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Diamond Schottky diodes operating at 473 K

In this paper, we present current-voltage characteristics of vertical and pseudo-vertical Diamond Schottky diodes operating up to 473 K. The functionality rate is greater than 75 % for each samples. For vertical diodes, current density at 473 K reaches 488 A/cm², while it is greater than 1000 A/cm² for pseudo-vertical diodes. Under reverse bias, the leakage current is less than 10^{-7} A/cm² at 50 V for all functional diodes. However, the high barrier height and high non-ideality factor observed are probably caused by high charges at the Diamond/Schottky contact interface. This article emphasizes the high reproducibility of the characteristics and the functionality rate at 473 K.

Keywords: Diamond, Diode, Schottky, High Temperature, Simulation, Characterization.

1. Introduction

Power electronics, specifically energy management, occupy a prominent place in systems. Dedicated electronic devices, mainly on Silicon (Si), reach their limits of development, both in terms of high temperatures and envisaged breakdown voltage. In this context, new wide band gap materials such as Silicon Carbide (SiC), Gallium Nitride (GaN) and Diamond emerge. Diamond offers indispensable potentialities in terms of thermal conductivity (20 $W.cm^{-1}.K^{-1}$) and breakdown electric field (10 $MV.cm^{-1}$) for the future power circuits. Today, technological steps for exploiting this potential are still poorly mastered, one of the major difficulties being the doping of Diamond material. Indeed, boron (p-type dopant) and phosphorus (n-type dopant) have high activation energies of 0.37 eV and 0.57 eV respectively limiting the number of free carriers at room temperature.

Doping process is performed during the layers growth [1] because ionic implantation is not still mastered despite recurring work in the literature [2]. The control of etching steps, the realization of low resistive ohmics contacts and a Schottky contact stable at high temperature with a good adhesion are also still under investigation. Another difficulty inherent to vertical components is to obtain thick layers of several hundred microns depth with high level doping [3].

Most of published works, such as R. Kumaresan's ones [4, 5], focus on Diamond Schottky diodes studies demonstrating notable performances, but the temperature increase causes a collapse of threshold voltage and a decrease of barrier height. Over recent years, many studies were conducted to improve high temperature performance [6-9], with encouraging results.

As a continuity of our research work [10, 11], this paper focuses on vertical and pseudo-vertical p-type diamond Schottky diodes operating at high temperature (473 K) with a rate of functionality greater than 75 %. We will detail the technological parameters of the fabricated samples and present the resulting current-voltage characteristics and a simulation-measurements comparison for each type of diode.

2. Samples presentation

The presented results concern three types of samples: the first one includes 64 vertical diodes of 100 µm diameter, the second includes 24 pseudo-vertical square diodes of different size and the third 64 pseudo-vertical diodes of 100 µm diameter.

Figure 1 shows a schematic view of the different samples. P^- layers were performed by Institut Néel and P^+ layers by LSPM laboratory: note the p-type diamond layers are boron-doped. Boron has high activation energy of 0.37 eV limiting the number of free carriers at room temperature [3]**.** The technological process of diamond Schottky diodes is performed in LAAS cleanroom. Ohmic contacts are made of Ti/Pt/Au of 50/50/500 nm thickness respectively, annealed at 723 K during 30 min and Schottky contacts of Ni/Au of 50/450 nm. No junction terminations were realized for several diode batches.

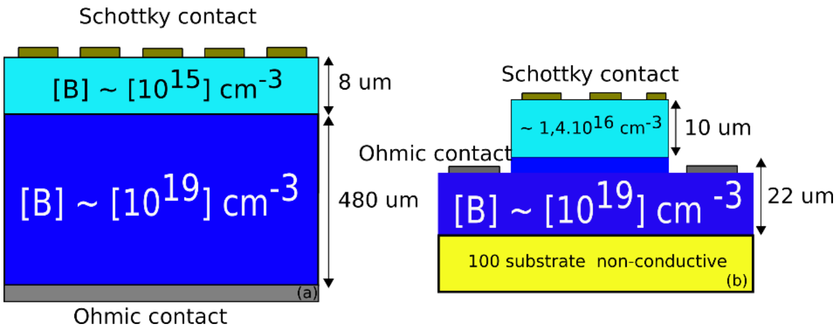

Figure 1: Schematic cross-section of samples, (a) vertical, (b) pseudo-vertical

For vertical sample, the P^- layer of 8 µm thick is doped between 1.10^{15} cm^{-3} and 5.10^{15} cm^{-3}. P^+ layer with a thickness of 480 µm is doped between 1.10^{19} cm^{-3} and 5.10^{19} cm^{-3}.

