Recent Progress in Understanding the Electrical Reliability of GaN High-Electron Mobility Transistors

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Outline

1. Motivation
2. Electrical and structural degradation of GaN HEMTs
3. Hypotheses for GaN HEMT degradation mechanisms
4. Paths for mitigation of GaN HEMT degradation
Breakthrough RF-μw-mmw power in GaN HEMTs

$P_{\text{out}} > 40$ W/mm, over 10X GaAs!

Wu, DRC 2006

Micovic, MTT-S 2010

Micovic, Cornell Conf 2010
GaN HEMTs in the field

Counter-IED Systems (CREW)

200 W GaN HEMT for cellular base station
Kawano, APMC 2005

100 mm GaN-on-SiC volume manufacturing
Palmour, MTT-S 2010
GaN HEMT: Electrical reliability concerns

ON:
- Mostly benign

High-power:
- Not accessible to DC stress experiments
- Device blows up instantly

High-voltage OFF and semi-ON:
- Degradation of $I_{D_{\text{max}}}$, $R_D$, $I_{G\text{off}}$
- $V_T$ shift
- Electron trapping
- Trap creation
Critical voltage for degradation in DC step-stress experiments

$I_D$, $R_D$, and $I_G$ start to degrade beyond \textit{critical voltage} ($V_{\text{crit}}$) + increased trapping behavior – current collapse
Critical voltage: a universal phenomenon

- **GaN HEMT on SiC**
  - Liu, JVSTB 2011

- **GaN HEMT on SiC**
  - Meneghini, IEDM 2011

- **GaN HEMT on SiC**
  - Ivo, MR 2011

- **GaN HEMT on Si**
  - Marcon, IEDM 2010

- **GaN HEMT on Si**
  - Demirtas, ROCS 2009

- **GaN HEMT on sapphire**
  - Ma, Chin Phys B 2011
Structural degradation: cross section

- Small dimple in early stages of $I_G$ degradation;
- $I_D$ degradation delayed

![Image](image-url)

**Graph**: $V_{DS}=0$ stress

- Device #1
- $I_{Goff}$
- $I_{Dmax}$
- $I_{Dmax}(0)$

<table>
<thead>
<tr>
<th>Device</th>
<th>$I_{Dmax}$</th>
<th>$I_{Goff}$</th>
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<td>#1</td>
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Joh, MR 2010
Correlation between pit geometry and $I_{D\text{max}}$ degradation

Pit depth and $I_{D\text{max}}$ degradation correlate:
→ both permanent degradation and current collapse (CC)
Structural degradation: planar view

OFF-state step-stress, $V_{GS}=-7\ V$, $T_{base}=150\ ^\circ C$

- Continuous groove appears for $V_{stress}<V_{crit}$
- Deep pits formed along groove for $V_{stress}>V_{crit}$

Makaram, APL 2010
Correlation between pit geometry and $I_{D_{\text{max}}}$ degradation

Makaram, APL 2010

$I_{D_{\text{max}}}$ degradation and pit cross-sectional area correlate
Planar degradation: the role of time

$V_{DS}=0, \ V_{GS}=-40 \ V, \ T_{base}=150 \ ^\circ C$

Joh, IWN 2010

- Very fast groove formation (within 10 s)
- Delayed pit formation
- Pit density/size increase with time
- Good correlation between $I_{D_{max}}$ degradation and pit area
Time evolution of degradation for constant $V_{\text{stress}} > V_{\text{crit}}$

$I_{\text{Goff}}$ and $V_T$ degradation:
- fast (<10 ms)
- saturate after $10^4$ s

CC degradation:
- slower
- hint of saturation for long time

Permanent $I_{\text{Dmax}}$ degradation:
- much slower
- does not saturate with time

Joh, IRPS 2011
The role of temperature in time evolution

• $I_G$: weak T dependence
• CC, $I_{D_{\text{max}}}$: T activated

Joh, IRPS 2011
Temperature acceleration of incubation time

- Different $E_a$ for $I_{Goff}$, CC, $I_{D_{max}}$ reveal different degradation physics
- $E_a$ for permanent $I_{D_{max}}$ degradation similar to life test data

* Saunier, DRC 2007; Meneghesso, IJMWT 2010
DC semi-ON stress experiments

Stress conditions:
I_D=100 mA/mm,
V_DS=40 or 50 V
Step-T experiments: 50<T_a<230°C

Prominent pits and trenches under gate edge on drain side

AFM

SEM

Wu, submitted to TED
Structural vs. electrical degradation

Trench/pit depth and width correlate with $I_{D_{\text{max}}}$ degradation

$\Delta I_{D}=25.8\%$

Wu, submitted to TED
• Pit/trench depth increase towards center of gate finger
  → self heating + thermally activated process
• Permanent $I_{D_{\text{max}}}$ degradation is thermally activated with $E_a \sim 1.0$ eV
Sequential $I_G$ and $I_D$ degradation

