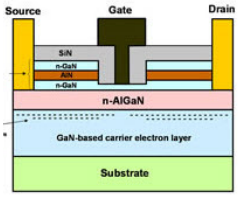
Status of Linear and Nonlinear Modeling for GaN MMICs

Presented at IMS2011 June, 2011



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Outline

- State of the Art
- Modeling considerations, types of models,
- Some physics of charge transport
- Important properties of analytical models
- GaAs and GaN device models available in simulators
- GaAs and GaN modeling differences
- Pulsed IV characterization
- Conclusions

State of the Art

- Many companies market AlGaN/GaN HFET MMIC products & provide foundry service (Cree,TriQ, …)
- Typical operating voltages are 30V with some 50V products.
- Available HPA MMICs show frequency ranges to X-band frequency (III-V Lab has > 35W , 33-37% PAE for 8.5-10.5 GHz)
- Ka band LNA & HPA MMICs reported by HRL , ARL
- Class-F GaN HP MMICs reported- IEE Mic.Ant.Prop.June'06
- MMIC publications show usage of GaAs models (EEHEMT)
- GaN models have evolved from GaAs models, but there are differences

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Types of Large-Signal Transistor Models

- Physical or "Physics-Based" Device Models
  - 2-D, 3-D Device modeling (ATLAS/BLAZE)
  - Calibrated Using Data
  - Not fast enough for circuit/system simulation
- Measurement-Based Models:
  - Analytical Models ← *This presentation will only deal with this type!*
  - Black Box Models: such as
    - 1-Table-Based Models
    - 2-Artificial Neural Network (ANN) Models

(Also called SPICE Models or Compact Models)

Characteristics of Black Box Models

**1-Users cannot customized a BB model.
The model has no parameters to adjust!
A new model is needed for each device**

2-The model must be constructed from an average of data for several devices.

3-Scalling of the model is not possible. That is, a 40 finger model cannot be made from a 2-finger BB model.

4-Self-heating effects can not be acomodated.

5-NVNA (nonlinear vector network analyzer) models and X-parameter models are BB models!

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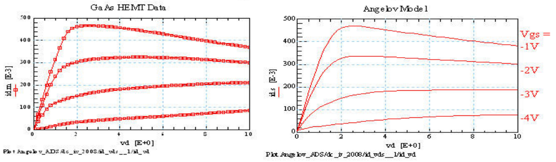
Analytical Modeling Considerations

- The models used for circuit design are, at best, a very simplified approximation of the physics of the device.
- Any given model can always be improved upon.
- Models should permit customization.
- A good large-signal model will also provide good agreement for small-signal operation.
- "All models can be shown to behave non-physically under some operating condition." – Curtice's Correlary

Angelov Model: an Analytical Example



Ids = IPK0*(1 + Tanh(P1*(Vgs-Vpk))*Tanh(A*Vds)

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

- Only 7 parameters
- Model interpolates, extrapolates and smoothes out data
- Ids derivatives well defined

Problem Areas for Analytical Transistor Models

- **Simulator models and foundry models often not accurate enough. Users need to customized models.**
- **Parameter extraction for models can be laborious!**
  Trapping effects make DC IV different from RF behavior.
- **Some important trapping effects are not supported by conventional models.**
- **Switch modeling requirements different from amplifier modeling.**

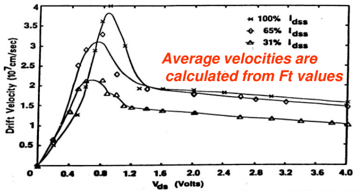
Some Physics of Electron Charge Transport in Semiconductors

The HEMT's frequency response is related inversely to the transit time under the gate and directly to the average electron velocity under the gate:

$$f_T = \frac{1}{2\pi\tau} = \frac{v_s}{2\pi L}$$

Drift velocity under gate
Gate length

Measured Electron Drift Velocities

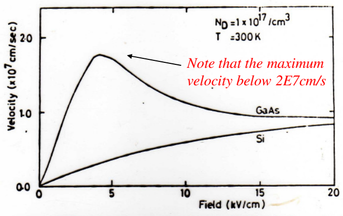


Average velocities are calculated from Ft values

Fig. 4. The characteristics of electron drift velocity versus drain-to-source voltage of an ion-implanted GaAs MESFET (0.5-μm gate length) for 100%, 65%, and 31% I_{dss}.