The doping of the 10 µm P^- layer of pseudo-vertical samples is determined by C(V) measurement (Figure 9) as $1.4.10^{16}$ cm^{-3}. The P^+ layer of 22 µm thick is doped between 1.10^{19} cm^{-3} and 5.10^{19} cm^{-3}.

3. Current-voltage characteristics with temperature

3.1. Vertical diodes

3.1.1. I(V) measurements

Electrical measurements were made under probes with an Agilent 4142: they demonstrate that 48 diodes on 64 are functional at 473 K. Figure 2 shows typical I(V) characteristics for a vertical diode under forward bias. A current density of 92 A/cm² under 10 V and a series resistance of 934 Ω are obtained at room temperature. At 473K, a current density of 488 A/cm² and a series resistance of 193 Ω are measured, consecutively to the activation of Boron atoms by temperature. The parameters extraction from the forward current-voltage graph gives a barrier height of 1.38 eV and a non-ideality factor n of 1.77. Under reverse bias, as reported on Figure 3, a leakage current density of only 10^{-7} A/cm² up to 50 V is obtained, thus allowing us to predict a high breakdown voltage.

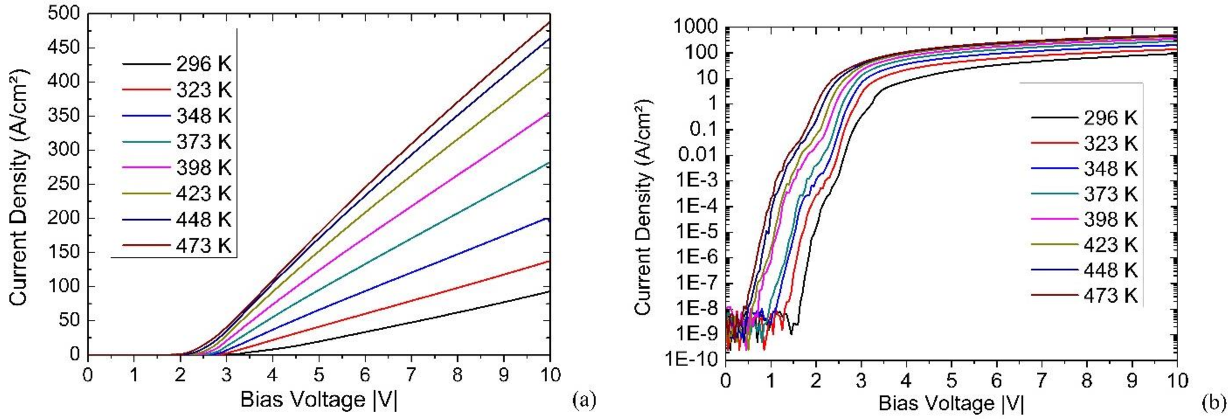

Figure 2: Linear (a) and semi-logarithmic (b) I(V) characteristics of a vertical diode under forward bias versus temperature.

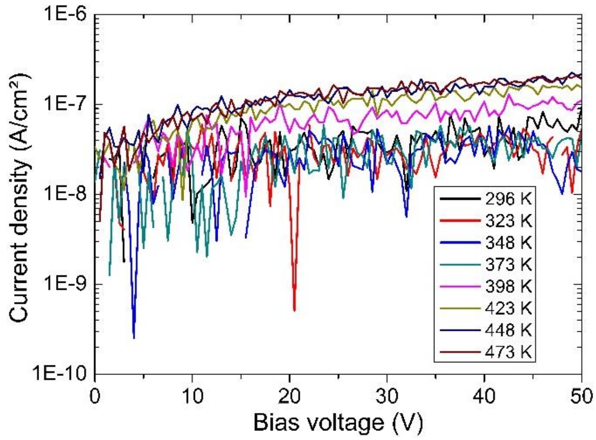

Figure 3: Semi-logarithmic I(V) characteristics of a vertical diode under reverse bias versus temperature.

