Evaluation of 600V GaN and SiC Schottky diodes at different temperatures

Conference Paper · September 2013

DOI: 10.1109/EPE.2013.6634641

Nasser Badawi
International University of Sarajevo

Eldad Bahat-Treidel
Ferdinand-Braun-Institut

S. Dieckerhoff
Technische Universität Berlin

Oliver Hilt
Ferdinand-Braun-Institut

Evaluation of 600V GaN and SiC Schottky Diodes at Different Temperatures

Nasser Badawi[1*], Eldad Bahat-Treidel[2], Sibylle Dieckerhoff[1], Oliver Hilt[2], Joachim Würfl[2]
[1]Technical University of Berlin, Power Electronics Research Group, Berlin, Germany
[2]Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Berlin, Germany
E-Mail[*]: nasser.badawi@tu-berlin.de
URL: http://www.pe.tu-berlin.de

Keywords

«Gallium Nitride (GaN)», «Schottky Diode», «Device Characterisation», «Wide Bandgap Devices»

Abstract

This paper presents a newly developed 600V/2A Gallium Nitride (GaN) Schottky diode feasible for high frequency operation. Static and dynamic characteristics of the diode are experimentally evaluated at different temperatures and compared to a commercially available 600V/2A Silicon Carbide (SiC) Schottky diode. The test for both diodes is carried out under identical conditions. The proposed GaN diode shows very good switching properties and the potential to operate at very high switching frequencies and high temperatures with low switching loss.

1. Introduction

Wide-bandgap power semiconductor devices are generally capable of operating at high voltages, high frequencies, and at elevated junction temperatures. Power semiconductors based on Silicon Carbide (SiC) are available from different manufacturers, and specifically SiC Schottky diodes have found their way into several applications as fast switching, low loss power devices. Another emerging class of wide-bandgap power semiconductors is based on GaN (Gallium Nitride). These devices are concurring with SiC semiconductors especially for use in lower power, high frequency applications. Both materials, GaN and SiC allow realizing Schottky diodes for higher blocking voltages. Since a Schottky diode (Schottky Barrier Diode - SBD) is a majority carrier device and has no stored minority carriers that must be injected into the device during turn-on and pulled out during turn-off, it switches faster than a Si-pn junction diode [1]. Only the charging of the junction capacitance is apparent during transient operation. Hence, significantly lower switching losses than those in comparable Si power diodes can be achieved.
In order to evaluate its performance, this work presents the measured characteristics of a newly developed 600V/2A GaN Schottky diode [2] and compares it to a SiC Schottky diode (C3D0260A) and a soft recovery pn diode (FR207). All devices are tested varying the junction temperature.

2. GaN Schottky Diode Technology

The Schottky diodes are manufactured on GaN-based epitaxial layers grown by Metal Organic Vapour Phase Epitaxy (MOVPE) on 3” *n*-SiC wafer consisting of a 3.1 µm carbon-doped (~2×10^{19} cm^{-3}) GaN buffer layer followed by an active layer composition consisting of a 100 nm unintentionally doped GaN channel and a 26 nm $Al_{0.25}Ga_{0.75}N$ barrier layer. The wafer median sheet resistance of a passivated transmission line test structure is ~475 Ω/☐. Ti/Al/Mo/Au based cathode ohmic contacts are evaporated and annealed at 830°C. Inter-device isolation is done by $^{14}N^{+}$ multi-energy ion implantation followed by a 150 nm thick SiN_x passivation. Fig. 1 shows the cross-sectional structure of the GaN Schottky diode and a device mounted in a microwave package.
A trench for the anode Schottky contacts is lithographically defined in the passivation and etched subsequently. At the anode side, the AlGaN layer exposed by the opened trench is fully recessed by BCl_3 based reactive ion etching using the same lithographic mask. The recess etch depth is estimated to ~40 nm. Pt/Ti/Au contacts are then evaporated for forming the anode Schottky metal, followed by a

metal lift-off. All samples are passivated with 5 µm BCB. The fabricated devices are 25 mm wide with anode-cathode separation of 15 µm. All the devices have a 1 µm overlapping field plate towards the cathode. More details on the specific GaN Schottky diode technology are published in [2].

