High Voltage GaN-on-Silicon Schottky Diodes

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ABSTRACT — M/A-COM Technology Solutions has continuing, multi-year 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. Continuing performance targets for this investigative project increment the reverse Schottky diode breakdown voltage capability, first to 1500 volts, followed by a 3000 volts level, and finally a 5000 volt device capable of handling 50 amperes of forward current. The following paper is a summary of the results to date of this DOE funded effort and a short description of on-going efforts.

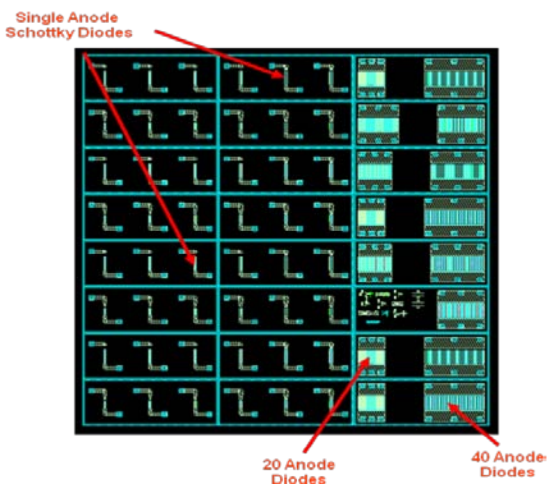

Figure 1 – High Voltage Schottky Diode Test Array

The initial GaN on Silicon high voltage Schottky diode design effort was completed. The results of this design effort are shown in Figure 1 and Figure 2 below. As can be seen in Figure 1 & Figure 2, the lateral diode construction is laid out similarly to a high voltage HEMT transistor but having parallel anode/cathode fingers. The cathode is formed by shorting what in the FET world would be "Source" & "Drain" ohmic contacts. The anode in turn consists of a symmetric "Gate" Schottky diode.

As can be seen in Figure 1, the basic design approach consisted of both single and multiple anode diodes with a total of 63 variants. The basic diode design can be best visualized in Figure 2 and consists of parallel anodes/cathodes, 10µm wide ohmic cathodes, 10µm wide anode structures, 250µm & 500µm anode lengths, multiple anode/cathode spacings of 10µm to 35µm, anode connected field plates (ACFP) of 42% - 45% of the anode/cathode spacing to reduce the peak field at the edge

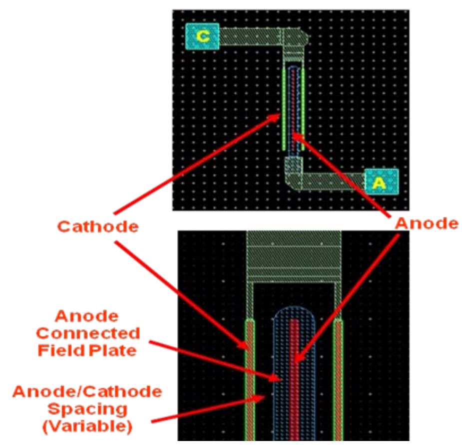

Figure 2 – Details of Single Anode High Voltage Schottky Diode

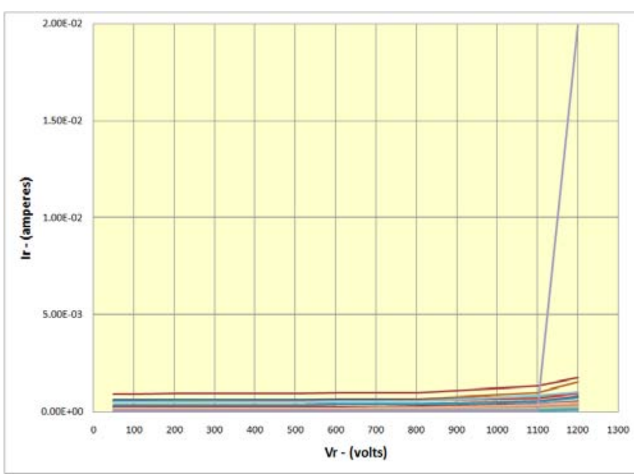

Figure 3 – Reverse Breakdown Characteristic of Lateral ACFP GaN Schottky Diode

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of the anode, single anode diodes, and 20 multiple anode designs. A minimum probe pad spacing of 400µm is employed to insure that the high voltage diodes can be automatically probed without arc-over issues.

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 test equipment.

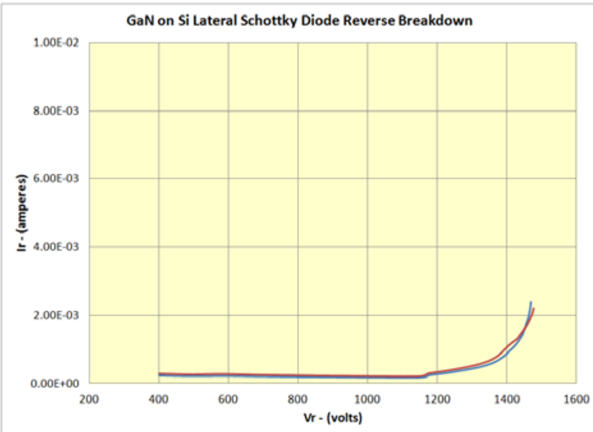

Figure 4 – Single Point Reverse Breakdown Measurements of GaN on Si Schottky Diode

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. While this tester is certainly capable of very high voltage testing and is fully programmable for multipoint sweeps for individual tests, the ability to probe multiple tests on multiple devices distributed across the wafer is limited. Having stated these limitations, single finger diodes were able to have sweep measurements made and, as 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.

