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High-temperature and high-voltage characteristics of Cu/diamond Schottky diodes

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Abstract

High-temperature and high-voltage characteristics of Cu/diamond Schottky diodes were investigated. Cu Schottky diodes showed clear rectification up to ~700°C and superior high-temperature stability at 400°C. The diodes showed specific on-resistance and breakdown voltage of 83.4 mΩcm^2 and 713 V at 400°C, respectively, which are comparable to reported highest values for diamond Schottky diodes and close to the theoretical limit for 6H-SiC at several hundred °C. These results indicate Cu/diamond Schottky diodes are promising for high-temperature power applications.

1. Introduction

Diamond is a promising semiconductor for high-power devices using in harsh environment (high-temperature, etc.). This is because it has excellent physical properties such as wide band-gap (5.5 eV), high thermal conductivity (22 W cm^{-1} K^{-1}), high electric breakdown field (>10 MV cm^{-1}), and so on. Based on its band gap, the intrinsic carrier concentration for diamond is estimated to be ~10^{10} cm^{-3} at 1000°C. This is comparable to that for Si at room temperature, suggesting that diamond devices can operate even at ~1000°C.

One important application is in devices used in automobiles such as power devices for inverters working at several hundred °C. However, there are only a few reports on power characteristics of diamond devices at the temperature [1], where high-temperature power devices for automobiles operate and diamond offers advantages over other semiconductors because of its high thermal conductivity, deep acceptor (boron) activation, etc. In this study, we show Cu/diamond Schottky diodes have are promising as high-power devices operating at several hundred °C for the first time.

2. Experimental

B-doped homoepitaxial diamond films were grown on commercial diamond (100) Ib substrates by microwave plasma chemical vapor deposition (CVD) using trimethylboron (TMB) as dopant gas. Cu Schottky diodes were fabricated on the B-doped diamond films (N_A: ~10^{17}cm^{-3}, μ: ~1000cm^2/Vs) [2, 3]. UV/ozone treatment was applied to convert the hydrogen-terminated surfaces of the as-grown B-doped diamond films to oxygen-terminated surfaces before depositing Schottky and ohmic electrodes. Their current-voltage (*I-V*) characteristics were measured in vacuum up to 800°C.

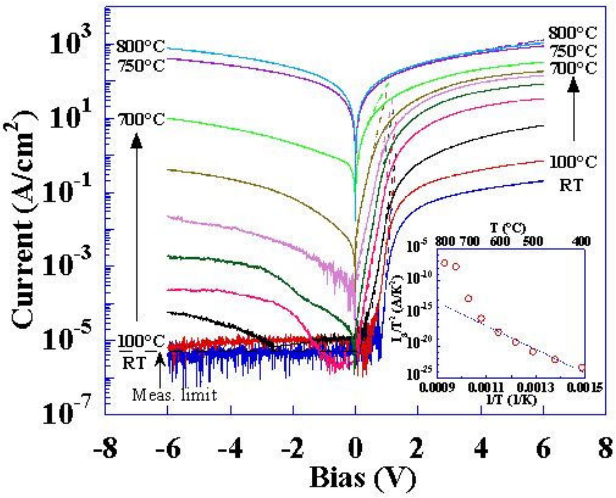

Fig. 1 Temperature dependences of current-voltage characteristics for Cu/diamond Schottky diodes. The dotted lines represent fits using the TE model. The inset shows a Richardson plot [ln (I_S/T^2) vs $1/T$, where I_S is the saturation current].

3. Results and Discussion

Figure 1 shows the current-voltage (*I–V*) characteristics of a Cu/diamond Schottky diode measured from room temperature (RT) to 800°C. A high rectification ratio of ~10^5 was observed at RT. The forward current systematically increased with temperature due to activation of the B acceptors. A rectification ratio of ~10^3 was obtained below 600°C though the reverse leakage current increased with temperature. Clear rectification with a rectification ratio of more than 10 was observed even at 700°C. The Schottky barrier height (ϕ_B) was estimated to be 1.50±0.20 eV for *n* (ideality factor) = ~1.5 below 700°C by the fitting of forward *I-V* characteristics using thermionic emission (TE) model. The ϕ_B was also estimated to be 1.64 eV from Richardson plot (Fig. 1 inset), which agree well with the estimated ϕ_B above. The Richardson plot for the Cu diode is approximately linear at temperatures below 700°C, indicating that the *I–V* characteristics can be explained using a TE model with a negligibly small tunneling contribution. The deviation from linearity above ~700°C is considered to be related to interfacial reactions and/or diffusion between Cu electrodes and diamond.

