A 21\textsuperscript{st} Century Approach to Reliability Program Overview

Mark Law, Toshi Nishida, Scott Thompson, Gijs Bosman
Department of Electrical and Computer Engineering
Steve Pearton, Cammy Abernathy, Brent Gila, Kevin Jones
Department of Materials Science and Engineering
Fan Ren
Department of Chemical Engineering
Agenda

• Monday
  – 12:00 Lunch, Welcome - Dean Abernathy
  – 1:00 Perspectives - Kitt Reinhardt
  – 1:30 Overview - Mark Law
  – 2:15 AFRL Devices - Via
  – 2:35 Tester Overview - Cheney
  – 3:00 Break
  – 3:30 Materials Characterization Abernathy / Holzworth
  – 4:30-6:00 Student Posters
  – 6:30 Dinner - Napolitano's

• Tuesday
  – 8:00 Continental Breakfast
  – 8:30 Electrical Measurements / Strain - Nishida / Thompson
  – 9:30 Noise Modeling and Measurements, Bosman
  – 10:00 Device Simulation, Law
  – 11:00 Summary
  – 11:15 Caucus
  – 12:00 Lunch / Feedback / Individual Discussions

Presentations at: www.reliability.ece.ufl.edu
Outline

• Background
• Goals and Objectives
• Status
• Research Highlights
• **Industry Objectives**
  – Reduce Early Failure
  – Reduce Random Failure
  – Length time to Wear Out

• **MURI Research**
  – Develop early detection tools
    Canary in the coal mine
  – Provide Understanding of Failure to reduce random components
  – Identify causes of long term wear
  – Develop better accelerated testing

Push the curve in the red directions
Degradation of GaN HEMT’s

Objectives:
- Develop a testing methodology for failure modes
- Develop physical understanding of the failure modes
GaN X - Sections of Structural Failure Mechanisms


Research Thrusts - Support Thrusts

• T1 Fabrication - Pearton
  – Several Industrial Partners
  – AFRL Base Line Devices
  – Experimental Fab Support for Test Structures
• T2 - Statistical Support - Pearton
  – Collaborate w/ Intel Reliability Team
  – Work with best Si techniques / approaches
Research Thrusts - Primary

• Thrust 2 - Materials Characterization - Abernathy
  – Optical Techniques
  – Electron Microscopy
  – LEAP

• Thrust 3 - Electrical Characterization - Nishida
  – Burn-in and Tester Development
  – Mechanical Stress
  – Noise

• Thrust 4 - Modeling - Law
  – TCAD Extended Approaches
  – Noise
  – Mechanical Stress
A 21st Century Approach to Reliability

Thrust to Problem Relationships

- Fabrication
  - Materials Characterization
    - Early Detection
  - Electrical Characterization
    - Failure Identification
    - Failure Understanding
  - Modeling and Simulation
    - Accelerated Testing
- Statistics
Research Work Plan

Thrust 1
Test Structure Fab either in house or partnerships

Thrust 2, 3, 5
Failure Analysis - Materials and Electrical, Statistical

Thrust 3
UF Developed Testing Station - Mech, Elec, Temp

Thrust 4
Simulation & Modeling

Development of New Testing Strategies, Better Lifetime Prediction and Scaling, Improved Device Behavior and Design

Research Goal
Precompetitive Engineering Scientific Research Focus

- Scientific Understanding of Materials Properties
- Understanding of Electrical Signatures
- Modeling / Simulation of Failure

- Black’s Equation Empirically Captured Aluminum Electromigration in 1969
- Subsequent work on
  - Characterization of field, current density, temperature dependence
  - Characterization of mechanical stress
  - Characterization of grain size diffusion along grain boundaries
  - Characterization of etch effects related to grain size
  - Full 3-Dimensional Grain Models

Recent Papers in 2008 and 2009 - 40 years of science based pubs
Collaborations with Industry

• **RFMD**
  - 77 stressed devices attached to RF boards
    *Survived 1000 hour RFMD lifetime test in October 2008*
  - 2500 unstressed devices

• **Nitronex**
  - 60 unstressed devices

• **WIN Semiconductor**
  - 20 unstressed devices
  - 8 stressed devices
  - 15 TLM strips

• **Northrop Grumman**
  - 3 unstressed devices
ITAR / Export Control

- Controlled Room in NRF
- Devices kept in locked room and locked cabinet
- Sign in / sign out for experimentation
- ITAR Training Provided

- We can work with corporate devices
- Have controls in place
A 21st Century Approach to Reliability

Materials Characterization Thrust

Fabrication

Statistics

Materials Characterization

Early Detection

Failure Identification

Failure Understanding

Accelerated Testing

Electrical Characterization

Modeling and Simulation

Materials Characterization

Failure Understanding

Accelerated Testing
A 21st Century Approach to Reliability

Cathodoluminescence (CL) system

FEI Nova NanoSEM (FEG source) with:
EDAX Apollo silicon drift detector (TE cooled)
Gatan MonoCL3+

FEI SEM arrived Sept 1st and is installed.
Landing energy 50 V to 30 kV, continuously adjustable
Resolution High-vacuum: <1.0 nm @ 15 kV, 1.6 nm @ 1 kV

EDAX installed EDS detector on Sept. 15th. Boron lowest element detected.

