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The performance of 4H–SiC detector at high temperature after gamma irradiation

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ABSTRACT

A 4H–SiC detector based on the Schottky diode was fabricated and the combined influence of high temperature and gamma irradiation on 4H–SiC detector has been investigated. We tested the detector's performance at high temperature before gamma irradiation. I–V characteristics and the alpha energy spectra were measured with the 4H–SiC detector before gamma irradiation at high temperature up to 200 °C. The leakage current of the 4H–SiC detector was only 98.7 nA at 200 °C and with a operating voltage of 70 V. The detector showed an energy resolution of 2.36% at 200 °C in detection of ^{241}Am alpha-particles. Then the detector was irradiated by ^{60}Co gamma-ray up to a dose of 1 MGy. I–V characteristics measurements and α energy spectrum measurements were also performed at 200 °C after each irradiation. Both the forward current and the reverse current increased after gamma irradiation. The Schottky barrier height was extracted from the forward I–V curves and it decreased by 0.17 V at a dose of 1 MGy. The response for ^{241}Am source showed that the charge collection efficiency of the detector reduced by only 1.6% and the FWHM can be regarded as unchanged. It has been proved that 4H–SiC detector can work well at 200 °C after exposure to ^{60}Co gamma-ray of 1 MGy.

1. Introduction

Semiconductor detectors have some advantages over other detectors due to its small size, high speed of response and high sensitivity. Conventional semiconductors such as Si and Ge detectors can perform well at room temperature, but it can't withstand harsh environment with high temperature and irradiation (Metzger et al., 2002). 4H–SiC, a kind of semiconductor material with wide bandgap (4H–SiC: 3.26 eV), excellent thermal conductivity and high displacement threshold energy (Si: 35 eV,C: 25 eV), is promising to solve this problem (Das and Duttagupta, 2015).

It has been reported that 4H–SiC detector showed resistance to high temperature or γ irradiation. E. V. Kalinina and Sandro Rao have proved that the 4H–SiC detector can work well even temperature reaches 300 °C, respectively (Kalinina et al., 2008) (Rao et al., 2016). Frank H. Ruddy et al. developed a 4H–SiC detector, which can stand gamma-ray exposures to 5.445 MGy and show no significant deterioration in detection of ^{238}Pu alpha-particles (Ruddy and Seidel, 2007). However, it is still uncertain whether 4H–SiC detector can work at high temperature after intense gamma irradiation. In order to clarify the combined influence of high temperature and gamma irradiation on 4H–SiC detector, a series of experiments were carried out in this work. This paper presents 4H–SiC detector's performance at high temperature before and after γ irradiation.

2. Test samples and experiment procedure

The 4H–SiC detector was fabricated based on a 4H–SiC Schottky barrier diode. Fig. 1 shows the structure of 4H–SiC Schottky barrier diode. A 25 μm thick n^- epitaxial layer (with a donor doping of 1×10^{14} cm^{-3}) was grown on a 350 μm thick n^+ substrate, then a 100 nm thick Ni layer was deposited on the surface of the epitaxial layer to form the Schottky contact. A Ni/Au (100nm/6 μm) multilayer was deposited on the substrate to form the Ohmic contact. The active area of this detector is 1×1 cm^2.

Fig. 2 shows the experiment setup for I–V characteristics and α energy spectra measurement with 4H–SiC detector. The 4H–SiC detector was placed on a heat panel in a metal case, and surrounding temperature can be controlled from room temperature to 200 °C with an accuracy of ± 1 °C. The I–V characteristics of 4H–SiC detector was

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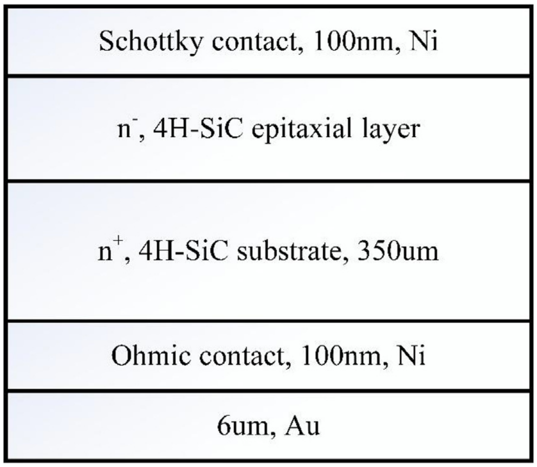


Fig. 1. The structure of 4H–SiC Schottky barrier diode.

measured using a Keithley 2450 Source Meter. In order to test the detector's response to charged particles, the detector was exposed to an ^{241}Am source. The ^{241}Am spectrum consists of 5443 keV and 5486 keV alpha-particle energies with emission probability per decay of 12.8% and 85.2%, respectively (Table of Radioisotopes in). And the average energy of alpha particles is regarded as 5.486 MeV in this paper. The experiments were performed in vacuum and in darkness and the distance between ^{241}Am source and 4H–SiC detector was 32 mm.

