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Quality of the ohmic contact on 4H-SiC p⁺ area and its impact on direct conduction and voltage capability

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Abstract

Based upon the characterization of two types of 4H-SiC JBS diodes compared to SiC Schottky diode, this paper presents the influence of the p⁺ activation and well-contacting on the electrical characteristics in forward and reverse mode. The papers will mainly focus on the forward current level, lower without p⁺ activation than with a fully efficient p⁺ layer, compared to state-of-the-art devices. The reverse leakage current is also determining, since it will be higher if there is only a Schottky barrier to protect the blocking mode. After discussing the static results, dynamic measurements will be performed to confirm the non-activation of some p⁺ and analyzing its influence on switching mode. Finally, a destructive measurement of the surge current of each diode will complete the study.

Keywords: Buck converter, Edge termination, High integration level, High voltage, JBS diodes, Power devices, Schottky diodes, Silicon carbide.

Introduction

Today's trend is to save energy and a widely used energy carrier is electricity. Great projects such as smart grid networks need static power converters with high voltage capabilities. Devices with high performances and low loss are needed. In this context, this paper presents a key issue of the efficiency of power devices : the reliability of the ohmic contact on the p⁺ area. Indeed, as we will discuss later, a good quality ohmic contact will improve direct

current conduction and reduces leaks in reverse mode [1, 2].

4H-SiC allows the design of high voltage devices with a high integration level thanks to its 3.3 eV wide band gap, 2.5 MV.cm⁻¹ high critical electric field and carriers mobility in the same order of magnitude as the one in silicon. Proposed diode can be implemented as free-wheeling diodes in an inverter leg configuration.

After some technological considerations on

design and fabrication, electrical characterization will be presented. The static characterization first focuses on determining the forward current density, reverse voltage sustainability and temperature influence on the robustness of the diode. Those results will be compared to previous works on ohmic contact improvements and on the bipolar conduction impact on JBS diodes. Dynamic behavior is then investigated, in order to confirm the behavior of the diodes and the influence of the contact.

Past works on edge termination lead to reliable process options [3]. So the focus was on the active area of the device, leading to a reduced number of technological steps.

1. State of the art of power diodes

Schottky and bipolar diodes have already been fabricated with a 3.3 kV voltage capability [4] in ambient temperature as high as 300°C and commercialized [5]. Since the Schottky diode on-state resistance is quite high, the junction area for a given forward current must be larger than bipolar diodes one.

Since diode devices compatible with a JFET process [6] have been investigated, reliable 3.3 kV JBS diodes have been demonstrated [7] combining low threshold voltage of a Schottky diode and the low on-state resistance of the bipolar counterpart. Moreover, in reverse mode, such diodes present a leakage current 10 times lower than Schottky diodes one. Such a technology is now fully understood and perfectly analyzed [8].

As a comparison, GeneSiC Semiconductor provides an example of state-of-the-art high voltage (3300 V) commercial diodes [5]. This paper discuss about bipolar-Schottky ratio for JBS diode and its influence on electrical performances.

2. Technological considerations

2.1. Process steps

First of all, the first epilayer was optimized with 10^{15} cm^{-3} doping level and 40 μm thickness [9] on 3" CREE SiC material. For this optimization, the edge termination and the passivation efficiencies were taken into account.

A 7-step process is needed to fabricate the proposed JBS diodes. It begins by a p⁺-implantation for the ohmic contact, followed by a p-implantation forming the edge termination, consisting in a 400 μm JTE with standard dose. In order to process a channel stopper, a n⁺ implantation is then performed around the edge termination. A first deposited oxide is opened where a thin and a thick metal (Ti-Ni-Al annealed as usual) creates the anode contact. Then comes a polyimide passivation.

2.2. Devices specific features

In order to determine the influence of the ohmic contact on the bipolar part on JBS electrical characteristics, three different kinds of diodes were implemented on each elementary die : two multifinger JBS diodes with 3 μm of p⁺ layer and 4 μm of n layer (JBS3-4) and one JBS diode with 3 μm of p⁺ layer and 8 μm of n layer (JBS3-8). The active area for both diodes is 3.9 mm². A cross section of those devices is presented in figure 1. In the last field is a Schottky diode, without p⁺ layer in its active area, but only on the edge, before the JTE, thus avoiding floating area.

This scribeline plane leads to the fabrication of more than 150 JBS3-4 diodes and 70 JBS3-8 diodes and Schottky diodes per wafer respectively. Such an important number of diodes fabricated following mature technological steps is compatible with industrial production related to a specific application but since the wafer still contains various geometries and

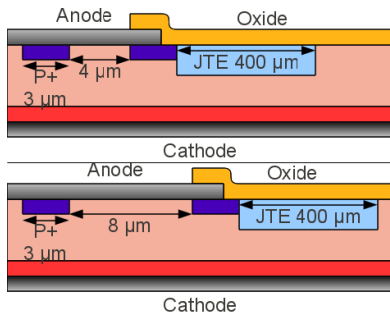


Figure 1: JBS diodes with 3 μm of p^+ layer and 4 μm of n layer (top) and with 3 μm of p^+ layer and 8 μm of n layer (bottom)

test structures, it enables specific measurements in order to estimate where barriers remains.

