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Effect of Au/Ni/4H–SiC Schottky junction thermal stability on performance of alpha particle detection*

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Au/Ni/n-type 4H–SiC Schottky alpha particle detectors are fabricated and annealed at temperatures between 400 °C and 700 °C to investigate the effects of thermal stability of the Schottky contact on the structural and electrical properties of the detectors. At the annealing temperature of 500 °C, the two nickel silicides (i.e., $Ni_{31}Si_{12}$ and Ni_2Si) are formed at the interface and result in the formation of an inhomogeneous Schottky barrier. By increasing the annealing temperature, the $Ni_{31}Si_{12}$ transforms into the more stable Ni_2Si. The structural evolution of the Schottky contact directly affects the electrical properties and alpha particle energy resolutions of the detectors. A better energy resolution of 2.60% is obtained for 5.48-MeV alpha particles with the detector after being annealed at 600 °C. As a result, the Au/Ni/n-type 4H–SiC Schottky detector shows a good performance after thermal treatment at temperatures up to 700 °C.

Keywords: alpha particle detector, silicon carbide, thermal stability, Schottky barrier

PACS: 73.40.Sx, 73.30.+y, 29.40.Wk, 29.30.Ep **DOI:** 10.1088/1674-1056/27/8/087304

1. Introduction

Silicon carbide (SiC) is a wide band-gap semiconductor material which has many excellent properties, such as high thermal conductivity, high saturated drift velocity, high critical field, and high thermal and chemical stability. It has an important application prospect in high-temperature, high-voltage, and high-frequency fields.[1–4] In recent years, the SiC radiation detector has attracted attention because of its potential operational capability under high temperature and hard radiation environment without additional cooling and protecting equipment.[5] These advantages make it lighter and smaller than the traditional narrow band-gap semiconductor detector. Therefore, it is very suitable for space environment detection, x-ray pulsar-based navigation, radionuclide exploration, portable radiation environment monitoring, etc.

The SiC radiation detector could be fabricated by choosing a Schottky, PN, or PIN structure. By comparison, the Schottky diode is widely used and investigated for the thinner dead layer and the simpler manufacturing process. The performance of the Schottky diode relies on the quality of metal/semiconductor contact, which depends on various factors, such as thermal stability and interfacial microstructures.[6] One problem is that the Schottky contact characteristics will be degraded at higher temperatures. This has a negative influence on reducing the reverse leakage current, and then, directly affects the energy resolution and sensitivity of the radiation detectors. In order to obtain a higher barrier height, the high working function nickel was widely used.[7] Currently, the Ni/SiC Schottky radiation detectors are formed by directly depositing Ni on the SiC surface. These radiation detectors have shown good alpha particle detection performance under room temperature.[8–10]

However, some important issues need to be further studied. Although the mechanism is not clear, researchers have found that the energy resolution and carrier collection efficiency (CCE) obviously decreased when the detector was measured at higher temperatures. Garcia *et al.*[11] investigated the alpha particle detection properties of the 4H–SiC Schottky detector between 23 °C and 450 °C, then they found that the detection properties became worse above 300 °C. This phenomenon was also found by Abubakar *et al.*[12] who discovered that the energy resolution and charge collection efficiency (CCE) decrease with temperature increasing from 300 K to 500 K. The SiC had a good thermal stability because of its high bond strength.[13] The melting point is over 2100 K and the maximum operating temperature is over 1200 K.[14] Therefore, the most probable reason for the performance degradation is the thermal stability of the Ni/4H–SiC Schottky con-

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tact.

In this paper, we investigate the relationship between thermal stability of the Schottky contact and the characteristic of the detector. The Au/Ni/4H–SiC Schottky detectors are fabricated and annealed at different temperatures. Their electrical property and alpha particle energy resolution are measured at room temperature. The obtained experimental results show that the solid state reaction leading to the formation of nickel silicides at the Ni/4H–SiC interface can be the reason for the variation of electrical properties and detection performance of the detectors after being annealed at different temperatures.