M. Feng, "An Experimental Determination of Electron Drift Velocity n 0.5-um Gate-Length Ion-Implanted GaAs MESFET's", IEEE ED Letters Vol. 12, no.2, Feb. 1991

Steady-State Electron Drift Velocity vs Field Characteristic for GaAs and Silicon



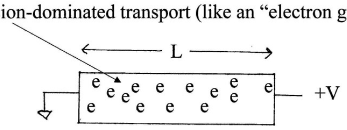
Note that the maximum velocity below 2E7cm/s

. Average drift velocity versus electric field relation obtained : steady state from Monte Carlo simulation for Si and GaAs.

Electron Charge Transport in a Semiconductor

IS NOT BALLISTIC!!!!

Collision-dominated transport (like an "electron gas")

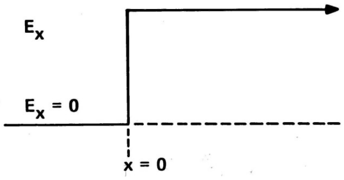


E = Electric Field ⟶ E = V / L
v = electron drift velocity ⟶ v = ***u***·E
I = electron current ⟶ I = N·e·v·A

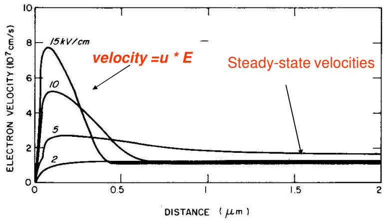
***u* = electron mobility** i.e., obeys Ohm's Law!

Consider This Simple Model for a GaAs Device

1- One Dimensional
2- Space Charge Not Included
3- Abrupt Electric Field Increase



Simple GaAs Device Simulation Illustrating "velocity overshoot"



*velocity =u * E*

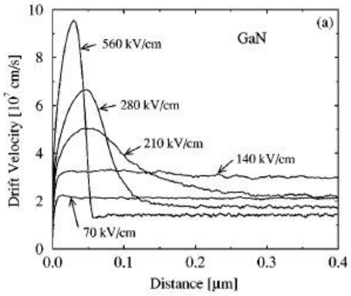
Steady-state velocities

Velocity as a function of position from the cathode for various values of (constant) electric field calculated using the electron-temperature Model. (Reference is Curtice and Yun, IEEE ED August 1981)

Velocity Overshoot Simulation in GaN

J. Appl. Phys., Vol. 85, No. 11, 1 June 1999

Foutz, O'Leary, Shur and Eastman



Conclusion

Electron transport in short gate-length transistors has effects not easily included in compact models !

This shows that external HEMT measurements cannot be used to make a truly physical compact model.

Compact models cannot be truly "Physics Based"

Simulator Built-in Models

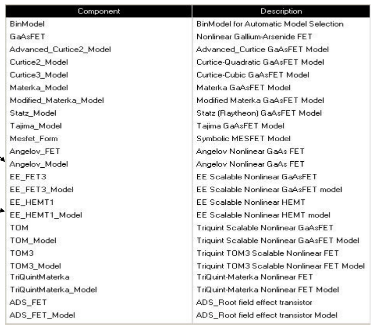
- **Agilent's ADS (Advanced Design System)**
- **AWR's Microwave Office**
- **SPICE versions**
- **Spectre**

ADS* FET Models

Angelov is the only model here that is electro-thermal!

This model has a crude thermal correction term applied

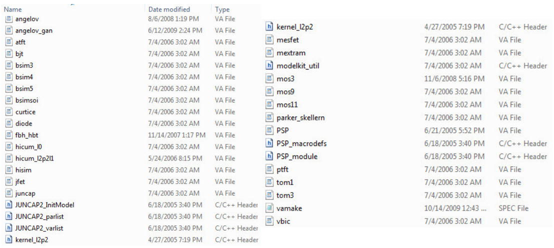
*Agilent Technologies, Inc.



