

Reliability considerations for recent Infineon SiC diode releases

M. Holz ^{a,*}, G. Hultsch ^b, T. Scherg ^a, R. Rupp ^a

^a Infineon Technologies AG, Am Campeon 1-12, D-85579 Neubiberg, Germany

^b Infineon Technologies AG, Siemensstrasse 2, A-9500, Austria

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Abstract

Silicon carbide (SiC) has long been shown to be one of the most promising materials for high-voltage power semiconductor devices. New device technologies and products have led to an ever increasing size and variety of the markets addressed by SiC. The specific material properties and the new applications served by SiC devices give rise to specific reliability requirements, reaching beyond the scope of standard tests established for silicon based devices. Here, we show details of Infineon's strategy to ensure high device reliability even under extreme operating conditions encountered in the field. E.g., an especially tailored dynamic reverse bias test shows that Infineon's new 1200 V SiC Schottky diodes can be continuously operated at high voltage slopes of 120 V/ns under the conditions specified in this paper.

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1. Introduction

In 2001 the commercialization of silicon carbide (SiC) diodes started, leading to today available product spectra in the voltage range from 300 V to 1200 V. Due to the high costs of such nearly loss-less switching SiC rectifiers, they found their way mainly into high-end applications like server or telecom power supplies. Others like solar power conversion are also near and mid term target applications of this new power device technology. One common demand for all these applications is high reliability. On the other hand, being a just rising technology, SiC devices so far could not easily prove this high reliability just by field experience. This chicken-and-egg situation hampered to some extent the market penetration by SiC diodes in the last years and led to a workshop embedded in the ESREF 2006 with the title: "Reliability of Power Electronics and Devices – Is Silicon Carbide a reliability challenge?".

This was the motivation for the authors to deal with this question again in the present paper. It will be shown based

on both reliability tests and field experience data, that excellent reliability and lifetime values can be achieved based on a ruggedness-by-design approach. Also the special requirements and stressors of the above mentioned target applications of SiC diodes will be identified and examined in order to allow application specific conclusions.

The devices considered in this paper are (1) Infineon's 2nd Generation of SiC diodes (merged pn-Schottky diodes, released in March 2006, [1,2]), (2) the modified 1st Generation devices (bare Schottky diodes, released in September 2006, with an edge termination optimized for extreme dV/dt) and (3) Infineon's new 1200 V SiC diodes.

2. Standard reliability tests

Ensuring that the newly developed SiC high-end power devices meet Infineon's high standard of product quality and reliability is an essential part of the product development process. Intensive care is being taken in design and simulation to conceive devices matching the specific requirements of multiple applications. To ensure that these requirements are fulfilled, a detailed system of critical reliability tests has been installed within Infineon. This comprises, both, standard accelerated reliability tests

* Corresponding author. Tel.: +49 0 89 234 20694; fax: +49 0 89 234 955 2719.

E-mail address: Matthias.Holz@infineon.com (M. Holz).

according to JEDEC standard, as well as the detailed analysis of device behaviour under application specific stress conditions.

Table 1 lists a selection of different standard accelerated stress tests, performed on package level on the three new Infineon SiC technologies mentioned above. All these tests were passed without any fails or critical parameter drifts. This result highlights the impact of the ruggedness-by-design approach, followed during the design phase. As part of this, the devices were designed, such that the maximum electrical field is shifted away from the surface. Another important feature is that, by design, the 2nd Generation diodes can show a stable avalanche. To achieve this, both, a positive temperature coefficient of the breakdown voltage and a low-ohmic avalanche path is required. This is realized via pinning of the maximum electric field at the corners of highly p-doped islands with good ohmic contacts [1,2].

The standard acceleration tests are designed, such that the device behaviour under severe stress conditions and long operating times needed in applications is simulated. While the underlying acceleration models due to long experience have been proven to be sound and solid for silicon based devices, however, their applicability to silicon Carbide devices still has to be demonstrated. Stating failure-in-time (FIT) and meantime-between-failures (MTBF) rates for SiC devices based on these models seems inappropriate and could prove inaccurate. We therefore refrain from stating such potentially misleading figures in this paper. One key difference between Si and SiC is the typical occurrence and structure of crystal defects, e.g., dislocations and stacking faults, inherent to the material. The total density of these defects in SiC is in the order of 10^4 cm^{-2} . However, most of them have not been observed to cause any failure or malfunction of the device. Anyhow, at least micropipes (super screw dislocations) or defect clusters with high local defect density have been already identified to be critical for long term device stability [3,4]. In order to ensure that the devices shipped to our customers do not have any such defect possibly causing premature failure, an advanced 100% testing routine has been established at Infineon. Active (open) micropipes easily can be detected by excess leakage current or early destructive breakdown. However, during the epitaxial growth process, micropipes can be overgrown (closed). While such overgrown micropipes initially do not produce a drastically elevated leakage current or premature breakdown, they can be activated during operation and pose a serious reliability risk [3]. It

