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Edge termination techniques for p-type diamond Schottky barrier diodes

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Abstract

The superior material properties of diamond power semiconductor devices make them a crucial technology. For high-voltage applications, optimized structures such as electric field edge termination are required for devices. In this paper, we have investigated the optimization of electric field relaxation techniques in oxygen-terminated p-type diamond Schottky barrier diodes and made comparisons with regard to electric field crowding and breakdown in oxides. Due to the low dielectric constant of diamond, Al_2O_3 is appropriate for the fabrication of field plate structures in diamond power devices.

Keywords: Diamond; Schottky barrier diode; Edge termination; Field plate

1. Introduction

Recently, in power device applications, attention has been focused on diamonds because of their superior material properties such as a large bandgap (5.5 eV), high critical electric field (5.7 to 20 MV/cm), high carrier mobility (3800 $cm^2/(V\ s)$ for holes, 4500 $cm^2/(V\ s)$ for electrons), and a high thermal conductivity (2200 W/(m K), highest among all materials) [1–4]. According to Baliga's figure of merit (BFOM, a standard indicator for studying power semiconductor materials), there are many advantages of using diamonds as a power device ($BFOM_{DIAMOND} = 44{,}000 > BFOM_{SiC} = 630 > BFOM_{Si} = 1$) [4]. These features are important under extreme conditions of semiconductor operation, such as high voltages and high temperatures. Very high breakdown field of diamond Schottky barrier diodes (SBDs) [2,3] have been reported; however, the breakdown field is usually smaller than 2 MV/cm, which is significantly low as compared with the commonly accepted limit of breakdown fields in diamond [5–7]. Recently, a higher breakdown field of 3.1 MV/cm has been confirmed [8], and further improvements are expected in the near future.

Edge termination is a crucial technology for maximizing the performance of power devices. In particular, an electric field concentration at a Schottky-metal edge is considered as a critical factor in diamond SBDs [9,10]. Several methods have been used for maximizing the performance of power Si and SiC devices, for example, field plate structure, guard ring, and junction termination extension (JTE) techniques [11,12]. Among these, the field plate structure technique is a potential candidate for diamond power devices since the surface of the diamond will be passivated. This technique has been used in conventional semiconductor manufacturing processes because of its relative simplicity. Additionally, it does not cause implantation defects that are caused by other methods [13]; such defects on diamond surfaces often result in current leakage. Recently, Brezeanu et al. have developed a ramp-type field plate structure for M-i-P diodes [14]. However, that was less effective than theoretically, estimated effect. That may because of interface issues including band offset. In this paper, the optimization of electric field edge termination techniques for p-type diamond SBDs are systematically studied and discussed in terms of reverse breakdown properties. Electric breakdown and the reliability of diamond power devices comprising oxides/dielectrics are also discussed with a concept of band offset. Although the study described here is performed for oxygen-terminated p-type diamond Schottky barrier diodes, it can easily be extended to n-type diamond devices as well.

1.1. Models

The fundamental structures used for device simulation are the conventional vertical-type SBDs, which are shown in Fig. 1. As a

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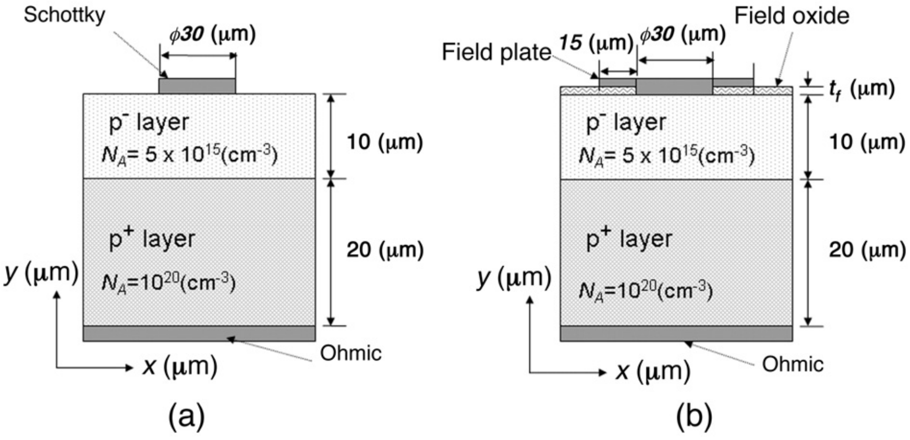

Fig. 1. Fundamental structure of diamond Schottky barrier diodes (cross-sectional views).

