Survey and Trends in Nonlinear Transistor Modeling Methodologies

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Presentation Outline

- Introduction
- I-V modeling
- Nonlinear Charge Modeling
- Non Quasi-Static Effects & Dispersion Modeling
- Electro-Thermal Modeling
- Advanced Measurements
- NVNA data and advanced dynamical FET modeling
- Symmetry Considerations
- Summary & Conclusions

Introduction

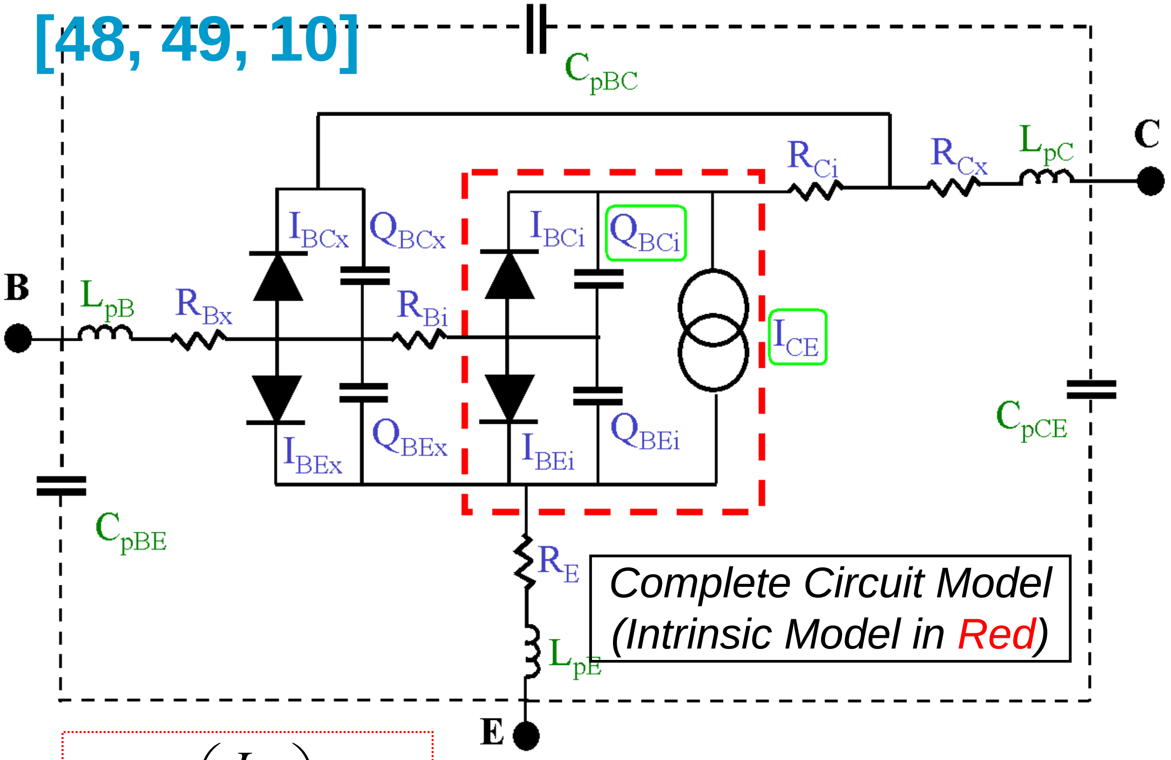
All models are wrong, but *some* are *useful*.“

- statistician George Box

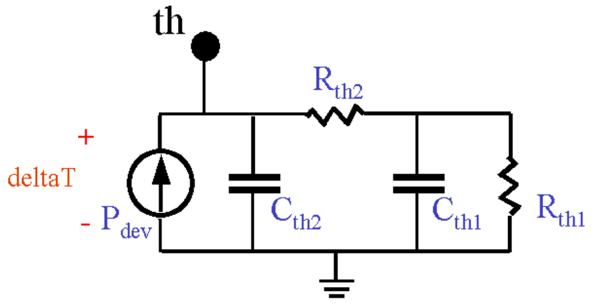
“All models are approximations.
Some models are useful.”

- attributed to Mike Golio and others

Compact Transistor Models (AgilentHBT model) [48, 49, 10]



Complete Circuit Model
(Intrinsic Model in Red)



Thermal Subcircuit
(Two-Poles)

Coupled nonlinear ordinary differential equations in the time domain

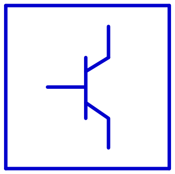
$$I_{CE} = \frac{\left(\frac{I_{cf}}{q3}\right) - I_{cr}}{d}$$

$$Icrit1 = IKDC3\left(1 - \frac{V_{BCi} - VJC}{VKDC}\right)$$

Equivalent Circuit with nonlinear elements

$$q3 = \frac{\sqrt{\left(\frac{1}{IKDC2}(Icf - Icrit1)\right)^2 + \left(\frac{IKDC1}{IKDC2}\right)^2} + \left[\left(\frac{1}{IKDC2}(Icf - Icrit1)\right) - \left(\frac{IKDC1}{IKDC2}\right)\right]}{2} + 1 - q3_o$$

Agilent HBT Model Parameters (over 100)



AgilentHBT_Model
HBTM1
Tnom=25.0
Re=2.0 Ohm
Rci=1.0 Ohm
Rcx=5.0 Ohm
Rbi=15.0 Ohm
Rbx=5.0 Ohm
Is=1.0e-25 A
Nf=1.0
Isr=1.0e-15 A
Nr=2.0
Ish=1.0e-27 A
Nh=1.0
Ise=1.0e-18 A
Ne=2.0
Isrh=1.0e-15 A

Nrh=2.0
Isc=1.0e-13 A
Nc=2.0
Abel=0.0
Vaf=500.0 V
Var=1000.0 V
Isa=1.0e+10 A
Na=1.0
Isb=1.0e+10 A
Nb=1.0
Ikdc1=1.0 A
Ikdc2Inv=0.0
Ikdc3=1.0 A
VkdcInv=0.1
Nkdc=3.0

Gkdc=0.0
Ik=1.0 A
Cje=4.0e-14 F
Vje=1.3 V
Mje=0.3
Cemax=1.0e-13 F
Vpte=1.0 V
Mjer=0.05
Abex=0.0
Cjc=5.0e-14 F
Vjc=1.1 V
Mjc=0.3
Ccmax=9.0e-14 F
Vptc=3.0 V
Mjcr=0.03

Abcx=0.75
Tfb=1.0e-12 sec
Fextb=0.2
Tfc0=2.0e-12 sec
Tcmin=5.0e-13 sec
Itc=0.006 A
Itc2=0.008 A
Vtc0Inv=0.3
Vtr0=2.0 V
Vmx0=2.0 V
VtcminInv=0.5
Vtrmin=1.0 V
Vmxmin=1.0 V
VtcInv=0.1
Vtc2Inv=0.1

Fextc=0.8
Tkrk=1.0e-12 sec
Ikrk=0.025 A
Ikrktr=1.0e-06 A
Vkrk=3.0 V
Vkrk2Inv=0.2
Gkrk=4.0
Vktr=1.0 V
Vkmx=1.0 V
Fexke=0.2
Tr=1.0e-09 sec
Cpce=1.0e-15 F
Cpbe=1.0e-15 F
Cpbc=1.0e-15 F
Lpb=0.0 H

Lpc=0.0 H
Lpe=0.0 H
Xrb=0.0
Xrc=0.0
Xre=0.0
Tvje=0.0
Tvpe=0.0
Tvjc=0.0
Tvpc=0.0
Tnf=0.0
Tnr=0.0
Ege=1.55 V
Xtis=3.0
Xtih=4.0
Xtie=3.0

Egc=1.5 V
Xtir=3.0
Xtic=3.0
Xtirh=4.0
Xtik3=0.0
Eaa=0.0 V
Eab=0.0 V
Xtfb=0.0
Xtcmin=0.0
Xtfc0=0.0
Xitc=0.0
Xitc2=0.0
Xtkrk=0.0
Xikrk=0.0
Xvkrk=0.0

Rth1=1000.0
Cth1=5.0e-10
Xth1=0.0
Rth2=0.0
Cth2=0.0
Xth2=0.0
Kf=0.0
Af=1.0
Ffe=1.0
Kb=0.0
Ab=1.0
Fb=1.0 Hz
Imax=10.0 A
AllParams=

Resistances:	5
DC Currents:	26
Depletion Charge:	14
Delay Charge:	25
Parasitics:	6
Temp., DC & R's:	22
Temp., Charges:	12
Noise:	6

Transistor Modeling

- Compact Models: Equivalent circuit models for IC design formulated in the time-domain. Examples are BSIM models for MOSFET, Angelov model for GaAs FETs, Gummel-Poon models for bipolars, AgilentHBT model for III-V HBTs
- “Compact” models can be complex (> 100 parameter values)
- Parameters typically extracted from DC and S-pars
  Ironic for a nonlinear model
  - Some devices may not be able to be characterized under DC and static operating conditions (power, temperature)
  - Advanced models may not be identifiable from only DC and S-parameter data.
  - No direct evidence that these nonlinear models will reproduce large-signal behavior

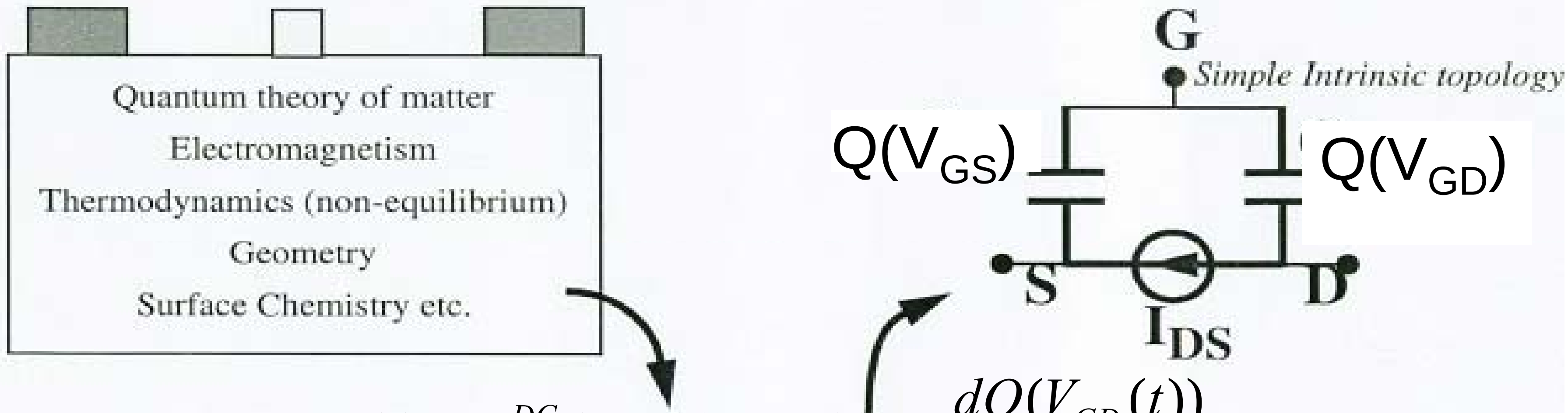
Device Requirements and Modeling Implications

