REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
05/14/2013

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
03/01/2010-12/31/2012

4. TITLE AND SUBTITLE
Enhancement Mode Power Switching AlGaN HEMTs

5a. CONTRACT NUMBER
N00014-10-1-0653

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
James R. Shealy

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Cornell University
Office of Sponsored Programs
373 Pine Tree Rd
Ithaca, NY 14850-2820

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Defense Technical Information Center
8725 John J Kingman Road Ste 0944
Fort Belvior, VA 22060-6218

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
In this program we have demonstrated that AlSiN is a preferred dielectric for high voltage AlGaN HEMTs for power switching applications. The grate-source capacitance will compare favorably over field-plated designs making the drive circuitry less challenging. We have achieved a 440 volt breakdown with a 40 GHz fmax which is clearly a state-of-the-art result. We have also developed a Mg vapor phase diffusion process which shows promise for obtaining stable threshold shift for enhancement mode operation.This program supported a single graduate student who is now employed at RFMD and engaged in the development of AlGaN HEMT transistors.

15. SUBJECT TERMS
AlGaN HEMTs for power switching applications, AlGaN HEMT transistors, Threshold Shift by Mg Diffusion, Fabrication of AlSIN Passivated HEMTs

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					James R. Shealy
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	11	607-255-4657

Final Technical Report ONR BAA 10-001

ONR code 312

Enhancement Mode Power Switching AlGaN HEMTs

Technical Contact: James R. Shealy
311 Phillips Hall
School of Electrical & Computer Engineering
Cornell University, Ithaca, NY 14853
phone/fax: (607) 255-4657 / (607) 255-1001
email: shealy@ece.cornell.edu

Introduction

GaN-based devices offer a number of material advantages, including a large bandgap which results in high breakdown field and high power density. Furthermore, the AlGaN/GaN system forms a spontaneous, confined 2-dimensional electron gas (2DEG) without doping. This 2DEG has a high sheet charge, which translates directly to large current densities. Because there is also less impurity scattering, the saturated drift velocity of GaN is relatively large, which means a high saturation current. This all translates into high voltage and high current operation, meaning high efficiencies and high power density per unit area. It is for these reasons that the GaN material system is ideal for power switching and power amplifier devices. High efficiency and low power loss mean lower cooling costs, a major issue for modern wireless communication systems, which require high efficiency to reduce energy consumption and improve reliability.

One goal of power switch research is to take full advantage of these material properties to obtain the highest possible breakdown voltage for the device. In recent years, the upper limit for off-state breakdown voltage has been continually pushed from a few hundred volts into the kilovolt range (Uemoto2007, Wu2008,Saito2007,Boutros2009). Record breakdown voltages of 1900 V (Dora2006) and 2200 V (Alpern2011) have been reported for traditional HEMT layouts, and Tsurumi reported a novel via drain structure on SiC with a breakdown of 10400 V (Tsurumi2008). Many of these high breakdown voltage devices mentioned above share a few common characteristics: long (> 1 μm) gate lengths, large gate drain spacings (> 10 μm), and typically one or more field plates.

Recently, there has been a trend toward GaN-on-Si for power switching applications, as the high frequency performance of substrates like SiC can be traded off for lower costs and high volume production (ikeda2008, Ikeda2010,Ueda2011). Much of this shift can be attributed to advances in the growth of good quality AlGaN/GaN films on 4" and 6" (111) Si substrates (Cheng2007). While GaN-on-Si technology faces a number of challenges, which include off-state leakage current and high dynamic on-resistance, device breakdown voltages on par with those of devices grown on SiC have been realized (Chu2011).

In this program there were two objectives. The first was to demonstrate the benefits of using AlSiN passivation for high voltage operation without field plates. This objective has been realized and the device results are summarized below. The second was to develop a suitable fabrication method to shift the device threshold to positive voltages so enhancement mode operation (normally off) could be realized. This objective was pursued using a novel Mg diffusion process to introduce acceptor ions under the gate electrode. This objective was only partially met, but a stable shift in device threshold was demonstrated. However, positive threshold voltages were not achieved through the introduction of acceptor ions alone. The methods used for Mg ion introduction are also summarized below.

Fabrication of AlSIN Passivated HEMTs

The epitaxial structure of the devices consisted of an Al nucleation layer, followed by a 0.5 μm GaN buffer, a 22 nm AlGaN barrier with 24.5 % Al fraction, and a 2 nm GaN cap grown on semi-insulating SiC. Device fabrication was performed with the high temperature dielectric deposition process first followed by metals deposited through etched windows top form the device electrodes. AlSiN was used as the dielectric, with a thickness of 35 nm as determined by ellipsometry. The fabricated devices were dual-gated and had 1.5, 1, or 0.5 μm gate lengths, 400 (2 by 200) μm peripheries, and gate-drain spacings of 3 or 5 μm. These features sizes are significant because most high breakdown voltage HEMTs have gate drain spacings in excess of 10 μm (Chow2012).

