# A “Snapshot” of AlGaN/GaN HEMT State-of-the-Technology

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## Abstract

**The Defense Advanced Research Projects Agency (DARPA) is currently sponsoring a Wide Band Gap Semiconductor Technology Initiative (WBGSTI). The objective of this program, managed by Edgar Martinez and Mark Rosker, is four-fold: (1) to scale (up to 4”) high quality SiC substrates, (2) to develop alternative substrates, (3) to develop uniform AlGaN/GaN High Electron Mobility Transistor (HEMT) epitaxial growth, and (4) to examine materials/device correlations. This paper will present measured AlGaN/GaN HEMT device results that provide a snapshot of the State-of-the-Technology with respect to this DARPA program.**

## INTRODUCTION

As part of this program, the Air Force Research Laboratory (AFRL), Army Research Laboratory (ARL), and Naval Research Laboratory (NRL) have joined to form a Tri-Service Support Team. The Tri-Service Team, led by Tom Jenkins of AFRL, is composed of a Materials Panel and a Device Panel (Figure 1). Briefly, the Materials Panel is responsible for analyzing substrates and epitaxy with respect to program goals through electrical, structural and optical characterization. The Device Panel examines processed deliverables, wafers with fabricated devices. Extensive electrical characterization including full wafer DC and small-signal RF screening, as well as, power and noise sampling of transistors and test structures is performed. This presentation will focus on testing, characterization and observations from the device panel.

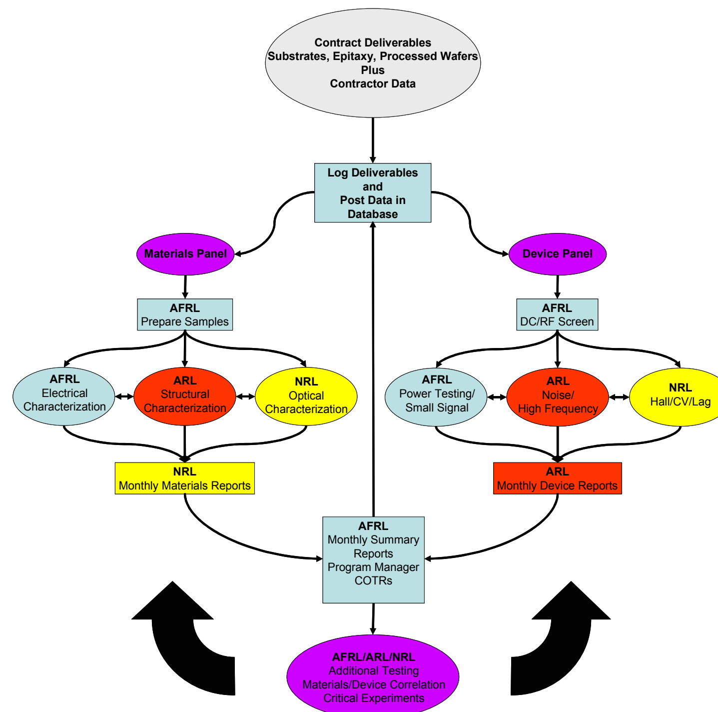


Figure 1 Tri-Service Support Team Activities

TESTING

A DoD test reticle (Figure 2) including both process control monitor structures (TLM, VDP, CV, etc) and small active devices (0.3 mm, FATFET) is included on processed deliverables. Standard test procedures are applied to obtain material characteristics, DC parameters, and RF performance. DC and small-signal RF screening is performed on all wafers via automated test routines at the wafer scale (up to 500 sites or more per wafer). Materials characterization, large-signal analysis and noise measurements are performed on a limited number of sites per wafer on a subset of all the processed deliverables. For example, mobility, sheet charge and AlGaN thickness values are obtained from on-wafer Hall and CV measurements.

