Effects of annealing temperature on the electrical property and microstructure of aluminum contact on n-type 3C–SiC*

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The 3C–SiC thin films used herein are grown on Si substrates by chemical vapor deposition. Al contacts with different thickness values are deposited on the 3C–SiC/Si (100) structure by the magnetron sputtering method and are annealed at different temperatures. We focus on the effects of the annealing temperature on the ohmic contact properties and microstructure of Al/3C–SiC structure. The electrical properties of Al contacts to n-type 3C–SiC are characterized by the transmission line method. The crystal structures and chemical phases of Al contacts are examined by X-ray diffraction, Raman spectra, and transmission electron microscopy, respectively. It is found that the Al contacts exhibit ohmic contact behaviors when the annealing temperature is below 550 °C, and they become Schottky contacts when the annealing temperature is above 650 °C. A minimum specific contact resistance of 1.8×10^{-4} Ω·cm^2 is obtained when the Al contact is annealed at 250 °C.

Keywords: Al/3C–SiC, ohmic contact, specific contact resistance

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1. Introduction

Silicon carbide (SiC) is a wide band gap semiconductor with excellent material properties, which can be widely used in the areas of high temperature, high power, high frequency, and nonvolatile memory devices, owing to its large band gap, high breakdown field, high electron saturation drift velocity, high thermal conductivity, etc.[1–4] 3C–SiC can be hetero-epitaxially grown on large diameter silicon (Si) substrate for microelectromechanical system (MEMS) application. High quality ohmic contacts are required to achieve high power devices. Although metal contacts to SiC have been widely investigated,[5,6] low specific contact resistance and high temperature stability are highly desired.[7,8] Thus, the electrical properties of metal/3C–SiC is very important for optimizing the device performance.[9] Generally, 3C–SiC is epitaxially grown on Si substrate by chemical vapor deposition (CVD) either using silane (SiH_4) and propane (C_3H_8) or using single precursor.[10,11] A variety of 3C–SiC electronic devices have been demonstrated, such as the metal–oxide–semiconductor field effect transistor (MOSFET), metal–semiconductor field effect transistor (MESFET), hetero-junction bipolar transistor, photoconductive semiconductor switches, etc.[12,13] However, such devices have not reached the expected performances because of high defect densities in epilayers and underdeveloped unit processing procedures.[14]

Ni is often used to form ohmic contact on n-type 3C–SiC, and the lowest specific contact resistance is about 10^{-5} Ω·cm^2 on highly doped 3C–SiC epilayers.[15] The low work function (4.28 eV) of Al metal implies a low barrier height specially for 3C–SiC with a relatively high electron affinity (χ = 4.0 eV) compared with for other SiC polytypes (such as 4H, 6H, and 15R), unless there is a strong Fermi level pinning at the metal-SiC interface. Among the metallization schemes, Al ohmic contacts to n-type 3C–SiC can be achieved without high temperature annealing. It was reported early that Al ohmic contact on n-type 3C–SiC was 1.6×10^{-1} Ω·cm^2 in the case without annealing[16] and the minimum value for the specific contact resistance for Al and 3C–SiC contacts could reach 1.4×10^{-5} Ω·cm^2.[17] It is very convenient to use Al contacts to fabricate high performance devices.[18] In this paper, we study in-depth the effects of the annealing process on the electrical properties and microstructure of the Al contact to n-type 3C–SiC.

2. Experiment

3C–SiC thin films were hetero-epitaxially grown on Si (100) substrates by a horizontal cold wall CVD reactor using SiH_4 and C_3H_8 as precursor gases and purified hydrogen as the carrier gas. Detailed growth conditions can be found in Ref. [19]. The thickness value of 3C–SiC thin film was 2.5 μm and the electron concentration was 7×10^{17} cm^{-3}. Before de-

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positing the Al contact, the grown 3C–SiC/Si substrates were chemically cleaned by using the RCA process as the following steps illustrate: (i) 10-min ultrasound bath in deionized water, (ii) 10-min ultrasound bath in acetone, (iii) 15-min boiling bath in NH_4OH–H_2O_2–H_2O (1:1:5) mixed solution, (iv) 15-min boiling bath with HCl–H_2O_2–H_2O (1:1:5) mixed solution, and (v) blown dry using high purity nitrogen.[20,21] After the washing and cleaning process, the Al contact was deposited on 3C–SiC epilayers by magnetron sputtering with a depositing speed of 6 nm/min. Finally, the samples were rapidly thermal-annealed at temperatures ranging from 150 °C to 750 °C for 2 min, the temperature rising rate was 250 °C/min. X-ray diffraction (XRD) and Raman spectra were used to analyze phase formations in the films and a transmission electron microscope (TEM) was used to characterize the structural changes after the annealing process. In order to study the characteristics of Al/3C–SiC contact, transmission line method (TLM) patterns were prepared to measure the specific contact resistance and evaluate the ohmic contact performance.[22]

