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ORIGINAL PAPER

Ni/W/Ni ohmic contacts for both n- and p-type 4H-SiC

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Abstract

In this study, we used a Ni/W/Ni-layered structure to provide low-resistive ohmic contacts with good thermal stability for both n-type and p-type 4H-SiC. As reference, we used Ni and Ni/Ti/Ni as control groups with specific contact resistivities, and we verified the thermal stability of the structures by specific contact resistivity measurements and thermal duration tests. We found that for both n-type and p-type semiconductors, Ni/W/Ni is superior in terms of thermal stability and specific contact resistivity. Using XRD, we also analyzed the components involved in ohmic contact and thermal stability tests.

Keywords 4H-SiC · Ohmic contact · Specific contact resistivity · Ni/W/Ni · Thermal stability

1 Introduction

Silicon carbide (SiC) is considered a suitable semiconductor material for power devices because of its wide bandgap and properties such as high breakdown voltage, high saturation electron velocity, and high thermal conductivity. However, the use of these excellent characteristics has been limited due to low-quality ohmic contacts. Particularly, carbon clusters that remain on the surface during ohmic contact formation cause problems in device packaging [1], which degrade device stability. It is also very difficult to provide ohmic contacts for both n-type and p-type semiconductors. This problem is affected not only by work-function mismatch between the metal and the semiconductor due to the wide bandgap of SiC but also by Fermi-level pinning [2]. This makes it difficult to lower the specific contact resistivity, which consequently makes it difficult to lower the on-resistance of the SiC device. These are the biggest issues affecting the formation of ohmic contacts with 4H-SiC, and many studies are under way to solve these problems. Furthermore, in terms of thermal stability, improvements to further reduce the specific contact resistance without lowering the stability of ohmic contacts during long-term aging are critical issue [3–6].

For n-type semiconductors, the use of Ni to form silicides at high temperature has attracted huge attention because of low specific resistivity of Ni silicide, and consequently, the use of Ni has been extensively studied. Specifically, the formation mechanism and thermal stability of Ni-based ohmic contact to n-type 4H-SiC have been deeply studied [7, 8]. However, it is difficult to effectively suppress the formation of carbon clusters on the remaining surface with Ni silicide, so as an alternative, Ni/Ti-layered structures have been introduced [9]. The use of a Ni/Ti/Ni contact structure showed improved adhesion and interface characteristics [10]. In previous studies, the reason for introducing Ti was that it could confine the remaining carbon through the formation of Ti silicide. Although the problem of residual carbon was solved in this way using Ti, the thermal stability of the structure was not clearly studied. This approach is also unsuitable for forming ohmic contacts with both n- and p-type semiconductors.

For p-type semiconductors, Au/Ti/Al [11] and Ni/Ti/Al [12] have mainly been used as ohmic contacts. However, in previous investigations, the thermal stabilities of those materials have rarely been studied. Also, these materials are not suitable for n-type ohmic contacts.

In contrast, we have been working to obtain thermally stable contacts using tungsten (W) to suppress carbon clusters on the remaining surface and to provide ohmic contacts with low resistivities for both n- and p-type semiconductors. In the present study, we have used Ni, Ni/Ti/Ni, and Ni/W/Ni and have theorized the creation of ohmic contacts, and we have compared it with the experimental result.

Dongwoo Bae and Gilcho Ahn have contributed equally to this work.

