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Characterization of breakdown behavior of diamond SBDs using impact ionization coefficients

Khaled Driche[1,2,3,5], Hitoshi Umezawa[1,2,4], Gauthier Chicot[1,6], Nicolas Rouger [1,6] and Etienne Gheeraert[1,2,3]

[1] University Grenoble Alpes, F-38000 Grenoble, France
[2] CNRS, Inst. NEEL, F-38000 Grenoble, France
[3]University of Tsukuba, Tsukuba, Ibaraki, 305-8577, Japan
[4]Nat'l. Inst. Adv. Ind. Sci. Tech. (AIST), Ibaraki, Tsukuba, 305-8568, Japan
[5]Nat'l. Inst. Adv. Ind. Sci. Tech. (AIST), Ikeda, Osaka, 563-8577, Japan
[6]CNRS, G2Elab, F-38000 Grenoble, France

Corresponding author: khaled.driche@aist.go.jp

Abstract

Based on comparison between experimental on reverse operation limit of diamond-based power devices and simulated structures, we discuss the limits of impact ionization coefficients reported in the literature. Additional to doping concentration and thickness of drift layer, geometrical optimized structure is needed to ensure better estimation of ionization rate parameters.

Introduction

Due to its outstanding electrical and thermal properties, diamond is a promising materials for the next power electronics. Diamond Schottky Barrier Diodes (SBDs) able to withstand up to 10 kV have been already reported [1, 2] and diamond Field Effect Transistors (FETs) are under investigation through MESFET [3] and MOS capacitor [4, 5]. However, the process to determine the reverse operation limits of diamond devices is still both experimentally and theoretically imprecise but is at present under study. Recently, Hiraiwa *et al* and Kamakura *et al* studied the avalanche breakdown process by extracting impact ionization coefficients (IIC) in Chynoweth's form from an arbitrary relationship between breakdown voltage and doping density [5] and from the high-field carrier transport using a full band Monte Carlo (FBMC) method based on *ab initio* calculations [6], respectively. Nevertheless, in order to bring out the best characteristics of diamond power electronic devices both experimental and simulated approaches have to converge. In this study, the reverse characteristics of both fabricated and simulated diamond SBDs for different temperature were investigated. The geometry of the structure plays a crucial role in determining the ionization rate parameters.

Experimental

Diamond pseudo-vertical SBD

Table I Devices parameters

[B]$_{p-}$ (cm^{-3})	2.8x10^{15}	5.6–10x10^{16}
[B]$_{p+}$ (cm^{-3})	> 2x10^{20}	> 10^{20}
p- thickness (µm)	0.96	1.2
p+ thickness (µm)	1.1	5
Ohmic metal	Ti/Pt/Au	Ti/Pt/Au
Schottky metal	Pt	Mo

The cross-sectional structure of the two fabricated diamond SBDs is shown in Fig. 1. The devices were fabricated on p$^-$/p$^+$ homoepitaxiallly grown diamond layers on Ib (001) HPHT diamond substrate. Table I encloses the details on boron doping levels [B], thicknesses of each layer determined by secondary ion mass spectroscopy (SIMS) and Schottky and ohmic metals for the two diodes. The surface of the p$^-$ diamond layer was terminated by oxygen. No edge-termination technique are utilized in these devices.

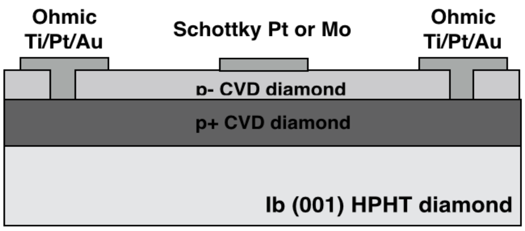

Fig. 1 Cross-sectional structure of fabricated diamond SBDs

Simulation

The fabricated devices described above were simulated using finite element simulation TCAD Silvaco software. The structures were a diamond vertical SBDs (vSBDs) implementing in one hand, the ionization coefficient reported by Hiraiwa *et al* and, in another hand, the ones reported by Kamakura *et al.* To reproduce the main parameter of the real devices, a diamond surface electron affinity was set to 1.7 eV corresponding to an O-terminated diamond surface and a Schottky Barrier Height (SBH) of 2.62 eV and 1.92 eV for Pt and Mo contact, respectively. The physical models used include incomplete ionization of acceptors, temperature and concentration dependent mobility [9], and avalanche impact ionization parameters for electrons n and holes p following Chynoweth's form shown in eq. (1).

$$\alpha_{n,p} = A_{n,p} \exp\left(-\frac{B_{n,p}}{|E|}\right) \qquad (1)$$

Parameters used for IIC are listed in table II. Mesh has been optimized for each simulation.

