GaN HEMT Reliability

J. A. del Alamo and J. Joh
Microsystems Technology Laboratories, MIT

ESREF 2009
Arcachon, Oct. 5-9, 2009

Acknowledgements:

ARL (DARPA-WBGS program), ONR (DRIFT-MURI program)
Jose Jimenez, Sefa Demirtas
1. Introduction: GaN Reliability

- GaN HEMT: commercial technology since 2005
- Great recent strides in reliability:
  - MTTF=10^7 h at 150 C and 40 V demonstrated [Jimenez, IRPS 2008]
- Unique issues about GaN HEMT reliability:
  - No native substrate (use SiC, Si, sapphire) \(\rightarrow\) mismatch defects
  - High-voltage operation \(\rightarrow\) very high electric fields (~10^7 V/cm)
  - Strong piezoelectric materials: high electric field \(\rightarrow\) high mechanical stress
  - Electron channel charge set by polarization, not dopants
- Work to do before demonstrating consistent, reproducible reliability with solid understanding behind:
  - When will we be able to put GaN in space?
Outline

1. Introduction
2. Experimental
3. Results
4. Hypothesis for high-voltage degradation mechanism:
   - Defect formation through inverse piezoelectric effect
5. Discussion
6. Conclusions
2. Experimental

GaN HEMT Reliability Test Chip

- 3.25 x 3.175 mm²
- DC and mmw HEMTs
- HEMTs with different dimensions (L_{rd}, L_{rs}, L_g, W_g, #fingers)
- HEMTs with different orientations (0, 30°, 60°, 90°)
- TLM’s, side-gate FET, FATFET
- Most devices completed before vias
- Implemented by BAE, TriQuint and Nitronex with own design rules
DC Stress Experiments

START

Characterization
\( I_{D_{\text{max}}}, R_S, R_D, I_{G_{\text{off}}}, V_T \ldots \)
Trapping Analysis

Electrical Stress
\( V_{DS}, V_{GS} \) (or \( I_D \))
Characterization Suite

- **Comprehensive**, three sets of measurements:
  - *Coarse characterization*: basic device parameters
  - *Fine characterization*: + complete set of I-V characteristics (output, transfer, gate, subthreshold, kink)
  - *Trap analysis*: transient analysis under various pulsing conditions

- **Fast**:
  - Coarse characterization: <20 secs
  - Fine characterization: <1 min
  - Trap analysis: <10 min

- **Frequent**:
  - Coarse characterization: every 1-2 mins
  - Fine characterization, trap analysis: before, after, at key points

- **“Benign”**:
  - 100 executions to produce change <2% change in any extracted parameter
DC Stress Schemes

- **Stress-recovery** experiments:
  - to study trapping behavior

- **Step-stress** experiments:
  - to study a variety of conditions in a single device (for improved experimental efficiency)

- **Step-stress-recovery** experiments:
  - to study trap formation under different conditions in a single device
Electrical Stress Bias Points

- **High current, low field**
  - $V_{GS} = 1\, V$
  - $V_{DS} = 5\, V$
  - **ON**

- **Low current, high field in barrier, low field in buffer**
  - $V_{GS} = 40\, V$
  - $V_{DS} = 0$

- **High current, high field**
  - $V_{GS} = -1\, V$
  - $V_{DS} = 40\, V$
  - **Hot electrons**

- **OFF**
  - $V_{GS} = -6\, V$
  - $V_{DS} = 40\, V$

Graph:
- $I_d$ vs $V_{ds}$
  - **ON**
  - **High Power**
  - **OFF**
  - $V_{gs}$

Note: The graph shows the current density ($I_d$) vs drain voltage ($V_{ds}$) for different bias conditions.
Typical GaN HEMT

Standard device with integrated field plate:
- \( L_G = 0.25 \) um, \( W = 4 \times 100 \) um
- \( f_T = 40 \) GHz, \( I_{D_{\text{max}}} = 1.2 \) A/mm
- \( P_{\text{out}} = 8 \) W/mm, PAE=60% @ 10 GHz, \( V_D = 40 \) V

Test device: \( W = 2 \times 25 \) um

Typical values:
- \( t = 13-18 \) nm
- \( x = 25-30\% \)
3. Results: $V_{DS}=0$ Degradation

$V_{DS}=0$ step-stress; $V_{DG}$: 10 to 50 V, 1 V/step, 1 min/step

![Graph showing degradation effects]

