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Diamond High Power Devices

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1. Introduction

Diamond is the most promising material for future high power and high temperature devices because of its material properties. Up to now, high power (> 6.5kV [1], > 1kA/cm^2 [2], 3.5MW/cm^2 [3]) or high temperature (> 500 ^{o}C [2]) Schottky barrier diodes (SBDs) have been demonstrated. However, reported maximum fields of diamond SBDs are much lower than the expected value. Consequently, the performance of diamond SBDs are lower than the SiC's material limit that is determined from trade-off relationship of on-resistance and blocking voltage. One of the reasons of low breakdown field has been clarified as the increase of tunneling current through the barrier [4]. Defect is the other reason to decrease the breakdown field [5].

Recently, we have proposed a model to answer the narrow operation range of diamond SBDs from TFE modeling [4]. We have concluded sudden increase of reverse current at around 2 MV/cm is due to the tunnelling transport through the Schottky barrier. Consequently, to improve the device operation limit in reverse condition, increase of Schottky barrier height (SBH) is the most important technique. In this study, we demonstrate high power diamond SBDs with SBH variations. And also, to characterize the effect of defects, the device size dependence of the operation current and voltage are characterized on p-/p+ pseudo vertical SBD (pVSBD).

2. Experimental

To characterize operation limit of diamond power devices, pVSBDs were fabricated on CVD grown p$^-$/p$^+$ stacked diamond layer. Ib(001) single crystal diamond was utilized to grow diamond films. The Ohmic contacts were obtained on 1-µm-thick-heavily-doped p+ layer on the corner of the substrate. The specific ohmic contact resistance was 10 µΩcm^2. Boron concentration of p- layer was decreased to 10^{14} cm^3. The thickness of the p- layer is 0.94 µm measured from SIMS and C-V method. SBH is controlled by changing Schottky metal and surface treatment. Schottky contacts were fabricated on the same substrate with a diameter of 30-50 µm.

The device size dependence of the operation current and voltage are characterized on pVSBD fabricated by EB lithography and ICP etching process. The pVSBD was fabricated on p-/p+ stacked CVD diamond. The thickness of p-/p+ layer and acceptor concentration were controlled as 5/10 µm and 10^{16} /cm^3, respectively. Ti Ohmic contacts were formed on p+ layer after the lithography and the etching of p- layer utilizing reactive ion etching. Mo Schottky contacts were fabricated utilizing alignment technique of EB lithography with electrode area of 8.8x10^{-4} to 4.1x10^{-2} mm^2. In order to decrease the parasitic resistance, the distance between Ohmic to Schottky electrode was decreased to less than 20 µm.

3. Results and Discussion

Improve of operation limit by SBH control

Forward and reverse I-V characteristics of Al, Mo and Pt are shown in fig. 1 (a) and (b), respectively. SBH at n=1 of Al, Mo and Pt SBDs are 1.75, 1.92 and 2.61 eV, respectively. Maximum forward current at -8 V exceeds 2kA/cm^2 due to the low on-resistance of 1.7-1.9 mΩcm^2. Decrease of

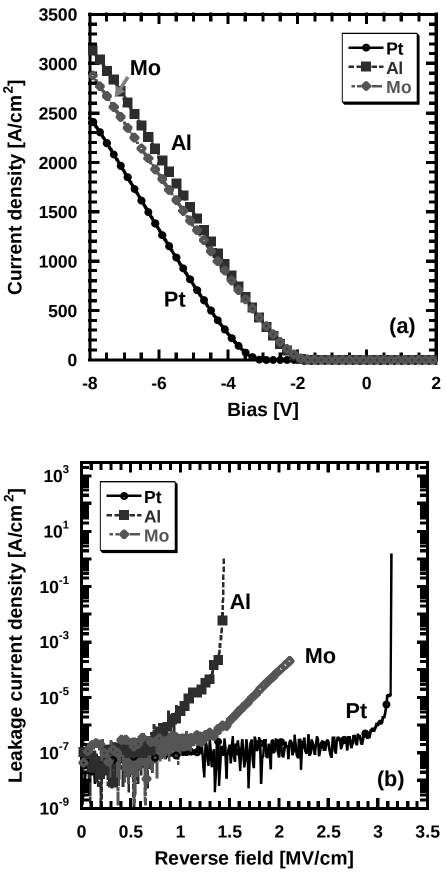

Figure 1(a) Forward and (b) reverse characteristics of diamond pVSBDs with various SBH.