3.1.2. Simulated I(V) characteristics

Physical simulations presented in this work were performed with SENTAURUS TCAD [12]. Models and parameters used are derived from previous works of F. Thion [11]. The measured barrier height (1.38 eV) is introduced in model parameters. To converge towards the experimental resistance value, various doping levels are chosen (Figure 4). For simulation 1, P^- and P^+ layers doping are 10^{15} cm^{-3} and 10^{19} cm^{-3} respectively, for simulation 2 they are of 3.10^{15} cm^{-3} and 6.10^{19} cm^{-3} respectively.

Simulation 2 leads to a serial resistance of 860 ohms, matching to the measured one and allowing to conclude that the current limitation is not only due to the contact resistance but mostly to the layers resistances. The strong non-ideality factor (n) observed and the dispersed values of the threshold voltage may be attributed to the high charges density at the Schottky interface. To date, physical models and physical parameters available in SENTAURUS TCAD to describe Schottky contact on p-type diamond do not allow to take into account the influence of the traps located at the interface metal/semiconductor.

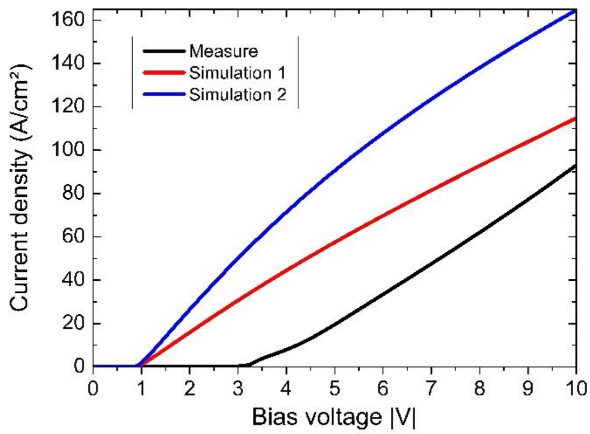

Figure 4: Simulation-measurement comparison at 296 K: Simulation 1 with a doping are 10^{15} cm^{-3} and 10^{19} cm^{-3} for P^- and P^+ layers respectively; Simulation 2 with a doping are 3.10^{15} cm^{-3} and 6.10^{19} cm^{-3} for P^- and P^+ layers respectively.

Simulation of the ideal Schottky diode behavior with temperature for a P^- doping of 3.10^{15} cm^{-3} and P^+ doping of 6.10^{19} cm^{-3} is illustrated in Figure 5. There is a crossing of the characteristics, related to the temperature increase, allowing dopant activation and current density increase. At the same time, there is a decrease of the electronic mobility from 423 K, thus limiting the current increase.

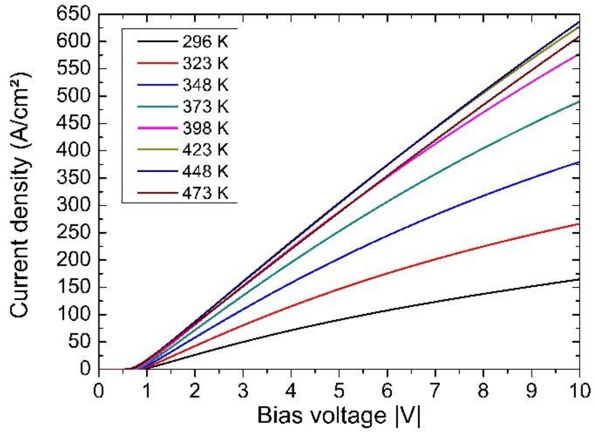

Figure 5: Simulated I(V) characteristics for an ideal diode versus temperature.