- $I_{Dmax}$ ↓
- $R_{ON}$ ↑
- $g_m$ ↓
**$V_{DS}=0$ Degradation**

$V_{DS}=0$ step-stress; $V_{DG}$: 10 to 50 V, 1 V/step, 1 min/step

![Graphs showing $I_D$ and $I_G$ vs. $V_{GS}$ for $V_{DS}=0.1$ V and $V_{DS}=5$ V, with labels indicating fresh and degraded states.](image-url)
Critical voltage for degradation:

At \( V_{\text{crit}} \approx 21 \) V, \( I_{\text{Goff}} \) increases \( \sim 100X \), \( I_{\text{Dmax}} \), \( R_S \), \( R_D \) start degrading
V_{DS}=0 Degradation

At \(V_{\text{crit}} \approx 21 \, \text{V}\), |I_{\text{gstress}}| < 10 mA/mm

→ self-heating, hot electrons not responsible for \(V_{\text{crit}}\) degradation
OFF-state Degradation

OFF-state step-stress: $V_{GS} = -5 \text{ V}; \ V_{DS} : 5 \text{ to } 45 \text{ V}, 1 \text{ V/step}, 1 \text{ min/step};$

- Critical behavior, but $V_{\text{crit}} \approx 34 \text{ V} \rightarrow V_{\text{crit}}$ depends on detailed bias
- $R_S$ does not degrade
- $I_{\text{GDoff}} \uparrow$, $I_{\text{GSoff}}$ unchanged

Drain side degrades, source side intact
High-Power Degradation

High-power step-stress (fixed $I_{\text{Dstress}}$); $V_{DS}$: 5 to 40 V, 1 V/step, 1 min/step

Critical behavior, but $I_{\text{Dstress}} \uparrow \rightarrow V_{\text{crit}} \uparrow$

$\rightarrow$ Current is not accelerating factor
Trapping in stressed devices

$V_{DS} = 0$ stress-recovery experiment; $V_{GS} = -40$ V (beyond $V_{crit}$)

- $I_G$ follows same trapping behavior as $I_D$
  - common physical origin for $I_G$ and $I_D$ degradation
- In recovery phase: $I_{D_{max}} \uparrow$, $I_{G_{off}} \uparrow$ → trapped electrons block $I_G$
- $I_{G_{on}}$ steady → traps not accessible from channel?
Are traps also generated at $V_{\text{crit}}$?

- $V_{DS}=0$ step-stress-recovery experiment with diagnostic pulse
  - 10 min step, 5 min recovery, 2.5 V/step
- Under light to speed up recovery

---

Joh, IEDM 2006
The graph illustrates the trap density vs. damage in GaN HEMT, showing current collapse (~trap density) and degradation. The critical voltage $V_{\text{crit}}$ marks the onset of $I_G$, $I_D$, $R_S$, $R_D$ degradation and trap formation.
Other Reports of Critical Voltage Behavior

$V_{\text{crit}} = 30-60 \text{ V}; \text{ Ivo, IRPS 2009}$

GaN HEMT on Si, $V_{\text{crit}} = 10-75 \text{ V}$
Demirtas, ROCS 2009

$V_{\text{crit}} = 10-80 \text{ V}; \text{ Zanoni, EDL 2009}$
4. Hypothesis for high-voltage degradation mechanism

1. Defects in AlGaN
   - provide path for reverse $I_G$ ($I_{Goff}$↑)
   - electron trapping $\rightarrow n_s \downarrow \rightarrow I_{D_{max}} \downarrow$, $R_D$↑
   - transient effects
   - additional non-transient degradation

\[ \Delta \Phi_b \]

\[ \text{AlGaN} \]
\[ \text{GaN} \]

\[ \text{S} \]
\[ \text{G} \]
\[ \text{D} \]

\[ \text{High } V_{DG} \]

\[ \text{2DEG} \]
Hypothesis for high-voltage degradation mechanism

2. Defects originate from excessive mechanical stress
   • introduced by high electric field through inverse piezoelectric effect
   • concentrated at gate edge
   • builds on top of lattice mismatch stress between AlGaN and GaN
   • when elastic energy density in AlGaN exceeds critical value
Role of $V_{GS}$

OFF-state step-stress experiments at different $V_{GS}$:

