High temperature switching operation of a power diamond Schottky barrier diode

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Abstract: Diamond is considered to be the most promising wide band gap semiconductor material for the fabrication of power switching devices with respect to the figure of merit. The authors have developed a high voltage and high current diamond Schottky barrier diode (SBD). This paper evaluates the static and dynamic electrical performance of the developed diamond SBD as a power switching device. The experimental results obtained under different operating conditions validate the fast switching, unipolar device characteristics, and high temperature operation capability of the developed diamond SBD.

Keywords: diamond Schottky barrier diode, switching characteristics, diamond semiconductor

Classification: Electron devices, circuits, and systems

References

1 Introduction

For wide band gap semiconductor materials, much focus has been on finding ways to overcome the limitation of Si power switching devices by raising the breakdown voltage, reducing the conduction and switching losses, raising the switching frequency, and raising the operating temperature. There have been many reports on the high breakdown voltage, low conduction loss, fast switching, and high temperature operation of power switching devices that utilize SiC and GaN semiconductors [1, 2]. Diamond semiconductors have a superior index for the figure of merit when compared to other wide band gap semiconductor materials [3]. Therefore, power switching devices are expected to have superior performance when utilizing diamond as the semiconductor material. There are several reports on the development of electronic devices using diamond semiconductors, but there are few reports involving power switching devices. Reference [4, 5] reported the static rectification characteristics of the p-type diamond Schottky barrier diode (SBD) and its temperature dependency; however, it did not evaluate the dynamic switching characteristics. The authors reported the dynamic switching characteristics of high voltage diamond SBD at room temperature in reference [6], but the conduction current was small (~100 mA) because of the small active area of the device. Recently, the authors developed a high voltage (200 V) and high current (0.8 A) p-type diamond SBD with a relatively large active area. This paper reports the static and dynamic characteristics of the developed diamond SBD and its temperature dependency. The operation properties of majority carrier device, fast switching capability, and high temperature operation were confirmed for the developed device.

Section 2 gives the specification and process of the developed diamond SBD. Section 3 evaluates the static current and voltage (I–V) characteristics and its temperature dependency for the developed device. Section 4 validates the performance of the majority carrier device based on the experimental result of fast switching operation, and clarifies the switching capability under high temperature conditions. Finally, section 5 concludes this study.
2 Device specification and process

Fig. 1 (f) shows the overview of developed diamond SBD. Diamond vertical Schottky barrier diode is fabricated on single crystal p− homoepitaxial film on p+ substrate. Firstly, p-type drift layer with 12 μm thickness is deposited as a drift layer by chemical vapor deposition (CVD) on low resistive p+-type high-pressure and high-temperature synthesized (HPHT) single crystalline diamond (001) substrate. The carbon sources of the growth are CH4 and CO2 diluted by hydrogen. The CH4 +CO 2/H2 ratio, O/C, the gas pressure, the plasma power and the growth temperature used are 3.8%, 0.4, 120 Torr, 3.9 kW, and 950°C, respectively. To control the acceptor concentration (boron), 0.2-0.5 ppm of tri-methyl-boron (TMB) is added during the growth. At the end of the growth, TMB gas flow is stopped to decrease the doping concentration at the surface. The grown film is cleaned by acid treatments to remove graphitic or amorphous layer to suppress the unintentional leakage current path. The Ohmic contact (Au 100 nm/Pt 30 nm/Ti 30 nm) is formed on the backside of the substrate. After the surface oxidation by UV/O3, Al2O3 field-plate (FP) is fabricated by photolithography and lift-off technique. Al2O3 with 1.5 μm thickness is deposited by r.f. sputtering. The Schottky electrodes of (Au 200 nm/Mo 30 nm) are fabricated by photolithography and lift-off technique. The FP length is 50 μm. The size of Schottky electrode is 1000 μm and the active area is 0.97 mm2 (1000 μm × 1000 μm).

3 Static I–V characteristics and temperature dependency

Fig. 1 (a) shows the forward conduction current and voltage (I–V) characteristics of the developed diamond SBD from room temperature to high temperature (250°C). The knee voltage is approximately 1 V. The forward voltage drop for the rated forward current (0.8 A) is 4 V at room temperature, and decreases as the temperature rises. The terminal voltage $v_d$ and current $i_d$ characteristics of a diode can be expressed by Eq. (1).

$$
\begin{align*}
    v_d &= v_c + i_d R_s \\
    i_d &= I_s \left( e^{\frac{v_c}{nqT}} - 1 \right)
\end{align*}
$$

where, $R_s[\Omega]$ is the series resistance, $n$ is the emission factor, $I_s[A]$ is the saturation current, $k$ is the Boltzmann constant, $q[C]$ is the unit charge, $T[K]$ is the absolute temperature, and $v_c[V]$ is the junction voltage.

The temperature characteristics of the saturation current $I_s$ and the emission factor $n$ are extracted from the I–V characteristics in the low current region (10 nA < $i_d$ < 1 mA), as shown in Figs. 1(b) and (c), respectively. Although the saturation current in Fig. 1 (b) increases for high temperatures, it retains a sufficiently low value. There is no significant slope change found in the low current region of Fig. 1 (a). The extracted emission factor in Fig. 1 (c) remains at approximately 1 irrespective of temperature. However, it underruns 1 for the temperature higher than 373 K. The one possible cause is that the actual junction temperature is lower than the calculated junction.
temperature of the hot chuck in the measurement setup. The precise junction temperature measurement is left as a future work.

