LEAP and TEM of Nitronex GaN HEMTs

Ray Holzworth and Dr. Kevin S. Jones
Last Review: Reported First LEAP analysis of bulk GaN

- Demonstrated that GaN can be analyzed by LEAP despite low conductivity
- 78,000,000 Atoms collected from this run
- LEAP reconstruction under gate in bulk GaN
New LEAP Analysis

• LEAP reconstruction of gate region
  – Gate metal stack
  – Gate/Semiconductor interface
  – AlGaN/GaN interface
LEAP Reconstruction

A 21st Century Approach to Reliability
TEM and LEAP Comparison

- TEM

- LEAP
Reproducibility

- 3 completed LEAP runs of the gate region
  - 2M28
  - 2M30
  - 2M36
Making Site Specific LEAP Tips

• Possible to make site specific tips
  – Areas of interest are not random but purposely chosen

• Procedure:
  1) Find area of interest during mill
  2) Find a permanent marker layer on LEAP post
  3) Measure distance from marker to the feature
  4) Measure distance from feature to the end of the tip
  5) Mill tip and simultaneously record these measurements
  6) When tip is ~100-500 nm from feature, stop
Making Site Specific LEAP Tips

Freshly Mounted

Middle of 1st Mill
- 3390 nm
- 700 nm
- Gate
- 2750 nm
- Marker Layer

End of 1st Mill
- 3450 nm
- 3070 nm

A 21st Century Approach to Reliability
Making Site Specific LEAP Tips

Middle of 2\textsuperscript{nd} Mill

Middle of 3\textsuperscript{rd} Mill

Completed

<table>
<thead>
<tr>
<th>Middle of 2\textsuperscript{nd} Mill</th>
<th>Middle of 3\textsuperscript{rd} Mill</th>
<th>Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2780 nm</td>
<td>3040 nm</td>
<td>3160 nm</td>
</tr>
<tr>
<td>2810 nm</td>
<td>2270 nm</td>
<td></td>
</tr>
</tbody>
</table>

A 21\textsuperscript{st} Century Approach to Reliability
Interfacial Curvatures

- Diffuse
- Smooth

Au/Ni

Ni/Al

Al/Ga

A 21st Century Approach to Reliability
Analysis Cross Section

- Use data pipe to collect information
  - Analysis occurs along the length of the pipe and across the cross sectional area
1-D Concentration Profile

Gold  Nickel  AlGaN  GaN

Concentration (Atomic %)

Distance (nm)

Al  Ga  Au  N  O  Ni
Comparison between STEM and LEAP Analysis

- STEM
  - Gold
  - Nickel
  - Gallium
  - Aluminum
  - Nitrogen
  - Oxygen

- LEAP

1D Concentration Profile (Preview)
Diffusion Profile
Comparing Diffusivity Values

- Boltzmann-Matano Method

J. Reynolds, Ph.D. Dissertation, Diffusion in Gold-Nickel Alloys
Diffusivity Product Curves

- 2M30
- 2M36
Interfacial Layer Analysis

- Nitronex has reported the presence of an interfacial layer between the gate and AlGaN

S. Singhal, et al., GaN-on-Si Failure Mechanisms and Reliability Improvements

- LEAP analysis has been used to characterize this layer
LEAP of Interfacial Layer

- Oxygen Layer
  - Oxygen layer present between Ni and AlGaN
- Oxygen/Ni interface
  - $\text{AlO}_x$ and $\text{NiO}_x$ were also detected
- No $\text{GaO}_x$ detected
LEAP of Interfacial Layer

• AlO$_x$ Layer

• AlO$_x$/AlN interface

• NiO$_x$/O interface
Interface Concentration Profiles

- Layers always appear in order of NiO$_x$/O/AlO$_x$ at interface

- 2M28
- 2M30
- 2M36

![Graphs showing concentration profiles for 2M28, 2M30, and 2M36, with peaks indicating concentration of NiO, O, and AlO at different distances.](image-url)
Deprocessing

- Virgin Encapsulated Device
  - Exposed to nitric acid for 116 hours
    - Some encapsulant remained on surface
  - Ultrasonicated in nitric acid for 1 hour
    - Removed most remaining encapsulant

- Process completely removes source and drain metal contact stacks
- $\text{SiN}_x$ protects the surface from nitric exposure
  - Gate metal protected
Non Encapsulated
After Nitric Exposure
After Sonication
SE-SEM Images
SE-SEM Images
Work in Progress

• In-plane stress experiments
  – Stress applied to Nitronex epi-structure wafers
    – Courtesy of Edwin Piner
  – Utilizes quartz bending jig
    • No applied bias or electric field
  – Two wafer thicknesses
    • Standard (as shipped)
    • Ultra-thin
      – Allows higher stress states due to greater curvature

• Outcome?
  – Stress required to produce defects
  – Effect of stress on diffusivity of Si and other interfacial reactions
A 21st Century Approach to Reliability

Previous Studies - Conway

- DC testing
  - 3000 hours
  - $T_{Ch} = 172^\circ C$
  - $V_{DS} = 30 V$
  - $I_{DS} = 40 mA$
  - Air

(a) XTEM micrograph of the reaction product
(b) EELS map of oxygen distribution
(c) EELS map of nitrogen distribution
(d) Combined EELS map of oxygen (yellow) and nitrogen (blue)

Previous Studies - Chowdhury

- **DC testing**
  - 1000 hours
  - $T_{Ch} = 250^\circ C, 285^\circ C, 320^\circ C$
  - $V_{DS} = 40 V$
  - $I_{DQ} = 250 \text{ mA/mm}$

(a) XTEM micrograph of the pit defect
(b) XTEM micrograph of the crack defect
(c) XTEM micrograph of gate metal diffusion into crack defect

Previous Studies - Park

- DC testing
  - 1000 hours
  - $T_{ch} = 250^\circ C, 285^\circ C, 320^\circ C$
  - $V_{DS} = 40$ V
  - $I_{DQ} = 250$ mA/mm

(a) XTEM micrograph of the pit defect
(b) XTEM micrograph of the pit and crack defects

A 21st Century Approach to Reliability

Previous Studies - Park

- Analysis of the reaction product in the pit defect

(a) XTEM micrograph of the reaction product in a pit defect near the gate’s drain side
(b) EDS spectrum of a defect free AlGaN/GaN interface
(c) EDS spectrum of the reaction product in the pit defect.

Experiment Setup

- 2 quartz bending jigs
  - One for each wafer thickness
- Wafers cleaved into strips
- Strips are bent
- Strip deflection measured by laser system
  - Measures curvature of strip

\[
\frac{1}{r(x)} = \frac{d^2 y(x)/dx^2}{(1 + (dy(x)/dx)^2)^{3/2}}
\]

\[
\sigma(x) = \frac{Ec}{r(x)}
\]


Future Work

• TEM and LEAP
  – LEAP reconstruction of the Gate/Si/AlGaN gate edge interface
  – TEM micrographs and LEAP reconstructions of stressed and failed devices

• Deprocessing
  – Asher
  – Additional chemical solutions
Conclusions

• Completed the first set of LEAP runs on AlGaN/GaN HEMTS
• Showed the interface layer at the AlGaN/Ni Gate contact region is an oxide
  – involves an Al oxide and Ni Oxide but there does not appear to be any Ga oxide
• Studied the diffusion couple between Gold and Nickel in the gate contact
• Demonstrated the reproducibility of the results
• Next step: apply LEAP to failed devices and to stressed blanket wafer studies