- Linearity: Harmonic & Intermod. Distortion; ACPR; AM-AM; AM-PM
- Efficiency: PAE; Fundamental Output Power; Self-biasing
- Memory: Slow thermal effects, slow trapping phenomena
- Modeling Challenges from
- Device physics (III-V transport, trapping dynamics)
  Complex signals, multiple time-scale dynamics
  Amplifier, switch, and mixer applications
  Wide variety of device designs in many material systems
- Accuracy required over
- Bias, frequency, and temperature; power;
- Different types of models may be required at different stages in the development of a technology

Physical Models to Circuit (compact) Models [16,17]

Shockley: Physical PDEs and approximations such as *field-independent mobility, gradual channel approximation*, etc.:

Derive *terminal dynamics* and *constitutive relations*:



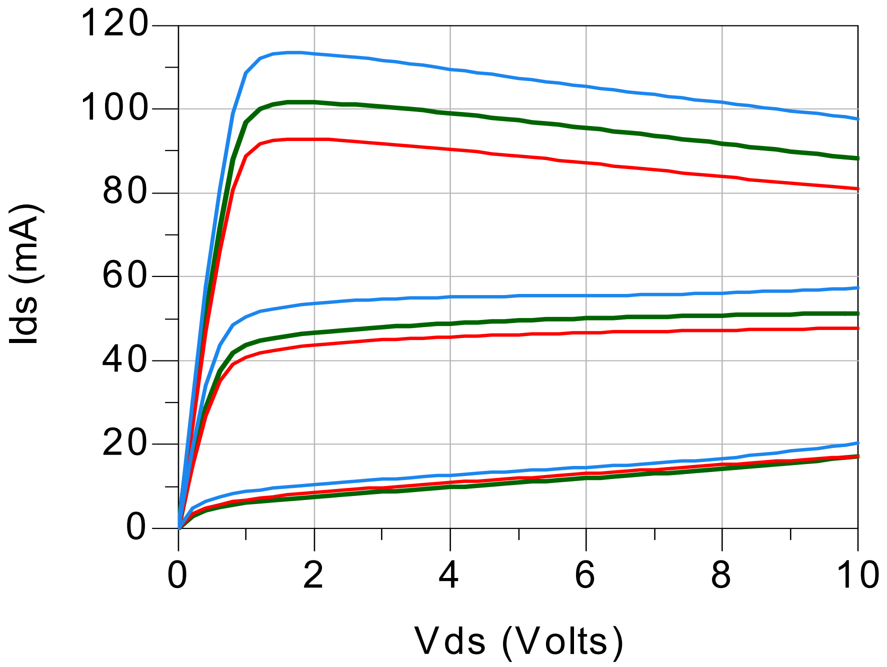
$$I_D(t) = I_D^{DC}(V_{GS}(t), V_{DS}(t)) - \frac{dQ(V_{GD}(t))}{dt}$$

$$I_G(t) = \frac{dQ(V_{GS}(t))}{dt} + \frac{dQ(V_{GD}(t))}{dt}$$

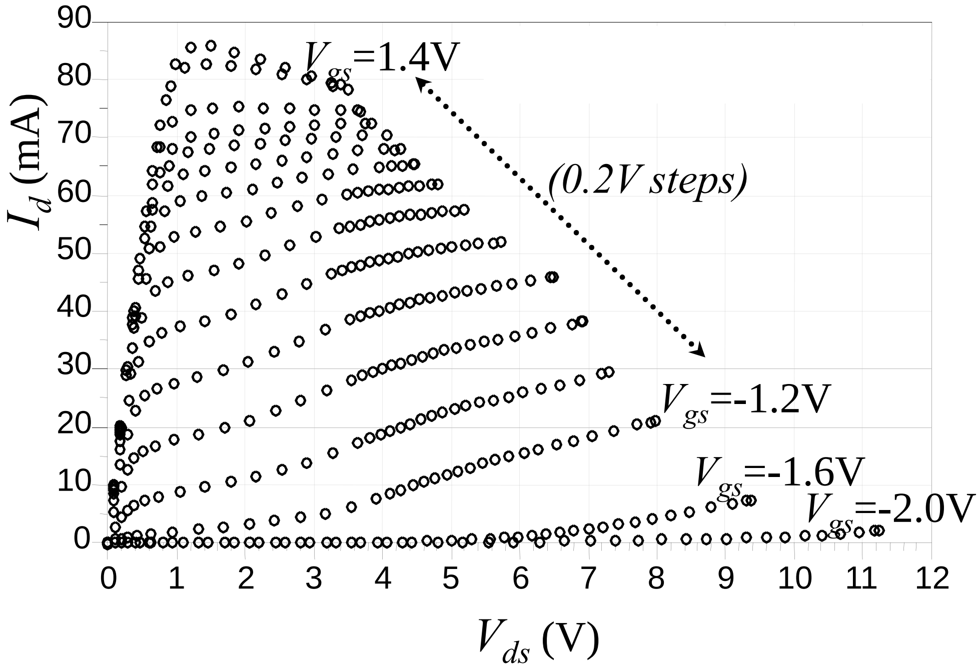
$$I_D^{DC}(V_{GS}, V_{DS}) = \frac{W\mu q N_D a}{\varepsilon L}\left(V_{DS} - \frac{2}{3}\left[\sqrt{\frac{2\varepsilon}{qN_D a^2}}\left((V_{DS}+\phi-V_{GS})^{3/2} - (\phi - V_{GS})^{3/2}\right)\right]\right)$$

$$Q(V) = -WL\sqrt{2q\varepsilon N_D(\phi - V)}$$ (up to a constant)

Typical characteristics of real devices not ideal



MESFET 3 temperatures



pHEMT

Typical Features of real device often not captured by simple physics-based models

Non-zero, and sometimes negative, output conductance
Drain-voltage dependent “pinch-off voltage”
Higher drain current at *lower* ambient temperature (near Vp)

Measurement-Based (Empirical) Modeling

“The Device Knows Best”

Electrons know where to go, even if the modelers don’t!

***Use device data as much as possible* in the model**

Useful for circuit design when good measurements are available, and when no good (fast, robust, extractable) physical models are available

- Empirical models (fitting closed-form functions to data)
- Table-based models with spline interpolation
- Neural-network based models

Experiment Design:

measure the device I-V (and Q-V)

Model Identification

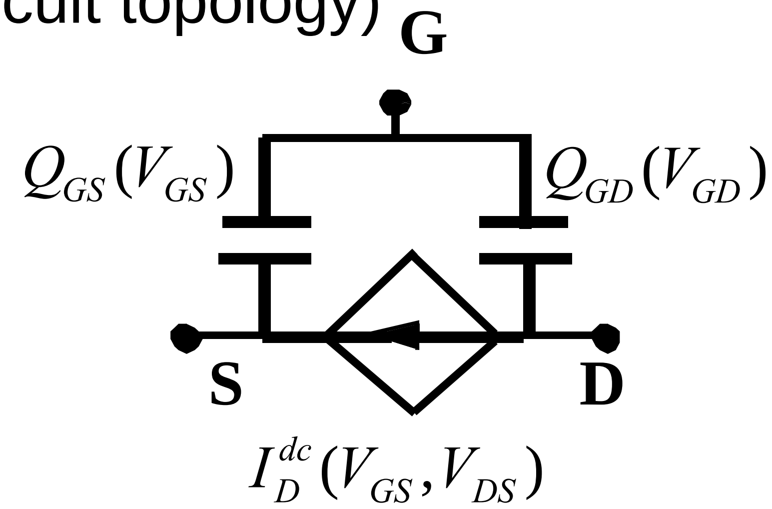
fit the empirical expressions to data (parameter extraction)
or store data and interpolate

Empirical Models

The same dynamics (equivalent circuit topology)

$$I_D(t) = I_D^{DC}(V_{GS}(t), V_{DS}(t)) - \frac{dQ_{GD}(V_{GD}(t))}{dt}$$

$$I_G(t) = \frac{dQ_{GS}(V_{GS}(t))}{dt} + \frac{dQ_{GD}(V_{GD}(t))}{dt}$$



Large-Signal Equivalent Circuit

Modified Constitutive Relations for easy fitting (Curtice Cubic[7])

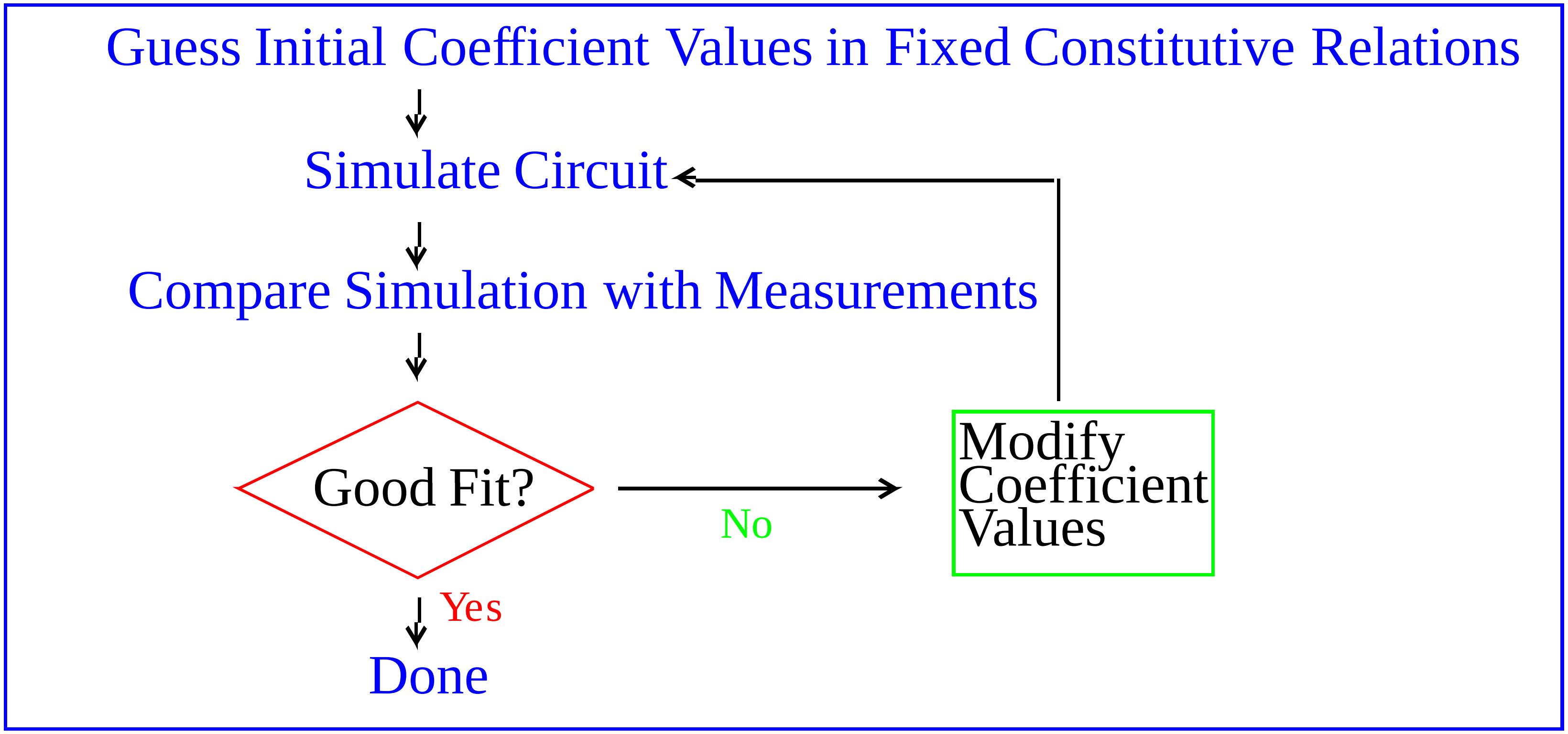
$$I_D^{DC}(V_{GS}, V_{DS}) = \left(A_0 + A_1V_1 + A_2V_1^2 + A_3V_1^3\right) tanh(\gamma V_{DS})$$

$$Q_{GS}(V) = -\frac{C_{j0}\phi}{\eta+1}\left(1-\frac{V}{\phi}\right)^{\eta+1} \qquad Q_{GD}(V) = C_{GD0}V$$

