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A complete methodology for determining the influence of the design for 3.3 kV silicon carbide diodes : JBS compared to Schottky

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Abstract

The paper presents the design and the characterization of Schottky and JBS diodes, for high voltage matching. Design for manufacturing has been preferred and diodes have been fabricated following a semi-industrial methodology. Then electrical characterization was performed on devices : static characterization, including temperature influence, dynamic characterization in a buck-like configuration to evaluate the behavior in switching mode and C-V characterization to identify some parameters like the junction area. Whereas forward conduction is provided with low on-state resistance, 3.3 kV capability is demonstrated with low leakage current, low turn-on and low turn-off delays.

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 the design, the fabrication and the characterization of 3.3 kV high voltage 4H-SiC Schottky and JBS diodes based on a sim-

ple industrial fabrication process.

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 characteriza-

tion will be presented. The static characterization first focuses on determining the forward current density, reverse voltage sustainability and temperature influence. Dynamic behavior is then investigated, in order to estimate turn-on and turn-off times in a buck-like configuration. Finally, surge current capabilities are estimated.

Past works on edge termination lead to reliable process options [1]. 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 [2] in ambient temperature as high as 300°C. 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 [3] have been investigated, reliable 3.3 kV JBS diodes have been demonstrated [4] 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 [5].

As a comparison, ST provides an example of state-of-the-art medium voltage (1200 V) commercial diodes [6]; the device is capable of 12 A forward current with short switching times. This paper focuses on 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 [7] 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. 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 creates the anode contact. Then comes a polyimide passivation.

2.2. Devices specific features

In order to determine the influence of the bipolar part on JBS electrical characteristics, three different kinds of diodes were implemented on each elementary scribeline : two 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 protection step process.

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

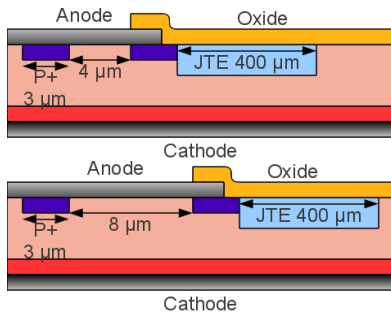


Figure 1: JBS diodes with $3 \mu\text{m}$ of p^+ layer and $4 \mu\text{m}$ of n layer (left) and with $3 \mu\text{m}$ of p^+ layer and $8 \mu\text{m}$ of n layer (right)

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

3. Measurements, results and 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 the reliability of the front and rear ohmic contacts. Then the voltage capability was tested. The breakdown criterion is first set to 400 V because measurements are performed in air atmosphere. This ensures a rectifying contact without significant leakage in reverse bias, whereas it drives current in forward mode.

Table 1: Quality factor and Schottky part for diodes

Kind of diode	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, wafers were submitted to a higher voltage than theoretical limits but under vacuum atmosphere at room temperature [8].

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 $250 \mu\text{A}$ 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.

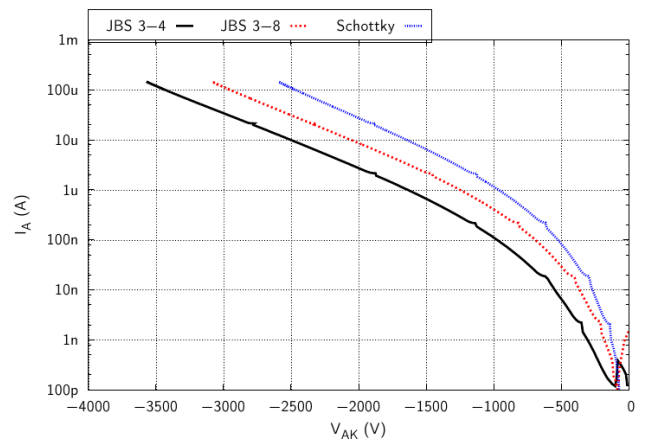


Figure 2: Influence of bipolar part on leakage current (wafer level measurement in vacuum atmosphere, $250 \mu\text{A}$ leakage current criterion, ambient temperature)

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

Thanks to the high number of available samples, reliable statistics presented in figure 3, emerged from the measurements.

This figure shows that the majority of Schottky diodes (without p^+ layer) or JBS3-8 (with a minor part of p^+ layer) are limited to 3 kV.

