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Study of Different Edge Terminations Used for 6H-SiC Power Diodes

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(including resonance tunneling devices)

Abstract. — Silicon Carbide is a wide bandgap semiconductor (3 eV for 6H-SiC at 300 K) suitable for high voltage, high temperature, high frequency and power devices. Its drift velocity is high (2 × 10^7 cm s^-1), its thermal conductivity is similar to that of copper (5 W m^-1 °C^-1) and its critical electric field is almost 10 times higher than that of silicon. In the field of power devices, many publications refer to PN structures (4.5 kV), Schottky diodes (1.3 kV) as well as MOSFET and JFET PN junction diodes have been designed and characterized with two different peripheral protections to achieve high breakdown voltage. The first protection is the MESA structure. In this approach, the curvature region of the main junction where the electric field is higher than in the bulk, is etched off. The efficiency of a P^+NN^+ MESA structure can be increased by decreasing the doping level of the N-type layer. For this purpose compensation by boron atoms is used for P^+NN^+ MESA structures. The second peripheral protection is a planar structure in which equipotential lines are spread around the lateral P-type low-doping implanted zones for P^+N junction or N-type Schottky diodes. The experimental breakdown voltage of these diodes lies between 600 and 1500 V

1. Introduction

Silicon Carbide is a wide bandgap semiconductor (3 eV for the 6H-SiC polytype at 300 K) of potential interest for high voltage, high temperature, high frequency and power devices. Its drift velocity is high (2 × 10^7 cm s^-1). Its critical electric field is almost 10 times higher than that of silicon and its thermal conductivity is similar to that of copper (5 W m^-1 °C^-1). Nevertheless, technological processes such as chemical etching, diffusion of doping atoms or deep implantation usually used in silicon technology cannot be easily transferred to silicon carbide.

In the field of power devices, recent improvements in material quality have led to the manufacture of silicon carbide diodes of high voltage blocking capabilities. Many publications refer to PN devices [1] and Schottky diodes [2] with breakdown voltages of 4.5 kV and 1.3 kV,

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respectively. In order to avoid electric field peaks at the junction periphery which can produce premature breakdown, it is necessary to have a peripheral protection. 6H-SiC bipolar power diodes with various edge terminations have been designed, built and characterized. Two edge terminations have been explored. The first is the MESA structure that consists in etching the high electric field zones, the second approach is a planar structure in which the main junction is expanded by a lateral extension in order to spread out equipotential lines at the junction vicinity.

2. The MESA Structure

6H-SiC P+NN+ and N+PP+ MESA structures have been studied. They are depicted in Figure 1. Medici software enables us to determine the geometric parameters of the MESA structure versus doping level and the thickness of the active epilayer suitable for a breakdown voltage value. These parameters are the MESA bevelled angle \( \alpha \) and the MESA depth \( Y \). The passivation is completed with a deposited and annealed SiO\(_2\) layer. The charge density at the SiC/SiO\(_2\) interface \( Q_s \) greatly influences the equipotential lines distribution at the surface. This parameter has been also taken into account in the simulations.

The highest breakdown voltages are obtained for a MESA edge almost vertical \( (\alpha \approx 0^\circ) \) and for a depth equal to the sum of the emitter and the active epilayer thicknesses. The charge density \( Q_s \) is positive and estimated to be \( 10^{12} \text{ cm}^{-2} \). Nevertheless, this optimized structure does not allow to obtain the theoretical value according to the ionisation coefficients of Ruff [3] for a 1D ideal plane junction as shown below.

In fact, two factors tend to decrease the simulated breakdown voltage. First, the dry etch process produces an overetch at the lower MESA corner that brings about a premature breakdown. Furthermore, the problem of breakdown in an ambient atmosphere at the surface vicinity is not negligible in SiC. Thus, the maximum electric field in the SiC lies between \( 1 \sim 3 \text{ MV cm}^{-1} \) depending on the doping level of the active layer and approaches the critical electric field of the air \( (1 \text{ MV cm}^{-1}) \) or of the oxide \( (9 \sim 10 \text{ MV cm}^{-1}) \). Consequently, a high quality oxide together with the adequate choice of the ambient atmosphere remain crucial for breakdown requirements in SiC.
Fig. 2 — Equipotential lines distribution inside the MESA N⁺PP⁺ structure at the breakdown voltage and electrical field distribution (in grey and black) for values superior to 10⁶ V cm⁻¹