Simulations at 473 K are shown in Figure 6. The measured I(V) characteristics and those obtained from simulation 2 are parallel and a shift of the threshold voltage is observed, confirming the current limitation by the serial resistance.

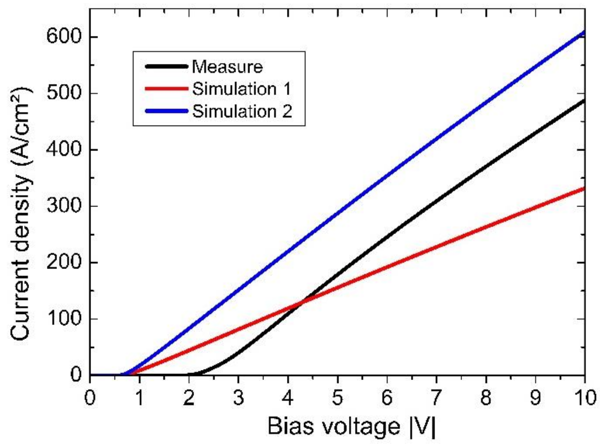

Figure 6: Confrontation simulation-measurement at 473 K

Under reverse bias with ionization parameters of Rashid et al [13], the breakdown voltage of 2D simulated Schottky diode reaches 1600 V. The low leakage current measured and the concordance of measured / simulated curves confirm encouraging prospects of high breakdown voltages.

3.2. *Pseudo-vertical diodes*

3.2.1. I(V) measurements

Measurements were performed under the same conditions than for the vertical diode: 97% of the 64 diodes are functional at 473 K. Figure 7 shows I(V) characteristics as a function of temperature for a typical diode. A low current density of 45 A/cm² is measured at room temperature under 10 V, far from the expected value. By increasing the temperature, 200 A/cm² at 348 K and 1000 A/cm² at 473 K under 10 V are obtained.

The Schottky barrier height deducted from these measurements is brought up at 2.09 eV and the non-ideality factor n of 1.24 is low relatively to the values obtained typically. This could be attributed to a dominant thermionic emission mechanism. In the reverse regime, leakage current is lower than 10^{-7} A/cm² under 50 V, which is satisfactory.

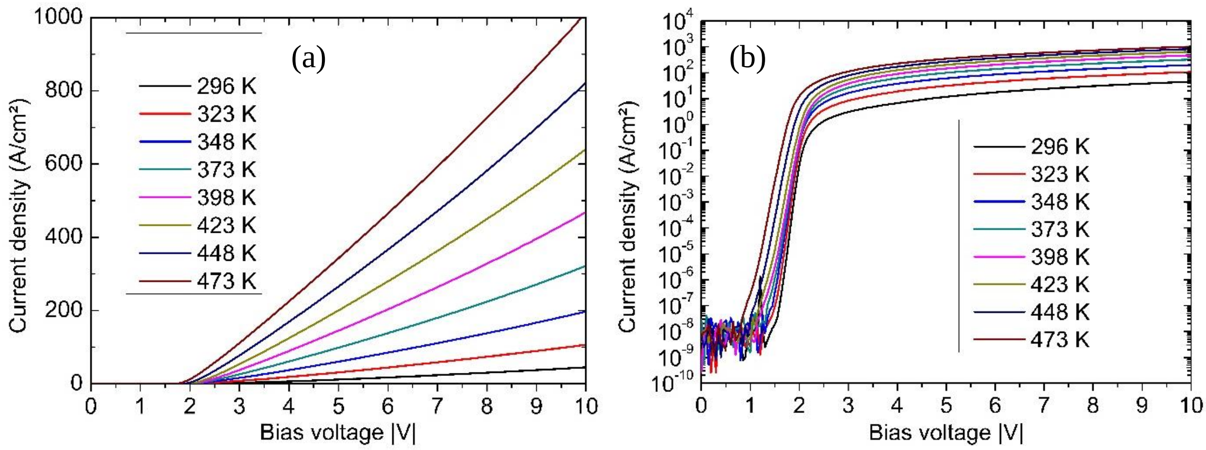

Figure 7: Linear (a) and semi-logarithmic (b) characteristics of a pseudo-vertical diode under forward bias versus temperature

