Analysis of 600 V/650 V SiC Schottky Diodes at Extremely High Temperatures

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Abstract—This paper evaluates the thermal characterization of late generation SiC schottky diodes. 600 V/650 V SiC diodes from 3 well-known manufacturers are tested: Wolfspeed, Infineon and Rohm. A comprehensive study is performed for a wide temperature range from 20 °C (room temperature) up to 500 °C, aiming to find the absolute maximum parameters of SiC schottky diodes at extremely high temperature environments. Both static and dynamic characterizations are evaluated and explained. TCAD simulations are proposed to express the abnormal phenomenon occurred in test results, especially the mechanism of hole carrier transportation in extremely high temperature. This work exhibits the performance of SiC schottky diodes for high temperature application conditions.

Index Terms—High temperature, performance evaluation, SiC schottky diodes, TCAD simulation.

I. INTRODUCTION

RECENT years, the power electronics application systems like battery management, electric vehicles become widespread used in industry and personal life. The performance of power electronics devices becomes an important limitation of energy storage and convert systems. Compared to traditional Si devices, Silicon Carbide (SiC) devices show overwhelming superiority. As the most mature WBG semiconductor materials, SiC shows high speed, high operation voltage and high temperature capabilities, which makes better efficiency and reliability in application systems.

This paper focuses on the analysis of high temperature performance of SiC schottky diodes, the temperature range is from room temperature to 500 °C. Several researches are already done in the field of SiC diodes temperature performance[1]–[5], but the temperatures are limited under 350 °C. However, harsh application conditions of higher temperature exist as well. For example, the device junction temperature could reach nearly 800 °C after avalanche breakdown within a short time [6], [7]. A few publications mentioned higher temperature analysis [8], [9], but the devices belong to the previous commercial generation, or they do not have comparison. Therefore, it's necessary to study the

TABLE I
PARAMETERS OF DIODES UNDER TEST

Manufacturer	Device	IF (25 °C)	V _{RRM} (25 °C)	T _{Max}	Package
Wolfspeed	C3D10060A	10 A	600 V	175 °C	TO-220-2
Infineon	IDW10G65C5	10 A	650 V	175 °C	TO-247-3
Rohm	SCS110AG	10 A	600 V	175 °C	TO220AC

Fig. 1. Double pulse test and heater platform.

extremely high temperature performance and reliability of SiC schottky diodes for specific working conditions of power electronics applications.

We test three SiC schottky barrier diodes from different manufactures in wide temperature range, and reasonable explanations are performed. In particular, two of the schottky diodes show evident electronic performances as bipolar devices, which need to be discussed intensively relevant to the device structure. After years of process improvements, the JBS/MPS structure becomes a typical structure of SiC schottky diodes [11], [12]. A few researches focus on the minority carrier injection of JBS/MPS diodes, explaining the influence of electrostatic doping [14], high-barrier [15], but they do not mentioned the direct temperature influence of SiC schottky diodes.

In this paper, we evaluate the thermal performance of late generation SiC schottky diodes from room temperature to 500 °C, the comprehensive performance of devices are proposed and extensive TCAD simulations are also performed. The paper is organized as follows: in Section II, we present the experimental setup of our test, including the curve tracer, double test and heater platform; in Section III, we investigate the static and dynamic characterizations of devices tested, forward/reverse dc characteristics, capacitance and reverse recovery

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Fig. 2. Current-voltage curves at different temperatures. (a) Wolfspeed forward current. (b) Infineon forward current. (c) Rohm forward current.

effect are all evaluated using curve analyzer and double pulse test board; in Section IV, the device structure and test results are analysed in detail using TCAD, which perform to give a strong evidence of test results, especially the abnormal phenomenon of device operation method, finally, the conclusions of device performance in extremely high temperature and the effect on applications are drawn in Section V.

II. EXPERIMENTAL SETUP

The devices under study are listed in Table I, which shows the representative characteristics. 600 V/650 V 10 A SiC schottky barrier diodes manufactured by Wolfspeed, Infineon and Rohm are chosen for comparison, they all have extremely fast switching time, nearly zero reverse recovery current and high-frequency operation, which are high-performance fast-recovery diodes in electrical application circuits.

In order to measure the characteristics of SiC schottky barrier diodes mentioned in Table I, a complete test platform with a special heater is built. The DC characteristics of SiC SBDs are measured by Keysight B1505A and N1265A. The capacitances are measured by Keysight N1272A, which could offer a high voltage bias for capacitance measurements. The dynamic characteristics are measured using a well-designed double pulse test board with little parasitic influences. Several instruments are used cooperatively with test board shown in Fig. 1, including a high voltage power supply, signal generator, oscilloscope and appropriate probes. Since the fast turn-on/turn-off speed of SiC devices, the drive signal generated from signal generator should reach an edge less than 10 ns, and the oscilloscope and probe must capture the switching signals correctly. For diode characteristics measurement in extremely high temperature, a special heater is made to offer a temperature range from room temperature to 600 °C, including heater band, control system, spliced blocks, and an attenuator is necessary as well. The shape of the heater is convenient to be used with test platform mentioned before.