semiconductor, the physical properties of diamond are under investigation; thus, we employed recent physical parameters, with the exception of factors governing impact ionization. For the structure shown in Fig. 1(a), the breakdown voltage was set to approximately 880 V, with the arbitrary impact ionization factors set according to the model of Overstraeten and Man with regard

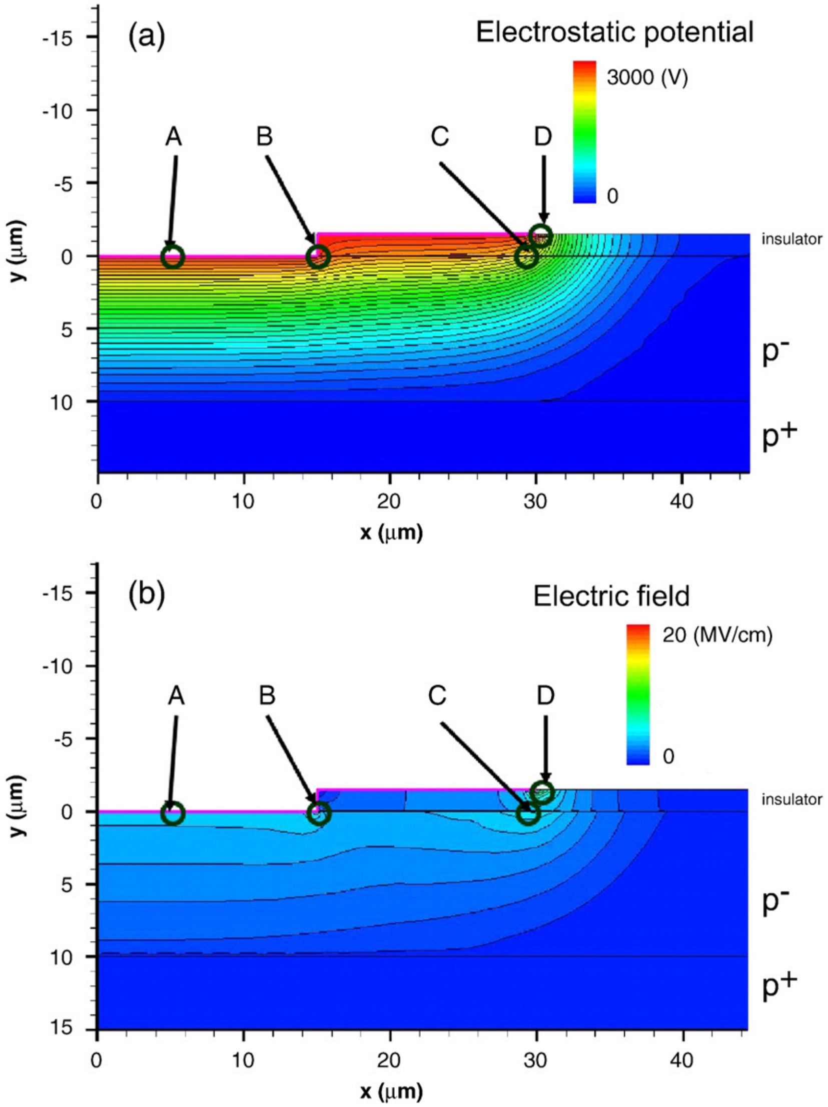

Fig. 2. The distribution of the (a) electrostatic potential and (b) electric field for an SBD with a field plate structure. Point B is the Schottky contact edge. Point C is a field concentration area in the diamond underneath the field plate edge. *D* is a field concentration point at the field plate edge in the insulator.

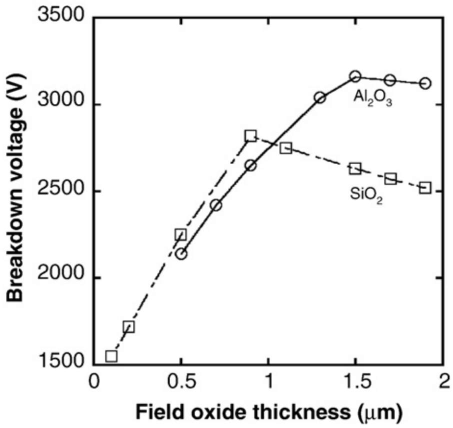

Fig. 3. Breakdown characteristics for edge terminations.