Component	Description
BinModel	BinModel for Automatic Model Selection
GaAsFET	Nonlinear Gallium-Arsenide FET
Advanced_Curtice2_Model	Advanced_Curtice GaAsFET Model
Curtice2_Model	Curtice-Quadratic GaAsFET Model
Curtice3_Model	Curtice-Cubic GaAsFET Model
Materka_Model	Materka GaAsFET Model
Modified_Materka_Model	Modified Materka GaAsFET Model
Statz_Model	Statz (Raytheon) GaAsFET Model
Tajima_Model	Tajima GaAsFET Model
Mesfet_Form	Symbolic MESFET Model
Angelov_FET	Angelov Nonlinear GaAs FET
Angelov_Model	Angelov Nonlinear GaAs FET
EE_FET3	EE Scalable Nonlinear GaAsFET
EE_FET3_Model	EE Scalable Nonlinear GaAsFET model
EE_HEMT1	EE Scalable Nonlinear HEMT
EE_HEMT1_Model	EE Scalable Nonlinear HEMT model
TOM	Triquint Scalable Nonlinear GaAsFET
TOM_Model	Triquint Scalable Nonlinear GaAsFET Model
TOM3	Triquint TOM3 Scalable Nonlinear FET
TOM3_Model	Triquint TOM3 Scalable Nonlinear FET Model
TriQuintMaterka	TriQuint-Materka Nonlinear FET
TriQuintMaterka_Model	TriQuint-Materka Nonlinear FET Model
ADS_FET	ADS_Root field effect transistor
ADS_FET_Model	ADS_Root field effect transistor Model

ADS Verilog-A Models

No new models with Self-heating,
but, any of these model can be modified for new effects.



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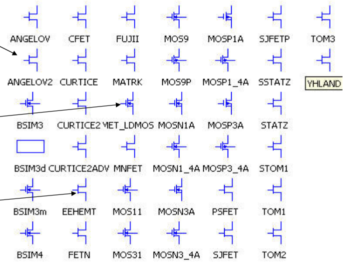
angelov_gan	6/12/2009 2:24 PM	VA File
atft	7/4/2006 3:02 AM	VA File
bjt	7/4/2006 3:02 AM	VA File
bsim3	7/4/2006 3:02 AM	VA File
bsim4	7/4/2006 3:02 AM	VA File
bsim5	7/4/2006 3:02 AM	VA File
bsimsoi	7/4/2006 3:02 AM	VA File
curtice	7/4/2006 3:02 AM	VA File
diode	7/4/2006 3:02 AM	VA File
fbh_hbt	11/14/2007 1:17 PM	VA File
hicum_l0	7/4/2006 3:02 AM	VA File
hicum_l2p2l1	5/24/2006 8:15 PM	VA File
hisim	7/4/2006 3:02 AM	VA File
jfet	7/4/2006 3:02 AM	VA File
juncap	7/4/2006 3:02 AM	VA File
JUNCAP2_InitModel	6/18/2005 3:40 PM	C/C++ Header
JUNCAP2_parlist	6/18/2005 3:40 PM	C/C++ Header
JUNCAP2_varlist	6/18/2005 3:40 PM	C/C++ Header
kernel_l2p2	4/27/2005 7:19 PM	C/C++ Header
kernel_l2p2	4/27/2005 7:19 PM	C/C++ Header
mesfet	7/4/2006 3:02 AM	VA File
mextram	7/4/2006 3:02 AM	VA File
modelkit_util	7/4/2006 3:02 AM	C/C++ Header
mos3	11/6/2008 5:16 PM	VA File
mos9	7/4/2006 3:02 AM	VA File
mos11	7/4/2006 3:02 AM	VA File
parker_skellern	7/4/2006 3:02 AM	VA File
PSP	6/21/2005 5:52 PM	VA File
PSP_macrodefs	6/18/2005 3:40 PM	C/C++ Header
PSP_module	6/18/2005 3:40 PM	C/C++ Header
ptft	7/4/2006 3:02 AM	VA File
tom1	7/4/2006 3:02 AM	VA File
tom3	7/4/2006 3:02 AM	VA File
vamake	10/14/2009 12:43 ...	SPEC File
vbic	7/4/2006 3:02 AM	VA File

FET Models in MWO (AWR Design Environment)

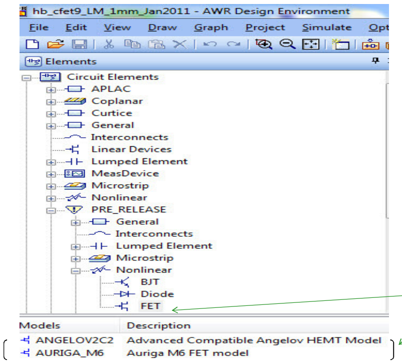
Angelov2 is the only
FET model here that is
electro-thermal!