III. CHARACTERIZATION RESULT

In the following section, measurement results for both static and dynamic characterizations of SiC schottky diodes listed in Table I are presented. The parameters include forward current, buildup voltage, serial resistance, leakage current, capacitance

and reverse recovery effect, which are measured from 20 °C to 500 °C.

A. DC Characterization Measurement

From Fig. 2, we can see that the forward current of all devices decrease clearly. As we know, for high mobility semiconductors such as gallium arsenide and silicon carbide, the thermionic emission process is the dominant current transport mechanism in the current flow of SiC schottky power rectifiers, so the current density is proportional to the ambient temperature. In addition, since the temperature is going higher, the electronic mobility drops sharply affected by the phonon and lattice vibration scattering which is shown in (1). In application field, the decrease of forward current may cause the degradation of overall circuit performance. For example, the threshold voltage is defined as the current density exceeds 100 A/cm², the typical values of SiC SBDs are in range of 1.5 V–1.8 V at room temperature. Wrong operation would appear as wrong premature conduction caused by variation of threshold voltage. Besides, to observe the current slope, the Wolfspeed and Infineon diodes increase singularly as temperature reaches 300 °C, the phenomenon shows that higher temperature leads to stronger carrier impact and abnormal characteristics which will be discussed in detail in Section IV.

$$\mu_n(4H - \text{SiC}) = 1140 \left(\frac{T}{300} \right)^{-2.7} \quad (1)$$

Fig. 3 shows a more distinct trend of forward DC changing by temperature. In Fig. 3(a), buildup voltages are extracted as current equals 0.5 A, which could approximately reflect changes of on-state voltage. The buildup voltages decrease from 1 V to nearly 0.8 V since the thermionic emission becomes more active, the devices become conducting state easier. The on-state voltage is given by (2), where J_F/J_S is the forward/saturation current density, and $R_{s,sp}$ is the total series resistance. As the reduction of the schottky barrier height, the saturation current density increases with temperature, which leads to the on-state voltage drop.

$$V_F = \frac{kT}{q} \ln \left(\frac{J_F}{J_S} \right) + R_{s,sp} J_F \quad (2)$$

Fig. 3. Forward DC characteristics at different temperatures. (a) Buildup voltage 1. (b) Serial resistance. (c) Buildup voltage 2.

Fig. 4. Reverse DC characteristics at different temperatures. (a) Wolfspeed leakage current. (b) Infineon leakage current. (c) Rohm leakage current.

According to Fig. 3(b), the series resistances are rising as temperature goes higher. As the specific resistance of the ideal drift region can be expressed in (3), the specific on-resistance of the drift region becomes larger since the electronic mobility decreases, which leads to more power dissipation.

$$R_{\text{on-ideal}} = \frac{4BV^2}{\epsilon_s \mu_n E_c^2} \quad (3)$$

Fig. 3(c) shows the buildup voltages as current equals 10 A, the voltage increases as the temperature rises, but for Wolfspeed and Infineon devices, voltages start to drop after 300 °C, which indicates the same phenomenon just as forward current. The reason is the thermal runaway effect will seriously cause changes of SiC performance [10]. Although the thermal resistances are similar for the three devices in a reasonable temperature range, the device junction temperature of Wolfspeed and Infineon must be higher than ambient temperature as the different device size, packaging used, which cause the performance change evidently. From Fig. 3, we can also see that Rohm device has superior performance, more stable voltage and lower resistance.

As Fig. 4 shows, the leakage currents increase quickly, the Wolfspeed and Infineon diodes reaches 10⁻² A and Rohm diode reaches 10⁻⁴ A at 500 °C, the breaking down voltage decreases relatively. The thermionic emission component is the dominant theory of leakage current, which can be obtained by (4). From the equation and the previous discussion, we can

see that the leakage current density can be strongly effected by schottky barrier height and temperature. The leakage current is influenced by schottky barrier injection and diffusion current, high temperature can highly increases diffusion of schottky barrier. At the same time, there is a reduction of the Schottky barrier height due to the image force lowering phenomenon which cause a significant increase in the leakage current with increasing reverse bias voltage. In addition, as the feasible JBS/ MPS structure discussed in Section IV, the inverse depletion region of p+n junction is another reason of leakage current. The reverse saturation current of p+n junction is due to the diffusion of minority carrier holes on the n-side and carrier electrons on the p-side, which is highly sensitive to temperature variations as (5) shows.

$$J_L = AT^2 e^{-(q\phi_{\text{Bn}}/kT)} \left[e^{-(\frac{qV_R}{kT})} - 1 \right] \quad (4)$$

$$\frac{d\{\ln(I_s)\}}{dT} = \frac{3}{\eta T} + \frac{E_G}{\eta TV_{\text{Thermal}}} \quad (5)$$

B. Capacitance Characterization Measurement

From Fig. 5, we can see that the capacitances increase as temperature increases, since leakage current becomes larger as the height of schottky barrier changes. Note that as the leakage currents increase rapidly, the capacitors disappear between 400 °C and 500 °C since the leakage current is too large and

Fig. 5. Capacitance at different temperatures. (a) Wolfspeed capacitance. (b) Infineon capacitance. (c) Rohm capacitance.