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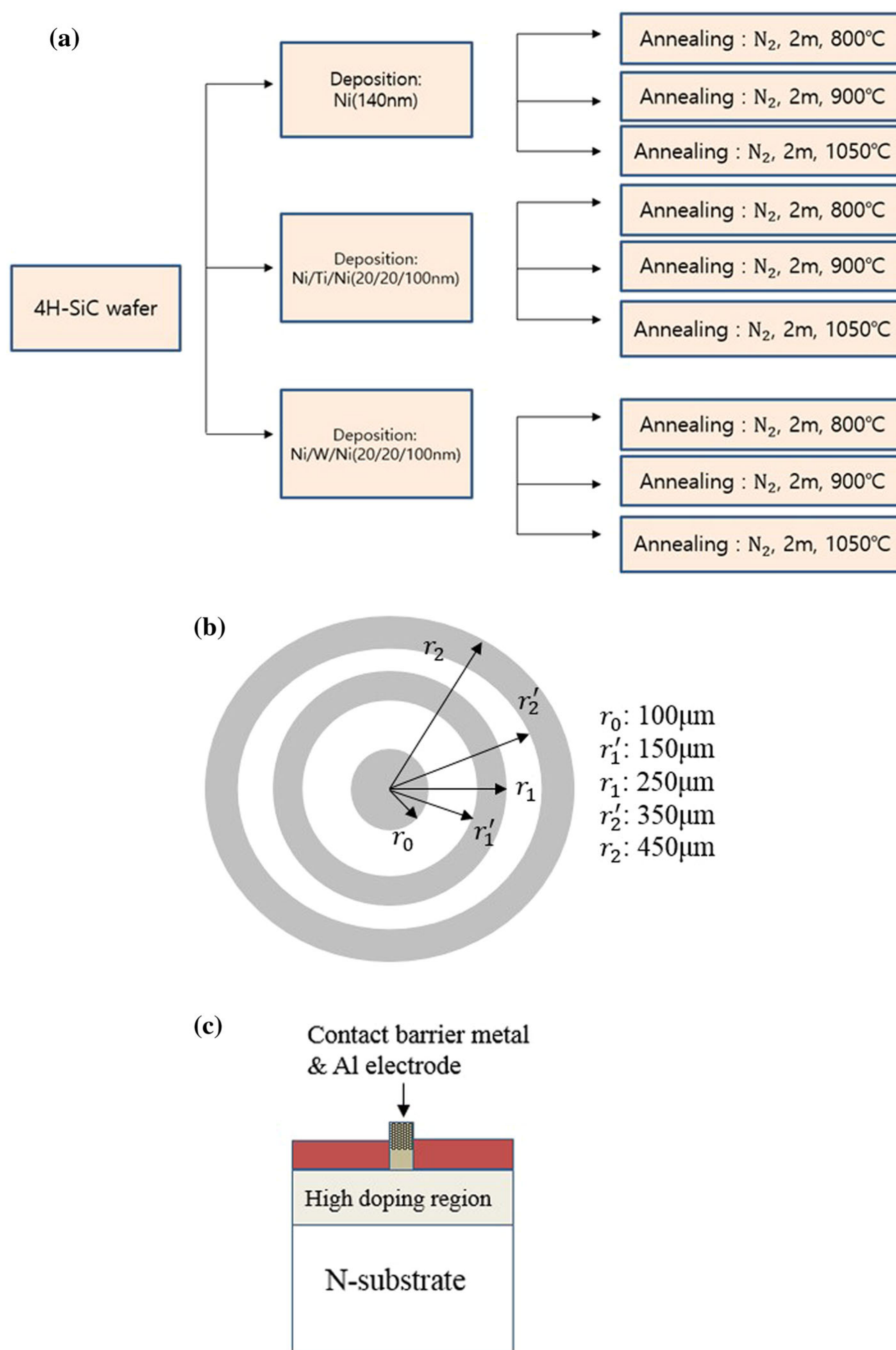

Fig. 1 **a** Process conditions of the split samples. **b** Circular TLM pattern. **c** Cross-sectional view of the sample

Tungsten is known for its unique ability to react with C, leading to the formation of metal carbides and limitation of the presence of carbon clusters [13]. Because of this advantage, W can be used to replace the Ti employed in previous studies. The superior thermal conductivity of W is also valuable for device stability. Furthermore, alloys using W and Ni showed low specific contact resistivity with both n- and p-type semiconductors [14]. We have, therefore, assumed that W-silicide is suitable for forming ohmic contacts with both n- and p-type materials. We obtained low resistivities in our experiments, and we verified our assumptions using XRD analysis. We also verified the thermal stability by thermal duration experiments.