Device Performance

The methodology and results described in this section have been previously published (Harvard). DC, small-signal, and large-signal RF measurements were performed. The pinch-off voltage was -5.5 V, and the quiescent point for small and large signal biasing was chosen at the point of maximum transconductance. Figure 1 shows the combined DC measurements of the parameter space of a typical device, including the output curves, constant power measurements, and high voltage off-state breakdown measurement.

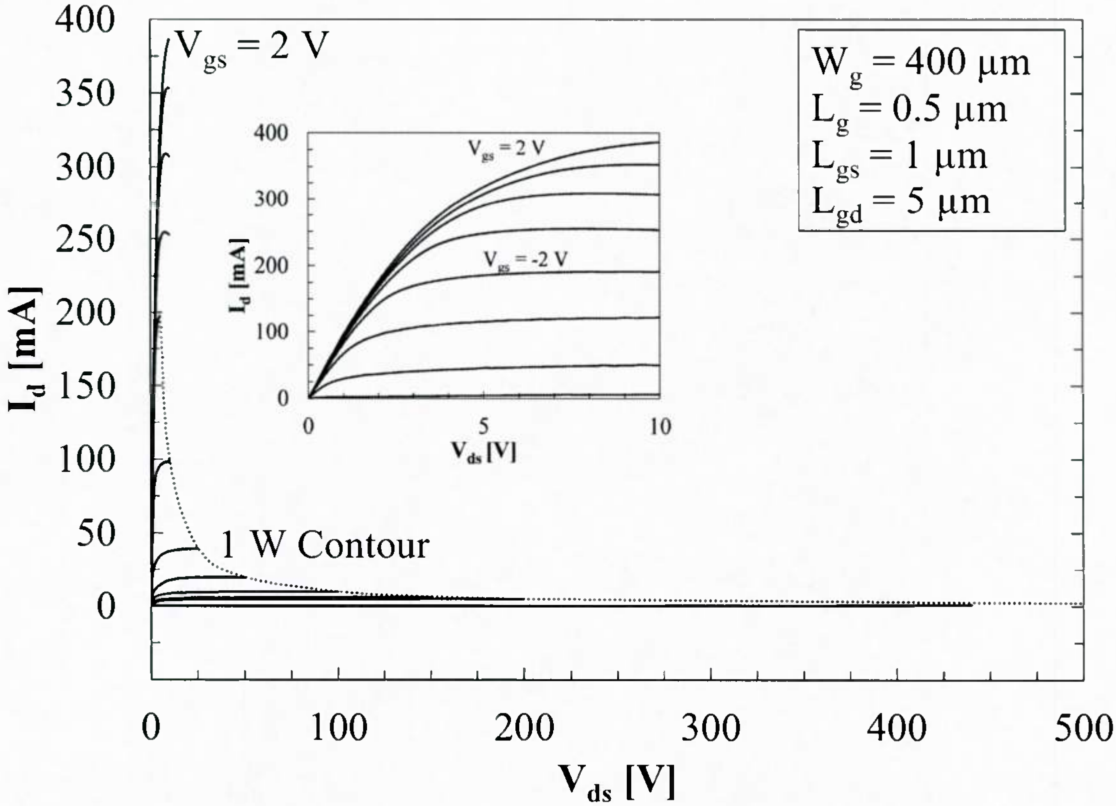

Figure 1. Combined DC parameter space measurements. Inset shows the detailed output curves for this device up to 10 V on the drain.

At V_{ds} = 10 V and V_{gs} = 2 V, the drain current was approximately 1 A/mm. Constant power measurements (1 W) were taken up to 200 V. The highest f_T of 18 GHz and f_{max} of 40 GHz was obtained on a 0.5 μm gate length device with a 5 μm gate-drain spacing.

Large signal measurements were performed at 10 GHz on a load pull bench. The input was matched for reflection and the output was loaded for maximum efficiency. A typical device power sweep is shown in Figure 2, which at V_{ds} = 30 V had 12.2 dB of linear gain, 4.9 W/mm of output power, and 41 % peak power-added efficiency, which is in line with our previous measurements on 400 μm gate width devices of 0.25 μm gate length.