is therefore crucial to identify all devices which do not show an excess leakage current at rated voltage initially, but are showing leakage current filamentation for voltage spikes beyond rated voltage or under avalanche conditions. This would lead to hot spots with high power density in the μm^2 scale, providing enough local energy dissipation to initiate degradation processes by defect multiplication. The introduced testing procedure therefore comprises also a detection of overgrown micropipes, using a 100% breakdown voltage (VBR) test for the 2nd Generation diodes: A reverse current of 20 mA is applied for 10 ms both on wafer level and again later on after packaging. The leakage current at maximum rated voltage is measured before and after this VBR test. By applying avalanche conditions during this test, the overgrown micropipes are activated [3]. Comparing the leakage current before and after VBR test, overgrown micropipes are detected, too. Here, the allowed upside leakage current deviation is only in the range of a few %, to take into account the self-heating of the chip during the avalanche test pulse. To ensure high quality, all the devices with larger deviation are rejected and will not be delivered to the customer. This test will also identify local Schottky barrier inhomogeneities. In case of our 600 V 2nd Generation diodes the minimum test limit for the avalanche test is 650 V allowing a nearly 10% voltage safety margin with respect to rated voltage, typically the avalanche voltage is $>700 \text{ V}$.

Additionally, leakage current tests at various voltages up to rated voltage are performed in the standard 100% test scheme for all our current SiC diodes. Purpose of these is not only to ensure datasheet parameters but also to track the slope of the leakage current versus voltage. Any abnormal behaviour which is not explainable with the theory of SiC Schottky diodes leads also to scrapping of the affected device. Reasons for such abnormalities can, e.g., be high-ohmic leakage current paths or stacking faults penetrating the Schottky interface and locally altering the barrier height.

The VBR test aims at detecting crystal defects in the active device area. Such defects are known to be most severe for long term device stability. Crystal defects in the p^- edge termination cannot be easily detected to 100% by this test. However, here, by device design, the electrical field is reduced, such that these defects are harmless. Even under avalanche conditions the maximum E-field in the p^- well surrounding the device is below the threshold field strength necessary for the activation of crystal defects.

Table 1
Standard reliability tests – laboratory stress testing results (devices in SMD packages with precon acc. to JESD22 A-113)

Test description acc. to standard	Abbr.	Conditions	Total device hours	Fails
High temperature reverse bias JESD22 A-108	HTRB	$T_a = 175 \text{ }^\circ\text{C}$ for 1000 h $V = V_{\text{max}}$	693,000	0
Temperature cycling JESD22 A-104	TC	$-55 \text{ }^\circ\text{C}$ – $+150 \text{ }^\circ\text{C}$ 2 cycles/h	77,0000	0
Autoclave JESD22 A-102	AC	$T_a = 121 \text{ }^\circ\text{C}$, 100% rh	73,920	0
High humidity high temperature reverse bias JESD22 A-101	H3TRB	$85 \text{ }^\circ\text{C}/85\% \text{ rh}$, $V = 80 \text{ V}$ for 1000 h	539,000	0
Intermittent operational life test MIL-STD 750/Meth.1037	IOL	Delta $T = 100 \text{ K}$ for 15 000 c (7 min)	10,27,250	0

3. Customized reliability testing

While the standard reliability tests cover a wide range of application requirements, the advantages of SiC allow its usage in an ever increasing number of applications, giving rise to specific new requirements like very hard switching conditions. Specific tests have been developed to ensure high reliability under extreme operating conditions and in very different environments and utilisations. This has proven especially important, since standard reliability testing procedures alone as put down in AEC-Q101 [5], are not sufficient to guarantee a long device life time in the new applications addressed with SiC. Significant success has been made by Infineon in developing and implementing testing procedures, leading to an expanded reliability assessment, specifically tailored for the needs of the ever-increasing SiC market.

The low switching losses of SiC Schottky diodes render them as ideal power devices for high switching frequencies. As one example of an application tailored reliability test, the so-called Dynamic Reverse Biasing (DRB) test, has been established especially for SiC devices to ensure that they fulfil these critical dynamic requirements. During the DRB, the maximum specified reverse voltage is applied with voltage slopes dV/dt as high as 90 V/ns for the 600 V devices and 120 V/ns for the 1200 V diodes. The technologies underwent this test twice: Once with a switching frequency of 10 kHz and once with 100 kHz, see Table 2. All newly developed SiC technologies have passed the two tests without any fail and without noticeable trace of physical degradation after 1000 h (3.6×10^{11} cycles per device for the 100 kHz test). Fig. 1 shows a typical voltage characteristic during switching test for a 600 V 2nd Generation diode. This test ensures high reliability of the tested devices in switching applications with high voltage slopes, which surpass even the strict testing conditions included in AEC-Q101. While in typical applications, the diodes are used with only about 400V reverse voltage, we stressed the 2nd Generation diodes with rated voltage of 600 V as displayed in Fig. 1, showing no significant degradation after 1000 h.

