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# Ohmic contacts study of P<sup>+</sup>N diodes on (111) and (100) diamond

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**Abstract.** Pseudo-vertical P<sup>+</sup>N diamond diodes are fabricated. We focused on the determination of specific contact resistance of Ti-based contacts for (111) and (100) p-type diamond layers doped around 10<sup>19</sup> at/cm<sup>3</sup> using circular Transfer Length Method (cTLM). Ohmic behavior is obtained and the variation of the specific contact resistance is discussed.

## I. INTRODUCTION

In the field of higher frequencies and higher power applications, diamond seems to be a very attractive material for switching devices, with its outstanding physical and electrical properties. Its high electric breakdown field ( $E_c \sim 10$  MV/cm), high carriers mobilities (2200 cm<sup>2</sup>/V.s for electrons and 2050 cm<sup>2</sup>/V.s for holes [1]) and low dielectric constant ( $\epsilon_r \sim 5.7$ ) offer many advantages for power applications. Diamond's wide bandgap ( $E_g \sim 5.5$  eV) and unique thermal conductivity (20 W/cm.K)[2], 5.3 times higher than the copper thermal conductivity (3.8 W/cm.K), can be well exploited for a wide field of high temperature applications.

To be able to use it as a semiconductor, mastering electrical contacts on diamond is essential. However, one of actual limitations is the fabrication of ohmic contacts on p-type and n-type diamond. Ohmic behavior has been achieved with Ti/Pt/Au contacts on p-type diamond [3][4], but was not yet obtained for n-type diamond. We describe in this paper the technological fabrication process of pseudo-vertical P<sup>+</sup>N diodes and circular-TLM structures on n and p-type layers on the same sample. We focus on the characterization of the ohmic contacts for both p and n-type diamond layers.

## II. P<sup>+</sup>N DIODE PROCESSING

Fig. 1a shows the schematic cross section of a P<sup>+</sup>N diamond diode. The p-type and n-type diamond films are homoepitaxially grown on HPHT Ib diamond substrates using microwave plasma enhanced chemical vapor deposition (MPCVD) at the LSPM for p-type and GEMaC for n-type. The crystal orientations of the studied substrates are (111) and (100) with areas of 2x2mm<sup>2</sup> and 3x3mm<sup>2</sup> respectively. The epitaxial layers thicknesses and chemical concentrations of dopants introduced during growth are reported on Table 1.

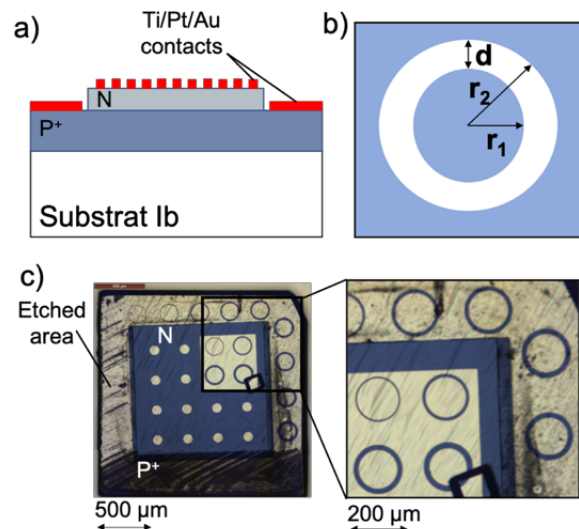


Fig 1. a) Schematic cross section of a P<sup>+</sup>N diode. b) Schematic representation of a cTLM pattern. c) Optical images of the (111) 2x2mm<sup>2</sup> sample after processing.

The fabrication process starts with the definition of the n-region by using ICP-RIE dry etching with Ar/O<sub>2</sub> and CF<sub>4</sub>/O<sub>2</sub> optimized plasma steps [5], using an Al metallic mask in order to reach the p<sup>+</sup> underlayer. The Ti(50nm) / Pt(50nm) / Au(500nm) stack for the n and p-type ohmic contacts is then deposited with a single lift-off step [6]. To do that we have developed a specific lithography process available for very small samples such as diamond substrates.

Table 1. Thicknesses and doping levels of the stacked layers forming the studied samples

Sample	p-type layer		n-type layer	
	Thickness (μm)	Boron content, [B] (at/cm <sup>3</sup> )	Thickness (μm)	Phosphorus content, [P] (at/cm <sup>3</sup> )
(111)	19	7.5x10 <sup>19</sup>	1.9	7.5x10 <sup>17</sup>
(100)	13	3.0x10 <sup>19</sup>	3	5.0x10 <sup>16</sup>

The NLOF photoresist (negative photoresist for single layer lift-off) is deposited with a spray coater in order to ensure a good homogeneity of the layer, thus enabling the definition of high-resolution circular patterns of both the TLM and diodes ohmic contacts by laser lithography. Indeed, circular-type TLM (cTLM) structures (Fig. 1b) were integrated on both p and n regions to allow direct characterization of the contacts. This is made possible by the development of those lithography technics, as a 2 $\mu$ m thick ring is preferable to obtain precise measurements.