Stress conditions:
$I_D=100$ mA/mm,
$V_{DS}=40$ or $50$ V
Step-Temperature: $50<T_a<230^\circ C$

“Universal degradation” pattern:
• $I_G$ degradation takes places first without $I_D$ degradation
• $I_D$ degradation takes place next without further $I_G$ degradation

Wu, ROCS 2014
RF power degradation

- RF power degradation pattern matches that of OFF-state DC stress
- But not always…

<table>
<thead>
<tr>
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<th>HV OFF-state DC</th>
<th>RF power</th>
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<tbody>
<tr>
<td>$I_{D_{max}}$</td>
<td>↓ beyond $V_{crit}$</td>
<td>↓ beyond $P_{in-crit}$</td>
</tr>
<tr>
<td>$R_D$</td>
<td>↑ beyond $V_{crit}$</td>
<td>↑ beyond $P_{in-crit}$</td>
</tr>
<tr>
<td>$R_S$</td>
<td>small increase</td>
<td>small increase</td>
</tr>
<tr>
<td>$I_{Goff}$</td>
<td>↑ beyond $V_{crit}$</td>
<td>↑ beyond $P_{in-crit}$</td>
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Current Collapse
- ↑ beyond $V_{crit}$
- ↑ beyond $P_{in-crit}$

Permanent $I_{D_{max}}$
- ↓ beyond $V_{crit}$
- ↓ beyond $P_{in-crit}$

| Pits under drain end of gate | Yes | Yes |
| Pits under source end of gate | No | No |

Joh, IEDM 2010
Joh, ROCS 2011
Joh, MR 2012
Summary of electrical and structural degradation

1. $I_G$ degradation
   - Fast
   - Electric-field driven
   - Little temperature sensitivity ($E_a \sim 0.2$ eV)
   - Tends to saturate

Correlates with appearance of shallow groove and small pits
   - On S and D side (bigger on D side)
   - Groove/small pits appear for $V_{\text{stress}} < V_{\text{crit}}$
2. Current-collapse degradation (trapping)

- Slower
- Enhanced by temperature, electric field
- Tends to saturate for very long times

Correlates with *pit growth*:
- Pits randomly located on drain side
- Pits grow with $V_{\text{stress}}$, time and temperature
- Pits eventually merge

Dominant trap created by stress already present in virgin sample, $E_a=0.56$ eV

*Joh, IRPS 2011*
Summary of electrical and structural degradation

3. $I_{D_{\text{max}}}$, $R_D$ degradation
   - Much slower
   - Temperature activated ($E_a \sim 1 \text{ eV}$)
   - Electric-field driven
   - Does not saturate

Correlates with geometry of pits and trench
   - Pits grow larger and merge into trench
   - Trench grows deeper
Initial hypothesis: Inverse Piezoelectric Effect Mechanism

Defects:
- Trap electrons
  - $n_s \downarrow \rightarrow R_D \uparrow, I_D \downarrow$
- Strain relaxation
  - $I_D \downarrow$
- Provide paths for $I_G$
  - $I_G \uparrow$

Strong piezoelectricity in AlGaN
$\rightarrow |V_{DG}| \uparrow \rightarrow$ tensile stress $\uparrow$
$\rightarrow$ crystallographic defects beyond critical elastic energy

Joh, IEDM 2006
Joh, IEDM 2007
Joh, MR 2010b
Model for critical voltage

$V_{GS} = -5\, \text{V}, \quad V_{DS} = 33\, \text{V}$

16nm 28% AlGaN

\[ T_1 = \left( C_{11} + C_{12} - 2\frac{C_{13}^2}{C_{33}} \right) S_{10} + \left( \frac{C_{13} e_{33}}{C_{33}} - e_{31} \right) E_3 \]

Mismatch stress

Inverse piezoelectric stress

\[ W = \frac{C_{33}}{C_{11} C_{33} - 2C_{13}^2 + C_{12} C_{33}} T_1^2 \]

\[ \propto (T_{10} + aE_3)^2 \]

Joh, MR 2010
Predictions of Inverse Piezoelectric Effect model borne out by experiments

To enhance GaN HEMT reliability:

• Reduce AlN composition of AlGaN barrier (Jimenez, ESREF 2011)
• Thin down AlGaN barrier (Lee, EL 2005)
• Use thicker GaN cap (Ivo, IRPS 2009; Jimenez, ESREF 2011)
• Use InAlN barrier (Jimenez, ESREF 2011)
• Use AlGaN buffer (Joh, IEDM 2006; Ivo, MR 2011)
• Electric field management at drain end of gate (many)

Can’t explain:

• Groove formation/$I_G$ degradation below critical voltage
• Presence of oxygen in groove/pit
• Role of atmosphere during stress
• Role of surface chemistry
$I_G$ degradation for $V_{\text{stress}} < V_{\text{crit}}$