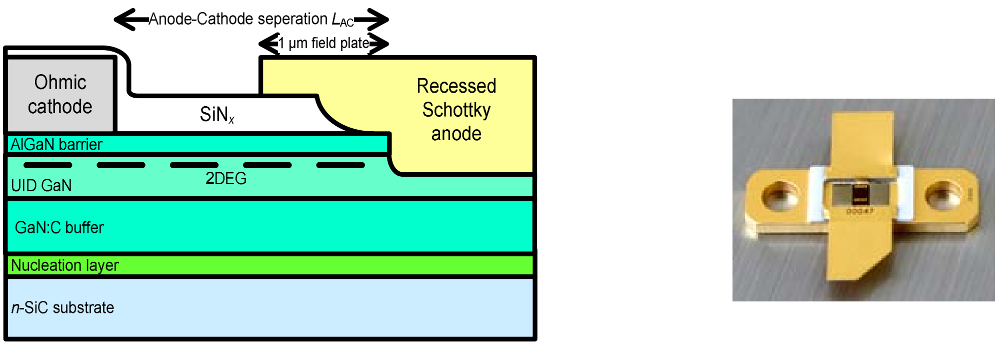


Fig. 1: Cross-sectional structure and Schottky diode mounted in a typical microwave package.

3. Static and Dynamic Performance Tests

3.1 Static Test (DC Characteristics)

The static forward voltage drop and the reverse current are basic characteristics of power semiconductor devices. Here, both quantities are measured at heatsink temperatures ranging from 25°C to 225°C. Figure 2a depicts the static test circuit. The input DC voltage is controlled to vary the current in the diode, and the forward current I_F and voltage V_F are measured. Figure 2b shows the resulting *I-V* forward and reverse characteristics of the GaN Schottky diode. It is clearly visible that the on-state resistance in forward direction increases nonlinearly with the temperature; this effect is more pronounced than in SiC Schottky diodes [4]. The reverse current is also sensitive to elevated temperatures: it increases by two orders of magnitude between 25°C and 175°C. For a width *W*=25mm, the reverse current ranges from approx. 10µA, which is comparable to the SiC diode [4] up to several 100µA at high temperatures.

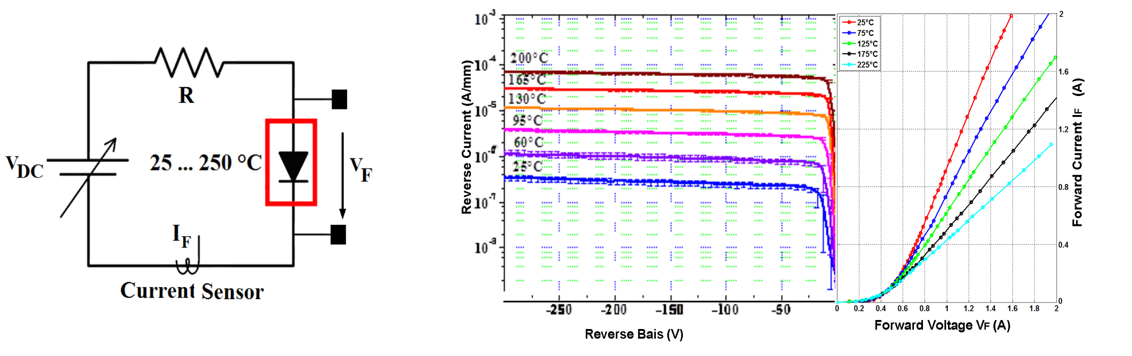


Fig. 2a: Static test circuit [3]
Fig. 2b: Temperature-dependent DC characteristics

3.2 Dynamic Test (Switching Characteristics)

The proposed GaN Schottky diode is tested under typical hard switching conditions applying the dynamic test circuit given in Figure 3. The circuit is composed of a buck converter with inductive load, the gate driver and the measurement equipment. Special care was taken in order to realize a very low inductive commutation loop. Since no matching GaN or SiC power transistor (2A rated current) was available, experiments are conducted with a commercial SiC MOSFET from Cree (CMF10120) and with a newly developed 400V/12A normally-on GaN HEMT (High Electron Mobility Transistor) from Ferdinand-Braun-Institut, Berlin [5,6], as active switch. The devices operate from $300V_{dc}$ and switch a current of 2A. The switching tests are carried out at different double-pulse frequencies up to

2 MHz. The entire set of measurements presented in this work is based on 1.5 MHz double-pulse frequency and 50% duty cycle.