After lift-off, an annealing step in Ar atmosphere at 500°C for one hour is necessary to form ohmic contacts. As one can see on Fig. 1c for a 2x2mm<sup>2</sup> chip, the device patterning thanks to lithography developments on such small substrates was optimized to allow the fabrication on the same sample of both cTLM structures and P<sup>+</sup>N diodes.

Concerning the cTLM technique, if  $r_1+r_2$  is constant, the total resistance  $R_T$  between two electrodes linearly depends on the spacing  $d=r_2-r_1$ , as expressed by equation 1 [7].

$$R_T = \frac{R_S}{2\pi} \left[ L_T \left( \frac{1}{r_1} + \frac{1}{r_2} \right) + \ln \left( \frac{r_2}{r_1} \right) \right] \quad (1)$$

where  $R_S$  is the sheet resistance of the semiconductor layer,  $r_1$  and  $r_2$  are the radius of both circular edges, and  $L_T$  is the transfer length.

By fitting the values of the measured  $R_T$  for different  $d$  spacing, it is possible to determine the parameters  $R_S$  and  $L_T$ . The specific contact resistance  $\rho_C$  can then be deduced using [7]:

$$\rho_C = R_S L_T^2. \quad (2)$$

Note that after processing the exact dimensions of the circular TLM are measured using a Scanning Electron Microscope (SEM).

### III. RESULTS AND DISCUSSION

Current-voltage (I/V) measurements, using a probe station and a HP4142 modular DC source, are carried out at room temperature (RT) on the n-type cTLM structures. One probe is positioned at the center of the cTLM pattern and the other on the ground plane. Ohmic behavior is not yet obtained (Fig. 2.a), as we can observe Schottky contacts behavior. As a consequence, the measurements made on the P<sup>+</sup>N-junction do not show diode-like expected comportment, as can be seen in Fig. 2. b., because the Schottky contacts on the n-type diamond is predominant.

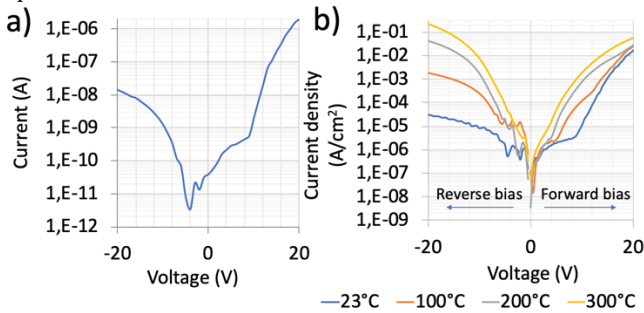


Fig. 2. Current-voltage measurement of a) n-type cTLM structures and b) P<sup>+</sup>N junction at different temperatures

Concerning the p-type cTLM structures, the goal is to check their ohmic behavior on layers doped around 10<sup>19</sup> at/cm<sup>3</sup> and verify that the specific contact resistance is not altered by the RIE-ICP etching step. An ideal I/V linear variation, characteristic of an ohmic contact can be observed in Fig. 3, and the total resistance of two neighboring contacts is plotted as a function of the spacing  $d$  of each circular structure. The sheet resistance  $R_S$  and the transfer length  $L_T$  are estimated by fitting experimental measurements with equation 1 (Fig. 4).

The specific contact resistance is estimated for the (111) sample to be  $\rho_{C(111) RT} = 3.6 \times 10^{-4} \Omega \cdot \text{cm}^2$  at RT, and  $\rho_{C(100) RT} = 4.4 \times 10^{-3} \Omega \cdot \text{cm}^2$  for the less doped (100) sample at RT. The effect of the ICP-RIE etching step seems to be minimal as these values are within literature range [8][9]

The variation of the specific contact resistance with the temperature is also studied (Fig. 5). As the temperature increases, the specific contact resistance reduces. This is explained by the effect of incomplete ionization of dopants that has to be considered when using diamond layers. At RT, all dopants are not ionized. It is possible to calculate that when the temperature rises up to 200°C, the carrier density will increase by a factor 39 for the (111) sample and by a factor 70 for the (100) sample, using equation 3 [5].

$$Na^- = \frac{Na}{1 + g_A \exp \left( \frac{\Delta E_A - kT \ln \left( \frac{N_V}{Na} \right)}{kT} \right)} \quad (3)$$

$Na^-$  is the ionized concentration of acceptors,  $Na$  is the boron content,  $g_A$  is evaluated to 4 in [5],  $\Delta E_A$  is the activation energy (eV) and is evaluated using the Pearson Model for both samples [2],  $k$  is the Boltzmann constant,  $N_V$  is the effective density of states at the valence band edge.

The carrier mobility will decrease by a factor 1.1 for the (111) sample and by a factor 1.5 for the (100) sample [10] while increasing temperature measurement to 200°C.

The effect of the incomplete ionization exceeds the decreasing mobility, therefore reducing the specific contact resistance. When the ionization is complete, the specific contact resistance will start to increase, due to the continuing degradation of the carrier mobility with the temperature.