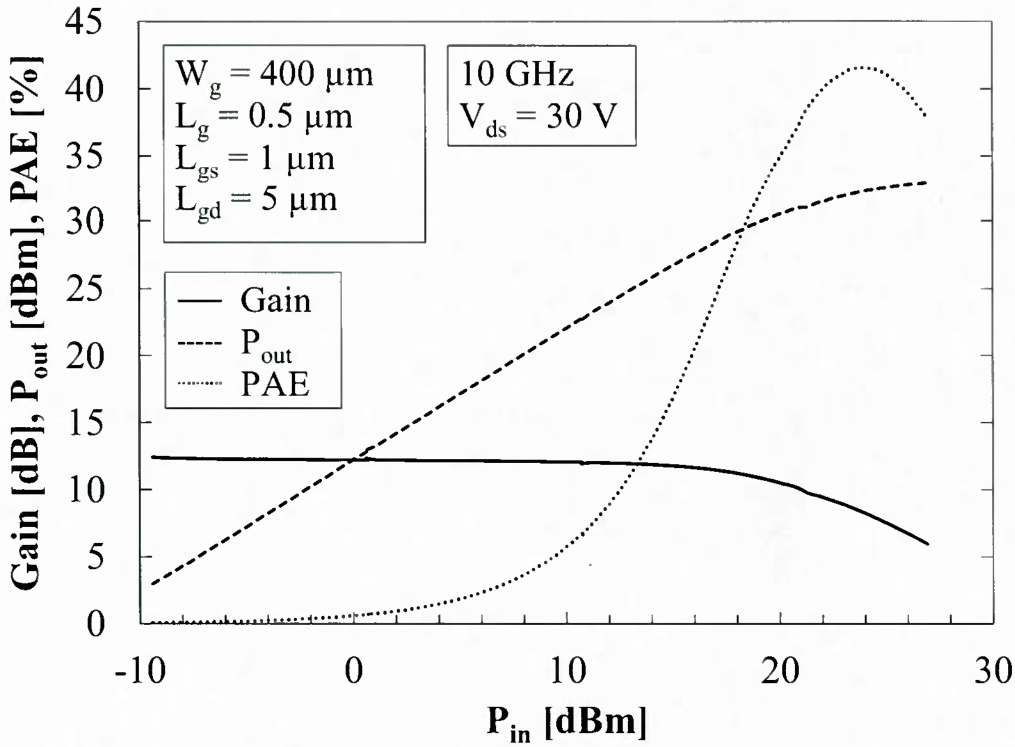

Figure 2. Typical 10 GHz load pull power sweep at 30 V of drain bias of a 0.5 by 400 µm device.

The off-state breakdown voltage measurement required a number of adjustments. First, because the off-state breakdown measurement is a three-terminal measurement, the standard ``U"-device coplanar probe pad layout could not be used as-is. Instead, the sources were connected and the contact pads made larger to facilitate the use of needle probes. Figure 3 shows the standard ``U" (a) and modified ``O" (b) layouts. An HP 4145A Parameter Analyzer was used to supply the gate and source bias, and a Keithley 2410 SMU was used to supply the drain bias and measure the drain current.

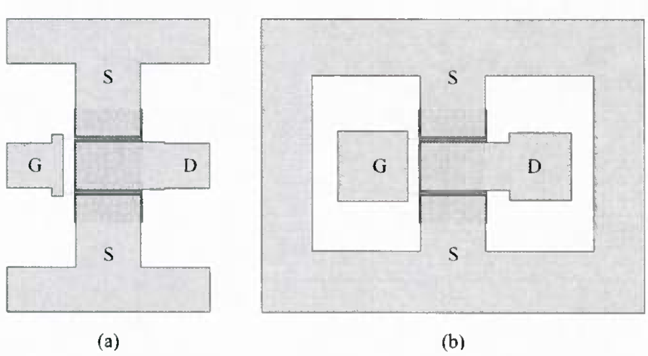

Figure 3. Schematic of (a) standard ``U" layout for coplanar waveguide probing and (b) modified ``O" layout for three terminal off-state breakdown probing.

For the purposes of the DC high voltage testing, we defined the device off-state breakdown as reaching 1 mA of drain current. The devices were submerged in Diala AX insulating oil to prevent premature air breakdown. With the gate biased at -7 V, breakdown was observed at 440 V for a 0.5 μm gate length device and 470 V for a 1 μm gate length device, both of which had a source-gate spacing of 1 μm and a gate-drain spacing of 5 μm (Figure 4). To our knowledge, this is the highest recorded off-state breakdown voltage for an AlGaN/GaN HEMT device with a relatively small gate-drain spacing and no field plate, exceeding 320 V for a device with similar feature sizes with Al_2O_3 passivation (Kanamura2010) and 238 V with SiN passivation (Lee2010). In fact, with our LPCVD SiN passivation, the 0.5 μm gate length devices typically experience static breakdown at approximately 100 V.

