Time Evolution of Electrical Degradation under High-Voltage Stress in GaN HEMTs

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Purpose

• GaN HEMT Reliability: big concern
  – RF power degradation
  – $I_D \downarrow$, $R_D \uparrow$, $I_G \uparrow$, $\Delta V_T$...
• Goal: understand degradation mechanism

RF stress
10 GHz, $V_D=28$ V
$I_DQ=150$ mA/mm
$P_{in}=23$ dBm
$P_{out}=33.7$ dBm
Outline

• Background
• Project goal
• Experimental
  – Procedure
  – Results
• Discussion
• Conclusions
ID, RD, and IG start to degrade beyond critical voltage ($V_{\text{crit}}$) (+ trapping behavior – current collapse) Common physical origin in $I_D$ and $I_G$ degradation

$I_D$, $R_D$, and $I_G$ start to degrade beyond critical voltage ($V_{\text{crit}}$) (+ trapping behavior – current collapse)

Common physical origin in $I_D$ and $I_G$ degradation
Structural Degradation

1. $V_{\text{stress}} \approx V_{\text{crit}}$:
   Groove formation in GaN cap

2. $V_{\text{stress}} > V_{\text{crit}}$:
   Pit formation in AlGaN barrier

3. $V_{\text{stress}} \gg V_{\text{crit}}$:
   Pit growth (to AlGaN/GaN interface) and merge + crack formation

Cross-section

Plan-view

Joh, MR 2010

Makaram, APL 2010
Trapping vs. Permanent

13 % permanent degradation + 15 % trapping degradation
Project Goal

- Investigate **time evolution** of degradation and correlate with **structural degradation**
**Experimental Procedure**

1. **START**
2. **Detrapping**
   - Detrapping step to flush trapped electrons quickly
3. **Full Characterization (DC, CC)**
   - **T_{base} = 30°C**
   - Benign device characterization:
     - Full $I_D$-$V_{DS}$, $I_D$-$V_{GS}$ curves
     - $I_D$ transient measurement: current collapse, detrapping time constant
4. **Electrical Stress**
   - $T_{stress}$
   - Performed at 30 °C
5. **End?**
   - NO
     - **END: detrapping + Full characterization**
   - YES
     - **YES**
       - Stress conditions:
         - OFF-state: $V_{DS} = 40$ V, $V_{GS} = -7$ V
         - $T_{stress} = 75–200$ °C
Gate Current and $V_T$

- Very fast $I_{Goff}$ and $V_T$ degradation (<10 ms)
  - E-field driven oxide punch-through? Electrochemical etching?
- Degradation saturates after $10^4$ s.
After electrical stress:
Permanent degradation + trapping related degradation

CC = \frac{\text{uncol. } I_{\text{Dlin}} - \text{col. } I_{\text{Dlin}}}{\text{uncollapsed } I_{\text{Dlin}}}

- trapping pulse (1 s \( V_{\text{GS}} = -10 \) V, \( V_{\text{DS}} = 0 \) V)

\( @ t = 0^- \)

stress time = 0-1 s

uncollapsed \( I_{\text{Dlin}} \) (fresh)

permanent degradation

uncollapsed \( I_{\text{Dlin}} \) (stressed)

current collapse:
trapping degradation

collapsed \( I_{\text{Dlin}} \) (stressed)

After 10ks

10/20
• Sharp increase in DP1 ($E_a=0.56$ eV) + long time constant slow traps beyond incubation time.
Drain Current Degradation

Stress: $V_{GS}=-7$ V and $V_{DS}=40$ V
125 °C

For current collapse and permanent $I_{Dmax}$ degradation, incubation time is observed.

$CC = \frac{\text{uncol. } I_{Dlin} - \text{col. } I_{Dlin}}{\text{uncollapsed } I_{Dlin}}$
Temperature Dependence: $I_G$

- Weak temperature dependence

Stress:
$V_{GS} = -7 \, \text{V}$ and $V_{DS} = 40 \, \text{V}$

Normalized $|I_{Goff}|$ vs. Stress Time (s)

- 125 °C
- 75 °C
- 150 °C
- 100 °C
Temperature Dependence: $V_T$

- No dependence during initial negative $V_T$ shift
- Positive turn-around seems to occur earlier at high $T$
Permanent $I_{Dmax}$ Degradation

- Shorter incubation time at high $T$
- No saturation behavior up to $>10^5$ s

Stress:
$V_{GS}=-7$ V and $V_{DS}=40$ V

Graph showing degradation of $I_{Dmax}$ with stress time at different temperatures ($75^\circ C$, $100^\circ C$, $125^\circ C$, $150^\circ C$).
Current Collapse

- $V_{GS} = -7 \, V$ and $V_{DS} = 40 \, V$

- Shorter incubation time at high $T$
- More degradation at high $T$
Temperature Acceleration of Incubation Time

- Different level of temperature acceleration for incubation time.
- $E_a$ for permanent $I_{D_{max}}$ degradation is similar to life test data*.

* Saunier, DRC 2007; Meneghesso, IJMWT 2010
Discussion: Time Evolution of Structural Degradation

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

- Very fast groove formation (10 s) on gate edge.  
  → Related to gate current degradation
- Pit density/size gradually increase with time.
Electrical vs. Structural Degradation

Similar time dependence in current collapse and pit formation.
Conclusion

• Investigated time evolution of electrical degradation in GaN HEMTs
  • Fast $I_G$ degradation ~ 10-100 ms
    – Weak temperature dependence
    – Oxide punch through / groove formation?
  • Current collapse degradation ~ 10-100 s
    – Related to pit formation
  • Permanent $I_D$ degradation >100 s
    – Strong thermal activation ($E_a = 1.1$ eV)