Strain and Temperature Dependence of Defect Formation at AlGaN/GaN High Electron Mobility Transistors on a Nanometer Scale

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Outline

**Background**: AlGaN/GaN HEMT physical degradation mechanisms – Historical efforts

- Techniques: DRCLS, KPFM, $I_D$ & $I_{GOFF}$ vs. $V_{DS}$

- **Device Conditions**: ON-state vs. OFF-state stress

- Electric field vs. Thermal stress: Surface potential, leakage current, defect generation → Failure prediction

**Conclusions**: (1) Dominant impact of $V_{DS}$ vs. $I_{DS}$ on device reliability

(2) Primary defects located *inside* AlGaN
Motivation

- AlGaN/GaN HEMT: high power, RF, and high speed applications
- Reliability challenge: Hard to predict failure
- High current, piezoelectric material, & high field due to high bias → Defect generation
- Micro-CL, AFM, and KPFM: Follow evolution of potential, defects, and failure
Background: All-Optical Methods


Raman/IR Technique

PL Technique

Background: Scanned Probe Methods


SThM Technique


DRCLS Technique


$T = 218.7 + 112.3 \times V$

$E_G$ versus $T$

$V_{DS} = 18.2 \, V$, $I_{DS} = 194 \, mA$, $V_{GS} = -2 \, V$

$T$ versus Gate-Drain Location
**Depth and Laterally-Resolved CLS**

*Image of JEOL JAMP 7800F: SEM, Micro-CL*

**T, σ, defects, atomic composition**

- Source
- Gate
- Drain
- AlGaN
- 2DEG
- GaN
- Buffer layer
- Substrate

5 kV, 10 nm beam

![Graph showing intensity vs. depth for different energies](image)

- 1 keV
- 2 keV
- 3 keV
- 4 keV
- 5 keV

Intensity (a.u.)

Depth (nm)

Grading AlGaN

*(25%)*

*(10%)*

50 nm

10 nm
Background: Temperature Maps

- Hottest spot at drain-side gate edge
- Hot spots also inside GaN buffer

Electroluminescence detects gap states forming inside HEMT during operation.


Electrochemically-Produced Defects

- High C, O, and Si concentrations at gate foot “lattice disruption” area
- Gate leakage current promotes electrochemical reaction


Impact of Structural Defects


High field at drain-side gate can form structural defects that affect $I_{G-OFF}$ & $I_D$
Inverse Piezoelectric Effect and Defects

\[ V_{DS} + V_{\text{piezo}}^{\text{inv}} \rightarrow \text{strain energy} \]
\[ \rightarrow \text{exceed elastic energy of crystal} \]
\[ \rightarrow \text{form defects at gate foot} \]


Measurement Strategy

- **Thermal Mapping**: DRCLS NBE laterally (<10 nm) & in depth (nm’s to µm’s)
  - Obtain T vs. $I_{DS}$; locate “hot” spots
- **Stress Mapping**: DRCLS NBE near gate foot vs. $V_{DS}$ with $I_{DS}$ OFF (no heating)
- **Potential Mapping**: Kelvin work function vs. $V_{DS}$ with $I_{DS}$ OFF (no heating)
- **Device testing**: Step-wise ON & OFF-state $I_{D\text{MAX}}$ and $I_{G\text{OFF}}$ vs. $V_{DS}$
- **Defect Generation**: CLS defect peak intensities vs. thermal and electrical stress
- **Defect Localization**: DRCLS intensities vs. depth
Stress Conditions

- **Reference:** No stress

- **ON-state stress:** high $I_D$, low $V_{DS}$
  
  \[
  (I_D = 0.75 \text{ A/mm}, \ V_{DS} = 6 \text{ V}, \ V_G = 0 \text{ V})
  \]

- **OFF-state stress:** low $I_D$, high $V_{DS}$
  
  \[
  (I_D = 5 \times 10^{-6} \text{ A/mm}, \ V_{DS} = 10 \sim 30 \text{ V}, \ V_G = -6 \text{ V})
  \]

- $I_{GOFF}$ taken at $V_{DS} = 0.5 \text{ V}, \ V_{GS} = -6 \text{ V}$

Aim: Test electric field-induced strain vs. current-induced (e.g., heating) mechanism
Strain Measurements: Drain-side Gate Foot

- Applied voltage blue-shifts band gap, increases mechanical strain at drain-side gate foot
- 26 meV CL shift = 1 GPa; $V_{DG} = 32$ V $\rightarrow 0.27$ GPa

**I_{DMAX}, I_{G-OFF} vs. Time & Applied Voltage**

**OFF-state**
- **OFF-state** $I_{G-Off}$ rises sharply at threshold $V_{DG}$

**ON-state**
- **ON-state** $I_{G-OFF}$ decreases vs. time
  - → device degradation with external stress
Surface Potential Evolution (OFF-state)

Low potential regions appear and expand with increasing applied stress $V_{DG}$

Surface Potential Evolution (ON-state)

Current stress seems to degrade device in a different way
Device Failure under OFF-state Stress

- Device failure occurs as $V_{DG}$ increases further
- Large, cratered failure area appears; morphology of drain metal exhibits huge change
Correlation between AFM, KPFM & SEM

AFM, KPFM and SEM results reveal that device fails at the lowest surface potential area, where defect density is highest.
Within low potential region and at depth of 2DEG, DRCLS reveals formation of deep level defects.

