Introduction to Large-Signal Modeling of Compound Semiconductor Transistors

Walter R. Curtice, Ph. D.
W. R. Curtice Consulting
53 Commanders Drive
Washington Crossing, PA 18977
walter@curtice.org
Introduction

• Philosophy of Modeling

• Modeling of HEMT Devices

• Modeling of Bipolar Devices
Modeling Considerations

- Device application must be considered when choosing a model and when characterizing a device.
- Pulsed modulated applications require more attention to the time domain behavior than do CW applications.
- Large-signal, nonlinear equivalent circuit models are more useful than behavior models (for trimming model, for scaling model, etc.).
Modeling Considerations

- Modeling accuracy requirements are related to the device application
- The model’s accuracy need not be better than the variation in the device data
- Any given model can always be improved upon, at a price
- All models can be shown to behave non-physically under some operating condition
Modeling Choices

- Range of usefulness?
- Number of model parameters?
- Include self-heating effects?
- Include dispersion effects?
- Include breakdown effects?
- Model useful for statistical analysis?
Types of Large-Signal Transistor Models

- Physical or “Physics-Based” Device Models
  Calibrated Using Data

- Measurement-Based Models:
  - Analytical Models
  - Black Box Models
  - Table-Based

- Artificial Neural Network (ANN) Models

This presentation will only deal with this type!
(Also called SPICE Models)

W. R. Curtice 2008
Angelov Model: an Analytical Example

The model parameters for current are IPK0, P1, Vpk and A plus Rth and temperature coefficients

\[ \text{Ids} = \text{IPK0}*(1 + \text{Tanh}(P1*(Vgs-Vpk)))*\text{Tanh}(A*Vds) \]

W. R. Curtice 2008
Part 1: HEMT Modeling

Characterization and Modeling of GaAs, GaN, SiC and Si LDMOS RF Power Devices

W. R. Curtice 2008
Modeling Pluses

• GaAs, GaN, SiC and Si LDMOS devices are all three terminal devices
• Many large-signal circuit models available for use with these devices
• Many conventional models can be enhanced to be more accurate for a specific device type.
Angelov is the only model here that is electro thermal!

This model has a crude thermal correction term applied

*Agilent Technologies, Inc.

W. R. Curtice 2008
Angelov2 is the only FET model here that is electro thermal!

MET_LDMOS is electro thermal

EEHEMT also here

W. R. Curtice 2008
Other HEMT Model Choices

- EE_HEMT, Materka, Tajima, etc. models can be enhanced to be electro-thermal.
- A new model for large devices is reported by Tajima in Microwave Journal, May 2007.
- C_FET model (Curtice Consulting) is electro-thermal.
- Modified models can be entered into ADS or MWO.
- Verilog-A models may be used with ADS.
Example of Self Heating

GaN $I_d$ vs. $V_d$ for $V_g=0$ V

$V_g$ (V)

$I_d$ (A)

DC
Pulsed

W. R. Curtice 2008
C_FET GaN Chip Model
(W. R. Curtice Consulting)

Temperature monitored here

Typical GaN Model using C_FET8D

New Rds and Cgd Parameters

Vds Voltage For Characterization (10V)

W. R. Curtice 2008
C_FET Model

*GM dispersion
circuit not shown

*Thermal analog
Circuit is critical for
Large periphery devices
Charge-based Capacitance Functions Needed for Cap(Vgs, Vds)

Example of capacitance modeling for a Triquent HEMT

W. R. Curtice 2008
• $Q_{gs}(V_{gs}, V_{ds})$ gives rise to two capacitive current terms
• Likewise, $Q_{gd}(V_{gs}, V_{ds})$ gives rise to two current terms
• One term is the same as the small-signal cap term. The other is a transcapacitance term
Jansen et al. Approach

MTT Transactions, January 1995

• Assume \( Q_{gd} = 0 \)

• Then \( Q_{g} = Q_{gs}(V_{gs}, V_{ds}) \)

• The transcapacitance then Accounts for the conventional drain to gate capacitance
Cgs (Vgs) Function needs to Accommodate Capacitance “Overshoot” Behavior of HEMTs

Both models use a charge function to compute Cgs and Cgd

Note decreasing Values after “turn-on”
RF Transconductance must be modeled accurately to get agreement with IMD3 and IMD5

