Correlation of materials characteristics with microwave device performance in AlGaN high electron mobility transistors

R. L. Messham, H. G. Henry, G. Augustine, M. F. MacMillan, I. Ferguson[a], D. Gotthold[a], D. Thomson[b], R. Davis[b], G. C. DeSalvo and J. J. Zingaro

Northrop Grumman Electronic Sensors and Systems Sector
1212 Winterson Road, Linthicum, MD 21090

AlGaN based high electron mobility transistors offer the promise of 5-10X the power density of similar InP and GaAs based structures coupled with attractive noise figure, at frequencies up to mmWave. Although significant advances in materials deposition and device fabrication have been made, the quality and reproducibility of epitaxial structures deposited on mismatched substrates remains a key factor limiting device performance. We have fabricated AlGaN HEMTs using structures deposited on sapphire and high resistivity SiC substrates in various MOCVD systems with distinct cross wafer uniformity traits. The resulting device DC and small signal RF characteristics show a strong correlation to cross wafer trends measured prior to processing using a range of nondestructive physical and electrical techniques. These provide an approach for rapid and effective characterization of AlGaN HEMT material that can be implemented prior to device processing, and provide predictive information on completed device performance.

Projections indicate that devices fabricated from AlGaN MODFETs will provide 6-10 Watts/mm of output power density (>10X the power density for GaAs and InP based devices), due to their inherent breakdown field strength and transport properties. An additional benefit of the high breakdown voltage is improved efficiency over GaAs at high output power levels, which occurs due to the high output impedance of the wide bandgap material. Although initial development in this materials system was largely focused on optical devices for lighting and data storage, demonstrations of the frequency[1], noise[2], and power performance[3] of AlGaN MODFETs is also stimulating development of microwave devices for defense and commercial applications. Despite these promising results, devices suffer from gate and drain lag phenomenon that are attributed to materials quality, and limit power performance. Problems with obtaining uniform and reproducible materials, and the lack of a volume commercial supplier of AlGaN device structures on sapphire, SiC or other substrates indicate that the technology requires significant development before it will approach manufacturing capability.

At Northrop Grumman, device fabrication has focused on AlGaN MODFET structures deposited using metal organic chemical vapor deposition (MOCVD). A key issue identified early in device development was the need for a reliable, nondestructive approach to the characterization of incoming MODFET structure materials to determine their suitability for device processing, and predict ultimate device performance. In practice, these studies were assisted by cross wafer non-uniformity patterns present in MOCVD reactors available to us for MODFET film deposition, allowing a range of materials and device characteristics to be obtained from a modest number of processing runs. Subsequent adjustments to reactor flow and temperature uniformity have been used to remove these non-uniformity patterns.

Materials Structure Growth and Characterization

AlGaN MODFET structures were deposited on 2" diameter SiC and sapphire substrates in several MOCVD reactors, with varying gas flow and wafer rotation mechanisms[e.g.4, 5]. The target structure deposited used an AlN nucleation layer, undoped GaN

---

[a] EMCORE Incorporated, Somerset, NJ
[b] North Carolina State University, Raleigh, NC

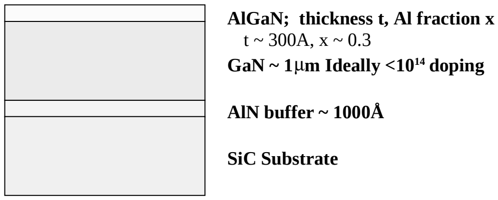

Figure 1: Target AlGaN HEMT device structure deposited using MOCVD.

buffer, and undoped AlGaN capping layer to make use of the piezoelectric effect to produce a two dimensional electron gas (Figure 1). Following deposition, the carrier profile, pinchoff voltage, and 2DEG sheet charge depth was measured across the wafer using Capacitance-Voltage profiling. Measurements were performed with both liquid Hg and photolithographically defined NiAu Schottky, and large area ohmic contacts. Both types of devices were initially used to allow evaluation of the accuracy and reproducibility of the liquid contact. Cross wafer conductivity measurements were taken using a Lehighton LEI 1500 contactless sheet resistance measurement system (e.g. Figure 2). Film Al content was determined at various wafer positions with a Phillips x-ray diffractometer, and using 300K photoluminescence[6]. Selected samples were also submitted for Hall characterization.

AlGaN HEMT Fabrication and Characterization

Following characterization, wafers were processed into AlGaN HEMTs. The process includes direct write gate definition, with a range of gate lengths from 0.3 to 0.55µm (determined using scanning electron microscopy). Devices make use of Ti-Au ohmic and Ni-Au Schottky barrier metalization, He implant isolation, and airbridge interconnects. At completion of gate and first layer metalization, wafers are submitted for cross wafer dc and small signal test of 2x100µm gate length structures in the process control monitor (PCM). These tests record device Idss, maximum current (I_{max}), maximum available gain (MAG) at 10 GHz, unity current gain (f_T) and transconductance (g_m).

Gate and drain lag tests were performed before and after device passivation with PECVD nitride, and selected devices tested for on wafer power performance. Power test results from thinned, diced and packaged devices will also be reported.

