Temperature-accelerated Degradation of GaN HEMTs under High-power Stress: Activation Energy of Drain Current Degradation

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Outline

1. Motivation
2. High-power and high-temperature stress experiments
3. An improved approach
4. Conclusions
Motivation

- Activation energy, $E_a$: essential in predicting lifetime
- Conventionally: high temperature accelerated life test

N. Malbert, IRPS 2010
Motivation

- Activation energy, $E_a$: essential in predicting lifetime
- Conventionally: high temperature accelerated life test

Problems:
- Requires multiple devices
- Carrier trapping not properly dealt with
- Different degradation mechanisms can emerge at different temperatures

N. Malbert, IRPS 2010
Motivation

• Activation energy, $E_a$:
  essential in predicting lifetime
• Conventionally:
  high temperature accelerated life test

Desirable: $E_a$ extraction from measurements on a *single device*

Step-temperature stress

N. Malbert, IRPS 2010
Outline

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Setup for DC reliability studies

Devices: Prototype GaN Power Amplifier MMIC from industry

Accel-RF AARTS RF10000-4/S system

Augmented with:
- external instrumentation for DC/pulsed characterization
- software to control external instrumentation and extract DC FOMs
High-power DC Experiment Flowchart

- **Detrapping**: $T_{\text{base}} = 250 \, ^\circ\text{C}$ for 7.5 hours
- **Full characterization**
  - At $T_{\text{base}} = 50 \, ^\circ\text{C}$
  - Full DC I-V sweep
  - Current collapse

Start → Detrapping → Full Characterization → DC and Temperature Stress → Short Characterization (DC) → End: detrapping + full characterization
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- **Full characterization**
  - At $T_{\text{base}} = 50 \, ^\circ\text{C}$
  - Full DC I-V sweep
  - Current collapse
- **Stress:**
  - High-power condition
  - Base temperature stepped up
- **Short characterization**
  - Every 30 minutes at $T_{\text{base}} = 50 \, ^\circ\text{C}$
  - DC FOMs: $I_{\text{Dmax}}, I_{\text{Goff}}, R_D, R_S, V_T,$ ...
High-power DC Experiment Flowchart

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Start

Detrapping

Full Characterization

DC and Temperature Stress

Short Characterization (DC)

End: detrapping + full characterization
## Definitions of Various Figures of Merit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$I_{D\text{max}}$</td>
<td>$I_D$ at $V_{GS}=2$ V, $V_{DS}=5$ V</td>
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<tr>
<td>$I_{G\text{off}}$</td>
<td>$I_G$ at $V_{GS}=-5$ V, $V_{DS}=0.1$ V</td>
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<tr>
<td>$R_D$</td>
<td>Drain resistance measured with $I_G = 20$ mA/mm</td>
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<tr>
<td>$R_S$</td>
<td>Source resistance measured with $I_G = 20$ mA/mm</td>
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<td>$V_T$</td>
<td>$V_{GS} - 0.5V_{DS}$ when $I_D = 1$ mA/mm at $V_{DS} = 0.1$ V</td>
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<tr>
<td><strong>Current Collapse</strong></td>
<td>Percentage change in $I_{D\text{max}}$ after 1 sec. $V_{DS} = 0$ V,</td>
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<td></td>
<td>$V_{GS} = -10$ V pulse</td>
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</table>
High-power DC Experiment

High-power stress: $V_{DS} = 40$ V, $I_D = 100$ mA/mm, $T_{base} = 50^\circ C – 230^\circ C$, 600 min/step

- outer loop data

![Graph showing $I_{Goff}$ vs. time with temperatures: 50, 120, 140, 160, 180, 190, 200, 210, 220°C.]

- outer loop data

![Graph showing $I_{Dmax}/I_{Dmax}(0)$ vs. time with temperatures: 50, 120, 140, 160, 180, 190, 200, 210, 220°C.]