**GaN MOSHFET Example**

**Transconductance at** $V_D=10\text{V}$ **extracted respectively from**

- CW-IV (xxx),
- pulsed I-V (ooo),
- CW s-parameter (ΔΔΔ),
- pulsed s-parameter ( ),

**compared with simulated result (—)**

**Quiescent biasing:** $V_{GQ}=-3\text{V}$, $V_{DQ}=25\text{V}$.

**Fundamental and 2-tone output Power at 1.9GHz for 25V, -4V operation**

See Also: The COBRA Model  
Cojocaru and Brazil; MTT Trans. 1997
Characterization Problems

- It is difficult to test large periphery devices, so many important characterization tests are done on small devices and the results scaled.
- DC and pulsed I/V data are influenced by many test conditions.
- RF I/V and reactance data are also affected by measurement and environmental conditions.
Parameter Extraction

• Pulsed I/V and pulsed S-parameters for various ambient temperatures enables separation of temperature effects from voltage effects
• Compound semiconductor HEMTs exhibit “surface gating” effects, due to traps
• Must characterize Gm and Gds dispersion
• For switching or logic applications, lag effects due to traps are important to characterize
Parameter Extraction

• Need short-pulse testing capability as well as longer pulses. See Teyssier et al., [Ref. 7]

• IC-CAP (Agilent Tech.) provides testing capability and parameter extraction for “SPICE” models
Some Factors Influencing DC I/V Data

• Ambient temperature effects
• Self heating effects- Importance increases with device periphery

Device current scales directly with area, but thermal resistance does not scale inversely with area.

• Trapping effects- Charge traps cause I/V “kinks”
Importance of Modeling Self-Heating in Large HEMTs

Self-Heating is more important in larger devices because the thermal resistance does not decrease strongly with periphery increase.

W. R. Curtice 2008
Example of I/V Kink

Notice kink here

$V_{GS} = -1.5 \text{ to } -0.5, \text{ step}=0.25$

W. R. Curtice 2008
I/V Kink Due to Aval. & Traps

Plot of gate voltage vs. drain current for a Triquint 900um HEMT with kink region. The graph shows gate current occurring after kink.
Short Pulse Testing Permits Transistor Characterization for Temperature Effects and Trapping Effects
The following viewgraphs show typical data for a 1-mm AlGaN/GaN device on SiC substrate and with low dispersion (Courtesy, WPAFB)
Evaluate the Dispersion in GaN HEMTs by comparing DC and Pulsed I/V

Low Dispersion Case (WPAFB)

Large Dispersion Case (Other Vendor)

Note that Ids is about the same for VDS=5V

W. R. Curtice 2008
Final DC I/V Family Data and the C_FET Model

Red = Data
Blue = C_FET Model

5 W heating power (R_TH = 8)
DC Sub-threshold Characteristic

Note that model follows the sub-threshold characteristic very well!
Transconductance Nonlinearity

- gm(V) is the most important nonlinearity in any transistor
- Fundamental frequency output is directly related to gm
- Second harmonic output is directly related to first derivative of gm
- Third harmonic output (and IMD3) is directly related to second derivative of gm
- Nonlinear capacitance becomes more important at higher RF frequencies

W. R. Curtice 2008
External Transconductance, \( g_{mx} \)

Model and Data Are in good agreement

W. R. Curtice 2008
RF Modeling Procedure

• Use IC-CAP to extract capacitance parameters using capacitance data
• Optimize model parameters using “hot-FET” S-parameter data
• Evaluate the temperature dependence of the capacitance parameters
• Use load-pull data and power-sweep data to optimize the model parameter set
Typical S-Parameter Comparison

\[ S_{21}, S_{12}, S_{11}, S_{22} \]

0.5-26GHz

W. R. Curtice 2008
Tuned Power Sweep at 10GHz

C_FET8 Simulation vs. 441 Data, VDS=20V, Iq=300 mA, 6-02-04

Red is model
Blue is data

T_rise=47C
W. R. Curtice 2008

4W/mm output
T_rise=36C
Modeling the GaN on Silicon Substrate HEMT
(Courtesy, Nitronex Corp.)
Over 100W Pulsed Power Obtained
36mm Packaged Device