A first run counts 3 wafers and measurements on the devices from these latter wafers are presented in next section.

3. Static measurements, results and first discussion

Measurements performed on those devices will lead to the complete knowledge of the behavior of diodes in static and switching mode, temperature drift and stress. Moreover it will allow estimating design influence on electrical characteristics, specifically the bipolar-Schottky ratio on JBS.

3.1. High voltage capability

All diodes were first measured in forward bias mode in order to estimate if a direct current can flow through the device.

Table 1: Quality factor and Schottky part for diodes

Type	n (quality factor)	Schottky area
Schottky	1.05	3.90 mm^2
JBS3-8	1.06	1.98 mm^2 (51%)
JBS3-4	1.12	1.23 mm^2 (32%)

Based on these primary results, the conducting diodes were submitted to a higher voltage

than theoretical limits but under vacuum atmosphere at room temperature [10].

As a first result, the influence of the p^+ strips on breakdown voltage is analyzed: their presence or not for Schottky diodes and their spacing for JBS. Typical electrical characteristics are presented in figure 2.

Since avalanche is often not visible with this kind of diodes, the experimental breakdown criterion is set to 250 μA reverse leakage current. As it can be seen in figure 2, for a given voltage, there is one order of magnitude in leakage current between JBS3-4 devices and Schottky diodes.

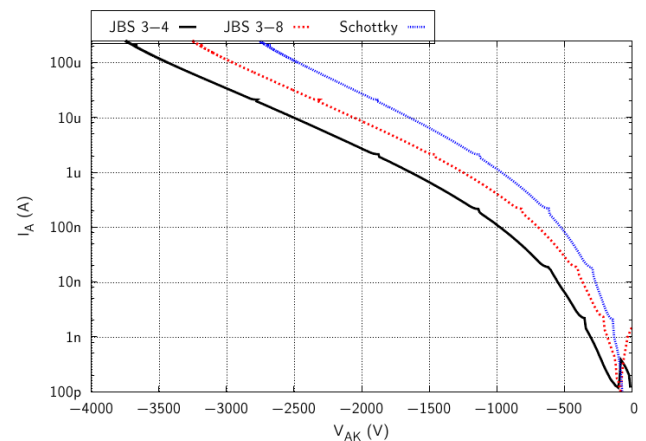


Figure 2: Influence of bipolar part on leakage current (wafer level measurement in vacuum atmosphere, 250 μA leakage current criterion, ambient temperature)

Overall for a higher bipolar part, diodes sustain higher voltage and present lower leakage current.

3.2. Influence of temperature

Diodes were then diced and packaged in TO3 cases once all components static characteristics were extracted in forward and reverse modes for the whole working area. Components can now be submitted to higher current density and higher voltage in normal atmosphere and higher temperature.

Three characterizations were performed. First a static characterization under warm pulsed air 25, 75, 125, 175 and 225°C.

As presented earlier, all diodes have a more or less important Schottky part. Classical effects of temperature on such diodes electrical characteristics in forward mode are a decrease in the threshold voltage and an increase in the on-state resistance; figure 3 presents this latter effect, leading to a decrease of the forward current for a given voltage.

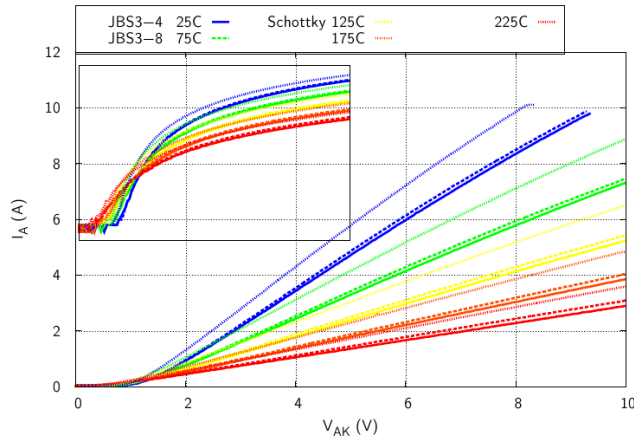


Figure 3: Effect of temperature on the diodes : increasing the on-state resistance and reducing the threshold voltage; moreover, none of the diodes presents a double-barrier

At room temperature, threshold voltages are the same for all diodes, likewise at 225°C. Nonetheless, if JBS3-4 or JBS3-8 diodes have about the same on-state resistance, Schottky diodes on-state resistance is about 25% lower than JBS devices' one at room temperature as well as at 225°C, contradicting the expected effect. Moreover, as it can be seen on the figure 3 on the embedded figure, JBS diodes do not present the JBS typical double-barrier effect. A first conclusion of those measurement is that the p^+ area of the JBS diodes is not activated, or the contact on this area is very bad.