2. Experiment

Figure 1 shows the schematic diagram of the Au/Ni/n-type 4H–SiC Schottky alpha particle detector, which consisted of 370-μm n-type 4H–SiC substrate, 0.5-μm buffer layer, 21-μm epitaxial layer, and metal electrodes. The samples were degreased by ultrasonic bath for 10 min each in acetone, ethanol, and de-ionized water. They were etched in 40% hydrogen fluoride for 10 min to remove the oxide layer, then rinsed in de-ionized water, and followed by blowing dry with nitrogen gas. Aluminum, titanium, and gold were orderly deposited on the back surface of the sample (substrate) by high vacuum thermal evaporation and then annealed at 900 °C for 5 min in the nitrogen atmosphere to form the Ohmic contact. The epitaxial layer was shadow-masked with a square contact of 3 mm in length, metallized with nickel and gold by high vacuum thermal evaporation to form the Schottky contact. Then, some samples were annealed at 400 °C, 500 °C, 600 °C, and 700 °C for 5 min in the nitrogen atmosphere respectively.

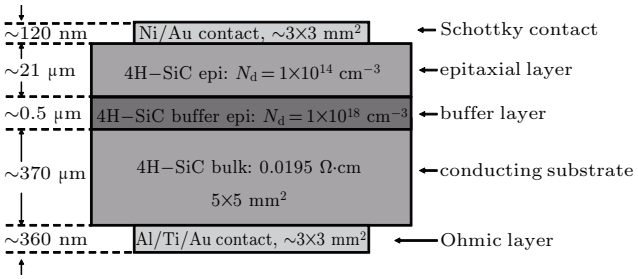


Fig. 1. Schematic diagram of Au/Ni/n-type 4H–SiC Schottky alpha particle detector.

The structure of the Schottky contact was characterized by grazing incidence x-ray diffraction (GIXRD). The evolution of the electrical property of the Au/Ni/4H–SiC detector was monitored by measuring the *I*–*V* characteristic at room temperature with the KEITHLEY 4200. The alpha particle detection performance was measured at room temperature using a ^{239}Pu and ^{241}Am mixed plate type source of energy 5.15 MeV and 5.48 MeV.

3. Results and discussion

Figure 2 shows the GIXRD spectra of the Au/Ni/n-type 4H–SiC detectors. For the unannealed detector or 400 °C annealed detector, no diffraction peaks are detected. At an annealing temperature of 500 °C, five diffraction peaks are detected at 38.2°, 45.9°, 64.5°, 66.6°, and 78.9°, which are corresponding to Au (111), $Ni_{31}Si_{12}$ (115), and Ni_2Si (420) (312) (430), respectively.[15] The coexistence of two silicide phases is caused by the solid state reaction between the Ni layer and the 4H–SiC epitaxial layer. At the annealing temperature of 600 °C, the GIXRD spectra show that the diffraction peak of $Ni_{31}Si_{12}$ (115) disappears but the diffraction peaks of Ni_2Si (220) (420) (140) appear at 44.4°, 64.5°, and 77.5°, respectively. A small shift of Au peak is detected due to the recrystallization of Au grains and strain relaxation at the metal interface.[16] Further increasing the temperature to 700 °C, the GIXRD spectra also show the presence of diffraction peaks of Ni_2Si, which grows in intensity by increasing the annealing temperature. It indicates that the Ni_2Si is the final stable reaction product. Therefore, the GIXRD analyses indicate that the solid state reaction leading to the formation of the nickel silicides occurs at the Ni/4H–SiC interface over 400 °C.

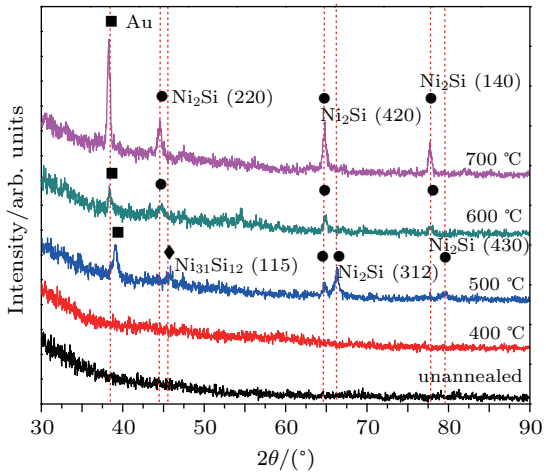


Fig. 2. (color online) X-ray diffraction spectra of the Au/Ni/n-type 4H–SiC Schottky detectors after deposition and after being annealed between 400 °C and 700 °C.