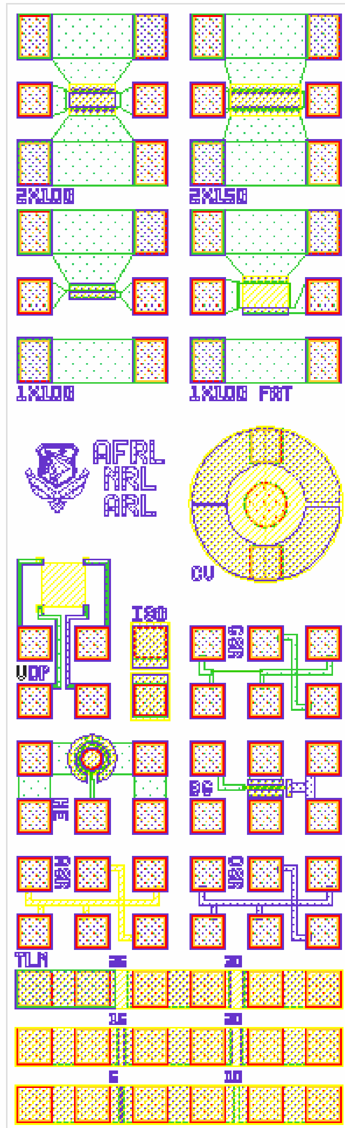


Figure 2 DoD Test Reticle

Over 100 wafers (combination of 2” and 3” SiC substrates) from six different epi sources, both MBE and MOCVD, which were processed at several different foundries, have been characterized to date. Test conditions for select parameters being measured by the Tri-Service team are shown in Table 1. For parameters measured via the automated test routines, wafermaps (Figure 3) are generated from the raw data to obtain statistics (average and standard deviation) as well as gauge the yield and “goodness” of the data. For other parameters (material characteristics and power) simple spreadsheet routines re used to obtain statistics.

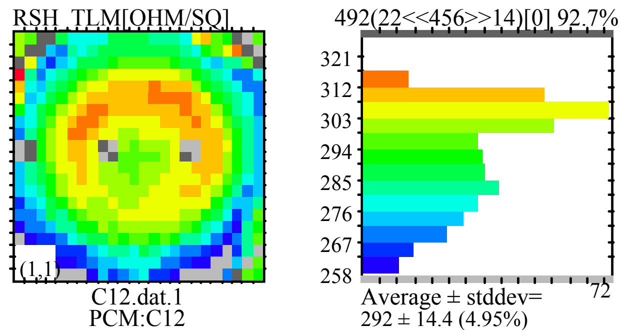


Figure 3 Sample Wafermap with Statistics

The range (minimum and maximum values) in observed data as well as the median and average values for select parameters can be seen in Table 2. Summary charts showing wafer averages and standard deviations for all wafers tested will be presented. An example is seen in Figure 4. These are not trend charts as material structures and device fabrication processes are continuing to undergo optimization. Nor are they intended as direct comparison charts as a standard epi-structure and/or process is not being applied. What can be gleaned from these charts is an assessment of the state-of-the-technology. What are global vs. local issues? Is there a difference between growth techniques (MBE vs. MOCVD)? What is the range of values for a given material or device parameter? Does it vary across wafer lots? Is device parameter uniformity (standard deviation) improving with respect to material and process optimization efforts?

