Electrical Degradation of InAlAs/InGaAs Metamorphic High-Electron Mobility Mobility Transistors

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Outline

• Introduction
• Electrical Degradation of mHEMTs
• Degradation of TLMs
• Degradation Mechanisms
Metamorphic HEMT: InP HEMT on GaAs Substrate

\[ L_g = 0.125 \, \mu m, \, f_T = 150 \, GHz, \, g_m = 1.05 \, S/mm, \, BV_{DG,off} = 4.8 \, V \]
Electrical Degradation of InAlAs/InGaAs mHEMTs

Little known about reliability of mHEMTs

Observations in InP HEMTs:
- Change in $R_D$ [Wakita et al]
- Change in $R_D$ and $R_S$ [Suemitsu et al]
- Change in $V_T$ [Christianson et al]

Linked to:
- Impact ionization [Rohdin et al]
- Hot electrons [Menozzi et al]

No systematic studies of InP HEMT electrical reliability
Effects of Electrical Stress

Stress at $V_{DS} = 1.5 \text{ V}$ and $I_D = 250 \text{ mA/mm}$ for 12 hours

Main effects of bias stress:
• Increase in $R_{DS}$
• Decrease in $I_D$
• Decrease in $g_m$ and $f_T$

Most Worrying
The degradation of $R_D$ is most important, irreversible, initially very fast, and tends to saturate.

Stress at $V_{DG0} + V_T = 1.6\, \text{V}$ and $V_{GS} - V_T = 0.3\, \text{V}$

The degradation of $R_D$:
- is most important
- is irreversible
- is initially very fast
- tends to saturate
Studied several bias stress schemes:

• Constant $V_{DS}$ & constant $V_{GS}$
• Constant $I_D$ & constant $I_G$
  - Device characteristics change $\rightarrow$ bias point changes

• Constant $V_{DG0}$ & constant $I_D$
  - Different devices, different degradation

• Constant $I_D$ & constant $V_{DG0} + V_T$
• Constant $V_{GS} - V_T$ & constant $V_{DG0} + V_T$
  - Reproducible degradation
  - Keep impact-ionization constant
$R_D$ Degradation Associated with Impact-Ionization?

Impact-ionization rate $\propto I_D \exp\left(-\frac{A}{V_{DGO}+V_T}\right)$

$V_{DGO}+V_T = 1.65$ V

$I_D$ =
- 450 mA/mm
- 400 mA/mm
- 350 mA/mm
- 300 mA/mm
- 150 mA/mm

Higher impact-ionization $\rightarrow$ Higher degradation
Impact-ionization behind $R_D$ degradation

Impact-ionization rate $\propto I_D \exp\left(-\frac{A}{V_{DG0} + V_T}\right)$

Degradation rate follows classical impact-ionization behavior
Other Drain-Related Figures of Merit Change

Both $BVDG_{off}$ and $R_D$ depend on $n_s$ on drain side

Drop in $n_s$ probable cause of degradation

$C_{dg}$ also degrades
Step-Stress Experiments

Improved experimental productivity

2 Degradation mechanisms can be identified
Simpler Case: TLMs

Ohmics
Cap
Etch-Stop
Insulator
δ-Doping
Channel
GaAs
Substrate

Integrated TLMs: uniform field in channel

V=3.8 V
L=12 µm

Only two figures of merit: R, I_{sat}

More Stress
Two mechanisms appear:
V<4.5 V R and I_{sat} track each other
V>4.5 V only R increases
Increase of Lateral and Contact Resistance

Mechanism 1: Degradation of $n_s$ → $R_s \uparrow, R_C \uparrow$

Mechanism 2: Degradation of $R_C$ only

$R = R_s + 2R_C$
Field Reversal

Mechanism 1
Independent of stress polarity
Uniform degradation

Mechanism 2
Dependent of stress polarity
Degradation of one ohmic contact
Critical Voltage for Degradation

Threshold of degradation ≈ Threshold of impact-ionization

Degradation exhibits constant-field behavior

\[ V_{\text{critical}} \approx E_{\text{th (InGaAs)}} + 2R_c I_{\text{sat}} \]
Degradation Mechanisms

Mechanism 1

- Occurs at lower voltage
- \( n_s \) drops on drain-side
- Saturates
- Occurs at surface (cap plays a role)
- Correlated with impact-ionization (also temperature)
- Polarity Independent

Mechanism 2

- Occurs at higher voltage
- Drain-ohmic contact degrades
- Does not saturate
- Polarity Dependent
Degradation Mechanisms

Mechanism 1
- Hot electron/hole generation by impact-ionization
- Hot carriers change drain side of device (trapping, recombination-enhanced damage) close to surface

Mechanism 2
- Hot electrons
- Drain-ohmic contact degrades

Nothing specific about metamorphic substrate
Conclusions

• Degradation in mHEMTs correlated with impact-ionization
• Two degradation mechanisms identified
  – Extrinsic drain surface
  – Drain ohmic contact
• No specific degradation mechanism identified specifically associated with metamorphic substrate