Thermally Stable Schottky Barrier Diode by Ru/Diamond

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For the high temperature operation of diamond for high power devices, a new Ru/diamond material contact was proposed for the first time for thermally stable Schottky barrier diode (SBD). This contact showed very good Schottky properties, with the further advantages of low resistivity, high chemical stability and very high adhesion characteristics. The devices were tested for thermal stability at 400 °C for 1500 h and 500 °C for 250 h. The SBD characteristics were highly stable, and after an initial stabilization time of 250 h, further changes in the parameters were less than 2.5% from 250 to 1500 h at 400 °C. For 500 °C testing, there was no change from 100 to 250 h. This thermally stable Schottky contact is promising for future high temperature operation device, such as those applied in the cooling systems-free power modules.

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Recently, diamond has been receiving much attention for power device applications because of its superior material properties, such as a large band gap, high thermal stability, high critical electric field, high mobility, and extremely high thermal conductivity. Thus, diamond has been nominated as a material candidate with very high figure of merit (FOM) for application in future high power devices. Diamond is expected to perform especially well in the for high temperature operations aiming cooling system free operation of power modules. And for this purpose, high stability up to 100,000 h of operation at 250 °C is required. For diamond devices, high temperature operation such as 310 and 400 °C has been reported, however only for a limited operation time. Long-term stability study has not been examined to date. To realize the high temperature operation of diamond devices, the thermal stability of the metal contacts on the diamond is of critical importance. In this respect, the reliability of ohmic contact had been confirmed; for instance, the stability at 800 °C for 400 h of the TiMoPt/diamond. For a Schottky contact on diamond, tungsten carbide (WC) has been studied; however degradation of both the n value and barrier height was observed following annealing at 500 °C for 5 h. Pt/diamond is a candidate for a high temperature durable Schottky contact, having high stability at 400 °C for 117 h. However, this system suffers from poor adhesion characteristics and can not be used in practical application. Silicon carbide has good stability, having been observed at 500 °C for 100 h for a Ti-based Schottky, but when annealing at 500 °C for more than 448 h, degradation of leakage has been observed. Thus, herein a new Schottky metal for use in a Ru/diamond system is examined. The Schottky characteristics of Ru on B-doped p+ type diamond are investigated with respect to the doping level of power Schottky barrier diode (SBD) drift layer, with the long term thermal stability at 400 and 500 °C in compared with a well known Mo/diamond contact. Ru was selected from amongst various materials, because of its high melting point (2,555 K), very low resistivity, good adhesion to diamond, and good chemical stability.

In this study, a pseudo-vertical SBD structure of Schottky/p− diamond/p+ diamond on an insulating (100) diamond substrate was adopted in order to avoid fabrication complexity. The boron concentration of the p+ layer was higher than 10^20/cm³, which was sufficient to realize an good ohmic contact. The p− drift layer was prepared after p+ layer deposition. The total gas pressure, RF power, methane concentration ratio, substrate temperature during deposition, and the overall growth rate of the microwave chemical vapor deposition system were 120 Torr, 4,000 W, 4%, 1,000 °C, and 15 nm/min, respectively. The final thickness of the film was 1.5 to 2 μm, calculated using the growth rate and weight. The boron concentration was measured to be 5 × 10^19/cm³. Prior to fabrication of the ohmic contacts, oxygen plasma treatment was employed to suppress reverse leakage current. A Ti (30 nm)/Pt (30 nm)/Au (100 nm) ohmic contact was fabricated followed by alloy annealing at 400 °C for 30 min. Ru and Mo Schottky metals were prepared on the p− layer using electron beam (EB) lithography and RF sputtering. During the sputtering process, RF power was fixed at 200 W in the background pressure of 0.5 Pa with Ar, and the substrate temperature was naturally heated to 40 °C. The thickness of the resulting metal was 150 nm. For initial stabilization of the Schottky barrier, the samples were annealed at 400 °C for 30 min. Then, the Schottky contacts were tested for high temperature stability at 400 and 500 °C with measurements being carried out at room temperature using an Agilent 4156C parameter analyzer.

