Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp189-190

D-1-06 (Late News)

# Diamond Schottky Barrier Diodes Fabricated on Heteroepitaxial Substrates

Phongsaphak Sittimart[1,2], Shinya Ohmagari[1] and Tsuyoshi Yoshitake[2]

[1] AIST
807-1 Shuku-machi, Tosu, Saga 841-0052, Japan
Phone: +81-92-583-8845 E-mail: phongsaphak_sittimart@kyudai.jp
[2] Kyushu Univ.
6-1 Kasuga-koen, Kasuga, Fukuoka 816-8580, Japan
Phone: +81-92-583-8845

**Abstract**

**Pseudo-vertical diamond Schottky barrier diodes (SBDs) were fabricated on heteroepitaxial substrates. In this study, metal impurity incorporated buffer layer to suppress killer defects was inserted. SBDs exhibited large rectifying ratio and highly uniform properties. High breakdown voltage with sudden increase in current was observed at 375 V, which is at least 6 times greater than conventional SBDs on heteroepitaxial diamond using similar device configurations. In order to discuss the carrier transport mechanism at metal-semiconductor interface, forward characteristics were fitted by thermionic emission (TE) theory and Tung's model. From the temperature-dependence, ideality factor (*n*) and Schottky barrier height ($\phi_B$) were modified from 1.56 to 1.10 (0.96 to 1.27 eV for $\phi_B$) with increasing temperature from 300 to 480 K. The standard deviation of $\phi_B$ was estimated to be 0.21 eV. These results indicating that heteroepitaxial substrates are promising alternative for large-area low-cost diamond electronics.**

## 1. Introduction

Diamond is a promising candidate of ultrawide bandgap semiconductors for application in next generation power and high-frequency electronics with low switching loss. This is owing to its superior physical features, high electron and hole mobilities (4500 and 3800 $cm^2/Vs$, respectively), high breakdown strength (10 MV/cm), high thermal conductivity (2200 W/mK), in addition to the high chemical inertness and thermal durability. So far, superior device performance has been reported using Schottky barrier diodes (SBDs) as well as *pn* rectifiers. However, most of their devices were tested using high-pressure and high-temperature (HPHT)-grown diamond substrates, in which typical sizes is 2-10 mm square, making device processing difficult. Heteroepitaxial diamond is therefore interesting alternative for large-area low-cost substrates. The large crystal domains up to 3.5 inch have been demonstrated [1]. Device performance of SBDs on heteroepitaxial diamond have been also reported [2],[3]. In their reports, good device properties with large rectifying actions were demonstrated, however in-plane uniformity was obviously degraded. Ohmic-like leakage current was observed when the electrode size increased. This is presumably due to the high density of dislocations (~$10^8$ $cm^{-2}$), which is at least three to four orders of magnitude larger than HPHT substrates. Recently, Ohmagari *et al.* demonstrated a novel technique to suppress killer defects by in-situ doping of metal impurities, called metal-assisted termination (MAT) [4]. The device properties and in-plane uniformity of SBDs fabricated on HPHT substrates and CVD-grown wafers were improved after insertion of MAT buffer layer.

In this study, SBDs properties on heteroepitaxial substrates after insertion of MAT buffer layer was investigated. Highly uniform device properties with large rectifying actions were demonstrated. In addition, diode parameters, ideality factor (*n*) and Schottky barrier height ($\phi_B$) were evaluated from the temperature dependence of electrical properties.

## 2. Experimental Details

Pseudo-vertical SBDs were fabricated on commercially available semi-insulative heteroepitaxial substrates (AUDIATEC, Germany). At first, heavily B-doped (p+) contact layer involving W impurity was prepared by hot-filament chemical vapor deposition. The typical B concentration and W impurities were $10^{20}$ and $10^{19}$ $cm^{-3}$, respectively. This contact layer acts as MAT buffer layer to suppress killer defects [4]. Then, lightly B-doped (p–) layer was grown by microwave plasma-enhanced CVD. The B concentration and film thickness were ~$10^{16}$ $cm^{-3}$ and 1 μm, respectively. Ti/Mo/Au Ohmic electrodes and Mo/Au Schottky contacts were deposited by electron-beam evaporator. The temperature dependence of electrical properties were investigated by microprober station using a source meter (KEITHLEY 2612) from 300 to 480 K. Diode parameters were evaluated based on thermionic emission (TE) theory. Standard deviation of $\phi_B$ inhomogeneity was estimated from Tung's model.

## 3. Results and Discussion

Figure 1 shows superimposed *I-V* characteristics of 20 SBDs. Schottky contacts were prepared on identical substrate surface, and in-plane uniformity was investigated. The diameter of Schottky contacts were 100 μm. All diodes exhibited good properties with a high rectifying ratio surpassing 8 orders at voltage between ±8 V. Low leakage current below the detection limit were observed among examined diodes, indicating high in-plane uniformity.

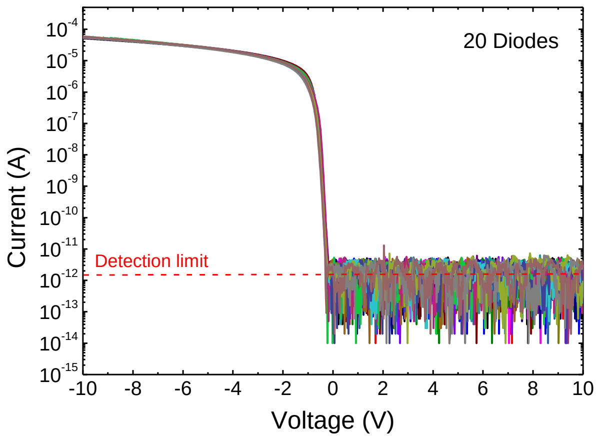


Fig. 1. *I*-*V* characteristics of 20 SBDs fabricated on heteroepitaxial substrate using MAT buffer layer.

