Ir/Ni/W/Ni Ohmic contacts for n-type 3C-SiC grown on p-type silicon substrate

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Abstract

In this work, Ohmic contacts to n-type 3C-SiC grown on p-type Si substrate employing Ni layer and Ir/Ni/W/Ni multilayers were investigated. Specific contact resistances of $2.57 \times 10^{-4} \, \Omega \cdot \text{cm}^2$ and $2.74 \times 10^{-5} \, \Omega \cdot \text{cm}^2$ were achieved with Ni layer and Ir/Ni/W/Ni multilayers, respectively, at an annealing temperature of 1050 °C. Samples were characterized using XRD, AFM and SEM. The result indicates the W is effective as a carbon absorbing and stabilizing layer and the presence of Ir cap layer facilitates lowering the surface roughness. As a result, the thermal stability and contact surface morphology of Ir/Ni/W/Ni/3C-SiC is greatly improved compared with Ni/SiC contact.

1. Introduction

Silicon carbide (SiC) is considered a promising semiconductor material for devices operating at high temperature and high power due to its wide bandgap and unique properties, such as high breakdown voltage, high thermal conductivity and high saturation electron velocity. 3C-SiC is the cubic form of SiC which has a band gap of 2.36 eV and can be deposited on silicon wafers in various forms, such as epitaxial, polycrystalline, nanocrystalline and amorphous. The ability to deposit on large silicon wafers enables the use of advance and mature low cost silicon fabrication technologies makes this material to be adopted as a new platform technology in a mass of applications. It is possible to use the 3C-SiC on Si for a lot of products such as MEMs, ultra-thin membranes for e-beam and x-ray applications and many discrete devices and provide significant product benefits. The use of SiC on Si for LED is also attractive as the lattice constant match of SiC with AlN and GaN provides epitaxial deposition compatibility [1].

However, the utilization of 3C-SiC and their superior characteristics have been limited because of some unsolved issues related to the material quality, such as low quality of ohmic contacts. Among many alternative metals, Ni is one of the most commonly utilized to form ohmic contacts for n-type SiC. Although lower $\rho_c$ can be achieved by employing Ni for SiC ohmic contacts, they are readily to degrade under the condition of long-term operation at a raising temperature [2]. One opinion for this is the formation of carbon clusters, remaining on the surface during annealing and causing problems in device packaging [3], which degrade device stability. Another view is the formation of Kirkendall voids in treating of annealing at the contact interface which provides a path for the diffusion of oxygen and reduce the reliability for high-temperature application [4].

In order to address these problems, Ti, Ta, and W, having a high affinity with C, were introduced as contact metals to absorb the free carbon in the processing of annealing. Free carbon was absorbed by Ti to form TiC, and electrical property was improved in Ti/Ni/SiC [5]. However, TiC is prone to convert to the stable Ti$_2$Si$_3$C$_6$ at elevated temperature aging, deteriorating the surface morphology and thermal stability. It’s clear from the ternary diagram of W–Si–C [6] that WC will not transform into other phases. For the above reason, W is an
excellent contact material for SiC in the aspect of improving thermal stability. Shu-Yue Jiang et al [7] treated the W/Ni/4H-SiC contact at 1000 °C for 2 min in the atmosphere of N2, and ohmic contact with $\rho_d$ as low as $3.2 \times 10^{-3} \Omega \cdot \text{cm}^2$ was achieved. Ohmic contacts of n type SiC can also be achieved by utilizing W-Ni alloys, but the electrical properties are not as good as W/Ni bilayer. Okojie et al [8] fabricated the n type SiC ohmic contact employing W50:Ni50 alloy, and obtained a $\rho_d$ of $1 \times 10^{-4} \Omega \cdot \text{cm}^2$ under the conditions of $N_d > 2 \times 10^{18} \text{cm}^{-3}$ and annealing at 900 °C. Therefore, SiC ohmic contacts are likely better in the form of multilayer metal stacks. Patrick et al [9] obtained the ohmic contact with $\rho_d$ as low as $2 \times 10^{-3} \Omega \cdot \text{cm}^2$ after treating Au/Ag/Ni/3C-SiC contact at 750 °C for 2 min in a flow of pure N2. Although, Cr is able to effectively hinder the interdiffusion of Ni, C and Au, the formation of free carbon is inevitable. Li et al [10] gained the Ti/Ni/3C-SiC ohmic contact with outstanding electrical property, and the values of $\rho_d$ is $3 \times 10^{-3} \Omega \cdot \text{cm}^2$ under the condition of without annealing. However, the largely high doping concentration makes ion implantation process difficult.

