Compact Modeling of Intrinsic Capacitance in AlGaN/GaN HEMT Devices

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Motivation

• HEMTs seen as promising candidates for high power, high speed applications

• Available compact models are empirical, numerical or based on simplifying approximations

• Need for physics based compact model providing insight into the device operation
2-DEG Charge Density

- 2DEG formation is the heart of HEMT device operation
- Accurate model for 2DEG charge density is essential for complete compact model
- 2-DEG formation takes place at heterojunction in quantum-well

Ref. Fig. [1]
Basic Device Equations for 2DEG

- Derived from Fermi-Dirac statistics & solution of Schrödinger equation for triangular potential barrier

\[
n_s = DV_{th} \left\{ \ln \left[ \exp \left( \frac{E_f - E_0}{V_{th}} \right) + 1 \right] + \ln \left[ \exp \left( \frac{E_f - E_1}{V_{th}} \right) + 1 \right] \right\}
\]

\[
E_0 = \gamma_0 n_s^{2/3} \quad E_1 = \gamma_1 n_s^{2/3}
\]

- Gauss Law at heterojunction

\[
n_s = \frac{\varepsilon}{qd} \left( V_{go} - E_f \right)
\]

Ref. [1]
2-DEG Charge Density Modeling

• Basic device equations are transcendental in nature

• We divide variation of $n_s$ with $V_g$ into regions to develop fully analytical expression

• Regional models are combined in one analytical expression

• No fitting parameters introduced
Numerical Solution and Regions

- Region I: Sub-V_{off} region
- Region II: $E_f < E_0$ moderate 2-DEG region
- Region III: $E_f > E_0$ strong 2-DEG region
Regional models for $n_s$

- **Sub-Voff model**

$$n_{s,\text{sub-Voff}} = 2DV_{th} \exp\left(\frac{V_{go}}{V_{th}}\right)$$

- **Moderate 2-DEG region model**

$$n_s^{\text{II}} = \frac{C_g V_{go}}{q} \frac{V_{go} + V_{th} \left[1 - \ln(\beta V_{go})\right]}{3} - \frac{\gamma_0}{3} \left(\frac{C_g V_{go}}{q}\right)^{2/3}$$

$$V_{go} + V_{th} + \frac{2\gamma_0}{3} \left(\frac{C_g V_{go}}{q}\right)^{2/3}$$

- **Strong 2-DEG region model**

$$n_s^{\text{III}} = \frac{C_g V_{go}}{q} \frac{V_{go} - \gamma_0}{3} \left(\frac{C_g V_{go}}{q}\right)^{2/3}$$

$$(1 + \beta V_{th}) V_{go} + \frac{2\gamma_0}{3} \left(\frac{C_g V_{go}}{q}\right)^{2/3}$$
GaN HEMT Unified $n_s$ Model

- Regional Models are combined to produce one unified analytical solution
2-DEG Modeling Highlights

- Analytical and Physics-Based
- No empirical/fitting parameters
- Developed for both AlGaN/GaN and AlGaAs/GaAs HEMT devices
- Excellent Model Agreement with Numerical Solutions
Gate-Channel Capacitance Modeling

- Variation in 2-DEG charge with the applied bias

\[ C_{ch} = \frac{dqn_s}{dV_g} \]

\[ C_{ch} = 2V_{th}C_g \left\{ \frac{V_{ge}'}{V_{ge}} \left( G(V_{go}) + \beta V_{th} (V_{ge} - 1) \right) \right\} - 2V_{th}C_g \left\{ \ln(V_{ge}) \left( G'(V_{go}) + \beta V_{th} V_{-ge}' \right) \right\} \]

\[ G(V_{go}) = 1 / H(V_{go}), V_{ge} = 1 + e^{V_{go}/2V_{th}}, V_{-ge} = 1 + e^{-V_{go}/2V_{th}} \]

\[ H(V_{go}) = \frac{V_{go} + V_{th} \left[ 1 - \ln(\beta V_{gon}) \right] - \gamma_0 \left( \frac{C_g V_{go}}{q} \right)^{2/3}}{V_{go} \left( 1 + \frac{V_{th}}{V_{god}} \right) + \frac{2\gamma_0}{3} \left( \frac{C_g V_{go}}{q} \right)^{2/3}} \]
Intrinsic Capacitance Modeling

- $C_{ch}$ gives gate-channel capacitance in all regions of device operation

- $C_{ch}$ is used in conjunction with Meyer capacitance model

- $C_{gs}$ and $C_{gd}$ obtained for all regions of device operation
Intrinsic Capacitance Modeling

- $C_{gs}$ Model

$$C_{gs} = \frac{2}{3} C_{ch} \left[ 1 - \left( \frac{V_{goe} - V_{dse}}{2V_{goe} - V_{dse}} \right)^2 \right]$$

- $C_{gd}$ Model

$$C_{gd} = \frac{2}{3} C_{ch} \left[ 1 - \left( \frac{V_{goe}}{2V_{goe} - V_{dse}} \right)^2 \right]$$
Intrinsic Capacitance Modeling

- Expressions for $V_{goe}$ and $V_{dse}$

\[
V_{goe} = V_{th} \left\{ 1 + \frac{V_{goe}}{2V_{th}} + \sqrt{\frac{\Delta^2}{2V_{th}} + \left(\frac{V_{goe}}{2V_{th}} - 1\right)^2} \right\}
\]

\[
V_{dse} = \frac{1}{2} \left[ V_{ds} + V_{goe} - \sqrt{\left(\frac{V_{ds} - V_{goe}}{\Delta} \right)^2 + \left(\frac{V_{ds} - V_{goe}}{\Delta} \right)^2} \right]
\]

- $\Delta$ and $V_{\Delta}$ defines the width of transition regions
- Along with long-channel approximation all nine non-reciprocal capacitances can be obtained from the model
Result: $C_{gs}$ Model Validation
Result: $C_{gd}$ Model Validation
Conclusions

• Analytical physics-based 2-DEG charge density model presented
• Model has minimal fitting parameters and is valid in all the regions of device operation
• Channel capacitance model derived from 2-DEG charge model
• Model is in excellent agreement with experimental data
• Model can serve as basis for developing a complete physics-based compact model for these devices
References


Thank You for Attention!