

Zero reverse recovery in SiC and GaN Schottky diodes: a comparison

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Abstract—Similarly to the unipolar SiC Schottky diodes, AlGaIn/GaN Schottky devices have been suggested to have a negligible reverse recovery current during turn-off and can therefore be switched at very high frequencies with low power losses [1-2]. This study aims to investigate this claim by comparing the reverse recovery characteristic of an AlGaIn/GaN diode with that of a SiC diode and a fast recovery Si P-N diode for the same current (4 A) and voltage rating (700 V). TCAD models of a SiC Schottky diode and an AlGaIn/GaN diode have been developed and calibrated against fabricated devices for a better physical understanding of the experimentally observed results. The analysis is based on the trade-off between on-state and reverse recovery parameters at both room and high temperatures. Experimental and TCAD results show that while the AlGaIn/GaN heterostructure Schottky diode is expected to provide a significant improvement in switching performance when compared to the conventional bipolar Si P-N diodes, the SiC diode offers a more favourable trade-off between on-state and reverse recovery.

I. INTRODUCTION

Wide bandgap semiconductors such as SiC and GaN are considered very promising materials for use in the field of power devices with the potential to achieve increases in power density, reduced on-resistance and high frequency response. The wide bandgap of the material ($E_g = 3.39$ eV for GaN, $E_g = 3.26$ eV for SiC) allows a high critical electric field to be sustained ($E_c = 3.3$ MV/cm for GaN, $E_c = 3$ MV/cm for SiC) which can lead to the design of devices with shorter drift regions than silicon devices for the same breakdown voltage [3]. SiC Schottky diodes have in recent years found use in several applications allowing a reduction in power losses and increase in switching frequencies [4]. GaN-on-Si lateral diodes have been suggested as possible alternatives to these SiC schottky diodes in the 600 V - 1.2 kV voltage range. These GaN diodes are based on an AlGaIn/GaN heterostructure where a high density two dimensional electron gas (2DEG) with high carrier mobility ($\mu = 2000$ cm²/Vs) is formed at the interface between AlGaIn and GaN layers [3]. These properties can indeed lead to the production of GaN Schottky barrier diodes with very competitive performance [5]. Both SiC and GaN-based diodes are unipolar devices proposed to have a negligible reverse recovery current during turn-off. This study investigates this claim by comparing the reverse recovery characteristic of an AlGaIn/GaN diode with that of a SiC diode and fast recovery Si PIN diode for the same current (4A) and voltage rating (700V) both experimentally and in TCAD simulations.

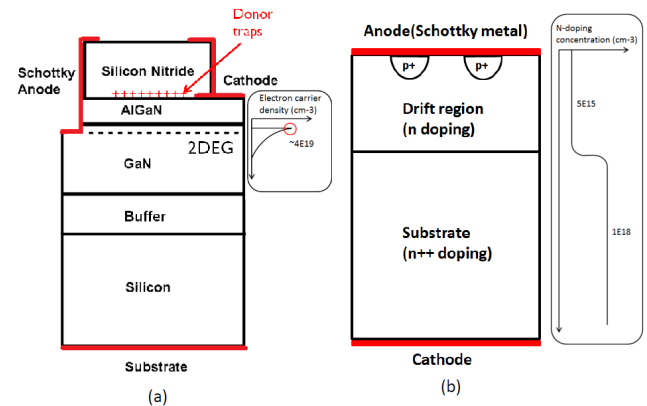


Fig. 1. Cross section of (a) AlGaIn/GaN device and (b) SiC device used for experimental measurements and TCAD model.

II. DEVICE STRUCTURE AND TCAD MODELS

The schematic cross-sections of the AlGaIn/GaN and SiC Schottky diodes analysed in this work are presented in Fig. 1. In this figure, the electron concentration forming the channel of the GaN diode and the N-doping included in the SiC diode are also shown. The SiC diode is based on a vertical two-terminal structure with the anode Schottky contact on the top and the cathode contact at the bottom of the device (Fig. 1(b)). The design includes a P-N junction grid under the conventional metal-semiconductor junction of the Schottky contact (MPS concept) to improve off-state performance [4]. A uniform distribution of N-doping concentration of $5e15$ cm⁻³ has been included in the drift region of the TCAD model in order to match the experimental data. A higher concentration of $1e18$ cm⁻³ has been added in the substrate region. The GaN Schottky diode is a lateral three-terminal device with an AlGaIn/GaN heterostructure grown epitaxially on a standard silicon wafer (Fig. 1(a)). A buffer layer is used to allow a high quality GaN layer to be grown despite the significant lattice mismatch between GaN and Si. Fixed charges were included in the TCAD simulation deck according to [6] to take into account the piezo-polarisation effect observed in GaN devices. A surface donor trap concentration at the AlGaIn/passivation interface was included in the TCAD model according to the analysis discussed in [7]. Finally, a P-type doping of $1e16$ cm⁻³ was added in the GaN layer to take into account the carbon doping effects as reported in literature [8].

