Total current collapse in High-Voltage GaN MIS-HEMTs induced by Zener trapping

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Current collapse or dynamic ON-resistance in GaN FETs

- $R_{ON}$ depends on device history $\rightarrow$ After high $V_{OFF}$, $R_{ON}$ $\uparrow\uparrow$
- Big problem in power switching applications
Multi field-plate (FP) technology

Key challenge for current collapse↓↓↓:
Engineering electric-field profile at high-V in the gate-to-drain gap of GaN MIS-HEMTs (Metal-Insulator-Semiconductor High-Electron-Mobility Transistors)

→ Multi field-plate technology developed
Multi field-plate (FP) technology

- In high-V OFF-state,
  - Non-FP → intense E-field peak → current collapse ↑↑
Multi field-plate (FP) technology

- In high-V OFF-state,
  - **Non-FP** → intense E-field peak → *current collapse* ↑↑
  - **Multi-FP** → depletion region extension and E-field peak ↓↓
  - *Effectiveness in current collapse?*

**Diagram:***
- **Non-FP**:
  - $V_G < V_T$
  - High-V
  - AIGaN
  - GaN
  - E-field

- **Multi-FP**:
  - $V_G < V_T$
  - High-V
  - AIGaN
  - GaN
  - E-field

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Current collapse at high $V_{OFF}$

GaN MIS-HEMTs with multi-FP (FP1,2,3):

- OFF-state step-stress with $V_{DS} \uparrow$
- Monitor $I_{Dlin}$ (equivalent to $R_{ON}$)

![Diagram showing voltage levels and time intervals](image)
Current collapse at high $V_{OFF}$

GaN MIS-HEMTs with multi-FP (FP1,2,3):

- OFF-state step-stress with $V_{DS} \uparrow$
- Monitor $I_{Dlin}$ (equivalent to $R_{ON}$)

![Diagram showing current collapse and stress characterization](image)

- Total current collapse for $V_{DS} > 300$ V
- $R_{ON} \uparrow \uparrow$ by $> 10^{10}$ by $V_{DS} = 720$ V
Questions to answer

• Is current collapse recoverable?
• Where in the device does this happen?
• What are the dynamics of this process?
• What is the mechanism responsible?
• How to mitigate/eliminate?
Current collapse recovery?

- 6 consecutive measurements
- UV exposure + thermal treatment (180 min at 200 °C) in between

**Current collapse fully recoverable → trapping!**
Lateral extent of current blockage?

Change in output characteristics after $V_{DS}=300$ V stress for 300 s:

Current collapse for low $V_{DS}$ but $I_D$ flows again at high $V_{DS}$
→ punchthrough-like characteristics
→ current blockage is short along channel direction
Evolution of subthreshold characteristics and 4 terminal currents:

Change in $V_T$ and terminal currents?

- No change in $V_T \rightarrow$ current blockage in extrinsic device region
- At the onset of severe trapping, all currents are negligible
Impact of device geometry?

Current collapse independent of $L_{GD}$ and geometry of field-plates
Current blockage location?

Capacitance-voltage characteristics of virgin device:

Channel under field plates fully depleted by $V_{DS} = 50$ V

→ For $V_{DS} > 50$ V, electric field peaks in channel under edge of FP3
→ Current blockage under edge of FP3
Role of temperature?

OFF-state step-stress at different T:

- Terminal currents $\uparrow \uparrow$ as $T \uparrow$ → Not source of trapping
- Total current collapse independent of $T$ → Trapping through tunneling process
Dynamics of trapping

Evolution of $I_{\text{Dlin}}$ during trapping process:

- Trapping accelerated as $V_{\text{DS\_stress}}$ ↑
- Characteristic trapping time exhibits Zener-like dependence on peak electric field under FP3 edge (from simulations)

Zener tunneling law:

$$\ln(\tau) = A \frac{(E_T - E_V)^{3/2}}{E_{\text{PEAK}}} + B$$

$E_T - E_V \approx 1 \text{ eV}$
Dynamics of thermal detrapping

Evolution of $I_{\text{Dlin}}$ during detrapping at different temperatures:

- Detrapping accelerated as $T \uparrow$
- Activation energy: $E_A = 0.63$ eV
Dynamics of UV-enhanced detrapping

Evolution of $I_{Dlin}$ during detrapping under UV exposure (300K):

OFF-state stress: $V_{DS, stress} = 300$ V, $t=3$ min

Detrapping accelerated by UV with $E_{hv} > 2.8$ eV
Electric field simulations

Silvaco simulations of electric field at top surface of AlGaN barrier from gate to drain:

- In OFF-state for \( V_{DS} > 100 \) V, field peaks under edge of FP3
- \( E_{PEAK} \) increases with \( V_{DS} \)
- At \( V_{DS} = 200 \) V, \( E_{PEAK} = 3.4 \) MV/cm
Summary of key findings

• Total current collapse after high $V_{OFF}$ bias:
  – Fully recoverable
  – Triggered and accelerated by electric field
  – Follows Zener-like dependence with $E_T - E_V = 1.0$ eV
  – Trapped region very short and located under FP3 edge
  – No effect from variations of $L_{GD}$ and FPs lengths
  – Temperature independent trapping process
  – Detrapping enhanced by UV with $E_{hv} > 2.8$ eV
  – Detrapping enhanced by temperature with $E_A = 0.63$ eV
Mechanism for total current collapse

Observations consistent with:
• Field-induced trapping process → Zener trapping
• Takes place in narrow region under edge of FP3
• Electrons from valence band tunnel to traps
• Trapped electrons lift bands in ON state and create blockage

**At high-**$V_{OFF}$**

**After high-**$V_{OFF}$
Energy location of traps?

- From Zener trapping calculations: $E_T - E_V \approx 1.0 \text{ eV}$
- From UV detrapping experiments: $E_{hv} \approx 2.8 \text{ eV}$
- For reference: $E_g(\text{GaN}) = 3.4 \text{ eV}$, $E_g(\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}) = 3.8 \text{ eV}$
Thermal detrapping with $E_A = 0.63 \text{ eV}$?

Thermal detrapping $E_a = 0.63 \text{ eV}$ seems inconsistent with energy picture...

If blockage region is short, thermal detrapping possible with $E < E_C - E_T$
Physical origin of traps?

- Trap energy consistent with traps responsible for yellow luminescence in AlGaN and GaN.
  - In GaN: $E_C - E_{YB} = 2.5$ eV (Calleja, PRB 1997)
  - In Al$_{0.2}$Ga$_{0.8}$N: $E_C - E_{YB} = 2.8$ eV (Hang, JAP 2001)
- Yellow luminescence traps attributed to C in N site (Lyons, APL 2010)

Mitigation: carefully manage C doping in buffer and migration to AlGaN barrier
Conclusions

• Total current collapse in high-voltage GaN MIS-HEMTs
  – Current collapse is recoverable
  – Attributed to Zener trapping in AlGaN barrier or GaN channel under edge of outermost field plate
  – Traps are consistent with those responsible for yellow luminescence in GaN and AlGaN
  – Main suspect: C

• Attention to defect control during epitaxial growth and appropriate design of multi field-plate structures