3.3. Robustness and reliability

Secondly, the robustness of the diodes in conduction was tested with a 4 A forward pulsed current during 1 h, repeated 5 times. The pulses are 100 μs long and repeated every 200 ms. After each 1 h period, a static characterization was performed to estimate a possible degradation.

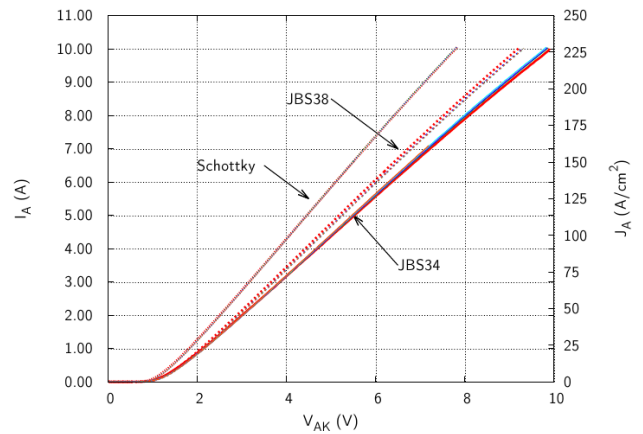


Figure 4: Static characterization during and after robustness test, consisting of a 4 A forward conduction during 1 h, repeated five times, do not present significant variations of the forward current after the test

During and after the test, the threshold voltage and the on-state resistance show the same experimental values than before. So a 5 h stress under high current is not harmful for diodes so far. The typical self-heating phenomenon in the Schottky is here avoided thanks to the use of pulsed current. What can be deduced is that there is no bipolar degradation (or only minor degradation), thus confirming the non-contributing bipolar p^+ area.

3.3.1. Discussion on the static characteristics

Unlike what has been seen so far [11], the bipolar conduction mode never starts on this diodes, neither for a high current density not at high temperature. A consequence for the

high current is a negative temperature coefficient due to the decrease of the carrier mobility with the temperature, leading to an increase of the on-state resistance in forward mode. For the low current and the reverse mode, the consequence is the decreasing of the voltage drop when temperature increase, due to the decrease of the Schottky barrier height with the temperature, leading to a lower voltage drop in forward mode and higher leaks in reverse mode. In fact, the difference between the reverse currents of the Schottky diode and what was expected as a JBS diode is not as great as what is classically measured.

4. Dynamic characteristics

4.1. C-V measurement and junction area determination

Figure 5 presents a C-V characterization of the three types of diodes. Voltage varies from 0 down to -40 V in order to offer a correlation with switching mode results, with 20 mV amplitude, at 10 kHz. Under -20 V, capacitances are the same for all types of diodes.

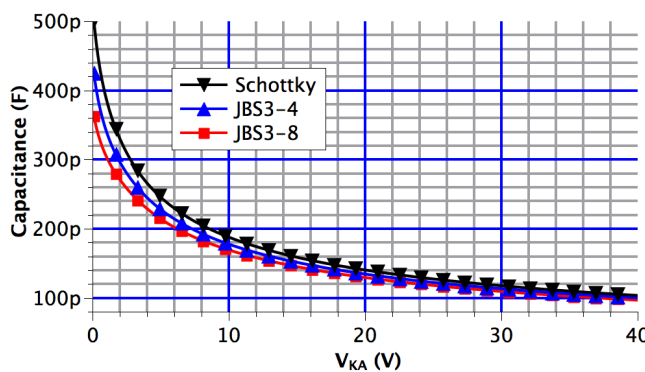


Figure 5: C-V characterization for junction area estimation

For low voltages (until -20 V), the diode capacitance is higher if the bipolar part is larger.

The phenomenon is due to the small space-charge region around p^+ bulks. Indeed, the ratio written between JBS3-4 and Schottky area, and between JBS3-8 and Schottky, respectively 2.25 and 1.71 is the equivalent junction area including the $0.5 \mu\text{m}$ depth of p^+ bulks.

But it must be noted that under a -20 V reverse-voltage applied to diodes, capacitances are the same for all types of diodes. It means that for higher voltage, the junction area is the same for JBS and Schottky diodes [12]. So, the JBS traditional bipolar part is not activated under high reverse voltage.

4.2. Switching results

The junction area has a strong influence on switching performance : a smaller junction area means less charge, so the diode presents a lower switching time. This will be estimated with the circuit presented on figure 6, used for the last characterizations in switching mode.