Concerning the pseudo-vertical sample with square diodes, all the 24 tested diodes are functional at 473 K. Figure 8 shows typical characteristics of 300 µm x 300 µm pseudo-vertical Schottky diode versus temperature. At room temperature, the current density is 17 A/cm² with a resistance of 310 Ω: only 48 A/cm² is achieved at 473 K while much higher values were expected. This limitation is probably due to an insufficient doping of the P^+ layer leading to a high contact resistance value but also due to the high contact area. The values of the measured current densities at 296 K and 473 K are reported on Table 1 for different diodes sizes. The barrier height is 1.71 eV and the non-ideality factor is high, close to 2.

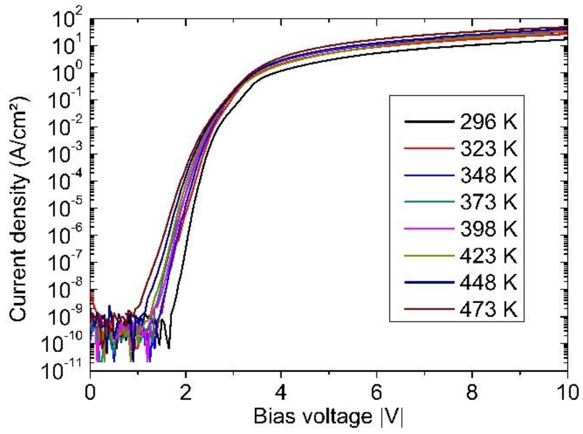

Figure 8: I(V) characteristics of a 300 x 300 µm square pseudo-vertical diode under forward bias versus temperature

Table 1: Summary of current density values for square pseudo-vertical diodes at room temperature and at 473 K

Size (µm) □	J_s at T=296 K (A/cm²)	J_s at T=473 K (A/cm²)
100	50	196
150	25	134
200	20	100
300	17	48
400	15	34
500	8	27
1000	3	6

3.2.2. C(V) measurements

C(V) measurements were made at room temperature with an Agilent 4294A under dynamic small signal of 100 mV and a 5 MHz frequency. Electrical characterizations under reverse bias allow to determine the doping concentration of the P^- layer, here unintentionally doped [10, 14]. Figure 9 represents a C(V) measurement for a 100 µm diameter pseudo-vertical diode. For low voltages, we can note a nonlinear behavior for the $1/C^2$ curve, probably induced by charges at the diamond-metal interface. The depleted zone extension is 0.7 µm under a -10 V bias and 1.5 µm for -40 V. The extracted doping level of the P^- layer is 1.4×10^{16} cm^{-3}. This value when integrated into the model allows to approach the real parameters of a Schottky diode.

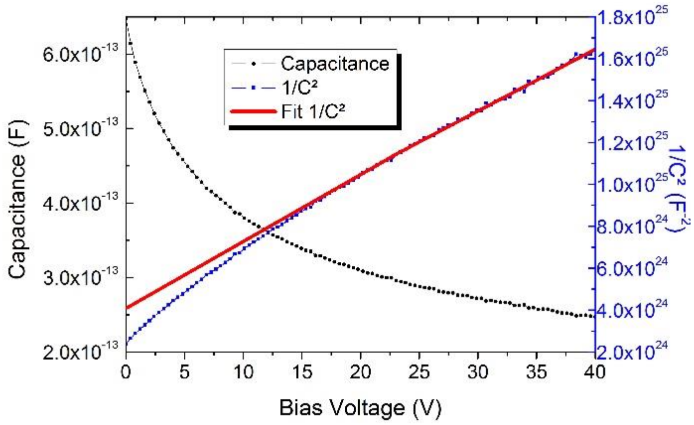

Figure 9: C(V) measurement and 1/C² calculation for a 100 µm diameter pseudo-vertical diode at room temperature and under reverse bias

3.2.3. Breakdown Voltage measurements

Breakdown voltage (BV) measurements were made under vacuum at room temperature. Figure 10 shows a I(V) characteristic for a pseudo-vertical diode under reverse bias. A breakdown voltage of 190 V is obtained, far from the expected value. After this test, despite the breakdown voltage is reached, the diode is not destroyed.