Figure 3 shows the forward and reverse *I*–*V* characteristics of Au/Ni/n-type 4H–SiC Schottky detectors. According to the thermionic electron emission theory, the *I*–*V* relationship is expressed as[17]

$$I = I_0\left[\exp\left(\frac{qV}{nkT}\right)-1\right] = AA^*T^2\exp\left(-\frac{q\Phi_B}{kT}\right)\left[\exp\left(\frac{qV}{nkT}\right)-1\right], \quad (1)$$

where I_0 is the reverse saturation current, A is the area of Schottky contact, A^* is the effective Richardson coefficient (146 A·cm^{-2}·K^{-2} for 4H–SiC at room temperature), Φ_B is the zero-bias Schottky barrier height, V is the forward voltage, k

is the Boltzmann constant, T is the absolute temperature, and n is the ideality factor.

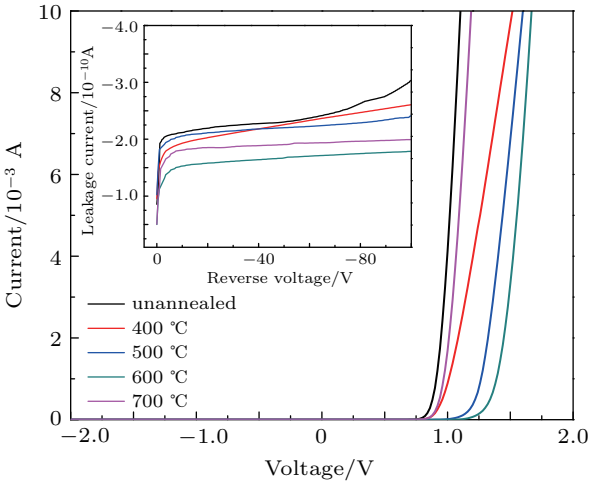


Fig. 3. (color online) Room temperature forward I–V characteristics of the Au/Ni/n-type 4H–SiC Schottky detectors after deposition and after being annealed between 400 °C and 700 °C. Inset shows reverse I–V characteristics of detectors.

The reverse saturation current, I_0, and the slope are obtained by a least square fit of the linear part of the semi-logarithmic I–V curve. With the saturation current and slope thus established, the ideality factor and barrier height are calculated from Eqs. (2) and (3)[18]

$$n = \frac{q}{kT}\left(\frac{\partial V}{\partial(\ln I)}\right), \tag{2}$$

$$\Phi_{\mathrm{B}} = \frac{kT}{q}\ln\left(\frac{AA^{*}T^{2}}{I_0}\right). \tag{3}$$

Table 1 shows the values of Schottky barrier height and ideality factor for the Au/Ni/4H–SiC detectors after annealing at different temperatures. Comparing with the unannealed detector, the n and Φ_{B} of the 400 °C annealed detector increase slightly.

Table 1. Comparison of electrical parameters among Au/Ni/n-type 4H–SiC detectors annealed at different temperatures, estimated from forward I–V characteristics.

Annealing temperature/°C	n	Φ_{B}/eV
Unannealed	1.16	1.33
400	1.20	1.37
500	1.46/1.35	1.16/1.22
600	1.22	1.55
700	1.19	1.41

Figure 4 shows the forward semi-logarithmic I–V characteristics of the Au/Ni/4H–SiC detectors. The curve of the 500 °C annealed detector has two distinct linear regions with different slopes, indicating that the Schottky barrier is no longer unified.[19,20] During the solid-state reaction between Ni and SiC, the $Ni_{31}Si_{12}$ is the first phase formed in the reaction because of its more negative enthalpy.[21] At this temperature, the inhomogeneous Schottky barrier is caused by the coexistence of $Ni_{31}Si_{12}$ and Ni_2Si near the Ni/4H–SiC interface, which is detected by the GIXRD measurement. Thus the forward I–V curve has two linear regions corresponding to different Schottky barriers. According to the two different slopes, the calculated high Schottky barrier height (HSBH) is 1.22 eV, and the low Schottky barrier height (LSBH) is 1.16 eV. In the meantime, the ideality factor obviously increases to around 1.35–1.46, indicating the deviation from the thermionic electron emission model.