In contrast, since about half of the JBS3-4

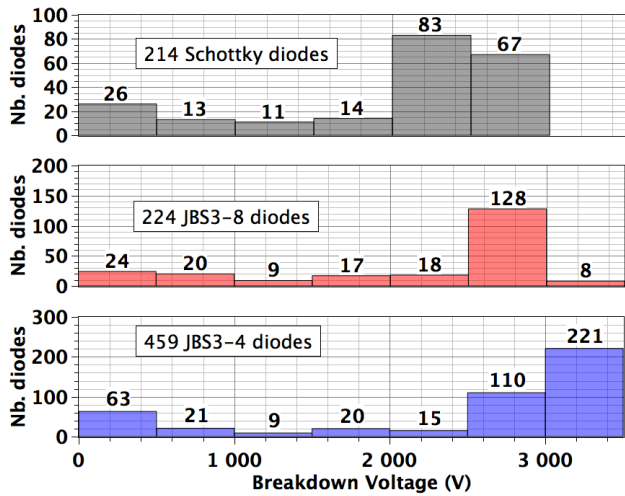


Figure 3: Histogram of breakdown voltage of diodes ($50 \mu\text{A}$ leakage current criterion, vacuum atmosphere, ambient temperature)

devices with a thicker p^+ layer sustain more than 3 kV, the importance of the bipolar on high voltage capability is confirmed.

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 4 presents this latter effect, leading to a decrease of the forward current for a given voltage.

A typical effect of temperature in reverse mode is an increase leakage current. figure 5

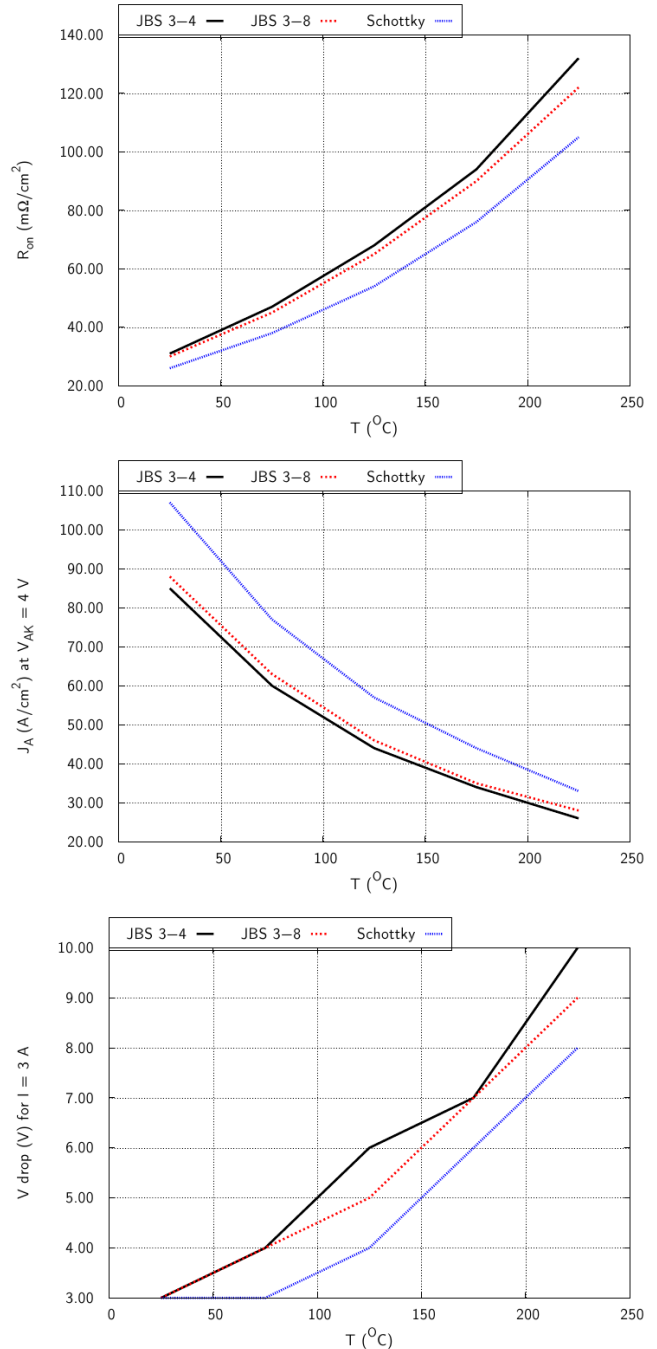


Figure 4: Influence of temperature on different kinds of packaged diodes (JBS3-4, JBS3-8 and Schottky respectively) in terms of on-state resistance drop, forward current for $V_{AK} = 4 \text{ V}$ and voltage drop for $I_A = 3 \text{ A}$

illustrates this effect, showing the drop of the current for a given voltage of -1000 V .