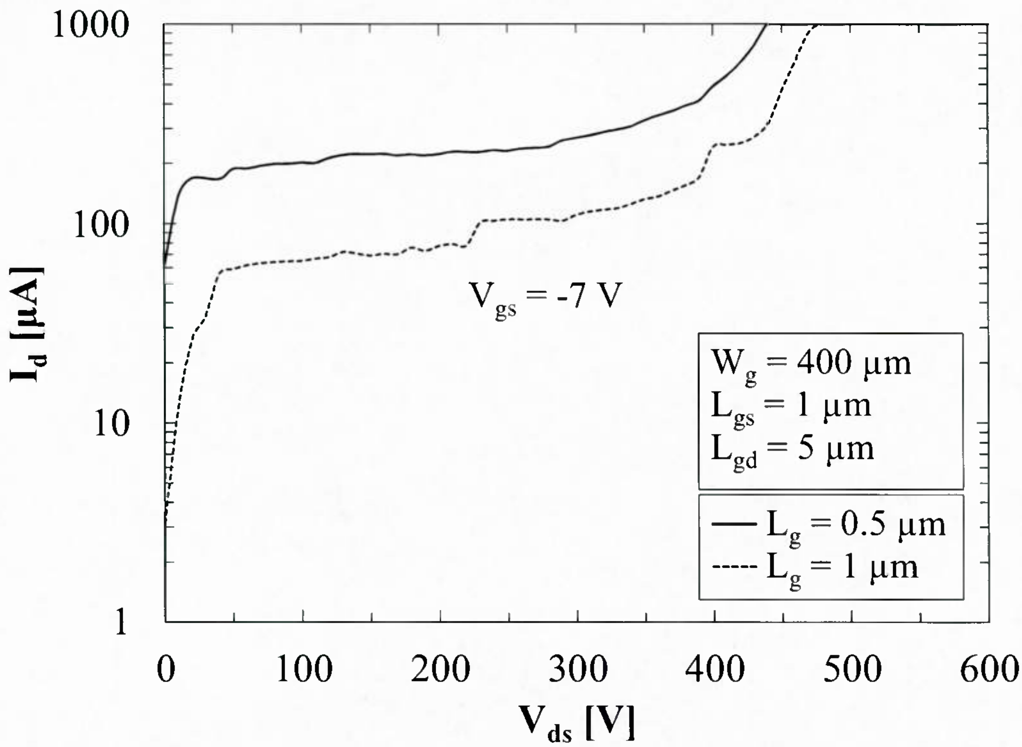

Figure 4. Off-state breakdown curve of two 400 μm devices.

To take the loadline measurements, the loadpull bench was modified to include an HP 71500A microwave transition analyzer (MTA). The diplexer and second harmonic termination branch were removed. The output power meter was replaced by the MTA. On the input side, the narrow-band 40 dB amplifier was replaced by a wider band 20 dB amplifier. Instead of 10 GHz, a 2.5 GHz signal was generated so that multiple harmonics could be measured. Figure 5 shows the modified bench schematic.

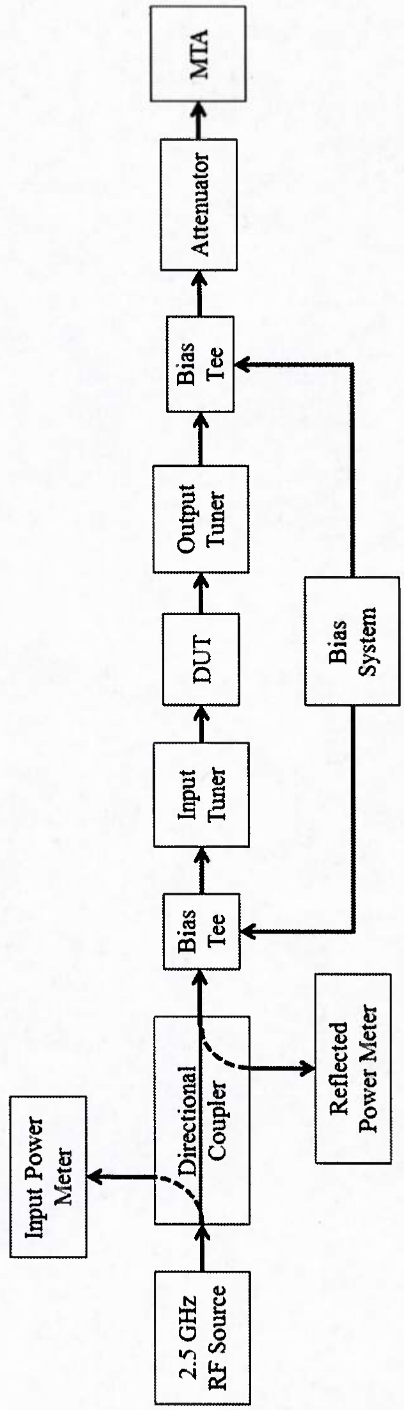

Figure 5. Schematic of the modified power bench for loadline measurements at 2.5 GHz. The diplexer and second harmonic branch have been removed, and the output power meters have been replaced by an MTA.