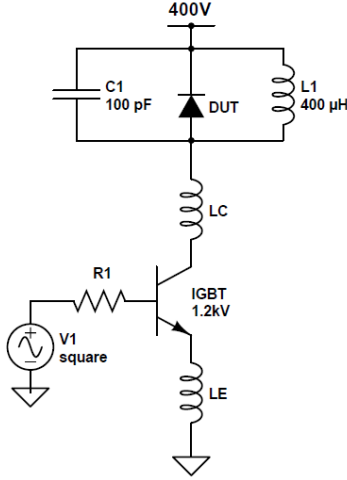


Fig. 2. Experimental and simulation reverse recovery test circuit

III. EXPERIMENTAL METHODS

Reverse recovery measurements were carried out using a standard inductive switching circuit (see Fig. 2) which comprises of a gate resistance ($R1$) for controlling the dI_F/dt to define the switching condition ($300 \text{ A}/\mu\text{s}$). The main inductor $L1$ ($400 \mu\text{H}$) behaves as a constant current source. The diodes to be characterised correspond to the device under test (DUT) shown in the circuit. Parasitic inductances and capacitances (LC , LE , $C1$) are also included. The same circuit was also reproduced in mix-mode simulations using the Sentaurus TCAD simulation software platform.

IV. RESULTS AND DISCUSSION

A. Experimental Measurements

Several 700 V Si, SiC and GaN diodes of the same current rating were tested using the experimental circuit shown in Fig. 2. On-state performance of these diodes is shown in Table I.

Type of Diode	Forward Voltage, V_F at $I_F = 4 \text{ A}$	
	$T=25^\circ\text{C}$	$T=150^\circ\text{C}$
GaN	1.4V	1.9V
SiC(1)	1.4V	1.9V
SiC(2)	1.5V	1.8V
Fast recovery Si(1)	2.6V	1.5V
Fast recovery Si(2)	2.2V	1.3V

TABLE I. FORWARD VOLTAGE DROP OF TESTED DEVICES AT ROOM TEMPERATURE AND INCREASED TEMPERATURE.

Figures 3 and 4 show the measured reverse recovery curves of the same devices at 25°C and 150°C . One can note that the vertical SiC diode offers the best trade-off between on-state and reverse recovery losses. Both the SiC and the GaN diodes outperform the fast recovery Si diodes, and have an insignificant increase in the reverse recovery losses when operating at high temperatures, unlike silicon. The opposite trend is however observed in on-state losses where the performance of the unipolar GaN and SiC diodes is diminished at increased temperatures due to reduced carrier mobility. On

the other hand the on-state performance of fast recovery Si diodes is improved at increased temperatures due to increased conductivity modulation.

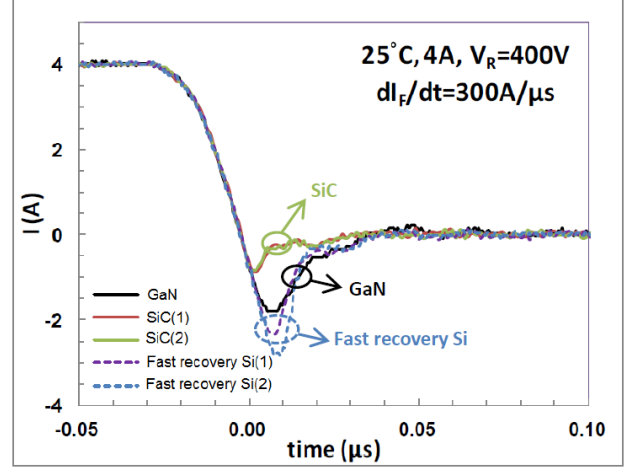


Fig. 3. Experimental reverse recovery characteristic of AlGaIn/GaN diode compared with SiC schottky diodes and fast recovery Si diodes of similar rating at room temperature.

