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Concept of Novel CVD Diamond High Voltage, High Power and Study of ohmic contacts on diamond

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Keywords

«diamond», «ohmic contacts», «High voltage», «power electronic»

Abstract

Diamond exceptional electronic and thermal properties make it a very promising material for future applications in power electronics, especially for high voltage and/or high temperature applications. In this paper, the principle of high power, high voltage switches that take advantage of these properties are illustrated by simulations. Technological steps necessary to their fabrication have been developed. We present heavily B-doped layers, the way we characterized them and ohmic contacts deposited on them.

Introduction

Diamond is well known to possess physical, optical and electronic properties of high interest for device fabrication. The combination of a wide band gap (5.47 eV), which allows high temperature operation, a large breakdown field (>10 MV/cm) which allows to sustain very high voltage, a very good thermal conductivity (20 W/cm.K) and high carriers mobility (4500 cm²/V.s for electrons and 3800 cm²/V.s for holes) [1] makes it an ideal candidate for the conception of power electronic devices [2]. Recently, the progress achieved on single crystal CVD diamond synthesis has led to the fabrication of novel devices with superior performances. However, there are still several key points that need to be improved, such as the doping methods and the control of ohmic and Schottky contacts fabrication. The most important problem remains n-doping which is still far from being overcome, and particularly if high current density is needed : this results essentially from the relatively deep energy level of the P donor level at 0.6eV [3]. This motivates here the design of optically controlled unipolar devices, using only in-situ boron-doped layers, which is a more readily available technology [4]. Moreover, contact technology is still the object of several studies, especially for ohmic contacts [5,6], which are necessary for any device development.

In a first part, simulations are presented that illustrate the principle of two types of high voltage electronic triggered devices under development.

In a second part, technological advances, i.e. heavily Boron-doped layers growth, ohmic contacts deposition and means to characterize the outcome of our techniques are presented.

Principle of the electronic triggered switches

Principle

N-doping is still not readily available for diamond, thus only unipolar solutions are explored here.

Fig. 1 shows the principle of two common power electronic switches, the first one dedicated to DC/AC applications and the second one being a bidirectional switch. Such devices can both be efficiently triggered using an e-beam. Brezeanu and al. [7] showed simulation results demonstrating the possibility of modulating the turn-on and the breakdown voltages of a Schottky diode from carrier injection via photons from a light source. We would like to take advantage of such properties, but using an electron beam excitation rather than a photon source in order to generate more carriers in the device structure. The second device is an electron beam triggered switch in which three areas can be distinguished: an intrinsic drift zone and two heavily boron doped contact zones. The former one is insulating, allowing the device off-state. The p+ zones are used to improve ohmic contacts, which are necessary to collect the device current. In this structure, the on-state is triggered using an electronic beam, which allows the generation of free carriers that will lead to the on-current when the electric field is applied.

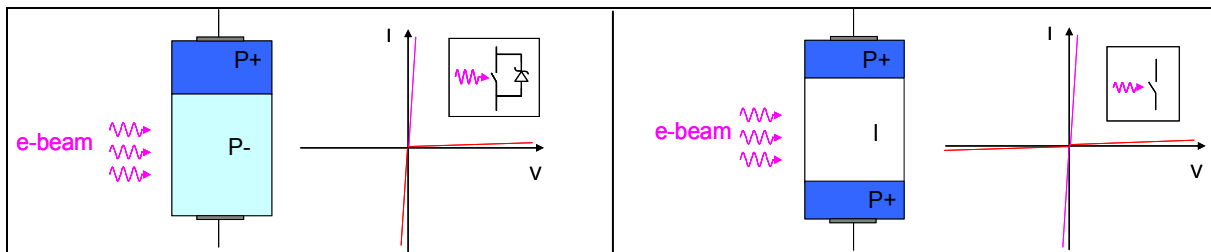


Fig. 1: a) cross section of the electronic triggered Schottky diode b) cross section of the electronic triggered switch

The switch is intended to exhibit a high voltage breakdown ($> \text{tens kV}$); this point should be insured from the high dielectric strength of diamond (theoretical value $\sim 1.5 \text{ MV/cm}$). Moreover, the voltage drop in the on-state should be minimized in order to avoid significant power losses and device self-heating, such latter properties being strongly dependent on the quality of the ohmic contacts used.

