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High-Temperature Diamond SBDs

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1. Introduction

In recent years, wide-gap semiconductor materials such as SiC, GaN and diamond have attracted much attention due to the strong requirement for saving energy. Compared with other wide-gap materials, diamond is the most promising material for future high power and high temperature devices because of its superior material properties. Based on the high saturation carrier velocity and high breakdown field, Baliga's figure of merit (BFOM) is 150, 12 and 10 times higher than Si, SiC and GaN, respectively [1]. Up to now, high power or high temperature Schottky barrier diodes (SBDs) have been demonstrated on single crystalline diamond [2-5]. One of the big advantages of diamond power device is the low-loss operation with long-term stability under the high temperature conditions. In this paper, we give an overview of current state of diamond power devices for high temperature applications.

2. Simulation of Device performance at high T

As mentioned above, due to the superior material properties, diamond shows high BFOM. Here, BFOM is estimated on the assumption that the doped impurities are fully activated at room temperature; however, the low dielectric constant of diamonds leads to a deeper impurity level (p-type: E_A=0.37eV, boron); as a result, the carrier activity at room temperature is less than 10 %. Subsequently, analytical methods utilizing a deep activation model are required to estimate the effective Baliga limit.

Figure 1 shows the trade-off characteristics between blocking voltage (BV_{BD}) and specific on-resistance ($R_{on}S$) for diamond SBDs with various temperatures with concerning the deep activation model. Because of the high E_A, device performance of diamond is almost comparable to that of SiC's within a 0.5-3kV range at room temperature. On the other hand, diamond reveals its advantages across all voltage ranges under high temperature conditions, because of increase in carrier activation. The best performance of diamond SBD is expected at the operation temperature at around 500 K. Low-loss high-power devices without cooling system are expected. Recently, high performance diamond SBDs have been reported with higher Baliga limit as shown in fig. 1. Improvement in breakdown field and optimization of the doping concentration are required to reach the theoretical limit of diamond SBDs.

3. High temperature characteristics of diamond SBD

One of the important advantages of diamond SBD is the wide-range controllability of Schottky barrier height (SBH)

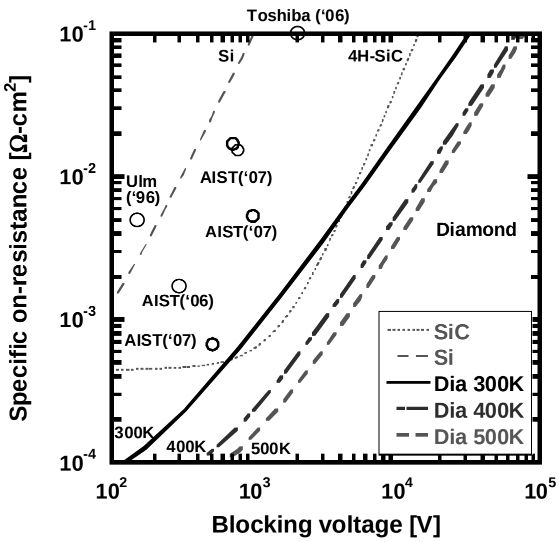

Fig. 1: Estimated $R_{on}S$ vs. BV_{BD} of diamond SBDs with various operation temperatures.

from 1.0 to 3.4 eV. When the reverse operation of diamond power device is limited due to the increase of leakage current by the thermionic field-emission (TFE), high SBH is advantageous to the high blocking voltage applications [6, 7]. High SBH is also advantageous to high temperature low leakage operation of SBDs.

Figure 2 (a) and (b) show the forward and reverse leakage current characteristics of the diamond pseudo-vertical SBD (pVSBD) as a function of the reverse electrical field (E_{1D}) at various temperatures. Mo is utilized for the Schottky metal. SBH of the pVSBD is extracted to be 1.9 eV from the forward characteristics utilizing thermionic emission (TE) model. The reverse leakage current density (J_L) is within the measurement limit when E_{1D} is below 1.5 MV/cm at room temperature. J_L starts increasing at around 1.5 MV/cm and reaches 10 μA/cm^2 (>10^8 rectification) at 2 MV/cm. Increasing the operation temperature leads to an increase in the reverse leakage current; however, the current level is still low. This leakage current is 4 orders of magnitude lower than that of SiC SBDs [8].

The leakage current characteristics of the diamond SBD cannot be explained by using TE model. TFE model is more suitable for modeling the leakage current of the diamond SBD. Using effective barrier height (V_{bn}) equal to 1.29 eV as a fitting parameter, the leakage characteristics are modeled, as shown in Fig. 2(b). The TFE model shows a good agreement with the experimental results at the ob-