leakage current by increasing SBH is observed clearly. The operation limits which are determined as the electric field at the reverse current exceeding 1mA/cm^2 (10^6 rectification) are 1.4, 2.3 and 3.1 MV/cm for Al, Mo and Pt SBDs, respectively. The maximum field of 3.1 MV/cm is one of the top values ever reported, and better than the SiC material limit. BFOM ($BV_{BD}^2/R_{on}S$) of the device reaches 51 MW/cm^2 which is 10 times higher than Si limit. In addition, high SBH of diamond keeps leakage current lower than SiC. Leakage current at high temperature operation is also lower than that of SiC SBDs. because the breakdown field highly depends on SBH.

Device size dependence of diamond pVSBD

Figure 2 shows the maximum operation voltage (BVBD@J_L=1mA/cm^2) and forward current (I_F@V_F=-8V) of the SBDs at room temperature. Because of the low parasitic resistance on Ohmic contacts and p+ layer, the differential on-resistance (RonS) of the SBDs are kept small at 15-20 mΩ-cm^2 with increasing diode area. Consequently, the operation current increases proportionally with the increase of diode area. The highest current of 0.1A is obtained at 0.035mm^2 diode area. Even if the Ohmic contact requires same electrode area on the surface, more than 5 A of operation current is expected for diamond pVSBD on 3 mm substrate.

On the other hand, operation voltage decreases with the increase of diode area. The maximum operation voltage of 769V is obtained on an SBDs with diode area of 8.8x10^{-2}mm^2. The depletion layer reaches to p+ layer and the maximum field (1D) is estimated as 1.96-2.37 MV/cm which is the average value of diamond SBDs ever reported. However, increasing diode area to 10^{-2} mm^2 decreases operation voltage to 250V (0.91-1.24MV/cm). Decrease of operation voltage is due to the incorporation of defects such as dislocations in Schottky electrode. The dispersion of operation voltage such as smallest electrode will be explained by the different number of defects in electrode. Accordingly, defect density of more than 10^4/cm^2 is estimated. This value is smaller than that of GaN substrate and comparable to that of Ib diamond substrate or SiC wafers. Characterization of defects on epitaxial diamond layers are needed to improve the SBD characteristics under high voltage operation.

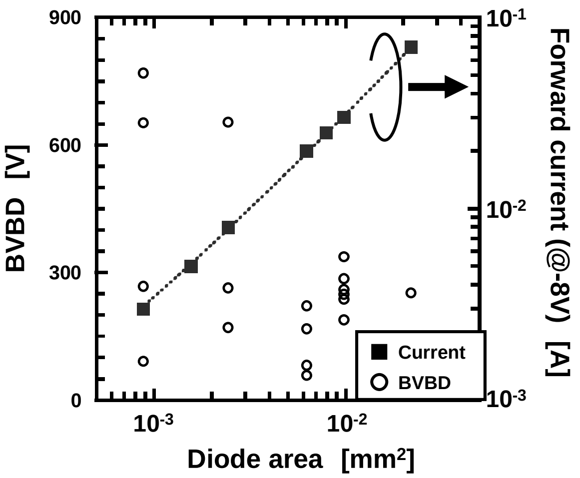

Figure 2. Maximum operation voltage (BVBD) and forward current (@-8V) of diamond pVSBD for various diode areas.

4. Conclusions

Control of SBH on diamond surface by changing surface termination and Schottky metals. Punch-through type diamond pVSBDs with various SBH shows clear improvement of reverse performance by increasing SBH. The maximum reverse operation field of 3.1 MV/cm has been obtained on Pt pVSBDs. The devices also realize low $R_{on}S$, consequently, high Baliga's figure of merit of 51 MW/cm^2 has been obtained. This value is the highest in diamond power devices at present. The device performance scaling of the device size on diamond pVSBD has been characterized by utilizing EB lithography technique. Because of low parasitic resistance on p+ layer, the operation current of the pVSBD is proportionally increased by increase of the device size. However, the leakage current under reverse bias condition is also increased due to the defect. The estimated density of defects is 10^4 – 10^5 /cm^2, which is comparable to the dislocation density of Ib substrate. Decrease of dislocation density to less than 10^2 /cm^2 is required to realize 10 A class high power devices.

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