At first, we tested the 4H–SiC detector's performance at high temperature. The I–V characteristic of 4H–SiC detector and alpha detection performance of this detector was measured at temperature ranged from 25 °C to 200 °C. Then the 4H–SiC detector was irradiated by ^{60}Co gamma-ray up to 1 MGy. The I–V characteristic of 4H–SiC detector and alpha detection performance of this detector was also measured at 200 °C after irradiation.

3. Results and discussion

3.1. Before irradiation

Fig. 3 shows I–V characteristics of 4H–SiC detector at different temperature. It can be seen from Fig. 3 that the forward current increases and the turn-on voltage decreases while the temperature increases. The reverse current is fairly small under 100 °C, and the reverse current started to increase rapidly when the temperature is above 100 °C. Anyway, the reverse current is 98.7 nA at 200 °C and 70 V (the working condition bias), which indicates that the leakage current is much smaller than 1 μA, so the leakage current won't induce too much noise.

Fig. 4 shows the 4H–SiC detector's response to ^{241}Am source from 25 °C to 200 °C. The details of spectra is given in Table 1. It can be observed that the channel number of the centroid peak moves rightwards slightly from 977.35 to 978.91. The tendency for spectrum to move rightwards can be ascribed to three factors: (1) the bandgap will decrease and the e-h creation energy also decreases with the bandgap as temperature is increased (Garcia et al., 2013); (2) ionization rate of dopant will increase at high temperature, so the concentration of carriers will increase; (3)both majority and minority carriers can survive for a longer time at high temperature (Das and Duttagupta, 2015). Thus more charges are produced and collected.

The observed peak FWHM value, $\mathrm{FWHM_t}$, consists of several contributions, and it can be classified as follows (Ruddy et al., 2005):

$$\mathrm{FWHM_t}^2 = \mathrm{FWHM_s}^2 + \mathrm{FWHM_l}^2 + \mathrm{FWHM_i}^2 + \mathrm{FWHM_d}^2 + \mathrm{FWHM_o}^2 \tag{1}$$

where $\mathrm{FWHM_s}$ is the spectral broadening due to the statistical variations in the number of charge carriers produced by each alpha particle, $\mathrm{FWHM_l}$ is the spectral broadening due to the leakage current of detector, $\mathrm{FWHM_i}$ is the spectral broadening due to the electronic noise caused by the detection system, $\mathrm{FWHM_d}$ is the spectral broadening due to Ni layer above the sensitive region of the detector, and $\mathrm{FWHM_o}$ is the spectral broadening due to energy straggling of the alpha particles, interference caused by the heating panel and vacuum bump.

$\mathrm{FWHM_s}$ can be calculated from (Raja et al., 2017):

$$\mathrm{FWHM_s} = 2.35\sqrt{\varepsilon \mathrm{F E}} \tag{2}$$

where ε is the e-h creation energy, F is the Fano factor, and E is the alpha particle energy. $\mathrm{FWHM_s}$ is calculated to be 5.525 keV according to Eq. (2). $\mathrm{FWHM_i}$ can be determined by using signal generator instead of the detector: we recorded the average pulse height caused by ^{241}Am alpha-particles in the oscilloscope, then we used signal generator (ORTEC 419) instead of the 4H–SiC detector to generate signals with the same pulse height. The signals generated by ORTEC 419 were injected into the preamplifier of the detection system, hence we acquired the energy spectrum of signal generated by ORTEC 419. The FWHM of that energy spectrum is $\mathrm{FWHM_i}$ and it is estimated to be 13.02 keV. $\mathrm{FWHM_d}$ can be determined using Geant4 simulation code. We simulated the 4H–SiC detector in detection of ^{241}Am alpha particles with Ni layer and without Ni layer, so $\mathrm{FWHM_d}$ should be:

$$\mathrm{FWHM_d}^2 = \mathrm{FWHM_w}^2 - \mathrm{FWHM_{wo}}^2 \tag{3}$$

where $\mathrm{FWHM_w}$ is the FWHM with Ni layer, and $\mathrm{FWHM_{wo}}$ is the FWHM without Ni layer. $\mathrm{FWHM_d}$ is estimated to be 33.47 keV. $\mathrm{FWHM_t}$ is 129.42 keV at 200 °C, so the contribution of $\mathrm{FWHM_l}$ and $\mathrm{FWHM_o}$ to $\mathrm{FWHM_t}$ is 124.22 keV according to Eq. (1). $\mathrm{FWHM_t}$ increases from 99.39 keV to 129.42 keV as temperature changes from 25 °C to 200 °C, and it can be ascribed to the leakage current of the detector.