So far, an increasing number of researchers made the SiC ohmic contact investigations with regard to high doped substrate, but few on moderately doped, especially for 3C-SiC. In this work, Ir/Ni/W/Ni ohmic contact on moderately doped n-type 3C-SiC was investigated, and each metal layer performs a different effect. Ni provides the electrical contact and adhesion characteristics. W is the refractory metal with excellent stability and high melting point. It is used to suppress carbon clusters on the remaining surface and acting as a diffusion barrier layer. To prevent the high roughness of Ni upper layer due to coarsening during aging in air, cap layer of Ir is introduced. Ir is a kind of precious metal known for its anti-oxidative capability [11], which would increase the stability of contact and improves the electrical contact by reducing oxide formed on the surface.

2. Experiments

N-type 4 inches 3C-SiC epitaxial wafer grown on p-type Si (100) substrate is purchased from Beijing Innotronix Technologies Co., Ltd The resistivity of p-type Si wafer is 8–15 $\Omega \cdot \text{cm}$. The thickness of epitaxial layer, with a resistivity, $\rho = 0.001 \Omega \cdot \text{cm}$ and a donor concentration, $N_D = 2 \times 10^{18} \text{cm}^{-3}$, was 500 nm. The 4-in wafer was cut into square pieces of $2 \times 2$ cm using a diamond saw. The individual rectangle pieces of wafer were cleaned in 10% HF for 15 s to remove the oxidation on the surface, and then boiled for 10 min in boiling water to lower the density of surface state [12, 13]. The circular transmission line model (c-TLM) was fabricated by lithographic process of ‘lift-off’ to calculate the $\rho_d$. Figure 2 shows the contact pattern with a conducting circular inner region of radius L, a gap of width d and a conducting outer region. The radius (L) of inner circular is 150 $\mu$m, and the gap width (d) is 10, 20, 30, 40, 50, 60, 70, and 800 $\mu$m, respectively in figure 3. Sequential layers of either Ni(140 nm) or Ni(70 nm)/W(30 nm)/Ni(20 nm)/Ir(20 nm) were deposited by direct current magnetron sputtering on the surface of n-type 3C-SiC, and then the annealing was performed in the atmosphere of N2 at temperature of 850 °C, 950 °C and 1050 °C for 2 min. The processes are illustrated in figure 1. Current-Voltage(I-V) characteristics were carried out by Agilent B1505A semiconductor tester. Surface morphology of contacts was

![Figure 1. Process conditions of the split samples.](image-url)
monitored by atomic force microscopy (AFM). The contact phases were analyzed utilizing x-ray Diffraction (XRD) analysis. Then, thermal duration experiments were performed under the condition of 400 °C and air, to determine the thermal stability of sample.

3. Results and discussions

The I-V curves of Ni/SiC and Ir/Ni/W/Ni/SiC contacts are shown in figures 4(a) and (b), measured from same spacing gap of 40 μm, which are liner across the entire voltage range, suggesting that ohmic contacts have been formed. On the basis of c-TLM, the total contact resistance \(R_t\) can be simplified as the equation for \(L \gg d\) \[14\]

\[
R_t = \frac{R_{sh}}{2\pi L} (d + 2L_T) C
\]

where \(R_{sh}\) is sheet resistance, \(L_T\) is transfer length and \(C\) is correction factor \[15\].

\[
c = \frac{L}{d} \ln \left(1 + \frac{d}{L_T}\right)
\]

However, the \(R_t\) can be expressed as the reciprocal of the slope of the I-V curves. As shown in figures 4(c) and (d), the values of \(R_t\) approximately linearly increases with the increase of spacing gap \(d\). With the linear fitting processing, sheet resistance \(R_{sh}\) and transfer length \(L_T\) are obtained from the slope and intercept of fit linear curve. Therefore, we can obtain \(\rho_x\) from

Figure 2. Contact pattern of sample.