The typical current–voltage (I–V) characteristics of the Ru/diamond SBD are shown in Fig. 1. The Ru Schottky contact is shown in (a) with a Mo Schottky contact in (b) for comparison. As is described below, the interface is oxygen terminated in order to reduce reverse leakage current. As can be seen in the figure, Ru can form a very good Schottky contact to diamond, having a rectification ratio of more than 10, with an ideality factor of 1.04 and barrier height of 1.16 eV. More than 20 devices were tested, and the the yield of the “killer defect” free area of the Ru/diamond SBD was found to be as high as 100% for. The deviations in characteristics were less than 0.014 for the ideal factor. In addition to the SBD characteristics, Ru/diamond contacts have advantages in both fabrication process margin and high reproducibility of measurements due to their high adhesion characteristics; such as almost 100% by tape peel off testing. For the Mo/diamond SBD, for comparison, the ideality factor was around 1.1, and the yield of “killer defect” free area was 60%. The difference in the current density between Ru/diamond and Mo/diamond SBDs is the result of the thickness of the p− drift layer. The Schottky barrier heights of both Ru/diamond and Mo/diamond were almost the same after the annealing; 1.16 and 1.2 eV, respectively. These are

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far from the calculated values of Mo 2.06 and Ru 2.17 eV, using workfunction of Mo (4.60 eV) and Ru (4.71 eV) respectively; that are due to the unknown pinning state formed by metals with an oxygen terminated diamond surface.

To investigate the thermal stability of Ru/diamond SBD toward high temperature operation, high temperature storage testing was carried out at 400 and 500 °C. Figure 2(a) shows the forward properties of Ru/diamond SBDs annealed at 400 °C for 1500 h with plots of initial (0 h) and 250 h testing results. The data are also shown in (b) for SBD annealed at 500 °C for 250 h with plots of initial and 100 h testing results.

There seems to be no degradation for 400 °C storage and also no change can be seen from 500 °C storage from 100 to 250 h after the initial stabilization. In Fig. 3, the characteristics of a Mo/diamond SBD after 400 °C 1500 h storage are shown in (a), with an example of a degraded device in (b). Among the devices tested for up to 1500 h, 40% of Mo/diamond SBDs showed an increase in the degradation of the reverse leakage current with increased annealing time, whereas no such phenomenon is found for Ru/diamond. This is probably the result of a formation of defective contacts presumably

Fig. 1. Typical current–voltage (I–V) characteristics of a Ru SBD with a Mo SBD for comparison. (a) Ru/diamond and (b) Mo/diamond.

Fig. 2. The I–V properties of a Ru/diamond Schottky barrier diode. (a) Storage at 400 °C for 1500 h. (b) Storage at 500 °C for 250 h.

Fig. 3. The I–V properties of a Mo/diamond Schottky barrier diode annealed at 400 °C for 1500 h. (a) Good device and (b) degraded device.
gamma MoC$_{1-x}$ phase formed by carburization of metallic molybdenum.\textsuperscript{12)} The reactivity toward carbon is presumably a critical factor in the difference between Ru and Mo. In a prior investigation of diamond crystal defects in Mo/diamond SBDs, we found that the numbers of “deep pits” originated from the epi-layer interface; likely by screw type dislocation, influencing the device leakage characteristics.\textsuperscript{13)} This fact also supports the results of thermal degradation observed in these experiments.

For the Ru/diamond SBD, characteristics such as the forward current density (A/cm$^2$), turn-on voltage (V), on-resistance (mΩ cm$^2$), Schottky barrier height (eV), and ideality factor $n$ are plotted as a function of annealing time in Fig. 4 for 400 °C storage samples. For this SBD, there is an initial change during the first 50 h in the on-resistance and current density, however after the stabilization; there are almost no changes in the parameters to 1500 h. The changes to all of the parameters from 250 to 1500 h were less than 2.5%. For 500 °C testing results, ideality factor and barrier height average values are 1.07 and 1.08, respectively for 100 h storage samples. For this SBD, there is an initial change during the first 50 h in the on-resistance and current density, however after the stabilization; there are almost no changes in the parameters to 1500 h. The changes to all of the parameters from 250 to 1500 h were less than 2.5%. For 500 °C testing results, ideality factor and barrier height average values are 1.07 and 1.08, respectively for 100 h storage samples.

In conclusion, for high temperature operation of diamond in high power devices, a new material system of Ru/diamond has been developed for the first time as a thermally stable Schottky barrier diode. Ru/diamond showed very good Schottky contact properties to diamond, with the further advantages of low resistivity, high chemical stability during the fabrication process and very high adhesion characteristics. To probe its use in high temperature operation, devices were tested for at 400 and 500 °C and very high stability of the SBD characteristics, was confirmed. After initial stabilization, changes to all parameters from 250 to 1500 h for 400 °C were less than 2.5% and no change were observed for 500 °C from 100 to 250 h. This material system is promising for use in future high temperature operation devices, such as in the “cooling system free” power device modules.

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\begin{figure}
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\includegraphics[width=\textwidth]{figure4.png}
\caption{Typical parameters plotted as a function of annealing time at 400 °C for Ru/diamond Schottky diodes.}
\end{figure}

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