MET_LDMOS
is electro-thermal

EEHEMT
also here



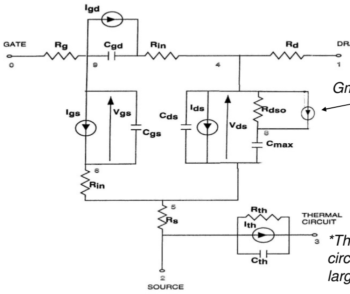
Pre-Release Models in MWO



Models	Description
ANGELOV2C2	Advanced Compatible Angelov HEMT Model
AURIGA_M6	Auriga M6 FET model

HERE!

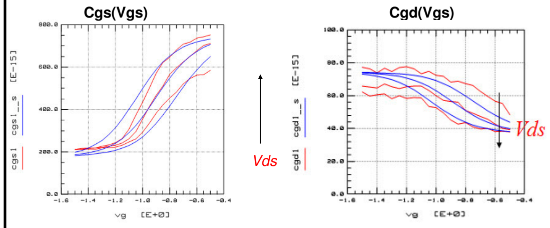
Electro-Thermal Models Include Self Heating (C_FET & C_HEMT Model Topology)



Gm Dispersion Circuit

**Thermal analog circuit is critical for large periphery devices*

Charge-based Capacitance Required for Cgs(Vgs, Vds) and Cgd(Vgs,Vds)



Modeling example for GaN HEMT

Types of User-Defined Compact Models

- **SDD- Symbolically Defined Device model**
- **C-coded model**
- **Verilog-A coded model**
- **Table-Based & ANN models**

Verilog-A Modeling

- Requires current and charge expressions
- Derivative expressions computed automatically and are extremely accurately
- Convergence properties excellent; Coding time short
- See Kharabi et al., 2010 CSIS Symposium

C_HEMT in C Code (ADS) ~ 1100 lines

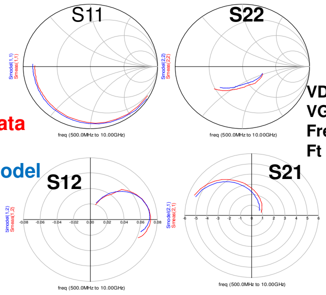
C_HEMT in Verilog-A Code ~ 210 lines

(*VA code can be used in MWO, Spectre, ADS, APLAC, HSPICE , etc.)*

Consider GaAs Device Modeling

1.75 mm GaAs C_HEMT Model

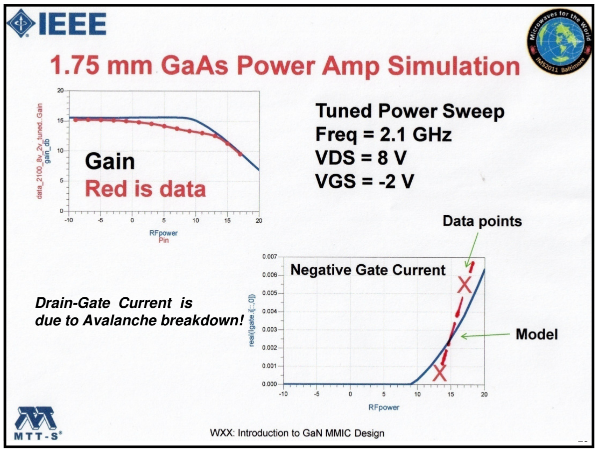
SS agreement is excellent



RED is Data

Blue is Model

VDS = 8 V
VGS = -2 V
Freq = 0.5 – 10 GHz
Ft = 12 GHz



1.75 mm GaAs Power Amp Simulation

Gain
Red is data

Tuned Power Sweep
Freq = 2.1 GHz
VDS = 8 V
VGS = -2 V

Data points

Negative Gate Current

Model

Drain-Gate Current is due to Avalanche breakdown!