$T_{base}(^\circ C) = 220$
High-power DC Experiment

High-power stress: \( V_{DS} = 40 \, V, \, I_D = 100 \, mA/mm, \, T_{base} = 50 \, ^\circ C – 230 \, ^\circ C, \, 600 \, min/step \)

- \( |I_{Goff}| \) increases from \( T_{base} = 170 \) to \( 190 \, ^\circ C \); then saturates
- Significant \( I_{Dmax} \) degradation for \( T_{base} > 180 \, ^\circ C \)
- Thermally activated \( I_{Dmax} \) degradation rate shown
High-power DC Experiment

High-power stress: \(V_{DS} = 40\) V, \(I_D = 100\) mA/mm, \(T_{base} = 50\) °C – 230 °C, 600 min/step

- \(R_D\) increases significantly, consistent with \(I_{D\text{max}}\) decrease
- \(R_S\) increases much less
Activation Energies of Degradation Rates

**Inner loop data**

- $R_b$: $E_a = 1.00$ eV
- $I_{D_{max}}$: $E_a = 0.58$ eV

**Outer loop data (device detrapped)**

- $R_b$: $E_a = 0.91$ eV
- $I_{D_{max}}$: $E_a = 0.94$ eV

$T_{\text{channel}}$ obtained from thermal model of MMICs
**Activation Energies of Degradation Rates**

- Inner loop data:
  - \( I_{D_{\text{max}}} : E_a = 0.58 \text{ eV} \)
  - \( R_D : E_a = 1.00 \text{ eV} \)

- Outer loop data (device detrapped):
  - \( I_{D_{\text{max}}} : E_a = 0.94 \text{ eV} \)
  - \( R_D : E_a = 0.91 \text{ eV} \)

\[ \ln\left(\frac{1}{|\text{slope}|}\right) = \frac{1}{kT_{\text{channel}}} (\text{eV}^{-1}) \]

\( T_{\text{channel}} \) obtained from thermal model of MMICs

- Inner loop data:
  Large difference between \( E_a \) for \( I_{D_{\text{max}}} \) and \( R_D \)
Activation Energies of Degradation Rates

- Inner loop data:
  
  Large difference between $E_a$ for $I_{D_{max}}$ and $R_D$

- Outer loop data:
  
  Thermally activated behavior

$T_{channel}$ obtained from thermal model of MMICs
**Activation Energies of Degradation Rates**

- **Inner loop data:**
  
  Large difference between $E_a$ for $I_{D_{\text{max}}}$ and $R_D$

- **Outer loop data:**
  
  Close $E_a$ values for $I_{D_{\text{max}}}$ and $R_D$ $\Rightarrow$ common physical origin

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- $R_D$: $E_a = 1.00$ eV
- $I_{D_{\text{max}}}$: $E_a = 0.58$ eV
- $R_D$: $E_a = 0.91$ eV
- $I_{D_{\text{max}}}$: $E_a = 0.94$ eV

$T_{\text{channel}}$ obtained from thermal model of MMICs
Conclusions Drawn from the Experiment

• $I_G$ degradation:
  - Increases fast at first
  - Eventually saturates

• $I_D$ degradation:
  - Significant degradation only after $I_G$ degradation is saturated
  - Thermally activated

\[ T_{\text{base}} (\degree C) = 220 \]
Conclusions Drawn from the Experiment

- $I_G$ degradation:
  - Increases fast at first
  - Eventually saturates

- $I_D$ degradation:
  - Significant degradation only after $I_G$ degradation is saturated
  - Thermally activated

- Desirable: separate $I_G$ and $I_D$ degradation
- Key idea: short stress to degrade $I_G$ without $I_D$ degradation, then long stress to degrade $I_D$
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1. Motivation
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DC Experiment : Improved Approach

» **Phase 1**: degrade $I_G$ without significant $I_D$ degradation

• Short stress period
  
  o $T_{\text{base}} = 50$–$220$ °C, in $20$ °C steps
  
  o Stress time: 6 minutes
Phase 1: degrade $I_G$ without significant $I_D$ degradation

- Short stress period
  - $T_{\text{base}} = 50-220 \, ^\circ\text{C}$, in 20 °C steps
  - Stress time: 6 minutes

Phase 2: degrade $I_D$ without further $I_G$ degradation

- Longer stress period
  - $T_{\text{base}}$: from 120 °C, increase in steps
  - Stress time: 24 hours
A Typical Experiment (Phase 2)