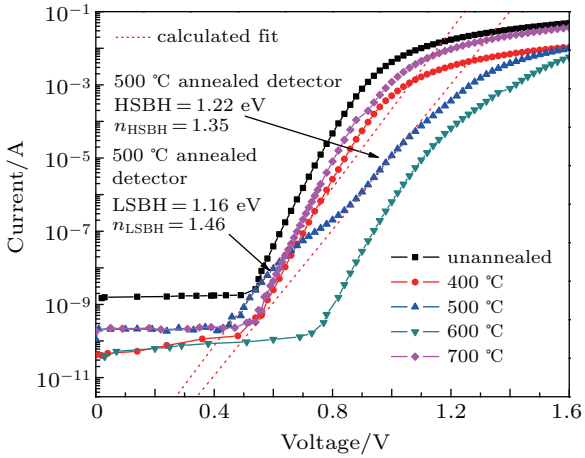


Fig. 4. (color online) Forward semi-logarithmic I–V characteristic curves of Au/Ni/4H–SiC detectors after being deposited and after being annealed between 400 °C and 700 °C.

When the annealing temperature increases to 600 °C, the Φ_{B} increases to 1.55 eV. At this temperature, the $Ni_{31}Si_{12}$ phase transforms into the most stable Ni_2Si phase, thus leading to the formation of a more uniform barrier on the entire Schottky contact area. The work function of Ni_2Si is 0.36 eV higher than that of Ni.[22] Further increasing the annealing temperature to 700 °C, the value of Φ_{B} decreases with the annealing temperature increasing. It is due to the forming of C vacancies near the SiC interface region by outdiffusion of C atoms under this temperature.[16] The C vacancies increase the electron concentration and result in the reduction of the Schottky barrier height.[23] The Ni_2Si is a conductive metal compound that resists oxidation while providing a good Schottky contact up to high temperature.[24]

Under the reverse voltage of 50 V, the leakage current densities are 2.56 nA/cm^2, 2.51 nA/cm^2, 2.44 nA/cm^2, 1.83 nA/cm^2, and 2.11 nA/cm^2 for the detectors after being deposited and after being annealed between 400 °C and 700 °C, respectively. The structural evolution of the system in the interface region affects the electrical properties of the Schottky contact, which gives rise to the decrease of reverse leakage current.

The alpha particle detection performance of the detector is measured at room temperature using a ^{239}Pu and ^{241}Am mixed plate type source of energy 5.15 MeV and 5.48 MeV. The depletion width (d) of the Au/Ni/n-type 4H–SiC Schottky

detector is calculated for the following equation:

$$d = \sqrt{\frac{2\varepsilon_0 \varepsilon_r V_{\text{bias}}}{qN_d}}, \tag{4}$$

where V_{bias} is the reverse voltage, ε_0 is the vacuum permittivity, ε_r is the relative permittivity of 4H–SiC, and N_d is the doping density of 4H–SiC epitaxial layer ($N_d \approx 1 \times 10^{14}/\text{cm}^3$). The 21-μm full-depletion width will be achieved at a reverse voltage of 41 V. So we choose a little bigger reverse voltage of 50 V for achieving full charge collection.

The radiation source and SiC detector are placed inside an aluminum box. A reverse voltage of 50 V is applied to the detector, which is connected to an Ortec 142 H preamplifier. Bias to the detector is provided by a bias supply through the preamplifier. The preamplifier is connected to the main amplifier Ortec 572 and Amptek MCA8000 A digital multichannel analyzer. A computer with the DPPMCA software is used to obtain MCA pulse height spectra.[25] Figure 5 shows the alpha particle responses of different detectors at a reverse voltage of 50 V.

The energy resolution of each detector is obtained by Gaussian function fitting. The results are summarized in Table 2. As is well known, the reverse leakage current is the main electrical noise, which can directly affect the detection performance. As the leakage current density decreases with the increase of annealing temperature, an improvement in energy resolution is observed. The 600-°C annealed Au/Ni/n-type 4H–SiC Schottky detector with higher Schottky barrier height and lower leakage current density has better energy resolutions of 2.72% and 2.60% for the 5.15-MeV and 5.48-MeV alpha particles, respectively.

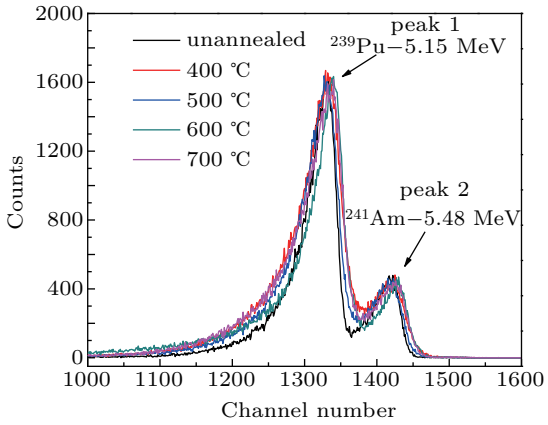


Fig. 5. (color online) Energy spectra of alpha particles, measured with the Au/Ni/n-type 4H–SiC Schottky detectors after being deposited and after being annealed at different temperatures with 50 V of reverse voltage.