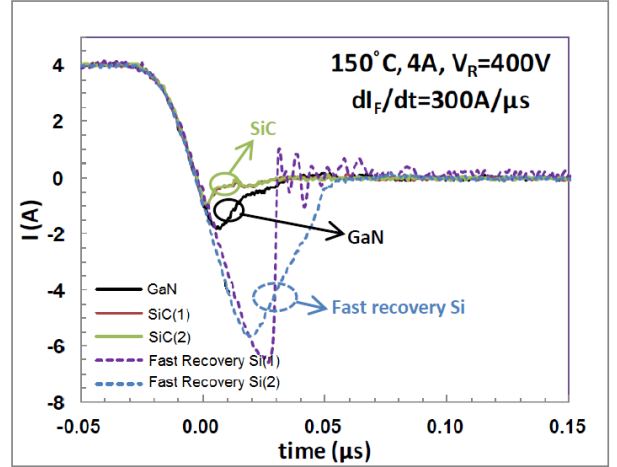


Fig. 4. Experimental reverse recovery characteristic of AlGaIn/GaN diode compared with SiC schottky diodes and fast recovery Si diodes of similar rating at room temperature.

As shown by the reverse recovery measurements summarised in Table II, the SiC vertical Schottky diodes are by far the closest to the claim of *zero reverse recovery losses*. This very significant result can be explained when considering the differences in the structure of the GaN and SiC diode. While charge is uniformly distributed in the volume of the drift region of a SiC diode, it is confined at the interface of the heterojunction for the AlGaIn/GaN Schottky diode (see Fig. 1). When the SiC diode is turning off, the depletion region extends vertically into the drift region along the entire length of the Schottky contact. On the other hand, when the GaN Schottky diode is turning off the 2DEG layer is depleted laterally from the recessed Schottky contact and vertically from the GaN layer. A high concentration of carriers is removed through the narrow path of the 2DEG layer which extends only up to a few nm away from the heterointerface. To provide a more robust

	AlGaN/GaN		SiC(1)		SiC(2)		Fast Recovery Si(1)		Fast Recovery Si(2)	
	I _F = 4A, di/dt = 300A/us, V _R = 400V									
Temp	25°C	150°C	25°C	150°C	25°C	150°C	25°C	150°C	25°C	150°C
I _R (A)	1.80	1.70	0.70	0.73	0.64	0.67	2.28	7.04	2.55	5.58
t _{rr} (ns)	30.9	32.0	26.6	29.7	28.9	29.1	30.8	32.3	22.9	51.7
t _{rrA} (ns)	33.2	34.3	28.9	32.3	31.5	31.6	33.1	32.7	24.2	54.6
Q _{RA} (nC)	29.8	29.2	10.2	11.9	10.1	10.6	37.7	115.1	30.9	152.2

TABLE II. REVERSE RECOVERY PARAMETERS OF ALGaN/GaN SCHOTTKY DIODE AT ROOM TEMPERATURE AND INCREASED TEMPERATURE COMPARED WITH SiC SCHOTTKY DIODES AND FAST RECOVERY SI DIODES OF SIMILAR RATING.

analysis of the effects that the distribution and magnitude of the drift region charge has on the reverse recovery characteristic of the GaN and SiC Schottky diodes, TCAD simulations were performed. The results of this analysis are discussed in the next section.

B. TCAD simulations

TCAD simulations of on-state, leakage and reverse recovery characteristics were matched thoroughly with the corresponding experimental data. A very accurate match was obtained between the simulated reverse recovery characteristic of the AlGaIn/GaN Schottky diode model and the experimental result, as shown in Fig. 5.

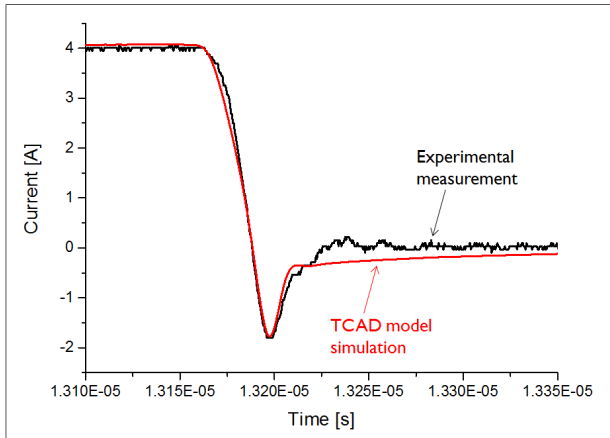


Fig. 5. AlGaIn/GaN Schottky diode reverse recovery characteristic match between TCAD model simulation and experimental result at room temperature.