Experiment Design: Measure DC I-V curves

Model Identification (1): minimize error

$$I_D^{DC}(Vgs, Vds) = \left(A_0 + A_1 V_1 + A_2 V_1^2 + A_3 V_1^3\right) \cdot \tanh(\gamma V_{ds})$$


Guess Initial Coefficient Values in Fixed Constitutive Relations

Simulate Circuit

Compare Simulation with Measurements

Good Fit?

No

Modify Coefficient Values

Yes

Done

Issues with parameter extraction

Optimization-based parameter extraction can be:

- Slow (simulate circuit and update parameters hundreds of times)
- Sensitive to initial parameter values
- Non-repeatable
- Can get stuck in local minima of optimizer cost function
- Require user interaction
- Good parameter values depend on good data

- May never achieve good fit

(constitutive relations may not be flexible enough)
Changes to constitutive relations -> changes to extraction routines

Parameter Extraction: What can go wrong

(Curtice Cubic example also see [30])

$$I_D^{DC}(V_1,V_2)=\left(A_0+A_1V_1+A_2V_1^{2}+A_3V_1^{3}\right)tanh(\gamma V_2)$$

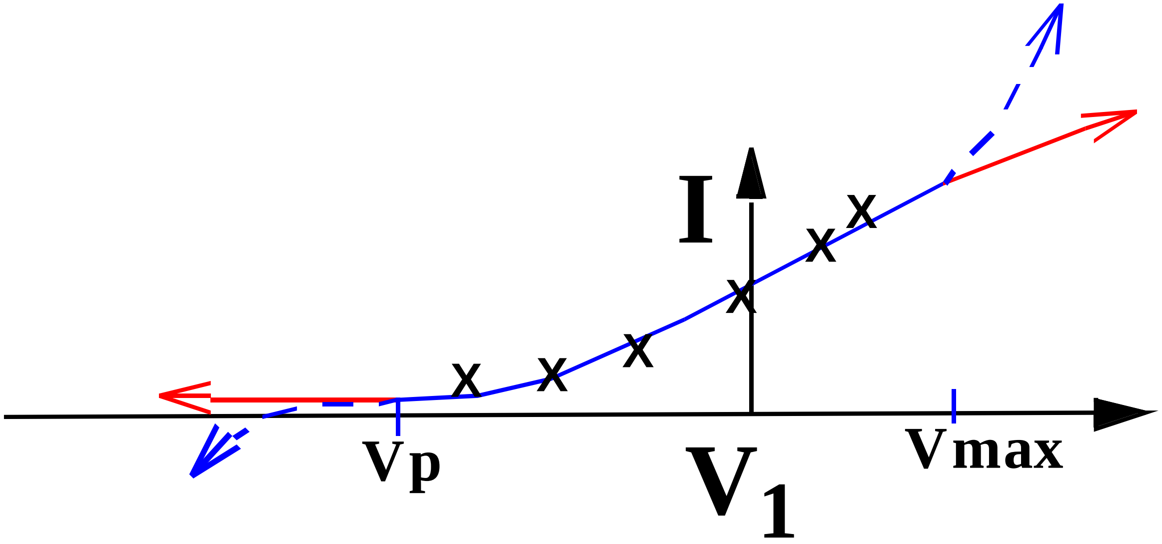
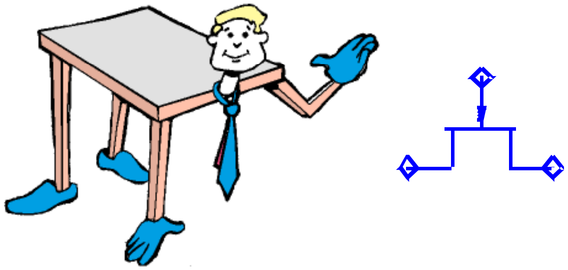
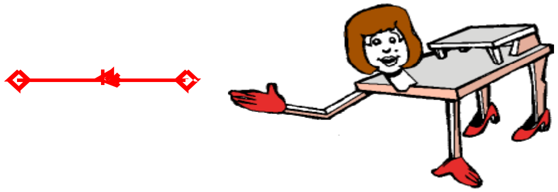


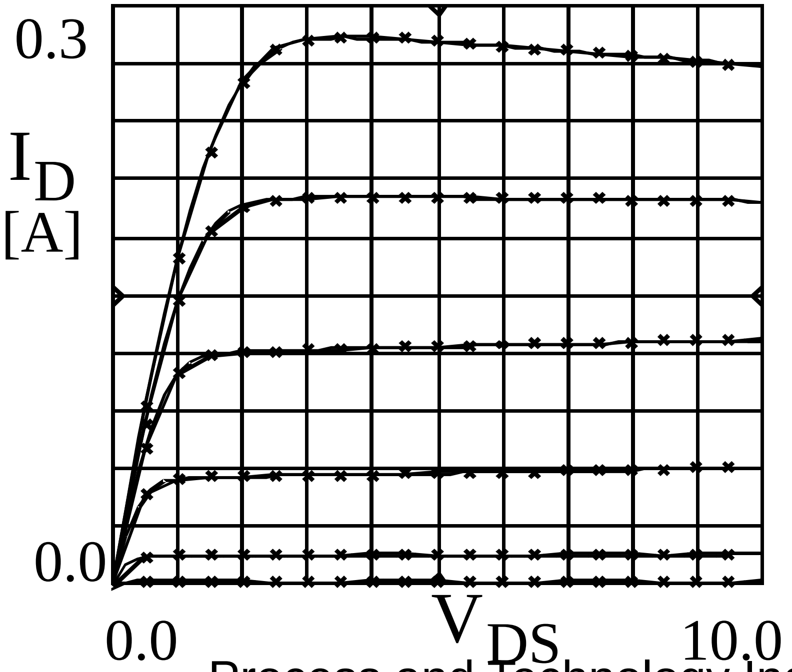
Table-Based Models: Accurate and General [3,17,21]



