Large-Signal Operation of AlGaN/GaN Microwave HFET’s

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Microwave/MM-Wave Power Sources

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Amplifier Fundamentals

Power Delivered to Load

\[ P_L = \frac{1}{2} \text{Re}\{V_L I_L^*\} = \frac{1}{2} |I_L|^2 R_L \]

\[ P_L = P_{out} \left[ 1 - |\Gamma|^2 \right] \]

Maximum Power Transfer Conditions

\[ \Gamma = 0, \quad \text{or when,} \quad Z_L = Z_{out}^* \]
**Semiconductor Parameters and RF Power**

### Materials Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_g$(eV)</th>
<th>$\varepsilon$</th>
<th>$\kappa(W/K\cdot cm)$</th>
<th>$E_c$(MV/cm)</th>
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</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.12</td>
<td>11.9</td>
<td>1.5</td>
<td>0.3</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.43</td>
<td>12.5</td>
<td>0.54</td>
<td>0.4</td>
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<tr>
<td>InP</td>
<td>1.34</td>
<td>12.4</td>
<td>0.67</td>
<td>0.45</td>
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<td>3C-SiC</td>
<td>2.3</td>
<td>9.7</td>
<td>4</td>
<td>1.8</td>
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<tr>
<td>4H-SiC</td>
<td>3.2</td>
<td>10</td>
<td>4</td>
<td>3.5</td>
</tr>
<tr>
<td>6H-SiC</td>
<td>2.86</td>
<td>10</td>
<td>4</td>
<td>3.8</td>
</tr>
<tr>
<td>GaN</td>
<td>3.4</td>
<td>9.5</td>
<td>1.3</td>
<td>2</td>
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<tr>
<td>Diamond</td>
<td>5.6</td>
<td>5.5</td>
<td>20-30</td>
<td>5</td>
</tr>
</tbody>
</table>

**High RF output power requires high RF current and voltage**

Current $\propto$ Electron Velocity  \hspace{1cm} Voltage $\propto$ Breakdown Voltage
4H-SiC MESFET
$L_g = 0.5 \mu m$, $W = 1 \text{mm}$, $V_{ds} = 40\text{v}$

dc I-V Characteristics

Class A RF Performance at 10 GHz

Class A Performance vs. Frequency

$\text{f}_T = 24 \text{ GHz}$

$\text{f}_{\text{max}} = 56 \text{ GHz}$
AlGaN/GaN HFET

**Structure**

- Gate
- Source
- Drain
- Undoped AlGaN
- Highly Doped AlGaN
- Undoped AlGaN
- Undoped GaN
- Substrate

**Energy Band Diagram**

- Gate Metal
- AlGaN-undoped
- GaN-undoped

$\Phi_b$

2DEG Electron Density (~$10^{13}$ cm$^2$)

Where do the electrons come from?

Heterojunction
AlGaN/GaN HFET RF Amplifier Performance*
Tuned for Maximum PAE

*Designed for Maximum RF Output Power
RF Performance vs. $V_{ds}$ for an AlGaN/GaN Class A Amplifier at 10 GHz
AlGaN/GaN HFET

$L_g = 0.2 \, \mu m$, $W = 250 \, \mu m$

$F = 16 \, GHz$, $V_{ds} = 25 \, v$, Class A
AlGaN/GaN HFET Problem Areas

- Undoped AlGaN
- Undoped GaN
- 2DEG
- Surface Traps
- Space-Charge Effect
- Interface Effects
- Charge Dipole Domain
- Substrate (SiC, Sapphire)
Dynamic Load Line for an AlGaN/GaN HFET Amplifier

\[ F = 10 \text{ GHz}, \ P_o = 10 \text{ W/mm}, \ V_{ds} = 40 \text{ v}, \text{ Tuned for Max. PAE} \]
\[ L_g = 0.5 \text{ mm}, \ W = 1 \text{ mm} \]
Real Time Terminal Waveforms for a AlGaN/GaN HFET Tuned for Maximum Class A PAE

\[ V_{ds} \]
\[ V_{gs} \]
\[ I_{ds} \]
\[ I_{gs} \]

RF Gate Current Exceeds RF Drain Current
Source Region Space Charge Effects Under High Injection Conditions

\[ \delta n(0) \quad I = JA \quad \delta n(x) > N_d - n_0 \quad C_{gs} \text{ (Charge Storage)} \]

\[ x = 0 \]
**Space-Charge Effects Under High Injection Conditions**

**Electric Field**

\[
\frac{dE}{dx} = \frac{q}{\varepsilon} \left( N_d - n_0 - \delta n(x) \right) \approx -\frac{q}{\varepsilon} \delta n(x)
\]

\[
E(x) - E_0 = -\frac{q}{\varepsilon} \int_0^x \delta n(x)
\]
Space-Charge Resistance
AlGaN/GaN 2DEG