The carrier concentration in the 2DEG channel of the TCAD model was varied by adjusting the Aluminium mole fraction in the AlGaIn layer of the heterostructure. The simulated effect of the 2DEG carrier concentration on the reverse recovery performance of the device is shown in Fig. 6. A trade-off is observed between the on-state and reverse recovery characteristic of the GaN diode where increased channel charge leads to reduced on-state losses but increased reverse recovery losses. The TCAD model of the SiC diode was built with equivalent on-state and breakdown capabilities as the AlGaIn/GaN diode. This was done in order to enable a direct comparison of the reverse recovery of the two devices in these conditions, as was the case with the real devices used. This revealed the difference in the charge present in the two devices when these matching conditions were achieved. Furthermore, a hypothetical SiC diode with a drift region charge equal to

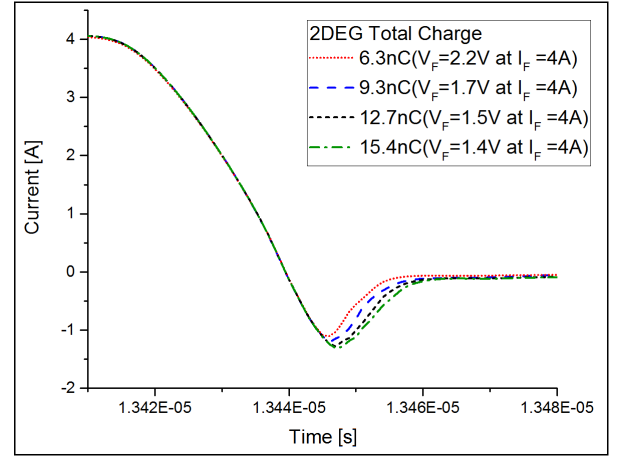


Fig. 6. Effects of 2DEG charge level on TCAD model reverse recovery characteristic for AlGaIn/GaN Schottky diode device shown in Fig. 1.

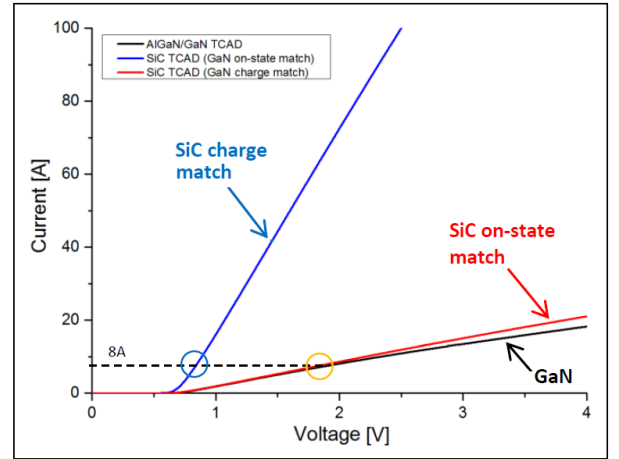


Fig. 7. Simulated on-state I-V characteristic of AlGaIn/GaN diode model matched with SiC diode model. The on-state I-V characteristic comparison between the two devices is also shown with equal drift region charge.

the charge in the 2DEG of the GaN diode was simulated. This was done to enable a comparison between the two devices when the drift region charge was matched, rather than the on-state characteristic. Fig. 7 shows the simulated on-state characteristics of the AlGaIn/GaN and SiC devices for on-state matching and drift region charge matching.

