Reverse Leakage Current and Breakdown Voltage Improvements in GaN Schottky Diodes

Timothy Boles[1], Ling Xia[2], Allen Hanson[1], Anthony Kaleta[1], and Chris McLean[1]

[1] MACOM Technology Solutions, Lowell, MA 01851
timothy.boles@macomtech.com; +1978-580-1394
allen.hanson@macomtech.com;
anthony.kaleta@macomtech.com;
chrismclean@macomtech.com;
[2] Formerly with MACOM Technology Solutions, Lowell, MA 01851

Keywords: GaN, GaN-on-Silicon, Schottky Diode

Abstract

This paper utilizes the results of a study that has been previously published [1] by the authors of the underlying mechanisms for reverse leakage current in GaN High Electron Mobility Transistors (HEMTs). This analysis concluded that managing electric field in gate Schottky on GaN HEMTs is extremely critical for enhancing device reverse leakage and breakdown. The results of this electric field investigation demonstrate a viable method employing properly engineered field plates to optimize GaN HEMT and Schottky diode reverse characteristics.

INTRODUCTION

Reducing reverse leakage current and increasing breakdown voltage of is critical for GaN HEMT and Schottky diodes. The reason this optimization of is that GaN HEMT and Schottky diodes target both high-voltage power amplifiers and high-voltage switching applications. A typical GaN HEMT power amplifier typically operates with five times higher supply voltage when compared to a more conventional GaAs approach. More recently, GaN HEMT and corresponding Schottky diodes have been considered for high-voltage switching applications, in which the voltage of operation can be more than 1000 V. While GaN provides outstanding intrinsic material properties, sophisticated engineering efforts are required at the device level to best leverage these inherent advantages.

DISCUSSION

The dominant mechanisms of reverse leakage current in GaN-on-Silicon HEMT devices, as fabricated at MACOM Technology Solutions, were analyzed. As was seen on similar studies on GaN-on-SiC and GaN-on-sapphire structures, the analysis quickly focused on two underlying leakage mechanisms in the Ni/Au Schottky diode gate electrode of the HEMT device. The first leakage process is Frenkel–Poole (FP) emission. FP tunneling is a trap-assisted process and has strong temperature dependence. The second dominant mechanism is referred as Fowler-Nordheim (FN) tunneling. FN tunneling increases with electric field, but does not need assistances from trap states.

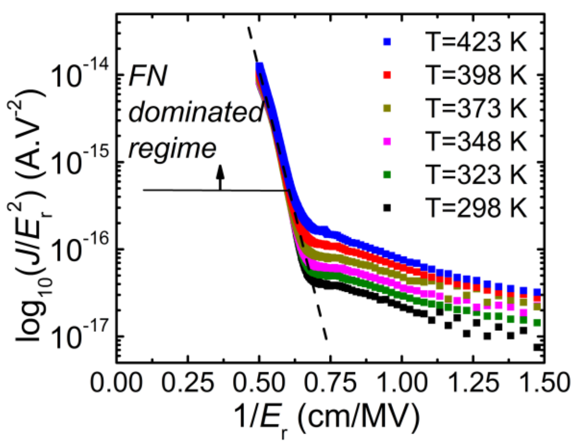

Fig. 1. – Plot of $\log(J_r/E_r^2)$ as a Function of $1/E_r$. Showing both FN and FP Tunneling Regimes

As shown in Figure 1, the results of this study found that the dominant leakage mechanism, either FP or FN, is a function of the peak electric field and, thus, the applied operating voltage. As can also be seen in Figure 1, the

$$J_{FN} = AE_r^2 \exp(-\frac{B}{E_r}) \quad (1)$$

leakage current is both temperature independent for an electric field >1.6 MV/cm while demonstrating a very strong dependence on the value of electric field at the edge of the gate Schottky diode. This characteristic is considered to be Fowler-Nordheim tunneling. FN tunneling is seen to increase with electric field, but does not need thermal assistance from trapping states. The functional relationship for leakage versus the electric field for FN tunneling is shown in Equation (1) above.

Given that the critical electric field for GaN is above 3 MV/cm, FN tunneling is expected to be significant for the reverse leakage current in a large range of applied voltage. As FN tunneling heavily depends on electric field, it is critical to properly engineer the reverse electric field, in order to reduce gate leakage current in GaN HEMTs or the anode leakage in high voltage GaN Schottky diodes.