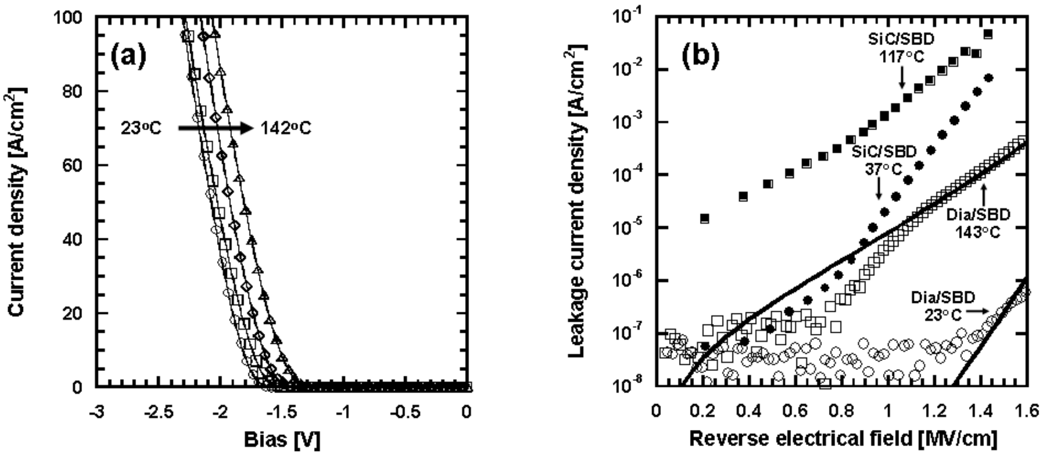

Fig. 2: (a) Forward and (b) reverse leakage characteristics of diamond SBD at elevated temperatures. Leakage characteristics of SiC/SBD is shown in (b) for comparison.

served temperatures in the field range of 1.0–1.5 MV/cm.

To realize high temperature diamond power device, development of stable metal/diamond interface is the key issue. In this study, the stability of metals (Al, Ni, Pt, Ir and Ru) and diamond interfaces were characterized using pVSBDs. The annealing process was carried under the vacuum condition ($<10^{-5}$ Pa) at 400 ^{o}C. pVSBDs were characterized at room temperature after predetermined annealing time up to 1500 hr.

Estimated SBHs as a function of annealing time are summarized in Fig. 3. Because of the carbide formation at the interface of Al/diamond or Ni/diamond, the decrease of SBH is observed in Al and Ni SBDs. Al or Ni are known as the metals to form carbides on diamond easily. Small amount of carbide layer formation is enough to change the carrier transport of SBDs especially on reverse condition. On the other hand, Pt, Ir or Ru are the metals hardly form

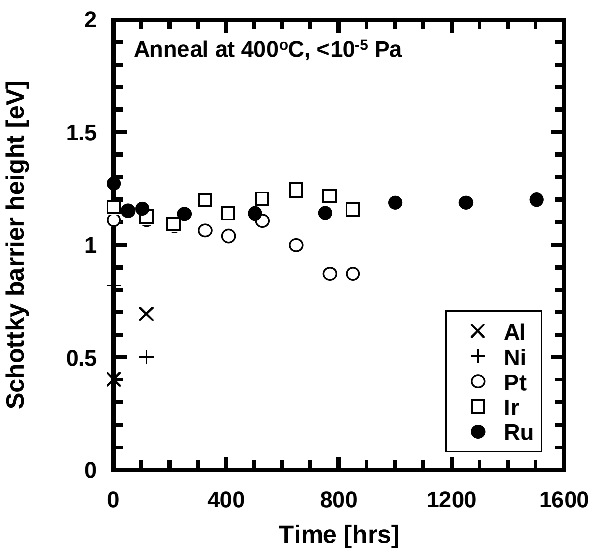

Fig. 3: Schottky barrier height of diamond pVSBDs after 400 ^{o}C annealing.

carbides on diamond even at 1000 K. Superior thermal stability of Ru/diamond pVSBDs up to 1500h has been demonstrated at present [9]. After initial stabilization, changes of the parameters in Ru SBDs such as SBH or ideality factor from 250 to 1500 h for 400 ^{o}C were less than 2.5 %. Ir/diamond or Pt/diamond interface also shows thermal stability under the annealing conditions of 500oC/250h or 800oC/110h.

4. Conclusions

The potential of diamond power devices for high temperature application have been demonstrated. Baliga limit analysis of diamond power device indicate that the advantage of diamond power device is expected when the operation temperature is higher than 400 K. Because of high SBH, low leakage current has been realized even at the temperature. Excellent thermal stability on Ru/diamond interface has been demonstrated at 400 ^{o}C. High temperature and low loss operation of diamond power devices are expected with high reliability.

Acknowledgements

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References

[1] B. J. Baliga, IEEE Electron Device Lett., 10 (1989) 455.
[2] J. E. Butler et al., Semicond. Sci. Technol. 18 (2003) S67.
[3] W. Ebert et al., Diam. Relat. Mater., 6 (1997) 329.
[4] S. J. Rashid et al., Diam. Relat. Mater., 15 (2006) 317.
[5] H. Umezawa et al., Diam. Relat. Mater., 15 (2006) 1949.
[6] H.Umezawa et al., Apl. Phys. Lett. 90, (2007) 073506.
[7] T. Teraji et al., Jpn. J. Appl. Phys., 46 (2007) L196.
[8] T. Hatakeyama et al., Mater. Sci. Forum, 433-436, (2003) 831
[9] K. Ikeda et al., App. Phys. Lett., 2 (2009) 011202.