Gatan to install detector on Sept. 22nd, MonoCL3+ detector allows for spectrum mapping with 150 line/mm grating or high resolution spectrum at a spot with a 1200 line/mm, grating. Short working distance parabolic mirror allows for higher resolution.

Tool and facility optimized for highest resolution possible.
XPS/UPS Summary

Design experiment to determine changes in SiNx passivation during device operation/stressing
- MOCVD u-GaN/sapphire and AlGaN/GaN/sapphire
- 5nm PECVD SiNx deposited on substrates (250°C, 60W) to ensure the Ga peak is visible.

Use 200°C anneal as a starting temperature and perform first anneals in the controlled environment of UHV. Temperature approximates device temperature under normal operation.

SiNx on u-GaN
Shift in VB of -0.4eV after vacuum anneal at 200°C. Ga-O portion of peak lost. No significant changes in Si 2p peak.
VB offset recovers to initial value after anneal in air at 200°C. Ga 3d peak recovered Ga-O portion. Peak positions and relative intensities are nearly identical to pre vacuum anneal values.

SiNx on HEMT
Shift in VBM of -0.9eV after vacuum anneal. No determined Ga-O bonding in the Ga 3d peak.
VB offset recovers to initial value after air anneal, similar to SiNx/u-GaN sample.

Different mechanism for the SiNx/u-GaN and SiNx/HEMT causing a VB shift.
Previous LEAP Analysis

- First Ever Reported LEAP image from GaN
- LEAP reconstruction under gate (GaN layer)
- LEAP reconstruction of part of the source ohmic contact stack
New LEAP Analysis

- Recently completed First Reported LEAP reconstruction of the entire gate stack.

- Reconstruction Features
  - Gate metal stack
  - Gate/Semiconductor interface
  - AlGaN/GaN interface

- Analysis
  - Interface curvatures
  - Interfacial layers
  - Concentration Profiles
Work in Progress / Future Research

• On going Work
  – Stress experiments on Nitronex epi-structure wafers
    • In-plane stresses will be applied to the wafers by bending them in quartz bending jigs.
    • This will replicate the stresses the HEMTs experience due to the inverse piezoelectric effect under high bias conditions.
      – Because the wafers will be mechanically bent, no electric field will be applied to the wafers and no orthogonal stress component will be examined.
      – This will characterize the importance of the electric field and vertical stress component to defect formation compared to the in-plane components.
      – A critical stress for defect formation will be established by performing experiments at different stress states.
      – Also, the effect of stress on the reactions between the epi-layers will be determined.

• Future Work
  – TEM and LEAP on devices
    • Produce a LEAP reconstruction of the Gate/SiNx/AlGaN gate edge interface.
    • Produce TEM micrographs and LEAP reconstructions of stressed/failed devices.
Electrical Characterization Thrust

- Fabrication
- Statistics

- Materials Characterization
- Electrical Characterization
- Modeling and Simulation

- Early Detection
- Failure Identification
- Failure Understanding
- Accelerated Testing
# Testing System Turnkey vs. In-house

<table>
<thead>
<tr>
<th></th>
<th>Turnkey</th>
<th>In-house</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Timeline</strong></td>
<td>Purchase lead time</td>
<td>On-going</td>
</tr>
<tr>
<td><strong>System</strong></td>
<td>Proven</td>
<td>Custom design</td>
</tr>
<tr>
<td><strong>Objective</strong></td>
<td>Determine Lifetimes</td>
<td>Research</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Determine failure mechanisms</td>
</tr>
<tr>
<td><strong>Test Types</strong></td>
<td>Industry standards</td>
<td>Flexible</td>
</tr>
<tr>
<td>DC Drain Gate</td>
<td>0-100V, up to 4A, 400W max</td>
<td>0-60V, up to 6A, 300W max</td>
</tr>
<tr>
<td></td>
<td>±18.5V, up to 200mA</td>
<td>±10V, up to 20mA</td>
</tr>
<tr>
<td>RF</td>
<td>600MHz-3 GHz</td>
<td>1.8-2.2 GHz</td>
</tr>
<tr>
<td></td>
<td>2-18 GHz</td>
<td>expandable with additional hardware</td>
</tr>
<tr>
<td></td>
<td>58-60 GHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>900MHz-10GHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>36-40 GHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>76-78 GHz</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>50° to 250° C</td>
<td>25° to 250° C</td>
</tr>
<tr>
<td>Optical</td>
<td>NA</td>
<td>Research with wavelength and intensity</td>
</tr>
<tr>
<td>Thermal Imaging</td>
<td>NA</td>
<td>IR, Micro Ramon additional hardware</td>
</tr>
<tr>
<td>Pulse</td>
<td>1-100kHz</td>
<td>Up to 80MHz</td>
</tr>
<tr>
<td>Data Storage</td>
<td>Independent test files</td>
<td>SQL database</td>
</tr>
</tbody>
</table>
UF Semiconductor Reliability System