WXX: Introduction to GaN MMIC Design

GaAs Modeling

- Typical GaAs device has significant gate-drain breakdown current which limits VDS to lower values
- This also limits the output power
- GaAs pHEMT breakdown voltage is quite similar to MESFETs, but the impact ionization starts earlier in pHEMTs and displays faster buildup of drain current with drain voltage, due to shorter gate lengths and thinner channels.
- D-G breakdown must be included in GaAs model!

GaN Power Advantages

Note larger mobility Compared with Si, SiC

Higher breakdown than Si or GaAs

		Si	GaAs	SiC	GaN	
Energy Gap		1.11	1.43	3.2	3.4	eV
Breakdown Field		6.00E+05	6.50E+05	3.50E+06	3.50E+06	V/cm
Electron LF Mobility		1200	8500	800	1600	cm^2/V-s
Thermal Conductivity		1.5	0.46	3.5	1.7	W/cm-C

Si is a poorer substrate for heat conduction than SiC

Higher RF power capability than GaAs

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GaN and GaAs **amplifiers show an unusual current effects that should be included in model**

Drain Current Reduction with Input RF Power

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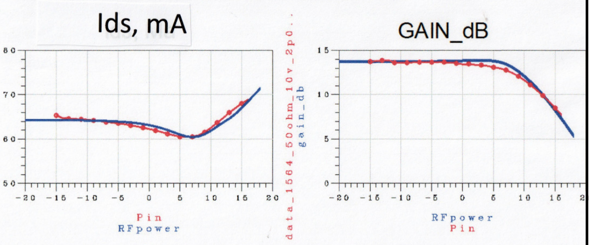
Drain Current Reduction in AlGaN/GaN HEMTs

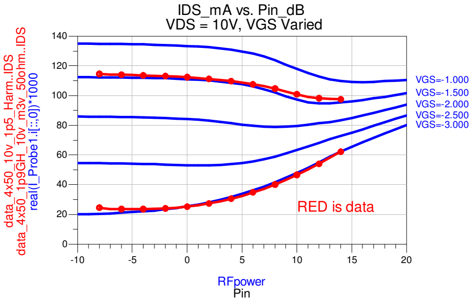
- This is due to charge trapping effects (reference – Jardel, et al.)
- Up to now, it has not been included in compact models
- Here is data for a 4x50 GaN HEMT
- C_FET model is shown to agree well with data



10V, -2V, CFET9

WSA: Introduction to GaN MMIC Design

RF Power Sweep for Model and Data for 4x50 GaN HEMT



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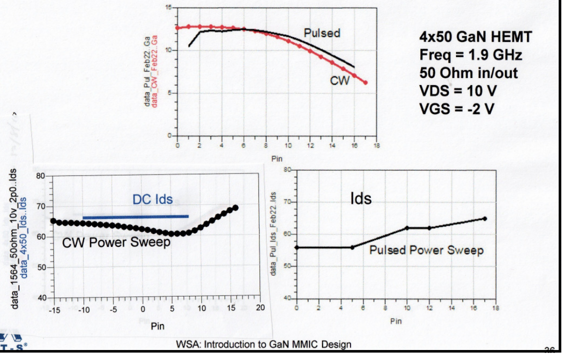
More Recent Data : CW and 1-us Pulsed RF Power Sweeps



4x50 GaN HEMT
Freq = 1.9 GHz
50 Ohm in/out
VDS = 10 V
VGS = -2 V

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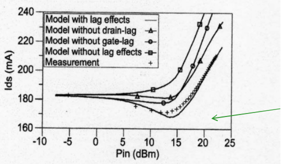
Reference shows this effect is due to a charge trapping effect!

This figure is from GaN modeling work by Jardel et al., IEEE Trans. on MTT, December 2007.



Data and model with trapping

Fig. 13. Measured (crosses) and modeled average output current in different conditions: by taking into account any trapping effect, by modeling only gate lag, by modeling only drain lag, and by modeling gate and drain lag, at the optimum load impedance.

