Study of Silicon Carbide high voltage ability: experimental results on expitaxial-emitter and implanted-emitter diodes

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STUDY OF SILICON CARBIDE HIGH VOLTAGE ABILITY : EXPERIMENTAL RESULTS ON EPITAXIAL-EMITTER AND IMPLANTED-EMITTER DIODES.

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INTRODUCTION

Silicon carbide is considered as the most promising semiconductor for power electronics, superior to silicon with regard to future application trends in terms of voltage, power, temperature or frequency increases [1]. Very attractive physical properties (high energy bandgap, high breakdown electric field, high saturated velocity and good mobility of carriers, high thermal conductivity), and good recently published electrical performance of experimental structures, both explain this general interest for SiC electronics.

Concerning the high voltage ability of silicon carbide, the availability of better quality thick epilayers has allowed rapid progress in high breakdown voltage diode realisation during the last five years (1000V-Schottky diode [2], 2000V- [3] and more recently 4500V-bipolar diodes [4]). These structures confirm the ability of SiC-pn junctions in sustaining much higher reverse voltage than silicon ones, under equivalent conditions of layer doping levels and thicknesses. However, these SiC-high breakdown voltage-diodes still present a destructive breakdown, leading to leaky reverse I(V) characteristics. Moreover, they are limited in maximum forward current, having low active areas due to substrate micropipe densities still relatively high [5] (especially for 6H-SiC polytype). These remaining difficulties in the realisation of high voltage power diodes show the need for further research effort in this field.

This paper presents experimental results we obtained studying reverse electrical characteristics of high voltage bipolar diodes. The influences of junction diameters, and ambient natures (air or silicone oil), on breakdown locus and breakdown voltages are given and discussed, for both epitaxial- and implanted- emitter mesa structures. In the end, we also present more recent experimental results corresponding to planar diodes, with implanted junction termination extension as a peripheral guard.

EXPERIMENTAL STUDY OF MESA STRUCTURES

The mesa diodes have been realised at CEA-LETI, using two 1 inch 6H-SiC wafers (purchased from CREE Research in 1992). Each wafer consisted in a p^--epilayer (with specified thickness of 8 µm, and net doping level of few 10^{14} cm^{-3}) on a p^+-substrate, and allows the creation of a n^+p^--junction using one of the two following techniques : an epitaxial growth by in-situ N-doping CVD, and a multiple N-ion implantation. Circular mesa-devices were patterned on each wafer by plasma etching of its surface through an aluminum mask. 5.7 µm-deep mesa structures, with seven different diameters from 100 µm to 1200 µm, were thus obtained. Passivation of the etched surfaces was realised by deposition of a 6500 Å-SiO_2-layer. Contact metallizations were made by sputtering tungsten on the top of n^+-cathodes, and by evaporating aluminum on p^+-substrates. Figure 1 presents a schematic view of these mesa structures.

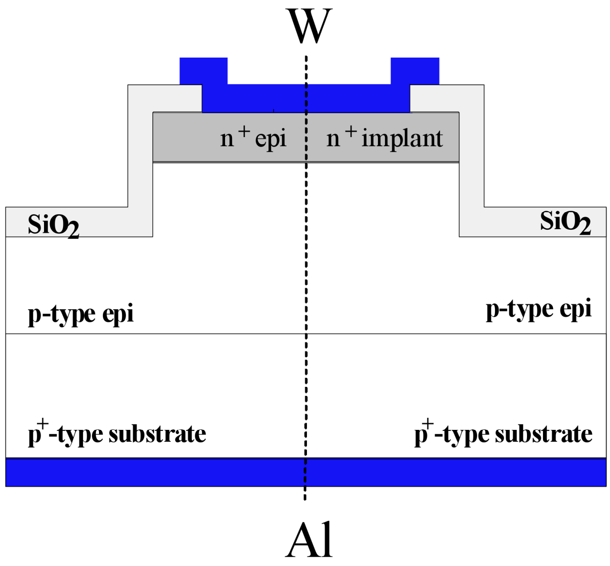

Figure 1 : Cross-section of 6H-SiC mesa diodes.