\( \rho \) vs. J at Various Distances from Source

\( \rho \) vs. Distance from Source for Various J

\( J_{sc} \sim 40 \text{ MA/cm}^2 \)

\( J_{sc} = 40.0 \text{ MA/cm}^2 \) \( J_{sc} = 40.6 \text{ MA/cm}^2 \)
**HFET Current Density**

**Critical Current for Space-Charge Effects**


**Measured:**

*For* $I_{ds}=1.2A$ and $W=1mm$

- $J \sim 50 \text{ MA/cm}^2$

**For Space-Charge Effects in:**

- **2DEG:**
  - $J_{sc} \sim 40 \text{ MA/cm}^2$

- **GaN-outside 2DEG:**
  - $J_{sc} \sim 30 \text{ kA/cm}^2$
Source Region Space Charge Effects Under High Injection Conditions

High Current Portion of Cycle

Electrons forced from 2DEG into GaN

Trapped Electrons Charging/Discharging Time, $\tau$

GaN

AlGaN

2DEG

Vg $(dc+RF)$

$I_s$

Traps

Electrons forced from 2DEG into GaN

Source Region Space Charge Effects Under High Injection Conditions

High Current Portion of Cycle

Electrons forced from 2DEG into GaN

Trapped Electrons Charging/Discharging Time, $\tau$

GaN

AlGaN

2DEG

Vg $(dc+RF)$

$I_s$

Traps

Electrons forced from 2DEG into GaN

Trapped Electrons Charging/Discharging Time, $\tau$

GaN

AlGaN

2DEG

Vg $(dc+RF)$

$I_s$

Traps

Electrons forced from 2DEG into GaN

Trapped Electrons Charging/Discharging Time, $\tau$

GaN

AlGaN

2DEG
**HFET Source Resistance vs. Current Density**

\[ V_{ds} = 8\, \text{v}, \quad V_{gs} = -3.5\, \text{v} \text{ to } +1\, \text{v} \]

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**Equivalent Circuit**

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**Source Resistance vs. Current**

\[
\begin{align*}
R_s & \quad (\text{ohm}) \\
I_s & \quad (\text{A}) \\
\text{Time Step (pS)} & \quad \text{ (x-axis)}
\end{align*}
\]
RF Effects due to Space Charge Resistance at High Injection Conditions in Source Region

Real-Time Waveforms

Large-Signal Simulation
Class A/B Amplifier
Optimum PAE Tuning
Knee ‘Walk Out’ Under RF Drive

RF ‘Knee’ Voltage

Dynamic Load Line

$P_{in1}$

$P_{in2}$

$P_{in3}$

$P_{in3} > P_{in2} > P_{in1}$
High Field Breakdown

• During the high voltage portion of the RF cycle high electric fields are produced, and this can cause breakdown by two separate mechanisms:
  – Breakdown at the gate edge on the drain side by a surface tunnel mechanism
  – RF breakdown in the conducting channel due to high localized field
Conducting Channel Dipole Domain Formation

Linear Region

Saturation Region

\[ I = JA = qnv(aW) \]

\[ I \approx qN_d \mu_n E(aW) \]

\[ n \approx N_d \]

‘a’ decreasing

‘a’ increasing

\[ I = qnv(aW) \]

\[ I = qnv(aW) \]

\[ n > N_d \]

\[ n < N_d \]
Domain Electric Field in the Conducting Channel of a GaAs LDD MESFET (Vds=9 v)

**Surface**

**Mid Channel**

**Channel/Substrate Interface**
Gate Tunnel Leakage to Surface

For Standard FET’s Depletion Region
Primarily Determined By $L_g$
Gate-Surface Tunnel Model

\[ E_g = \frac{q}{\varepsilon f_G L_g} \left[ d_s \int_0^{d_1} N_D(y)dy - \int_0^{d_s} N_{ss}(x)dx \right] \]

\[ n_t = \frac{J_t(E_g)}{q v_s} \]

\[ I_t = f_G L_g W_g J_t(E_g) = I_{tf} - I_{tr} \]
FET Gate Tunnel Leakage Model
Simulated and Measured Data (GaAs MESFET)
Detection of FET Channel Avalanching

Power Spectral Density vs $I_{ds}$ at $V_{gs}=0$ v.