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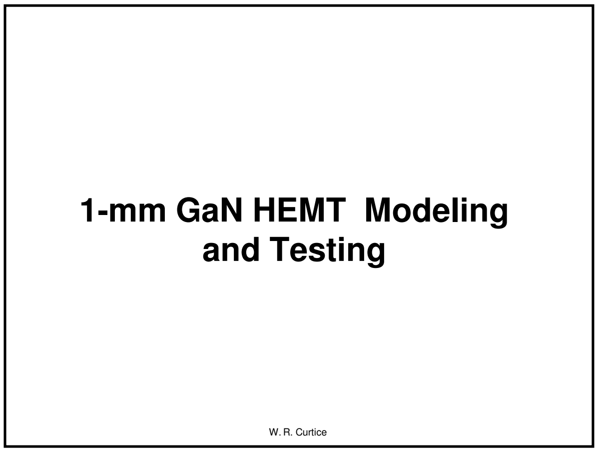

1-mm GaN HEMT Modeling and Testing

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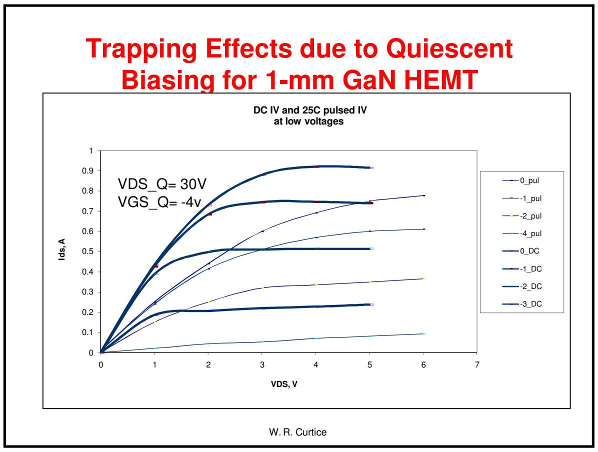

Trapping Effects due to Quiescent Biasing for 1-mm GaN HEMT

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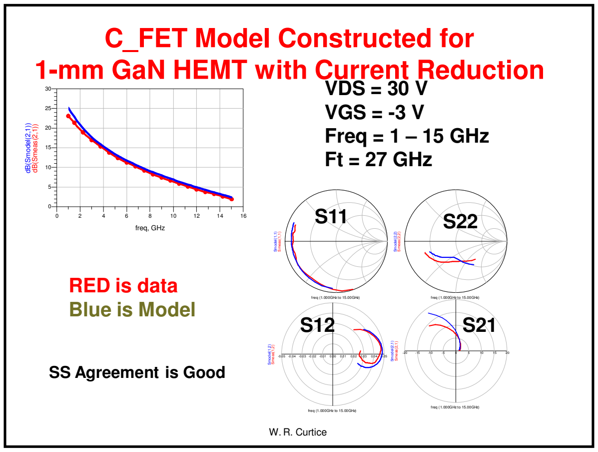

C_FET Model Constructed for 1-mm GaN HEMT with Current Reduction

VDS = 30 V
VGS = -3 V
Freq = 1 – 15 GHz
Ft = 27 GHz

RED is data
Blue is Model

SS Agreement is Good

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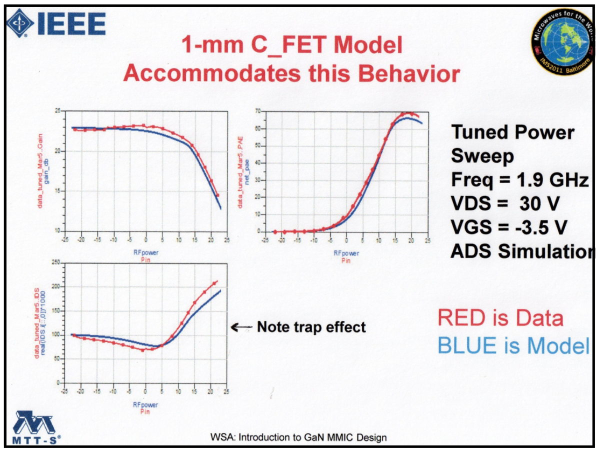