Defect Generation vs. Location

Largest defect increase at lowest potential region

Areas of highest defect intensities and highest stress correlate

Lower defect creation for On-state stress

Largest defect increase at lowest potential region

Increasing defects densities correlate with decreasing potential.
Surface Potential vs. Electrical Stress


\[ \sigma^* = \sigma_0/[1+\exp[(E_F - E_a)/kT]] \]

\[ q\Delta V = q^2 \sigma_a d/\varepsilon \]

• \( E_F \) moves lower in gap as acceptor-like defects increase
• Drain-side surface potential decreases (\( \Phi \) increases) with increasing \( V_{DG} \)
• Above \( V_{DG} \) threshold, faster decreases at low \( \Phi \) patches
• Higher \( \Phi \) patches decrease slower
CLS Energy Comparison with Trap Spectroscopy

- **DLOS**: 3 traps observed: $E_C-0.55$ (dominant), 1.1, &1.7-1.9 eV


- **DRCLS**: 2.8 eV BB and 2.3 eV YB emissions: Traps that grow under DC stress – high $10^{12} \text{ cm}^{-2}$ densities

\[
\begin{align*}
\text{GaN} &: E_C - 0.55 \text{ eV}, \ 1.1 \text{ eV}, \ 1.7-1.9 \text{ eV} \\
\text{AlGaN} &: E_C - 0.55 \text{ eV}, \ 1.35 \text{ eV} \\
&: E_V - 3.6 \text{ eV}, \ 2.8 \text{ eV}
\end{align*}
\]


**AlGaN/GaN HEMT Defect Location**

**Pre-stress**

- Source
  - AlGaN: $E_g = 4.2$ eV
  - $E_v + 2.2$ eV
  - $E_v + 1.6$ eV
  - $E_C - 2.0$ eV
  - $E_C - 3.4$ eV

- Drain
  - AlGaN: $E_g = 4.2$ eV
  - $E_v + 2.2$ eV
  - $E_v + 1.6$ eV
  - $E_C - 2.0$ eV
  - $E_C - 3.4$ eV

**Post-stress**

- Source
  - Before stress
  - $E_c$ range: 4.1 $\sim$ 4.2 eV
  - $E_v$ range: 4.1 $\sim$ 4.2 eV
  - $E_C$ range: 3.4 $\sim$ 2.0 eV
  - YB

- Drain
  - After stress – source side
  - $E_c$ range: 4.1 $\sim$ 4.2 eV
  - $E_v$ range: 4.1 $\sim$ 4.2 eV
  - $E_C$ range: 3.4 $\sim$ 2.0 eV
  - YB

- After stress – drain side
  - $E_c$ range: 4.1 $\sim$ 4.2 eV
  - $E_v$ range: 4.1 $\sim$ 4.2 eV
  - $E_C$ range: 3.4 $\sim$ 2.0 eV
  - YB

- BB

**Key Observations**

- **New 3.6 eV feature** 0.5-0.6 eV below $E_C$ → **BB defect within AlGaN**
- **Larger 2.2 eV threshold feature** → **higher YB defects with stress**
- **Higher Drain-side vs. Source-side changes**: consistent with DRCLS
AlGaN/GaN HEMT Physical Degradation Mechanisms

Strain- and Field-induced Impurity Diffusion

Inverse Piezoelectric Effect

Electronically-Active Defect Formation

Multiple possible mechanisms that all create electronically-active defects
BB peak shifts with AlGaN \rightarrow BB defect in AlGaN

Shifted AlGaN NBE and BB features appear only when excitation reaches 40 nm Al_{0.22}Ga_{0.78}N layer \rightarrow Additional piezoelectric strain field
Conclusions

- DRCLS measures electric field-induced stress and current-induced heating on a nanoscale *during* OFF-state and ON-state operation.
- KPFM maps reveal expanding low potential patches where defects form and device failure will occur.
- Separation of field- vs. current-induced degradation demonstrates their relative impact on AlGaN/GaN reliability.
- Nanoscale patch potential and defect evolution inside AlGaN vs. $V_{DG}$ threshold effect at drain-side gate foot support inverse piezoelectric degradation model.