RED = data, Blue=model

VDS = 28V
Freq = 3.5GHz
Input, output tuned

W. R. Curtice 2008
Modeling Large Periphery Devices

- I/V data can often be scaled accurately from smaller devices
- S-parameter data may or may not be useful due to the low impedance values
- Load-pull and power sweep data can help with capacitance modeling
- Accurate packaging models with losses are extremely important for the large devices
- More data needed for modeling larger devices operated at frequencies at or above 10GHz
Conclusion: Part 1- HEMT Models

• Thermal analog circuit for self-heating effects
• $R_{ds}$, $C_{gd}$ function of $V_{ds}$
• Charge function for modeling capacitance
• $C_{gs}(V_{gs})$ permits fitting of “overshoot”
• RF $gm(V_{gs})$ must be modeled accurately to several derivatives
• $R_{ds}$ and $gm$ dispersion should be accommodated
• Trapping effects may need to be included
Part 2: Bipolar Modeling

A thermal analog circuit is critical for accurately simulate temperature effects in power bipolar devices.
Simulator Models Available with Self-Heating Effects

- ADS
  VBIC, HICUM, AgilentHBT

- MWO
  VBIC, HICUM, UCSD HBT

One Problem with VBIC:
It is hard coded for Silicon

W. R. Curtice 2008
Compact BJT/HBT Models

- Gummel-Poon Model – All SPICE versions hard coded for Silicon only (TF Equation), No self-heating effects
- VBIC - VBIC95 BCTM Meeting 1995, Weak Aval., Self-heating effects, Some NQS effects
- MEXTRAM - 1995, Weak Aval., NQS effects
- HICUM – Weak Aval., Self-Heating, NQS
Cut-off Frequency, $F_t$

- $F_t$ is frequency of unity current gain
- $F_t$ is a measure of the frequency response

![Graph showing $F_t = 40.68 \text{ GHz}$](image)

**HEMT Example**

$H_{21}$ vs. freq

$10^x_{\log{s2h.m.21}} [E+0]$  
$1\times10^8$  $1\times10^9$  $1\times10^{10}$  $1\times10^{11}$

Slope $= 2.242E+001 \ [\text{LIN/DEC}]$  
$Y_0 = 2.378E+002$  
$X_0 = 4.068E+010$  

$F_t = 40.68 \text{ GHz}$  
(Data = Red points)

W. R. Curtice 2008
Bipolar Model must Accommodate the Behavior of the Material

In Silicon

This behavior is related to the electron velocity-field relationship.

In the models

Ft behavior is controlled by the parameters of the TF function.

W. R. Curtice 2008
GP_M Model
(Curtice Consulting)

- Uses GP current and capacitance expressions
- The thermal analog circuit was added to model self-heating and elevated heat sink temperatures
- B-C breakdown current, punch-through capacitance and other effects were added
- TF function changed for GaAs to get correct dependence of FT upon VC
Thermal Analog Circuit

I_Tran = Instantaneous power dissipation

R_th * C_th = Thermal time constant

V_th is numerically equal to the temperature rise

Note: Some models use Two thermal time constants

W. R. Curtice 2008
Thermal Modeling Example

- AlGaAs/GaAs HBT with emitter ballast resistance
- 4-finger(2x20) device on a thinned wafer
- $R_{th} = 200 \text{ C/W}$
- Modified Gummel-Poon model (GP_M) used to model device
- GP has most model parameters as function of device temperature
Model and Data for
IC-VC Family for IB = .2, .4, .6, .8 ma
Heat Sink = 25 C

Data is red
RF Parameters
VC=1.5V
IB=.6 mA

W. R. Curtice 2008
Thermal run-a-way simulation and data
Heat Sink = 25 C

IC vs VC

Data is red

VB=1.4 V
1.375 V
1.350 V
1.325 V
1.3 V
Previous data and thermal run-a-way simulation with ballast resistance removed

Heat Sink = 25 C

IC vs VC

Data is red

VB=1.4 V
1.375 V
1.350 V
1.325 V
1.3 V

W. R. Curtice 2008
Thermal run-a-way for SiGe HBT using HICUM model

Heat Sink = 25 C

IC vs VC

Data is red

VB=0.85 V

0.825V

0.80 V

0.775 V

0.75V

W. R. Curtice 2008
Conclusion: Bipolar Modeling

- The thermal analog circuit is needed to accurately simulate temperature effects in GaAs-based HBTs.
- The TF function must be adaptable to characteristics like GaAs, which is opposite to Si BJT behavior.
- Breakdown behavior is important to model.