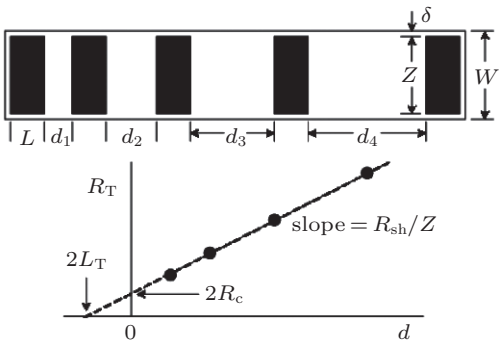


Fig. 1. Distribution of electrodes and the calculation principle of TLM.

TLM is an effective method to characterize and evaluate the performance of ohmic contact. In this method, the current through the metal, semiconductor interface, and semiconductor are regarded as an equivalent model of a linear transmission. The test and calculation principle of TLM are shown in Fig. 1.[23] Z and L are the length and width of aluminum electrode respectively, and d is the distance between the electrodes. The total resistance between two adjacent electrodes consists of the contact resistance and the volume resistance. The specific contact resistance can be calculated by the formulas:

$$R_T = 2R_c + R_{sh} \cdot d/Z, \tag{1}$$

$$\rho_c = R_c \cdot L_T \cdot Z, \tag{2}$$

where R_c is the contact resistance between 3C–SiC and the Al electrode; R_{sh} is the volume resistance of 3C–SiC thin film around the surface; $2L_T$ and $2R_c$ are the intercepts between the X axis and the $R_T \sim d$ curve and between the Y axis and the $R_T \sim d$ curve, respectively. Accurate specific contact resistance can be obtained through the test and data analysis above.

3. Results and discussion

The Al contacts, each with a thickness value of 60 nm, are deposited on 3C–SiC and then annealed at 150, 250, 350, 450, 550, 650 °C, respectively. Figure 2(a) and 2(b) show the I–V curves of Al/3C–SiC annealed at different temperatures. The I–V curves are measured by the transmission line method (TLM). It can be seen that the as-deposited Al contacts to 3C–SiC exhibit linear characteristics in the case without the annealing process. Clear linear I–V curves are observed for the samples annealed at 150, 250, 350, 450, and 550 °C, while a rectifying I–V curve is observed on the sample annealed at 650 °C. From the above observations it can be concluded that the transformation from ohmic contact to Schottky contact appears at 650 °C. To evaluate the ohmic contact performance, the corresponding contact resistance is calculated from the TLM characterization. Table 1 shows the contact resistances at different annealing temperatures. The contact resistance slowly decreases with annealing temperature increasing when the annealing temperature is below 250 °C, while it sharply increases with the temperature increasing from 250 °C to 550 °C. The specific contact resistance of Al/3C–SiC after being annealed at above 450 °C is one order of magnitude larger than those after being annealed at below 450 °C. The lowest contact resistance of 1.8×10^{-4} Ω·cm^2 is obtained after being annealed at 250 °C. The increase in contact resistivity is possibly due to the oxidation of the Al layer and the formation of Al_2O_3, which can increase the barrier height between Al and 3C–SiC.

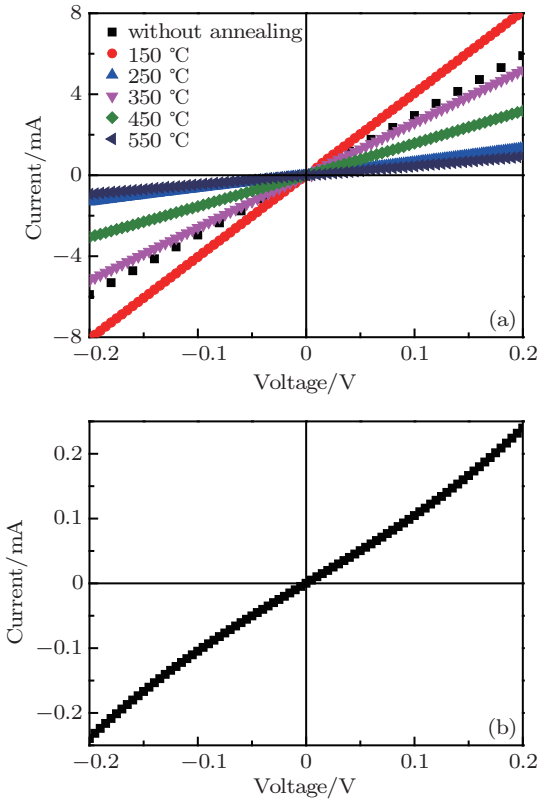


Fig. 2. (color online) (a) I–V curves of Al/3C–SiC contacts after being annealed at different temperatures. (b) I–V curves of Al/3C–SiC contacts after being annealed at 650 °C.

