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High termination efficiency using polyimide trench for high voltage diamond Schottky diode

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ABSTRACT

Using finite element simulations with Sentaurus TCAD (Technology Computer-Aided Design) software, a progress from simple and classic termination for a Schottky diode to new topology termination has been studied in this paper. A polyimide trench under field plate termination has been used. The efficiency increases from 67% for a simple field plate with optimum parameters up to 97%. The maximum electric field in the termination dielectric has been evaluated also. A wide study of the termination geometry has been made in order to extract the optimum parameters in two directions. The first one is to obtain a high efficiency regarding the breakdown voltage, and the second one is to have the minimum electric field peak at the termination edge.

1. Introduction

Due to its super properties such as high breakdown field, high saturation velocity, high carrier mobility and the highest thermal conductivity of all materials, diamond becomes the best material for the power devices [1]. At high temperature, the conventional semiconductors cannot be used because of intrinsic carrier generation across the band gap. For these cases wide band gap semiconductor materials like SiC, GaN, and diamond are promising candidates. For example, due to a bandgap energy of 5.45 eV the diamond intrinsic carrier concentration at 1000 °C is in the range of 10^{10} cm^{-3}, which is similar to that of silicon at room temperature and similar device performance may be expected [2]. Therefore, diamond is a very attractive material for high temperature, high-voltage and high-power switching applications in future power electronics.

The device under study in this paper is a diamond P type Schottky diode. As all power devices, a junction termination is needed in order to spread the equipotential lines, to reduce the electric field at the edge of devices and to reach the theoretical breakdown voltage. Several junction terminations have been explored for the Schottky diode in wide-band-gap semiconductors. Some of the more common ones are the guard ring [3,4], the metal field plates extending over an insulating surface layer [5,6], resistive Schottky barrier field plate (RESP) [7], and junction-termination extension (JTE) [8].

Due to difficulties associated with donor atom doping in diamond and destructive effects of ion implantation on the diamond crystal, N-type region is not yet optimized. Therefore, techniques commonly used for terminating Si or SiC devices, such as field rings or junction termination extensions, cannot be employed for diamond. That's why the field plate termination is chosen for this study.

Several materials and architectures have been used in order to optimize the efficiency of the field plate termination. Due to its high dielectric permittivity, Ikeda [5,9] used the aluminum oxide ($\varepsilon \approx 9$) as a dielectric under the field plate. His results show an increasing of breakdown voltage from 200 V without termination to 700 V with field plate. Brezeanu [10,11] used the graduated, ramp dielectric form and high K dielectric under field plate in order to increase the breakdown voltage. Thion [12] used semi-resistive material upon a layer of silicon nitride in order to diffuse the equipotential lines and therefore decrease the maximum electric field and increase the breakdown voltage.

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The results of Thion [13] show a difference between simulated and experimental results. One of the reasons can be the electric field peak at the edge of the termination. This peak is probably higher than the critical field of the dielectric used under the field plate.

The principal goal of this study is to decrease the maximum electric field peak in the structure, which is normally localized at the edge of termination, using polyimide trench under field plate.

An architecture using a polyimide trench under field plate has been studied in this paper. Several architectures with many geometrical parameters have been tried in order to extract the optimum values and geometry.

2. Diamond Schottky diode simulation parameters

The structure under study is a diamond pseudo vertical Schottky diode. The technological and geometrical parameters were chosen using TCAD (Technology Computer-Aided Design) simulation to have a breakdown voltage equal to 1700 V at room temperature. One dimension simulations with Sentaurus have been made in order to extract these parameters. Assuming that, the termination efficiency is around 85%, that means, the insures a breakdown voltage equals 85% of the breakdown voltage of the ideal component (one dimension simulation), the thickness of P^- layer should be equal to 11 or 12 μm with boron doping concentration equal to 2×10^{15} or 4×10^{15} cm^{-3} successively. The second parameters set (12 μm; 4×10^{15} cm^{-3}) have been chosen because simulation results show a forward current density greater than for the first parameters set (11 μm; 2×10^{15} cm^{-3}) at ON state. So, the structure consists of two diamond layer (Fig. 1), the first is a 7 μm P^+ doped diamond with a doping concentration of 3×10^{20} cm^{-3} and the other is a 12 μm P^--doped diamond with doping concentration of 4×10^{15} cm^{-3}. The physical model used to calculate the breakdown voltage is the default Van Overstraeten model [14–16] with parameters value given in the paper of Rashid et al. [17]. The carrier mobility, maximum electric field and other parameters are detailed in the thesis report of Thion [13].

