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# Impact of design on electrical characteristics of 3.5 kV 4H-SiC JBS diode

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**Abstract.** This work reports on the fabrication and electrical characterization of 3 different diodes. The first one is a Schottky diode with a single 50  $\mu\text{m}$  P<sup>+</sup> ring between the edge termination and the active area. The two other diodes are JBS with a 3  $\mu\text{m}$  P<sup>+</sup> strips separated by 4  $\mu\text{m}$  and 8  $\mu\text{m}$  respectively. The breakdown voltage ranges from 2.7kV up to 3.7kV depending on the P<sup>+</sup>/N area. The 3 different diodes exhibit a similar on-resistance versus the temperature behavior. Moreover, no contribution of the bipolar conduction is observed and no degradation has been observed when a forward stress is performed in forward mode and also in reverse.

## Introduction

Nowadays, Gallium Nitride (GaN) and Silicon Carbide (4H-SiC) are the most promising Wide Band Gap (WBG) semiconductors for high power applications. GaN is very attractive due to its hetero-epitaxial growth on large inexpensive Silicon substrate. However, due to the insulated buffer layer, devices fabricated on GaN are either lateral or quasi-vertical and must have a lateral conduction. As a result, the on-resistance ( $R_{\text{on}}$ ) / Breakdown voltage ( $V_{\text{br}}$ ) trade-off is limited for breakdown voltage higher than 1.2 kV. In contrast, high quality 4H-SiC substrates and epilayers are commercially available for high  $V_{\text{br}}$  applications.

This paper-presents different results on 4H-SiC 3.5kV diodes. Our diodes design is based on the Junction Barrier Schottky (JBS) diode concept [1]. The coexistence of P<sup>+</sup>/N junction and Schottky contact leads to an improvement of the  $V_{\text{br}}$  and protects the device against overloads. The first part of this paper deals with the design of fabricated diodes and describes the process flow. Then, the reverse performances will be presented. Therefore, the forward characteristics will be detailed. Finally, current stress and capacitance measurements will be analyzed.

## Design and fabrication of JBS diodes.

The first high voltage 4H-SiC JBS diode was developed at Linköping university [2]. This work exhibited that a JBS diode has a lower threshold voltage in forward mode and a higher leakage current in reverse mode than a PiN diode. This paper also demonstrates the dependence of the switching losses to the Schottky area - P<sup>+</sup>/N junction area ratio. So, a JBS diode is a very good trade-off between a pure Schottky diode (low threshold voltage, fast switching) and a bipolar rectifier (high forward current, high breakdown voltage). 3.5kV 4H-SiC diodes suitable for DC/AC converter have been designed to be implemented in a 100 A-3.5kV power module. Fig. 1 shows the cross section of a JBS diode with  $L_{\text{P}}$  as the P<sup>+</sup>/N junction length and  $L_{\text{N}}$  as the Schottky contact length. Three different designs have been implemented in a set mask layout. Table 1 summarizes the

main parameters of each diode. The active area of all diodes is  $3.9 \text{ mm}^2$ . A Schottky diode has been also implemented. It is not a pure Schottky because a  $P^+$  ring is implemented between the edge termination and the Schottky contact. A lower leakage current and a higher surge current than a pure Schottky diode are expected thanks to this ring.

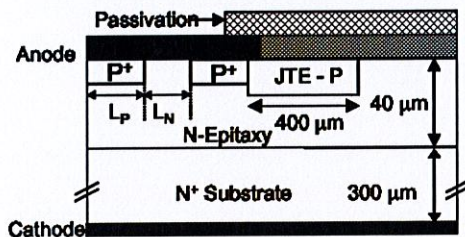


Fig. 1 Schematic cross-section of a 4H-SiC JBS diode.