2 Experiments

For the present experiments, we prepared n- and p-type doped 4H-SiC wafers. We implanted nitrogen to create n-type semiconductors and aluminum for p-type. We implanted the dopants at a concentration of 1E15 cm^{-3} with an energy of 200 keV. Post-annealing was performed at 1700 °C for

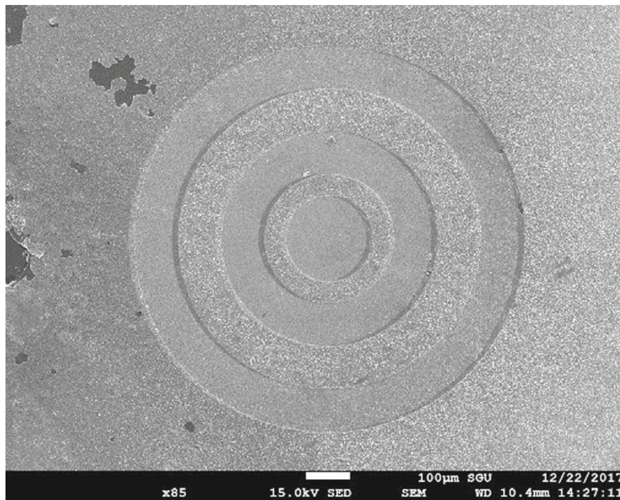

Fig. 2 **a**–**c** SEM image of a fabricated sample

30 min to activate the dopants and cure the defects formed due to the implantation. In the post-annealing process, we used graphite to prevent out-diffusion of the dopants [15]. The junction depth of the dopants was 0.2 μm. The sheet resistance of the n-type material was 165.25 (Ώ/square), and that of the p-type was 554.17 (Ώ/square).

The samples were chemically cleaned to remove surface contamination. We performed degreasing using acetone for 5 min followed by using methanol for 5 min. Cleaning was completed using a solution of H_2SO_4:H_2O_2 =1:1 for 15 min. We used a circular transfer length measurement (CTLM) as a test pattern. Unlike a conventional transfer length measurement (TLM), CTLM has the advantage that mesa isolation does not require [16]. After patterning, cleaning was performed with a HF 10% solution for 3 min, and the solution was washed away with DI water. We then sputtered Ni (140 nm), Ni/Ti/Ni (20/20/100 nm), and Ni/W/Ni (20/20/100 nm) contact structures onto the surfaces to enable comparisons among the contact metal materials. In order to analyze the characteristics of the ohmic contacts that occur due to changes in the annealing temperature, we conducted the annealing process at temperatures of 800, 900, and 1050 °C. The processes are illustrated in Fig. 1, which also shows the circular TLM pattern and a cross-sectional schematic of the sample.

The pattern formed for the experiments is shown in Fig. 2.