Table 2. Energy resolutions of the Au/Ni/n-type 4H–SiC Schottky detectors annealed at different temperatures

Annealing temperature/°C	Energy resolution/%		Reverse leakage current density/(nA/cm^2)
	5.15 MeV	5.48 MeV	
Unannealed	3.00	2.91	2.56
400	2.97	2.86	2.51
500	2.92	2.81	2.44
600	2.72	2.60	1.83
700	2.82	2.73	2.11

In order to further investigate the detection performance, the alpha particle response of the 600-°C annealed Au/Ni/n-type 4H–SiC Schottky detector is systematically measured under the reverse voltages ranging from 0 V to 100 V. Figure 6 shows the dependence of the peak centroid and energy resolution on the reverse voltage varying from 0 V to 100 V. Because of the built-in potential, the detector has a response signal at zero bias. However, the active region is very thin. The generated electrons and holes are easily trapped and recombined during their drift process before being collected by the electrodes. This results in incomplete charge collection and poor energy resolution. When the reverse voltage is below 50 V, the peak center shifts towards higher channels, and the energy resolution becomes better. This phenomenon is caused by the enlargement of the active region width with increasing reverse voltage. The larger active region increases charge collection efficiency (CCE), and then improves the energy resolution. After the 21-μm epitaxial layer is fully depleted at −50 V, the effect of the additional voltage becomes weaker, resulting in little change of the peak position and the energy resolution.

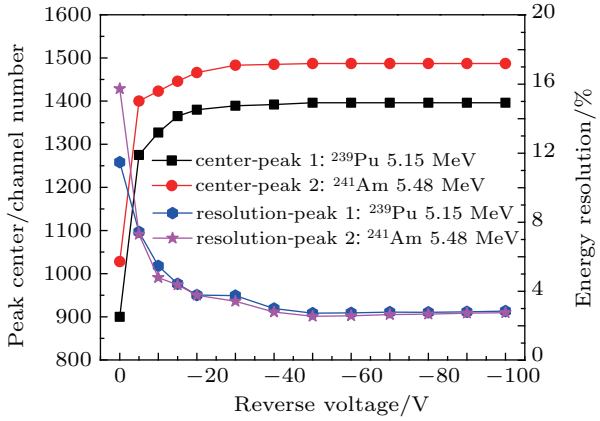


Fig. 6. (color online) Variations of energy resolution and main peak positions of Au/Ni/n-type 4H–SiC Schottky detector after being annealed at 600 °C with reverse voltage.

4. Conclusions

In this work, the Au/Ni/n-type 4H–SiC Schottky alpha particle detectors are fabricated and measured. For obtaining the effect of thermal stability of the Schottky contact on the structural and electrical properties of the detectors, the detectors are annealed between 400 °C and 700 °C. The GIXRD analyses reveal the occurrence of a solid state reaction at the Ni/SiC interface above 400 °C. The coexistence of two nickel silicides (i.e., $Ni_{31}Si_{12}$ and Ni_2Si) are detected in the GIXRD spectra after being annealed at 500 °C. By increasing the annealing temperature the disappearance of the diffraction signal of $Ni_{31}Si_{12}$ in the GIXRD spectra reveals that the Ni_2Si is the final stable reaction product.

According to *I*–*V* results, both the Schottky barrier height and leakage current density are directly dependent on the Schottky contact interface state. Hence, a higher Schottky barrier and a lower leakage current density are obtained in the Au/Ni/n-type 4H–SiC Schottky detector after being annealed at 600 °C. Furthermore, the changes of electrical properties have an effect on the detection performance of the detector. A better energy resolution of 2.60% is obtained in the Au/Ni/n-type 4H–SiC Schottky detector after being annealed at 600 °C with a lower device leakage current density. As a result, the fabricated Au/Ni/n-type 4H–SiC Schottky detector possesses good electrical properties and an alpha particle energy resolution after thermal treatment at temperatures up to 700 °C.

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