High-Voltage GaN-on-Silicon Schottky Diodes

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Keywords: GaN; GaN-on-Silicon; Lateral Schottky Diode

Abstract

M/A-COM Technology Solutions has continuing joint development efforts sponsored by the Department of Energy with MIT main campus and MIT Lincoln Laboratory to develop GaN-on-silicon two and three-terminal high-voltage/high-current switching devices. The initial developmental goals were for a Schottky diode that has a reverse breakdown blocking voltage of >600 volts and is capable of handling 10 amperes of forward current.

A comparison of the M/A-COM Technology Solutions lateral GaN Schottky diode on-resistance as a function of reverse breakdown voltage for a number of both lateral and vertical GaN Schottky diode geometries taken from the literature is presented. The substrates employed for all of these data points are either sapphire, SiC, silicon, and even one study which utilized single crystal GaN. Also included in this plot are theoretical limits for the basic materials typically used in GaN Schottky diode construction. It can be seen that the reverse breakdown results of approximately 1500 volts for M/A-COM Technology Solutions lateral anode connected field GaN Schottky diodes on silicon substrates compare extremely favorably with the reported performance of the state-of-the-art devices, regardless of substrate material or design geometry.

Introduction

The following paper is a summary of the results to date of continuing joint development efforts sponsored by the Department of Energy with MIT Lincoln Labs and the MIT Electrical Engineering and Computer Science Department to develop GaN-on-silicon two-terminal and three-terminal high-voltage/high-current switching devices. The initial developmental goals were for a Schottky diode that has a reverse breakdown blocking voltage of >600 volts and is capable of handling 10 amperes of forward current.

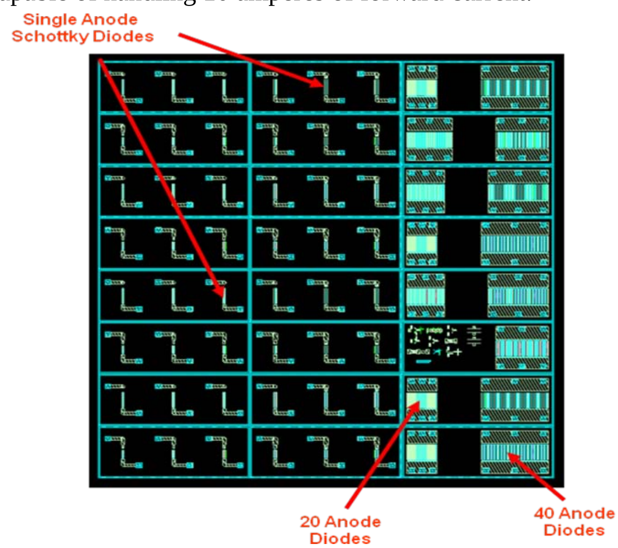

Fig. 1 – High-voltage Schottky Diode Test Array

The GaN-on-silicon high-voltage Schottky diode design effort centered upon utilizing a lateral as opposed to vertical diode design geometry. This basic approach was chosen for two reasons. First, the lateral design approach can build upon the results achieved with previous three-terminal HEMT transistor designs. In fact, as will be discussed below, the basic design layout will utilize many FET design concepts except that the "source" and "drain" will be shorted to form the device cathode. Second, the lateral design approach will enable the standard GaN HEMT process flow, which forms the ohmic contacts prior to the deposition of a passivating gate dielectric and gate Schottky metallization, including the standard GaN HEMT process control monitors as well as in-line characterization elements to be used to characterize the

(*) Sponsored by Department of Energy under Contract Number DOE IA No.: DE-AI26-OE0000121
Award No. :DE-AI26-07NI43294/006. The Lincoln Laboratory portion of this work was sponsored by the Department of Energy under Air Force Contract #FA8721-05-C-0002. The opinions, interpretation, conclusions and recommendations are those of the authors and are not necessarily endorsed by the United States Government.