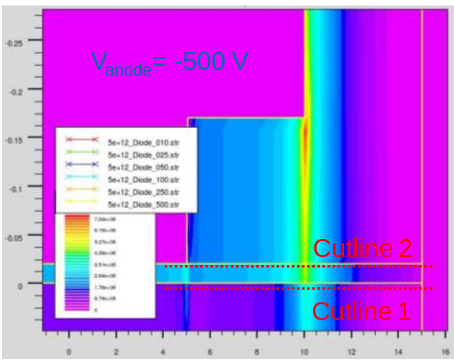

Fig. 2 – Simulated Two-Dimensional Electric Field Distribution for GaN Schottky Contact - V_r = -500 V

A viable solution to effectively suppress the electric field in both GaN HEMT and GaN Schottky diode devices is through the application of field plates. Two-dimensional electric field distributions in a simplified GaN Schottky contact that has an integrally attached field plate, which would be applicable to either a GaN gate electrode or a stand-alone GaN Schottky diode, were simulated. Figure 2 presents a cross-section of this simplified field plated structure and the resultant simulated electric field distribution. It can be seen in Figure 3 that two electric field peaks appear at the edge of the electrode and the edge of the field plate. This figure further illustrates that the increase of electric field peaks with increasing reverse voltage.

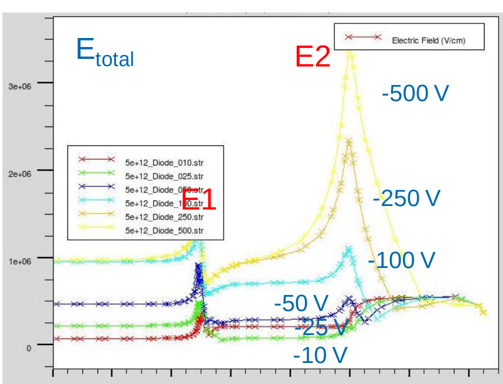

Fig. 3 - Evolution of the two electric-field peaks (E1 and E2) as a function of reverse bias

Additional simulations suggest that the relative magnitude of the two electric field peaks can be engineered by varying the field plate dimension as well as the corresponding dielectric material and thickness. Simulation results for a single field plate structure as a function of SiN thickness and field plate dimension are presented in Figure 4 and Figure 5. In an optimal design, the two peak fields are expected to be at similar levels when critical field is reached and the device exhibits avalanche breakdown. Under such a circumstance, the electric field has been distributed and spread across the drain/cathode regions of the structure as uniformly as possible and the breakdown voltage is considered to be maximized.

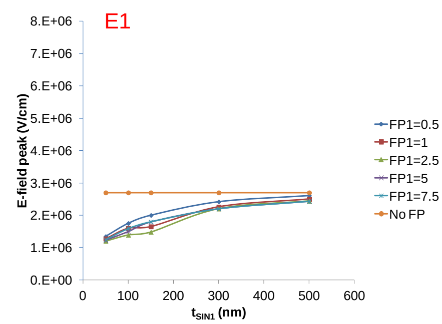

Fig. 4 - Effect of Field Plate Dielectric Thickness on E1 magnitude with Various Field Plate Dimensions

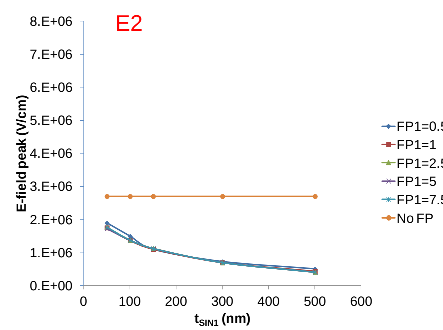

Fig. 5 - Effect of Field Plate Dielectric Thickness on E2 magnitude with Various Field Plate Dimensions

Extensive studies on the dimensions of the field plates and corresponding dielectric thickness have been completed for single, double, and triple field plate structures. Based on these analyses, device simulations were performed that point to viable ways of managing the reverse leakage current and hence increased breakdown voltage of GaN HEMT and GaN Schottky diodes.

RESULTS

Based upon the above structure/field modeling, a test matrix of various GaN-on-Silicon, double anode connected field plates were designed to validate the electric field simulations, reduce the reverse GaN diode leakage, and improve the reverse breakdown voltage. The detail of these dual ACFP overlap dimensions is presented in Figure 6. It can be seen that various combinations of the 1st ACFP, the 2nd ACFP, and anode-to-cathode spacings are included in this experimental array. The design variants indicated in yellow in Figure 6 have undergone on-wafer, high voltage, Schottky diode reverse breakdown characterization, both utilizing automatic wafer probe equipment and manually using a high voltage curve tracer.