About seventy diodes of each type (epitaxial and implanted) were characterised until breakdown voltage at room temperature. The behaviour of the device at breakdown was studied by measuring the Current(Voltage) characteristic evolution (using a curve tracer Tektronix 370A in DC bias) on one hand, and by directly viewing the device under test through a binocular on the other hand, for breakdown locus observation. Breakdown voltages, and leakage current (I_R) versus reverse voltage (V_R), were studied in correlation with diode sizes.

RESULTS AND DISCUSSION ON MESA STRUCTURES

A common observation for both types of studied mesa-diodes was the occurrence of a reverse voltage for which the reverse current suddenly strongly increased. Simultaneously a possible appearance of a bright flash, resulting afterwards in a black mark on the top of the devices, could be observed. We defined this particular reverse voltage as the breakdown voltage of the device. After breakdown, voltage capability of the device was generally reduced, with leakage currents irreversibly higher than before breakdown, for the same applied voltage. Different kinds of pre-breakdown electrical characteristics could be distinguished.

Description of $I_R(V_R)$ characteristics before breakdown

Two main different behaviours of $I_R(V_R)$ curves before breakdown at 300 K were observed for the two types of studied mesa diodes. The first behaviour corresponds to as-defined "leaky diodes". These diodes are presenting high current versus reverse voltage with discontinuities and slope changes of the $I_R(V_R)$ curve. In these cases, breakdown occurs for reverse currents between 100 µA and 5 mA, and for reverse voltages lower than 400 V for epitaxial-emitter diodes and 350 V for implanted-emitter diodes. The second behaviour corresponds to "non-leaky" diodes, with a stable reverse current component lower than 1 µA for increasing voltages, until breakdown. The latter occurs without any precursor sign for voltages higher than 500 V.

Figure 2 shows an example of a Current(Voltage) characteristic obtained on a 100 µm-diameter epitaxial-emitter diode, dipped in silicone oil, just before a breakdown happens. 1100 V-breakdown voltage corresponds to the highest value obtained from our diodes at room temperature, all measurements mixed up. Such a value corresponds to 75 % of the theoretical evaluation calculated for a planar asymmetrical n^+p^--junction with base thickness of 8 µm and a base doping of $8x10^{14}$ cm^{-3}, and using a critical electric field of

$1.7x10^6$ V/cm derived from impact ionization coefficients found in [6]. The high voltage drop that can be noticed on figure 2 for high currents in on-state operation is both due to the high resistivities of low-doped p-type base and of ohmic contacts realised on top-emitter and bottom-substrate.