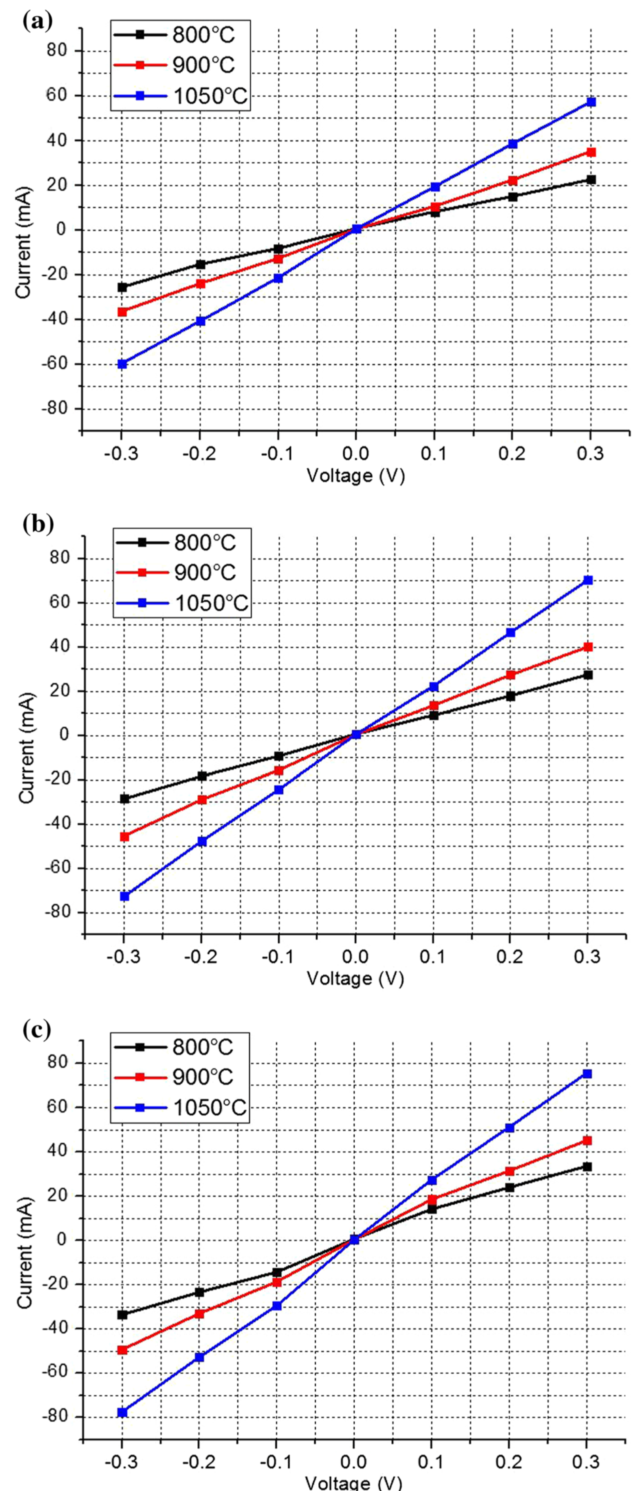

Fig. 3 **a**–**c** Properties of ohmic contacts with n-type 4H-SiC. **a** Ni, **b** Ni/Ti/Ni, and **c** Ni/W/Ni

3 Results and discussions

3.1 Ohmic contact properties

Figure 3 shows the properties of the ohmic contacts formed with Ni, Ni/Ti/Ni, and Ni/W/Ni on n-type semiconductors. We confirmed that the ohmic contact characteristics were obtained for all annealing conditions. Also, we confirmed that high current flows with the same voltage levels when the annealing temperature is high. For all the contact metal structures we tested, we found that the lowest resistance occurred

