. The constant C can be obtained from the noise amount at room temperature. On the other hand, the noise of the pre-amplifier should be removed by Eq. (12).

$$S_t^2 = S_d^2 + S_e^2 \ , \tag{12}$$

where S_t is the total noise while S_e is the noise due to electronics.

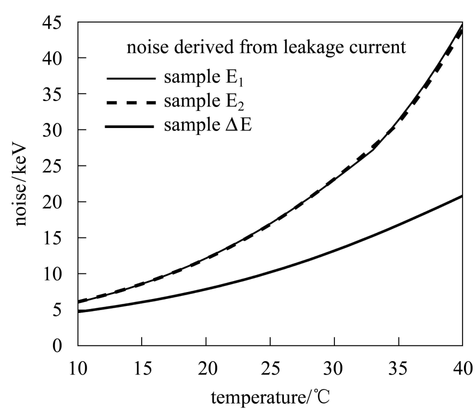

Fig. 6. Noise estimate of the samples.

As Section 1 introduced, the noises at 24 ℃ for E_1, E_2, and ΔE are 16.4, 16.3, and 10.5 keV respectively. The typical noise of the pre-amplifier at 24 ℃ is about 4 keV. Fig. 6 exhibits the evaluation of the noise of the samples from their leakage currents. At 35 ℃, the noises of E_1, E_2, and ΔE are 31.3, 30.9, and 16.8 keV respectively.

However, the noise of the pre-amplifier is also thermal related. It depends on the design and the components. Typically, the noise of the pre-amplifier may be double if the temperature increases 7 ℃. From this, one can roughly reckon the noises of E_1, E_2, and ΔE, addition with the pre-amplifiers, to be 33.6, 33.1, and 20.6 keV respectively at 35 ℃.

5 Conclusions

The temperature dependence of the leakage current represents the thermal performance of the silicon PIN detector in our experiment. It was measured by the simplified circuit as Fig. 1 shows, which let the detectors be in the same electronic environment as applications. The leakage current in the experiment is not only due to the detector but also restricted by the bias resistance (R_1 to R_3).

While the temperature rises, the leakage current increases, so the voltage supplying on the detector drops. On the other hand, the depletion voltage rises with temperature according to the principle of semiconductor. The detector may not be depleted at high temperature. In our experiment, the critical temperatures for depleting E_1, E_2, and ΔE are about 33.1 ℃, 34.9 ℃, and 50.0 ℃ respectively. Supposing that the working temperature is up to 35 ℃, the depletion rates of E_1, E_2, and ΔE at 35 ℃ will be 94.9%, 99.7%, and 100% respectively. It fits in the error margin of about 5%.

The noise of the PIN detector in the applications can be analyzed by the equivalent circuit of Fig. 5. Two main sources are the leakage current and the bias resistance. The thermal relationship of noises can be extrapolated from the value at room temperature according to the noise principles of the leakage current and resistance as Eq. (11). The noises of E_1, E_2, and ΔE at room temperature (24 ℃) are 16.4, 16.3 and 10.5 keV in FWHM respectively, while at 35 ℃ they are 31.3, 30.9, and 16.8 keV respectively.

Actually, the noise of the pre-amplifier is mixed to the noise of the detector. The typical noise of the pre-amplifier at room temperature is about 4 keV and increases with temperature by the rate of double per 7 ℃. The total noises with the pre-amplifier for E_1, E_2, and ΔE at 35 ℃ will be about 33.6, 33.1, and 20.6 keV. Setting noise margin as 2.5 times (about 150 db), E_1, E_2, and ΔE are suitable for the particle detection that the energy depositions are more than 84, 82.9 and 51.5 keV respectively; and the system can work well up to 35 ℃. This typical evaluation of noises may become a reference for designing a measurement that needs to work in the environment more than room temperature.

The silicon PIN detectors are manufactured at the institute of microelectronics of Peking University.

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