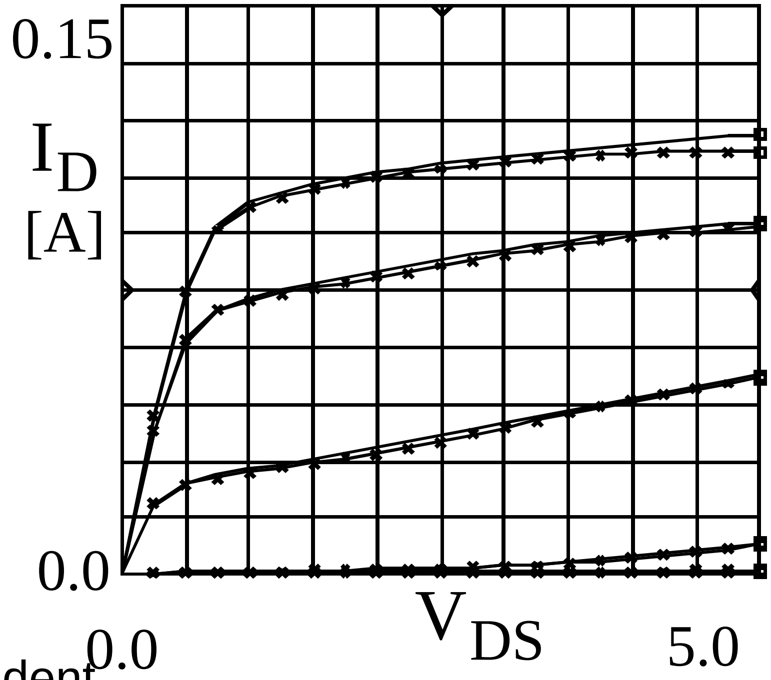


Measure, transform data, tabulate, interpolate, scale

Vertical Power Si MOSFET



GaAs pHEMT



Process and Technology Independent

Table Models

Constitutive Relations are interpolated from data

Table 1

Vgs	Vds	Id_DC
-5	-0.3	7.14E-08
-5	-0.2	7.55E-08
-5	-0.1	7.98E-08
…	…	…

Table 2

Vgs	Vds	Qd
-5	-0.3	-1.20E-13
-5	-0.2	-1.13E-13
-5	-0.1	-1.08E-13
…	…	…

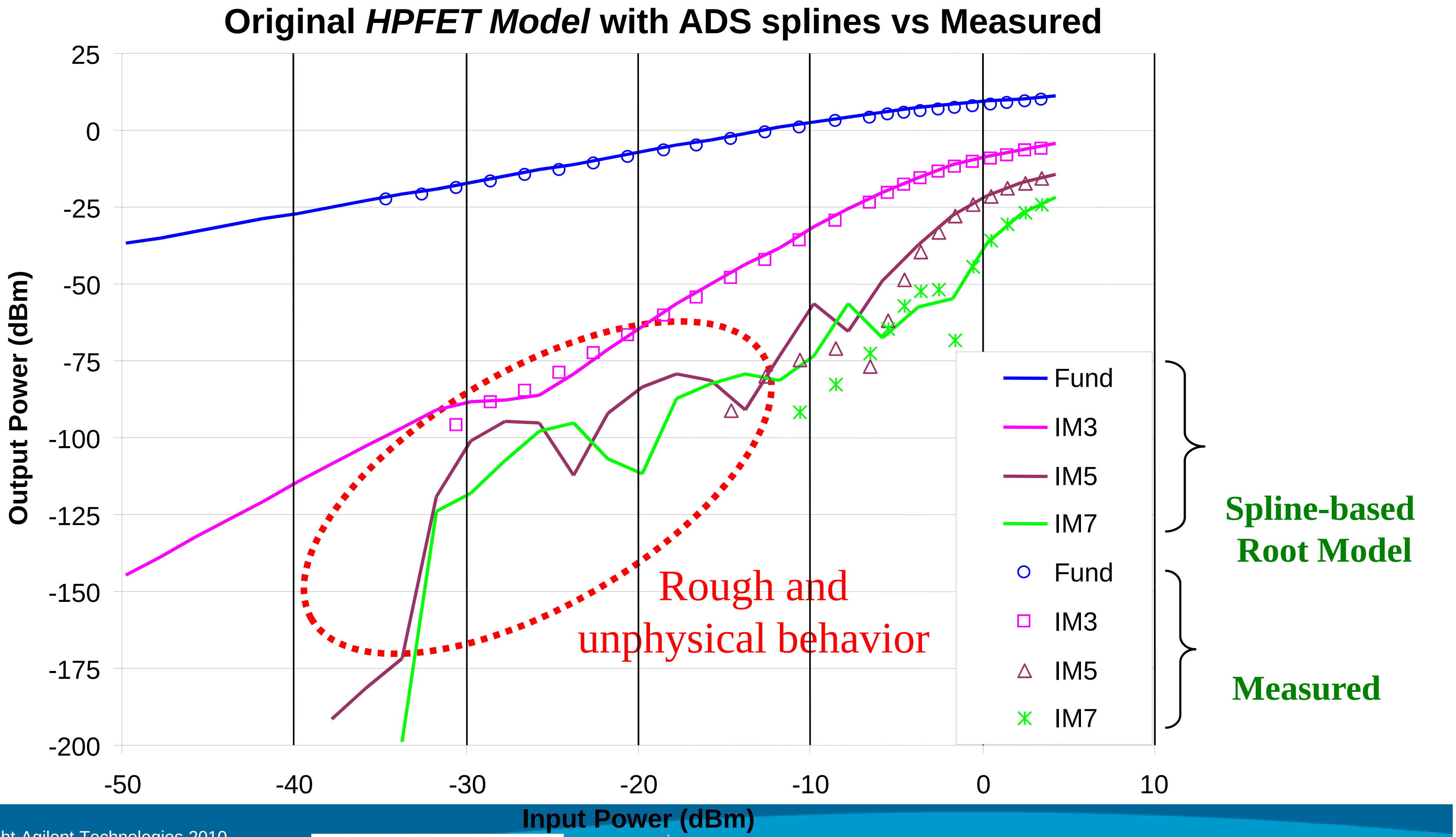
$$I_d(t) = \text{Interpolate}\{\text{Table1}, [V_{gs}(t), V_{ds}(t), I_{d\_dc}]\}$$

$$+\frac{d}{dt}\text{Interpolate}\{\text{Table2}, [V_{gs}(t), V_{ds}(t), Q_d]\}$$

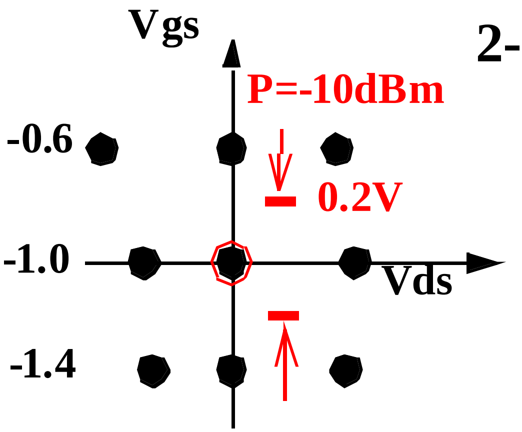
Works well for dc, S versus bias & freq., med-high power signals

Warning: Interpolation algorithms may limit table models! [43]

Two-tone Intermodulation



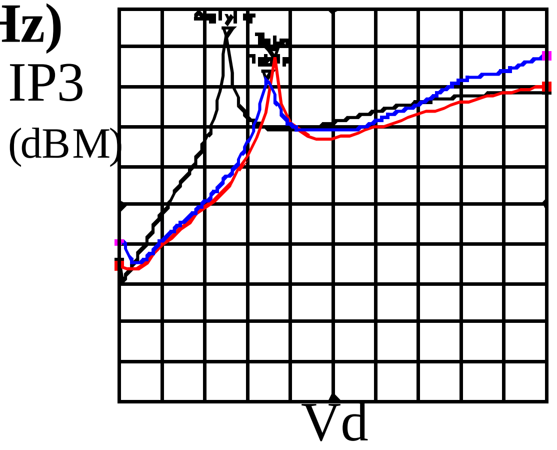
Naïve Splines Limit Distortion Accuracy [17, 8]

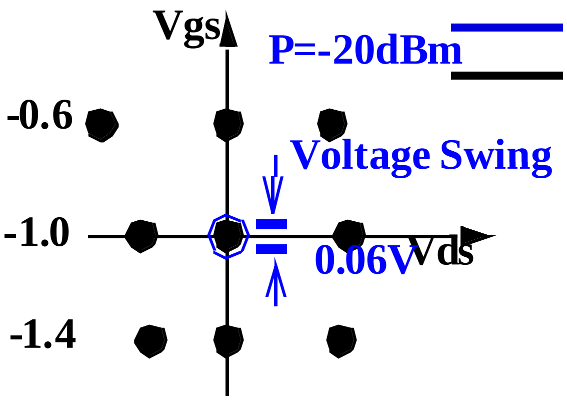


2-tones @ 100MHz (+1MHz)

Si NJFET
Table Model

(a) Vg=-1V Power=-10dBm



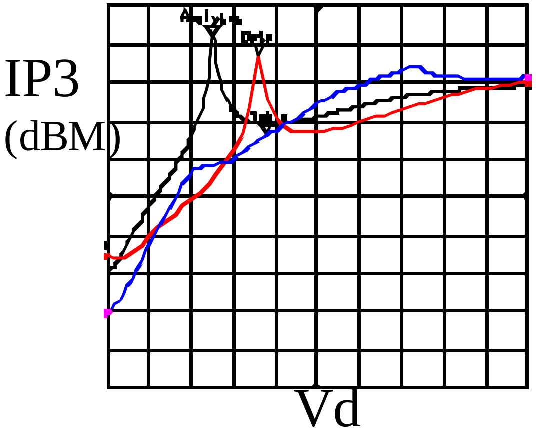


🟥 Data

🟦 HPFET table model

⬛ Curtice analytic model

(b) Vg=-1V Power=-20dBm

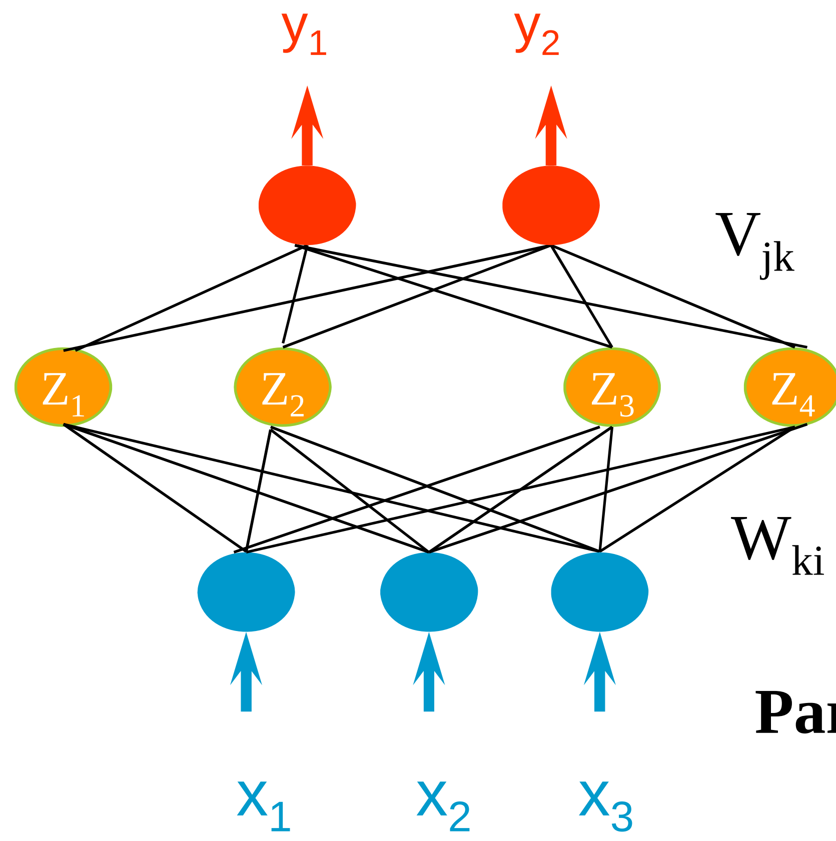


Simple Cubic Splines

- Third order derivative vanishes at symmetry points
- Low order polynomial can't predict high-order distortion at low amplitudes
  interpolation model is better when signal size ~ data spacing