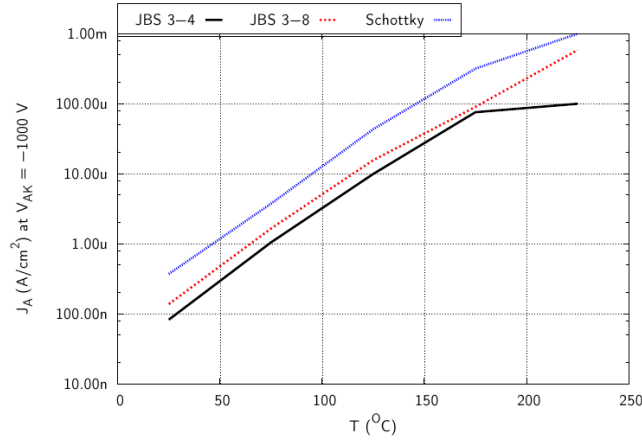


Figure 5: Influence of temperature on leakage current for different kinds of packaged diodes (JBS3-4, JBS3-8 and Schottky respectively) under 1 kV reverse voltage

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 .

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 $100\ \mu\text{s}$ long and repeated every 200 ms. After each 1 h period, a static characterization was performed to estimate a possible degradation. As shown in figure 6, there is only minor degradation. As a conclusion, it can be said that all diodes are able to drive a high forward current.

During and after the test, the threshold voltage and the on-state resistance show the same experimental values as before. So a 5 h stress under high current is not harmful for diodes so far. The typical self-heating phenomenon in

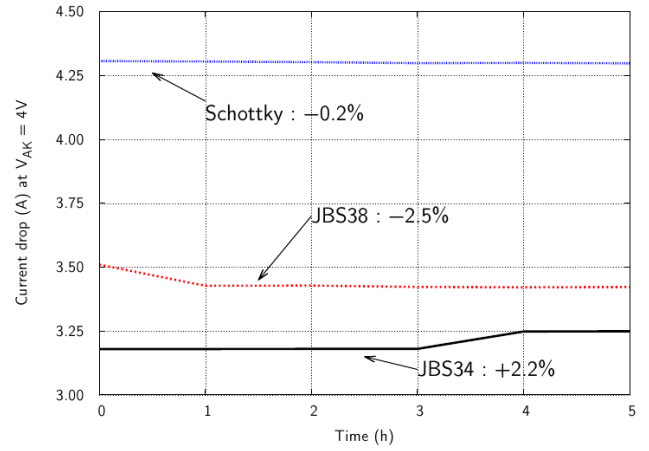


Figure 6: Static characterization during and after robustness test, consisting of a 4 A forward conduction during 1 h, repeated five times, and relative variations of the current at $V_{AK} = 4\text{ V}$ after the test

the Schottky is here avoided thanks to the use of pulsed current.

3.4. Summary: preferred geometry for improved static characteristics

Presented results on the high voltage capability, the behavior under different temperatures or the robustness shows a trend for the influence of bipolar/Schottky ratio on JBS static electrical characteristics. As a first conclusion it has been said that even if Schottky diodes have a lower on-state resistance (figure 4), if the bipolar part is important, the device sustain higher voltage with less leaks (figure 2). This phenomenon is more true for a high temperature ambience in reverse mode (figure 5).

Robustness of the diodes is not engaged, so for a high voltage reaching, the preferred design will be the one with a larger bipolar part : the JBS3-4 diode, even if it is a little bit more resistive.

3.5. Dynamic characteristics and influence of geometry

Figure 7 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.

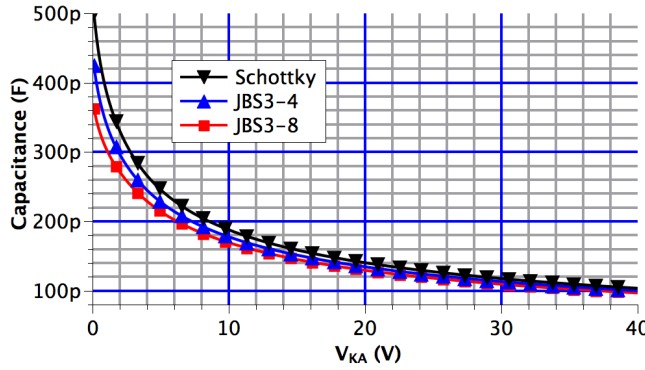


Figure 7: C-V characterization for junction area estimation

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. So, the JBS traditional bipolar part is not activated under high reverse voltage.

This 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 8, used for the last characterizations in switching mode.