Figure 3. SEM image of a fabricated sample.
The values of \( r_c \) annealing at different temperature for Ni/SiC and Ir/Ni/W/Ni/SiC contacts are shown in tables 1 and 2, decreasing with the increase of annealing temperature and decreasing more significant as temperature increased from 850 °C to 950 °C than 950 °C to 1050 °C. Under the same annealing condition, the Ir/Ni/W/Ni/SiC obtains a more excellent ohmic contacts than Ni/SiC. The values of \( r_c \) for Ir/Ni/W/Ni/SiC contacts are an order of magnitude smaller than Ni/SiC contacts, confirming that the introduction of W and Ir plays a key role in ohmic contacts. It is known that high-temperature annealing is necessary for ohmic contacts with n-type SiC \([16]\), owing to the formation of silicide, which is well-known to be more pronounced at high temperature. Therefore, the results of this work are agreement with the conventional theories. For example, higher-temperature annealing changes the electronic properties to obtain a better ohmic contact \([17]\).

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For a moderate doping material, ohmic contacts with \( r_c \) of \( \sim 10^{-5} \Omega \cdot \text{cm}^2 \) are reasonable outstanding, which is low.

Table 1. The values of \( r_c \) annealing at 850 °C, 950 °C and 1050 °C for Ni/SiC contacts.

| Temperature (°C) | 850 | 950 | 1050 |
|------------------|-----|-----|------|
| \( r_c \) (Ω · cm²) | \( 1.62 \times 10^{-3} \) | \( 5.31 \times 10^{-4} \) | \( 2.57 \times 10^{-4} \) |

Table 2. The values of \( r_c \) annealing at 850 °C, 950 °C and 1050 °C for Ir/Ni/W/Ni/SiC contacts.

| Temperature (°C) | 850 | 950 | 1050 |
|------------------|-----|-----|------|
| \( r_c \) (Ω · cm²) | \( 7.62 \times 10^{-4} \) | \( 4.07 \times 10^{-5} \) | \( 2.74 \times 10^{-5} \) |

\[ r_c = R_k L^2 \]  \hspace{1cm} (3)
enough for power device fabrications. The measurements of $\rho_c$ in the present investigation is consistent with the n-type 4H-SiC after annealing at 950 °C–1050 °C [18]. In comparison, Ni/3C-SiC contacts of n-type with a light-doping level of $N_D \sim 1 \times 10^{17}$ cm$^{-3}$ have been reported with the $\rho_c$ of $3.7 \times 10^{-3}$ Ω·cm$^2$ [19, 20].

Figure 5 shows the XRD date for Ni/SiC contacts after annealing at 850 °C, 950 °C and 1050 °C. This pattern shows the several phases affecting ohmic contact on the contact surface. As a consequence of annealing at high temperature, nickel reacted with SiC to form Ni silicide. As shown in the figure, Ni$_2$Si was formed after annealing at 850 °C, 950 °C and 1050 °C, while Ni$_3$Si$_2$ and C were formed annealed at above 950 °C, and as the temperature increases, the corresponding diffraction peak intensity becomes stronger, demonstrated that the content of Ni$_3$Si$_2$ and C increases. Furthermore, there are diffraction peaks of Ni, and the intensity of the diffraction peaks decreases as the temperature increases, indicating that excess Ni is present, but when annealing at a higher temperature, the remaining Ni content decreases.

Figure 6 shows the XRD date for Ir/Ni/W/Ni/SiC contacts after annealing at 850 °C, 950 °C and 1050 °C. The distinctive feature different from previous figure is the presence of WC. That is, not only was nickel silicide formed during annealing, but also WC, and both compounds suppress the formation of carbon-cluster remaining on the surface, which makes interface between contact layer and SiC smoother and greatly reduces the quantity of Kirkendall voids at interface [7]. Moreover, Ni$_3$Si$_2$ was formed, while NiSi$_2$ was not in
Ir/Ni/W/Ni/SiC contact, indicating that Ir/Ni/W/Ni/SiC possesses a better thermal stability. In other words, it is more difficult for Ni silicide to further react with SiC to form silicide with higher Si content. There is no Ir or corresponding compound peak in the XRD patterns, indicating that Ir was not involved in the reaction and the interdiffusion between Ir layer and adjacent Ni layer was likely taken place. The mixed layer is able to absorb out-diffusion Si atoms to form Ni silicide and hinder the diffusion of C atoms to the surface to decrease the formation of carbon clusters.