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basic process. This process approach combined with the standard three-terminal GaN-on-silicon epitaxy will enable, not only high-voltage discrete Schottky diodes to be achieved, but also, when integrated with high-voltage transistor designs, the formation of monolithic, high-voltage inverter MMICs.

DISCUSSION

As can be seen in Figure 1, a test array of both single and multiple anode lateral Schottky diodes with a total of 63 variants was designed. The single junction diodes consist of a matrix of forty-eight, discrete, lateral diodes having incrementally increasing anode-to-cathode spacings; with and without anode connected field plates, ACFP's; two different anode lengths/areas; and two different ion implantation isolation schemes. The multiple anode lateral structures all have twenty anodes per device, a fixed anode length of 500 μm translating to a total anode periphery of 20.0 mm having six different anode-to-cathode dimensions, from 10 μm to 35 μm and having both non-field plate and ACFP designs to reduce the peak field at the edge of the anode and spread the high field over the cathode region. This field reduction and spreading of the peak field in the cathode should result in higher applied voltage before the onset of critical field in the semiconductor and the resultant avalanche breakdown.

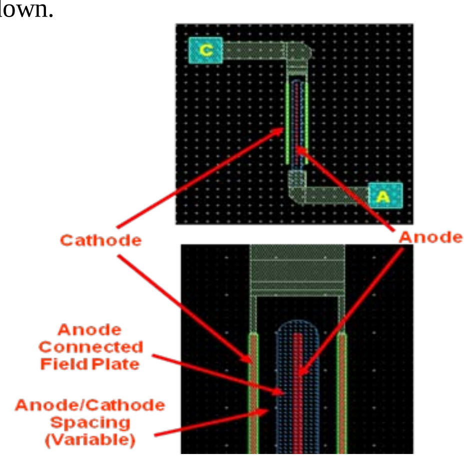

Fig. 2 – Details of High-Voltage Schottky Diode

The basic diode construction exhibiting the basic FET transistor layout can best be visualized in Figure 2 and can be seen to consist of parallel anode and cathode fingers. The cathode is formed by shorting what in the FET world would be "Source" & "Drain" ohmic contacts. The anode is formed by the insertion of a symmetric "Gate" Schottky diode between the cathodes. The common design elements of the single finger lateral diode consist of 10 μm wide ohmic cathodes, 10 μm wide "Tee" configured anode structures, and a minimum probe pad-to-probe pad spacing of 400 μm to insure that the high-voltage diodes can be automatically probed without arc-over issues

RESULTS

Figure 3 is a plot of the reverse breakdown characteristics for 28 ACFP GaN Schottky diodes having 500 μm of anode periphery and a 35 μm anode-to-cathode spacing. The measurements were taken across the wafer to provide a clear distribution of device performance. It can readily be noted that these lateral GaN diodes have reasonably low baseline leakage levels with a reverse breakdown at >1200 volts, which is the limit of the present M/A-COM Technology Solutions' test equipment.