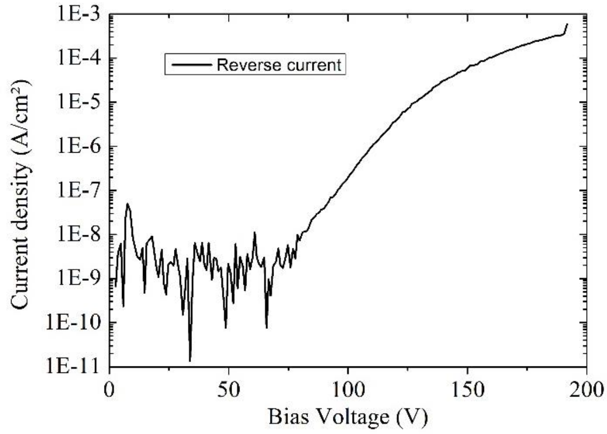

Figure 10: BV measurement for a 100 µm diameter pseudo-vertical at room temperature and under reverse bias

3.2.4. I(V) *simulations*

Simulations of a 100 µm diameter pseudo-vertical diode with the previous measured barrier height of 1.71 eV and layers doping of $1.4.10^{16}$ cm^{-3} (P^-) and 10^{19} cm^{-3} (P^+) are plotted on Figure 11.

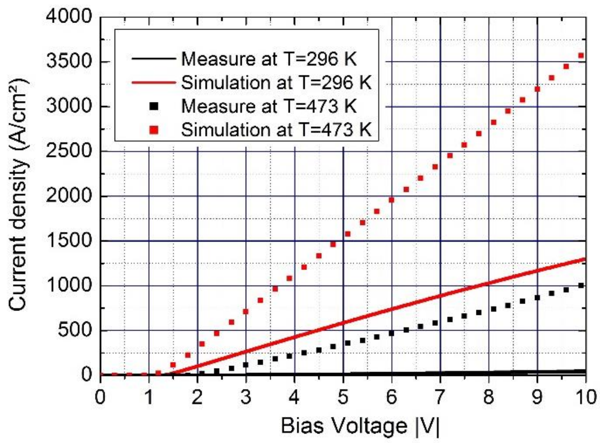

Figure 11: Simulation-measurement confrontation at 296 K and 473 K

For both temperature conditions, a significant difference between current density measurements and simulations is observed. At room temperature, a current density limited to 45 A/cm² is achieved instead of the expected value of 1300 A/cm².

In reverse bias, the breakdown voltage of 2D simulated Schottky diode reaches 510 V, which is far from the measured value (Figure 10).

4. Discussion

The current of a vertical sample will be limited by the P^- layer resistance (Figure 4). In our case, it corresponds to 40 % of the total diode resistance, the remaining 60 % including the P^+ layer and electrical contact resistances, and the part due to the traps. To reduce this influence and maintain a high breakdown voltage, it is necessary to optimize the growth of the P^+ layer by increasing the doping level and also by optimizing the thickness. Indeed, unlike silicon, the diamond has a high mechanical strength and a solution is to reduce the layer thickness for decreasing the serial resistance. In addition, it is necessary to optimize the ohmic contact process in order to reduce the electrical contact resistivity on diamond P^+ layer doped around 10^{19} cm^{-3}.

A low forward current density is measured for pseudo-vertical samples (Figure 11): it can be explained by the quality of the interface between the Schottky contact metal and diamond. A new surface treatment before metallization and an annealing to improve the metal adhesion should provide a stable interface.

High functionality rate at high temperature is obtained for all samples, even for square diodes of great size. Specifically for vertical sample, studies show vertical defects in diamond explaining the lowest percentage of functionality with 75 % which is encouraging [15, 16]. The different parameters measured are honorable and reproducible, evidence that the quality of diamond films is clearly improved. However, in order to control all the outstanding potentialities of the diamond, we must optimize technological steps in order to improve the performance of our diodes. Figure 12 shows a comparison of current densities for Schottky diodes fabricated on different materials for analyzing the possible evolution of diamond [17 - 20]. Despite less mature technological advances, the results obtained for diamond are competitive [21].