Spline Alternatives: Artificial Neural Networks

$$y_i = F_i(x_1, x_1, x_3)$$



Outputs

↑

$$y_j = \sum_k V_{jk} Z_k$$

Hidden Neuron Output

$$Z_k = \tanh(\Sigma\, W_{ki}\, x_i)$$

↑

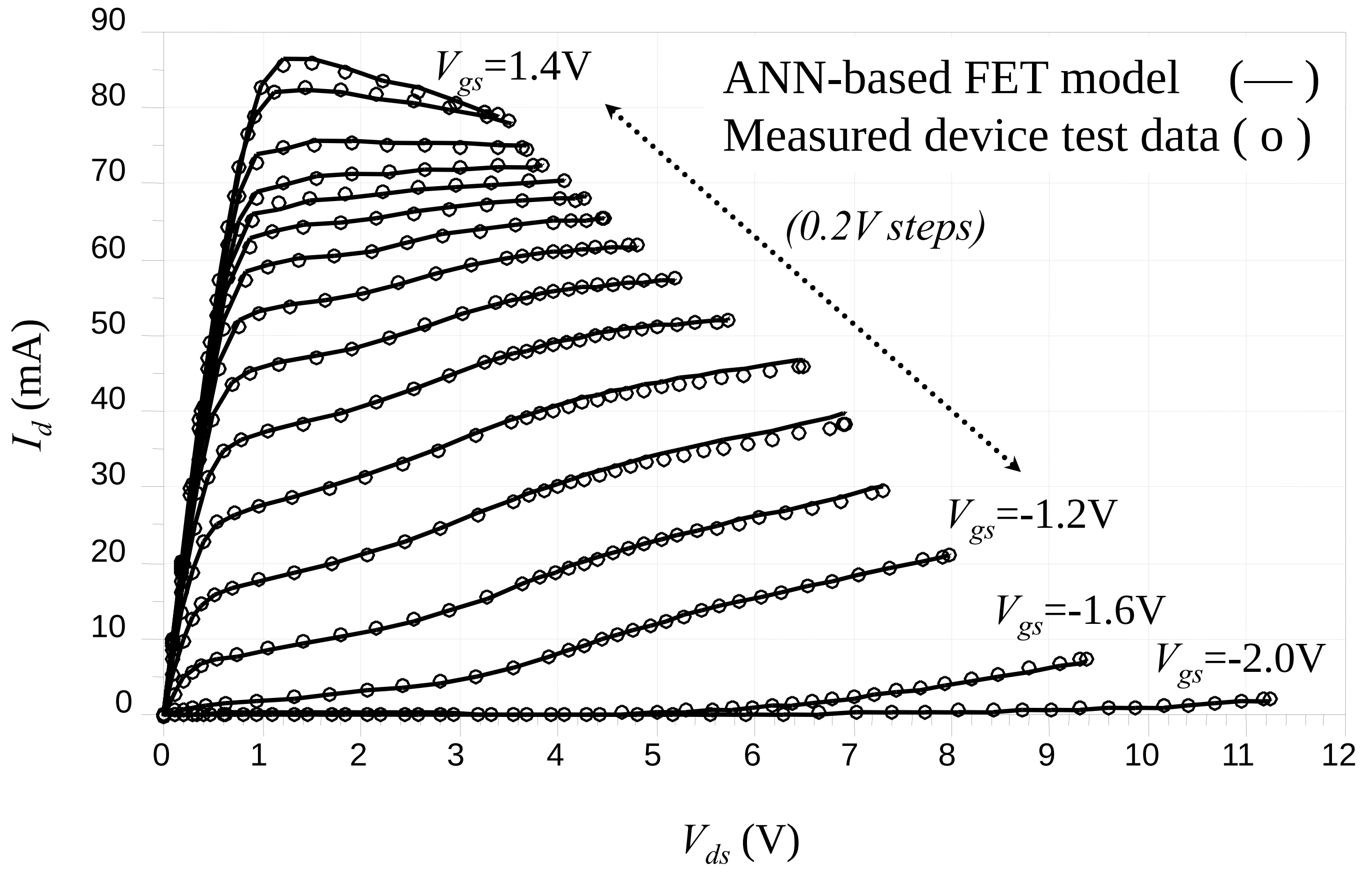
Parameters $w = [W_{ki}, V_{jk}]$

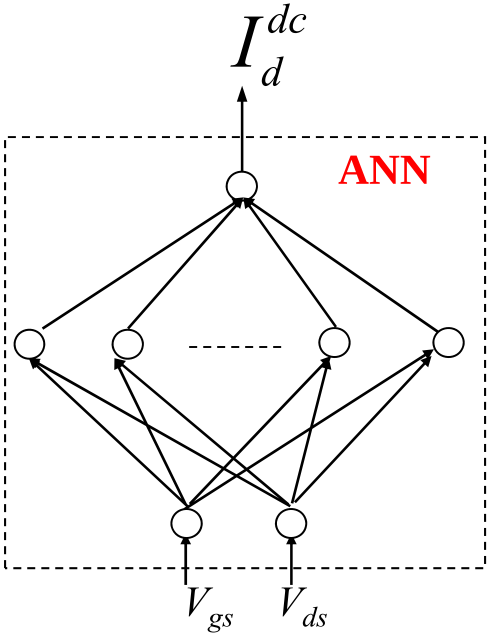
Inputs

- Universal Approx. Thm: Can fit any nonlinear function of many variables
- Infinitely differentiable: *better for distortion* than naïve splines
- Easy to train (identify) using standard third-party tools (MATLAB)

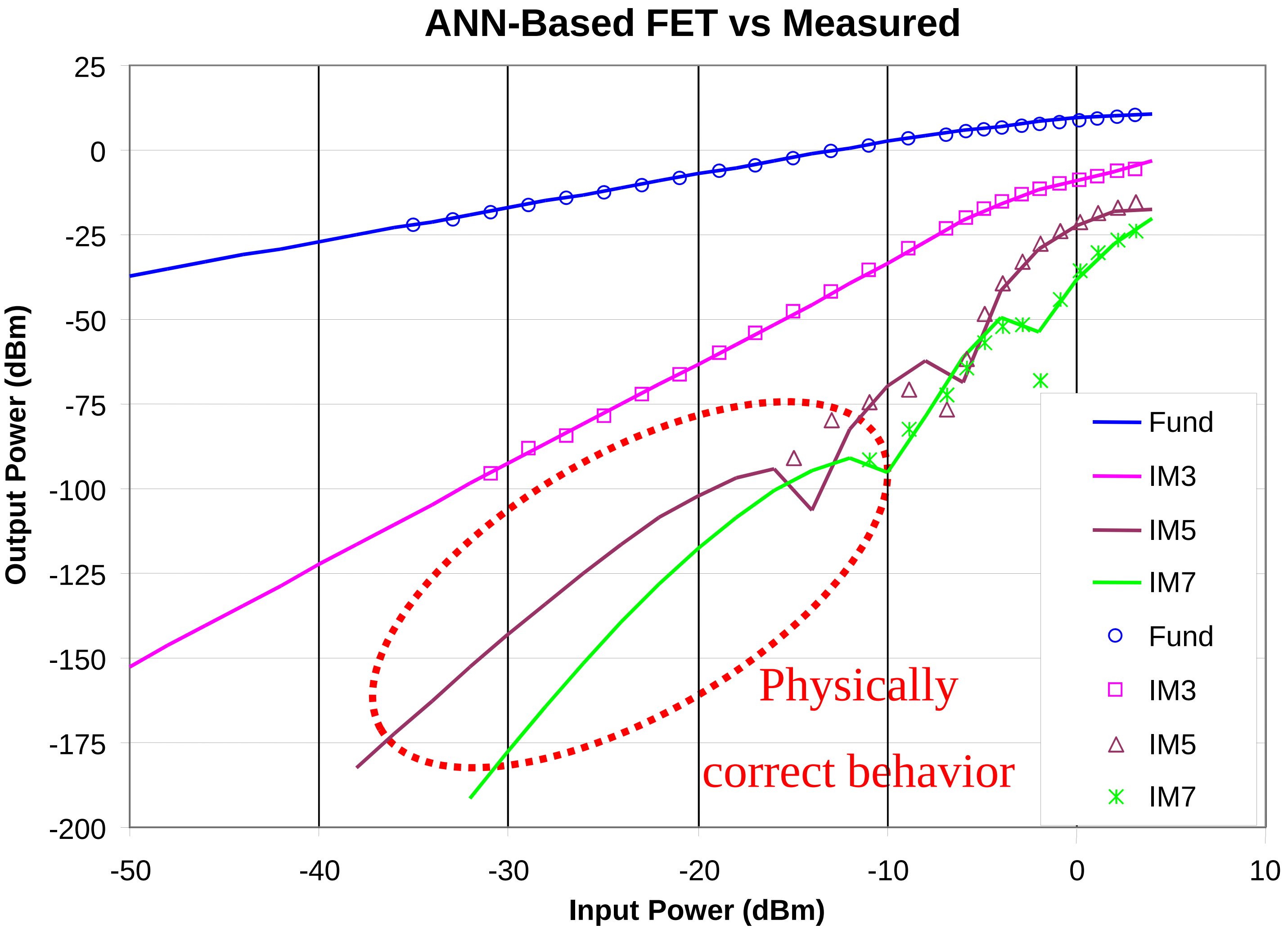
NeuroFET: FET Model using ANNs [43]

Constitutive Relations are ANNs!





NeuroFET Distortion Validation (2-tone) [43]

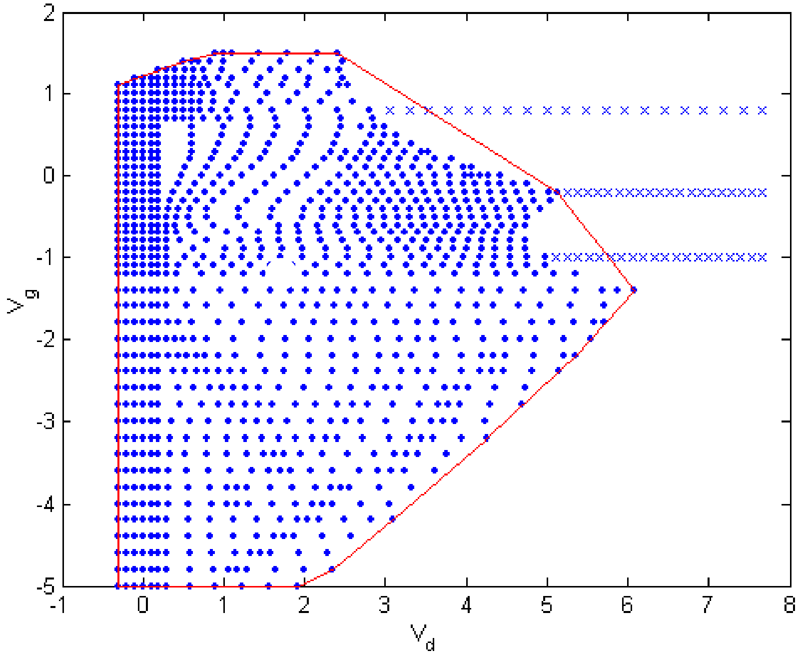


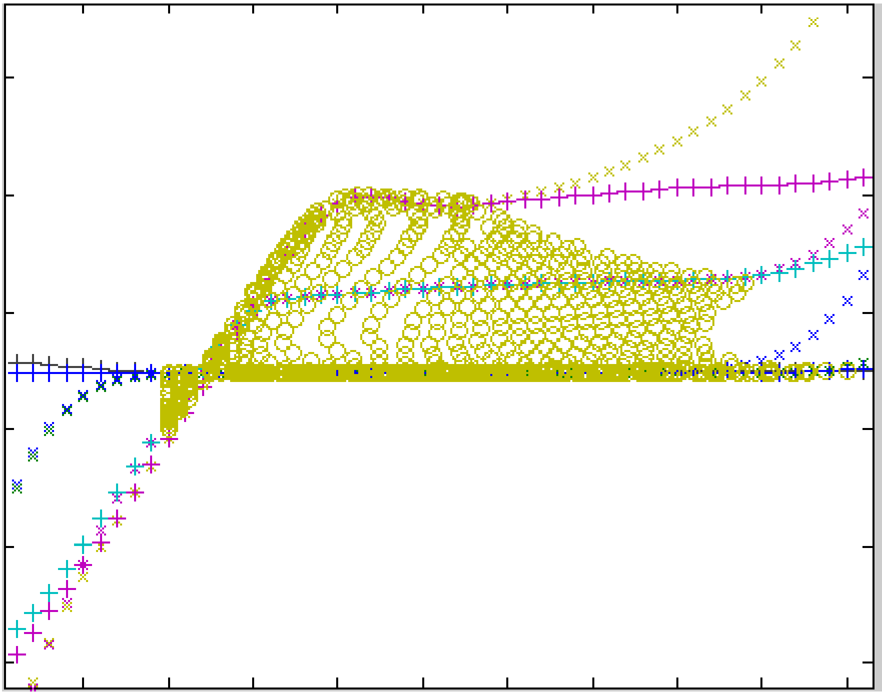
Alternatives to ANNs are “Smoothing Splines” [5] but they don’t have all the advantages

Global Domains for Measurement-based Models

Enables nonlinear simulation from discrete, bounded, measured data

ANNs inside, Intelligent Extrapolation outside [44]