To test switching performance, devices are often measured with the aid of harmonic tuners that change the impedance the device sees on the input and output. The input is usually set to minimize the reflected power to the device, while the output is designed to shape the time domain voltage and current waveforms to get the maximum voltage swing. To observe switching, the device is driven into power saturation, where the drain voltage swings between pinch-off and saturation. When a non-zero reactance is presented to the device output, a delay induced between the voltage and current waveforms, which results in power dissipation, and ``loopiness" in the loadline. These effects increase with increasing reactance. When the reactance is zero, the voltage and current waveforms are exactly out of phase, and the loadline collapses to a straight line.

The goal of these measurements is to observe a loadline on which voltage swings between near zero and some large positive value at high drain bias. To test the validity of the time domain transformation to the device plane, a known high efficiency 0.25 by 250 μm device was tested. The tuner was first set to approximately 50 Ω. The total load impedance was calculated to be 58.5 - 12.2i Ω. The gate was biased near pinch-off (-10 V), and the drain bias was set to 5 V. At the maximum power the sweeper and amplifier could deliver, the input power was 23 dBm. Figure 6 shows the loadline at this setting, with the frequency spectrum of the output signal inset.

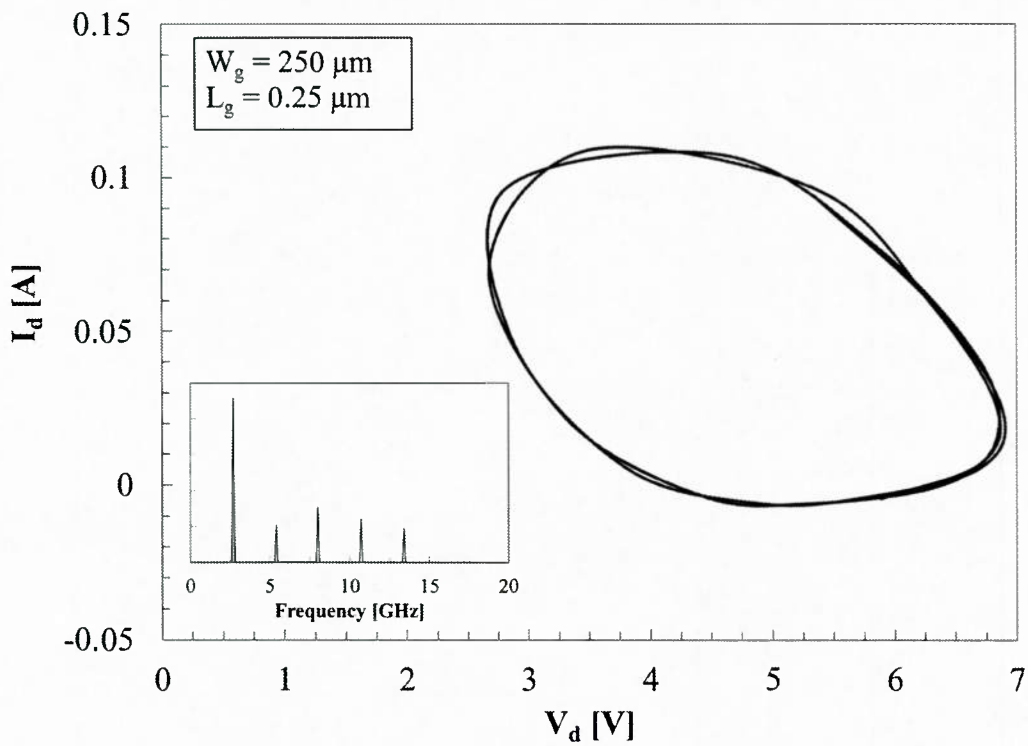

Figure 6. Loadline of a 0.25 by 250 μm device at 5 V drain bias and load impedance of 58.5 - 12.2i Ω, with P_{in} = 23 dBm.

The tuner was then set to a high impedance value. The load impedance was calculated to be 90.1 + 117i Ω . Figure 7 shows the loadline at the same gate and drain biases and input power as before, with the frequency spectrum of the output signal inset. Note that this signal has a significantly higher second harmonic component.