High-field on source side adds to stress on drain side

$|V_{GS}| \downarrow \rightarrow V_{crit} \uparrow$
Role of Gate Length

$V_{DS}=0$ step-stress experiments for different $L_G$

$L_g \uparrow \rightarrow$ less cumulative stress at edges

Joh, IEDM 2007

$L_G \uparrow \rightarrow V_{crit} \uparrow$
Role of Mechanical Strain

External tensile strain $\uparrow \rightarrow V_{\text{crit}} \downarrow$

$\rightarrow$ reveals mechanical origin of degradation

Joh, IEDM 2007
Crack and pits in stressed GaN HEMTs

ON-state degradation at 40 V, $I_D=250 \text{ mA/mm}$, $T_a=112 \text{ C}$

Physical degradation correlates with electrical degradation

Chowdhury, EDL 2008
Other observations of damage at edges of gate

Gate current degradation correlates with electroluminescence from gate edges

Zanoni, EDL 2009
5. First-order model for $V_{\text{crit}}$

- Key assumption: at $V_{\text{crit}}$, elastic energy density in AlGaN reaches critical value
  - Electrical model: 2D electrostatic simulator (Silvaco Atlas)
  - Mechanical model: analytical formulation of stress and elastic energy vs. electric field

![Graphs showing linear and superlinear relationships](image)

- Planar stress linear on vertical electric field
- Elastic energy density superlinear on vertical electric field

Joh, ROCS 2009
First-order model for $V_{\text{crit}}$

- Example: 16 nm thick AlGaN with $x=28\%$
- $V_{\text{crit}}$ condition in OFF-state ($V_{\text{GS}}=-5$ V, $V_{\text{DS}}=33$ V)

Large peak of electric field and elastic energy density under gate edge on drain side

Joh, ROCS 2009
$W_{\text{crit}}$ corresponding to $V_{\text{crit}}$ consistent with value for onset of relaxation of AlGaN/GaN heterostructures
Impact of AlGaN composition on $V_{\text{crit}}$

$$W_{\text{crit}} = YS_1^2 h$$

$V_{\text{GS}} = -5 \text{ V}$

$x(\text{AlN}) \downarrow \rightarrow \text{initial elastic energy} \downarrow \rightarrow V_{\text{crit}} \uparrow\uparrow$

Joh, ROCS 2009
Consequences:
HEMT reliability improved if…

1. Elastic energy density in AlGaN barrier is minimized:
   - Thinner AlGaN barrier [Lee 2005]

![Graph showing Al\textsubscript{0.32}Ga\textsubscript{0.68}N layers with different thicknesses and their effect on degradation]

- $t_{\text{ins}} = 14$ nm
- $t_{\text{ins}} = 18$ nm
- $t_{\text{ins}} = 21$ nm
- $t_{\text{ins}} = 26$ nm

Lee, TED 2005
Jimenez, TWHM 2009

40 V, $T_j=355$ C

- 25% lower Al
- Standard
1. Elastic energy density in AlGaN barrier is minimized (cont.):
   • AlGaN buffer layer [Joh 2006]
   • No AlN spacer [ref?]
Consequences:
HEMT reliability improved if…

2. AlGaN barrier is mechanically strengthened:
Consequences: HEMT reliability improved if…

3. Electric field across AlGaN at gate edge is minimized:
   - Field plate [Lee 2003, Jimenez 2006]
   - Longer gate-drain gap [Valizadeh 2005]
   - Add GaN cap [Ivo 2009, Ohki 2009]
   - Rounded gate edge [ref?]
Many unknowns

• What is the detailed nature of the defects at the gate edge?
  – Crack?
  – Metal diffusion down crack?
  – Aggregation of dislocations?
  – Other crystalline defects
• Role of stress gradient?
• Role of time?
• Role of temperature?
• Hot electron damage in high-power state?
• Are these mechanisms relevant under large RF drive?
• Why spatial variations?
• Role of buffer?
• Role of surface and surface treatments?
The surface matters…

Surface treatments prior to ohmic metal deposition and gate evaporation impact reliability

Jimenez, TWHM 2009
6. Conclusions

- Unique degradation aspects of AlGaN/GaN HEMTs with relevance to degradation

- Need fundamental research to provide understanding

- Many opportunities to improve reliability

- Not obvious today how to accelerate degradation to provide accurate estimation of MTTF

- Optimistic about long-term prospects of reliable GaN HEMTs
More materials
$V_{DS}=0$ step-stress; $V_{DG}$: 10 to 50 V, 1 V/step, 1 min/step

$E_a(I_{Goff}) \downarrow$

$E_a(I_{Gon})$ unchanged