Table 1. Summary of the different geometrical features for each JBS diodes

Diode name	$L_P$ ( $\mu\text{m}$ )	$L_N$ ( $\mu\text{m}$ )	Schottky area ( $\text{mm}^2$ )
JBS3-4	3	4	1.23 (32%)
JBS3-8	3	8	1.98 (51%)
Schottky	-	-	3.90

The diodes have been manufactured at IBS Company, SiC foundry services company, thanks to seven photolithography masks on three wafers from CREE. The thickness and the doping level of the drift layer is  $40 \mu\text{m}$  and  $10^{15} \text{ cm}^{-3}$ , respectively. Two different aluminum multi-energy implantations have been performed to implement the  $P^+$  rings and the  $P^-$  Junction Termination Extension (JTE). The edge termination length ( $L_{\text{JTE}}$ ) is  $400 \mu\text{m}$ . The wafers were annealed with classical parameters for dopant activation. The anode contact area has been defined by a selective etch of a  $\text{SiO}_2$  layer. Metallic stacks configurations are Ti/Ni and Ni for cathode and anode contacts respectively. The cathode contact has been annealed at  $900^\circ\text{C}$  and  $350^\circ\text{C}$  for the anode contact. Before a polyimide layer deposition, a thick (Ti/Ni/Ag) metallization have been deposited. The diodes have been packaged in a TO3-package at CIRTEM facilities. A Silgel<sup>TM</sup> from Vacker is used for the encapsulation. Its operating temperature is  $150^\circ\text{C}$ .

## Reverse mode

The blocking measurements have been performed in a vacuum chamber at ISL facilities prior to the packaging process [3]. Fig. 2 shows the reverse electrical characteristics for 3 different diodes. Each measure is representative of each diode category. One can see that a low Schottky/ $P^+$  rings area ratio (JBS3-4, 51% Schottky), led to the lowest leakage current. Considering a maximum leakage current value of  $200 \mu\text{A}$ , the breakdown voltage is between  $2750\text{V}$  for Schottky diode up to  $3750\text{V}$  for the JBS 3-4. The JBS 3-8 diode exhibits a breakdown voltage of  $3250\text{V}$ . Thanks to the  $P^+$  rings and the decrease of their spacing, the breakdown voltage increases.

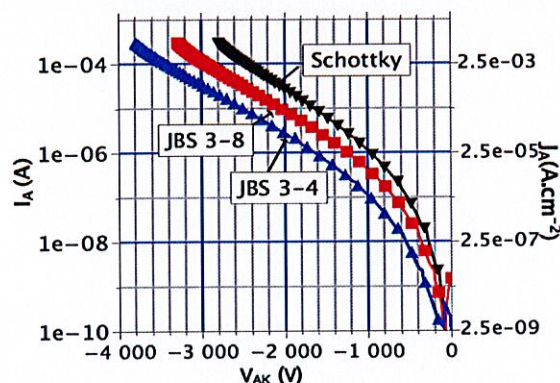


Fig. 2 : Reverse electrical characteristics of three different JBS diodes at  $25^\circ\text{C}$

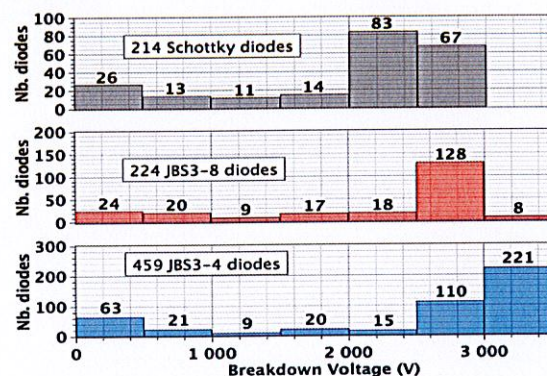


Fig. 3 : Histogram of breakdown voltage of diodes at  $50 \mu\text{A}$  leakage current criterion in vacuum at  $25^\circ\text{C}$

A statistic analysis is performed on the 3 different wafers. More than 700 diodes have been characterized, 214 Schottky diodes, 224 JBS3-8 diodes and 459 JBS3-4 diodes. Fig. 3 shows a histogram of all measured diodes. For a lowest leakage current value ( $I_A=50 \mu\text{A}$ ), 48% of the JBS3-4 diodes exhibit a breakdown voltage higher than  $3000\text{V}$ . These first results show that the

technological process is very promising for an industrial future confirming that a JBS 3-4 diode configuration is the best candidate from the reverse mode point of view.