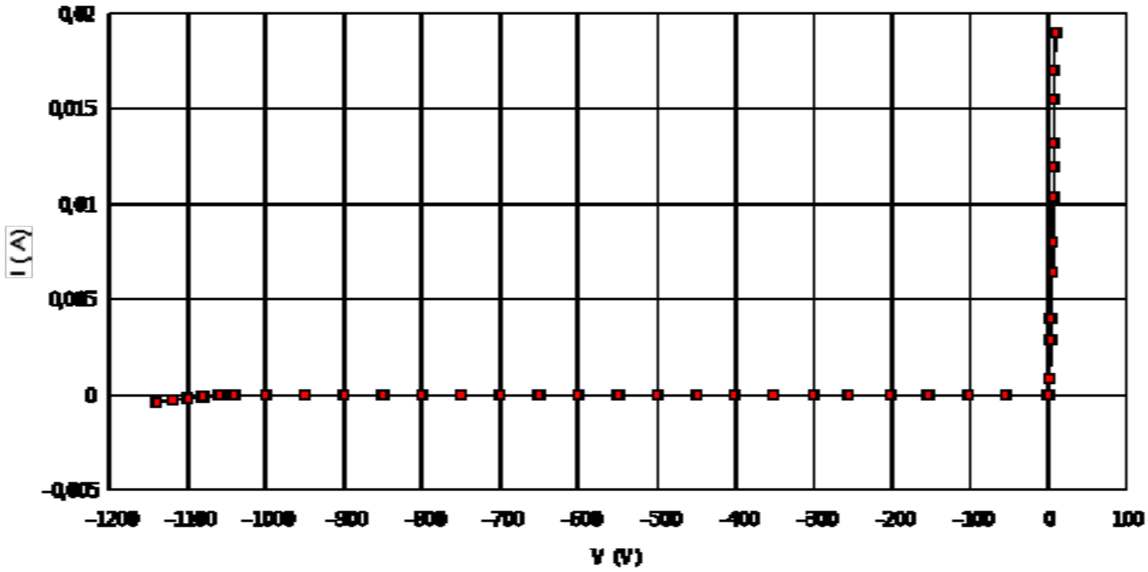

Figure 2 : Current(Voltage) characteristic of a 100 µm-diameter 6H-SiC mesa diode with a n^+-epitaxial emitter, measured at room temperature in silicone oil ambient.

In the case of devices with an implanted-emitter, a third typical electrical behaviour before breakdown was also noticed. First the $I_R(V_R)$ curve presents low but non-stable currents (with parasitic peaks) which vanish for a given maximum reached voltage (and after several bias scans). A further increase in maximum reverse voltage leads to a higher non stable level of $I_R(V_R)$ curve, with a final breakdown for currents lower than 100 µA and voltages higher than 400 V.

A great difference versus device diameters exists between epitaxial- and implanted-mesa diodes concerning the measured values of breakdown voltage.

Influence of the device diameter on reverse electrical behaviour

The epitaxial-emitter diodes show a large scattering of breakdown voltage values, from few tens of Volts to 900 Volts in air ambient at room temperature. This result is clearly correlated with the device size, since only 60 % of 100 µm- diodes and 20 % of 200 µm-diodes present breakdown voltages higher than 500 Volts (until 1100 V in silicone oil ambient). These small devices were also the only ones to show very low leakage currents under reverse biases (corresponding to the second type of behaviour described above). All the other diodes present a leaky behaviour, with low breakdown voltage values.

By comparison, the scattering in implanted-emitter diode breakdown voltages is lower, with measured values at room temperature between 400 V and 600 V in air, all diameters mixed up. In fact, very few implanted-diodes (about 10 %) were leaky under reverse biases, all having diameters higher than 600 µm. But most of the implanted-structures had an electrical behaviour under reverse bias of the third type described above, with "progressive" breakdown, equally distributed between the different diameters. The highest voltage capabilities are however obtained from non-leaky devices presenting a sudden and clean breakdown almost exclusively on 100 µm-diameter diodes. The maximum breakdown voltage value obtained with such devices was 780 V in silicone oil. The thickness of the p^--

base layer, smaller than the specified one (as derived from C(V) measurements) can be one reason for this apparent lower voltage capability of implanted-emitter diodes compared with epitaxial-emitter ones.

Observation of breakdown locus and ambient nature influence

For small-size epitaxial diodes that show the highest breakdown voltages, bright flashes can often be observed, leaving marks on the mesa top, near its periphery. Moreover the measurements realised using silicone oil as the ambient resulted in maximum breakdown voltages 20% higher that the corresponding values obtained using air ambient.

These observations suggest that the breakdowns mainly occur in periphery of these diodes, either in ambient or at $SiC/Si0_2$ interface. Probable degradation of the passivation, resulting in increased surface leakage could explain the higher reverse current after breakdown. No noticeable degradation of the forward characteristic after breakdown also confirms that the inside junctions is not affected by the breakdown. For the other epitaxial-emitter diodes, of the leaky-type, marks in the middle of the top metallization can be observed after breakdown (this one occurring at high current). This fact indicates a breakdown possibly due to structural defects in the junction bulk. Such structural defects, effectively noticed along the surface of the n^+-epilayer can also explain the higher leakage currents observed for large devices in comparison with small ones.