AFM 3D morphologies collected on the Ni/SiC and Ir/Ni/W/Ni/SiC contact surface after annealing at 850 °C, 950 °C and 1050 °C are shown in figures 7 and 8. The root mean square (RMS) of Ir/Ni/W/Ni/SiC is within 10 nm, especially for annealed at 850 °C and 950 °C, only 2.9 nm and 3.3 nm, respectively. While the minimum roughness of Ni/SiC is 14.0 nm and the maximum roughness is 34.4 nm, showing that the roughness of Ir/Ni/W/Ni/SiC is much lower than Ni/SiC under the same annealing conditions. From 3D photographs, one can more clearly see that the surface of Ir/Ni/W/Ni/SiC is much smoother than Ni/SiC, which further confirms that the introduction of W and cap layer Ir greatly improve the smoothness of contact surface. For Ni/SiC, the RMS approximately linearly increases with the increase of annealing temperature, while the RMS of Ir/Ni/W/Ni/SiC increased by only 0.3 nm as the annealing temperature is increased from 850 °C to 950 °C. However, the RMS of Ir/Ni/W/Ni/SiC multilayers annealed at 1050 °C increased by 5 nm compared to
annealed at $950^\circ$C. Therefore, Ir/Ni/W/Ni/SiC multilayers annealed at $950^\circ$C possesses a better comprehensive ohmic contact properties, considering the specific contact resistance.

Figures 9 and 10 provide the TEM cross section views information of Ni/3C-SiC and Ir/Ni/W/Ni/3C-SiC contacts, respectively. Ni/3C-SiC contact shows an irregular interface. During the annealing process, Si and C were diffusing out to react with Ni. The reacted layer is composed of both Ni$_2$Si and NiSi$_2$ phase with carbon clusters embedded inside. Carbon clusters are present even near the surface. In addition, excess Ni is present. The result is consistent with the XRD result in figure 5. From the TEM cross section analysis, one can clearly see that carbon clusters are mainly distributed on the interface and top, which roughened the contact surface, confirmed by AFM analysis in figure 7, and seriously affect the reliability of ohmic contact. Furthermore, an increasing number of voids are located at the interface, and they do not affect much the contact electrical performance [21], but they were known to degrade the contact reliability [22].

However, no carbon clusters are formed at the interface and voids are barely found in Ir/Ni/W/Ni/3C-SiC contact. Free carbon was absorbed by the in-diffuse W to form WC, which is also proved by XRD analysis in figure 6. The intermediate part of the contact layer is mainly Ni$_2$Si phase, which is a key factor for the realization of ohmic behavior [19]. Moreover, a Ni-Ir mixed layer is formed in the uppermost part of the metal stack, which accords well with the XRD result in figure 6, and is the reason for the absent of Ir peak. The Ir capping layer can not only be a barrier layer for free carbon out-diffusion, but also the Si atoms. Therefore, Ir/Ni/W/Ni/3C-SiC contact is provided with a much smoother contact surface.

![Figure 8](image-url) **Figure 8.** The AFM 3D morphologies of Ir/Ni/W/Ni/SiC annealed at $850^\circ$C (a), $950^\circ$C (b) and $1050^\circ$C (c).
Another factor affecting ohmic contacts performance is its thermal stability. In order to determine the thermal stability of samples, thermal aging experiments were performed at 400 °C in air for 200 h, and the specific contact resistivity was measured every 20 h, shown in figure 11. As a result, comparing with the measurements at initial stage, the change of $\rho_c$ for Ni/SiC is dramatic, increasing from $5.31 \times 10^{-4} \Omega \cdot \text{cm}^2$ to $4.39 \times 10^{-3} \Omega \cdot \text{cm}^2$, while the variation for Ir/Ni/W/Ni/SiC is little, just increased from $4.07 \times 10^{-5} \Omega \cdot \text{cm}^2$.
to $3.39 \times 10^{-4}$ $\Omega \cdot \text{cm}^2$. That is, Ir/Ni/W/Ni/SiC contact possesses a much better thermal stability than Ni/SiC. The SEM image after thermal duration is shown in figure 12, obviously, Ni/SiC contact surface is rough, with loose structure and voids which provide diffusion paths for oxygen in the process of aging and make the ohmic contacts be easily degradable. On the contrary, a smooth surface is observed in Ir/Ni/W/Ni/SiC contact, without any voids. Energy dispersive spectrometer (EDS) chemical analyses for Ni/SiC contact and Ir/Ni/W/Ni/SiC contact were carried out, as shown in table 3. The content of C and O in the Ir/Ni/W/Ni/SiC contact system is almost half of that in Ni/SiC contact system, indicating that the diffusion of oxygen into contact layer and the segregation of carbon are more difficult in Ir/Ni/W/Ni/SiC contact system, which further demonstrates that it has the more excellent thermal stability than Ni/SiC and still maintains the reasonable outstanding ohmic contact performance under high temperature and long-term aging treatment.

