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Improvement in Electrical Performance of Schottky Contacts for High-voltage Diode

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Abstract. We investigated the effect of high temperature annealing on the Schottky barrier height (Φ_b) and the ideality factor (n-factor) of a Mo contact. In a Mo contact, the Φ_b increased and the leakage current decreased by annealing at 600°C, while no increase in n-factor and forward excess current owing to the high temperature annealing was observed. The Schottky barrier diode with Mo contact annealed at 600°C showed a blocking-voltage (V_b) of 4.15 kV and a specific on resistance (R_{on}) of 9.07 mΩcm^2, achieving a high V_b^2/R_{on} value of 1898 MW/cm^2.

Introduction

Wide band gap semiconductor SiC is a promising material for high-voltage applications because the breakdown field strength of SiC (over 2 MV/cm) is ~10 times higher than that of Si [1]. 4H-SiC Schottky barrier diodes (SBDs) with a rating of 0.3-1.2 kV and 1-20 A are already commercially available [2, 3]. Because of the superior material property, a low specific on resistance (R_{on}) below 10 mΩcm^2 can theoretically be expected for 4H-SiC SBDs with a high blocking-voltage (V_b) of 3-5 kV.

For Schottky contacts, Ti and Ni contacts are most frequently used. The Schottky barrier heights (Φ_bs) of Ti and Ni on n-type 4H-SiC are 0.95 eV and 1.62 eV, respectively [4]. Although a Ti/4H-SiC SBD exhibits a low on-voltage (V_f) due to low Φ_b, the leakage current density (J_r) of the Ti/4H-SiC SBD tends to be large. The high leakage current may cause a large off-state power loss for high-voltage 4H-SiC SBD. The J_r of Ni/4H-SiC SBD is quite low, suitable for high-voltage 4H-SiC SBDs, however the large Φ_b is accompanied by a large on-state loss. Estimating on- and off-state power loss for 4H-SiC SBDs with a V_b of 3-5 kV by the thermionic field emission and field emission model [5], Φ_b of 1.2-1.3 eV may provide the minimum power loss for 4H-SiC SBDs in a 50% duty cycle. The development of a new Schottky contact with 1.2-1.3 eV is imperative for the fabrication of high-voltage and low-loss 4H-SiC SBDs.

In this paper, we propose a Mo contact annealed at high temperature as the new Schottky contact with a Φ_b of 1.2-1.3 eV and low leakage current for 4H-SiC. We also demonstrate the high-voltage and low-loss 4H-SiC SBD using the annealed Mo contact.

Experiment

Samples used in this study were commercial n-type 4H-SiC substrates with epitaxial layers formed by our group. Epitaxial growth was carried out in a vertical hot-wall reactor [6]. To realize 4H-SiC SBDs with the Φ_b of 1.2-1.3 eV, we investigated the effect of high temperature annealing on the Φ_bs and ideality factors (n-factors) of Mo and Ti contacts. The thickness and donor concentration of epitaxial layers in the investigation were typically about 15 μm and in the order of 10^{15} cm^{-3}. After a standard cleaning and oxidation at 1100°C for 5h in dry O_2, Ni ohmic contacts were formed on the back of samples and then Mo and Ti films were deposited on the samples using sputtering or an E-gun evaporator. The samples were annealed above 500°C for 10 min. The electrical properties of the fabricated SBDs were estimated by the current-voltage measurements.

Results and discussion

Figures 1(a) and (b) show the typical forward characteristics of the Ti and Mo contacts before and after annealing. The diameter of the Schottky contacts was 500 μm. The Φ_b and n-factor of the as-deposited Ti contact were 0.77 eV and 1.03, respectively. The Φ_b increased to 1.20 eV after annealing at 500°C. The Ti contact annealed at 500°C showed the target Φ_b (1.2-1.3 eV), however the n-factor also increased to 1.14. An increasing in the n-factor indicates that the electrical states were generated at the interface between the Ti contact and 4H-SiC. On the other hand, the Φ_b and n-factor of the as-deposited Mo contact were 1.09 eV and 1.02, respectively. After annealing at 600°C, the Φ_b increased to 1.22 eV and the n-factor was stable at 1.02 (values described above are close to the mean values). The Mo contact is successfully controlled to the target Φ_b by annealing at 600°C without any degradation of the n-factor.

To clarify the origin for increasing of Φ_b by annealing, we observed the interface between the Mo contact annealed at 600°C and 4H-SiC using a transmission electron microscope. We found a reacted layer of several nm thick at the interface. The increase in Φ_b for the annealed Mo contact is owing to the formation of the reacted layer at the interface.