It is observed that the SiC diode offers a better on-state performance for a given level of drift region charge. Fig. 8 highlights this observation, showing that the amount of charge

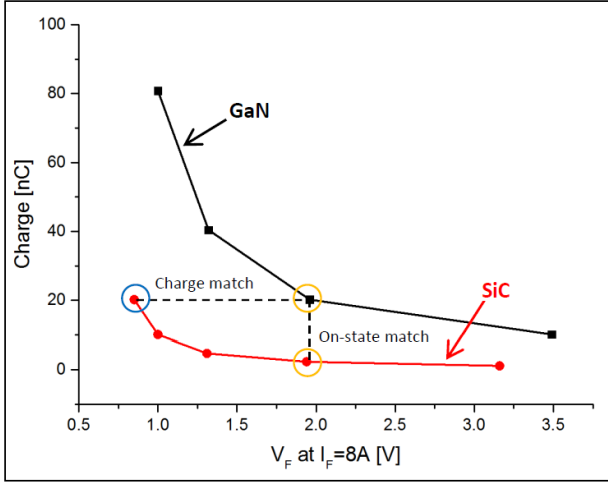


Fig. 8. Comparison of drift region charge for SiC and 2DEG charge for GaN vs forward voltage drop for a current rating of 8A for GaN and SiC Schottky diode TCAD models.

necessary for a SiC diode to conduct a fixed current (8A) is significantly lower than the one required from a GaN diode to conduct the same current at a fixed forward voltage drop. This is due to the vertical configuration of the SiC diode compared to the lateral geometry of the AlGaIn/GaN diode. Despite the higher critical electric field of GaN compared to SiC, a longer drift region is required in the GaN diode to achieve an equivalent breakdown voltage thus leading to increased drift region charge. This is a direct consequence of the less optimized electric field distribution observed in a lateral device. Simulations of the reverse recovery of the AlGaIn/GaN and SiC devices were compared for both the models with matching on-state characteristic and the models with matching drift region charge. This comparison can be seen in Fig. 9 and is found to agree with the experimental results presented in the previous section revealing the superior performance of the SiC diode. The following observations are made:

- The 2DEG charge in GaN is significantly higher than the drift region charge in a SiC diode for equal rating and on-state performance (see Fig. 8). This results in the GaN device having a slower turn-off characteristic as well as larger reverse recovery current peak and losses.
- In the hypothetical case where the drift region charge in SiC matches the 2DEG charge, the SiC diode still outperforms the GaN diode (with much lower on-state voltage drop and slightly better reverse recovery characteristics).
- The charge distribution in SiC and GaN is completely different. In SiC the charge is uniformly distributed in the drift region which leads to a smooth recovery as the depletion region gradually advances in the drift layer during the reverse recovery. In GaN, the 2DEG layer is confined at the interface, has a very high carrier density and depletes initially laterally from the anode field plate, and then vertically from below due to the acceptor charge in the GaN buffer.

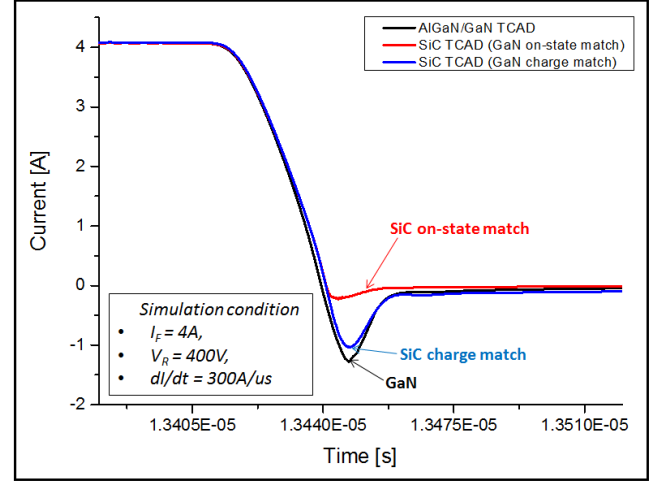


Fig. 9. Simulated reverse recovery characteristic of AlGaIn/GaN diode model compared with SiC Schottky diodes of equal on-state current characteristic and equal drift region charge.

V. CONCLUSION

Experimental and TCAD results show that while the AlGaIn/GaN Schottky diode is expected to provide a significant improvement in switching performance when compared to the conventional bipolar Si P-N diodes, the suggestion of *zero reverse recovery* is not truly valid. This is due to the high level of 2DEG charge density, necessary in the on-state to compensate for the lateral geometry of the heterostructure diode. In conclusion, the SiC diode offers a more favourable trade-off between on-state and reverse recovery and its performance can be controlled more accurately as it is not subject to surface or bulk traps. The analysis carried out here uses complex TCAD models matched to extensive experimental results and it contains aspects which contradict findings in literature [1-2] that suggest comparable turn-off performance between GaN and SiC Schottky diodes of equal rating.

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