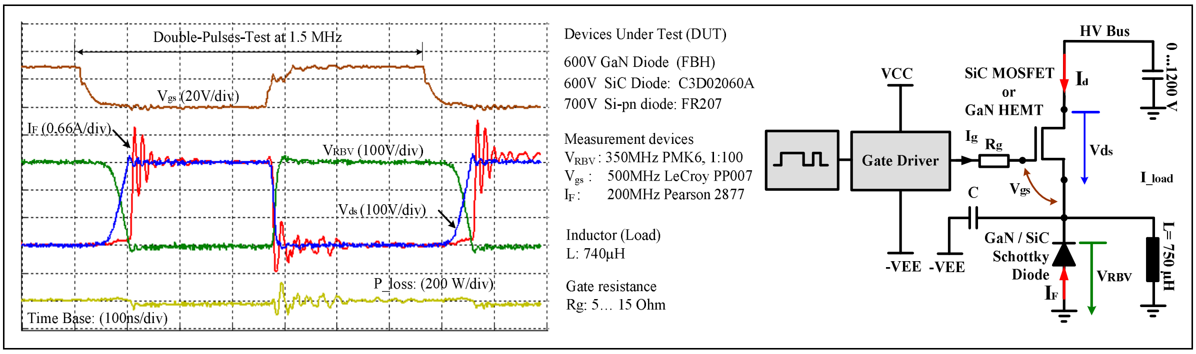


Fig. 3: Dynamic test circuit and double-pulse waveforms of GaN SBD at 1.5 MHz, reverse blocking voltage V_{RBV} = 300V and forward current I_F = 2A.

Figure 4 shows the measured GaN SBD turn-on and turn-off switching waveforms using the SiC MOSFET (CMF10120) as active switch in the dynamic test. The chip temperature is varied from 25°C up to 175°C. During the turn-off process, the peak reverse current as well as the current-time integral (the total capacitive charge Q_{rr}) are independent of the temperature. From the turn-on measurements, two parasitic effects can be observed: a slight rise of current during the fall of the blocking voltage due to internal capacitances, and a high frequency ringing of the current. The selected SiC MOSFET is a comparably large transistor (1200V/20A) with a long discharching time of the drain source capacitance C_{ds}. This is reflected in the falling time of the diode voltage V_{RBV} which is measured to t_f =35 ns starting from the off-state to on-state resulting in a dv/dt of 8.7 kV/µs.
An improvement can be achieved by applying a comparable GaN HEMT as active switch in the dynamic test. Using a newly developed normally-on GaN transistor, the measured falling time of the voltage is only 9 ns, resulting in a dv/dt of 28 kV/µs. Although this transistor still has a higher current rating than the proposed diode, considerably higher switching speeds compared to the test results in Figure 4 can be achieved.

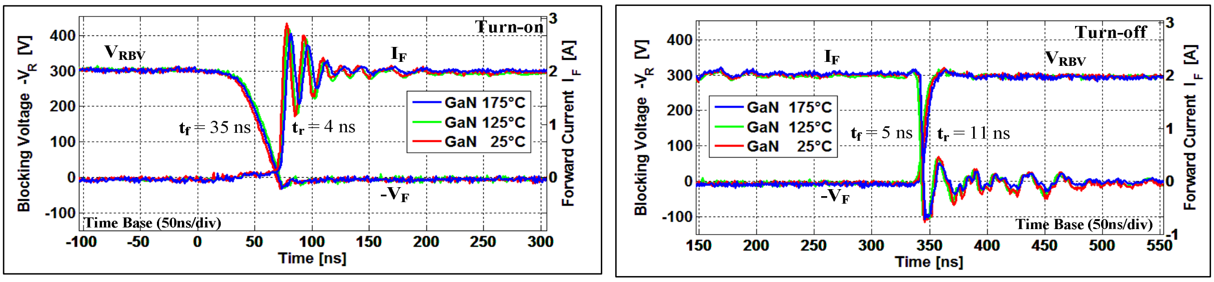


Fig. 4: GaN SBD measurement results using a SiC MOSFET (CMF10120) at different temperatures. Reverse blocking voltage V_{RBV} = 300V and forward current I_F = 2A.