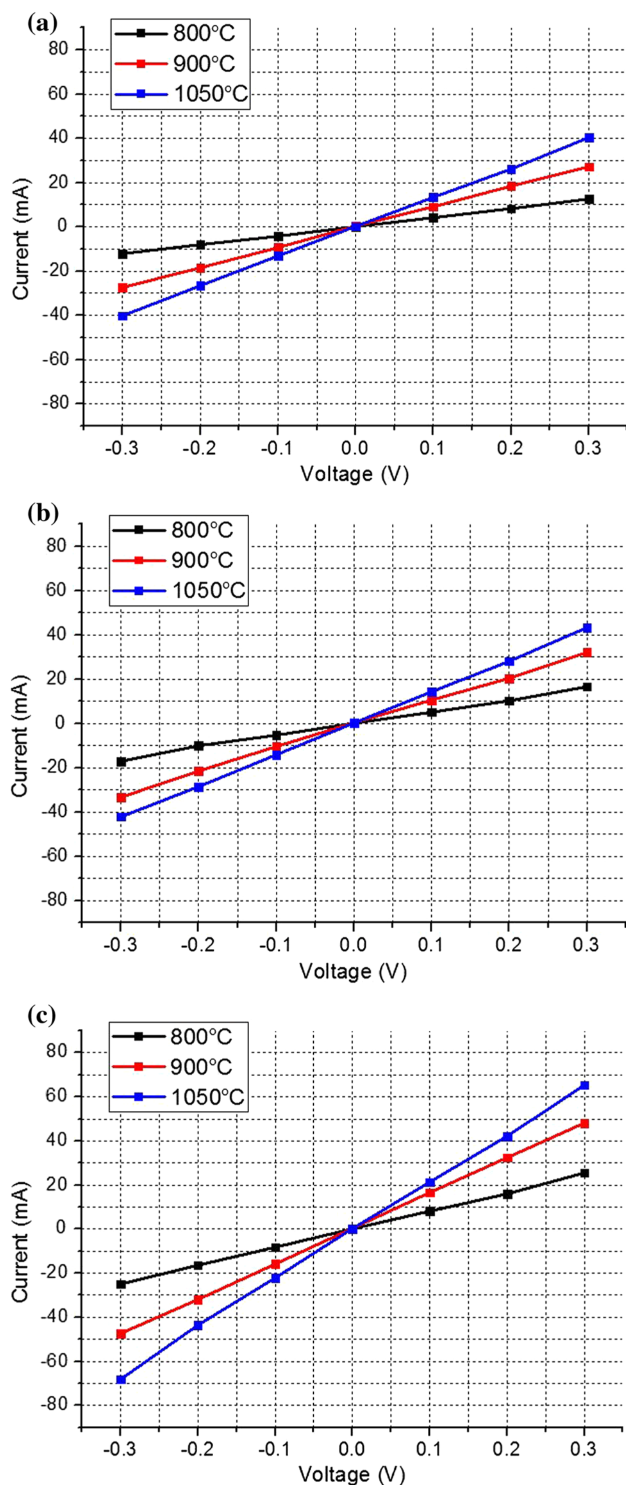

Fig. 4 a-c Properties of ohmic contacts with p-type 4H-SiC. **a** Ni, **b** Ni/Ti/Ni, and **c** Ni/W/Ni

at an annealing temperature of 1050 °C. Comparing these results with those of all the contact structures, one can see that the current is 24.09% higher when using Ni/W/Ni than when Ni is used and that it is also 6.88% higher than when Ni/Ti/Ni is used. It is known that high-temperature annealing is required for ohmic contacts with n-type and p-type SiC [17]. The reason for this is the formation of a silicide, which is known to be more pronounced at high temperatures. Thus, our experimental results are consistent with the conventional theories, i.e., higher-temperature annealing produces a better-quality silicide, resulting in a change in the electronic properties to produce a more suitable ohmic contact. Figure 4 shows the results of our ohmic contact experiments for p-type semiconductors with Ni, Ni/Ti/Ni, and Ni/W/Ni contacts. As in Fig. 3, the ohmic contact properties are shown under all conditions, and the lowest resistance occurred at an annealing temperature of 1050 °C. By comparing the results of all the contact metals, one can see that the current is 38.28% higher when using Ni/W/Ni than when pure Ni is used and that it is 33.69% higher than when Ni/Ti/Ni is used. We have also found that the improvement in ohmic contact characteristics when using W is higher for p-type semiconductors than for n-type semiconductors. When applying high-temperature annealing to SiC contacts, the main reason that a Schottky junction is converted to an ohmic contact [3] is because the electrical properties are changed by annealing, and not because of the presence of silicide as reported by Nikitina in 2005 [18]. From this research, it can be inferred that tungsten silicide forms an ohmic contact with a p-type semiconductor when the electrical characteristics of the material change. This hypothesis will be mentioned again in the next section on the XRD experiment. Specific contact resistivities (at 1050 °C) for the different contact metals are listed in Table 1. We used the circular TLM for the measurements and the Reeves model [16] for the calculations. The lowest specific contact resistivity was obtained when using Ni/W/Ni.