to electron-hole generation [15]. The structures used in this study were based on the doping concentrations of [B]~5×10^{15} and [B] ~10^{20} cm^{-3} for the drift region p−epilayer and the low-resistivity contact p+layer, respectively. These concentrations were easily obtained in our experiments. The Schottky contacts had a diameter, Ws, of 30 μm, which was obtained from a typical number of nonepitaxial crystallites [9,16], and the barrier height was set to 2.5 eV [9]. Thus, the breakdown mechanism involves a tunneling effect at the interface between the metal and the diamond. The dielectric constant of diamond is 5.7. Fig. 1(b) gives a simulation model of SBDs with high-voltage structures. The optimized metal overlap distance (field plate length) was set to 15 μm, which was considerably greater than the thickness of the epilayer. A two dimensional numerical simulation package known as Sentaurus Device® was used to simulate the following:

(I) Field plating with SiO_2 as the field material/oxide (k=3.9).
(II) Field plating with Al_2O_3 as the field material/oxide (k=8.7).
(III) Comparison of optimum structures for (a) and (b) at a reverse bias of 1500 V.

To reduce the calculation time, we folded the model at the center of the x axis. We set the breakdown point at 10^{-4} A/cm^2 for an abrupt increase in the current density. (I) and (II) were simulated to determine the appropriate thicknesses of the oxides because we need to prepare the field oxide with the minimum possible thickness. (III) was simulated for comparing the abovementioned field plate structures.

2. Results and discussion

Fig. 2 shows the distribution of the electrostatic potential and electric field for an SBD with a field plate structure. It can be clearly observed that the device suffers from corner breakdown due to an enhancement in the electric field at the corners. Hereafter, we mainly consider the electric field because an electric field crowding is as a result of potential crowdings. There are four important points in the SBD and they are labeled as A, B, C, and D. A is the center of the Schottky contact. B, C, and D are the points at which electric field peaks appear.

2.1. (I) Field plating with SiO_2 as a field oxide (low k for diamond)

The most widely used field oxide for conventional semiconductors such as Si and SiC is SiO_2. We therefore optimized the field plate structure by using SiO_2 for the diamond SBDs. The devices' breakdown voltages are plotted in Fig. 3(a) against their oxide thicknesses without taking into account the oxide breakdown. The maximum breakdown voltage of 2850 V was obtained at an oxide thickness of 0.85 μm. However, the maximum electric field in SiO_2 was 14.5 MV/cm at the field plate edge D. If we consider the oxide breakdown field, this value should generally be maintained below 10 MV/cm to ensure the reliability of the oxide. In Si power devices, this is not a problem since the critical electric field of Si is 0.3 MV/cm, that is, breakdown occurs well before the electric field inside SiO_2 approaches 10 MV/cm. Because the critical field of diamond is almost two orders larger than that of Si, edge terminations with SiO_2 suffer from an extremely high electric field inside SiO_2, thereby causing premature breakdown.

2.2. (II) Field plating with Al_2O_3 as a field oxide (high k for diamond)

Next, we used an Al_2O_3 layer as the field oxide. In this case, the relation of the dielectric constant between the semiconductor and the oxide was opposite. We expected a decrease in the electric field strength in the oxides in keeping with Gauss' law and hence an improvement in the device breakdown voltage. This structure was studied in detail with a field plate length of 15 μm. In Fig. 3(b), the breakdown voltage is plotted as a function of the field oxide thickness and compared with the plot for the case of SiO_2 field oxide. It can be observed that an increase in the thickness of Al_2O_3 up to 1.5 μm increases the device breakdown voltage. A breakdown voltage of 3200 V can be achieved at a field oxide thickness of 1.5 μm. Additionally, the maximum electric field in the field oxide is 10 MV/cm at the field plate edge D, whereas in the case of the field plate structure

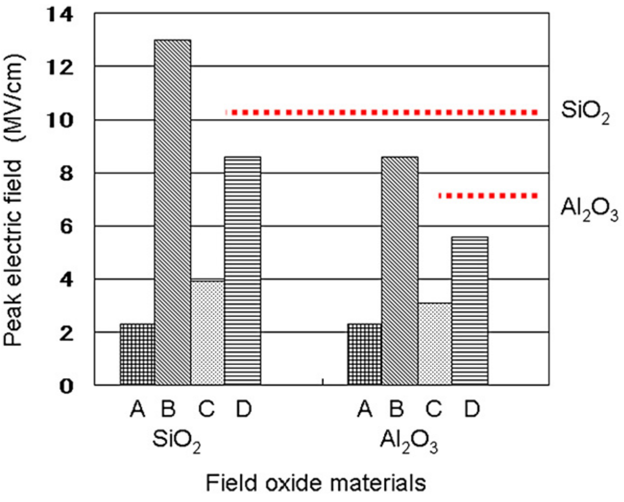

Fig. 4. Impact of field plate structures. All the values are obtained for the electric field distributions at a reverse bias of 1500 V in SBDs with optimized thicknesses of the field oxides (SiO_2 and Al_2O_3).

with SiO_2 under the same conditions, the maximum electric field in the field oxide exceeds 10 MV/cm. The electric field crowding at the metal corner is reduced by employing Al_2O_3 as the insulator, which is a dielectric with a relatively high *k*. The depletion region spreads along the surface of the field plate with a reduction in potential crowding.