Numerical device implementation

Numerical investigations into the behaviour of the bidirectional switch were carried out with the physics based SENTAURUS device simulator. Diamond is still a novel material and various parameters like concentration and temperature dependent carrier mobility and impact ionization coefficients have to be specified accurately. This work is under progress in our labs but for the moment, the simulations described below are implemented with Silicon Carbide parameters which is another wide band gap semiconductor.

Fig. 2a displays the current density circulating in the switch for an optical excitation coming from the bottom. Fig. 2b shows the temporal response of the switch to a $2.25 \mu\text{s}$ optical pulse.

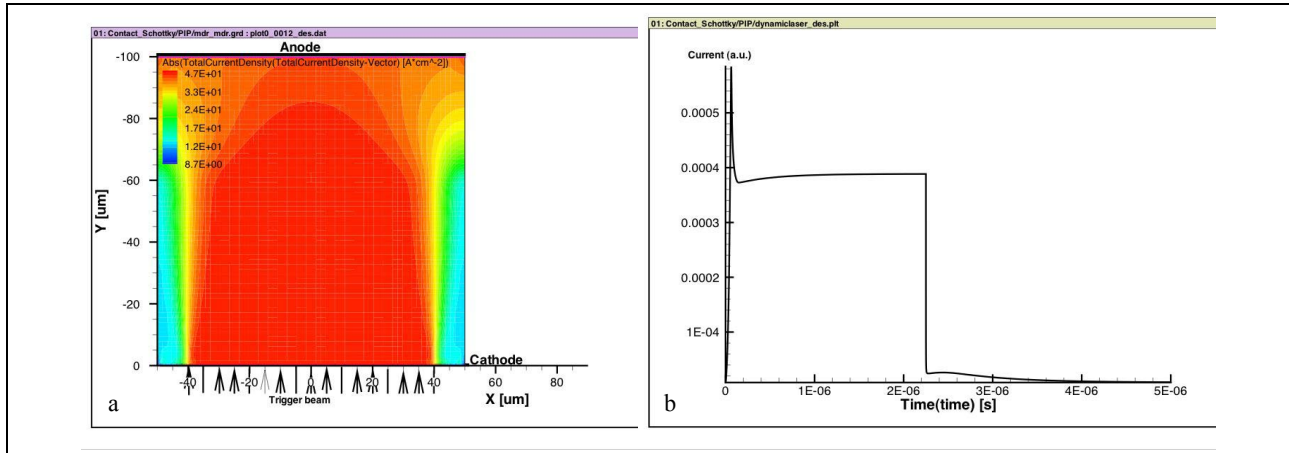


Fig. 2: a) current density distribution in the bidirectional switch b) current response to a 2.25 μs optical pulse

These simulations are only qualitative. Taking advantage of the exceptional diamond properties, this bidirectional switch is expected to exhibit a high breakdown voltage thanks to the huge breakdown field, as well as a short commutation times thanks to the low carriers lifetime. Its on-state resistance will depend on the quality of the crystal (particularly in the drift zone) on the one hand, and on the quality of the ohmic contacts on the other hand.

Ohmic contacts

The ability to build good quality ohmic contacts is a determining point for the conception of highly efficient power electronic devices. Two major aspects have to be considered to reach this goal.

First, a highly doped layer is needed. In fact, this heavily doped layer tightens the energy barrier created at the diamond-metal interface when depositing a contact. The free electric carriers are then able to cross the barrier, taking advantage of the tunnel effect.

Moreover, appropriate contact metals have to be chosen; typically, in the case of diamond, metals that react with carbons during the annealing phase to promote contact ohmicity.