Table 1 Comparison of specific contact resistivity by material

Material	ρ_{sp} for *n*-type (Ωcm^2)	ρ_{sp} for *p*-type (Ωcm^2)
Ni	5.20×10^{-5}	7.12×10^{-5}
Ni/Ti/Ni	4.32×10^{-5}	6.81×10^{-5}
Ni/W/Ni	4.17×10^{-5}	4.54×10^{-5}

3.2 Thermal stability

We conducted thermal duration experiments on air to determine the thermal stability of the ohmic contacts. That is, we measured the specific contact resistivity of samples at a temperature of 400 °C for about 20 h. In order to derive the specific contact resistivity, it was necessary to measure the sheet resistance at several points at varying time. These data are shown in Fig. 5. After measuring the sheet resistance, we again derived the specific contact resistivity using Reeves' model. As a result, in comparison with the measurements at

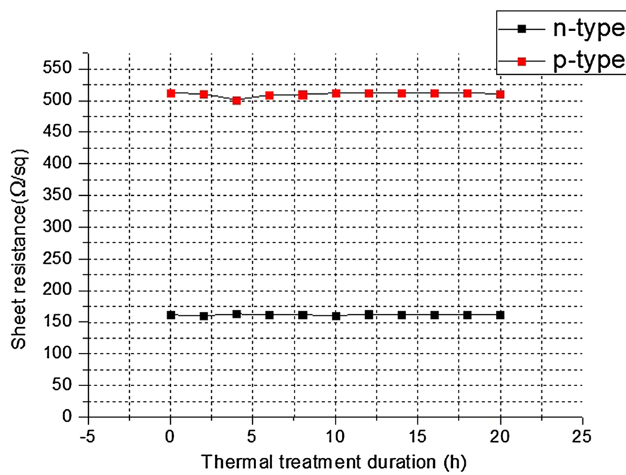

Fig. 5 Sheet resistance variations during the thermal duration experiments

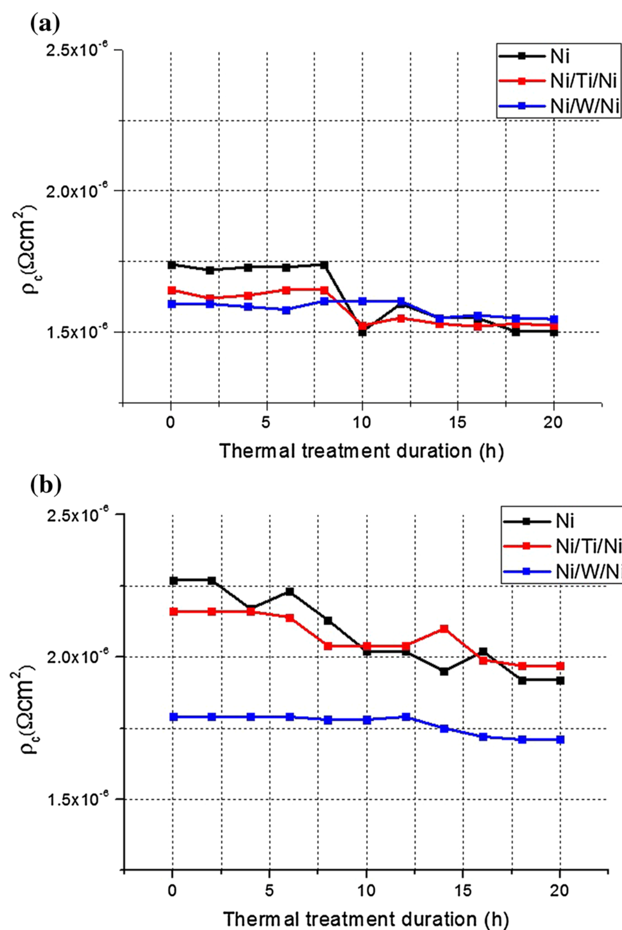

Fig. 6 **a**–**b** Resistivity variations in the thermal duration experiments. **a** n-type and **b** p-type