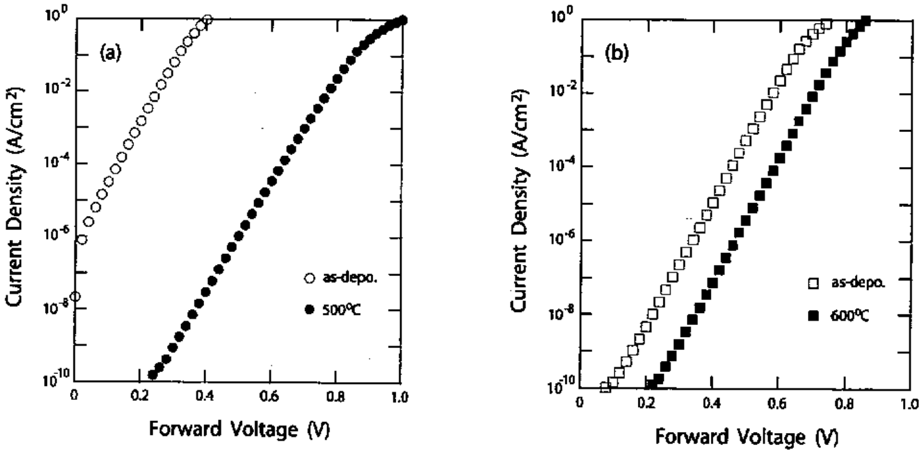

Fig. 1 Forward I-V characteristics of (a) Ti and (b) Mo contacts before and after annealing.

Figure 2 depicts the histogram of leakage current density at –100 V in the Mo contacts before and after annealing at 600°C. The area of the contacts was 1 mm^2. The number of Mo contacts with low leakage current density (<10^{-6} A/cm^2) increased after annealing, accompanying a reduction in the number of Mo contacts with high leakage current density (>10^{-4} A/cm^2). High temperature annealing for Mo contacts is effective in reducing the leakage current.

As shown in Fig. 1(b), no excess current was observed in the forward characteristic of Mo contact before and after annealing. Excess currents in forward characteristic indicate the existence of low Φ_b components, which may be the origin of the leakage current [7]. The results of the forward and reverse characteristics for Mo contacts suggest that annealing at 600°C does not affect generation of low Φ_b components.

In our previous experiment, activation annealing of implanted Al ions in a edge termination layer caused step bunching at the epitaxial layer surface. This could degrade the electrical properties of

Schottky contacts. Figure 3 shows the Φ_bs and n-factors of Ni contacts fabricated on n-type 4H-SiC epitaxial layers under different conditions. We prepared n-type 4H-SiC epitaxial layers annealed with and without a graphite cap made from photo-resist [8] (samples A and B). We also prepared a sample with no annealing (sample C). The annealing temperature ranged from 1500 to 1800°C. The Φ_bs and n-factors of Ni contacts on sample A were almost the same as those of sample C, while Ni contacts on sample A showed low Φ_bs and high n-factors in comparison with those of sample C. The graphite cap is effective in inhibiting the degradation of electrical properties in Schottky contacts by high temperature activation annealing.

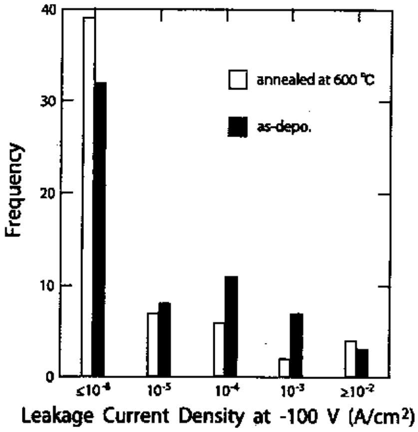

Fig. 2 Histogram of leakage current for Mo contacts before and after annealing.

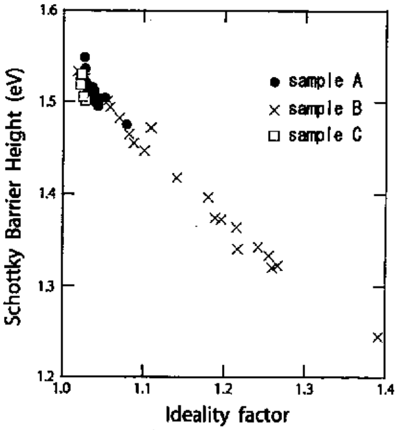

Fig. 3 Φ_b and n-factor of Ni contacts formed on samples A, B, and C.

We fabricated an annealed Mo/4H-SiC SBD with an internal ring and a 3-zone junction termination extension (JTE). The thickness and donor concentration of the epitaxial layer were 33 μm and $3\text{x}10^{15}$ cm^{-3}, respectively. The ideal V_b and R_{on} are 4.6 kV and 6.5 mΩcm^2, respectively. Al ions were implanted to samples to fabricate the JTE. The concentrations of the implanted Al in the JTE were $2\text{x}10^{18}$ and $6\text{x}10^{17}$, $3\text{x}10^{17}$, and $1.5\text{x}10^{17}$ cm^{-3}, respectively. The depth and width of the JTE were 250 nm and 130 μm, respectively. The Al ion implanted samples were annealed at 1700°C for 3min with a graphite cap. The sample was oxidized at 1100°C for 1h to remove the graphite cap, followed by a standard cleaning. After the oxidation at 1200°C for 5h and the fabrication of the Ni ohmic contact, Mo film (100 nm) was deposited and annealed at 600°C for 10 min to control the Φ_b. Finally an Al pad (1 μm) was deposited on the annealed Mo Schottky contact.