Table 1 Test Conditions

| Parameter | Descriptor | Structure | Conditions |
|---|---|---|---|
| μ | Mobility | Van Der Pauw | On wafer Hall measurement. Magnetic field = 2000 Gauss, test current typically 100 μA |
| Nsh | Sheet Charge | Van Der Pauw | On wafer Hall measurement. Magnetic field = 2000 Gauss, test current typically 100 μA |
| AlGaN d | AlGaN Thickness | CV | Zero bias capacitance measurement. (1 MHz) |
| RSH_TLM | Sheet Resistance (Active Layer) | TLM | Force 1 mA each gap, measure voltage using Kelvin technique. Calculate from curve fit to data. |
| IISO_50V | Buffer Isolation Current | Isolation | Force 50 V, measure current between 5 μm gap. |
| VISO_100nA | Isolation Voltage @ 100 nA | Isolation | Force 100 nA, measure voltage between 5 μm gap. |
| VISO_10μA | Isolation Voltage @ 10 μA | Isolation | Force 10 μA, measure voltage between 5 μm gap. |
| Idss | Ids for Vgs = 0V at Vds = 10V | 2x150 Transistor | Measured from Gm, Id vs. Vgs curve. |
| Imax | Ids for Vgs = 1V at Vds = 10V | 2x150 Transistor | Measured from Gm, Id vs. Vgs curve. |
| Vth | Threshold Voltage | 2x150 Transistor | Measured from IV curve. |
| Igl | Gate Leakage | 2x150 Transistor | Ig where Vds = 10 V, Vgs = Vth - 2 V. |
| Rc | Ohmic Contact Resistance | TLM | Force 1 mA each gap, measure voltage using Kelvin technique. Calculate from curve fit to data. |
| GmP | Peak Transconductance | 2x150 Transistor | Measured from Gm, Id vs. Vgs curve. |
| Ft | Cutoff Frequency @ GmP | 2x150 Transistor | s-parameters |
| Glag | Gate Lag | 2x150 Transistor | Vds = 1 V, Vgs swept from Vth -2 V to 0 V. Ratio of pulsed/dc current. |
| Dlag | Drain Lag | 2x150 Transistor | Vds = 0.1 V, 20 V, 0.1 V with Vgs = 0 V. Ratio of ending/starting drain current. |
| P1dB | Output Power @ 1 dB Compression | 2x150 Transistor | Optimized for power where Vds = 15 V, Vgs = 30% Idss. |
| Gp | Gain @ 1 db Compression | 2x150 Transistor | Optimized for power where Vds = 15 V, Vgs = 30% Idss. |
| PAE | Peak Power Added Efficiency | 2x150 Transistor | Optimized for power where Vds = 15 V, Vgs = 30% Idss. |