Heavily p-doped layers

CVD epitaxial diamond films were grown on Ib-type single crystalline (111) oriented diamond substrates ($3 \times 3 \times 0.5 \text{ mm}^3$) in a microwave plasma-enhanced (MWPE) CVD reactor, using hydrogen-diluted methane (500 sccm H_2 and 0.7 sccm CH_4), high power densities ($\sim 1000 \text{ W/cm}^3$) and high substrate temperature of $900 \text{ }^\circ\text{C}$ ensuring very high B-incorporation ratio. Trimethylboron (TMB) was used as a doping gas.

Many doped layers have been realized ranging from lightly to heavily boron doped by varying the TMB/ CH_4 ratio. For high enough TMB concentrations, the epilayers display metallic conduction. Fig. 3 illustrate the transition from band conduction to metallic conduction as the TMB/ CH_4 ratio increases.

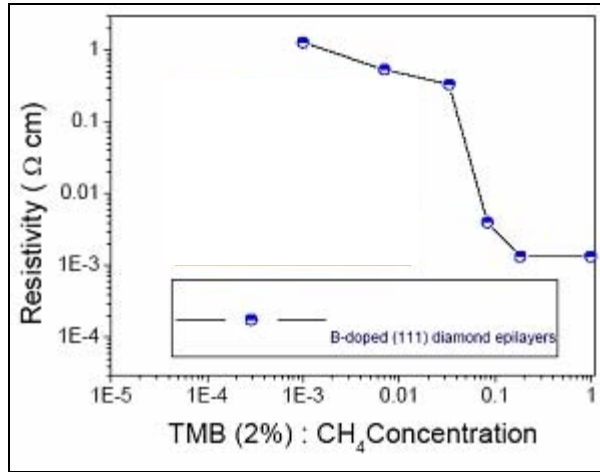


Fig. 3: Resistivity of the layers vs. TMB (2%) : CH₄ concentration

The doped samples were then studied using Raman spectroscopy and different electrical characterization. Heavily B-doped samples were analyzed clearly showing the so-called Fano resonances in the Raman spectra, confirming the metallic character of the layers. This was also confirmed by the stability of the electrical resistivity of these layers versus temperature, showing very low ionization energy.

Fig. 4 shows the SIMS profile of boron in the sample used for our contact tests. It shows boron concentration of $2-3 \cdot 10^{20} \text{ cm}^{-3}$, and a layer thickness of 1500 nm.

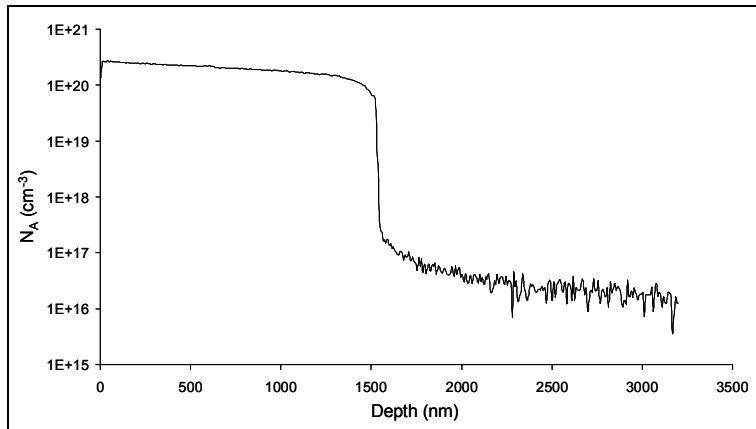


Fig. 4: Boron profile of the heavily B-doped sample

Ohmic contacts deposition

The contacts used to build our structure are Ti/Pt/Au contacts, which are commonly used in the literature. Titanium, when deposited on diamond, forms TiC (Titanium Carbide) during a high temperature annealing (500 °C, 1 hour). This carbide provides a good adhesion of the contacts on the semiconducting diamond surface and leads to a better ohmicity [8]. The Au is used to ensure a good potential repartition at the contact surface. Finally, the Pt is used to limit the Au diffusion during the annealing.

