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High Voltage 4H SiC Rectifiers Using Pt and Ni Metallization

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Abstract. We have fabricated high voltage 4H SiC rectifier diodes using Ni and Pt as metals for the Schottky contacts. At a current density of 100 A/cm^2, these diodes had a forward voltage drop of 1.76 and 1.86 V, respectively. Both Ni- and Pt-SiC diodes had breakdown voltages > 1000 V. Pt-based SiC diodes exhibited a higher on-off current ratio ($>10^8$) and lower ideality factor (1.11) at room temperature than the Ni-based diodes ($>10^6$ and 1.29). The diodes were operated at elevated temperatures up to 450°C for forward bias and 300°C for reverse bias. The room temperature barrier height of Ni on 4H SiC was determined to be 1.31 eV and the specific on-resistance of the diodes was found to be ~8 mΩ-cm^2.

1. Introduction

Wide-bandgap silicon carbide is receiving greatly increased attention for high power and high temperature applications in aerospace and ground-based power systems due to its excellent electronic and physical properties. SiC Schottky barrier diode (SBD) rectifiers offer the fast switching characteristics and high power handling capability often needed for these applications. Therefore, they have the potential to be a valuable alternative to Si-based switching devices for applications where both power and speed need to be delivered.

The first SiC high voltage SBDs were reported by Bhatnagar et. *al.* [1]. These Pt/6H SiC diodes had a blocking voltage in excess of 400 V. The reverse current density was ~7.3×10^{-3} A/cm^2 at a reverse bias of 400 V. Subsequently, high voltage Au/6H-SiC Schottky diodes were reported by Kimoto et. *al.* [2]. These diodes exhibited breakdown voltages exceeding 1100 V, but had a low forward current density of 42 A/cm^2 at a forward voltage drop of 2V. Recently, 4H SiC is considered a superior polytype to 6H SiC for power devices, since it has a higher electron mobility in the direction of current flow (parallel to the c-axis) [3]. The first high voltage Schottky barrier diodes on 4H SiC were reported by Itoh et *al.* [4]. Au, Ni and Ti were employed for forming the Schottky contact. The room temperature breakdown voltage for the Au-4H SiC diodes was reported to be 800 V. The leakage current at a reverse bias of 600V was ~1×10^{-5} A/cm^2. In forward bias, a current density of 100 A/cm^2 was obtained at a voltage drop of 1.67 V. Raghunathan et *al.* [5] also reported high breakdown (1000 V) Ti/4H SiC SBDs with a forward voltage drop of only 1.06 V at a forward current density of 100 A/cm^2. However, the leakage current for these diodes was significantly higher (~7×10^{-3} A/cm^2 at 600 V) due to a lower Schottky barrier height for Ti on SiC (0.99 eV).

We have previously reported [6] Ni/6H-SiC SBDs with a high breakdown voltage (>1000V) at both 25 and 300°C. We also investigated [7] the current mechanisms for these diodes in the temperature range from 100K to 573 K. In the present study, we have fabricated SBDs on 4H SiC using Ni and Pt metals for forming the Schottky contacts. Current-voltage characteristics of these diodes have been measured at room temperature and at high temperatures up to 450°C. The barrier height for these metals on 4H-SiC has been characterized from I-V and C-V analysis at different temperatures. The variation with temperature of other important parameters such as the current on/off ratio and the specific on-resistance has also been studied for these diodes.

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2. Experimental Procedure

Schottky diodes with a vertical structure were fabricated on commercially available 10 μm thick n-type doped 4H SiC epitaxial layers (nominal doping 6.1×10^{15} cm^{-3}) grown on heavily doped (9.4×10^{18} cm^{-3}) n-type 8° - off Si-face 4H SiC substrates [8]. The backside ohmic contact was formed first, using Ni sputter deposition followed by a 5-minute Ar anneal at 950°C. A thermally grown oxide served both as a passivation layer for regions away from the Schottky contact and as a sacrificial layer for regions where contacts were to be formed. The Schottky contacts were circular and their diameters varied from 30 to 240 μm. A standard lithographic process was used for Schottky contact patterning. Prior to Schottky metal deposition, the sacrificial oxide layer in the contacts regions was etched using BHF. For forming the Schottky contacts, Ni was sputter-deposited, while Pt was deposited by electron beam evaporation. The metals were subsequently patterned using wet chemical etching.