In this conditions, for low voltage switching, JBS3-4 will be faster. In the other hand, for high voltage switching, for which one

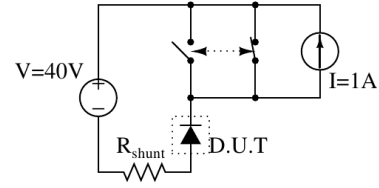


Figure 8: Schematic of the buck-like configuration used for diode switching behavior analysis, under 40 V and 1 A

diodes were designed, geometry and bipolar part width has no influence.

All diodes have mostly the same behavior when working in commutation. figure 9 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 as summarized in table 2.

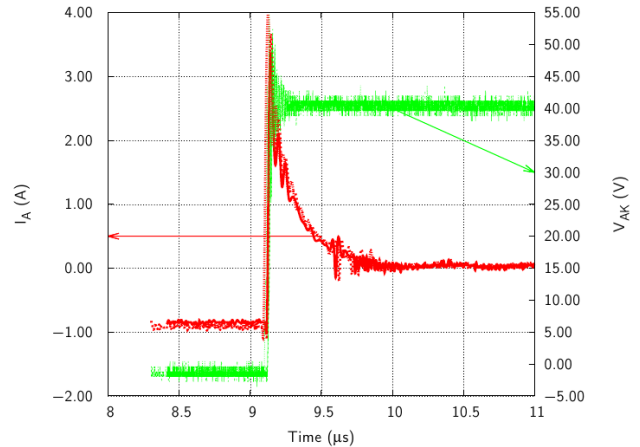


Figure 9: Turn-off switching waveforms for a JBS3-4 device, JBS3-8 device and a Schottky diode, under 40V and 1A in the circuit in figure 8

The t_{rr} value is the time between the first sign change in the current and the time the current meets 0 A after its first maximum. This value and Q_{rr} one are in the same order of magnitude as those of medium voltage commercial diodes [6]. The JBS3-4 Q_{rr} is the lower, thanks to its low junction area that enables a fast switch at high dI/dt .

Table 2: Comparison of main electrical characteristics for different types of diodes

	Schottky	JBS3-8	JBS3-4
V_{AK-max}	55 V	53 V	52 V
I_{A-max}	4 A	3.7 A	3.4 A
Q_{rr}	630 nC	550 nC	500 nC
t_{rr}	730 ns	585 ns	612 ns
dI/dt	136 A/ μ s	167 A/ μ s	162 A/ μ s

3.6. A destructive measurement : surge current measurement

Barcelona's microelectronics center (CNM-IMB) enables high current characterization thanks to a home-made tester [9], 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 10 presents the results of the measurement at the breakdown point. The breakdown current is summarized in table 3.

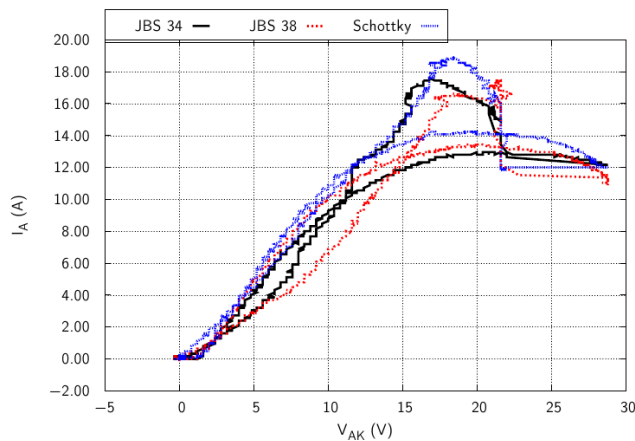


Figure 10: $I - V$ measurement at the breakdown current for the three kind of diodes

It can be seen on figure 10 that for a voltage higher than 20 V, the current first decreases 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

Table 3: 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

the package of the diode [10]. Traditionally, JBS diodes have a higher surge current capability thanks the bipolar injection. But what is also induced by this figure is that the p^+ layer is not activated, and thus cannot inject current through the diode [11]. In this case, Schottky diode has a higher current capability and a lower on-state resistance even when working at high current.

Conclusion

The existing 3.3 kV diode market is not widely covered with dedicated devices. Devices presented in this paper can be considered as a reliable answer for inverter applications, thanks to their high voltage capability.

Moreover, high performance JBS diodes allow a high forward current density and a fast switching time.

In facts, JBS3-4 will be preferred for its high voltage capability (more than 3.5 kV) with low leaks (less than 50 μ A). Thanks to the low influence of design on switching delays, this diode will be fast enough for many high voltage applications.

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