Figure 2 presents reverse voltage characteristics. The diode showed clear breakdown behavior with sudden increase in current at 375 V. Kawashima *et al.* evaluated SBDs characteristics of heteroepitaxial diamond on Ir/Si system with similar B concentration and drift layer thickness to our diodes. They demonstrated breakdown behavior at 52 V (~1 MV/cm). Our diode exhibited at least 6 times greater breakdown voltage.

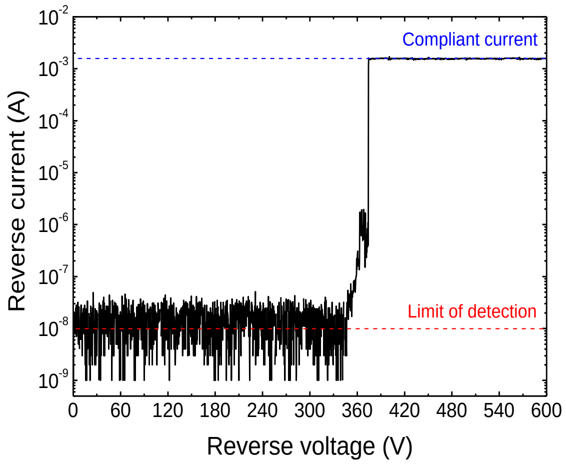


Fig. 2. Reverse voltage characteristics of diamond SBDs fabricated on heteroepitaxial substrate.

Figure 3 shows temperature dependence of $n$ and $\phi_B$, estimated from TE theory. The $n$ value was decreased from 1.5 to 1.1, while the $\phi_B$ increased from 0.96 to 1.27 eV with increasing temperature from 300 to 480K. Phenomenon for temperature dependence of $n$ and $\phi_B$ values was because of the inhomogeneous $\phi_B$. To further investigate the $\phi_B$ inhomogeneity for the fabricated SBDs, Tung's model was applied. The standard deviation ($\sigma$) of $\phi_B$, which is important parameter to discuss Schottky barrier inhomogeneity, was extracted. The $\sigma$ value was estimated to be 0.212, slightly larger than SBDs comprising W/4H-SiC (0.092) and GaN (0.143), and close to the reported value of diamond (0.227). The imperfection of metal-Schottky (MS) interface is suggested as origin inducing larger $\sigma$. Thus, there is a room for improvement of SBD characteristics on heteroepitaxial substrates. Selection of Schottky contacts to realize homogeneous MS interface is key issue to reduce $\sigma$.

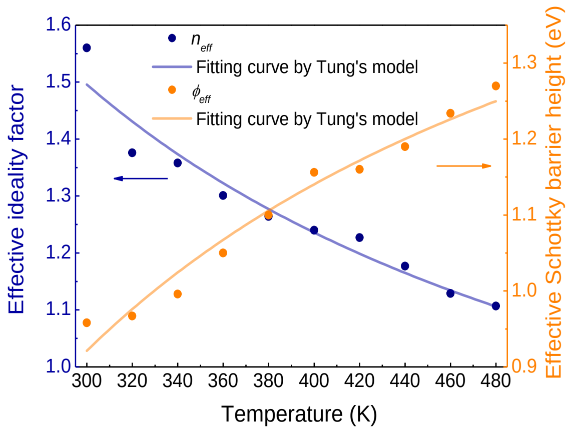


Fig. 3. Temperature-dependence of $n$ and $\phi_B$.

## 4. Conclusions

In this work, we investigated temperature dependence of pseudo-vertical diamond SBDs fabricated on heteroepitaxial substrate utilizing MAT buffer layer. At room temperature, 20 SBDs showed a good rectifying action with rectification ratio exceeding 8 orders. Reverse voltage properties showed breakdown voltage of 375 V. Based on TE theory, $n$ value was 1.5 and $\phi_B$ was 0.96 eV at 300 K. Both parameters decreased and increased to be 1.1 and 1.27 eV at 480 K, respectively. Temperature dependence of $n$ and $\phi_B$ due to $\phi_B$ inhomogeneity was observed. By applying Tung's model based Gaussian distribution of $\phi_B$, $\sigma$ value was estimated to be 0.212.


## Acknowledgements

We would like to express sincere thanks to national institute of advanced industrial science and technology (AIST), Kyushu center, for all instrument used in the present work.


## References


[1] M. Schreck, S. Gsell, R. Brescia and M. Fischer, *Sci. Rep.* **7** (2017) 44462.

[2] H. Kawashima, H. Noguchi, T. Matsumoto, H. Kato, M. Ogura, T. Makino, S. Shirai, D. Takeuch, and S. Yamasaki, *Appl. Phys. Express* **8** (2015) 104103.

[3] T. Murooka, J. Yaita, T. Makino, M. Ogura, H. Kato, S. Yamasaki, M. Natal, S. E. Saddow, T. Iwasaki and M. Hatano, *IEEE Trans. Electron Devices* **67** (2020) 212.

[4] S. Ohmagari, H. Yamada, N. Tsubouchi, H. Umezawa, A. Chayahara, Y. Mokuno and D. Takeuchi, *Phys. status solidi A* **216** (2019) 1.