3. Results and Discussion

The actual epi-layer doping was determined by C-V analysis and was estimated to be 6×10^{15} cm^{-3}. The current voltage characteristics of typical Pt and Ni SBDs at room temperature are shown in Figs. 1 and 2. A current density of 100 A/cm^2 was achieved at a forward voltage drop of 1.76 and 1.86 V, respectively. The ideality factors from the forward J-V plots were calculated as 1.11 and 1.29 for the two types of diodes. The Schottky barrier height and the specific on-resistance (R_{on}) for the Ni/4H SiC diodes was found to be 1.31 eV and 8 mΩ-cm^2, respectively. The saturation current

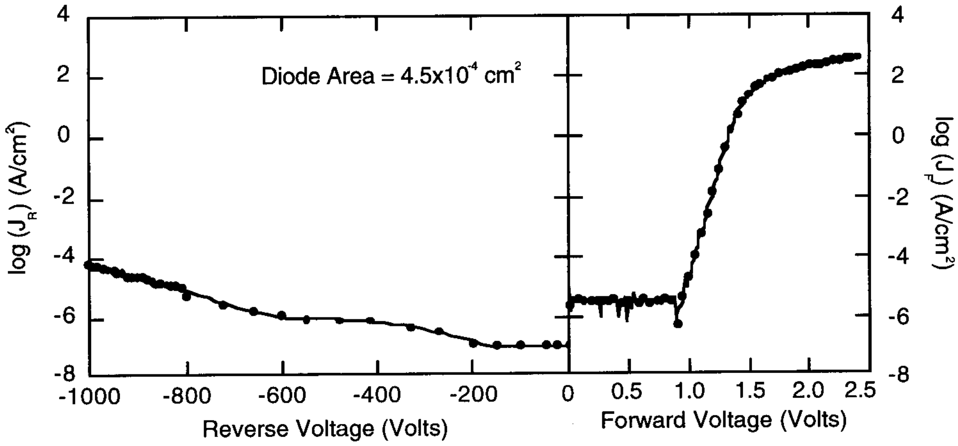

Fig. 1 Current-voltage characteristics of Pt/4H SiC SBD at room temperature.

density was found to be 4.7×10^{-15} A/cm^2. Both types of diodes were able to withstand reverse voltages in excess of 1000 V. Some diodes had a breakdown voltage as high as 1200 V. Under reverse bias, a leakage current density of 1.14×10^{-6} and 3.6×10^{-4} A/cm^2 was observed for the Pt and Ni diodes at -600 V. The room temperature current "on-off" ratio (corresponding to J_F at 2 V divided by J_R at -600 V) was measured to be 1.623×10^{8} and 2.85×10^{6} for the Pt and Ni diodes, respectively.

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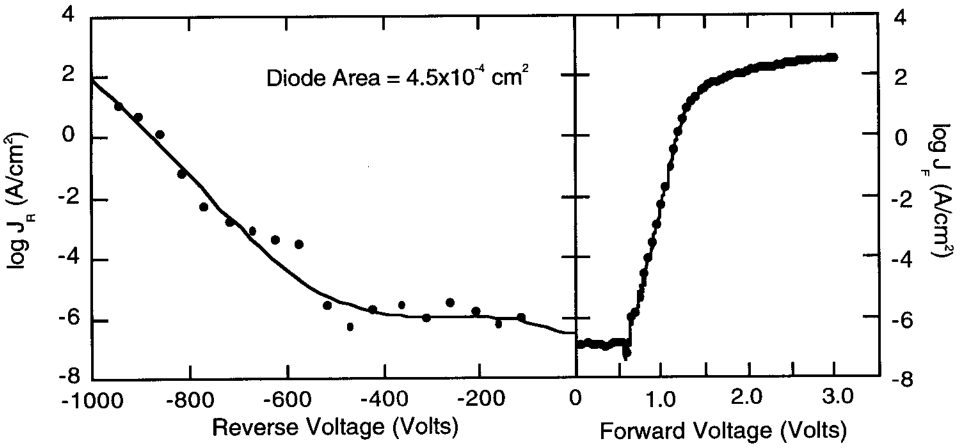

Fig. 2 Current-voltage characteristics of a typical Ni/4H-SiC SBD at room temperature.

