High Voltage GaN-on-Silicon HEMTs

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ABSTRACT — M/A-COM Technology Solutions has a 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 three terminal structure that has a reverse breakdown characteristic of >1200 volts and is capable of switching 10 amperes of current.

The following paper is a summary of the results to date of this DOE funded effort. With respect to three terminal design approaches to produce a GaN-on-silicon HEMT device with >1200 gate–to–drain breakdown, two main approaches were pursued. The first concentrated on "normally on" devices. This design approach was based upon M/A-COM Tech's standard high frequency structures. The required high voltage breakdown was enhanced by examining a range of larger Source-to-Drain spacings, employment of a Schottky drain contact, and utilizing source connected field plates. The second approach employed techniques developed by MIT Main Campus to produce a "normally off" device. This "normally off" device will be achieved by using dual gate HEMT structure which essentially places a low voltage enhancement structure in series with a high voltage depletion mode device. This structure will also attempt to use a Schottky drain contact.

A three terminal test reticule, shown in Figure 1, was designed. The details of the single finger test FETs with a SCFP are presented in Figure 2. A number of wafers of the "normally on" design/process devices were initiated into the wafer fabrication and have completed all frontside processing steps. On-wafer measurements were made for high voltage, three terminal, reverse breakdown characteristics on these single gate devices. All measurements were made on the single finger HEMT devices having a gate width of 250µm and a gate length of 1.0µm with the gate pinched-off at a gate bias of minus 6.0 volts and at a drain current of 250µA (1.0 mA/mm of gate periphery).

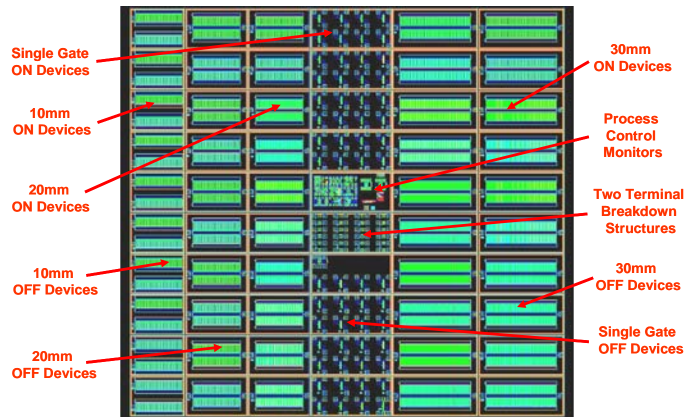

Figure 1 – GaN Three Terminal Test Reticule Layout

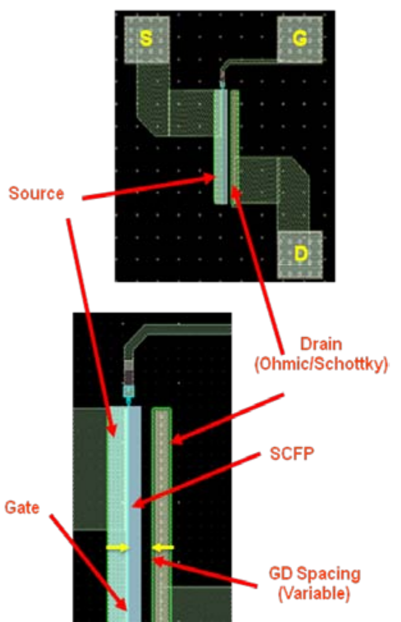

Figure 2 – Detail of Three Terminal GaN HEMT with SCFP

Figure 3 is a plot of the three terminal reverse breakdown voltages as a function of gate-to-drain spacing with and without a source connected field plate, SCFP fixed at a 1.5 µm drain overlap, and having standard

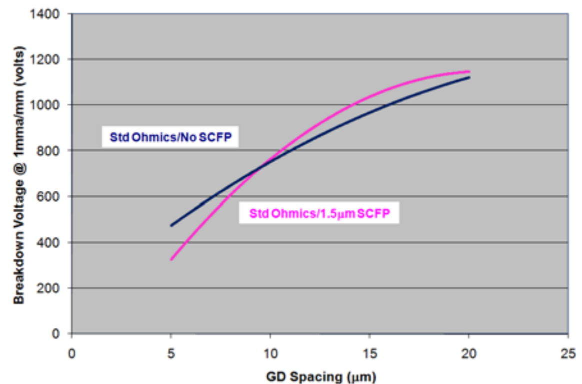

Figure 3– Breakdown Voltage as a Function of GD Spacing with 1.5µm SCFP and No SCFP

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ohmic contacts. The design purpose of the source connected field plate is to reduce and balance the peak fields at the drain edge of the gate and the edge of the SCFP that overlaps the drain region of the HEMT structure. This should allow higher voltages to be applied before critical field is reached at either of the two peak field sites enabling higher overall device reverse breakdown.