Figure 2 shows the equipotential lines distribution in an optimized N⁺PP⁺ MESA structure taking into account technological limits for a breakdown voltage of 900 V. We take care that simulation results do not depend on the boundary conditions related to the software. The active layer thickness is 8 μm with a doping level of 5 × 10¹⁵ cm⁻³, the critical electric field is estimated to be 2 × 10⁶ V cm⁻¹. The MESA etching is realized with α = 7° and Y = 5 μm. The breakdown takes place at the metallurgical junction at the MESA edge and the simulated breakdown voltage value corresponds to 69% of the theoretical value calculated for an ideal planar structure.

Taking into account these aspects, P⁺NN⁺ and N⁺PP⁺ MESA structures have been realized at LETI (Grenoble). Substrates and active epilayers were obtained from Cree Research, one of the two producers of SiC wafers in the world. The P⁺-type emitter is either implanted (imp.), or grown by epitaxy at LETI (epi.) or by Cree Research (Cree). Dry etching [4] produces two different angles (7° and 30°) depending on the mask (aluminium and oxide respectively). A deposited oxide layer was used as passivation, annealed or not, depending on the device. Ohmic contacts were implemented with aluminium on the P⁺-type layer and with tungsten + titanium silicide (W/TiSi₂) on the N⁺-type layer. These diodes have various geometric dimensions and technologies. For each reference, about 50 diodes with different diameters (100, 200, 400, 600, 800, 1000 and 1200 μm) were tested. Table I summarizes the diode characteristics and the main results concerning simulated (Vₙbr₁) and experimental (Vₙbr₂) breakdown voltage values as well as the theoretical value (Vₙth) calculated for an ideal planar structure. The first remark is that all the diodes have a common point: the destructive breakdown always located at the edge of the MESA structure except for D1b diode, which has a diameter larger than 400 μm, generally leaky.

D1 diodes seem to have the most optimized MESA structure because experimental breakdown voltages are rather the same as for D2 diodes with a thicker epilayer and a similar doping level. Note that the thicker the active epilayer is, the higher the breakdown voltage for a given doping level will be.
Table I. — Main results concerning experimental and simulated breakdown voltage of different MESA structures.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>D1a</th>
<th>D1b</th>
<th>D2a</th>
<th>D2b</th>
<th>D2c</th>
</tr>
</thead>
<tbody>
<tr>
<td>type</td>
<td>N⁺PP⁺</td>
<td>N⁺PP⁺</td>
<td>N⁺PP⁺</td>
<td>N⁺PP⁺</td>
<td>P⁺NN⁺</td>
</tr>
<tr>
<td>α (°)</td>
<td>7</td>
<td>7</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Y (µm)</td>
<td>5.7</td>
<td>5.7</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>emitter</td>
<td>impl.</td>
<td>epi.</td>
<td>Cree</td>
<td>epi.</td>
<td>Cree</td>
</tr>
<tr>
<td>active epilayer thickness (µm)</td>
<td>8</td>
<td>8</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>doping level (cm⁻³)</td>
<td>2 × 10¹⁴</td>
<td>8 × 10¹⁴</td>
<td>1 × 10¹⁶</td>
<td>5.9 × 10¹⁵</td>
<td>2.4 × 10¹⁵</td>
</tr>
<tr>
<td>oxide</td>
<td>annealed</td>
<td>annealed</td>
<td>non-annealed</td>
<td>non-annealed</td>
<td>non-annealed</td>
</tr>
<tr>
<td>V_{br1} (V)</td>
<td>770</td>
<td>870</td>
<td>690</td>
<td>430</td>
<td>300</td>
</tr>
<tr>
<td>with Qₙ (cm⁻²)</td>
<td>10¹²</td>
<td>10¹²</td>
<td>10¹²</td>
<td>10¹²</td>
<td>-10¹²</td>
</tr>
<tr>
<td>V_{br2} (V)</td>
<td>400–780</td>
<td>650–1100</td>
<td>800–1000</td>
<td>80–180</td>
<td>600–720</td>
</tr>
<tr>
<td>V_{brth} (V)</td>
<td>1324</td>
<td>1336</td>
<td>1291</td>
<td>1589</td>
<td>1764</td>
</tr>
</tbody>
</table>