		L_FP1	L_FP2
Variant Number	DG Spacing	Layer: DC	Layer: SCFP
Variant Number	Anode/Cathode Spacing	ACFP1	ACFP2
	(μ)	(μ)	(μ)
1	10.0	0.5	0.5
2	15.0	3.0	3.0
3	20.0	0.5	1.5
4	25.0	3.0	3.0
5	30.0	5.0	5.0
6	35.0	3.0	0.5
7	10.0	0.5	1.5
8	15.0	5.0	0.5
9	20.0	0.5	5.0
10	25.0	0.5	0.5
11	30.0	0.5	0.5
12	35.0	3.0	1.5
13	10.0	0.5	3.0
14	15.0	5.0	0.5
15	20.0	1.5	0.5
16	25.0	0.5	0.5
17	30.0	0.5	0.5
18	35.0	5.0	0.5
19	10.0	0.5	5.0
20	15.0	5.0	1.5
21	20.0	3.0	5.0
22	25.0	0.5	3.0
23	30.0	0.5	5.0
24	35.0	5.0	0.5

		L_FP1	L_FP2
Variant Number	DG Spacing	Layer: DC	Layer: SCFP
Variant Number	Anode/Cathode Spacing	ACFP1	ACFP2
	(μ)	(μ)	(μ)
25	10.0	0.5	5.0
26	15.0	5.0	5.0
27	20.0	5.0	0.5
28	25.0	1.5	5.0
29	30.0	0.5	5.0
30	35.0	5.0	3.0
31	10.0	1.5	0.5
32	15.0	5.0	5.0
33	20.0	5.0	3.0
34	25.0	3.0	5.0
35	30.0	0.5	5.0
36	35.0	5.0	5.0
37	10.0	1.5	5.0
38	15.0	5.0	5.0
39	20.0	5.0	5.0
40	25.0	5.0	0.5
41	30.0	1.5	1.5
42	35.0	5.0	5.0
43	10.0	3.0	0.5
44	15.0	0.5	0.5
45	20.0	1.5	1.5
46	25.0	5.0	1.5
47	30.0	1.5	3.0
48	35.0	5.0	5.0

Fig. 6 –Test Matrix of the Overlap Dimensions of the Dual ACFP Lateral GaN-on-Silicon Schottky Diodes

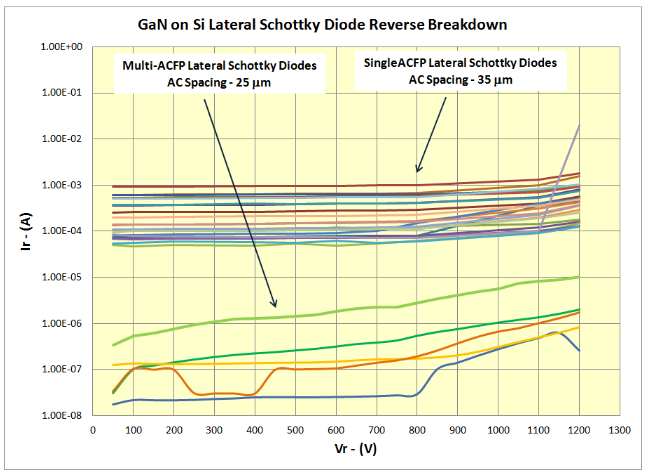

Fig. 7 – GaN-on-Silicon Schottky Diode Reverse Breakdown and Reverse Leakage Comparison of Dual ACFP vs Single ACFP

In Figure 7, a plot of the on-wafer, auto-probe, reverse breakdown and leakage characterization for device number 4, device number 16, and device 28 that are highlighted in the test matrix in Figure 6 is presented. These design variants are dual ACFP, GaN-on-Silicon lateral Schottky diodes, all having an anode-to-cathode spacing of 25 µm. It can be seen that a minimum reverse breakdown of 1200 volts was achieved, which is the voltage limit of the MACOM auto-tester. As suggested by the multi-field plate structure simulation which in turn was supported the underlying FN leakage mechanism, the baseline leakage for these double field plate structures is in the 10^{-6} ampere to 10^{-8} ampere range.