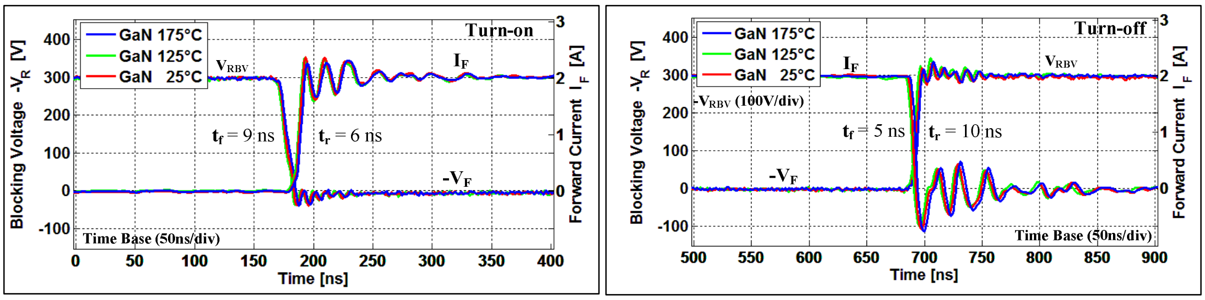


Fig. 5: GaN SBD measurements results using a 400V/12A normally-on GaN HEMT at different temperatures. Reverse blocking voltage V_{RBV} = 300V and forward current I_F = 2A.

The experimental results for the GaN HEMT / GaN SBD test combination are given in Figure 5 generally showing a good switching performance comparable to the performance of state-of-the-art SiC SBD.
Further experiments are conducted to analyze the impact of the blocking voltage on the switching behaviour. The blocking voltage is varied from 100V to 300V keeping the forward current I_F=2A constant. The measurement results using the GaN HEMT / GaN SBD combination are summarized in Figure 6. Although the voltage resolution is quite low, a difference in the dynamic on-state voltage depending on the blocking voltage can be observed. This topic will be further treated in section 3.4.

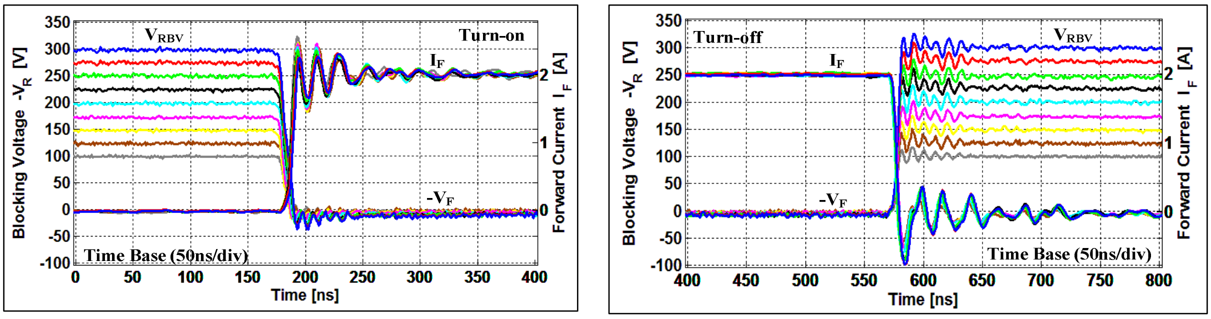


Fig. 6: GAN SBD measurement results using the 400V/12A normally-on GaN HEMT. Reverse blocking voltage V_{RBV} is varied from 100V to 300V and forward current I_F = 2A. T=25°C.

3.3 SiC and GaN Schottky Diode Comparison

In this section, the dynamic characteristics of the proposed GaN SBD and a commercially available SiC Schottky diode (C3D02060A) are compared. The switching waveforms are measured at different temperatures from 25°C to 175°C, they are demonstrated in Figure 7. One problem arises to the comparison due to the available packaging of the devices: The SiC diode is assembled in TO 220 housing whereas the GaN device is packaged in microwave housing. Therefore, the circuit layout cannot be identical, and stray inductances in the commutation loop differ slightly.
Analyzing the turn-off curves, it can be stated that the two devices have a very similar behaviour. Both diodes show the same stability with the operating temperature, i.e. the reverse current peak and its duration do not vary significantly with the temperature, and they possess the same reverse current area, hence the same capacitive charge.