It is reported that the microstructure of Ni-based ohmic contacts to n-type SiC is affected by four factors: the roughness of contact surface, the formation of void on the interface, the segregation of excess free carbon and the

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**Table 3.** EDS results of thermal duration sample: (a) Ni/SiC contact and (b) Ir/Ni/W/Ni/SiC contact.

|             | Ni   | Si   | C     | O     | W   | Ir   |
|-------------|------|------|-------|-------|-----|------|
| Ni/SiC      | 13.80| 50.33| 19.64 | 16.22 | 0   | 0    |
| Ir/Ni/W/Ni  | 15.73| 54.16| 10.51 | 9.44  | 4.29| 5.87 |
widening of contact layer and SiC interface [23]. The effects of Ir and W in Ni/3C-SiC ohmic contacts in this work is mainly displayed in two aspects.

In the first place, the reaction mechanism of Ni/SiC is changed by the diffusion barrier layers W and Ir. For Ni/SiC ohmic contacts system, the reaction of Ni with SiC is accompanied by the segregation and aggregation of free carbon which makes contact layer loose and contact surface roughen. This is the reason why Ni/3C-SiC contact is readily to degradation at high temperature working, shown in figures 11 and 12(a). However, the diffusion of W and the formation of nickel silicide occur simultaneously in Ir/Ni/W/3C-SiC contact. Once excess C meets the W, they will react to form WC, shown in figures 6 and 10, which greatly reduces the content of free carbon and avoids to form carbon clusters. Thus, Ir/Ni/W/Ni/SiC possesses a smoother contact surface and a denser structure, displayed in figures 8 and 12(b). Moreover, as shown in table 3, inward diffusion of oxygen is hindered by the cap layer Ir, reducing the surface oxide and improving the thermal stability. These advantages provided by W and Ir play a crucial role in electrical property and the ability of resisting degradation. Consequently, Ir/Ni/W/Ni/3C-SiC contact still possesses an outstanding ohmic contact property after long-term thermal duration at temperature of 400 °C, shown in figure 11.

In the second place, the quality of interface between contact metal and SiC was improved due to the introduction of W. From the figures 5 and 6, one can see that the first phase formed by the reaction was Ni5Si in the process of annealing for Ni/SiC contact, while the formation of Ni3Si was accompanied by WC for Ir/Ni/ W/Ni/SiC contact. The thermal expansion coefficients of WC and 3C-SiC, are 3.8 × 10⁻⁶ and 3.7 × 10⁻⁶ K⁻¹, respectively, which are very similar, but differ greatly from Ni5Si, 19 × 10⁻⁶ K⁻¹. Therefore, there is a less deformation amount for contact metal in Ir/Ni/W/Ni/SiC than that in Ni/SiC in dealing with of annealing, which may prevent the formation of voids on the interface. In this situation, the diffusion channels of oxygen disappear, which is in favor of hindering the inward diffusion of oxygen. This is another reason why the thermal stability of Ir/Ni/W/Ni/SiC is superior to that of Ni/SiC.

4. Conclusion

In conclusion, the fabrication and characterization of Ni and Ir/Ni/W/Ni ohmic contacts on moderately doped n-type 3C-SiC on P-type Si were presented in this work. Specific contact resistances of 2.57 × 10⁻⁴ Ω · cm² and 2.74 × 10⁻⁵ Ω · cm² were achieved with Ni layer and Ir/Ni/W/Ni multilayers, respectively, at an annealing temperature of 1050 °C. The best comprehensive ohmic contact properties were obtained after annealing at 950 °C for those two contact systems. Compared to Ni/SiC, Ir/Ni/W/Ni/SiC is proven to be with three advantages. In the first place, the content of free carbon was greatly reduced and the formation of carbon clusters was avoided since the free carbon was absorbed by W. W layer is also provided with the function of diffusion barrier, reducing the reaction rate of contact metals with substrate. Secondly, contact surface morphology is greatly improved because of the formation of WC and the present of barrier mixed layer Ni-Ir. Thirdly, the diffusion of oxygen into contact layer is impeded by the uppermost mixed layer Ir-Ni. These are in favor of the ohmic contact thermal stability. Consequently, electrical properties and thermal stability of Ir/Ni/W/Ni/SiC contact are largely superior to Ni/SiC contact. These results can contribute to the future development and utilization of 3C-SiC-based devices in different filed.

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