In order to evaluate high-temperature stability, *I–V* characteristics of the diodes were compared before and after keeping them at 400~700°C for ~30 hrs. The *I–V* characteristics at 400°C were almost unchanged after keeping

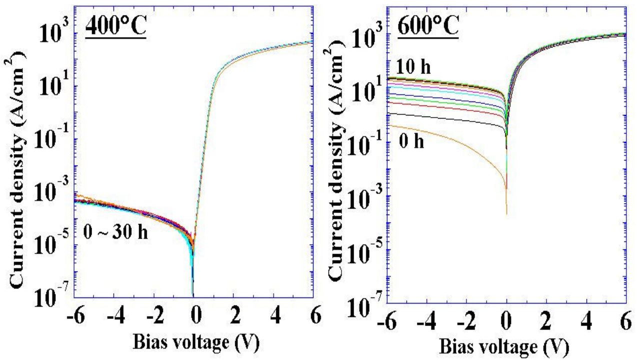

Fig. 2 *I–V* characteristics of Cu/diamond Schottky diodes measured at 400 and 600°C after keeping them for 0~30 hours at 400 and 600°C, respectively.

them for 30 hrs (Fig. 2), implying they have high stability at ~400°C. However, the reverse leakage current (J_R) systematically increased after keeping them at 500-700°C (Fig. 2) and the increase ratio of J_R increased as temperature increased. We consider it is related to interfacial reactions and/or interdiffusion at Cu/diamond interfaces induced by breakdown of the O-termination at the diamond surface above ~500°C [4].

Figure 3 shows bias voltage dependence of J_R of the Cu Schottky diodes measured at 400°C. The temperature of 400°C was adopted because it is well below the oxygen desorption temperature (~500°C) for oxygen-terminated diamond and is typical of the temperature at which power devices for automobiles operate.

The J_R of the diodes rapidly increase at 713 V. This means that hard breakdown of the diodes occurred at the voltage. The breakdown voltage and specific on-resistance (estimated from forward *I-V* characteristics) were estimated to be 713 V (~1.0 MV/cm) and 83.4

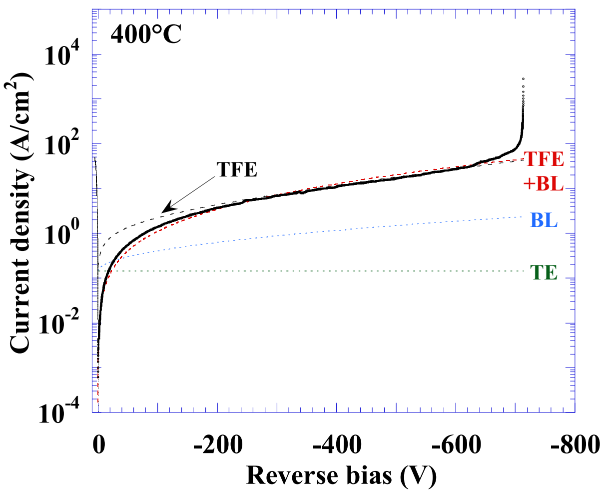

Fig. 3 Reverse leakage current characteristics of Cu/diamond Schottky diodes measured at 400°C. The dotted lines represent theoretical ones estimated by using the thermionic emission (TE), barrier lowering (BL), thermionic-field emission (TFE), and TFE combined with barrier lowering (TFE+BL) model.

mΩcm^2 at 400°C (952 V and 13.3 Ωcm^2@R.T.), respectively. These values are comparable to the reported highest values for diamond Schottky diodes at 250°C (9.4 mΩcm^2 and 840 V) [1] and close to theoretical limit for 6H-SiC at several hundred °C [5]. The J_R characteristics were analyzed by using the thermionic emission (TE), barrier lowering (BL), thermionic-field emission (TFE), and TFE combined with barrier lowering (TFE+BL) model [1] by assuming ϕ_B of 1.13 eV. The experimental J_R of the Schottky diodes were higher than the theoretical ones estimated by the TE and BL models. However, it agrees well with theoretical J_R estimated by using the TFE or TFE+BL model, and TFE+BL showed better results, especially for lower reverse bias region. In the case of Si Schottky diodes the J_R characteristics can be well explained by using BL models, however in the case of Schottky diodes of wide-gap semiconductors such as GaN, diamond, etc., the J_R is much higher, and we should take into account a tunneling transport component based on the TFE model [1]. Therefore, we consider the fact that the experimental J_R can be explained well by the TFE+BL model is reasonable. The TFE+BL model agrees well with the experimental data, however the ϕ_B of 1.13 eV was ~0.4 eV smaller than those estimated from forward I-V characteristics (~1.5 eV). Another models which incorporate other factors such as the edge effects should be considered to explain the mechanism for additional barrier height lowering, and this will be a subject for a future study.

4. Conclusions

High-temperature and high-voltage characteristics of Cu/diamond Schottky diodes were examined. Cu Schottky diodes showed clear rectification up to 700°C, indicating they can operate at ~700°C. The I-V characteristics at 400°C indicate Cu Schottky diodes have high high-temperature stability at ~400°C. The diodes showed specific on-resistance and breakdown voltage of 83.4 mΩcm^2 and 713 V at 400°C, respectively, which were comparable to reported highest values for diamond Schottky diodes at 250°C. We also found that the experimental J_R were well explained by the TFE+BL model. These results indicate Cu/diamond Schottky diodes are promising for high-temperature and high-voltage applications.

Acknowledgements

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