Table II Impact ionization coefficients (IIC)

	A_p	B_p	A_n	B_n
Units	cm^{-1}	V.cm^{-1}	cm^{-1}	V.cm^{-1}
Hiraiwa [5]	6.1x10^4	13.94x10^6	1.46x10^5	24x10^5
Kamakura [6]	4.2x10^6	58x10^6	3.7x10^6	21x10^6

Results and discussion

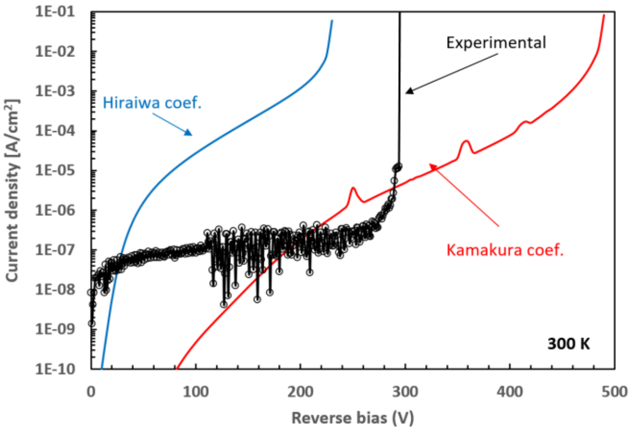

Fig. 2 a) Reverse conditions for experimental and simulated device 1 at Room Temperature (RT) / Pt Schottky

The device 1 showed a maximum leakage current at RT of 1 μA/cm^2 for a reverse electrical field of 3 MV/cm. The diode exposed its highest operation limit for a bias of 296 V corresponding to a reverse field of 3.1 MV/cm. The estimated leakage currents obtained by simulation at 300 K in fig. 2 a) were 59 mA/cm^2 for breakdown voltage of 230 V using Hiraiwa's IIC and 83 mA/cm^2 for a breakdown voltage of 490 V using Kamakura's IIC. Although only thermionic emission and surface leakage current model were used, leakage current are much higher than the experimental values.

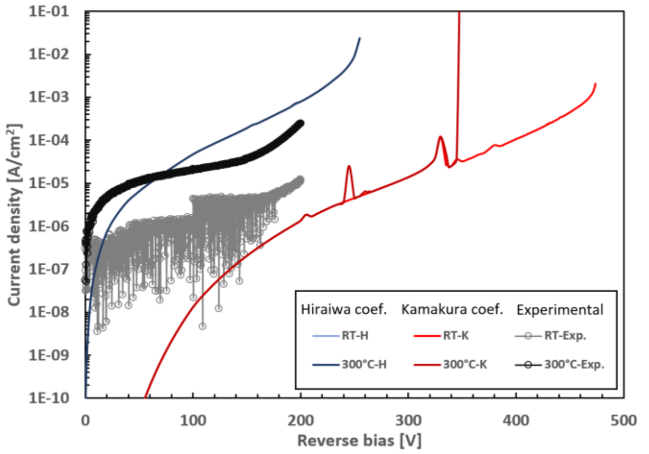

Fig. 2 b) Reverse conditions for experimental and simulated device 2 at different temperatures / Mo Schottky

This discrepancy is also observable in fig. 2 b) where measurement have been made at different temperature. The experimental biasing was stopped at 200 V to not damage the device. Temperature dependence of I-V characteristics are not clear from the simulation using Kamakura model. Current flowlines as well as electric field distribution under the main contact are shown in fig. 3. The maximum electrical field at 300 K at the metal/diamond interface (at y=0) for the device 2 (fig. 4) was 5.62 MV/cm under the Schottky and reached a peak of 9.94 MV/cm at the edge of the structure using Kamakura's parameters for a potential of 473.7 V. It was less important using Hiraiwa's parameters, going from 3.85 MV/cm under the Schottky to a peak of 6.23 MV/cm for a potential

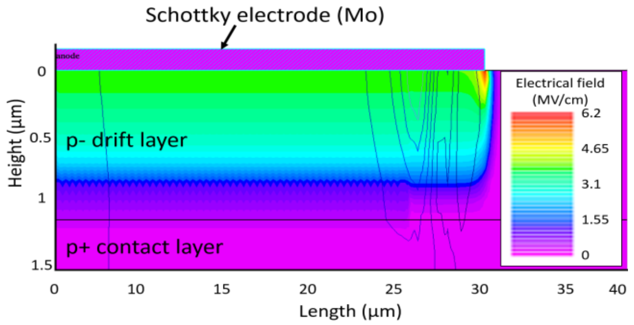

Fig. 3 Electric field map and current flowlines of simulated SBDs 2 just before the breakdown voltage (255 V) at 300°C

of 268.3V. Hiraiwa model prediction is under the experimental values and Kamakura model over.

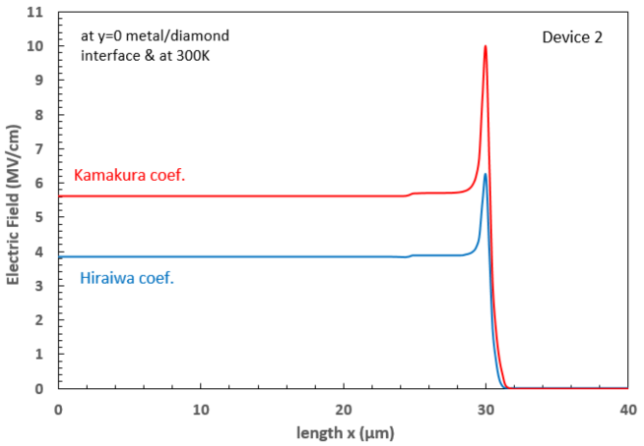

Fig. 4 Electric field peak at metal/diamond interface for the device 2 at 300K, at 230V for Hiraiwa model and at 490 for Kamakura's.

However, the values are still far from experimental data and suggest the importance of the ionization rate parameters.

Conclusion

A comparison study between experiment and simulation was investigated using the two different avalanche parameters reported in the literature. The discrepancy between experiments and simulations will be discussed, and we will propose an optimized structure which will take full advantage of electrical field on the devices and allows to improve ionization rate parameters estimation.

Acknowledgements

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