All of the above efforts concentrated on the reverse characteristics of the lateral GaN Schottky diode structures but it should be remembered that the Schottky diode development goals also require the ability to handle 10 amperes of current in the forward direction. In support of this requirement, the current handling of single anode diodes having 1 mm of anode periphery and 30 µm and 35 µm anode-to-cathode spacings was evaluated by sweeping the forward diode curve from 1.0 nanoamperes to 500 milliamperes.

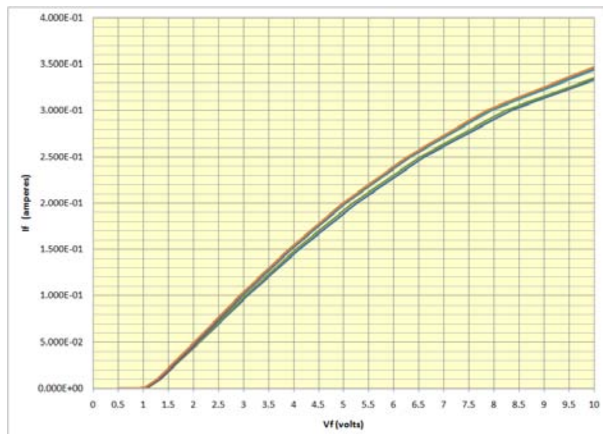

Figure 5 – Linear Plot of the Forward Characteristic of a GaN lateral Schottky Diode having an Anode Periphery of 1.0 mm of and a 35 µm Anode-to-Cathode Spacing

A linear graph of the forward diode parameter is presented in Figure 5. In this plot the typical GaN diode turn-on characteristic at approximately one volt can be seen. This response is followed by a linear region which defines the on-resistance of the diode and delineates the usable electrical space. Finally, forward current saturation is reached and results in a flattening of the diode curve. While the plot presented in Figure 4 is terminated at approximately the 350 milliampere/10 volt point, data was taken on all devices up to 500 milliamperes of forward current which required approximately 26 volts of forward bias (13 watts of dissipated power without a soldered heat sink) with no degradation in the diode characteristics. While this current and power handling is well beyond the usable electrical space for the ACFP Schottky diode, it is certainly a measure of the survivability and ruggedness of this design approach.

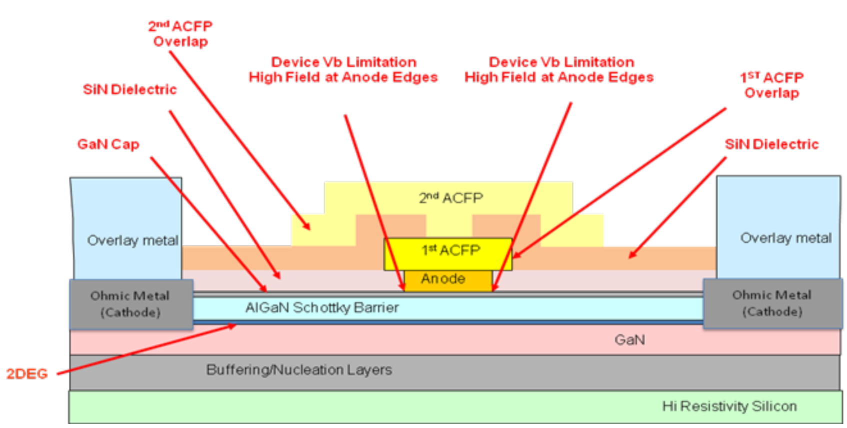

Figure 6 – Schematic Crossection for Double Field Plated Schottky Diode

From the data for the 1mm anode periphery and 35 μm anode-to-cathode spacing ACFP lateral Schottky diode presented in Figure 5, it can be seen that the linear region appears to extend up to approximately 110 milleamperes and 3.0 volts of forward bias. This would imply that approximately 90 mm of anode periphery would be required to achieve the 10 ampere current handling goal. The multi-finger Schottky diodes, shown in Figure 1, will be used to investigate the trade off of anode-to-cathode spacing, device on-resistance, and reverse breakdown voltage.

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. It was based entirely on the exiting single field planted structures that produced the 1500 volt reverse breakdown and 10 ampere forward current handling discussed in this paper. 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

CONCLUSION - In Figure 7, 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 these data points consist of sapphire, SiC, silicon, and even one study which utilized single crystal GaN. Also included in this plot are the theoretical limits for the basic materials typically used in GaN Schottky diode construction. It can be seen that the current 1500 volt results of M/A-COM Technology Solutions' lateral ACFP GaN Schottky diodes on silicon structure discussed above 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 7, 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 true monolithic integrated circuit.

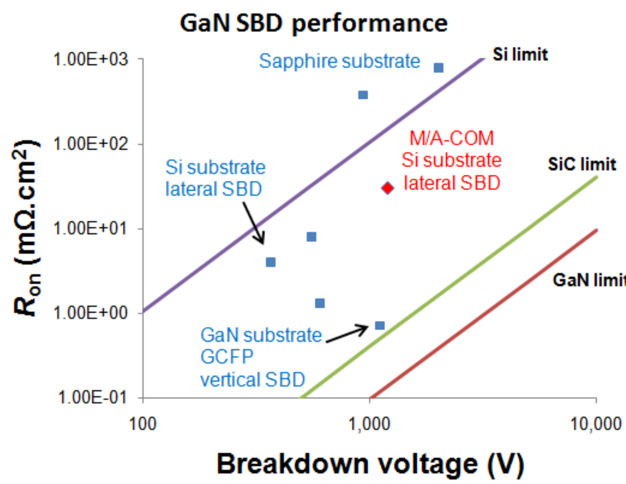

Figure 7 – Material Theoretical Limits and Plot of Ron vs Reverse Breakdown Voltage for GaN Schottky Diode Geometries