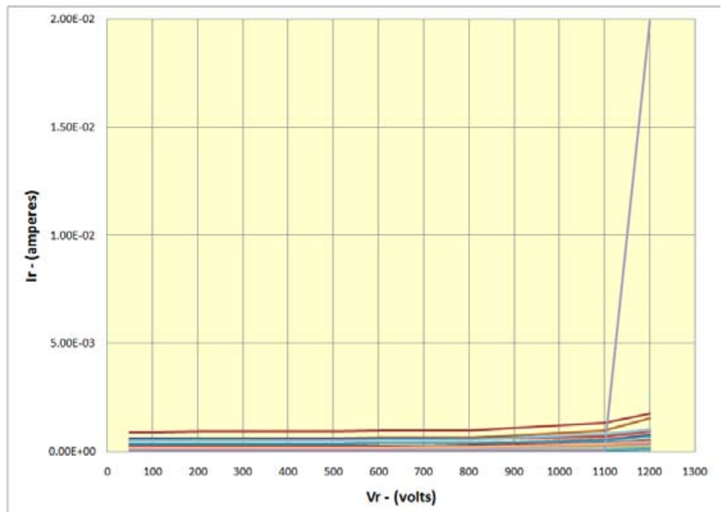

Fig. 3 – Reverse Breakdown Characteristic of Lateral ACFP GaN Schottky Diode

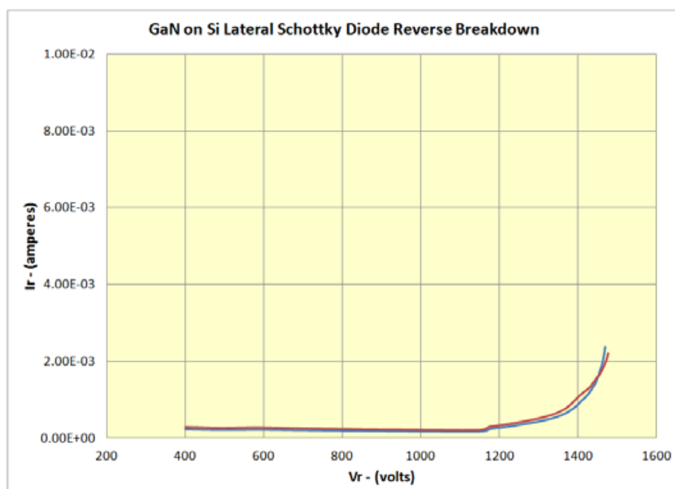

Fig. 4 – Single Point Reverse Breakdown Measurements of GaN on Si Schottky Diode

In order to more accurately determine the reverse breakdown limits of these lateral GaN Schottky diode structures, measurements were taken at the test laboratory at MIT Main Campus to make use of an on-wafer tester which has 3000 volt capability. A can be seen in Figure 4, a diode breakdown of approximately 1500 volts was achieved on lateral ACFP GaN Schottky diodes having 500 μm of anode periphery and a 35 μm anode-to-cathode spacing.

Since all of the high-voltage lateral diodes measurements have been achieved using an ACFP structure, the importance of this configuration relative to the diode reverse breakdown characteristic is most clearly demonstrated by the data presented in Figure 5. In this figure, plots of the diode reverse breakdown characteristic as a function of the anode-to-cathode spacing for both ACFP structures with a field plate cathode overlap dimension which is approximately 45% of the total anode-to-cathode spacing and designs without an intentional field plate are presented.

It can be seen that the ACFP lateral diodes had a minimum reverse breakdown of approximately 700 volts at an anode-to-cathode spacing of 10 μm. As the anode-to-cathode spacing was increased with this ACFP design, the reverse breakdown voltage increased relatively smoothly to a maximum value of approximately 1500 volts. It can also be observed that as the anode-to-cathode dimension is increased, the breakdown voltage plot begins to flatten at the 20 μm spacing point. The observed saturation in voltage and field strength suggests that the present design of the ACFP structure is non-optimal at the larger anode to cathode spacings.

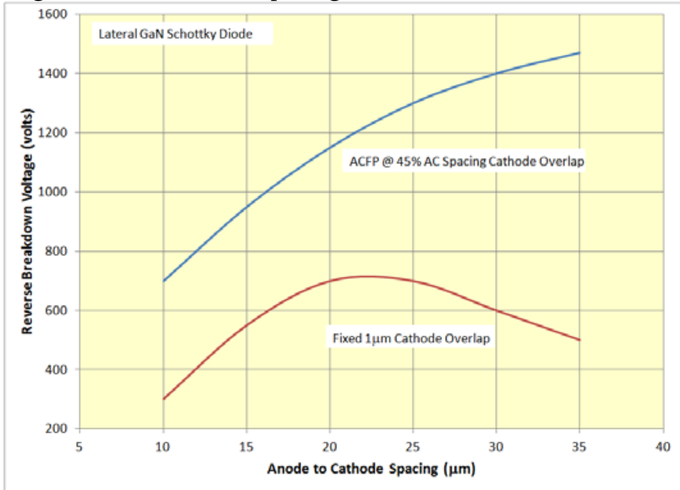

Fig. 5 – Lateral GaN Schottky Diode Reverse Breakdown as a Function of Anode to Cathode Spacing for ACFP and Fixed Cathode Overlap Designs