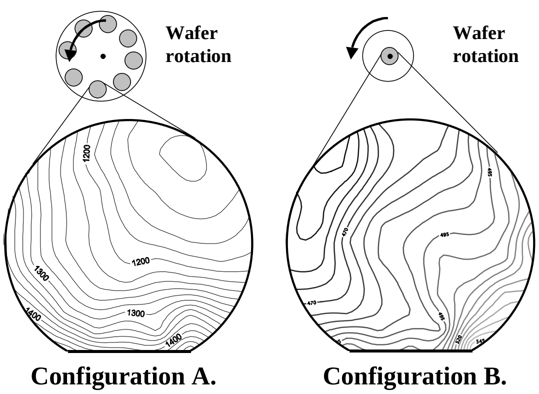

Figure 2: Cross wafer profiles of HEMT film conductivity show dependence on the MOCVD growth system and wafer rotation scheme in use

Results

As-grown wafers from the MOCVD reactors displayed distinct cross wafer uniformity patters, as revealed by the sheet resistance profile (Figures 2A and B). As we have seen in a wide range of wafers that we have examined, the patterns provide important information about the growth reactor and process, and reflect substrate rotation conditions. Variations in cross wafer sheet charge and pinchoff voltage extracted from C-V measurements taken using lithographically defined Schottky contacts on a sample with a similar wafer uniformity pattern to Figure 2A are shown in Table 1. Typically an improvement in C-V data is observed with the use of a liquid Hg Schottky barrier, despite identical underlying materials, and a ~5X reduction in Schottky barrier area with

Table 1: Variation in materials parameters measured using C-V for a sample with wafer uniformity similar to Figure 2a

Position	Ns (cm^{-2})	Vp (V)
Upper left	$9.6x10^{11}$	0.75
Upper right	$4.5x10^{12}$	1.7
Lower left	$9.9x10^{11}$	0.7
Lower right	$3.2x10^{12}$	1.9

the lithographically defined contacts. One possible explanation for this behavior is that the surface tension of the Hg barrier prevents coating of defects or features that penetrate the epitaxial material, eliminating a leakage path that degrades the lithographically defined contacts. Cross wafer values of small signal rf characteristics from completed devices fabricated using the wafer measured in Table 1 are shown in Figure 3. Both dc and small signal characteristics show the same cross wafer trends as those observed during as-grown materials characterization. Pulse measurements of completed devices showed the presence of gate lag (~ 13 - 35% compression). No significant change in power output characteristics was observed following SiN_x passivation. The results of more detailed cross wafer power test of packaged devices will be reported.

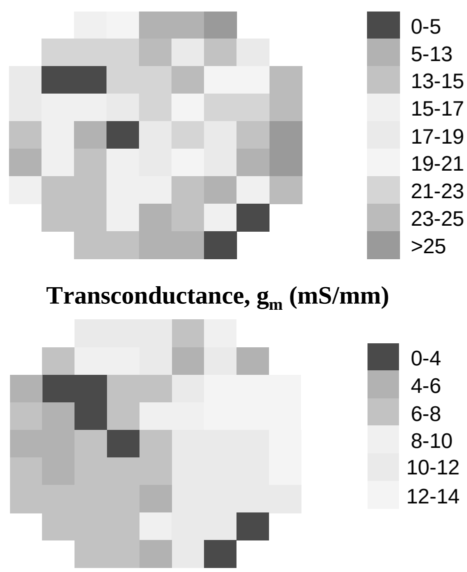

Figure 3: Cross wafer dc and small signal rf characteristics measured for AlGaN HEMT 2x100μm gate periphery test structures in the wafer process control monitor. Test device gate length is ~ 0.3μm. Maps show strong cross wafer performance variation, with the highest performance devices at the upper right hand wafer quadrant

Discussion

Cross wafer uniformity traits are readily identified with the use of contactless sheet resistance profiling. Coupled with C-V measurements at selected wafer sites (based on high, low and mid -range sheet resistance), this allows rapid identification of useful wafers for processing, or 'sweet spots' within nonuniform wafers. The variation in cross wafer values of subsequent device results shows a close correlation with the materials trends seen across wafers (e.g. Figure 4). We have observed and will discuss these trends in materials deposited with a range of device structures in different MOCVD reactors with markedly different cross wafer uniformity patterns. The combination of conductivity profiling and Hg-dot C-V measurements provides a rapid and powerful nondestructive technique for selection of wafers for processing. Measurements of cross wafer thickness and Al content indicate that changes in Ns, Vp, and dc and small signal characteristics are primarily attributable to cross wafer Al composition variations in the materials we have examined. Approaches we have used to eliminate these variations, and power test results will also be presented.

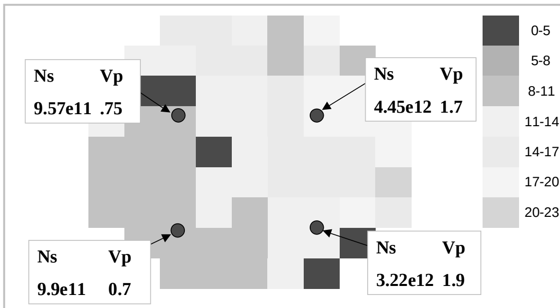

Figure 4: Changes in test structure rf characteristics (in this case f_T) observed in PCM profiling follow trends in wafer variations in doping, Ns and Vp observed in C-V measurements

References

1) K. Chu et. al., WOCSEMMAD, Monterey, CA, February 1998.

2) N.X.Nguyen et al 'Robust Low Microwave Noise GaN MODFETs with 0.6dB Noise Figure at 10 GHz' Electronic Letters, 2nd March 2000, vol. 36, nos. 5.

3) J.C.Zolper 'Wide Band-gap Semiconductor Microwave Technologies: From Promise to Practice'. IEDM Digest, Dec 1999

4) Matthew J. Sherman, "Growth and Characterization of III-N Semiconductor Based Quantum Well Structures by Organometallic Vapor Phase Epitaxy" Rutgers University Dissertation, May 1997

5) e.g. T. W. Weeks, J., M. D. Bremser, K. S. Ailey, E. P. Carlson, W. G. Perry and R. F. Davis, Appl. Phys Lett, 67, 401, (1995)

6) Measurements performed at Cornell University