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Leakage current analysis of diamond Schottky barrier diodes by defect imaging

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ABSTRACT

The leakage current of pseudo-vertical-type diamond Schottky barrier diodes (SBDs) was analyzed using a defect visualization technique. Even under a low electrical field, 50% of the fabricated diamond SBDs exhibited a high leakage current that cannot be explained by any of the carrier transport mechanisms through the Schottky barrier. The SBDs with high leakage current were confirmed to contain a high density of dislocations that are revealed as deep etch pits by H_2/CO_2 plasma treatment. The maximum operation voltage of the SBDs is clearly dependent on the number of deep etch pits.

1. Introduction

Diamond is a promising material for high-power and high-temperature device applications [1] due to its wide bandgap (5.5 eV), high breakdown fields (>10 MV/cm), the highest thermal conductivity (20 W/cmK), and high bulk carrier mobilities of 3800 and 4500 cm^2/Vs for holes and electrons, respectively [2]. Schottky barrier diodes (SBDs) with high current density [3], high temperature operation capability [4] and high breakdown voltages [5–7] have been reported by utilizing these superior material properties. However, the breakdown field does not exceed 4 MV/cm, which is 3–5 times lower than the expected value [6,8]. The first reason for this is the high leakage current due to carrier transport through the Schottky barrier by thermionic-field emission, which can be suppressed by an increase of the barrier height [9,10]. The second reason is the leakage current though defects. We have confirmed that an increase of the device size results in performance degradation [11] and the estimated density of defects is almost comparable to that of threading dislocations in the substrate; however, a clear relationship between device performance and the defects has not been confirmed. In the case of SiC power devices, a technique for the visualization of dislocations has already been established in etch-pit or X-ray topography (XRT), and the effects of defects on device performance have been discussed [12]. However, many other techniques have been established that can be used to visualize defects in diamond, such as cathodoluminescence, photoluminescence and Raman spectroscopy; however, the effect of defects on the device performance has rarely been discussed [13]. Recently, H_2/O_2 plasma treatment has revealed threading dislocations as etch-pits [14]. We have also confirmed that etch pits formed by exposure to H_2/CO_2 plasma can be visualized as dislocation images using XRT [15] In this paper, the effect of defects on device degradation, as revealed by the etch-pit method, is confirmed for pseudo-vertical diamond high voltage SBDs.

2. Experimental

Pseudo-vertical SBDs (pVSBDs) were fabricated [13] to analyze the effect of dislocations on the device performance. pVSBDs were fabricated on p−/p+ stacked layers epitaxially grown on single crystalline high pressure high temperature (HPHT) Ib(001) diamond wafer (3 × 3 × 0.5 mm). The pVSBD has Schottky and Ohmic electrodes formed on the same surface geometry as in a lateral SBD. However, the depletion layer expands vertically in the p− drift layer, and holes also run vertically through the p− layer as in a vertical SBD. The p+ layer was deposited using microwave plasma chemical vapor deposition (CVD) with CH_4 and B_2H_6 diluted with H_2. The CH_4 concentration diluted with hydrogen and B/C ratio were 0.6% and 16,000 ppm, respectively. The plasma power, gas pressure and growth temperature used were 1.2 kW, 50 Torr and 900 °C, respectively. The resultant p+ film was 1 μm thick and exhibited metallic conduction due to impurity band formation [16]. The p− layer was subsequently deposited by CVD on the film using a different clean chamber. To prevent the incorporation of impurity boron, CO_2 was added during film growth. The CH_4 concentration diluted with hydrogen and O/C ratio were 4% and 0.4, respectively. The plasma power, gas pressure and growth temperature used were 3.9 kW, 120 Torr, and 1000 °C, respectively. The resultant p− film was 18 μm thick. After epitaxial

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growth of the p−/p+ stacked layer, differential interference contrast (DIC) microscopy was used to confirm the absence of non-epitaxial crystals or hillocks.

Ti (30 nm)/Pt (30 nm)/Au (100 nm) Ohmic contacts were formed on the four corners of the p− epitaxial layer by electron beam evaporation. Pt (30 nm)/Au (100 nm) Schottky contacts with diameters of 10, 20, 30, 50, 75, 100 and 200 μm were fabricated using lithography, electron beam deposition and lift-off techniques.

Fig. 1 shows a schematic cross-section of a diamond pVSBD. Current–voltage (*I*–*V*) and capacitance–voltage (*C*–*V*) characteristics were conducted at room temperature using an on-wafer probing system (Vector Semiconductor) and a system comprised of a source measure unit (Keithley 237) and precision LCR meter (Agilent 4284A). Characterization was performed in a dielectric fluid (3 M Fluorinert^{TM}) to prevent surface leakage and discharge. The numbers of *I*–*V* characterized devices with Schottky electrode diameters of 10, 20, 30, 50, 75, 100 and 200 μm were 9, 9, 9, 11, 17, 15 and 42, respectively.

The dislocations were revealed by exposing the substrates to H_2/CO_2 plasma after all of the electrodes were removed by chemical processes using solutions such as HCl/HNO_3 (3:1, for Au and Pt), HCl/H_2O_2 (3:1, for Ti) and hot HNO_3/H_2SO_4 (1:3 at 200 °C, for TiC). 1% CO_2 diluted with H_2 was utilized for selective etching of the dislocations with the plasma power, pressure and substrate temperature set at 3 kW, 120 Torr and 900 °C, respectively. Observation of the etch pits on 28 devices with Schottky electrode sizes of 200 μm was performed using DIC microscopy. Secondary electron microscopy (SEM) and atomic force microscopy (AFM) were utilized to characterize the structures of the etch pits.

