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High temperature operation of diamond Schottky diodes above 750°C

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1. Introduction

Diamond has excellent physical properties, such as the highest thermal conductivity (22 W cm^{-1} K^{-1}), high electric breakdown field (>10 MV/cm), and high carrier mobility (4500 cm^2 V^{-1} s^{-1}) and so on. These are advantageous for high-frequency and high-power transistors. Recently, using hydrogen-terminated chemical vapor deposited (CVD) diamond field-effect transistors (FETs), a transition frequency (f_T) and maximum frequency of oscillation (f_{max}) of 45 and 120 GHz were achieved, respectively [1], and a maximum output-power density of 2.1 W/mm at 1 GHz [2]. These values are sufficient for power amplifiers used in wireless communications systems.

Diamond is also promising for high temperature applications such as devices close to the engine room of automobiles because of its high band-gap (~5.5 eV) and chemical stability. However, there are only several reports on high-temperature characteristics of diamond devices. In our previous study, we showed that high-temperature operation of B-implanted diamond FETs was possible up to ~550°C and the maximum working temperature of the FETs was limited by the temperature where magnitude of rectification ratio of gate-source Schottky diodes became less than ~10 [3].

In this study, we have tried fabricating diamond Schottky diodes, which have high rectification ratio at higher temperature.

2. Experimental methods

Boron (B)-doped CVD homoepitaxial diamond films were grown on commercial Ib (100) diamond substrates by microwave plasma CVD. Typical acceptor concentration and mobility of the B-doped films was ~$2*10^{17}$ cm^{-3} and ~1000 cm^2/Vs at room temperature, which were confirmed by Hall measurements. The conductivity was originated from unintentionally doped B during the CVD growth. Schottky diodes using various metals such as Ag, Ni, Cu, etc. were fabricated on the B-doped films. These electrodes were chosen because they were not reactive with carbon below 1000°C, which was confirmed by the binary phase diagram. The current-voltage characteristics of the diamond FETs were measured in vacuum up to ~800°C.

3. Results and Discussions

Figure 1 shows current-voltage (I-V) characteristics for Ag Schottky diodes measured from R. T. (~25°C) to 800°C. High rectification ratio of more than ~4 orders of magnitude was observed. The reverse leakage current was lower than the detection limit up to 300°C, indicating rectification ratio of more than ~5 orders of magnitude is expected below 300°C. Forward current systematically increased as temperature increased (E_a= ~0.4 eV) because of activation of B acceptors. The reverse leakage current increased as temperature increased above 300°C, however the rectification ratio was more than 3 orders of magnitude up to 600°C. From fitting of forward bias I-V characteristics using equation for thermionic emission (TE), Schottky barrier heights (ϕ_B) were estimated to be 1.65±0.20eV with ideality factor (n) of 1.2~1.6 below 700°C. Even at 750°C, the rectification ratio kept more than one order of magnitude. These behaviors agree with Vescan et al.'s results, which showed low leakage current up to ~500°C in diamond Schottky diodes [4]. These results suggest that the Ag Schottky diodes can work at ~750°C and diamond FETs using the Ag Schottky diodes could operate up to ~750°C.

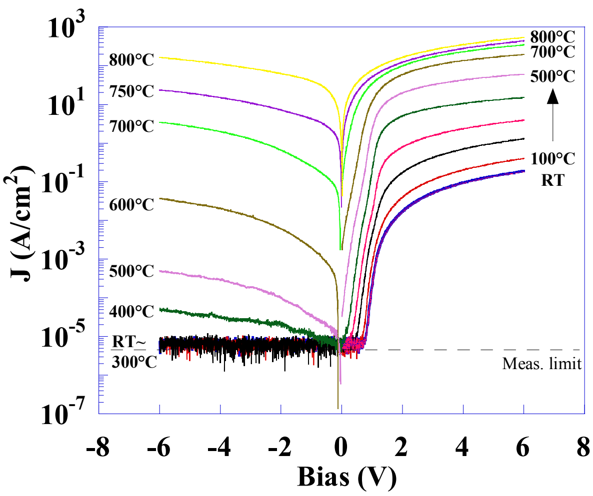

Fig. 1 Temperature dependence of current-voltage characteristics for Ag-Schottky diodes using B-doped diamond films. The dotted line indicate measurement limit for our instruments.