Thermistor: McShane TS104-170
TECs: Melcor HOT2.0-65-F2A

Temperature Measurement and Control
A 21st Century Approach to Reliability

Measured Piezoresistance:
- GaN HEMT: ~1 %/GPa
- Si nMOS: ~31 %/GPa

Graph showing time (s) vs. compression and tension with reference to sample A.
## Wide range of published gauge factors (GF)

<table>
<thead>
<tr>
<th>Reference</th>
<th>GF</th>
<th>(\Delta R/R)</th>
<th>(\varepsilon) (%)</th>
<th>(\sigma) (MPa)</th>
<th>Method of Stressing</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work</td>
<td>-2.6</td>
<td>0.3%</td>
<td>0.114</td>
<td>360</td>
<td>4-point bending</td>
</tr>
<tr>
<td>[1]</td>
<td>-4</td>
<td>0.14%</td>
<td>0.03</td>
<td>95</td>
<td>3-point bending</td>
</tr>
<tr>
<td>[2]</td>
<td>-42</td>
<td>0.2%</td>
<td>0.005</td>
<td>15</td>
<td>3-point bending</td>
</tr>
<tr>
<td>[3]</td>
<td>-75</td>
<td>3.5%</td>
<td>0.04</td>
<td>126</td>
<td>3-point bending</td>
</tr>
<tr>
<td>[4]</td>
<td>-90</td>
<td>15%</td>
<td>0.167</td>
<td>525</td>
<td>Cantilever</td>
</tr>
<tr>
<td>[5]</td>
<td>-350</td>
<td>5%</td>
<td>0.0143</td>
<td>45</td>
<td>Lever-Mass</td>
</tr>
<tr>
<td>[6]</td>
<td>-1,259</td>
<td>1.7%</td>
<td>1.35x10^{-4}</td>
<td>0.42</td>
<td>Cantilever</td>
</tr>
<tr>
<td>[7]</td>
<td>-38,889</td>
<td>15%</td>
<td>3.85x10^{-4}</td>
<td>1.2</td>
<td>Circular Membrane</td>
</tr>
</tbody>
</table>

Stable drain noise characteristics

- Drain noise measured as a function of $V_{GS}$ for constant low $V_{DS}$
- Frequency exponent ($\gamma$) is an inverse function of the gate overdrive voltage.
- Indicator of non-uniform trap distribution. High band-bending in AlGaN barrier creates a trap distribution skewed towards the interface leading to high frequency traps.
- No distinct generation-recombination components at room temperature.

$S_{ID}/I_D^2$ (1/Hz)

$V_{DS} = 80$ mV
Gate noise instability

\[ S(I_G) (\text{A}^2/\text{Hz}) \]

(a) 

(b) 

(c) 

(d) 

15.28 ms

\[ \Delta I_G / I_G \approx 20\% \]

\[ \Delta I_G / I_G \approx 40\% \]
Simulation Thrust

Fabrication

- Materials Characterization
  - Early Detection

Electrical Characterization

- Failure Identification
  - Failure Understanding

Modeling and Simulation

- Accelerated Testing

Statistics
2DEG Density Calculation Procedure

**AlGaN**

- Build in $P_{SP} + P_{PE, lattice}$
- Additional strain from mechanical stress
- Piezoelectric Constant

**GaN**

- Build in $P_{SP}$
- Additional strain from mechanical stress
- Piezoelectric Constant

$$P_{total} = P_{SP}(AlGaN) + P_{PE, lattice}(AlGaN) + P_{PE, mech}(AlGaN) - P_{SP}(GaN) - P_{PE, mech}(GaN)$$

2DEG Density:

$$n_s(x) = \frac{P_{total}}{e} - \left(\frac{\varepsilon_0 \varepsilon(x)}{de^2}\right) \left[ e\varphi_b(x) + E_F(x) - \Delta E_C(x) \right]$$

[Ref: JAP, vol.85, pp.3222]
\[ n_s(x) = \frac{+P^{\text{int}}(x)}{e} - \left( \frac{\ddot{a}_0 \dddot{a}(x)}{de^2} \right) \left[ e\ddot{o}_b(x) + E_F(x) - \dddot{A}E_C(x) \right] \]