IEEE

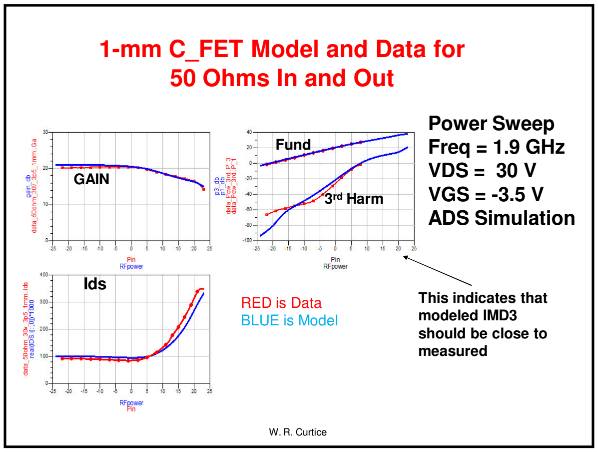
1-mm C_FET Model Accommodates this Behavior

Tuned Power Sweep
Freq = 1.9 GHz
VDS = 30 V
VGS = -3.5 V
ADS Simulation

← Note trap effect

RED is Data
BLUE is Model

WSA: Introduction to GaN MMIC Design



1-mm C_FET Model and Data for 50 Ohms In and Out

Power Sweep
Freq = 1.9 GHz
VDS = 30 V
VGS = -3.5 V
ADS Simulation

RED is Data
BLUE is Model

This indicates that modeled IMD3 should be close to measured

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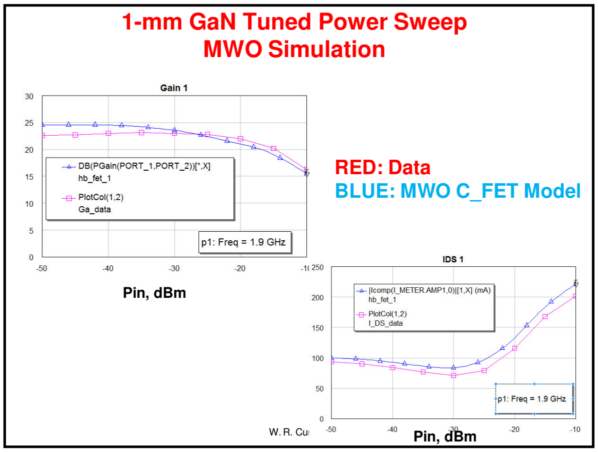

1-mm GaN Tuned Power Sweep MWO Simulation

RED: Data
BLUE: MWO C_FET Model

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1-mm GaN Modeling Summary

- Pulsed IV characterization necessary for modeling.
- GaN devices for HPA MMICs may have negligible drain-gate breakdown. Detailed characterization of breakdown often not necessary!
- The compact model for a short pulse GaN power amplifier should not include trapping effects.
- The best GaN HEMT models permit customization.

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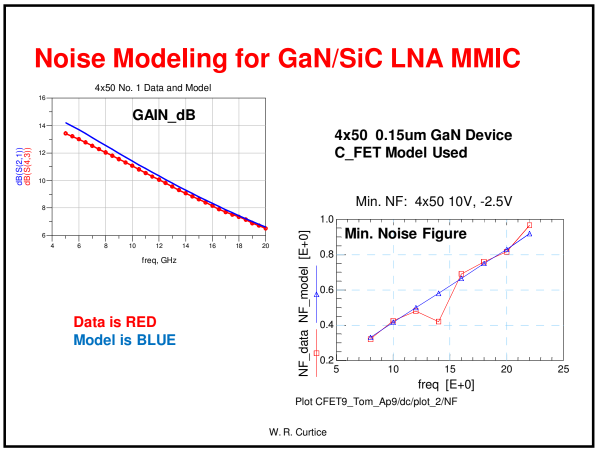

Noise Modeling for GaN/SiC LNA MMIC

4x50 0.15um GaN Device
C_FET Model Used

Data is RED
Model is BLUE

Plot CFET9_Tom_Ap9/dc/plot_2/NF

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Modeling Large Devices:
GaN on Silicon Example

(Courtesy, Nitronex Corp.)