In order to characterize the resistance of the contacts and the resistivity of the doped diamond layer, we use a Transmission Line Model (TLM) patterns. TLM structures have been extensively studied in the literature [9,10]. By building test structures with $W \gg L_1, L_2, L_3, L_4$, we avoid the MESA etching and the current spreading effect at the extremities zones is quasi negligible. The width W of our contacts is 400

μm , whereas the space between contacts are $L_1 = 5 \mu\text{m}$, $L_2 = 10 \mu\text{m}$, $L_3 = 20 \mu\text{m}$ and $L_4 = 40 \mu\text{m}$. The length of the contact is $L_C = 10 \mu\text{m}$. However, we need larger contact surfaces to put electrical probes down on the test structure. To obtain this configuration, we first deposited a SiO_2 layer on the diamond sample. Then, the effective dimensions of the contacts to the semiconductor are set by trenches made in the insulating layer by RIE (Reactive Ion Etching). Finally, we deposit large metal pads on the trenches to allow device probing.

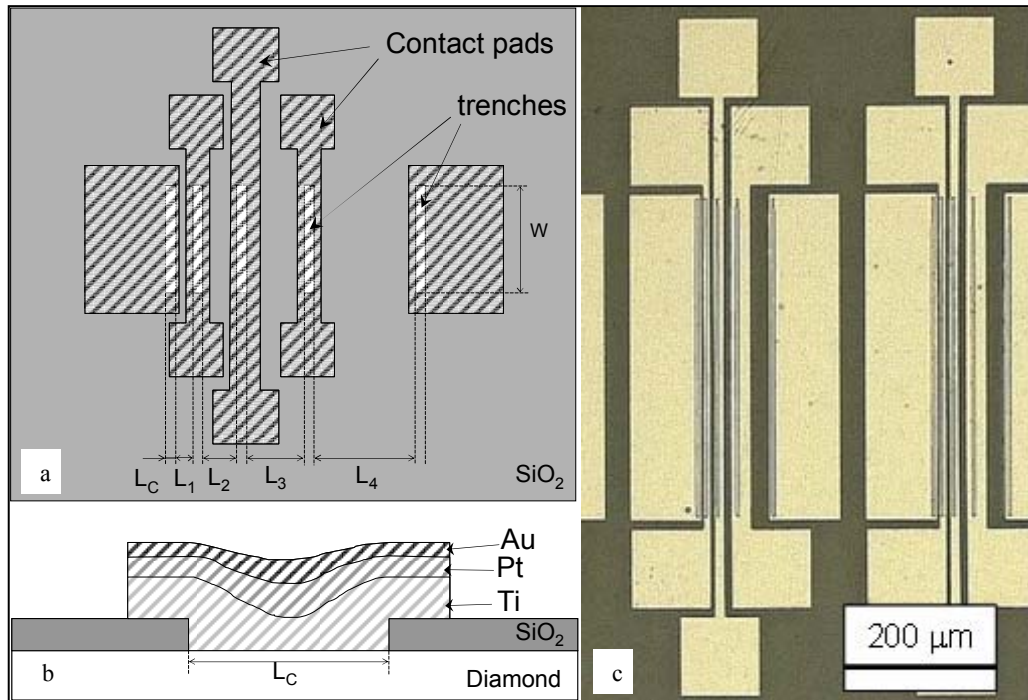


Fig. 5: TLM test structure. a) Schematic view of the test structure b) detailed cross view of the contacts c) picture of the realized structures

The data extracted from our TLM test structures are satisfying. The contacts show good ohmicity and good linearity, as shown on Fig.6. The slope is defined as $p = \frac{R_{SH}}{W}$, where R_{SH} is the square sheet resistance ($\Omega/$) of the doped layer. Moreover, $R(L=0) = 2R_C$, where R_C is the contact resistance from which we deduce the specific contact resistance ρ_C .