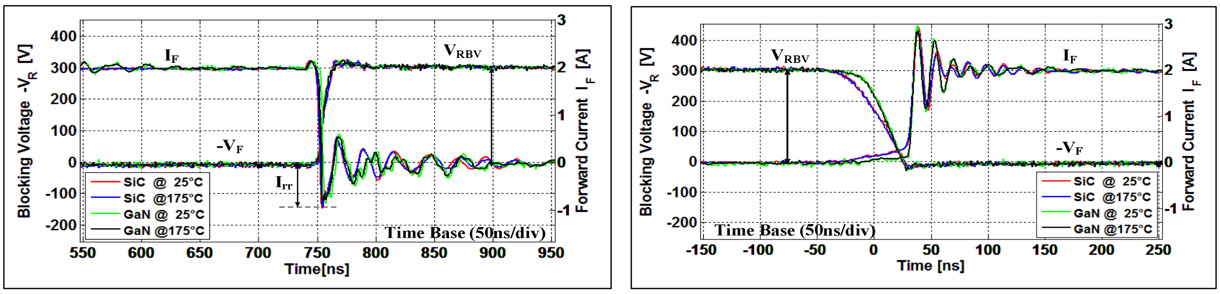


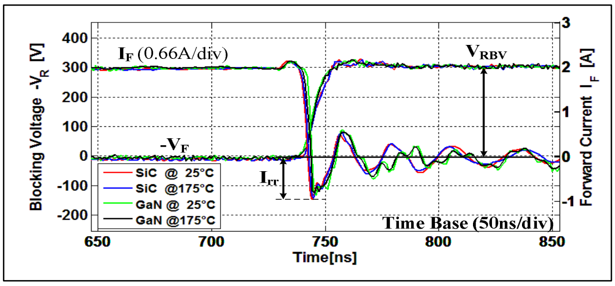
Fig. 7: Left: Reverse current comparison of GaN and SiC diodes during turn-off; reverse blocking voltage V_{RBV} = 300V and forward current I_F = 2A. Right: Turn-on comparison.

This charge is calculated from the measurements, the results are summarized in table I. In accordance with the definitions for pn-diodes, the charges are denoted Q_{rr} for the total charge and Q_s and Q_f for the partial charges, which add up to Q_{rr}. In fact, since SiC and GaN Schottky diodes are majority carrier devices there is no reverse recovery charge. However, they still show some reverse recovery effect due to the parasitic capacitance of the Schottky diode. The calculated Q_{rr} depends on three factors: the diode junction capacitance C_J, selected di/dt and the parasitic capacitances connected in parallel to the Schottky diode. As can be seen in Figure 8, the total charge Q_{rr} of the diode is obtained by integrating the current over time from the zero-crossing of the current when going from forward to reverse bias, until t_{rr}, which is the time that is needed to reduce, or rather recover, the reverse current up to 25% of its reverse peak value [7]. Both Schottky diodes have a t_{rr} of 10 ns.

Table I: Comparison of capacitive charge for GaN and SiC Schottky diode

	GaN Schottky Diode						SiC Schottky Diode					
	25ºC			175ºC			25ºC			175ºC		
	Q_{rr}	Q_s	Q_f	Q_{rr}	Q_s	Q_f	Q_{rr}	Q_s	Q_f	Q_{rr}	Q_s	Q_f
Charge [nC]	5.57	1.58	3.99	5.70	1.66	4.05	5.62	1.22	4.59	5.67	1.15	4.52
Q/I_N [nC/A]	2.78	0.79	1.99	2.85	0.83	2.02	2.86	0.61	2.25	2.83	0.57	2.26

As stated above, there is practically no difference in the turn-off behavior of the SiC and GaN diodes, and the switching process is only marginaly influenced by the temperature. On the other hand, the measured reverse recovery current of a fast soft recovery Si-based diode (FR207) clearly shows temperature dependency, see Figure 8. This Si-diode features an increase of the peak reverse recovery current I_{rr} of about 6% and 20% for 125°C and 175°C, respectively. Corresponding to this, the reverse recovery charge Q_{rr} increases by 16% and 50% just as the reverse recovery time t_{rr} increases by about 16% and 33%. The absolute value of I_{rr} is considerably higher than for the SBDs: at 175°C, the peak current reaches 24A in a reverse recovery time t_{rr} of 35 ns. This is caused by the high speed turn-on of the SiC MOSFET.