It should be mentioned that the Si substrate has little effect on the electrical characteristics of the Al/3C–SiC/Si structure. High quality n-type 3C–SiC thin films (~ 2 μm), each with a carrier concentration of 7×10^{17} cm^{-3}, are grown on Si (100) substrates. The Si substrate is a p-type material with a carrier concentration of 8×10^{14} cm^{-3}, and can form a p–n heterojunction with 3C–SiC film. Since the electron density of the Si substrate is much lower than that of 3C–SiC, the Si substrate has little influence on the electrical characteristics of Al/3C–SiC film. Hsieh *et al.*[24] proposed that high resistivity Si substrate could effectively stop the leak current transmission from 3C–SiC film to Si substrate. Rahimi *et al.*[25] obtained similar results when they studied the electrical properties of the 3C–SiC/Si heterojunction. In this paper, it can be concluded that the effect of Si/3C–SiC heterojunction on the contact properties of Al/3C–SiC is negligible. The ohmic structure of Al/3C–SiC/Si has been widely studied without considering the effect of high resistivity Si substrate.[26–28]

Table 1. Specific contact resistances of Al contacts each with a thickness value of 60 nm after being annealed at different temperatures.

Annealing temperature/°C	Al thickness/nm	ρ/Ω·cm^2
Without annealing	60	4.4×10^{-4}
150	60	2.3×10^{-4}
250	60	1.8×10^{-4}
350	60	3.9×10^{-4}
450	60	1.6×10^{-3}
550	60	3.2×10^{-3}

From the results of Al/3C–SiC contact characteristic versus annealing temperature, the transformation from ohmic behavior to Schottky behavior occurs between 550 °C and 650 °C. Thus, the annealing temperature has an obvious effect on the contact characteristic and specific contact resistance. In order to figure out the effect of Al thickness on the contact characteristic, Al contacts with different thickness values of 30, 60, and 90 nm are annealed at 550 °C and 650 °C, respectively. Figures 3(a) and 3(b) show the *I*–*V* curves of Al/3C–SiC contact with different thickness values after being annealed at 550 °C and 650 °C, respectively. For the Al/3C–SiC contacts that display ohmic behaviors when being annealed at 550 °C, the changes of Al thickness values ranging from 30 nm to 60 nm do not affect their ohmic contact properties. Meanwhile, when the Al thickness value increases from 30 nm to 60 nm in the Al/3C–SiC contacts that display Schottky behavior when being annealed at 650 °C, their Schottky contact behaviors are fixed. It is obvious to see that the change of the Al contact thickness value when it is larger than 30 nm does not affect the contact behaviors of the Al/3C–SiC contacts, no matter whether it has an ohmic or Schottky behavior.

Table 2 shows the specific contact resistances for different Al contact thickness values after being annealed at 550 °C. It can be seen that the specific contact resistance is in the order of 10^{-3} Ω·cm^2. It is obvious that the contact performance is mainly determined by the annealing temperature rather than the thickness value of Al.

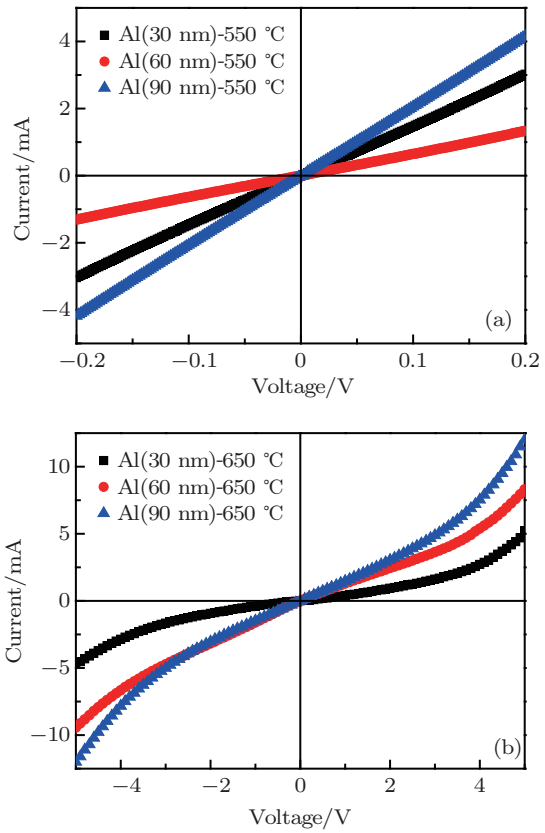


Fig. 3. (color online) The *I*–*V* curves of Al/3C–SiC contacts with different thickness values when being annealed at (a) 550 °C and (b) 650 °C.