As can be seen in Figure 3, as expected, larger gate-to-drain spacing results in higher reverse breakdown with a minimum average breakdown voltage of approximately 400 volts at a 5µm gate-to-drain spacing and approximately 1200 volts at a 20µm gate-to-drain spacing for the HEMT devices without a source connected field plate. This translates to a breakdown field strength in the drain region of 80 volts/µm ($8x10^5$ volts/cm) at a 5µm GD spacing. At a 20µm GD spacing the field strength begins to saturate but still has a very respectable value of 60 volts/µm ($6x10^5$ volts/cm). As can also be seen in Figure 3, the addition of a SCFP having a fixed 1.5µm drain overlap has no apparent effect on the device reverse breakdown. Recent modeling activities of single and multiple field plate designs using a two dimensional structure simulator indicate that a dimensional overlap of less than 2.5µm is insufficient to reduce the peak field that develops at the edge of the SCFP. In light of this subsequent modeling effort, the observed lack of effect on the HEMT three terminal reverse breakdown voltage is not surprising.

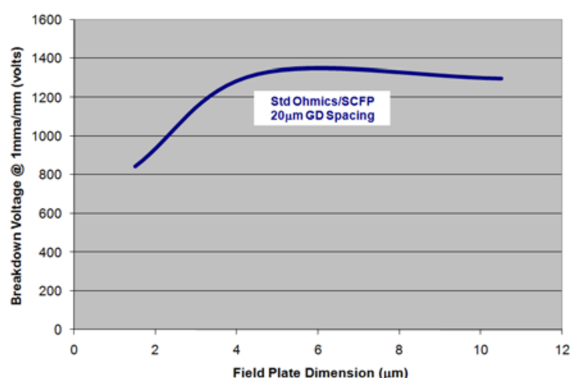

Figure 4 – Breakdown Voltage as a Function of Drain SFCP Overlap for Standard Ohmic Contact HEMTs

In Figure 4, a plot of the a HEMT device having standard ohmic drain contacts and a fixed 20µm gate-to-drain spacing as a function of a source connected field plate having a variable drain overlap dimension is prresented. In this case, it can be seen that the SCFP at larger drain overlap is certainly providing the expected boost in three terminal reverse breakdown voltage. It can be observed in Figure 4 that an increase of approximately 500 volts was achieved in the average breakdown voltage as the SCFP drain overlap was increased from 1.5µm to 4.5µm. The average breakdown value achieved at the 4.5µm SCFP overlap dimension was 1322 volts. This translates to an average field strength in the drain region of 66 volts/µm ($6.6x10^5$ volts/cm). The highest breakdown voltage achieved was measured at this 4.5µm SCFP drain overlap spacing and was 1632 volts, corresponding to a drain field strength of 82 volts/µm ($8.2x10^5$ volts/cm). Lastly, in Figure 4, it can be seen that as the SCFP drain overlap dimension is further increased to 10.5µm, there is virtually no additional effect on the average three terminal device breakdown voltage or field strength.

CONCLUSIONS - A three terminal evaluation mask was designed having a series of single finger HEMT structures to study the effect of SCFP plates, Schottky diode drain contacts, and gate recesses on the breakdown performance. An average three terminal breakdown of 1322 volts was measured on a single finger 250µm GaN on silicon HEMT device utilizing a source connected field plate with a 4.5µm drain region overlap. In addition, an individual breakdown voltage was observed on a single finger 250µm GaN on silicon HEMT device with a SCFP of >1630 volts at a current of 250µA (1mA/mm). The on-resistance of this single finger 1630 volt FET was measured and used to generate a plot of on-resistance versus breakdown voltage in order to compare against both material theoretical limits and various field plate geometries as presented in the literature. This plot is shown in Figure 5. It can be seen that the results compare extremely favorably with the reported state-of-the-art devices, regardless of substrate material or field plate approach.

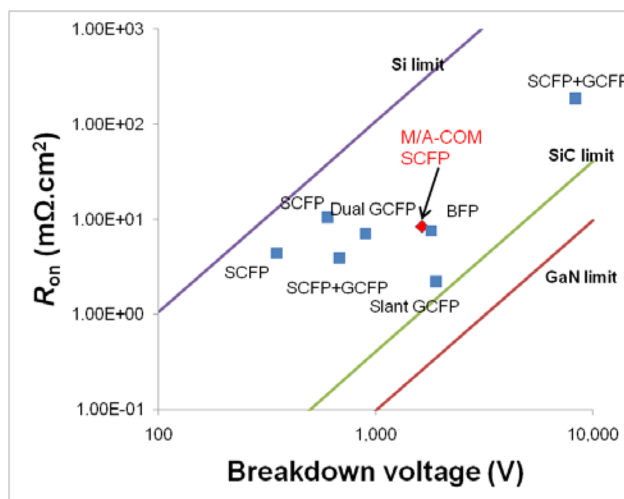

Figure 5 – Material Theoretical Limits and Plot of Ron vs Reverse Breakdown Voltage for Various Field Plate Geometries