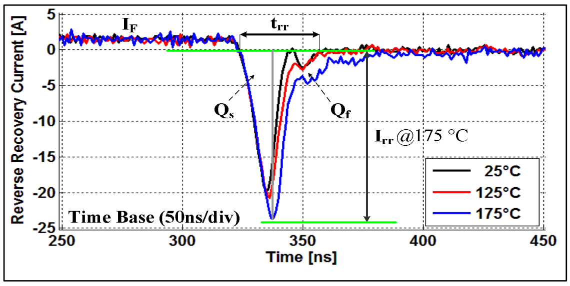


Fig. 8: Turn-off: Reverse current of the proposed GaN SBD compared to SiC SBD (C3D02060A) (left) and reverse recovery current of a pn diode (FS207) (right).
Blocking voltage V_{RBV} = 300V and forward current I_F = 2A.

The most important part of Schottky diode switching losses are the current reverse losses during turn-off. Compared to pn diodes, these losses are considerably reduced due to the small chip size and hence the small reverse current area. This advantage makes wide-bandgap devices very attractive for high frequency applications. However, GaN and SiC Schottky diodes have higher leakage currents, which affect the breakdown voltage rating of the device [8], [9] – see also the measurements in section 3.1.

3.4 Dynamic On-State Voltage

The dynamic on-state voltage is an important aspect in applying GaN semiconductors in high frequency applications. This parameter describes the effect that after turning on the GaN device from a high blocking voltage, the on-state voltage drop does not reach its low steady-state value [6]. In order to measure the dynamic on-state voltage accurately, specific measurement techniques are required, also taking into account the very fast switching speed of the wide-bandgap power semiconductors. Generally, the measuring of a high speed switching signal which is going to be transmitted using a differential probe over 100 cm to a DSO needs to be carefully considered [10]. Figure 9a exemplarily compares the measurement of the forward voltage drop V_F of the GaN diode using two different differential probes. In order to accurately capture V_F in the high dynamic range (P_2: 3µs), a passive clamping circuit is used, which contains a 10V Zener diode and a 50 kΩ high ohmic resistor [11], see Figure 9b. The on-state voltage measurement in the very high dynamic area (less than 1µs) requires a specific proportional probe with very small reaction time and an active clamping circuit [12].

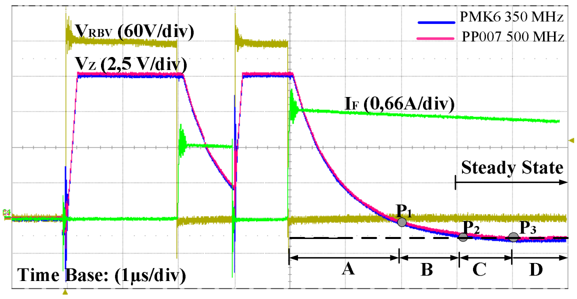


Fig. 9a: Forward voltage drop (V_F) measurement using two different voltage probes.

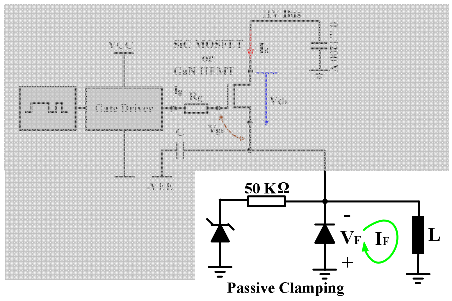


Fig. 9b: Passive clamping circuit

Figure 10 contains an evaluation of the dynamic forward voltage drop V_F and the dynamic on-state resistance R_{on} of the GaN and SiC Schottky diode at different temperatures. As described above, the voltage V_F is measured after 3µs from the start of the turn-on process at the point P_2. These results show good agreement with the steady state measurements which are also indicated in the figure.

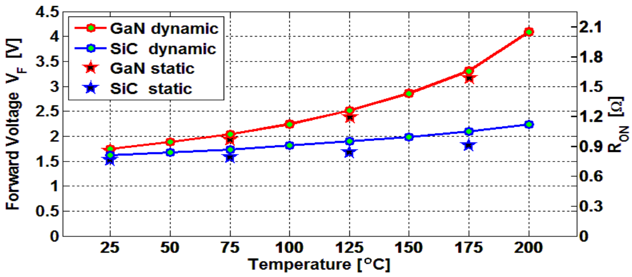


Fig. 10: GaN SBD dynamic on-state voltage $V_F = f(T)$ and resistance $R_{on} = f(T)$ compared to SiC SBD Static measurements are indicated for comparison.