3.2. After irradiation

I–V characteristics of 4H–SiC detector were measured at 200 °C after gamma irradiation, which are shown in Fig. 5. It's obviously that both the forward current and the reverse current increases after gamma irradiation. It's worth noting that the forward current increases sharply as cumulative dose beyond 0.1 MGy, while the reverse current increases gradually with cumulative dose. It has been reported that the reverse current decreases after gamma irradiation at room temperature (Kang et al., 2007), which is in contrast to the result we have achieved at 200 °C.

The forward current of SBD diode is (Sze, 1981):

$$I_\mathrm{F} = \mathrm{A}^{*}T^2 \exp\left(-\frac{q\varphi}{kT}\right)\left[\exp\left(\frac{qV}{nkT}\right) - 1\right] \tag{4}$$

where A* is Richardson constant, T is the temperature, φ is the Schottky barrier and n is ideal factor. The Schottky barrier (φ) and ideal factor (n) can be extracted from the forward I–V curves by (Sze, 1981):

$$\mathrm{n} = \frac{q}{kT}\frac{\mathrm{d}V}{\mathrm{dIn}I_\mathrm{F}} \tag{5}$$

$$\varphi = \frac{kT}{q}\mathrm{In}\left(\frac{\mathrm{A}^{*}T^2}{I_0}\right) \tag{6}$$

where I_0 is the saturation current at zero bias. The Schottky barrier and ideal factor are shown in Table 2. It has been found that the Schottky barrier decreased by 0.07 V and 0.16 V as cumulative dose reached 0.1 MGy and 1 MGy, respectively. The ideal factor decreased from 1.87 to 1.64 at 0.1 MGy and finally increased to 1.88 at 1 MGy.

It's obviously that the forward current is related to the Schottky barrier. Electrons move from n^- semiconductor to the surface of n^- semiconductor with holes left in the n^- semiconductor and the Schottky barrier is formed. Positive charges can be generated on the surface of n^- semiconductor after gamma irradiation, thus the electrons

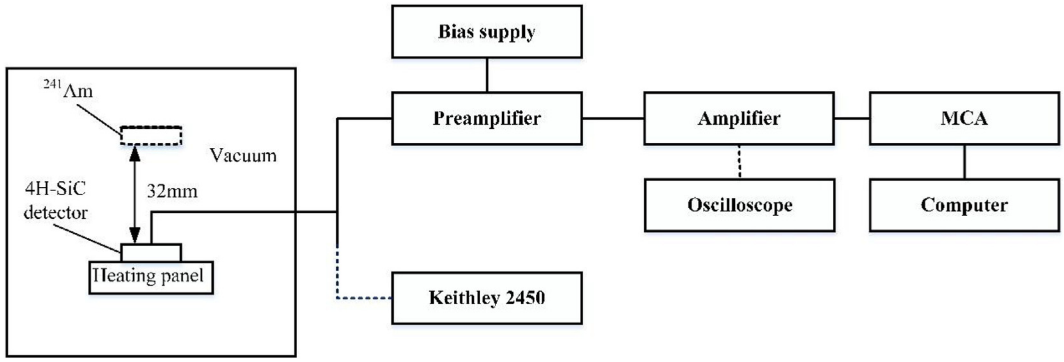


Fig. 2. The experiment setup for I–V characteristics measurements of 4H–SiC detector and alpha detection using 4H–SiC detector.