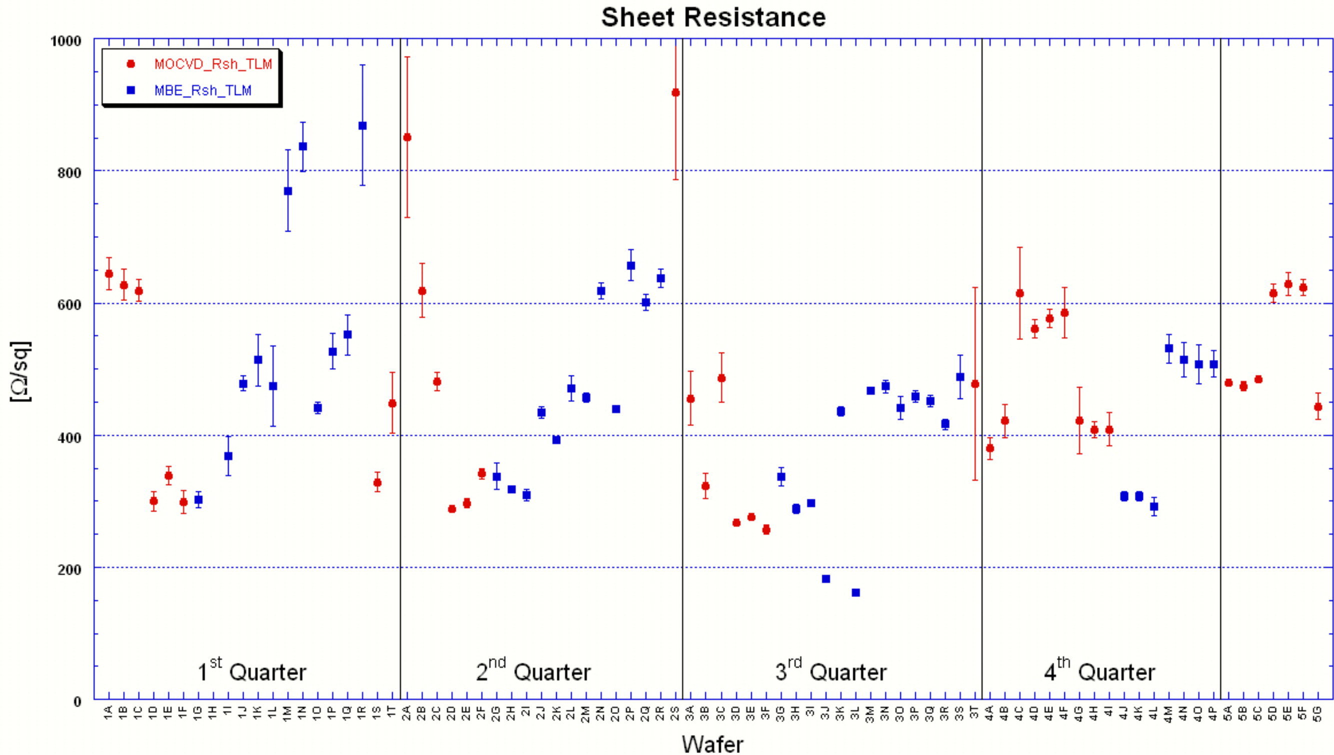


Figure 4 Sample Summary Chart

Table 2 Summary Data

| Parameter | Minimum | Maximum | Median | Average |
|---|---|---|---|---|
| µ [cm2/V*s] | 632 | 2027 | 1351 | 1317.73 |
| Nsh (e13) [cm-2] | 0.41 | 6 | 1.15 | 1.25 |
| AlGaN Thick [A] | 127 | 333 | 235 | 236.43 |
| Rsh_TLM [Ω/sq] | 162 | 918 | 457 | 466.20 |
| IISO @ 50V [A] | 1.02E-09 | 9.25E+01 | 3.35E-06 | 1.14E+00 |
| VISO @ 100nA [V] | 0.00065 | 60 | 9.87 | 24.43 |
| VISO @ 10uA [V] | 0.0857 | 60 | 59.5 | 40.05 |
| Idss [mA/mm] | 254 | 1330 | 793 | 838.69 |
| Imax [mA/mm] | 396 | 1420 | 968 | 986.98 |
| Vth [V] | -6.82 | -0.783 | -3.725 | -4.00 |
| AB_Igl [mA/mm] | 2.34E-05 | 50.5 | 0.2575 | 3.17 |
| Rc [Ω-mm] | 0.0976 | 3.14 | 0.516 | 0.68 |
| GMP [mS/mm] | 118 | 407 | 235 | 246.48 |
| Fmax/Ft | 0.73 | 3.15 | 1.72 | 1.77 |
| Glag | 0.7 | 1.07 | 0.92 | 0.92 |
| Dlag | 0.56 | 1.04 | 0.91 | 0.88 |
| P1dB [dBm] | 19.86 | 27.59 | 25.30 | 24.81 |
| Gp @ 1dB [dB] | 7.90 | 16.16 | 12.92 | 12.86 |
| PAE [%] | 25.68 | 46.36 | 36.20 | 36.28 |

## CONCLUSIONS

Significant progress has been made during Phase I of the WBGSTI program. Sheet resistance uniformity and mobility goals have been met on 3” wafers. While there are no specific device performance goals associated with the program, improvements with respect to uniformity (standard deviation) and repeatability (wafer-to-wafer averages) have been observed. Poor buffer isolation characteristics seen early in the program have for the most part been solved. Likewise, gate leakage present in the early deliverables has been reduced. High frequency response has been demonstrated and good power performance observed.

As will be evidenced by the State-of-the-Technology “snapshot” to be presented, the WBGSTI program has successfully established a 3” SiC substrate, AlGaN/GaN HEMT epitaxy and process capability.

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## ACRONYMS

DARPA – Defence Advanced Research Projects Agency
WBGSTI – Wide Bandgap Semiconductor Technology Initiative
HEMT – High Electron Mobility Transistor
AFRL – Air Force Research Laboratory
NRL – Naval Research Laboratory
ARL – Army Research Laboratory
TLM – Transfer Length Method
VDP – Van Der Pauw
CV – Capacitance Voltage
MBE – Molecular Beam Epitaxy
MOCVD – Metal Organic Chemical Vapor Deposition