- 2 mm through 36 mm models developed
- C_FET model used (electro-thermal model needed)
- VDS values 28V through 48V
- Silicon substrate increases the thermal resistance but little additional substrate loss up to 3.5 GHz
- Temperature rise not large for operation at high PAE
- Pulsed I/V data only available for 2 mm devices

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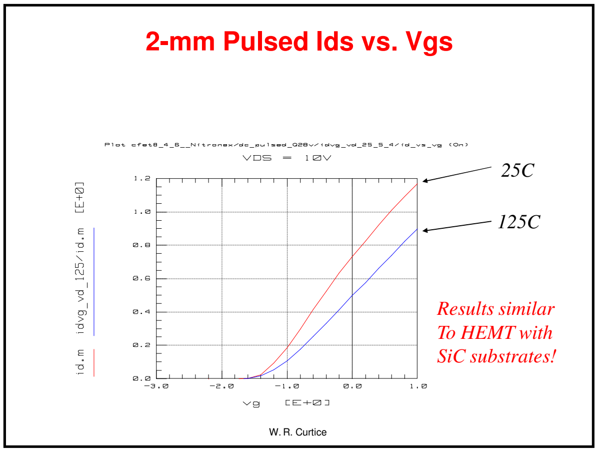

2-mm Pulsed Ids vs. Vgs

Results similar To HEMT with SiC substrates!

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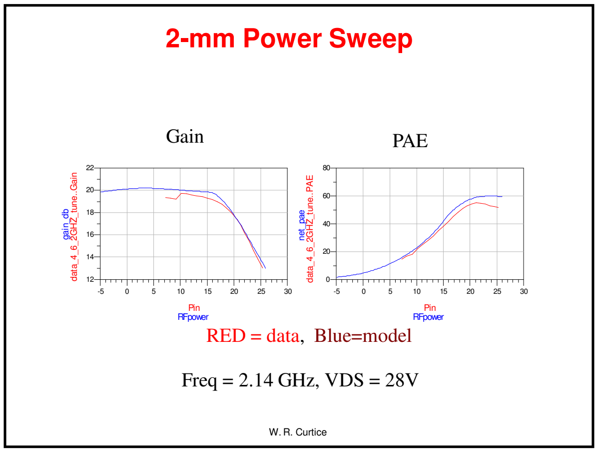

2-mm Power Sweep

RED = data, Blue=model

Freq = 2.14 GHz, VDS = 28V

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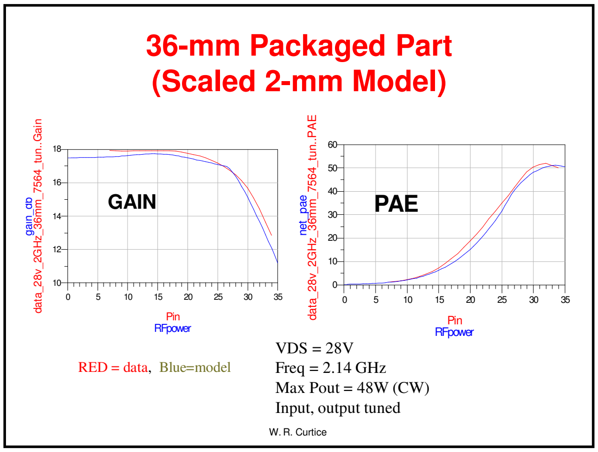

36-mm Packaged Part
(Scaled 2-mm Model)

RED = data, Blue=model

VDS = 28V
Freq = 2.14 GHz
Max Pout = 48W (CW)
Input, output tuned

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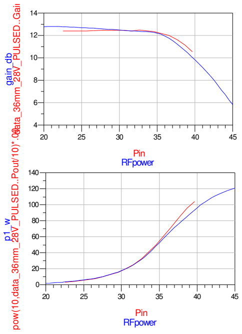
Over 100W Pulsed Power Obtained with 36-mm Packaged Device



RED = data, Blue=model

VDS = 28V
Freq = 3.5GHz
Tuned Input & output

Conclusion

- Installed simulator GaAs models need to be modified to accurately model GaN HEMTs for MMICs
- C-code or Verilog-A coded analytical models can produce accurate models and are easily tailored
- Verilog-A models are an excellent choice since the same code will run in any simulator
- Large periphery devices do require an electro-thermal model
- CW GaN models need to include trapping effects.
- Under some conditions, scaling of GaN models is possible by as much as a factor of 18