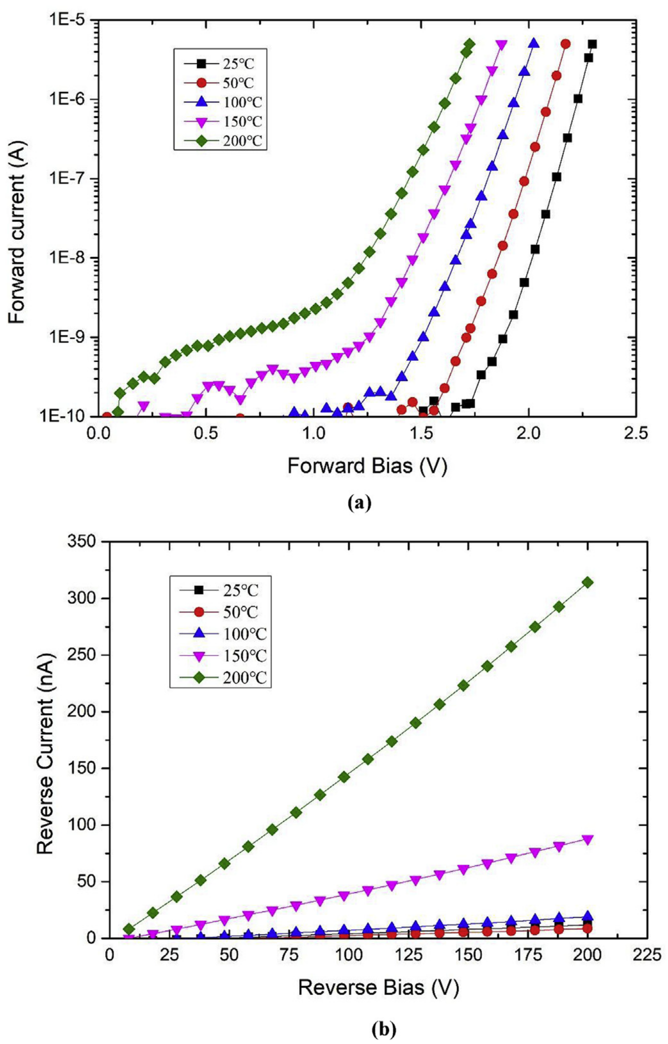


Fig. 3. Measured I–V characteristics at different temperature: (a) Forward I–V characteristics, (b) Reverse I–V characteristics.

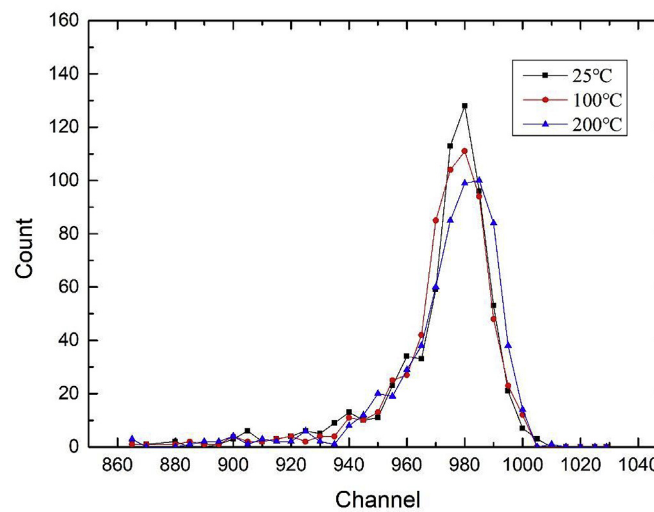


Fig. 4. The 4H–SiC detector's response for ^{241}Am at different temperature.

Table 1
The centroid peak, FWHM and energy resolution of spectra.

Temperature (°C)	Peak	FWHM (keV)	Energy resolution
25	977.35	99.396	1.81%
50	977.38	111.257	2.03%
100	977.31	115.635	2.11%
150	978.42	116.943	2.13%
200	978.91	129.422	2.36%

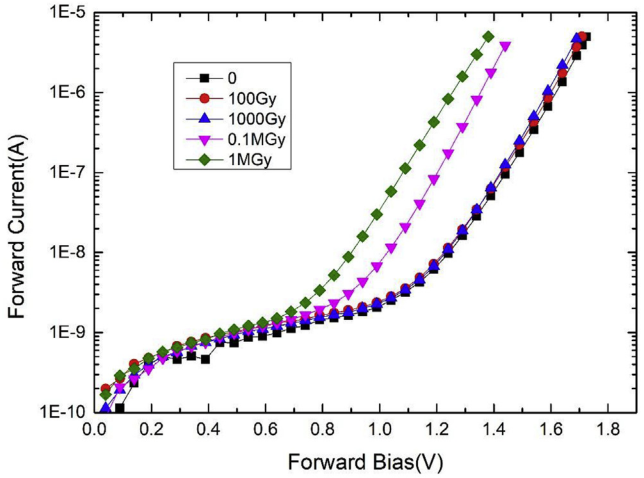
on the surface of n^- semiconductor will be increased and the Schottky barrier is lowered.