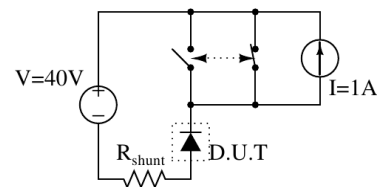


Figure 6: Schematic of the buck-like configuration used for diode switching behavior analysis, under 40 V and 1 A

In this conditions, for low voltage switching, JBS3-4 will be faster. In the other hand, for high voltage switching, for which one diodes were designed, geometry and bipolar part width has no influence, since it appears as non-activated bad-contacted.

All diodes have mostly the same behavior when working in commutation. Figure 7 shows the turn-off waveform for a JBS3-4 device, a JBS3-8 device and a Schottky diode. The differences between the waveforms are

minor and show similar recovery charges due a major unipolar conduction [11].

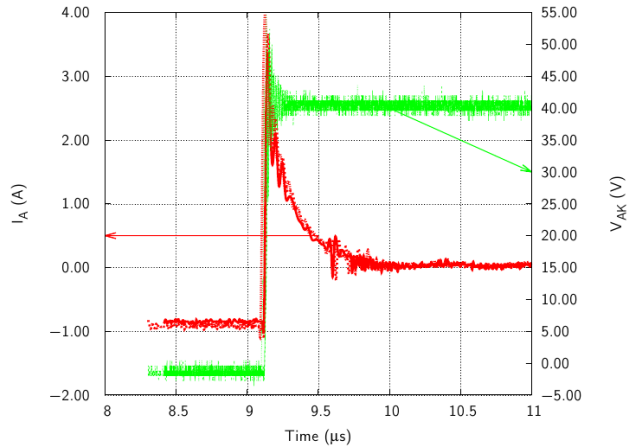


Figure 7: Turn-off switching waveforms for a JBS3-4 device, JBS3-8 device and a Schottky diode, under 40 V and 1 A in the circuit in figure 6

4.3. A destructive measurement : surge current measurement

Barcelona’s microelectronics center (CNM-IMB) enables high current characterization thanks to a home-made tester [13], applying the classical half-sine wave on the DUT. Since this kind of measurement is destructive for the device, surge current capabilities was estimated at the end. Figure 8 presents the results of the measurement at the breakdown point. The breakdown current is summarized in table 2.

Table 2: Summary of the breakdown current for different types of diodes

Kind of diode	I_{BR}	$0.8 \times I_{BR}$
Schottky	18.9 A	15.1 A
JBS3-8	17.4 A	13.9 A
JBS3-4	17.6 A	14.1 A

It can be seen on figure 8 that for a voltage higher than 20 V, the current first decreases

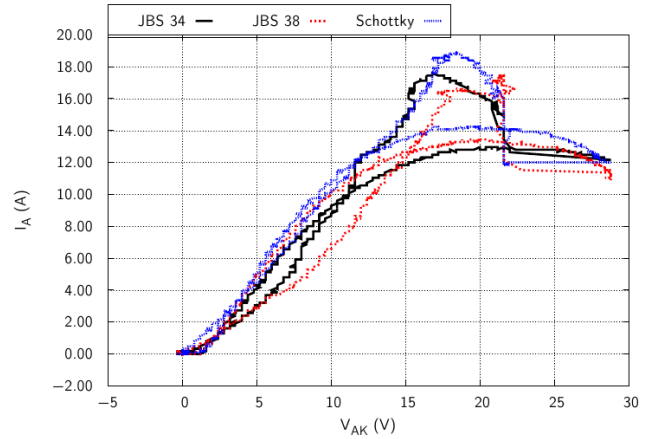


Figure 8: $I - V$ measurement at the breakdown current for the three kind of diodes

before breaking down. A high on-state resistance can lead to a self-heating of the diode and a self-increase of the on-state resistance. This maybe results from the device as well as the package or the bonding wires of the diode [14]. Traditionally, JBS diodes have a higher surge current capability thanks the bipolar injection. In that case, the breakdown currents are really close from each other for all kind of diodes, confirming the non-activation of the p^+ layer.

Conclusion

The existing 3.3 kV diode market is not widely covered with dedicated devices. This paper presents one of the key point of the reliability of high voltage devices : the bipolar conduction through p^+ layer activation and well contacting.

Moreover, high performance JBS diodes allow a high forward current density and a fast switching time when the p^+ is fully efficient.

In fact, JBS3-4 will be preferred for its high voltage capability (more than 3.5 kV) with low leaks (less than $50 \mu A$ in that case). such an electrical characteristic in reverse mode perfectly fits the state-of-the-art in reverse mode,

and a fully efficient p⁺ layer would bring those device to the direct mode state-of-the-art.

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