**Assumed independent of stress:**
- \( \phi_b \) since \( \Delta P^{\text{int}} \) is small
- \( \Delta E_C \) since only 26\% Al in AlGaN
- \( \varepsilon \) and \( E_F \) since no change in Si and no papers reporting change for GaN

- Small changes observed in \( n_s \) (0.28\%/GPa) since external stress creates offsetting piezoelectric polarizations
Simulation vs. Experiment

Change (%) vs. Stress (MPa)

- $R_{TOT}$
- $n_S$
- $e$

A 21st Century Approach to Reliability
Inverse Piezoelectric Effect Calculation

- Mechanical Simulation with InversePiezo and Lattice Mismatch Terms
- Low voltage applied
- Sharp bunching of strain from inversepizeo terms near drain edge
Temperature Models

All temperature dependence has been implemented

\[ c \cdot \left( \frac{\partial T}{\partial t} \right) = \text{div} \left( \kappa \nabla T \right) + H \]

\( \kappa \equiv \text{thermal conductivity} \)
\( c \equiv \text{lattice heat capacity} \)

<table>
<thead>
<tr>
<th>Material</th>
<th>( \kappa ) (W/cm°K)</th>
<th>( c ) (J/°K•cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaN</td>
<td>2.67</td>
<td>1.395</td>
</tr>
<tr>
<td>AlGaN</td>
<td>0.33</td>
<td>1.395</td>
</tr>
</tbody>
</table>

H = Heat Generation rate, several interpretations are in the literature

\[ H = q \cdot \text{div} \left( \phi_n \vec{j}_n - \phi_p \vec{j}_p \right). \]

\( \phi_n, \phi_p \equiv \text{quasi-fermi levels of e, h} \)

because hole concentration is negligible, simplified to

\[ \vec{j}_n = \mu_n \cdot n \cdot \nabla \phi_n \]
\[ \vec{j}_p = -\mu_p \cdot p \cdot \nabla \phi_p \]

Fixed temperature boundary condition applied to bulk contact:

\[ T_{\text{bulk_contact}} = 300 \text{ (K)} \]
Temperature Profiles

Contour plot of temperature
\( V_G = 0 \text{ V} \quad V_D = 8 \text{ V} \)

Temperature across device through AlGaN increasing bias
\( V_G = 0 \text{ V} \quad V_D = 0 \text{ V} \) to \( 8 \text{ V} \)

Michelle Griglione, Poster

A 21st Century Approach to Reliability
Collaborations w/ DRIFT and Others

- Vanderbilt
  - Surface Degradation
  - Hydrogen Behavior During Device Operation
  - Existing Collaboration on Radiation Effects

- MIT
  - Overlapping Interest in Stress
  - Share data and models

- Georgia Tech
  - Sharing devices, data

---

Fig. 11. Gate length dependence of degradation. Different gate length devices (type Al, \(L_g=0.25, 0.65, \) and 1.15 \(\mu m\)) are stressed at \(V_{GS}=0\) and \(V_{DS}=15−34 \text{ V}\) (1 V step, 5 min step). The threshold of the degradation increases with \(L_g\).
Degradation Mechanisms in InAlAs/InGaAs MHEMTs with 150 nm Mushroom Gates

Degradation mechanisms of InAlAs/InGaAs pHEMTs reported include:
- Ohmic Contact
- Layer Structure
- Fluorine Contamination
- Bias Dependence
- Gate Recess Depth
- Gate Metal Sinking

Private communications indicate that ALL InAlAs/InGaAs HEMTs suffer from an initial decrease in IDSS - this is accommodated by a burn-in to get the devices to a new equilibrium.

After DC stress, the Pt from the mushroom gate diffused into InAlAs layer, confirmed with TEM images and EDS analysis.
Degradation Mechanisms in InAlAs/InGaAs MHEMTs with 150 nm Mushroom Gates

Device stressed at higher current density at $10^2$ A/cm² exhibited electromigration induced void on the edge of the Ohmic metal contact pads. The effects of field, and changes in contact and sheet resistance were separated by using TLM patterns in addition to the actual devices.

TLM pattern with pad gap 3 µm, 6 µm, 9 µm, 12 µm and 15 µm.

The increases of the TLM resistance during DC stress and thermal storage resulted from different mechanisms

- The Rc deterioration was dominant in the thermal storage test and the Rs increase was observed in the DC stress.
- Metal spike formation and ohmic metal diffusion are observed during the thermal storage.

The DC stress would be further conducted (different stress conditions) to investigate the device electrical performance including saturation current, gate modulation behavior, threshold voltage, leakage, gate lag..etc in order to compare the degradation behavior.
Conclusions

• Science Based Program
• Directed at:
  – Improved Testing Methodology
  – Greater Understanding of Failures
  – Failure Prevention Strategies
• Strong Collaborations
  – Industry
  – University Partnership