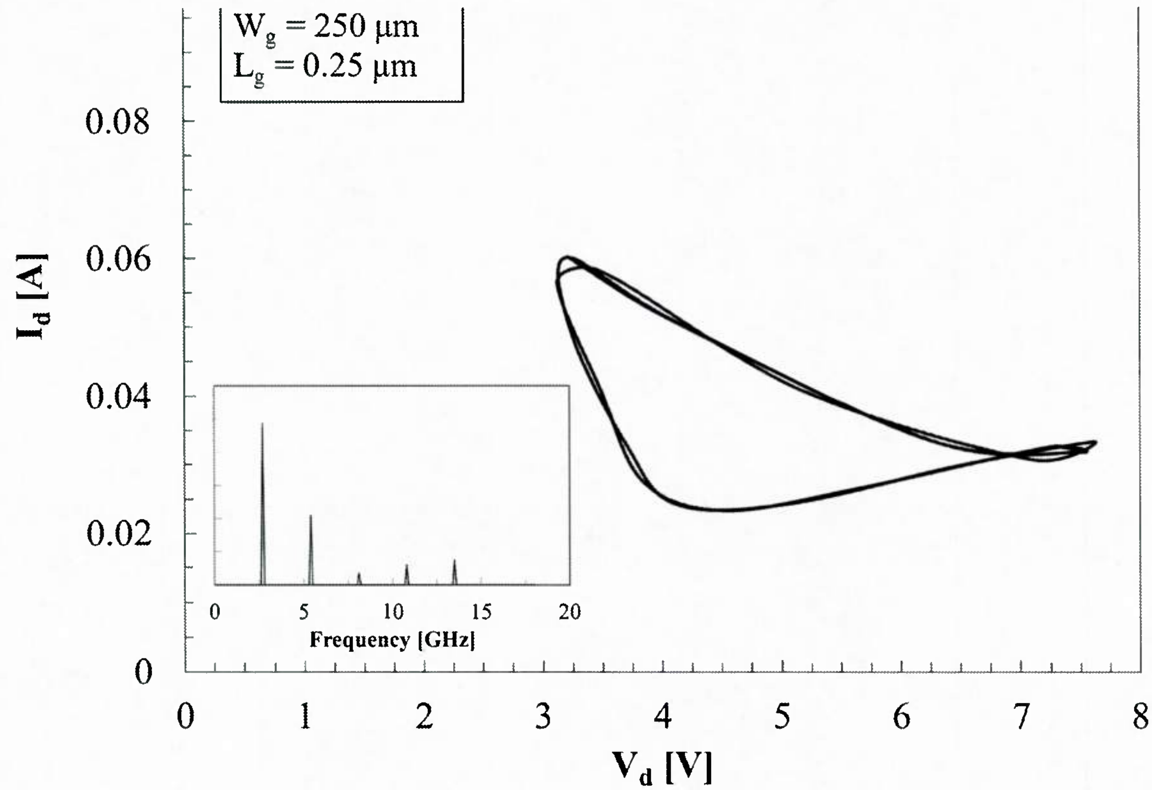

Figure 7. Loadline map of a 0.25 by 250 μm device at 5 V drain bias and a high-impedance tuner setting.

Because the switching behavior was not being observed, it was necessary to determine why. The simplest explanation was simply that there was not enough power being delivered to the device. To confirm this, and that the transformation to the device plane was correct, the above measurements were repeated at 10, 15, and 20 V drain bias. Figure 8 shows the results of these sweeps at different drain biases. As we would expect, the loadline ovals simply shift to higher drain biases, and while the swing did increase slightly from approximately 5 to 7 volts, the increase was not significant. This suggests that more power is required to drive the device into pinch-off.