### Forward mode

JBS diodes have been characterized in forward mode using a homemade curve tracer with 300 ms as period and 100  $\mu$ s as the power pulse for a temperature range from 25°C to 225°C. The maximal temperature is limited to 150°C by package gel properties. Fig. 4 exhibits the forward characteristics of a JBS3-4 diode. For a forward voltage  $V_{AK}=4V$  @  $T=25^\circ C$ , the current is 3.5 A and decreases with the temperature to reach  $I_A=1A$  at 225°C. At 25°C, the On-resistance is 31.5  $m\Omega.cm^2$ , 29.8  $m\Omega.cm^2$  and 24.8  $m\Omega.cm^2$  for JBS3-4, JBS3-8 and Schottky diodes, respectively. JBS diodes show a higher resistance due to the  $P^+$  rings. These results exhibit a pure Schottky conduction for the JBS diode having the higher  $P^+$  area. So a specific analyse has been done.

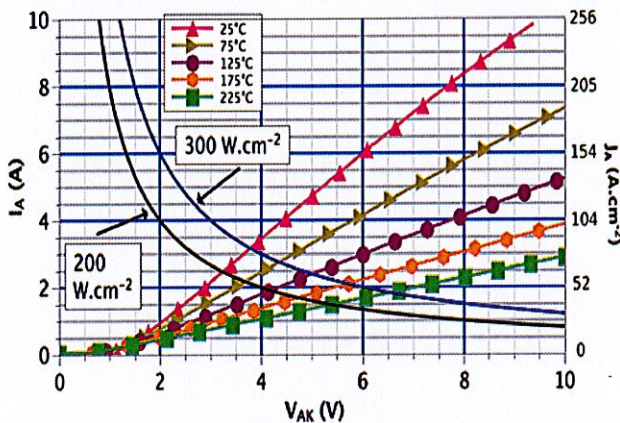


Fig. 4 : Forward electrical characteristics of JBS3-4 diode between 25°C up to 225°C.

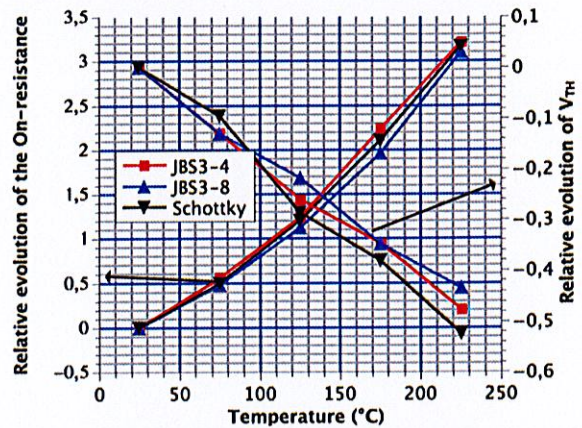


Fig. 5 : Relative evolution of on-resistance (@ 4A) on the left and threshold voltage on the right versus temperature for the 3 different diodes.

The relative evolution of the On-resistance (@ 4A) and Threshold voltage as a function of the measurement temperature have been extracted and reported in Fig. 5. The on-resistance is multiplied by 4 when the temperature increases from 25°C up to 225°C. The tendency is the same between the 3 different diodes. As a result, these first analyses tend to demonstrate that there is no bipolar contribution of the  $P^+$  rings. The origin of the no-contribution of the  $P^+$  rings is attributed to the non-ohmic characteristics of the anode metallization (Ni) on the  $P^+$  wells regions. Previous study has shown that even though  $P^+$  wells presence reduces the Schottky contact area, the current spreading under them minimizes the increase of on-resistance due to channeling [4]. Moreover, this effect is accentuated as the drift region thickness increases, which explains the low discrepancy between the On-resistance of our different devices.