In the case of the implanted-emitter diodes, assuming that the absence of mark or the presence of a mark within the middle of a device metallization are related to a bulk phenomenon, and that the existence of a mark near the mesa top edge revealed a peripheral breakdown, then the following observations could be made. Small devices (essentially of 100 µm- and 200 µm- diameters) preferably present a breakdown that occurs at the periphery of the mesa, slightly increased by the use of silicone oil instead of air. On the contrary, leaky-diodes preferably show a breakdown in the device bulk, possibly due to the presence of micropipes, which can explain the $I_R(V_R)$ curve discontinuities. For the most common behaviour observed, corresponding to "progressive" breakdown in three phases, $SiC/Si0_2$ interface instabilities can be involved. Peripheral phenomena can lead to breakdown in most of these cases.

RECENT RESULTS ON PLANAR IMPLANTED STRUCTURES

Planar diodes have been realised in collaboration with the Applied Physic Institute in Erlangen. They are based on a CREE 6H-SiC n^--epilayer (above n^+-substrate) with specified thickness of 10 µm and net doping level of $4x10^{15}$ cm^{-3}. The circular p^+-emitter region was realised by Al-ion implantation. The peripheral guard consists in a pn^- junction termination extension ("JTE" protection), that was created by ion implantation too. Total studied device diameters remain lower than 400 µm. Figure 3 schematically describes these structures, having contact metallizations made of aluminium and nickel on p^+-emitters and n^+-substrate respectively. No passivation was realised on the semiconductor surface.

Typically above 1000 V, up to 1300 V, the breakdown voltages in air ambient occur with reverse currents up to 250 µA at room temperature. Before breakdown, the reverse current values weakly evolve with bias time, and present the shape corresponding to curve n°1 shown on figure 4. The tests in oil ambient lead to the reduction of the leakage current measured for a given reverse voltage after several minute of bias supply. Under these conditions, higher typical breakdown voltages than those obtained in air are measured, reaching more than 1600 V at room temperature. The curve n°2 on figure 4 gives an example of a pre-breakdown I(V) characteristic obtained in oil ambient. After breakdown, either in air or in oil ambients, the I(V) characteristic is transformed into a stable and reversible curve like curve n°3 shown on figure 4. This characteristic presents a rapid increase of leakage current typically occurring between 600 V and 800 V. A visible degraded zone located at the edge of the guard termination is sometimes observed after breakdown. The high voltage capability obtained from these "JTE" 6H-SiC diodes represents an interesting experimental result.

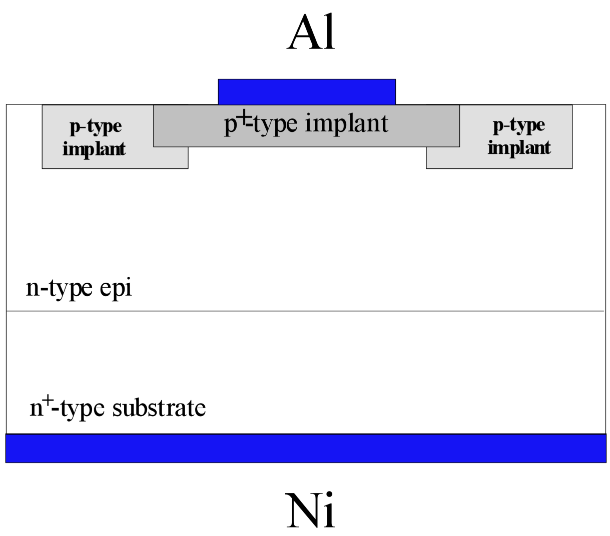

Figure 3 : Cross-section of 6H-SiC planar JTE diodes.