The technology used to realize the N⁺-type emitter highly influences the breakdown voltage value. The nitrogen-implanted emitter of the D1a diodes gives non-leaky diodes, although the results are relatively dispersed. Moreover, the epitaxied emitter from LETI has a lot of crystalline defects responsible for high leakage current: diodes showing high breakdown voltage are small, their diameter is inferior or equal to 400 µm, the other are leaky. The main cause of breaking for D1 diodes is the overetch at the lower MESA corner where a high local electric field takes place. Breakdown brings about the complete destruction of the diode emitting a flash light and producing a crater in silicon carbide. Current-voltage (I–V) characteristics of D1a and D1b diodes (200 µm) are shown in Figure 3, measurements were performed at room temperature with a curve tracer.

D2 diodes do not give good electrical results because of the bad quality of the non-annealed oxide. Charge density at the SiC/SiO₂ interface is probably very high and induces the formation of an inverted channel on the SiC surface. This channel short-circuits the diode and a very high leakage current appears at high reverse biases. This phenomenon is more noticeable for D2a diodes than for D2c diodes, which tends to prove that a non-annealed oxide has more fixed charges when it is deposited on P-type SiC rather than on N-type SiC. Figure 4 shows 200 µm-diameter D2a and D2c (I–V) characteristics at room temperature. The blocking capability is unusual in particular for D2a diodes: breakdown is produced step by step with two stages of current before the final avalanche. Experimental breakdown voltages are higher than the simulated value. The difference between simulated and experimental results is due to the incomplete knowledge of the ionisation coefficient in SiC estimated by empirical formula, to the non-homogeneous doping level of the active layer with the uncertainty concerning its thickness, and to some surface phenomena.

The relatively scattered results concerning breakdown values are due to technological criteria; i.e. the emitter implementation, the edge MESA geometry and the quality of the passivation layer. On the other hand, the state of art concerning the SiC bulk growth does not enable us to have substrate and epitaxied layers free of crystalline defects as micropipes or dislocations.
Fig 3 — \((I-V)\) characteristics of a \(N^+PP^+\) MESA structure with an annealed oxide as passivation layer \(d = 200 \mu m, W = 8 \mu m, \alpha = 7^\circ, Y = 5 \mu m\). a) D1a diode, b) D1b diode.

3. Boron Diffusion in Silicon Carbide

Compensation associated to the MESA structure can be used to increase the breakdown voltage of structures with high-doped active layer. In the studied case, this technique consists in diffusing doping atoms able to compensate doping atoms of the active layer in order to decrease the free carrier concentration. Generally, a very high temperature is needed for diffusing in silicon carbide because of the low diffusion coefficient of most of the dopants. Only the boron diffusion can be reasonably used.

\(P^+NN^+\) structures with a high compensated \(N\)-epilayer realized at the Ioffe Institute (St Petersburg) have been characterized. The residual nitrogen doping level \((2 \times 10^{17} \text{ cm}^{-3})\)
Fig. 4. — $(I-V)$ characteristics of MESA $N^+P^+$ (a) and $P^+N^+$ (b) structures with a non-annealed oxide as passivation ($d = 200 \ \mu m$, $W = 11 \ \mu m$, $\alpha = 30^\circ$, $Y = 3 \ \mu m$).