- Sudden irreversible increase in $I_G$, enhanced by $V_{\text{stress}}$
- No reported $I_D$ degradation
- Preceded by onset of $I_G$ noise
- Weakly temperature enhanced ($E_a=0.12$ eV)

$V_{\text{crit}}=75$ V

Meneghini, IEDM 2011

Marcon, IEDM 2010
\( I_G \) degradation correlates with electroluminescence hot spots

- Gate current electrons produce EL in GaN substrate
- EL spots tend to merge into a continuous line

Zanoni, EDL 2009
Meneghini, IEDM 2011
EL hot spots correlate with pits, pits are conducting

Montes Bajo, APL 2012

Shallow pits and groove responsible for $I_G$ degradation
Pits/Groove increase mechanical stress

Pit/groove increases mechanical stress due to inverse piezoelectric effect at drain end of gate

- 2 nm x 3 nm groove increases mechanical stress in AlGaN from 4.6 GPa to 13 GPa
- Groove has little effect in current underneath
- Pit formation brings major loss of current

Ancona, JAP 2012
Oxygen inside pit

- O, Si, C found inside pit
- Anodization mechanism for pit formation? (Smith, ECST 2009)
- Electrical stress experiments under N₂ inconclusive

Park, MR 2009

Conway, Mantech 2007
Role of atmosphere on structural degradation

Off-state stress: $V_{ds} = 43$ V, $V_{gs} = -7$ V for 3000 s in dark at RT

Stressed in ambient air
$\Delta I_D = 5.0\%$

Stressed in vacuum of $10^{-7}$ Torr
$\Delta I_D = 0.5\%$

Surface pitting significantly reduced in vacuum

Gao, TED 2014
Impact of Moisture on Surface Pitting

Off-state stress:
V_{ds} = 43 \text{ V}, \ V_{gs} = -7 \text{ V} 
for 3000 \text{ s in dark at RT}

Stressed in water-saturated gas (Ar)
\Delta I_D = 28.8\%

Stressed in dry gas (Ar)
\Delta I_D = 0.3\%

Gao, TED 2014

- Moisture enhances surface pitting
- Results reproduced with dry/wet O_2, N_2, CO_2 and air
New hypothesis: AlGaN corrosion at edge of gate

- Reduction of water:
  \[ 2H_2O + 2e^- \leftrightarrow 2OH^- + H_2 \]

- Anodic oxidation of AlGaN:
  \[ 2Al_xGa_{1-x}N + 6h^+ \leftrightarrow 2xAl^{3+} + 2(1-x)Ga^{3+} + N_2 \]
  \[ 2xAl^{3+} + 2(1-x)Ga^{3+} + 6OH^- \leftrightarrow xAl_2O_3 + (1-x)Ga_2O_3 + 3H_2O \]

- Complete redox electrochemical reaction:
  \[ 2Al_xGa_{1-x}N + 3H_2O \leftrightarrow xAl_2O_3 + (1-x)Ga_2O_3 + N_2 + H_2 \]
Source of holes: trap-assisted tunneling

High electric field under gate edge
→ Trap-assisted BTBT electron tunneling
→ hole generation at AlGaN surface
Source of water: diffusion through SiN

- Water-vapor transmission rate (WVTR) through 100 nm of PECVD SiN:
  \[ 0.01 \text{~to~} 0.1 \text{ g/m}^2\text{/day} \]

- Gao’s estimate of necessary WVTR to cause pits:
  \[ 0.05 \text{~to~} 0.1 \text{ g/m}^2\text{/day} \]

Gao, TED 2014
Tentative new model for GaN HEMT electrical degradation

**Step 1**: formation of shallow pits/continuous groove in cap
- Pits/groove conducting: $I_G \uparrow$

**Step 2**: growth of pits through anodic oxidation of AlGaN
- $I_{D_{max}} \downarrow$ as electron concentration under gate edge reduced
- $CC \uparrow$ due to new traps

Exponential dependence of tunneling current on electric field

→ “critical voltage” behavior
1. **Reduce hole production**
   - **Mitigate electric field at gate edge:**
     - gate edge design
     - field plate design
   - **Mitigate traps in AlGaN:**
     - optimize growth conditions
     - reduce AlN composition
     - thin down AlGaN
     - mitigate mechanical stress

2. **Reduce water around gate edge**
   1. Reduce SiN permeability
   2. Mitigate trapped moisture during process
   3. Hermetic package
Many questions...

• $I_G$ degradation:
  – Detailed physics of onset of pits/groove? Also of electrochemical nature?
  – Why weak temperature activation?
  – Why does $I_G$ degradation saturate?
  – Detailed mechanism for electrical conduction of pits?

• Trap formation:
  – Why traps introduced during degradation have similar dynamic signature as virgin traps?

• Mechanical stress:
  – Does mechanical stress and inverse piezoelectric effect still play role in degradation?

• Large variability in reliability:
  – Why? Also need effective screening process for virgin devices

• High-power RF stress
  – Is there a pulsed stress mode that faithfully emulates high-power RF stress?