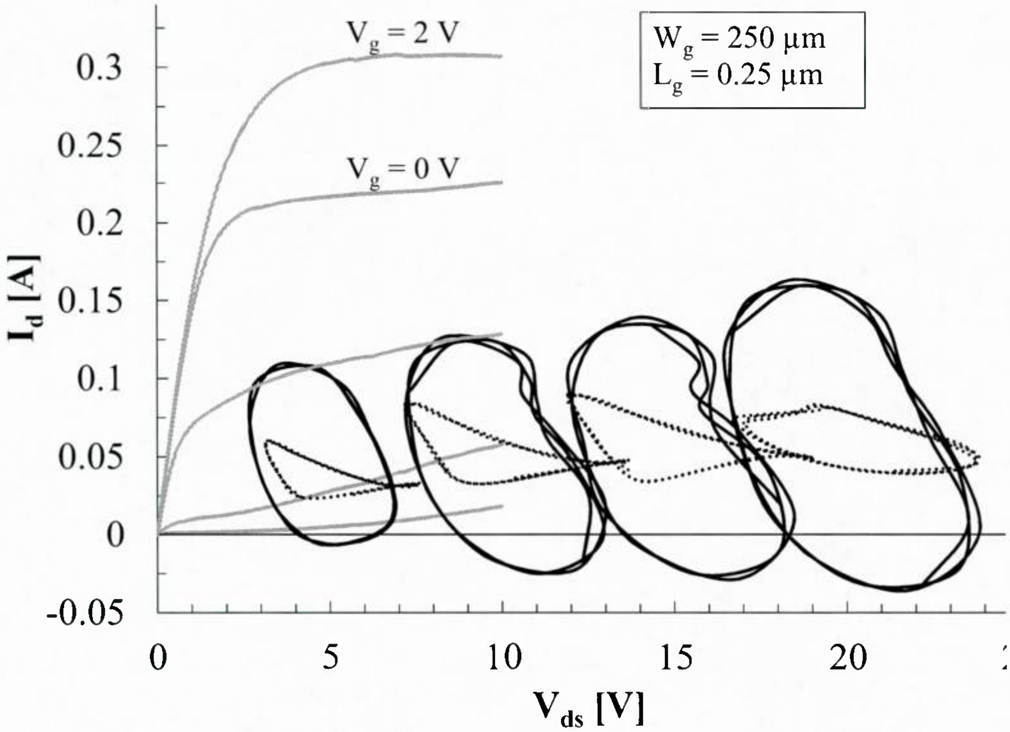

Figure 8. Output curves and loadline map of a 0.25 by 400 μm device at two load impedances and four different drain biases. The drain was biased at 5, 10, 15, and 20 V. The output curves are 2 V steps.

Threshold Shift by Mg Diffusion

We have recently developed two methods of Mg diffusion into AlGaN HEMT structures which shift the device threshold in the positive direction by the introduction of roughly 10^{13} cm^{-2} ionized Mg acceptors on the surface of the AlGaN barrier layer. In the first method, the sample is heated in a Cp_2Mg and ammonia vapor at 975 °C for roughly 2 hours. During this time a MgN film is deposited onto the samples surface which is presumably molten at this temperature, and Mg diffuses into the HEMT structure along with compensating hydrogen. Prior to cool down both vapor sources are removed and the sample remains at high temperature briefly in nitrogen gas. After the LPCVD step, the MgN film is removed (in aqueous HCl) and the sample is heated in an RTA in nitrogen gas as a hydrogen removal step. In the second method, a composite MgSiN (4 atomic % Mg) film is deposited by LPCVD followed by a high temperature (> 1000 °C) RTA Mg drive in step. A set of SIMS profiles for each process are shown in Figure 9 for HEMT structures with 27 % Al in the 20 nm thick AlGaN barrier layer.

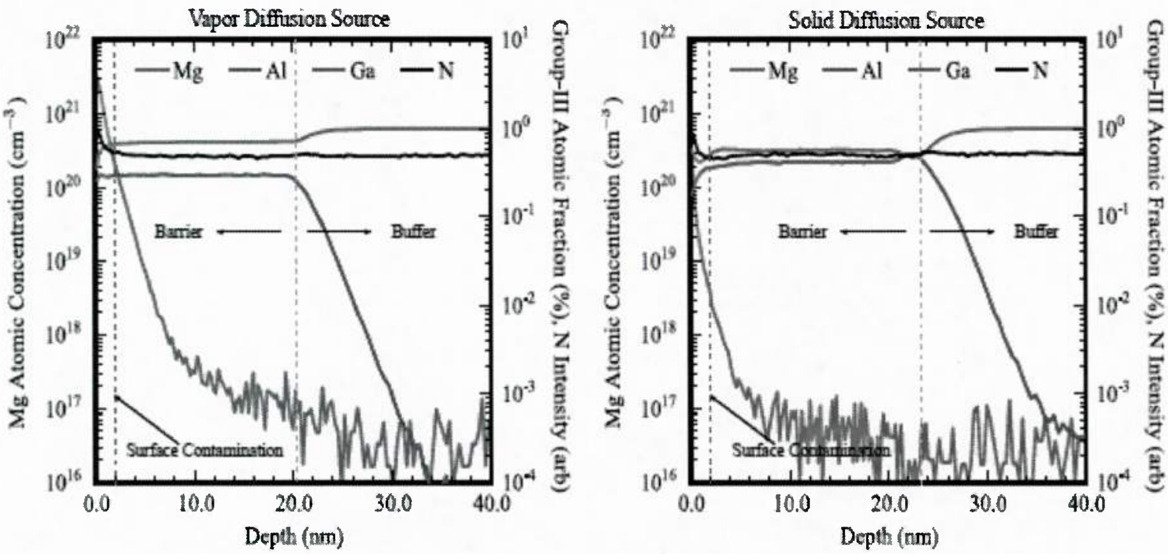

Figure 9. SIMS profiles of each diffusion process illustrating the penetration of Mg into the HEMT structure.

In this case the vapor source diffusion (and associated MgN deposition) introduces significantly more Mg into the HEMT structure than the higher temperature RTA treatment required with the MgSiN solid source. At this point the vapor diffusion seems the preferred method. Comparisons of the HEMT CV behavior (measured at 1 kHz) for the same HEMT wafer before and after the Mg diffusion is shown below in Figure 10.