### Forward stress

With our homemade curve tracer, we have also performed electrical stress at 4A (current density of 103  $A.cm^{-2}$ ) during 5 hours at 25°C. A current voltage (I-V) characteristic has been checked after each hour. The electrical stress was performed in pulse mode in order to avoid package and temperature contributions. Fig. 6 shows the relative variation of the on-resistance for 3 different diodes. The diodes exhibit a similar and low variation of the on-resistance (<3%). So, we do not observe any degradation of the forward properties of diodes. It is conventionally stated that the bipolar diode degradation is due to stacking fault formation under bipolar conduction conditions. The absence of diode degradation is thus coherent with the previous characterizations pointing-out the non-bipolar contribution of the  $P^+$ -rings. Then, the diodes have been characterized in reverse mode up to 1000V. The leakage current remains relatively constant as an increase of only  $\Delta I_A=5\%$  has been observed. These results are promising for an industrial future but electrical stress at higher

temperature (125 °C) must be done in order to validate the fabrication process. Furthermore, an optimization of the P<sup>+</sup> rings ohmic contact should enhanced the surge capabilities of those 3A-3.5kV JBS diodes

### Capacitance measurements

The junction capacitance of the 3 different diodes has been characterized at 25°C. Fig. 7 shows the evolution of the capacitance from 0V to 40V. At 40V, the capacitance is around 100pF for all diodes. At 0V, the Schottky diode has a higher capacitance than the JBS. This is probably due to the higher Space Charge Extension for a Schottky contact than the P<sup>+</sup>/N junction.

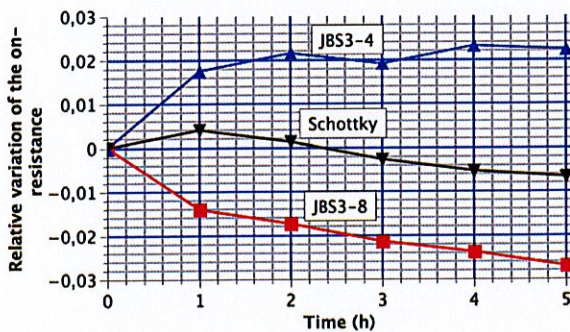


Fig. 6 : Relative evolution of the On-resistance for the 3 different diodes under continuous current stress conditions ( $I_f=4A @25^\circ C$ )

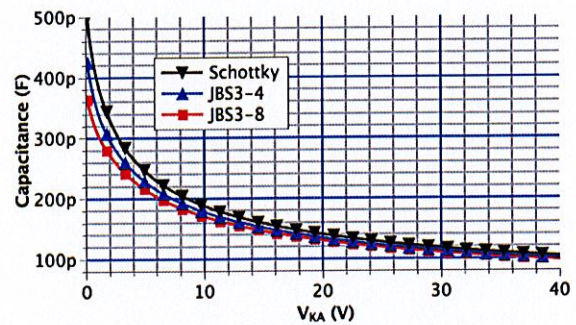


Fig. 7 : Anode/Cathode Capacitance versus reverse voltage at 25°C for the 3 different diodes.

### Conclusion

In this paper, 3 different diodes have been fabricated and characterized. The extracted On-resistance is very similar between the 3 different designs. On the JBS devices, no bipolar conduction has been observed. This phenomenon is probably due to a highly resistive contact between the anode metal and the P<sup>+</sup> strips. Moreover, the forward characteristics exhibit low discrepancy between the On-resistance of the different designs due to the current spreading under the P<sup>+</sup> wells. The reverse leakage current decreases when the P<sup>+</sup> to Schottky ratio on JBS diode increases. This evidences the positive effect of the P<sup>+</sup> wells on the reverse characteristics. So, the JBS 3-4 is the best solution.

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