Due to convergence problem at low temperature, all simulations in this paper have been made at 800 K. The electrical characterizations of this Schottky diode have been extracted by extrapolation after simulations at different temperatures. Other simulations have been made in order to evaluate the variation of the electric field with temperature shown a negligible difference.

The polyimide dielectric material has been used for all simulations as a secondary passivation.

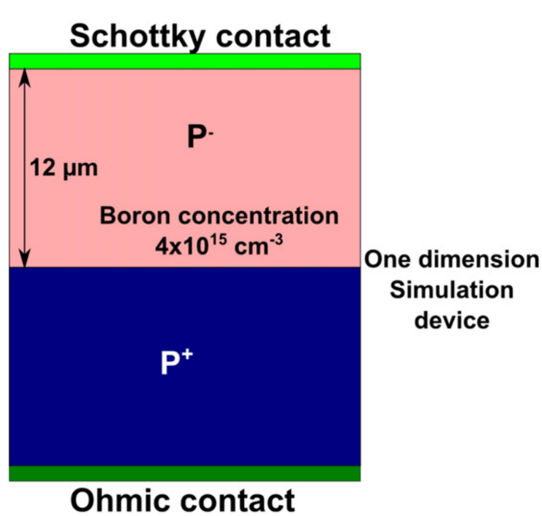

Fig. 1. One dimension simulation structure for diamond Schottky diode.

3. New termination architecture

Many field plate termination architectures have been used in majority of simulations in order to increase the breakdown voltage without noticing of the electric field peak at the end of field plate. Indeed, the case of diamond is specific, and due to its high critical field, which is much larger than that of the dielectrics frequently used in power devices, the electric field peak in the termination is very high. So, it is necessary to design new termination architectures that reduce drastically the electric field in the dielectrics.

In previous papers [18,19] an idea has been proposed to increase the efficiency of the field plate by eliminating the electric field peak in the diamond (Fig. 2 — structure B). It is to keep the whole electrode flat, with no corners, and replace the diamond below the field plate region, with an optimized thickness of a dielectric material. This idea is not used to decrease the electric field peak value at the end of the field plate (almost 60 MV/cm at 1700 V). Several termination architectures (pillars dielectric form, graduated dielectric form and mixed dielectric form) with different dielectric materials (silicon oxide and aluminum oxide) [18,20] have been proposed in order to decrease the electric field peak at the end of the field plate.

The electric field by definition is the potential variation in a given distance. If the potential lines in the structure can be displaced away the field plate, the maximum electric which located at the edge of field plate decreases. To achieve the spread of equipotential lines, it is necessary to use a dielectric with a value of permittivity smaller than the diamond in the lower part of the termination structure. An idea consists to make polyimide trench under the field plate (Fig. 2 — structure C). The used dielectric in this paper is the silicon oxide. Theolier [21, 22] has used this technique to design efficiency termination of superjunction silicon MOSFET (Deep Trench Termination DT^2), but by using the BCB (Benzo–Cyclo–Butene) as a dielectric in place of polyimide. The polyimide is a sort of polymer [23,24]. Its critical field is around 5 MV/cm. One of its use is for second passivation in the microelectronic devices and particularly for high voltage and high temperature SiC devices [25], which encourages the use of this material is the facility of the deposit and its permittivity very close to the silicon oxide (≈3) that's mean, smaller than that of diamond (≈5.7).

3.1. Technological process

Due to several reasons, the necessary technological processes to make diamond components are specifics. The small wafer dimension (3 mm × 3 mm) and the difficulty to make a local doping are some of the more reason. In this case, the technological process which is able to make the diamond Schottky diode with the new termination, is described in Fig. 3. The anode contacts of all diodes in the same wafer are interconnected. After etching until the P^+ layer, ohmic contacts must be made before the deposit of the polyimide layer. After the polymerization of the polyimide and the CMP (Chemical Mechanical Polish) process, the time of the silicon oxide deposit layer becomes. The final processes are the deposit of the Schottky contact and the etching of the polyimide at the edge of the wafer in order to have an access to the anode contacts.

3.2. Architecture parameters and results

The depth of the polyimide in this structure equals the diamond P^- one. The field plate on the polyimide, as Fig. 2(c) shows, is in the classic form. Three interest parameters can be effective in this architecture: the dielectric thickness, the field plate extension length and the position of the dielectric (Fig. 4).

3.2.1. Parameters effect on the breakdown voltage

The dielectric (silicon oxide) thickness was varied from 0 to 2 μm, the field plate extension length from 0.5 to 15 μm and the position of