The reverse diode breakdown characteristic for non-field plated diode designs is also presented in Figure 5. It can be seen that the lack of an ACFP results in a degradation in the reverse breakdown voltage by approximately 400 volts for anode-to-cathode spacings from 10 μm to 20 μm. For these non-field plated designs, the diode breakdown voltage peaks at a value of approximately 700 volts at an anode-to-cathode dimension of 20 μm. At anode-to-cathode spacings greater than 20 μm, the reverse breakdown voltage actually decreases to approximately 500 volts at a cathode spacing of 35 μm.

It is apparent from the saturation mechanisms in breakdown voltage displayed in Figure 5 that changes to the lateral GaN Schottky diode structure must be considered if breakdown voltages greater than 1500 volts are to be achieved. Based upon literature of both diode and HEMT structures, it seems obvious that simple optimization of the existing ACFP, i.e. changes in the field plate dielectric thickness or positional changes in the field plate overlap will not be sufficient to achieve the next developmental goal of 3000 volt reverse breakdown. In order to achieve the desired result, multiple ACFP field plates will certainly be required to reduce the peak field at the anode edge and spread the field throughout the cathode region.

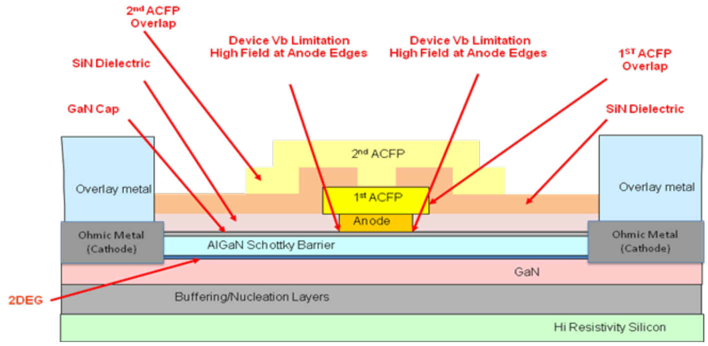

Fig. 6 – Schematic Crossection for Double Field Plated Schottky Diode

Further investigation into increases in the reverse breakdown capability of the Schottky diodes through the use of structure simulation models of multiple ACFP devices has been performed. Based upon these initial ACFP simulations, an experimental double field plated Schottky diode test matrix was designed. Utilizing the existing single field plated designs, 48 double field plate variants have been planned. This approach will not only enable the structure simulations to be validated but also is expected to demonstrate an increased Schottky diode reverse breakdown capability of at least 3000 volts. A typical crossectional schematic of the double ACFP structure is shown in Figure 6

All of the above efforts concentrated on the high breakdown reverse characteristics of the lateral GaN Schottky diode structures, but it should be noted that the Schottky diode development goals also required the ability to handle 10 amperes of current in the forward direction. In support of this requirement, the current handling of multi-anode diodes was measured and a linear graph of the forward diode characteristic for multi-anode diode structures having twenty parallel anodes with 20 mm of anode periphery and having anode-to-cathode spacing ranging from 10 μm to 30 μm is presented in Figure 7. In this plot a typical GaN diode turn-on characteristic at approximately one volt can be observed and is invariant with anode-to-cathode spacing. Following the initial anode forward turn-on response, a linear region which defines the on-resistance of the diode and delineates the usable electrical space is observed. As expected, it can be seen that the device on-resistance and the usable electrical space is very strong function of anode-to-cathode spacing, with smaller cathode dimensions having a much lower on-resistance. Finally, forward current saturation is reached and results in a flattening of the diode curve.