Fig. 1 (d) shows the temperature characteristics of the series resistance, which is extracted from the I–V characteristics in the high current region ($i_c > 0.6 \text{ A}$). The series resistance becomes a minimum at approximately 200°C. The mobility of the majority carrier in the semiconductor that governs the conduction of the unipolar device decreases as temperature increases and results in an increase of the series resistance. However, the experimental results do not correspond to the simple mobility degradation with temperature. Therefore, the activation of trapped carriers at a deep level due to increasing temperature is inferred from the decrement of the series resistance with temperature rise (< 200°C). In general, all carriers are activated at high temperatures (> 200°C), and the series resistance is affected by the reduced mobility.
The relation between saturation current $I_s$ and Schottky barrier height $\phi_B$ is expressed by eq. (2).

$$I_s = S A^* T^2 e^{-\frac{\phi_B}{kT}},$$

where, $S$[cm$^2$] is the device active area and $A^*$[Acm$^{-2}$K$^{-2}$] is the effective Richardson’s constant. The calculated Schottky barrier height from eq. (2) with the use of effective Richardson constant $A^* = 90$ Acm$^{-2}$K$^{-2}$ in reference [10] is $\phi_B = 1.2$ eV at room temperature, which coincide with the value reported in reference [5]. Fig. 1 (e) gives the Arrhenius plot of the extracted saturation current $I_s$, and approximately linear relationship is confirmed. The Schottky barrier height evaluated with the slope of collinear approximation is $\phi_B = 0.479$ eV. The difference is estimated as the saturation current does not increase with temperature as expected from eq. (2).

The reverse current blocking capability is indispensable for the switching operation of diodes. The I–V characteristics in the reverse blocking condition of the diode at different temperatures are shown in Fig. 2 (a). A 2 $\mu$A leakage current flows through the diode at room temperature for the rated reverse blocking voltage of 200 V. Fig. 2 (b) shows the temperature characteristics of the blocking voltage for a 2 $\mu$A leakage current. The leakage current in blocking condition considerably larger than the current originated from thermionic emission. The avalanche current multiplication is not observed in the reverse I–V characteristics, and the leakage current is estimated as the tunneling phenomenon stemming from thermionic field emission, whose details are discussed further in references [7, 8, 9]. The result shows that the diode retains a sufficiently high blocking voltage for high temperatures, e.g., $-160$ V for $250^\circ$C.

### 4 Switching characteristics

Fig. 3 shows the switching behavior of the developed diamond SBD in turn-off operation. The evaluation was performed for the experimental result that was obtained using the double pulse measurement method [6]. Figs. 3(a) and (b) show the terminal current and voltage response of the diode, respectively, for the different turn-off speeds ($di/dt$), which are regulated by
the switching speed of the driving MOSFET using its gate resistance. The results for three different values of di/dt (60 A/μs, 50 A/μs, and 30 A/μs) are shown. However, the peak value of the current in the reverse direction increases for higher di/dt in the turn-off transition, but the settling time of the recovery phenomenon decreases. This difference is reflected in the build-up of the terminal voltage of the diode, which results in a faster build-up of the blocking voltage for a higher di/dt switching operation. The recovery charge calculated using the time integral of the recovery current are 5.42 nC, 5.49 nC and 5.54 nC, respectively for 60 A/μs, 50 A/μs, and 30 A/μs of di/dt. They hardly differ with the turn off switching speed. This result confirms that the recovery current for the turn-off operation is due to the depleted majority carrier in the drift region of the diode.

Figs. 3 (c) and (d) show the voltage and current of the diode, respectively, for the different temperatures in the turn-off operation with the same forward conduction current, turn-off speed (di/dt), and reverse blocking voltage. The peak value of the reverse direction current and the amplitude of the ringing oscillation increased at higher temperatures. The recovery charge calculated using the time integral of the recovery current are 3.41 nC, 3.61 nC, 4.10 nC, 4.17 nC, and 4.24 nC, respectively for 298 K, 348 K, 398 K, 448 K, 498 K and 523 K. The evacuated charge at low temperature is slightly smaller than at high temperature, but it does not give significant increment in high temperature. Therefore, it cannot be explained with the minority carrier injection, and is deduced as the loss stemming from higher resistance in low temperature. The difference in the ringing oscillation is explained using the change in damping and overshoot of the second-order oscillation system, which consists
of the terminal capacitance and parasitic inductance in the circuit. The parasitic inductance in the measurement circuit is larger than the actual power conversion circuit because the circuit wiring is extended for the measurement of the current in the diode under high temperature conditions. This change results from the variation of the series resistance $R_s$ in the diode with temperature. Therefore, the recovery charge calculated from the time integral of the recovery current does not change with temperature. The buildup of the blocking voltage with the different temperatures also coincides with the subtraction of the oscillating component from the voltage response shown in Fig. 3 (d).

The rectification property of the transition between the forward conducting condition and reverse blocking condition, and the fast switching capability are validated for the developed diamond SBD from room temperature (25°C) to high temperature (250°C).

5 Conclusion

This paper evaluated the static and dynamic current and voltage characteristics and their temperature dependency for the developed high voltage and high current diamond SBD. The results confirmed the majority carrier device characteristics of the developed power diamond SBD from room temperature to high temperature (250°C). The series resistance of the diode becomes a minimum at approximately 200°C because of carrier activation by temperature elevation, which is trapped at a deep level. The fast switching capability in the rectification operation of the developed diode is guaranteed from room temperature to high temperature. The presented results show the feasibility of realizing power switching devices that utilize diamond as the wide band gap semiconductor material.

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