Two orders of continuity at boundary

Asymptotically ~ exponential

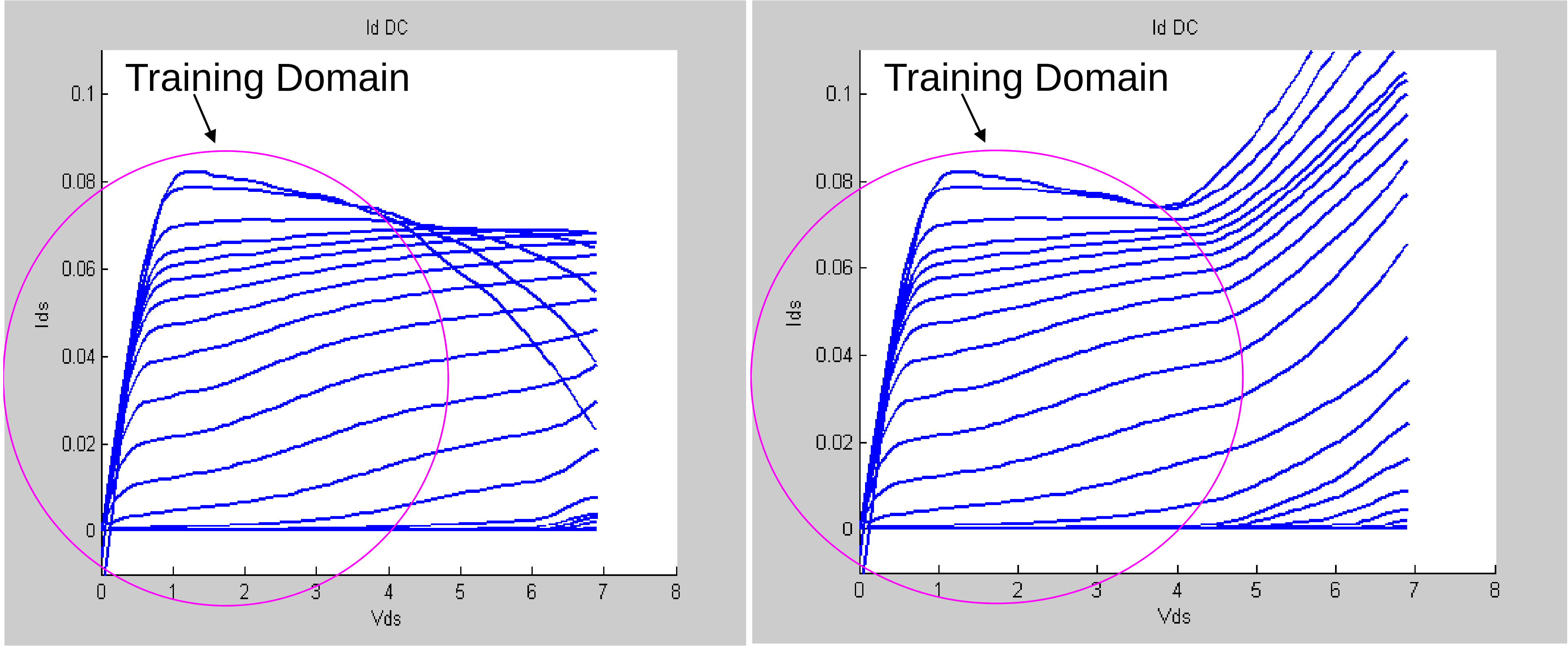
+ simpler algorithm

x robust algorithm

Required for robust convergence

Guided Extrapolation Algorithm *Compiled into Model*

Improves DC convergence, HB, TA range of use [45]



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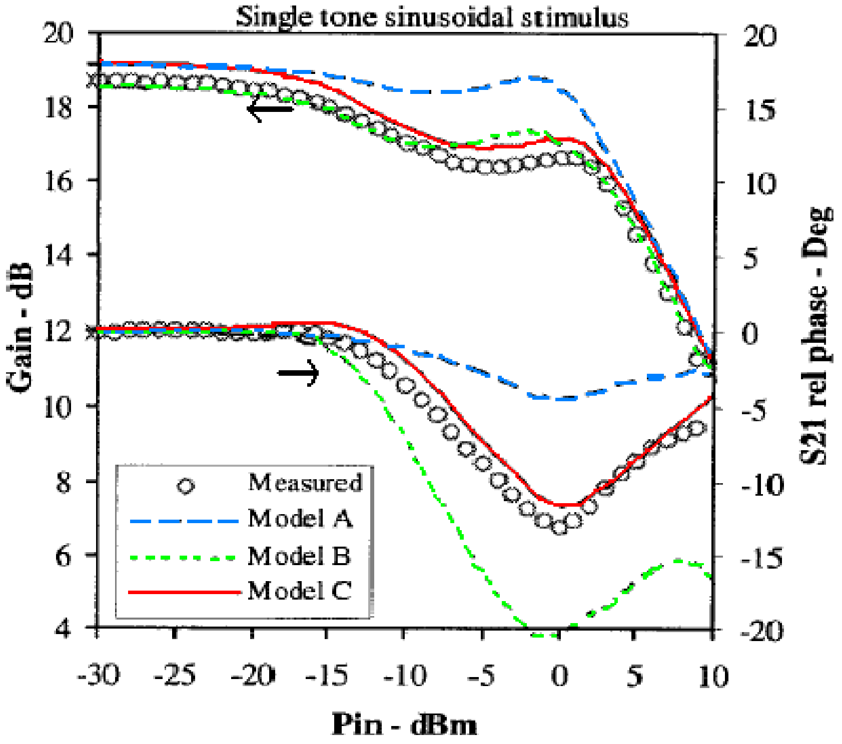
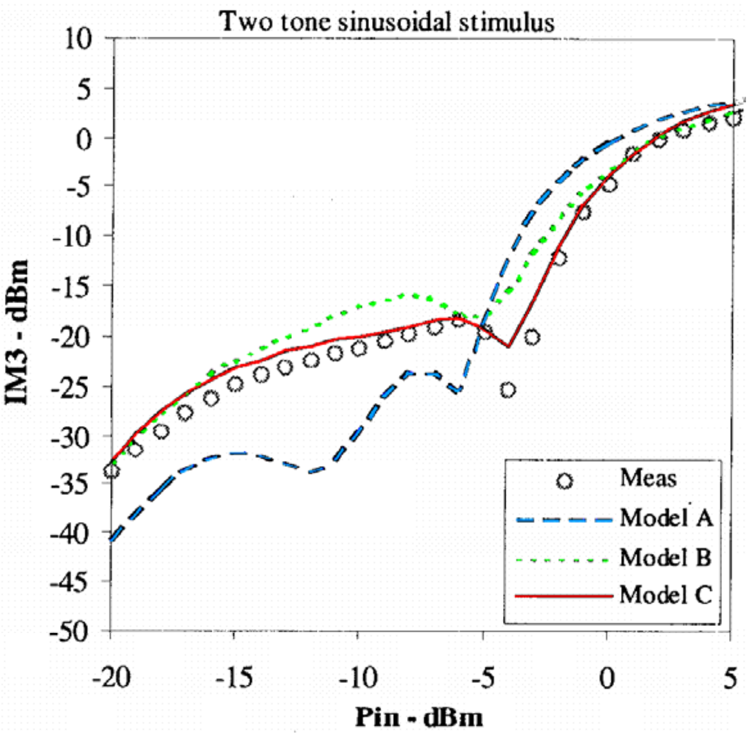
Artificial Neural Network applications given throughout

Charge Modeling: Key to Distortion at high frequencies [4]



Gain/Phase vs. P_{in}



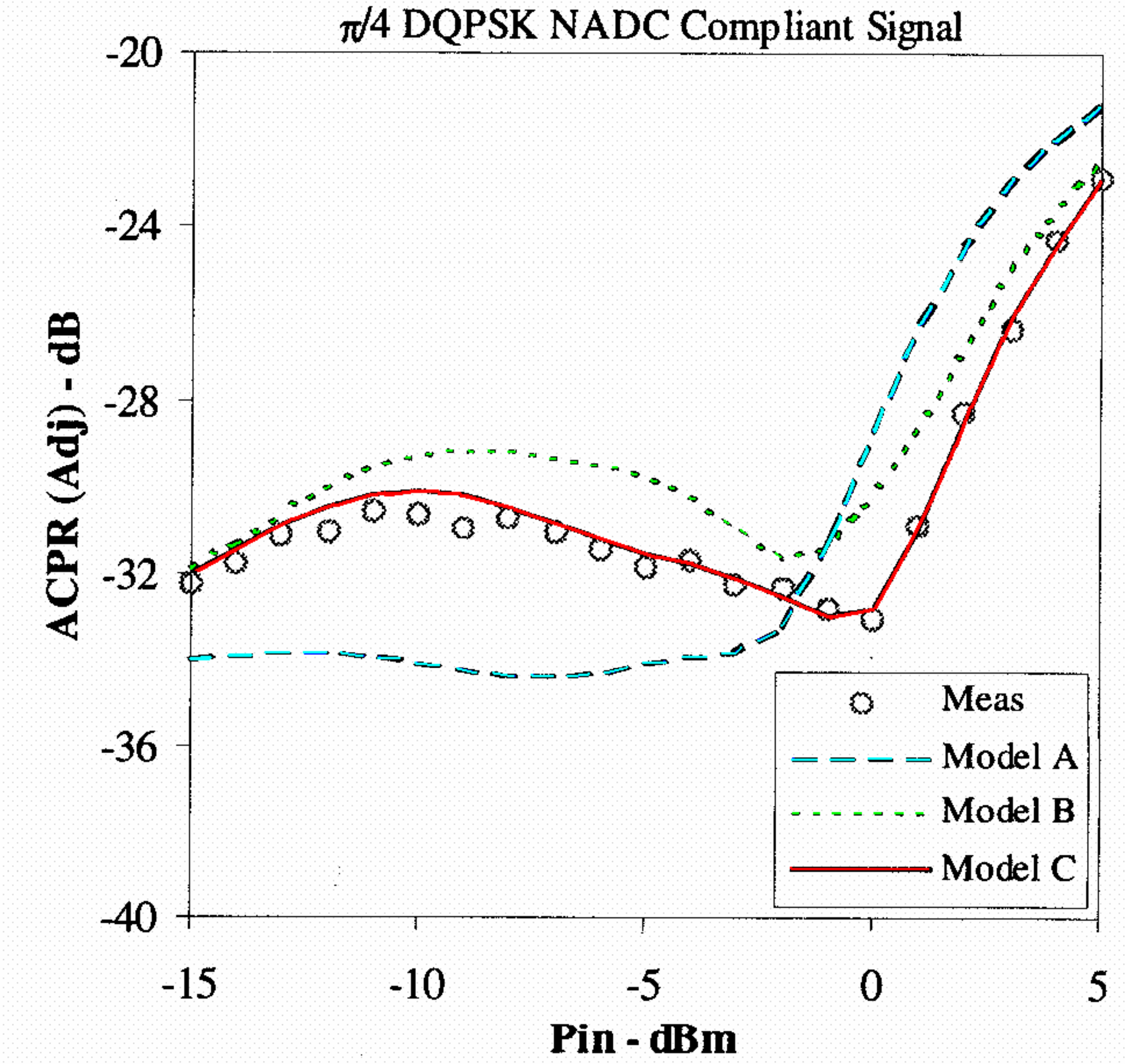
IM3 vs. P_{in}

Model A= Shockley **Model B = Statz[32]** **Model C =HP/AgilentFET [33]**

- All three models use the same DC analytical equations

[4] J. Staudinger, M.C. De Baca, R. Vaitkus, “An examination of several large signal capacitance models to predict GaAs HEMT linear power amplifier performance,” *Radio and Wireless Conference*, Aug. 1998 pp343-346.