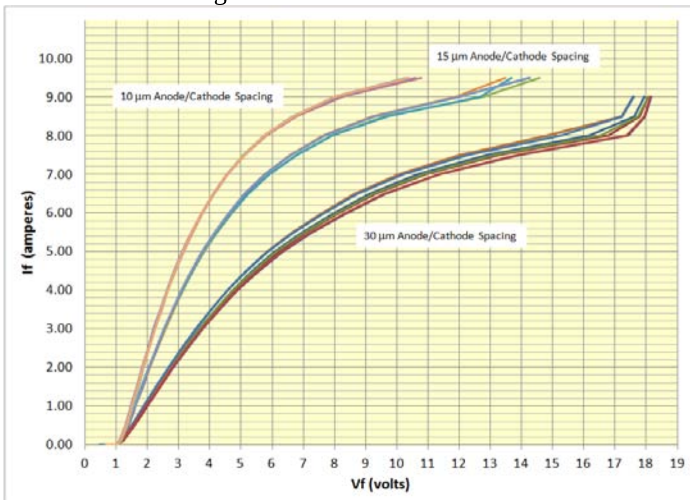

Fig. 7 – Linear Plot of the Forward Characteristic of 20 Anode Lateral GaN-on-silicon Schottky Diodes having a Total Anode Periphery of 20.0 mm and 10 µm to 30 µm Anode-to-Cathode Spacings

In the data presented in Figure 7, it can be seen that over 9.0 amperes of forward current was easily handled with all of the lateral ACFP Schottky diode geometries with no degradation in the diode characteristic. In fact, the measured current handling of these multi-anode designs was limited by the compliance of the high-voltage tester. This is a measure of the survivability and ruggedness of this lateral GaN-on-silicon Schottky diode design approach.

CONCLUSION

In Figure 8, a plot of GaN Schottky diode on-resistance, from the literature, as a function of reverse breakdown voltage for a number of both lateral and vertical GaN Schottky diode geometries is presented. The substrates employed for all of these data points are either sapphire, SiC, silicon, and even one study which utilized single crystal GaN. Also included in this plot are theoretical limits for the basic materials typically used in GaN Schottky diode construction. It can be seen that the results of M/A-COM Technology Solutions' lateral ACFP GaN Schottky diodes on silicon structures (20 mΩ cm^2 and 1500 V) compare extremely favorably with the reported performance of the state-of-the-art devices, regardless of substrate material or design geometry.

As can be seen in Figure 8, the only exception to the above performance comparisons is the vertical GaN Schottky barrier diode on a single crystal GaN substrate, which has the lowest on-resistance, while still having an approximate 1000 volt reverse breakdown, and actually approaches the SiC theoretical material limit. While this is a very impressive result, the use of a GaN substrate at this point in time is certainly not a cost effective solution for realizing a high-voltage Schottky diode. In addition, a vertical design geometry essentially precludes the possibility of designing and forming inverter structures as monolithic integrated circuits.

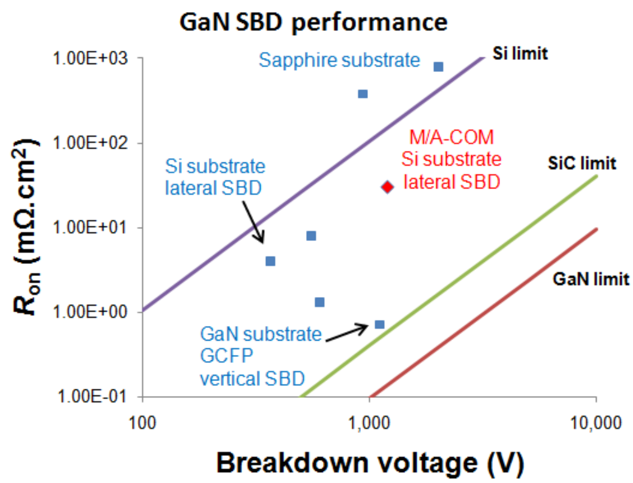

Fig. 8 – Material Theoretical Limits and Plot of R_{on} vs Reverse Breakdown Voltage for GaN Schottky Diodes

ACKNOWLEDGEMENT

The authors would like to acknowledge Mike Soboroff at the Department of Energy without whose support and funding none of this work would have been accomplished.

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