of the N-type active epilayer obtained by sublimation is too high to obtain a high breakdown voltage. Thus, boron diffusion is used to compensate the N-type layer and to increase its high voltage capability. At room temperature, a breakdown voltage of 670 V for a reverse current of 10 $\mu A$ is measured instead of the 120 V in the case of a structure without boron diffusion. Nevertheless, the breakdown voltage decreases and the leakage current increases rapidly when the temperature increases as shown in Figure 5. This phenomenon cannot be explained by the classical evolution of the physical and electrical properties of this wide-bandgap semiconductor. This great temperature dependence can only be explained by the presence of deep levels of the boron atoms and the compensation rate evolution of nitrogen by boron with temperature.
Capacitance measurements $C(V)$ show that the doping level in the N-type layer evolves in the same way as the temperature (it ranges from $10^{13}$ cm$^{-3}$ at 300 K to $10^{17}$ cm$^{-3}$ at 500 K). Therefore, we believe that a great concentration of boron is responsible for this doping variation with temperature. A deep-level study in the silicon carbide band-gap by admittance spectroscopy reveals the presence of D-centres at 0.63 eV from the valence band associated to boron at concentration similar or superior to nitrogen concentration in the N-type layer. Figure 6 shows the free holes (p) and electrons (n) concentrations evolution across the structure versus the temperature. After boron diffusion and at room temperature, the active N-type epilayer becomes a low-doped zone (I zone) able to give a high reverse voltage. This is due to the similar solubility limits of boron and nitrogen in silicon carbide that permits to have neighbour nitrogen ($N_D$) and boron ($N_A$) concentrations. I zone is probably low P-type doped towards the P$^+$-type emitter where $N_A > N_D$ and low N-type doped near the N$^+$-type substrate where $N_A < N_D$. When the temperature increases, trapped electrons in the N$^-$-type zone and trapped holes in the P$^-$-type zone become free and contribute to the increase of doping levels of N-region and P-region, respectively. This phenomenon damages for blocking behavior. A detailed analysis of the different mechanisms is given in literature [5].

In conclusion, boron diffusion significantly improves the breakdown voltage of P$^+$NN$^+$ structure with a high-doped active layer, but only for a certain range of temperature.

4. P$^+$NN$^+$ 6H-SiC Structure with a Planar Junction Termination

In order to avoid all problems related to the MESA etch, it might be interesting to devise a planar edge termination. Accordingly P-type Junction Termination Extension (JTE) is realized on P$^+$NN$^+$ planar 6H-SiC and N-type Schottky structures to spread out the equipotential lines at the silicon carbide surface, these two kinds of diodes are represented in Figure 7. Concerning bipolar diodes, P$^+$ type Al-implanted emitter is realized. P-type lateral extension is implanted, high energies must be used to create a deep junction in silicon carbide. A post-implantation
Fig. 6 — Evolution of free carriers concentrations profiles versus temperature, (—) at 300 K, (…) at 500 K.

Fig. 7. — P⁺NN⁺ protected planar diode (a) and N-type planar Schottky diode (b) with P-type lateral extension
annealing is performed at very high temperature (higher than 1500 °C) in order to activate P-type dopants which are boron atoms in this case.

Two junction diameters were used (160 and 250 μm), and either protected or unprotected diodes were built. Nickel is used to contact the N⁺-type substrate, aluminium for ohmic contact on P⁺-type and Schottky contact on N-type silicon carbide. The N-type active epilayer has a thickness of 10 μm and a doping level of $5 \times 10^{15}$ cm$^{-3}$. The best experimental breakdown voltages are 1.7 kV for bipolar and 1.2 kV for Schottky diodes. Figure 8 shows the $(I-V)$ characteristic of one of the smallest bipolar diodes measured at room temperature. Experimental results are better than the 1.5 kV breakdown voltage value predicted by simulation and than the 1.54 kV theoretical value obtained for an ideal plane structure.

These good results can be explained by considering the favourable part of the surface charge density that tends to spread out the depleted zone at the SiC surface. However, the epilayer can be thicker than 10 μm or with an advantageous non-homogeneous doping level. The breakdown takes place at the periphery of the lateral extension, as predicted by simulation. The lack of passivation is connected with breakdown in the ambient environment: breakdown voltage is higher and leakage current is lower when tests are performed in a silicon oil with a higher electric permittivity than that of the air. These first results concerning these planar structures are encouraging. Nevertheless, it is necessary to find an efficient way to protect the SiC surface against breakdown outside the semiconductor.

5. Conclusion

Planar peripheral protection seems to be the best solution for power silicon carbide devices (for blocking capabilities below 2 kV). Technological process steps (etching, oxidation, ...) and poor substrate and epiayer crystalline quality (presence of dislocations, micropipes, doping heterogeneity, ...) limit the obtaining of the theoretical breakdown voltage. However, it is necessary to have a better knowledge of the electric field distribution and avalanche mechanisms in silicon carbide to make comparisons between experiment and simulation.
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