This high dynamic ruggedness is, e.g., achieved by a good Ohmic contact of the edge termination. This, again, highlights the importance of the ruggedness-by-design approach.

An intermittent operating lifetime (IOL) test for Infineon's 2nd Generation of SiC diodes (merged pn-Schottky diodes, released in March 2006) has been performed using 4× nominal current and heating up the devices by 100 K in

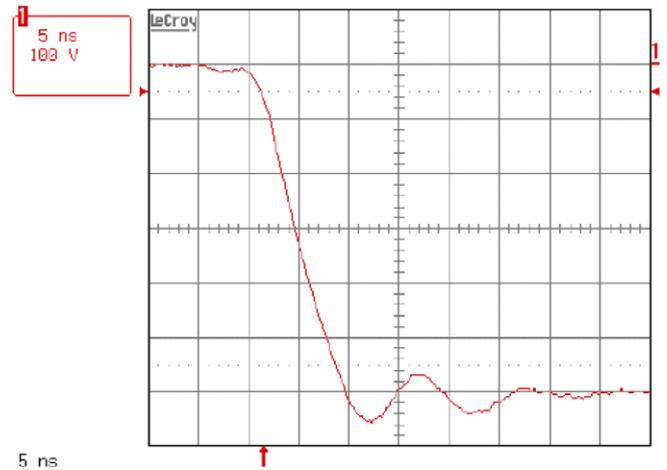


Fig. 1. Voltage characteristic during switching test after 1000 h DRB with 100 kHz for a 2nd Generation SiC diode. Note that unlike typical application conditions limiting the reverse voltage to about 400 V, in this test the diodes were turned off to maximum rated voltage of 600 V.

only 3 ms (see Fig. 2). Electrical testing especially of the forward voltage (VF) is done at nominal and 6× nominal current to ensure that the bipolar operation mode at 4× rated current during the IOL does not initiate any VF drift.

Additionally, a special, tightened IOL test, performed at 7× nominal current, using 3 ms pulse length is performed for 4000 cycles. Fig. 2 shows the calculated junction temperature profile during the heating pulse. One observes a temperature rise by more than 200 K, i.e., about twice as much as for the standard IOL test. Note that the temperature in this special test even rises above the maximum rated junction temperature of 175 °C. By driving the devices considerably over this rated junction temperature, we, again, ensure high robustness under the extreme conditions encountered during operation in the field (like AC brown out events in power factor correction stages in switch mode power supplies, where multiples of the rated current has to be handled in time ranges from 1 to 5 ms).

Fig. 3 shows a Scanning Acoustic Microscopy (SAM) image of a 2nd generation diode after 960 cycles with 7× nominal current (bottom view). Neither under the chip (shown in black) nor under the solder (shown in dark grey) any delamination is visible. In Fig. 4 VF values of different devices undergoing this tightened IOL stress conditions are shown. The last readout displayed in Fig. 4 is after 4000 cycles. Even under these tightened IOL stress conditions, no noticeable VF drift is observed. All measured values are far below the specification limit of 1.7 V for these 600 V diodes.

Table 2
Customized reliability tests – laboratory stress testing results

Test description	Abbr.	Conditions	Total device hours	Fails
Dynamic reverse biasing	DRB	$V = V_{\max}$, 10 kHz	598,000 (2.15e13 switching cycles)	0
Dynamic reverse biasing	DRB	$V = V_{\max}$, 100 kHz	70,000 (2.52e13 switching cycles)	0

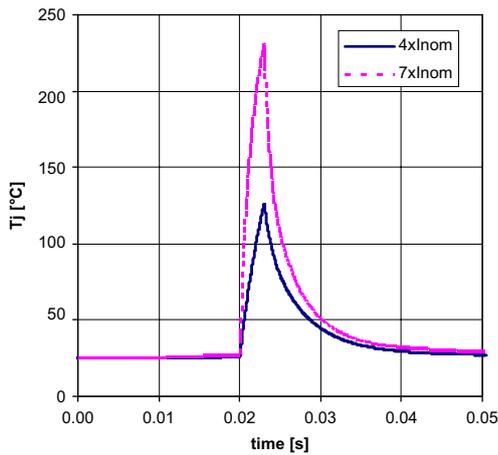


Fig. 2. Calculated junction temperature characteristic during IOL test with 4× and 7× nominal current, respectively, and 3 ms rectangular pulse length.