Fig. 6. Reverse recovery effect at different temperatures. (a) Wolfspeed reverse recovery current. (b) Infineon reverse recovery current. (c) Rohm reverse recovery current.

leads to overflow of capacitance test module. The capacitance of the schottky diode has influences on power electronic modules and circuits, including impedance and switching time. In addition, there are small platforms as the voltage bias reaches nearly 400 V, which shows the three SiC SBDs are punch-through structure, consisting of a low impurity concentration drift layer, and a high concentration buffer layer. When the voltage bias becomes larger, the punch-through occurs as the depletion region reaches the end of drift layer, which results in the capacitance clamping.

C. Dynamic Characterization

Fig. 6 presents the measurement results for the dynamic characterization of SiC schottky diodes. The diodes are used as reverse recovery diodes in double pulse test board. The picture shows that although SiC schottky diodes are known as zero reverse recovery devices, the reverse recovery effect should still be paid attention as temperature increases. Fig. 7 shows total capacitive charge of reverse recovery during switching. The capacitive charges of Wolfspeed and Infineon devices remain stable below 300 °C, but increase fast as temperature continues to go higher. For Wolfspeed and Infineon devices, the reverse recovery currents become non-negligible after 300 °C, power dissipations increase a lot at the same time, Rohm device has a good performance by contrast. In common, the SiC schottky diodes are conducting by electrons, no reverse recovery effect could appear, so the reverse recovery current for SiC schottky diodes are the current oscillations caused by parasitic

Fig. 7. Total capacitive charge.

components. However, the hole current becomes significant as temperature reaches 300 °C, which leads to the phenomenon similar as bipolar p-n diodes at temperature higher than 300 °C. For Rohm device, the reverse recovery current remains stable and the Q_{rr} is almost constant, which shows excellent performance of switching loss in extremely high temperature environment. The emergence of reverse recovery current is relevant to the appearance of hole carrier in the conducting process, on account of the structure and manufacture of the device, which will be discussed in Section IV.

IV. DEVICE ANALYSIS USING TCAD SIMULATION

From the experimental investigations and targeted explanation discussed above, we figure out the essential mechanism of SiC schottky diodes at extremely high temperature. The current flow can be produced to the n-type carrier transportation across the metal-semiconductor junction. Most of the similar experiments are clarified of thermionic emission process referred in the introduction. For performance temperature higher than 300 °C, the same principle still effect as well. However, there are special phenomenons occurred in both static and dynamic results. For Wolfspeed and Infineon devices, the forward current density mutates larger as temperature exceeds 300 °C. At the same temperature range, the reverse recovery currents rise as temperature goes up, which shows the typical performance of bipolar devices. In order to explore the device performance intensively, we bring in TCAD simulation.

The typical structure of SiC schottky diode is JBS/MPS, which consists of interdigitated schottky and p+ doping region [16], [17]. The structure of JBS and MPS diodes are similar, the main difference is the width of p+ region. The incorporation of p+ region around the contact closely could shield the schottky contact against high electric fields in the drifted region. To reducing the leakage current, the p+ region could improve ruggedness and result in a lower on-state voltage drop. So we use JBS/MPS structure for TCAD simulation, the total 2-D cell region is $12 \times 5 \mu\text{m}^2$. The epitaxial layer doping concentration could be determined using (6) [18]. As the target breakdown voltage is 600 V, the n-drift region donor concentration of $2 \times 10^{16} \text{cm}^{-3}$ is used for the structure design, and the n+ region donor concentration is defined of $2 \times 10^{19} \text{cm}^{-3}$. Both the n-drift and n+ substrate region use uniform doping profile. The barrier height of a schottky diode is also important, which determines the tradeoff between on-state and reverse blocking characteristics. A schottky contact is designed using Titanium with the metal work function of 4.33 eV.

$$N_{\text{Drift}} = \left(\frac{3 \times 10^{15}}{BV_{\text{pp}}} \right)^{\frac{4}{3}} \quad (6)$$

Another critical parameter of schottky diode is the design of p+ region. We use Gaussian doping in the region of 0–3 μm , 9–12 μm , with the depth of 0.1 μm and the concentration of 10^{19}cm^{-3} . The part of electrode contacting n-drift region is designed of schottky contact, and the part contacting p+ region is ohmic contact. The structure of designed device is showed in Fig. 8. There is one thing to notice that the real commercial devices have more complexed design such as ring structure, trench structure, which we do not focus on, so other parts of structures are neglected.