initial stage, the change of specific contact resistivity at 20 h was lower when using both n-type and p-type W. We found that usage of W leads to the highest thermal stability because W captures carbon clusters effectively. Specific results of our thermal duration experiments are shown in Fig. 6. We observed a maximum change in the specific contact resistivity when all the contacts were heated for 20 h. The rate of change is specified in Table 2. In order to test our assumptions that W suppresses the formation of carbon clusters on the remaining surface and that W-silicide lowers the specific contact resistivity, we conducted XRD analysis on the surfaces of the samples.

Table 2 Rate of change of resistivity during the thermal duration experiments over 20 h

	n-type (%)	*p*-type (%)
Ni	13.65	15.43
Ni/Ti/Ni	7.64	8.86
Ni/W/Ni	3.36	4.44

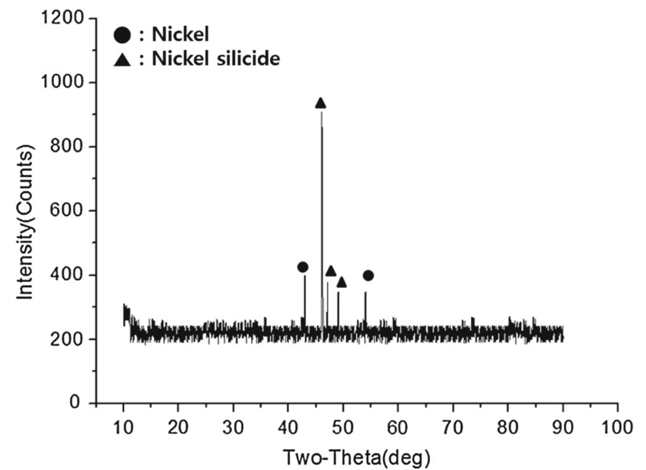

Fig. 7 Analysis of XRD for a Ni ohmic contact sample

Figure 7 shows the XRD data for a sample in which the ohmic contact was formed with Ni. This figure shows the materials affecting ohmic contact on the sample surface. As a result of annealing at high temperature, the nickel reacted with SiC to form silicide. As indicated in the figure, several types of nickel silicide were formed. In particular, NiSi (210), Ni (220), and Ni3Si (002) were predominantly formed.

Figure 8 shows the corresponding XRD data for the samples with ohmic contacts formed using Ni/Ti/Ni-layered structures. The distinctive feature from the preceding figure is the presence of TiC. That is, not only was Ni silicide formed in the high-temperature annealing process but so also was TiC. Both compounds suppress carbon-cluster formation on the remaining surface. This supports the conclusion in the previous section. In other words, Ti plays a significant role in securing the thermal stability of the ohmic contact by bonding with the remaining carbon. However, Ti silicide is not seen in the XRD results. This means that the only material contributing to the ohmic contact is Ni silicide. As a result,