$S_{id}(f) = 4kT_g g_m P$

With Avalanche

$S_{id}(f) = 2qI_p M^3$

$M = \frac{I_D}{I_p}$

Critical Electric Field for Avalanche Ionization in GaN and GaAs*

$E_c \approx (2-4) \times 10^6 \text{ V/cm}$

Field-Plate

Produces a Reduction in E Field at the Gate Edge

- Fixed Positive Charge
- 2DEG Electrons
- Reduced Tunneling Under High Field
- E Field
- Channel Partially Depleted of Electrons Throughout RF Cycle
- Depletion Region \( f(V_{ds} + V_{RF}) \)
- Depletion Region Length Oscillates with RF Voltage

High Drain Voltage Can be Applied
Electric Field vs Field Plate Length

K=65, t=100, Vds=100v

(a) No Field Plate  (b) L_{FP}=0.250\mu m  (c) L_{FP}=0.5\mu m
Electric Field vs Field Plate Length

K=65, t=100, Vds=40v

(a) No Field Plate  (b) L_{FP}=0.250\mu m  (c) L_{FP}=0.5\mu m
Electric Field and Electron Density
Mid Channel for $V_{gs} = 0$ V, Varying $V_{ds}$

Electric field Vs length for different $V_{ds}$
(1nm under the AlGaN/GaN interface, $V_{g}=0V$)

Electron concentration Vs length for different $V_{ds}$
(1nm under the AlGaN/GaN interface, $V_{g}=0V$)
Electric Field and Electron Density
Mid Channel for $V_{gs} = -2$ v, Varying $V_{ds}$

Electric field Vs length for different $V_{ds}$
(1nm under the AlGaN/GaN interface, $V_{g} = -2$V)

Electron concentration Vs length for different $V_{ds}$
(1nm under the AlGaN/GaN interface, $V_{g} = -2$V)
Electric Field and Electron Density
Mid Channel for $V_{gs} = -4$ v, Varying $V_{ds}$

Electrical field Vs length for different $V_{ds}$
(1nm under the AlGaN/GaN interface, $V_g=-4V$)

Electron concentration Vs length for different $V_{ds}$
(1nm under the AlGaN/GaN interface, $V_g=-4V$)
RF Effects due to Domain Breakdown

$\Delta i_{RF}$

$i_{RF}$ with breakdown

$\tau$

$R_L$

$V_{dc}$

$V_{ds}$

$v_{RF}$

RF Breakdown
Domain Breakdown

Channel E Field
Oscillates with RF Signal

Electron Motion
→
Hole motion
←

Breakdown Field

$E_{RF}(t)$

$J_n$ (electron current density)
Charge Generation in Conducting Channel
IMPATT-Mode Operation

Holes recombine with 2DEG electrons increasing source resistance

2DEG

Hole Motion
Generated Holes
Impact Ionization Region (Location in channel depends upon electric field profile)

Electron Motion
Generated Electrons

Depletion Region

$i_{RF} \sim e^{-j\omega\tau}$
IMPATT Diode Operation

![Diagram of IMPATT Diode Operation]

- Generation Region
- Drift Region
- Neutral Region
- $V_{DC}$
- $V_{RF}$
- $V_T$
- $J_{inj}$
- $J_{ind}$

Key Parameters:
- $W_C$
- $Q/A$
- $\omega t$
- $J_{max}$
**S-Type Active Element (Current Controlled)**

\[ v = f(i) \]

\[ v = -b_1i + b_3i^3 + \ldots \]

\[ R_d = \frac{\partial v}{\partial i} = -b_1 + 3b_3i^2 + \ldots \]

\[ jX_d \]

**first order resistance**

\[ Z_d = -R_d + jX_d \quad X_d > 0 \]
Equivalent Circuit & Element Values - LDD GaAs MESFET
High Field Domain Effects

\[ g_m \text{ and } C_{gs} \]

\[ V_{ds} = 3\,\text{v} \quad \text{---} \quad V_{ds} = 9\,\text{v} \]

\[ \text{Delay Time} \]

\[ \text{Resistance, Ohms} \]

\[ \text{Capacitance (pF)} \quad \text{Transconductance (mS)} \]

\[ V_{ds} = 9\,\text{v} \quad \text{---} \quad V_{ds} = 3\,\text{v} \]
Parameter Extraction
LDD Self-Aligned GaAs MESFET
$L_g=0.6 \ \mu m$, $W=600 \ \mu m$
Small-Signal Equivalent Circuit Performance

$V_{ds} = 3 \ \text{v}$

$V_{ds} = 9 \ \text{v}$
GaAs MESFET I-V Characteristics with -R Instability

Negative Resistance (-R) Region
Conclusions

- **AlGaN/GaN HFET’s can produce RF output power an order of magnitude greater than GaAs-based FET’s**
- **However, these devices are currently limited by a variety of physical effects, known by terms such as ‘current slump’, ‘dispersion’, ‘premature gain compression’, ‘gate lag’, etc. These effects become more significant with increasing RF drive**
- **The effects are transient in nature and occur under large-signal RF drive and high current and high voltage conditions**
- **These effects introduce nonlinearities that limit RF performance and dynamic range**
- **The observations are consistent with source resistance modulation due to high injection, space-charge effects, gate tunnel leakage/surface trapping, and RF induced channel breakdown creating an IMPATT type operating mode**
- **The outlook for these devices is excellent and problems can be solved with proper design. They will find use for applications requiring high RF output power.**