Good Charge Model Required to Predict ACPR



Model A= Shockley junction capacitances

Model B = Statz/Raytheon gate terminal charge conserving but not terminal charge conserving at drain

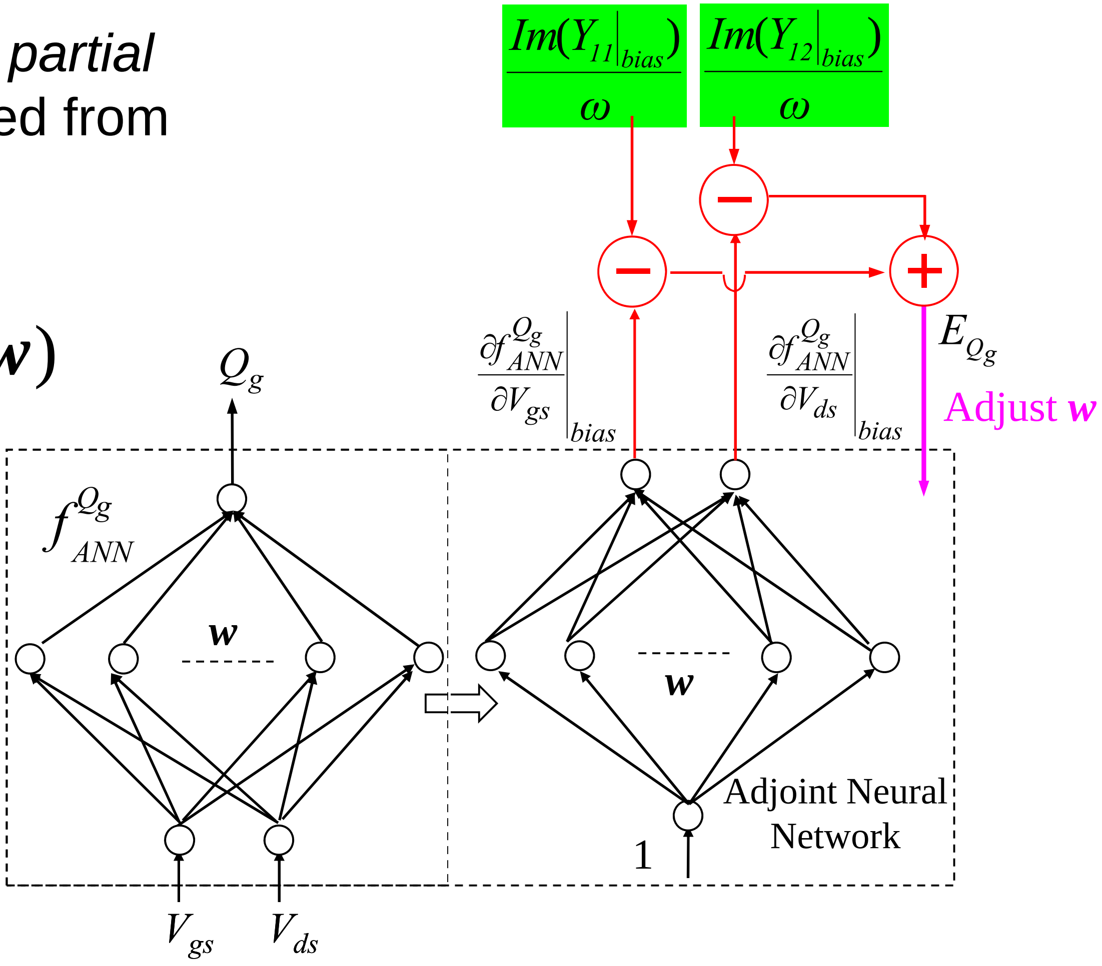
Model C =HPFET (Root model) terminal charge conserving model at both gate and drain by direct integration of measured admittances and spline interpolation

Adjoint Neural Network Training for Qg

Train Adjoint network on *partial derivative data* derived from S (Y) parameters

$$Q_g = f_{ANN}^{Q_g}(V_{gs}, V_{ds}, \mathbf{w})$$

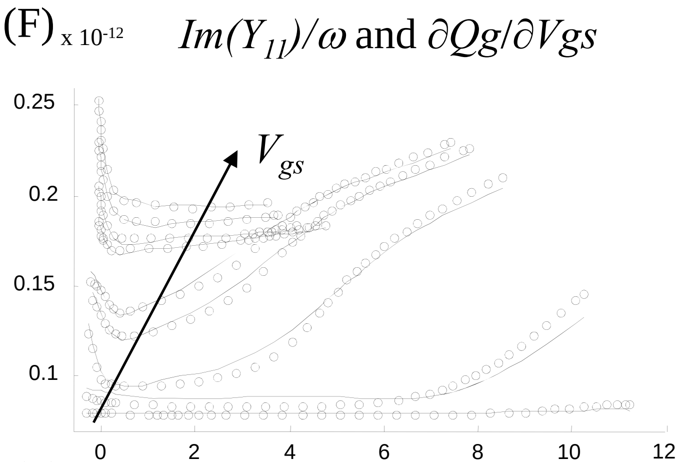
$$I_g(t) = \frac{dQ_g}{dt}$$

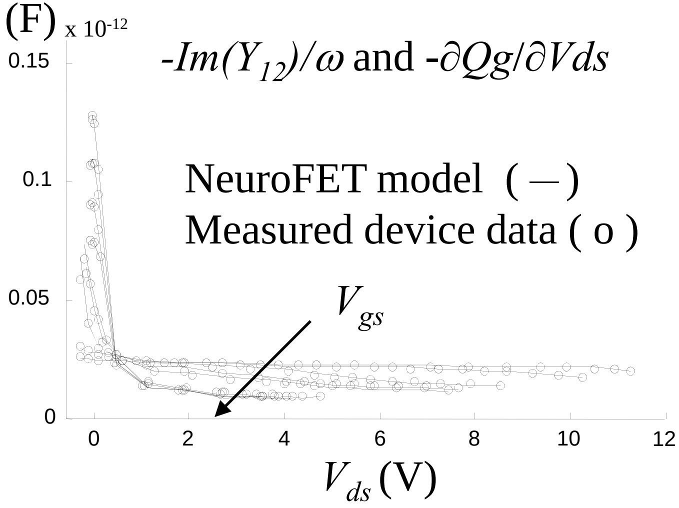


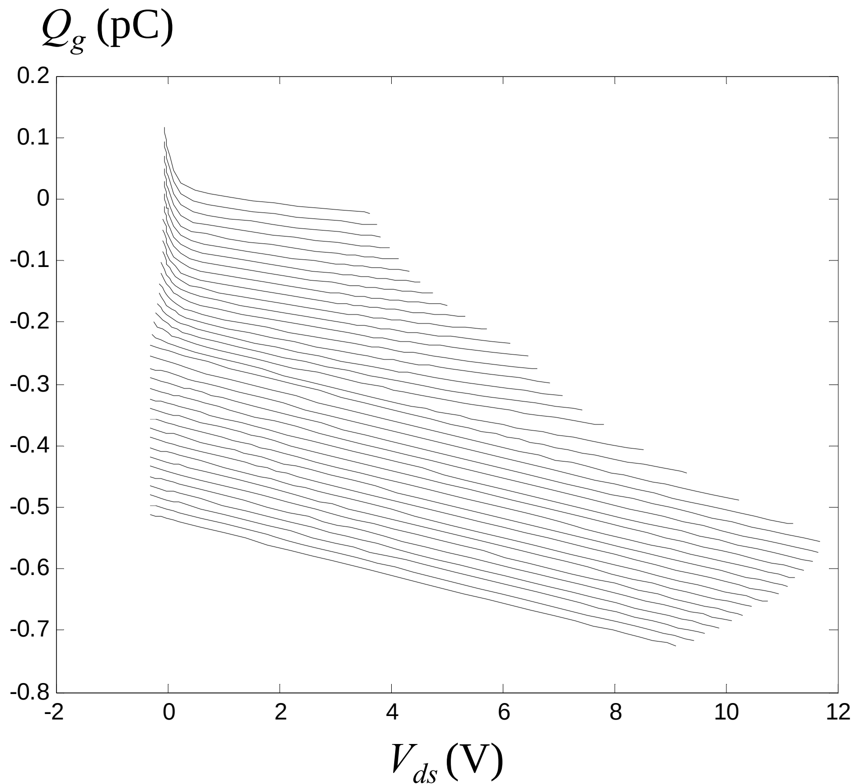
Jianjun Xu, M.C.E. Yagoub, Runtao Ding and Q.J. Zhang,
"Exact adjoint sensitivity analysis for neural based microwave modeling and design,"
IEEE Transactions on Microwave Theory and Techniques, vol. 51, pp.226-237, 2003.

Adjoint Neural Network Approach to Charge Modeling

Charge Q_g *obtained by Adjoint Training Methods* **[27,43]** (Generate an ANN function given *partial derivative data*)







Another experimental validation of *terminal charge conservation* at the gate for GaAs pHEMT

Advantages of Adjoint ANN over contour Integration

- More uniform approximation of terminal charges than implementations of contour integration
- Applies to scattered data. No gridding necessary.
- Results in infinitely differentiable charge function rather than finite-order spline representation
- More easily deals with complicated boundary of data domain
- More easily generalizes to higher number of terminals

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Artificial Neural Network applications given throughout

Dynamic electro-thermal (self-heating) model

$$I_d(t) = I_d(V_{ds}(t), V_{gs}(t), T(t))$$
$$Q_g(t) = Q_g(V_{ds}(t), V_{gs}(t), T(t))$$

Temperature evolution equation based on dissipated power

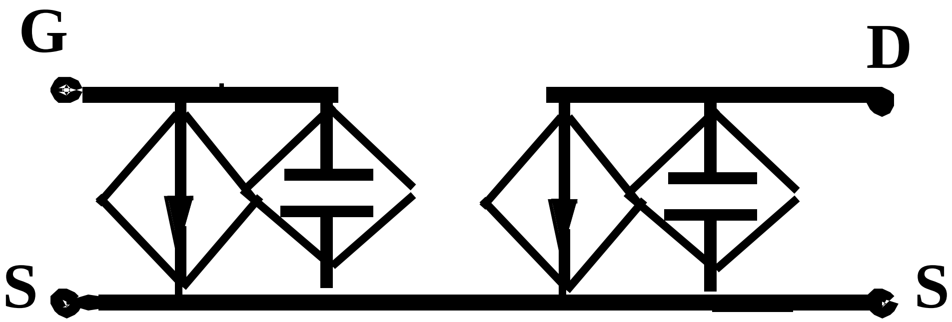
$$\tau \frac{dT}{dt} + \Delta T = R_{TH}\left(I_D(t)V_{DS}(t) + I_G(t)V_{GS}(t)\right)$$