3. Results and discussion

More than 70% of the SBDs with electrode diameters of 75 μm or less exhibited high blocking voltages of 1100 V, which is the limit of the measurement system. However, 50% of the SBDs with 200 μm diameter electrodes could not operate at 1100 V, due to an increase of the leakage current at low reverse voltage. Among these, 14% of the low breakdown SBDs exhibited a discontinuous increase of leakage current, which could be due to field enhancement at the edge of the electrode. The acceptor concentration from the surface to a depth of 6 μm was determined from the *C*–*V* characteristics to be $1.5 \times 10^{14}/cm^3$, and the corresponding maximum field at a reverse bias of 1100 V was less than 1 MV/cm, even if the acceptor concentration was increased at the deeper side of the p− drift layer. The leakage current is independent of the distances between the Ohmic and Schottky electrodes, i.e., the surface leakage is not a major component of the total leakage current. Fig. 2 shows the forward and reverse characteristics of two typical types of SBDs with 200 μm diameter electrodes; low leakage current SBD A and high leakage current SBD B. The Ohmic–Schottky distance of SBD A is almost half that of SBD B.

The high contact resistance of the Ohmic electrode fabricated on the p− drift layer causes the specific on-resistances of these devices to be

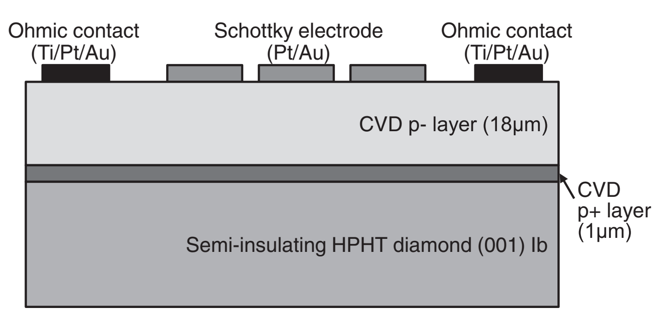

Fig. 1. Schematic cross section of a diamond pseudo-vertical Schottky barrier diode (pVSBD).

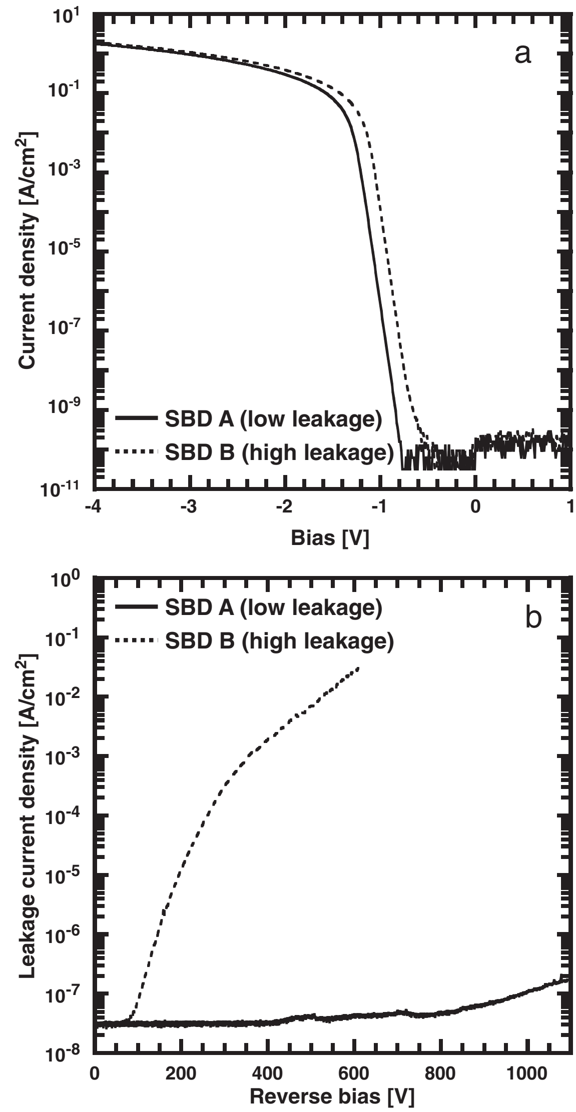

Fig. 2. a Forward and b reverse characteristics of low (SBD A) and high (SBD B) leakage current Schottky barrier diodes (SBDs).

high, at 0.93 and 0.91 Ω cm^2 for SBD A and B, respectively. The ideality factors of the SBDs are almost constant at 1.03. The average and standard deviation of the ideality factor for the 200 μm diameter SBDs were low at 1.04 and 0.0096, respectively, which indicates that the Schottky interface is almost ideal. In contrast to the low ideality factor and deviation, the Schottky barrier heights (SBHs) are widely distributed from 1.59 to 1.78 eV, with the average and standard deviation of the SBH at 1.69 and 0.052 eV, respectively. The SBHs of SBD A and B were 1.75 and 1.59, respectively; however, no clear relationships between the SBH and the leakage current or blocking voltage were obtained.

Fig. 2b shows that the leakage current of SBD A is lower than the measurement limit up to 800 V, and becomes 0.2 nA/cm^2 at 1100 V. The rectification ratio is 7 orders of magnitude, even at 1100 V. In contrast, the leakage current of SBD B starts to increase at around 100 V and reaches 10 mA/cm^2 at 530 V. Accordingly, the rectification ratio is less than 2 orders of magnitude at 600 V of reverse bias. The leakage current of SBD B cannot be explained by current transport mechanisms such as parasitic conductance (Ohmic-like paths) [13], barrier height lowering [17], thermionic field-emission [13], Fowler–Nordheim tunneling [17] or space charge limited current [17]. Potential reasons for the increased leakage current are crystallographic defects