On the other hand, Ni Schottky diodes showed

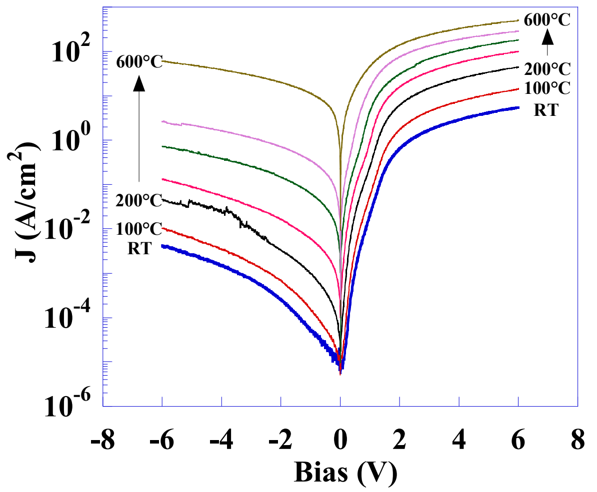

Fig. 2 Temperature dependence of current-voltage characteristics for Ni-Schottky diodes using B-doped diamond films.

rectification ratio of more than ~3 orders of magnitude below ~500°C (Fig. 2), however reverse leakage current was several orders of magnitude higher than that of Ag Schottky diodes. And, above 600°C, the rectification ratio of the Schottky diodes became less than one order of magnitude (ohmic like properties). The Schottky barrier height (ϕ_B) was estimated to be 0.61±0.12 eV below 500°C by the fitting of the forward I-V curves using the TE model. We consider lower rectification ratio of the Ni Schottky diodes at higher temperature is due to lower ϕ_B (Ni: ~0.61 eV, Ag: ~1.65 eV).

Suppression of the reverse leakage current is very important for obtaining Schottky diodes working at higher temperature. The reverse current-voltage characteristics of the Ag Schottky diodes were analyzed to understand the mechanism for increase of the leakage current at higher temperature. Figure 3 shows temperature dependence of reverse bias current at 6 V (J_R). The dotted lines are theoretical J_R values

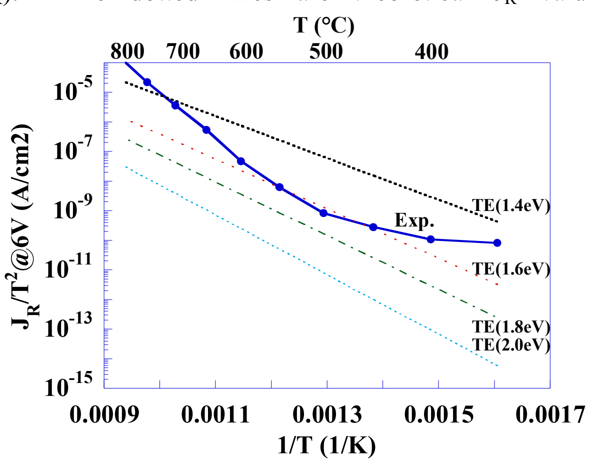

Fig. 3 Temperature dependence of reverse bias current at 6 V (J_R). The dotted lines are theoretical J_R values estimated by using thermionic emission (TE) model of various barrier heights (1.4~2.0 eV)

estimated by using the TE model by assuming various ϕ_B (1.4~2.0 eV). The J_R values agree with the theoretical J_R curves for ϕ_B of 1.6 eV and the ϕ_B agrees well with those obtained from fitting of forward current-voltage characteristics (1.65±0.20 eV). We think slight deviation from the theoretical J_R at higher temperature is probably due to the contribution from tunneling currents thorough defects, and/or reaction or diffusion between diamond surfaces and Schottky electrodes. These results suggest the current-voltage characteristics for the Ag Schottky diodes can mostly be explained by the TE model up to higher temperature and Schottky diodes with higher ϕ_B is needed for fabricating Schottky diodes working at much higher temperature.

4. Conclusions

Diamond Schottky diodes using various metals such as Ag, Ni as Schottky electrodes were fabricated on B-doped diamond and their high temperature characteristics were examined. The Ag Schottky diodes showed high rectification ratio of more than ~4 orders of magnitude up to 600°C. And, the rectification ratio kept more than one order of magnitude even at ~750°C, indicating diamond FETs using the Ag Schottky diodes could operate up to ~750°C. On the other hand, Ni Schottky diodes exhibited low rectification ratio of less than one order of magnitude above 600°C. Analysis of I-V curves indicates higher rectification ratio of the Ag Schottky diodes at higher temperature is due to higher ϕ_B (~1.65 eV for Ag and ~0.61 eV for Ni, respectively) and it is prerequisite for fabricating diamond devices working at higher temperature.

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