Table 2. Specific contact resistances of Al contacts with different thickness values after being annealed at 550 °C.

Annealing temperature/°C	Al thickness/nm	ρ/Ω·cm^2
550	30	1.3×10^{-3}
550	60	2.7×10^{-3}
550	90	1.2×10^{-3}

XRD and Raman spectrum characterizations were performed to investigate the phase and structure changes after the annealing process. Figure 4 shows the Raman spectra of Al/3C–SiC contacts with the Al thickness of 60 nm after being annealed at 350, 450, 550, 650, and 750 °C. The peaks corresponding to Si and 3C–SiC can be seen in samples after being annealed at 650 °C and 750 °C, while they are not seen in samples after being annealed at 350, 450, and 550 °C. The reason is that the thickness of the Al contact becomes thinner after high temperature annealing, which can be proved by TEM images in the following, and then substrate information can be detected. The molten Al and SiC chemically react and form aluminum carbide (Al_4C_3) and Si when the Al/3C–SiC

is annealed at 750 °C (higher than the Al melting point).[29] The Si peak can be observed both in the Raman spectra and XRD patterns. However, the XRD results show that Si phase can only be observed for the sample after being annealed at 750 °C. This phenomenon is attributed to a small number of Si atoms that are beyond the detection limitation when being annealed below 750 °C. Both Raman spectra and XRD patterns do not show the peak corresponding to Al_4C_3. But it can be observed in TEM images. This is due to the oxidation of Al_4C_3 and the formation of Al_2O_3. The peak of Al_2O_3 appears when the annealing temperature is above 650 °C, as shown in Fig. 5.

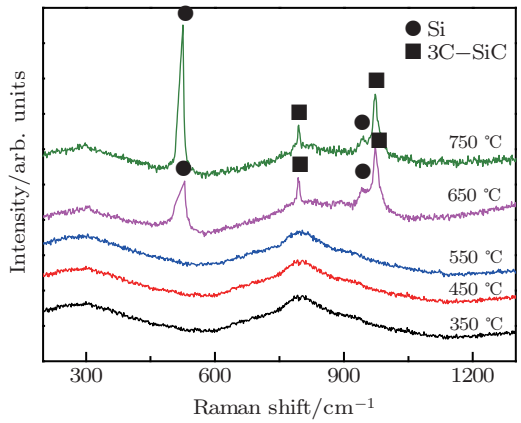


Fig. 4. (color online) Raman spectra of Al-60 nm/3C–SiC after being annealed at different temperatures.

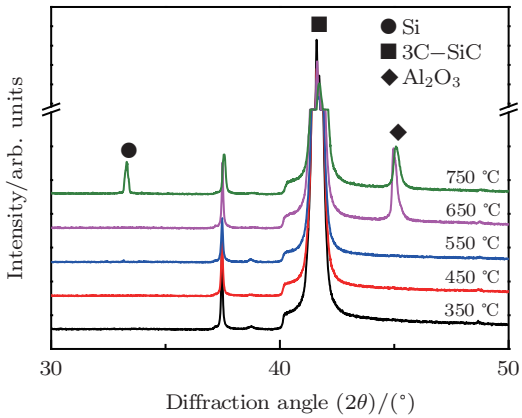


Fig. 5. (color online) The XRD patterns of Al-60 nm/3C–SiC after being annealed at different temperatures.

The Raman and XRD results indicate that both Si and Al_2O_3 are formed during high temperature annealing. In order to further study the microstructure after the annealing process, TEM and energy-dispersive spectrometry (EDS) are used to analyze the metal layer structure and element distribution. Figure 6 shows the cross-sectional TEM images of Al-60 nm/3C–SiC samples after high temperature annealing. It can be seen that the Al thickness value is 55.5 nm after being annealed at 550 °C and it decreases to 42.3 nm when the annealing temperature is increased to 650 °C. The possible reason is that Al atoms diffuse into SiC and thus they are densified as the annealing temperature increases, so the thickness of Al becomes thinner since the melting point of Al is 660 °C and the activity of Al atoms become stronger when the annealing temperature is above 650 °C.