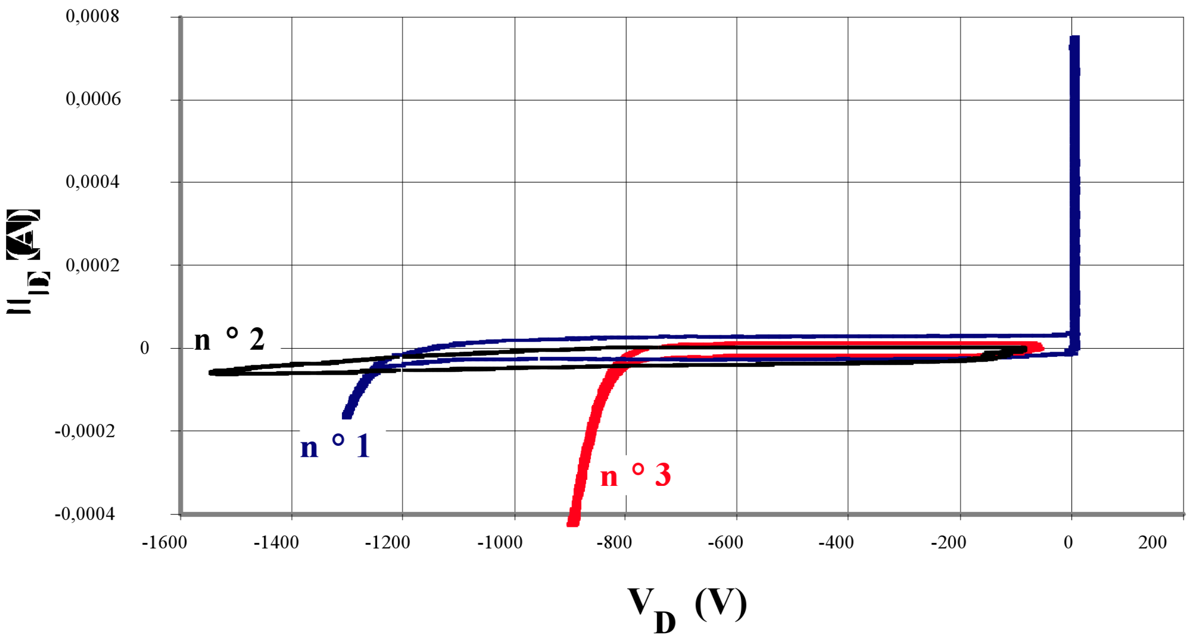

Figure 4 : Current(Voltage) characteristic of a 6H-SiC $p^+n^-n^+$ diode with a JTE guard, measured at room temperature in air and silicone oil ambients.

CONCLUSION

6H-SiC-mesa-bipolar diodes were realised using either an epitaxial-growth or a multiple-implantation for the n^+p^--junction creation, based on two comparable CREE p^--epilayers. A difference in maximum reverse voltage scattering has been shown between these two types of diodes. The lower reproducibility in breakdown voltage values of epitaxial-emitter structures compared to implanted-emitter ones is probably related to the higher density of structural defects arising from the epitaxial-emitter realisation. Correlatively a stronger effect of device size on the leaky or non-leaky behaviour results for epitaxial-emitter.

For both kinds of mesa-diodes however, the smallest diodes were able to reach the highest reverse voltages with sudden breakdown appearance. The breakdown locus are shown to occur near these device periphery, leading to I(V) characteristic degraded at reverse biases essentially. The respective roles of ambient nature (effective but weak) and passivation remain to be enlightened. More recently, a very interesting reverse voltage capability has been experimentally obtained with 6H-SiC $p^+n^-n^+$ Junction Termination Extension diodes, presenting breakdown voltages up to 1600 V at room temperature.

In conclusion, these experimental results are representative of two main current difficulties in the realisation of SiC high power devices. The first is related to basic- and epitaxial- material quality. The second corresponds to the critical influence of peripheral parameters including ambient natures. A better understanding of electric field distributions under reverse biases, especially along SiC surface, appears to be a third topic of important investigations.

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