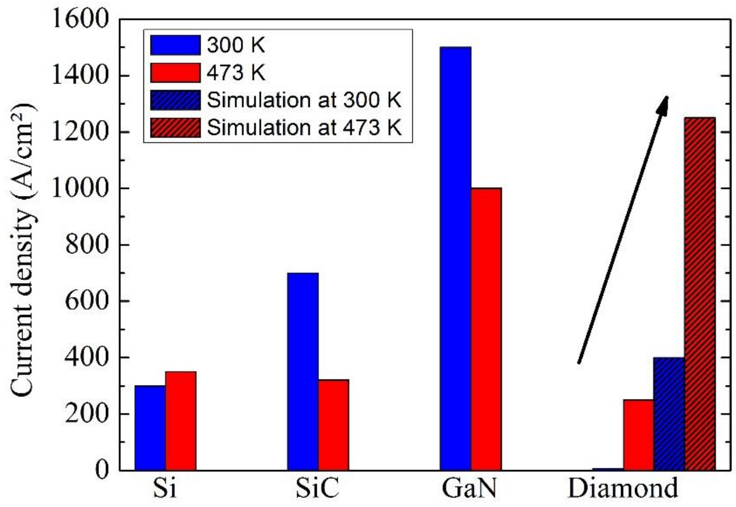

Figure 12: Comparison of current density under 4 V for pseudo-vertical schottky diodes

5. Conclusion

The results presented in this paper demonstrate a high functionality rate for the three studied samples, vertical and pseudo-vertical, with respectively 75 %, 97 % and 100 % of functional diodes at 473 K and a leakage current of the order of pA under 50 V reverse voltage.

Current density, relatively low at room temperature (between 20 and 100 A/cm²), reached the target of 200 A/cm² at 348 K for both vertical and pseudo-vertical diodes of 100 µm diameter. Let us note that the honorable value of 1000 A/cm² is exceeded at 473 K.

The three samples have a high non-ideality factor, the origin probably being charges located at the diamond-metal interface. The pseudo-vertical samples have a too low current density which may be caused by the contact resistance. Vertical sample has a high threshold voltage attributed to an insufficient doping of the P^+ layer.

The performance of these samples relies on the reproducibility of their electrical characteristics at room and high temperatures, while enabling to obtain satisfactory current density parameters.

6. Acknowledgements

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Figure 1: Schematic cross-section of samples, (a) vertical, (b) pseudo-vertical

Figure 2: Linear (a) and semi-logarithmic (b) I(V) characteristics of a vertical diode under forward bias versus temperature.

Figure 3: Semi-logarithmic I(V) characteristics of a vertical diode under reverse bias versus temperature.

Figure 4: Simulation-measurement comparison at 296 K: Simulation 1 with a doping are 10^{15} cm^{-3} and 10^{19} cm^{-3} for P^- and P^+ layers respectively; Simulation 2 with a doping are 3.10^{15} cm^{-3} and 6.10^{19} cm^{-3} for P^- and P^+ layers respectively.

Figure 5: Simulated I(V) characteristics for an ideal diode versus temperature.

Figure 6: Confrontation simulation-measurement at 473 K

Figure 7: Linear (a) and semi-logarithmic (b) characteristics of a pseudo-vertical diode under forward bias versus temperature

Figure 8: I(V) characteristics of a 300 x 300 µm square pseudo-vertical diode under forward bias versus temperature

Figure 9: C(V) measurement and $1/C^2$ calculation for a 100 µm diameter pseudo-vertical diode at room temperature and under reverse bias

Figure 10: BV measurement for a 100 µm diameter pseudo-vertical at room temperature and under reverse bias

Figure 11: Simulation-measurement confrontation at 296 K and 473 K

Figure 12: Comparison of current density under 4 V for pseudo-vertical schottky diodes