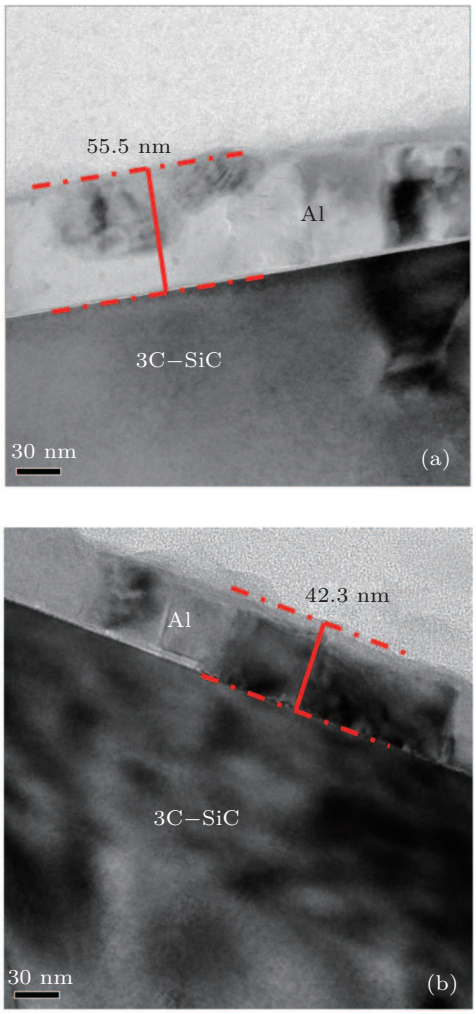


Fig. 6. (color online) Cross-sectional TEM images of Al-60 nm/3C–SiC samples annealed at (a) 550 °C and (b) 650 °C.

Figure 7 shows the HRTEM image and EDS results of sample Al-60 nm/3C–SiC after being annealed at 650 °C. New phases, such as Al_4C_3, Al_2O_3, and Si, can be identified by measuring the interplanar crystal spacing, while only Al, C, and O elements are detected in the EDS. Si is definitely formed through the chemical reaction, which has been evidenced by XRD and Raman spectra results. No Si signal is detected in EDS, which may be due to a small number of Si atoms, and it only appears in some areas rather than being homogeneously distributed throughout the contact layers.

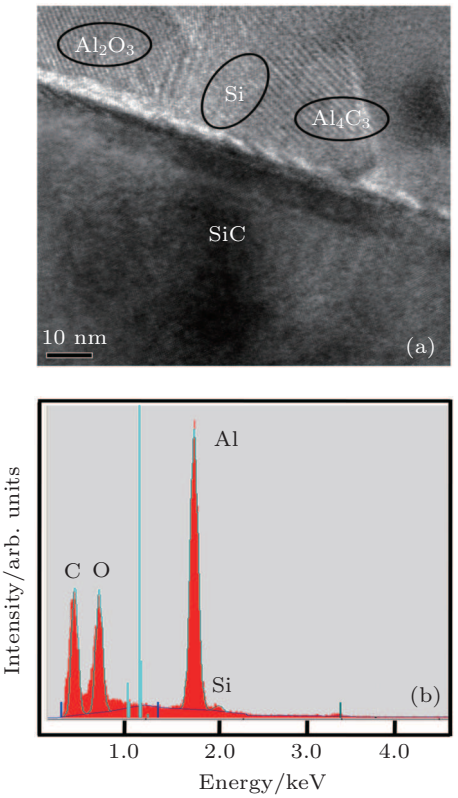


Fig. 7. (color online) (a) HRTEM image and (b) EDS of sample Al-60 nm/3C–SiC after being annealed at 650 °C.

4. Conclusions

The effects of annealing temperature and Al thickness value on the ohmic contact properties of Al/3C–SiC are investigated in this paper. The electrical properties of the Al/3C–SiC contacts are characterized by TLM. The crystal structures and chemical phases of Al contacts are examined by XRD, Raman spectra, and TEM. It is found that Al contacts exhibit ohmic contact behaviors when the annealing temperature is below 550 °C, and they become Schottky contacts when the annealing temperature is above 650 °C. The minimum specific contact resistivity is 1.8×10^{-4} Ω·cm^2 when the Al contact is annealed at 250 °C. The thermal budget for annealing or fabricating Al/3C–SiC devices should be below 650 °C in order to protect the Al contacts.

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