High-power stress: $V_{DS} = 40$ V, $I_D = 100$ mA/mm, $T_{base} = 120 \degree C - 215 \degree C$, 24 hours/step

During phase 1:

$|I_{Goff}|$ increases by 2 orders of magnitude; $I_{Dmax}$ decreases by 3%
A Typical Experiment (Phase 2)

High-power stress: $V_{DS} = 40\, V$, $I_D = 100\, mA/mm$, $T_{base} = 120\, ^\circ C - 215\, ^\circ C$, 24 hours/step

During phase 1:
- $|I_{Goff}|$ increases by 2 orders of magnitude; $I_{Dmax}$ decreases by 3%

During phase 2:
- $|I_{Goff}|$ stays at saturated level ($\sim 0.5\, mA/mm$)
- $I_{Dmax}$ degradation shows thermally activated characteristics
Activation Energies of Degradation Rates

$\ln(1/\text{slope}) = 1/kT_{\text{channel}}$ (eV$^{-1}$)

- $R_D$: $E_a = 0.84$ eV
- $I_{D_{\text{max}}}$: $E_a = 1.04$ eV

Outer loop data (long detrapping)
Activation Energies of Degradation Rates

$E_a$ for $I_{D_{\text{max}}}$ close to values reported on similar technologies in conventional long term experiments

$R_D$: $E_a = 0.84$ eV

$I_{D_{\text{max}}}$: $E_a = 1.04$ eV
# Activation Energy for Drain Current Degradation from Literature

<table>
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<tr>
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<th>Bias conditions</th>
<th>Temperature range</th>
<th>Activation energy $E_a$</th>
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<tbody>
<tr>
<td>S. Singhal, et al. IRPS 2006</td>
<td>$V_{DS}=28$ V</td>
<td>$T_j=260, 285, 310 , ^\circ C$</td>
<td>1.7 eV</td>
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<tr>
<td></td>
<td>$I_{DS}=64$ mA/mm</td>
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<tr>
<td>P. Saunier, et al. DRC 2007</td>
<td>$V_{DS}=40$ V</td>
<td>$T_j=260, 290, 320 , ^\circ C$</td>
<td>1.05 eV</td>
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<tr>
<td></td>
<td>$I_{DS}=250$ mA/mm</td>
<td></td>
<td></td>
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<tr>
<td>E. Zanoni, et al. Microwave</td>
<td>$V_{DS}=40$ V</td>
<td>$T_j=200, 245, 293 , ^\circ C$</td>
<td>0.68 eV - 1.58 eV</td>
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<tr>
<td>Integrated Circuits Conference 2009</td>
<td>$I_{DS}=167$ mA/mm</td>
<td></td>
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<tr>
<td>N. Malbert, et al. IRPS 2010</td>
<td>$V_{DS}=25$ V</td>
<td>$T_j=150, 175, 275,$</td>
<td>0.8 eV – 1.2 eV</td>
</tr>
<tr>
<td></td>
<td>$I_{DS}=417$ mA/mm</td>
<td>$320 , ^\circ C$</td>
<td></td>
</tr>
<tr>
<td>J. Joh, et al. IRPS 2011</td>
<td>$V_{DS}=40$ V</td>
<td>$T_j=75, 100, 125,$</td>
<td>1.12 eV</td>
</tr>
<tr>
<td></td>
<td>$V_{GS}=-7$ V</td>
<td>$150 , ^\circ C$</td>
<td></td>
</tr>
<tr>
<td>This work</td>
<td>$V_{DS}=40$ V</td>
<td>$T_j=223, 249, 269,$</td>
<td>1.04 eV</td>
</tr>
<tr>
<td></td>
<td>$I_{DS}=100$ mA/mm</td>
<td>$289, 296, 302 , ^\circ C$</td>
<td></td>
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</table>
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Conclusions

• Two-phase experiment: separates $I_G$ and $I_D$ degradation in GaN HEMTs under high-power and high-temperature stress

• Two mechanisms exist:
  - $I_G$ degrades first and eventually saturates
  - $I_D$ degrades after $I_G$ degradation is saturated

• Demonstrated new technique to extract $E_a$ from measurements on a single device

• $E_a$ for permanent $I_{D_{\text{max}}}$ degradation rate: 0.95-1.05 eV