We also tested the detector's response to ^{241}Am alpha particles at 200 °C after gamma irradiation, as shown in Fig. 6. It can be observed that the spectrum shifted leftwards after irradiation, which indicated that the CCE (charge collection efficiency, CCE) of this detector decreased. The details of the spectra are shown in Table 3. The CCE of the detector was 97.75% and the FWHM of the spectrum was 137.22 keV at dose of 1 MGy. The CCE of the detector of degraded only 1.6% compared to the result before gamma irradiation. And the FWHM can be regarded as unchanged because the variation of the FWHM is so small.

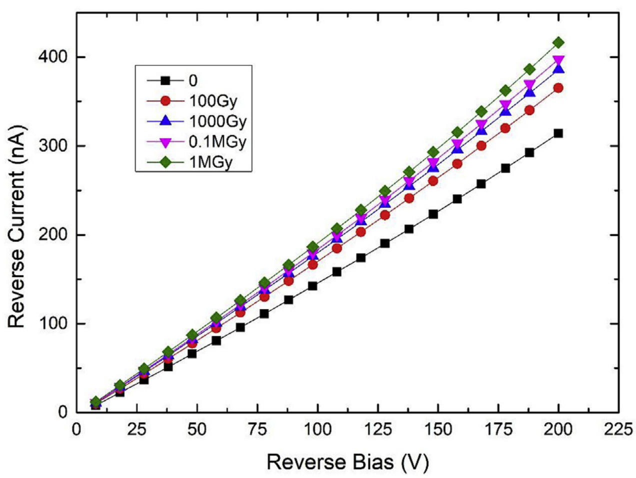
Gamma-ray can create point defects in the semiconductor, and enough point defects can reduce the lifetime of carriers, which contributes to the decrease in the charge collection efficiency and to the increase in the detector noise (Kang et al., 2007) (Nava et al., 2008). However, the experimental results confirm that the 4H–SiC detector shows good performance at 200 °C after gamma-ray irradiation up to 1 MGy.

4. Summary

The 4H–SiC detector's performance has been tested at high temperature (up to 200 °C) before and after gamma irradiation. The 4H–SiC detector showed low leakage current and good energy resolution of 2.36% in detecting alpha particles of 5.486 MeV at 200 °C. After the detector received ^{60}Co gamma-ray irradiation of 1 MGy, the CCE of the detector was 97.75% and the FWHM of the spectrum was 137.22 keV in detecting alpha particles of 5.486 MeV at 200 °C. This detector showed



(a)



(b)

Fig. 5. Measured I–V characteristics after each irradiation at 200 °C: (a)Forward I–V curves, (b)Reverse I–V curves.

Table 2
The ideal factor(n) and the Schottky barrier(φ) extracted from forward I–V curves.

Dose (Gy)	n	φ (V)
0	1.87	2.12
100	1.87	2.12
1000	1.77	2.15
0.1M	1.64	2.08
1M	1.88	1.92

little degradation in CCE and no significant change in FWHM. This study therefore indicates that 4H–SiC detectors can work well at high temperature after intense gamma irradiation.

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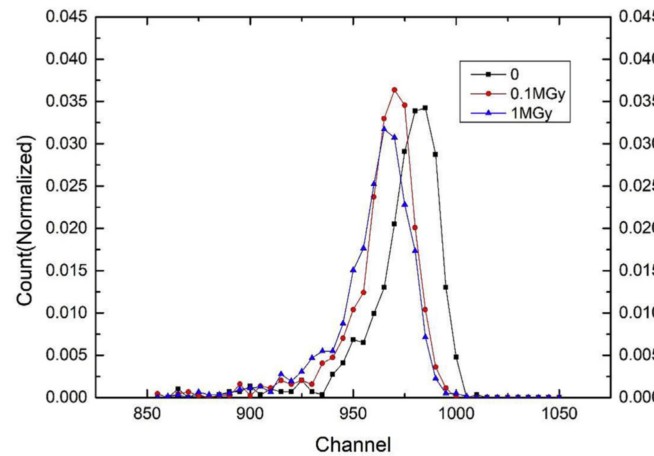

Fig. 6. The 4H–SiC detector's response to ^{241}Am source at 200 °C after each irradiation.

Table 3
The peak centroid, FWHM of the alpha spectra and the CCE of detector.

Dose (Gy)	Peak	CCE	FWHM (keV)
0	978.94	99.33%	129.42
100	974.11	98.84%	113.34
1000	970.66	98.49%	131.59
0.1M	968.14	98.23%	123.51
1M	963.41	97.75%	137.22

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