The dynamic on-state voltage V_F of both GaN and SiC Schottky diodes is measured switching 300V blocking voltage V_{RBV} and 2A forward current. The on-state resistance R_{on} is obtained by dividing the V_F by the forward current I_F. While the GaN SBD on-state voltage and resistance at room temperature is comparable to the SiC device, a significant increase of the GaN diode on-state voltage can be observed with rising chip temperature. GaN on-state R_{on} at 175°C increases by almost 0.8Ω with respect to 25°C. On the other hand, the SiC on-state R_{on} is just incremented by 0.25Ω.

4. Conclusion

This paper presents the on-state and switching performance of a new 600/2A Gallium Nitride (GaN) Schottky diode. The switching performance is compared to a 600V/2A SiC Schottky diode and a 700V/2A fast recovery pn diode in terms of switching speed and current recovery. Two different wide-bandgap transistors are used in the dynamic tests: a commercially available SiC MOSFET and a newly developed normally-on GaN HEMT. By using the GaN HEMT as active switch in the circuit, a considerable switching speed improvement of the proposed GaN Schottky diode is achieved. Moreover, further improvement is expected applying a GaN transistor with lower current rating comparable to the GaN SBD.

In summary, the proposed GaN diode clearly shows very good switching properties and the potential to operate at very high switching frequencies and high temperatures (up to 175 °C) with low switching loss. The on-state voltages on the other hand are comparable to commercially available SiC diodes at room temperature but increase considerably with temperature.

References

[1] N. Mohan, T. Undeland, W. Robbins, “Power Electronics Converter, Applications and Design”, 2003, Media Enhanced Third Edition, Page 535. USA ISBN 0-471-22693-9

[2] E. Bahat-Treidel, O. Hilt, R. Zhytnytska, A. Wentzel, C. Meliani, J. Würfl and G. Tränkle, "Fast Switching GaN based Lateral Power Schottky Barrier Diodes with Low Onset Voltage and Strong Reverse Blocking," Electron Device Letters, IEEE , vol.33, No.3, pp.357-359, March 2012.

[3] B. Ozpineci, L M. Tolbert, “Characterization of SiC Schottky Diodes at Different Temperatures”, IEEE Power Electronics Letters, Vol. 1, No. 2, June 2003

[4] Silicon Carbide Schottky Diode C3D02060A–Datasheet *Z-Rec*™ Rectifier from CREE

[5] J. Würfl, O. Hilt, E. Bahat-Treidel, R. Zhytnytska, K. Klein, P. Kotara, F. Brunner, A. Knauer, O. Krüger, M. Weyers, G. Tränkle, "Technological Approaches towards High Voltage, Fast Switching GaN Power Transistors", ECS Trans., Vol. 52, No. 1, pp. 979-989, 2013

[6] N. Badawi, O. Hilt, S. Dieckerhoff, E. Bahat-Treidel, and J. Würfl, “Switching Characteristics of 200V Normally-off GaN HEMTs”, Proc. of the PCIM Europe, Nürnberg, 2013

[7] D. Schröder, "Leistungselektronische Bauelemente", Springer, Second Edition 2006, Page 154 (in German)

[8] M. Chinthavali, B. Ozpineci, L. Tolbert, “Temperature-Dependent Characterization of SiC Power Electronic Devices”, Oak Ridge National Laboratory, USA, DE-AC05-00OR22725.

[9] B. J. Baliga, “The Future of Power Semiconductor Device Technology”, Proceedings of IEEE, Vol. 89, No. 6, June 2001, pp. 822-832

[10] N. Badawi, P. Knieling, S. Dieckerhoff, “High Speed Gate Driver Design for Testing and Characterizing WBG Power Transistors”, Proc. of the EPE-PEMC, Novi-Sad, 2012

[11] A. Calmels, "VDS(on), VCE(sat) Measurement in a High Voltage, High Frequency System", APT Europe, France, Application note APT0407, November 2004.

[12] B. Lu, T. Palacios, D. Risbud, S. Bahl, D. I. Anderson, “Extraction of Dynamic On-resistance in GaN Transistors under Soft- and Hard-switching Conditions”, Proc. of the IEEE Compound Semiconductor Integrated Circuit Symposium (CSICS), pp. 1550-8781, October 2011