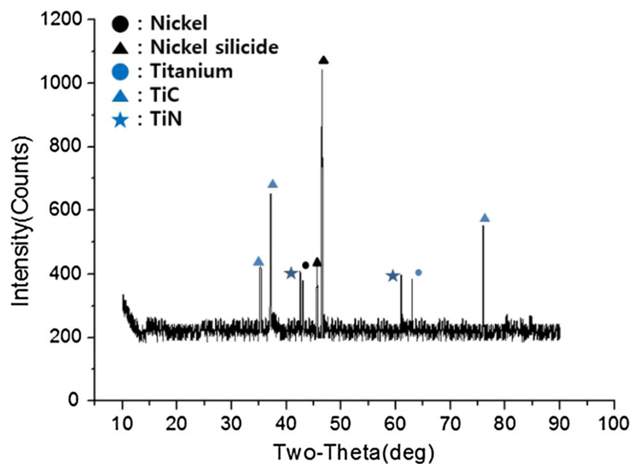

Fig. 8 Analysis of XRD for a Ni/Ti/Ni ohmic contact sample

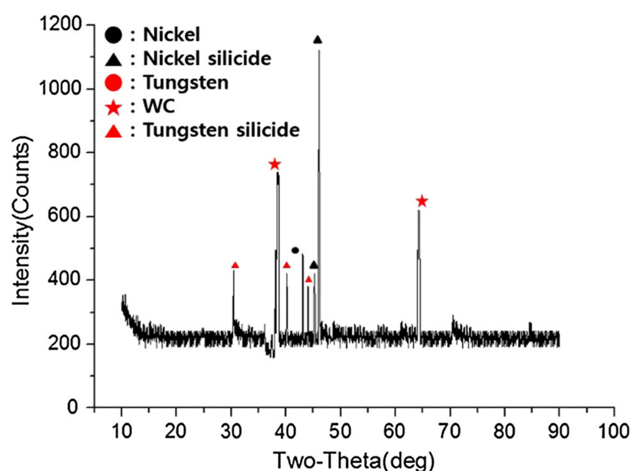

Fig. 9 Analysis of XRD for a Ni/W/Ni ohmic contact sample

the specific contact resistivity is not much different from that of a pure Ni contact for either n- or p-type ohmic contacts.

Figure 9 shows the XRD data for the samples with ohmic contacts formed using Ni/W/Ni-layered structures. Similar to the previous results with Ti, we can see that WC was formed on this sample. Based on these results, we have demonstrated that, similar to Ti, W can contribute to the improvement in thermal stability by suppressing the formation of carbon clusters on the remaining surface. Another noticeable feature is the presence of W-silicide. The ohmic contacts using Ti were effective in improving thermal stability; however, in comparison with the ohmic contacts using only Ni, there was no significant improvement in the electrical characteristics. Nevertheless, in previous sections, we showed that the specific contact resistivity was reduced with Ni/W/Ni contact structures for both n- and p-type semiconductors, and we concluded that W-silicide formation played a crucial role in this change. In addition, we found that the intensity of WC in this experiment using W was higher than that of TiC in the experiment using Ti. Also, we did not detect the formation of alloys, such as TiN, which is considered to be unnecessary. This means that in improving the thermal stability of ohmic contacts with SiC, using W is more effective than using Ti.

4 Conclusion

We proposed and fabricated ohmic contact structure for 4H-SiC using Ni/Ti/Ni to provide low-resistive ohmic contacts with good thermal stability for both n-type and p-type semiconductors. Both Ni and Ni/Ti/Ni were used as control group for tests. As a result, we found the specific contact resistivity of a Ni/W/Ni ohmic contact with n-type SiC to be 19.81% lower than the one using pure Ni and 3.47% lower than the one made of Ni/Ti/Ni. Also, its specific contact resistivity is 36.24% lower than Ni and 33.34% lower than Ni/Ti/Ni for p-type SiC. In order to investigate the thermal stability of the contacts, we analyzed the rate of change of the resistivity in thermal duration experiments at 400 °C over 20 h. As a result, the change of specific contact resistivity at 20 h was lower when using both n-type and p-type W. We also conducted XRD analyses to test the assumptions that formed the basis of our experiments. W contributed to improve thermal stability by suppressing the formation of carbon clusters on the remaining surface, and W-silicide played a key role in decrease of specific contact resistivity.

In conclusion, we have demonstrated that ohmic contacts using Ni/W/Ni on 4H-SiC have low specific contact resistivity and high thermal stability.

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