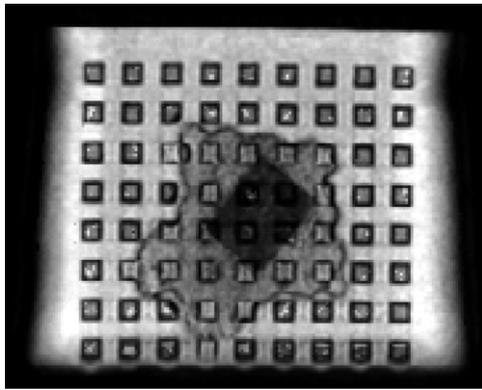


Fig. 3. SAM image (bottom view) of a 2nd generation diode after 960 cycles tightened IOL stressing using 7× nominal current. The chip is shown in black in the center. The solder is visible in dark grey around the chip. The waffle pattern is due to the lead frame structure. No delamination is observed.

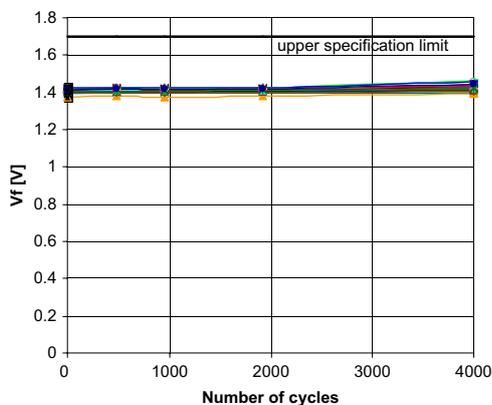


Fig. 4. Drift analysis of VF at nominal current under special IOL stress test conditions with 7× nominal current for a 2nd Generation diode. The upper black line shows the specification limit of 1.7 V. The other lines show the behavior of VF for different parts after increasing number of cycles. No significant VF drift is observed even after 4000 cycles.

4. Application specific conclusions

Infineon's SiC diodes have been shown to be an ideal choice in a broad variety of applications from a technical viewpoint. It was, e.g., shown earlier that the efficiency of a Power Factor Correction (PFC) stage can be enhanced by 2% by replacing the conventional benchmark ultra-fast Si diode with SiC Schottky [6]. This high efficiency renders SiC diodes as optimized solutions, e.g., for high-efficiency server power supplies. In this specific application, the device is typically operated under climate controlled room conditions over many years with only few interruptions, i.e., failures due to temperature cycling stress is unlikely. For size reduction purposes, the switching frequency is often chosen at high values of 100 kHz and above, such that Infineon's SiC diodes with their low switching losses and high dynamic robustness are especially qualified. But not the high frequency is most critical; it is the steepness of the voltage transient, which forces high displacement current densities especially in the edge termination area of the diodes. As explained above, among others the DRB test performed on the devices ensures a long lifetime even under extreme transient switching stress.

Another application of increasing interest is solar power conversion. Here, the thermal conditions under which the devices are operated differ tremendously from the usage in servers: Due to the day-and-night rhythm, both, the environment temperature and the input power over 24 h cycle during a targeted application life time of up to 20 years. Even more so, clouds blocking the sunlight can lead to variations of the input power on an even smaller time scale. By detailed reliability testing, e.g., temperature cycling (TC) and intermittent operating lifetime (IOL) tests, Infineon's SiC diodes have been proven to fulfil the targeted life time requirements even under these extreme environmental conditions.

Besides accelerated stress tests, the hitherto field experience allows another hint at the high reliability of the new SiC technologies: Under the conservative assumption that sold devices are engaged in field applications 6 months after shipping, we end up with approximately 2×10^9 device hours in field applications until now without any documented fail. However, assessment of such figures should be handled with care: Generally, the exact operating time and condition of each sold device is only vaguely known, and even for the above mentioned high-end applications it might be that not every failure is being reported to the manufacturer.

5. Conclusions

In this paper, the authors presented in detail stress test results of Infineon's new SiC diodes. Besides standard stress tests, special setups have been developed to cover the different requirements of specific applications. Among these, server power supplies and solar converters have been discussed as two important examples. Specific tests include

a dynamic reverse biasing reliability test at high voltage slopes and a specific IOL test at $7\times$ nominal current. Infineon's recently released SiC diodes passed all listed tests including standard reliability tests without any failure. Taking into account, both, the various test results and the very positive field experience, we conclude that Infineon's SiC diodes fulfil the high reliability expectations of such high-end applications.

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