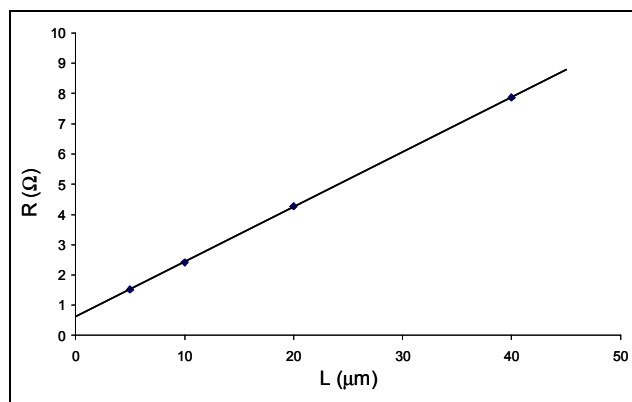


Figure 6 : Results extracted from measurements made on our TLM structure

The results extracted from these measurements give a square sheet resistance $R_{SH} = 75 \Omega/\square$, i.e layer resistivity $\rho_S = 11 \text{ m}\Omega\cdot\text{cm}$ and a specific contact resistance of about $8 \cdot 10^{-6} \Omega\cdot\text{cm}^2$.

Conclusion

Recent developments of single crystal CVD diamond growth that exhibit high electronic properties open up a new way for diamond semiconducting devices. Since it is very difficult to obtain sufficiently conducting n-type diamond, we have investigated novel device designs in order to fabricate active unipolar switches, as a parallel method to bipolar PIN junctions. In this paper, we presented the principle of an e-beam triggered Schottky diode as well as an e-beam triggered switch fabricated on CVD diamond. Problems such as doping, ohmic contact realisation, size of substrates still have to be solved before industrial applications could be foreseen. For these reasons we are working on device technologies dedicated to diamond.

References

- [1] Jan Isberg, Johan Hammersberg and al.: High Carrier Mobility in Single-Crystal Plasma-Deposited Diamond, *Science* 2002 September 6; 297: 1670-1672.
- [2] D. J. Twitchen, A. J. Whitehead, S. E. Coe, J. Isberg, J. Hammersberg, T. Wikström and E. Johansson: High-Voltage Single-Crystal Diamond Diodes, *IEEE Trans. Elec. Dev.*, vol. 51, no. 5, May 2004.
- [3] M. Nesladek: *Semiconductor Science and Technology*, 2005.
- [4] L. S. Pan: *Diamond : Electronic properties and applications*, Kluwer Academic Publishers
- [5] Y. Chen, M. Ogura, S. Yamasaki, H. Okushi: "Ohmic contacts on p-type homoepitaxial diamond and their thermal stability", *Semiconductor Science and Technology*, Volume 20, Number 8, August 2005, pp. 860-863
- [6] M. Wade, P. Muret, F. Omnès and A. Deneuve: Technology and electrical properties of ohmic contacts and Schottky diodes on homoepitaxial layers grown on (100) diamond surfaces, *Diamond and Related Materials*, Volume 15, Issues 4-8, April-August 2006, Pages 614-617
- [7] M. Brezeanu, S.J. Rashid, T. Butler, N.L. Rupesinghe, F. Udrea, K. Okano, G.A.J. Amaratunga, D.J. Twitchen, A. Tajani, C.Wort, M.P.Dixon: Optically triggered Schottky barrier diodes in single crystal diamond, *Diamond and Related Materials* 14, 499 (2005)
- [8] : Matthias Werner: Diamond metallization for device applications, *Semiconductor Science and Technology* 18 (2003) pp 41 - 46
- [9] G.K. Reeves , H.B. Harrison: Obtaining the specific contact resistance from transmission line model measurements, *IEEE Electron Dev Lett* 1982;3:111-3
- [10] M. Lijadi, F. Pardo, N. Bardou, J.L. Pelouard: Floating contact transmission line modelling: An improved method for ohmic contact resistance measurement, *Solid-State Electronics*, 49, 10 (2005) 1655-1661.