2.3. (III) Comparison of optimum structures for (I) and (II) at a reverse bias of 1500 V

Fig. 4 shows the impact of both the SBDs with the SiO_2 field plating and those with the Al_2O_3 field plating in optimum structures. The applied reverse bias is 1500 V, which is required for 1200-V class diodes [17]. The electric field concentration at the edge of the field plate of SiO_2 (D) is 8.6 MV/cm, while that at the field plate corner of Al_2O_3 is 5.6 MV/cm. Therefore, breakdown phenomena do not occur at this potential for both cases. However, the effect on an averaging of the electric field distribution is dramatically modified in the case of the field plate with Al_2O_3. Furthermore, the electric field inside the diamond is also significantly smaller (approximately 5 MV/cm) than that in an SBD with SiO_2 as the field oxide. This leads to a larger breakdown voltage for a device. In the case of Si and SiC, Al_2O_3 should be treated as a low-*k* material according to Gauss's law $E_{\mathrm{SiO2}}=(\varepsilon_{\mathrm{semiconductor}}/\varepsilon_{\mathrm{SiO2}})E_{\mathrm{semiconductor}}$. In the case of diamond with SiO_2 as the field oxide, the relation $E_{\mathrm{SiO2}}\sim 1.4E_{\mathrm{diamond}}$ is obtained. Further, for SiC and Si, $E_{\mathrm{SiO2}}\sim 3\ E_{\mathrm{SiC/Si}}$. In the case of diamond with Al_2O_3 as the field oxide, E_{Al2O3} is nearly $0.5E_{\mathrm{diamond}}$. At the same time, an electric field distribution of the form of a loose curve is established for the diamond SBD.

According to the simple calculation discussed above, it appears that a higher dielectric constant *k* results in a lower electric field concentration. For diamond devices, the small dielectric constant of diamond means that there are many possible candidates to reduce the electric field concentration, which are known to be high-*k* dielectrics. The concept of using high-*k* dielectrics as field oxides agrees with Brezeanu's concept [18]. High-*k* dielectrics provide relatively uniform electric potential curves. Although the electric field can be reduced, high-*k* dielectrics still have premature breakdown issues [18,19]. And, from the simple relationship between the energy levels of diamond and oxides containing high-*k* dielectrics, band offset problems arise. In the case of an oxygen-terminated p-type diamond SBD with HfO_2-field oxide, because of the diamond's positive electron affinity, the barrier for holes is very small (<0.5 eV). Therefore, tunneling may occur even at low electric fields. Thus, for the reliable operation of diamond Schottky barrier diodes, the dielectrics must be carefully chosen. Among well known dielectrics, only Al_2O_3 has a large band offset for oxygen-terminated diamonds [20,21], which blocks the hole transportation under reverse bias. Furthermore, in the cases of Si_3N_4 and HfO_2, they can not be applied for n-type diamond. Because, their conduction band offsets against oxygen-terminated diamond are smaller than zero. In contrast, Al_2O_3 has a finite band offset even for electrons against oxygen-terminated diamond. Therefore, this can easily be extended to n-type diamond devices as well. Additionally, the high thermal conductivity of Al_2O_3 (30 W/(m K)) is also an attractive characteristic for a junction reliability. Considering the points outlined above, we believe that Al_2O_3 is one of the most promising field materials for diamond power devices.

3. Conclusion

For diamond power rectifiers to mature into a reliable manufacturing technology, attention must be paid to the design and implementation of edge termination methods that maximize the reverse breakdown voltage. In this paper, field plate termination techniques were investigated, and materials with a low/high dielectric constant were compared for being used as field insulators for diamond power devices. It was demonstrated that all the existing field plate terminations are subjected to severe field crowding problems in the field material. When the breakdown and reliability of field materials are considered, existing field plate termination techniques yield device breakdown voltages that are generally unsatisfactory. We proposed a field plate structure with Al_2O_3 as a field oxide, and for the first time, we took into account the band offset of diamond with dielectrics for field plate structures. Further investigations of high-*k* dielectrics and pn junction for use in junction termination are necessary; additionally, the fabrication and thermal management of these junction termination should also be studied.

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