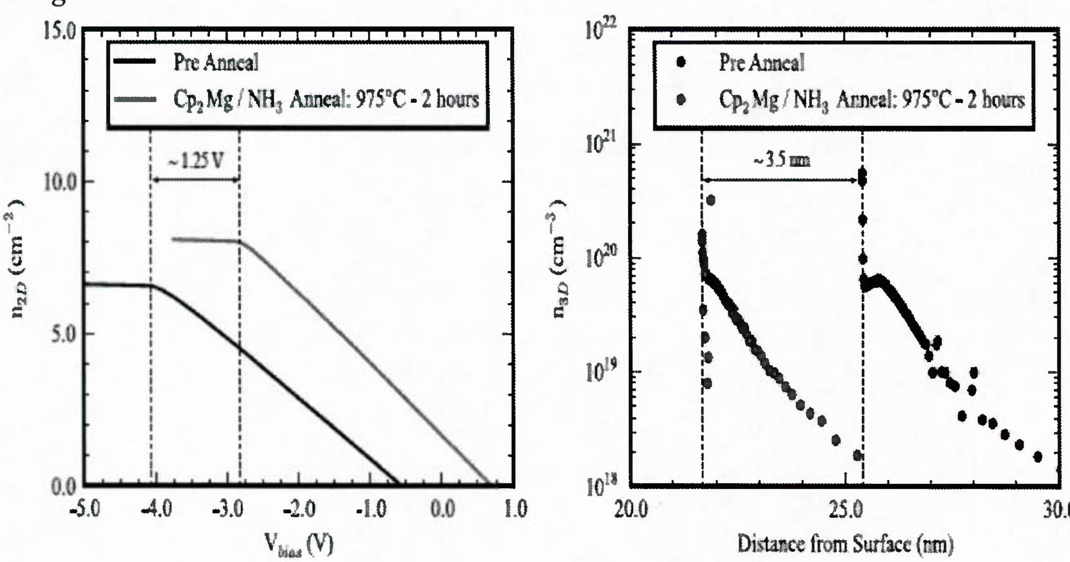

Figure 10. Depleted sheet density of the 2DEG versus bias (left) and volume concentration profiles (right) of a HEMT sample before and after Mg diffusion.

From the sheet electron concentration versus bias plot we observe that the Mg diffusion shifted the 2DEG threshold by 1.25 volts while actually increasing the

2DEG sheet charge by some 20 %. The volume concentration profile suggest that the Mg diffusion front penetrated by roughly 3.5 nm as shown. For this high charge structure, we can estimate the shift in the threshold assuming the Mg concentration is uniform (n_{Mg} = 10^{20} cm^{-3}) and distributed over the first x_d =3.5 nm of the AlGaN barrier layer. So $\rho(x)$=-qn_{Mg} and the change in threshold voltage is found using:

$$\Delta V_{th} \equiv \Delta V_{FB} = -\frac{1}{c_{AlGaN}} \int_0^{x_d} \frac{x\rho(x)}{t_{AlGaN}} dx = +\frac{qn_{Mg}x_d^2}{2\epsilon_{AlGaN}}$$
$$= +\frac{1.602(10^{-19})10^{20}[3.5(10^{-7})]^2}{2(9.4)8.854(10^{-14})}$$
$$= 1.18\ V\ ,$$

which yields a reasonable estimate of the +1.25 V shift observed in the post Mg diffusion sample. If we perform the same diffusion in a lower charge structure with a gate recess leaving 7.5 nm of an $Al_{0.25}Ga_{0.75}N$ barrier then this estimate yields a positive threshold voltage of +1.5 volts, adequate for enhancement mode operation. Furthermore, the resulting pn junction under the gate may serve to significantly lower the gate leakage current. To date we have successfully recessed one such structure to 10 nm of the AlGaN barrier layer remaining following by a brief diffusion at 950 °C resulting in the threshold at +0.1 volts. More aggressive diffusions on such structures resulted in removal of the 2DEG as the diffusion front penetrated the hetero-interface. Clearly on thin barrier structures the diffusion process must be fine tuned to get the large positive threshold required for enhancement mode devices.

Summary

In this program we have demonstrated that AlSiN is a preferred dielectric for high voltage AlGaN HEMTs for power switching applications. The gate-source capacitance will compare favorably over field-plated designs making the drive circuitry less challenging. We have achieved a 440 volt breakdown with a 40 GHz f_{max} which is clearly a state-of-the-art result. We have also developed a Mg vapor phase diffusion process which shows promise for obtaining stable threshold shift for enhancement mode operation. This program supported a single graduate student who is now employed at RFMD and engaged in the development of AlGaN HEMT transistors.