Fig. 3 shows the variation of the current density as a function of temperature at different forward voltage drops and reverse bias voltages. It is seen from Fig. 3a that the current density increases with temperature for lower forward voltage drops (1, 1.25 V). At higher forward voltage drops (1.5, 2V), the increased series resistance results in a slight decrease in the current density with temperature. The ideality factor for the diodes rapidly approaches unity as the temperature was increased to 300°C. Fig. 3b shows that the leakage current at a reverse bias of -500 V is not dependent on temperature. This is a significant result as it indicates that these diodes can be operated without degradation in characteristics at higher temperatures. The current on-off ratio as previously defined shows only a modest reduction with increasing temperatures up to 300°C. Even at 300°C, this ratio is in excess of 10^6. The leakage current density for this diode at a reverse bias of -600 V shows only a slight increase from 4.51×10^{-5} to 5.12×10^{-5} A/cm^2 as the temperature is increased from 27 to 300°C.

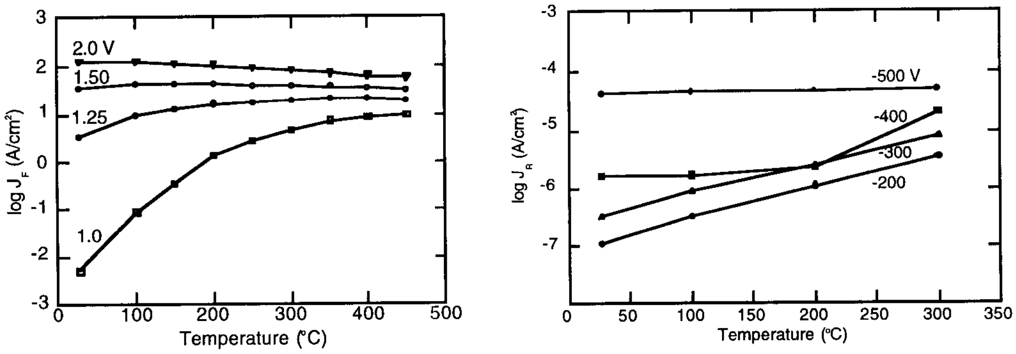

Fig. 3 Temperature dependence of current density: (a): forward bias; (b) reverse bias.

Fig. 4 shows the C-V characteristics of a Ni/4H-SiC SBD at 27 and 450°C. The best fit plots for the two temperatures have almost identical slopes, indicating no significant increase in carrier concentration at the higher temperatures. The voltage intercept gives a built-in voltage of 1.36 V at 27°C and 0.96 V at 400°C. According to the analysis of Fröjdh and Peterson [9], this seems to

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confirm that there are no deep levels associated with the dopant or defect sites in the n-type material used for these diodes.

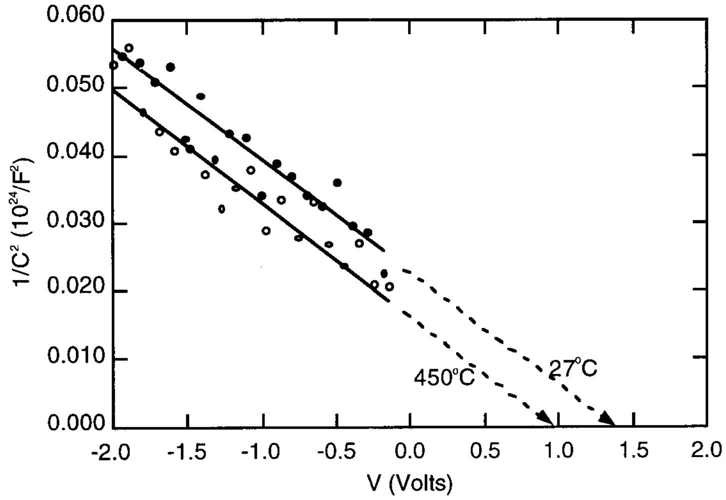

Fig. 4

C-V characteristics of a Ni/4H-SiC SBD at room temperature and at 450°C.

4. Summary and Conclusions

High breakdown voltage Schottky barrier diodes with on-off current ratio in excess of 10^8 at room temperature have been fabricated on 4H-SiC using Ni and Pt for the Schottky metal contacts. These diodes have been tested at elevated temperatures and show satisfactory operation at least up to 300°C (on-off current ratio $>10^6$). Ni SBDs have shown somewhat higher than expected ideality factors and specific on-resistance, but both quantities tend to improve after the devices are subjected to elevated temperatures (>200°C) for taking measurements. High temperature characterization also seems to decrease the leakage current and lower the forward voltage drop. This unintentional annealing effect is currently under investigation.

Acknowledgments

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