The determination of the temperature at which this phenomenon occurs can be evaluated with equation 3, but the experimental data do not match theoretical calculation: the ionization seems to be complete at a higher temperature than 200°C.

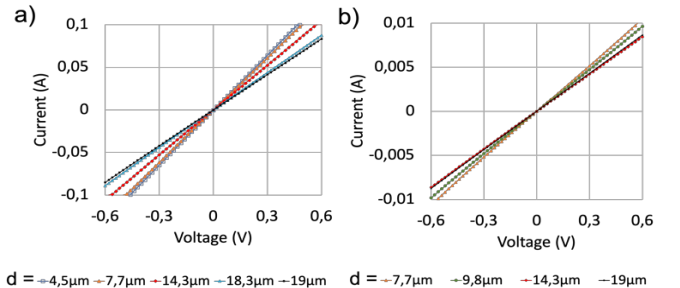


Fig. 3. I/V characteristics on p-type diamond for a) (111) sample and b) (100) sample for several spacing  $d$  (see Fig.1.b) corresponding to each cTLM pattern. The spacings were measured after processing by optical observation.

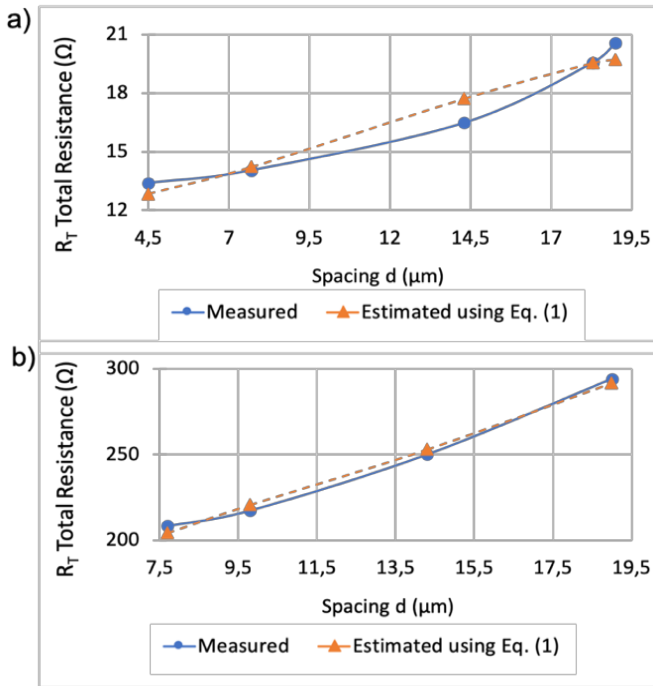


Fig. 4. Total resistance of each cTLM pattern on p-type diamond as a function of their spacing  $d$  for a) the (111) sample and b) the (100) sample

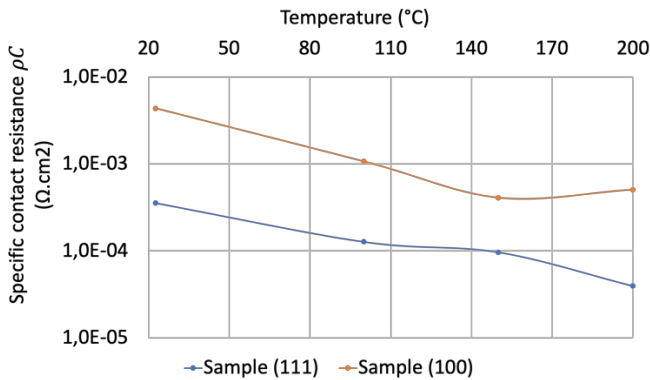


Fig. 5. Variation of the specific contact resistance with temperature for Ti (50nm)/Pt (50nm)/Au (500nm) on p-type diamond

#### IV. CONCLUSION AND PERSPECTIVES

$\text{P}^+\text{N}$  diamond junctions were fabricated on (111) and (100) films and cTLM structures were integrated for the first time in the same sample, allowing device contact characterization. Ohmic behavior was not obtained on the n-type diamond, therefore PN diode behavior was not yet observed.

The electrical properties of Ti-based/p-type diamond contacts were characterized and ohmic behavior has been obtained on both samples, even though the doping level was under  $1 \times 10^{20}$   $\text{at}/\text{cm}^3$ . The specific contact resistance was estimated to  $3.6 \times 10^{-4}$   $\Omega \cdot \text{cm}^2$  for the (111) sample and  $4.4 \times 10^{-3}$   $\Omega \cdot \text{cm}^2$  for (100) sample at RT. These contact resistances are within literature range, despite that the contacts were

fabricated on a degraded surface due to the ICP-RIE etching step.

Optimization of those contacts and improvement of the phosphorus-doped diamond layer fabrication have still to be made to obtain bipolar devices with better performances, such as high-power transistors. With the progress of p-type and n-type doping technologies, new tests and devices will be made in the near future.

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