Figures 4(a) and (b) show the forward and reverse characteristics of the fabricated Mo/4H-SiC SBD. The area of the annealed Mo contact was 1 mm^2. The Φ_b and n-factor of the SBD were 1.28 eV and 1.02, respectively. The V_b was 4.15 kV, 92.2% of the ideal V_b, suggesting that the JTE effectively minimize the electrical field concentration near the edge of the annealed Mo contact. The leakage current densities were 0.14 mA/cm^2 at 3.5 kV (about 2MV/cm) and 0.96 mA/cm^2 at 4.0 kV. The R_{on} and V_f were 9.07 mΩcm^2 and 1.89 V at 100 A/cm^2, respectively. The leakage current at 3.5 kV was below 1/100 in comparison with the reported Ni/4H-SiC SBD with a V_b of 5 kV [9], nevertheless the V_f (at 25 A/cm^2) was two times lower than that of the SBD. Therefore, we conclude that a Mo contact annealed at high temperature is effective in reducing the V_f and the leakage current for 4H-SiC SBDs. In addition, the V_b^2/R_{on} value was calculated to be 1898 MW/cm^2, significantly higher than the best reported V_b^2/R_{on} value of 1196 MW/cm^2 for the 4H-SiC SBD [10].

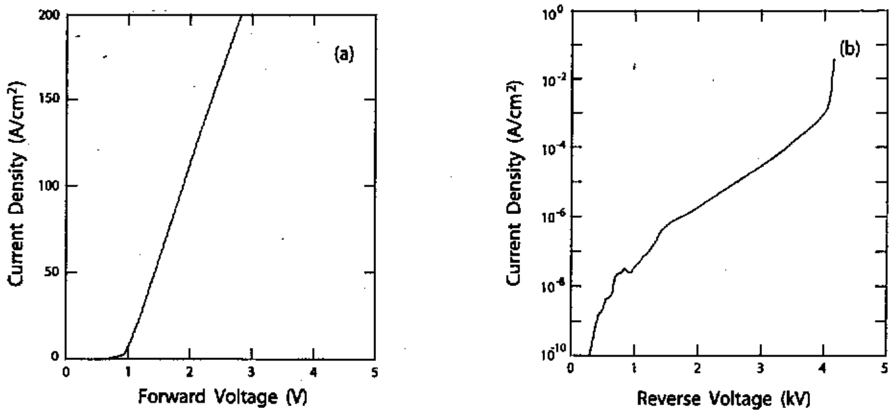

Fig. 4 (a) forward and (b) reverse characteristics of the fabricated Mo/4H-SiC SBD.

Summary

In summary, we reported improvement in the electrical performance of Schottky contacts for a high-voltage diode. The Φ_b of a Mo contact was found to be controllable without degradation of the n-factor by high temperature annealing. The high temperature annealing for the Mo contact was effective in reducing the leakage current without the generation of low Schottky barrier height components. We demonstrated the high performance annealed Mo/4H-SiC SBD with a JTE, which was formed using a graphite cap. The fabricated SBD showed a V_b of 4.15 kV (92.2% of the ideal value), leakage current density of 0.14 mA/cm^2 at 3.5 kV (about 2 MV/cm), R_{on} of 9.07 mΩcm^2, V_f of 1.89 V at 100 A/cm^2, and a best V_b^2/R_{on} value of 1898 MW/cm^2.

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References

[1] M. Bhatnagar and B. J. Baliga: IEEE trans. Electron Dev. Vol. 40 no. 3 (1993), p. 645.

[2] www.infineon.com

[3] www.cree.com

[4] A. Itoh and H. Matsunami: Phys. Stat. Sol. (a) Vol. 162 (1997), p. 389.

[5] T. Hatakeyama and T. Shinohe: Mater. Sci. Forum Vol. 389-393 (2002), p.1169.

[6] H. Tsuchida, I. Kamata, T. Jikimoto, and K. Izumi: J. Cryst. Growth Vol. 237-239 (2002) p.1206.

[7] H. Saitoh, T. Kimoto, and H. Matsunami: Mater. Sci. Forum Vol. 457-460 (2004), p.997.

[8] Y. Negoro, K. Katsumoto, T. Kimoto, and H. Matsunami: Mater. Sci. Forum Vol. 457-460 (2004), p.933.

[9] R. Singh, J. A. Cooper, Jr., M. R. Melloch, T. P. Chow, and J. W. Palmour: IEEE Trans. Electron Dev. Vol. 49 no. 4 (2002), p.665.

[10] J. H. Zhao, P. Alexandrov, and X. Li: IEEE Electron Dev. Lett. Vol. 24 no. 6 (2003), p. 402.