We set up the stimulus of 0–4V to anode, the current density of schottky diode in 25 °C and 500 °C are showed in Fig. 9. For a more legible view, only structures near p+ region are displayed. In Fig. 9(a), we can see that the current density near p+ region is lower than the current density of other regions,

Fig. 8. Structure of schottky diode.

Fig. 9. Current density in different temperature. (a) Total current density in 25 °C. (b) Total current density in 500 °C. (c) Hole current density in 25 °C. (d) Hole current density in 500 °C.

since most of the electric field is descend on the drift region, the p+n junction could not get the on-state voltage, the on-state current is designed to flow in the un-depleted gaps between p+ region. On the other hand, there is nearly no h+ current in Fig. 9(c), which gives another evidence to the cut off of p+n junction. From Fig. 9(b), we can see the current density becomes larger, the p+n junction starts to conduct as shown in Fig. 9(d). It shows clearly that high temperature descends the electric field of drift region, so the p+n junction could get the threshold voltage and start to conduct, the hole carrier operates in conduction reaction. The changes in electrical conductivity are reflected in the test curve we talked before. For Wolfspeed and Infineon devices, we consider the p+n junction start to conduct at the temperature higher than 300 °C. As the hole carrier start to conduct, the on-state resistance decreases, so the slope of conduction curve becomes larger suddenly, which is identical to the Fig. 2(a) and (b). For the diode of Rohm, the voltage of p+n junction does not get the threshold voltage, so the slope of forward current remains stable. The same principle can apply to the phenomenon of reverse recovery current in Fig. 6. As hole current exists at the temperature higher than 300 °C. the schottky diodes show up the characteristics of p+n junction diodes, so there is reverse recovery current in double

Fig. 10. Simulation of forward current in different p+ region.

pulse test, and the currents rise as the temperature increases higher. Similarly, as there is no conduction of p+n junction, no reverse recovery current exists in the test of Rohm device.

We also find the shape of p+ region has correlation of hole carrier density. We design 5 different types of p+ region, simulate the forward current of schottky diodes in the temperature of 500 °C for comparison, the results are shown in Fig. 10. Since the thickness is default to set as 1 μm , the value of forward current is small. For the first three color line of p+ region, the lengths of regions are 0.1 μm , and the widths of regions are 1 μm , 2 μm and 3 μm . From the curves in the picture, the inflection points shift forward as the widths becomes larger. The inflection points in the curve of the three p+ region coincide with Rohm, Wolfspeed and Infineon schottky diodes in sequence. The length of the p+ region also influences the forward current, for the third to the fifth color line, the widths of p+ regions are 3 μm , and the lengths are 0.1 μm , 0.2 μm and 0.3 μm . From the picture we can see the slope of forward current increase as the length of p+ regions become larger. Since the larger region of p+ doping, the more hole carrier could be offered in extremely high temperature. As the difference design of p+ region, the schottky diodes could reach different performance at extremely high temperature.

From the influence of p+ region we discussed above, we can draw a conclusion that the size of p+ region could make a difference of device characteristics at extremely high temperature. As the length and width increase, the device performance could be more likely to a p-n diode, the appearance of hole current results in larger forward current and more distinct reverse recovery effect. The existence of hole current has a great influence in SiC application fields, the upwelling forward current may cause an energy dissipation, even breaking the power limit of circuit, leading to overburning of devices. In addition, reverse recovery effect is an important factor of switching performance. As the reverse recovery current increases, the circuit operating frequency must drop, and the switching loss will increase rapidly, which seriously slumps the performance of SiC SBDs in high frequency applications.

V. CONCLUSION

In this paper we test three SiC schottky diodes at a wide temperature from 20 °C to 500 °C, to evaluate the high temperature performance of these devices. The theoretical explanations are presented to illustrate each phenomenon. There are different degrees of performances degradation including all the characteristics. Rohm device can mainly work at 500 °C, Wolfspeed and Infineon devices show good performance under 300 °C, but has a rapid degradation at higher temperature. TCAD simulations are presented to explain the internal mechanism of bipolar device like phenomenon of schottky devices behaved in extremely high temperature. The simulation results accord with the phenomenons in the test results, and the design optimization is discussed as well. This work is a comprehensive and detailed evaluation of late generation commercial SiC schottky diodes at extremely high temperature up to 500 °C, the explanation of the device structure is analysed for explanation of test results, which offers a performance guide and theoretical analysis of device used in power electronics application systems.

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