Also shown in Figure 7, a comparison to GaN-on-Silicon Schottky diodes having a single ACFP, the results of these single ACFP devices were presented at CSMANTECH 2013 [2], is contrasted with the dual ACFP designs. It can be seen in Figure 7, that while the single ACFP and the dual ACFP diodes both meet a minimum 1200 Volt reverse breakdown, which is the auto-tester limit, the single ACFP design required an anode-to-cathode spacing of 35 µm, while the dual ACFP approach achieved the 1200 volt level with a 25 µm anode-to-cathode spacing. Even more significant, especially relative to the validation of the FN leakage mechanism hypothesis and the ability of multi-field plate structures to spread the peak electric field and reduce the overall reverse leakage levels, the dual ACFP produced a reduction in the baseline leakage by a factor of 10^3 to 10^4 when compared to the single ACFP diodes.

LOT	WAFER	SCRIBE	DEVICE	VR(V)	IR(uA)	TESTER
1813008	2	AK050000DW	12	**>2000**	<5	curve Tracer
1813008	2	AK050000DW	12	**>2000**	<5	curve Tracer
1813008	2	AK050000DW	12	**>2000**	<5	curve Tracer
1813008	2	AK050000DW	30	**>2000**	<5	curve Tracer
1813008	2	AK050000DW	30	**>2000**	<15	curve Tracer
1813008	2	AK050000DW	30	**>2000**	<5	curve Tracer
1813008	2	AK050000DW	42	**>2000**	<5	curve Tracer
1813008	2	AK050000DW	42	**>2000**	<5	curve Tracer
1813008	2	AK050000DW	42	**>2000**	<5	curve Tracer
1813008	4	AI051000DW	12	**>2000**	<5	curve Tracer
1813008	4	AI051000DW	12	**>2000**	<5	curve Tracer
1813008	4	AI051000DW	12	**>2000**	<5	curve Tracer
1813008	4	AI051000DW	30	**>2000**	<5	curve Tracer
1813008	4	AI051000DW	30	**>2000**	<5	curve Tracer
1813008	4	AI051000DW	30	**>2000**	<5	curve Tracer
1813008	4	AI051000DW	42	**>2000**	<5	curve Tracer
1813008	4	AI051000DW	42	**>2000**	<5	curve Tracer
1813008	4	AI051000DW	42	**>2000**	<5	curve Tracer

Fig. 8 – GaN-on-Silicon Lateral Schottky Diode, On-Wafer, Manual, Curve Tracer, Dual ACFP Reverse Breakdown Characterization

In order to characterize these dual ACFP lateral GaN-on-Silicon Schottky diodes at higher voltages, testing of device number 12, number 30, and device number 42 from two different epitaxial variants, wafer #2 band wafer #4, was performed manually utilizing a high voltage curve tracer. The results are presented in Figure 8. It can be seen that all design double ACFP variants and both epitaxial designs produced a reverse breakdown >2000 volts, which again is

16

the limit of the high voltage curve tracer. This >2000 volt reverse breakdown voltage contrasts significantly with the previously reported 1474 volt result that was measured on the single ACFP approach.

CONCLUSIONS

The study of FP and FN tunneling mechanisms suggests that the reverse leakage current and breakdown voltage of GaN Schottky diode based electrodes heavily depends on the reverse electric field in the barrier. In particular, a process that is exponentially enhanced by electric field, FN tunneling, dominates the high-field leakage. On the device level, it is clear that employing multiple plates has demonstrated the ability to spread the peak electric field and improve high breakdown characteristics of GaN devices.

ACKNOWLEDGEMENTS

The authors would also like to thank Fredrick Hardy of The MACOM Technology Solutions test laboratory for all his efforts in obtaining the measurements for the large number of device variants.

REFERENCES

[1] L. Xia, A. Hanson, T. Boles and D. Jin, "On Reverse Gate Leakage Current of GaN High Electron Mobility Transistors on Silicon Substrate", *Applied Physics Letters*, **102**, 113510, 2013.

[2] T. Boles, C. Varmazis, D. Carlson, L. Xia, D. Jin, T. Palacios, G. W. Turner, R. J. Molnar, "High-Voltage GaN-on-Silicon Schottky Diodes", CS MANTECH, May, 2013

ACRONYMS

GaN: Gallium Nitride
SiC: Silicon Carbide
SiN: Silicon Nitride
HEMT: High Electron Mobility Transistor
ACFP: Anode Connected Field Plate