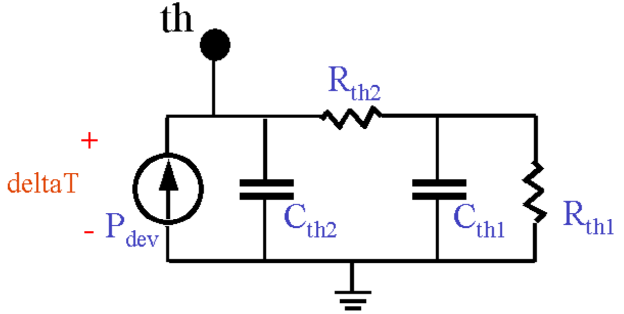
This example is a simplified to 1st order ODE
Heat propagates via diffusion Eqn. (PDE)

. Alternatively estimate T(t) as linear filter in frequency domain [34]
Trade off "fractional pole" response for nonlinearity

Dynamic electro-thermal (self-heating) model

Currents, Voltages, and Temperature calculated by the simulator *self-consistently* using *coupled electrical and thermal equivalent circuits*





Thermal Equivalent Circuit

$$T = T_{amb} + deltaT$$

$$Q_G(V_{GS}(t), V_{DS}(t), T(t)) \quad Q_D(V_{GS}(t), V_{DS}(t), T(t))$$

$$I_G(V_{GS}(t), V_{DS}(t), T(t)) \quad I_D(V_{GS}(t), V_{DS}(t), T(t))$$

Electrical Equivalent Circuit

Can approximate distributed nature of heat propagation by many sections

T=device junction temperature
T_{amb}=device ambient (backside) temperature

External node allows coupling to other heat sources

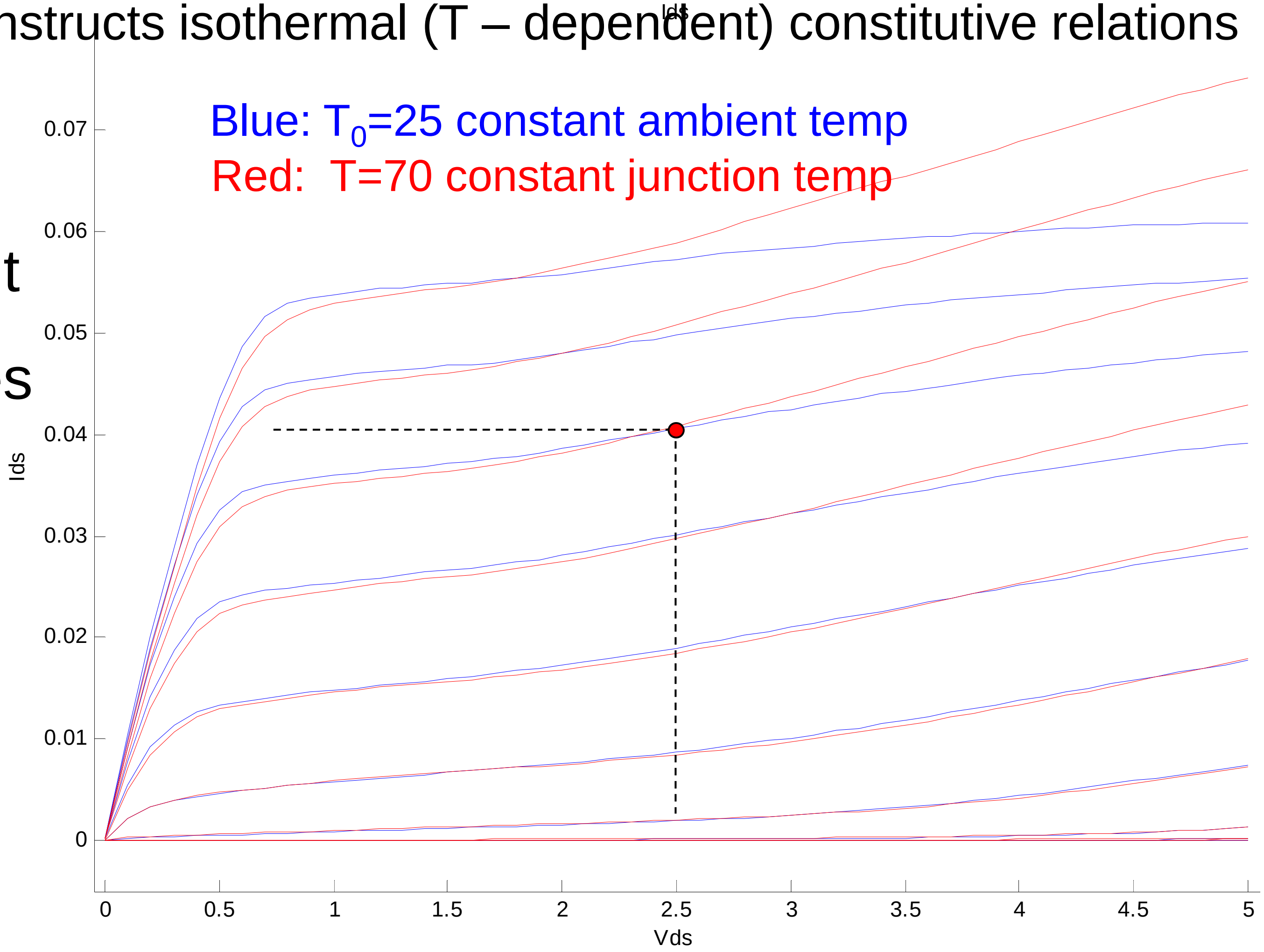
ANN T-dependent constitutive relations

Given measured non-isothermal ambient temp. (T_0 – dependence), one constructs isothermal (T – dependent) constitutive relations

NeuroFET

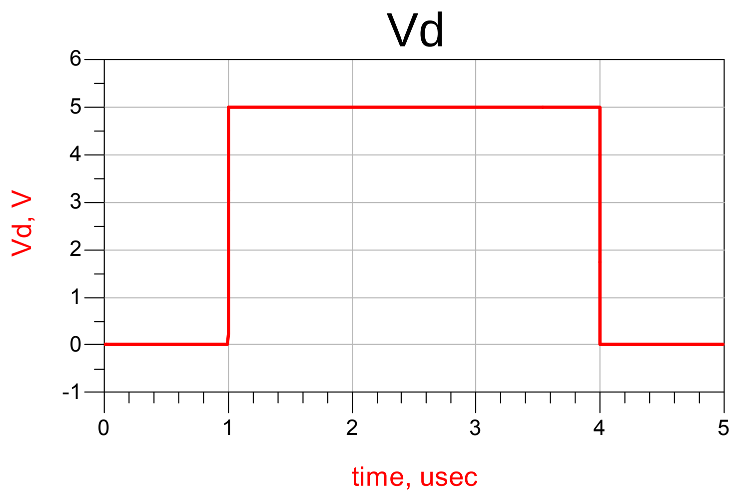
T-dependent

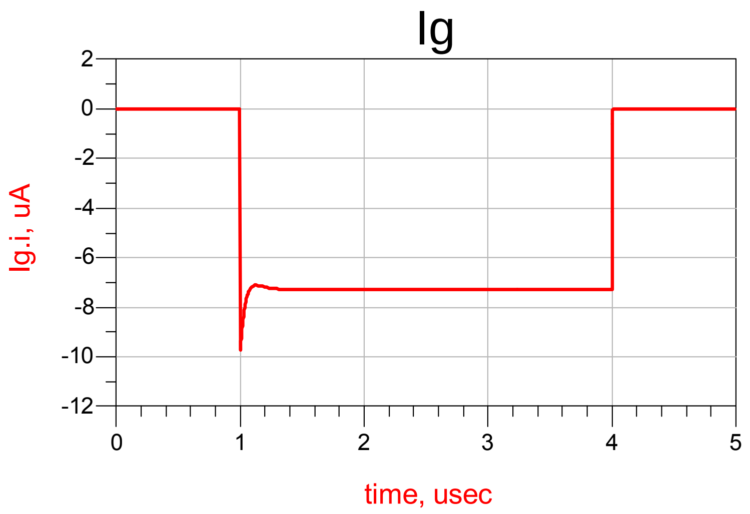
dc I-V curves

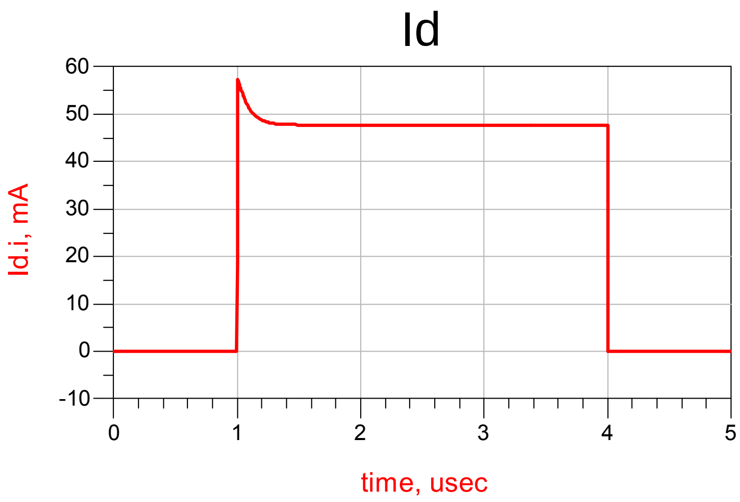


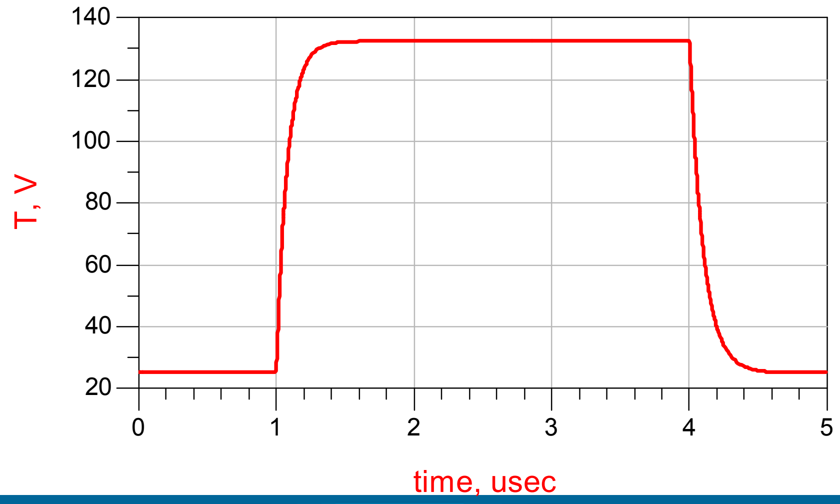
NeuroFET **dynamic self-heating results**

Fixed Vg

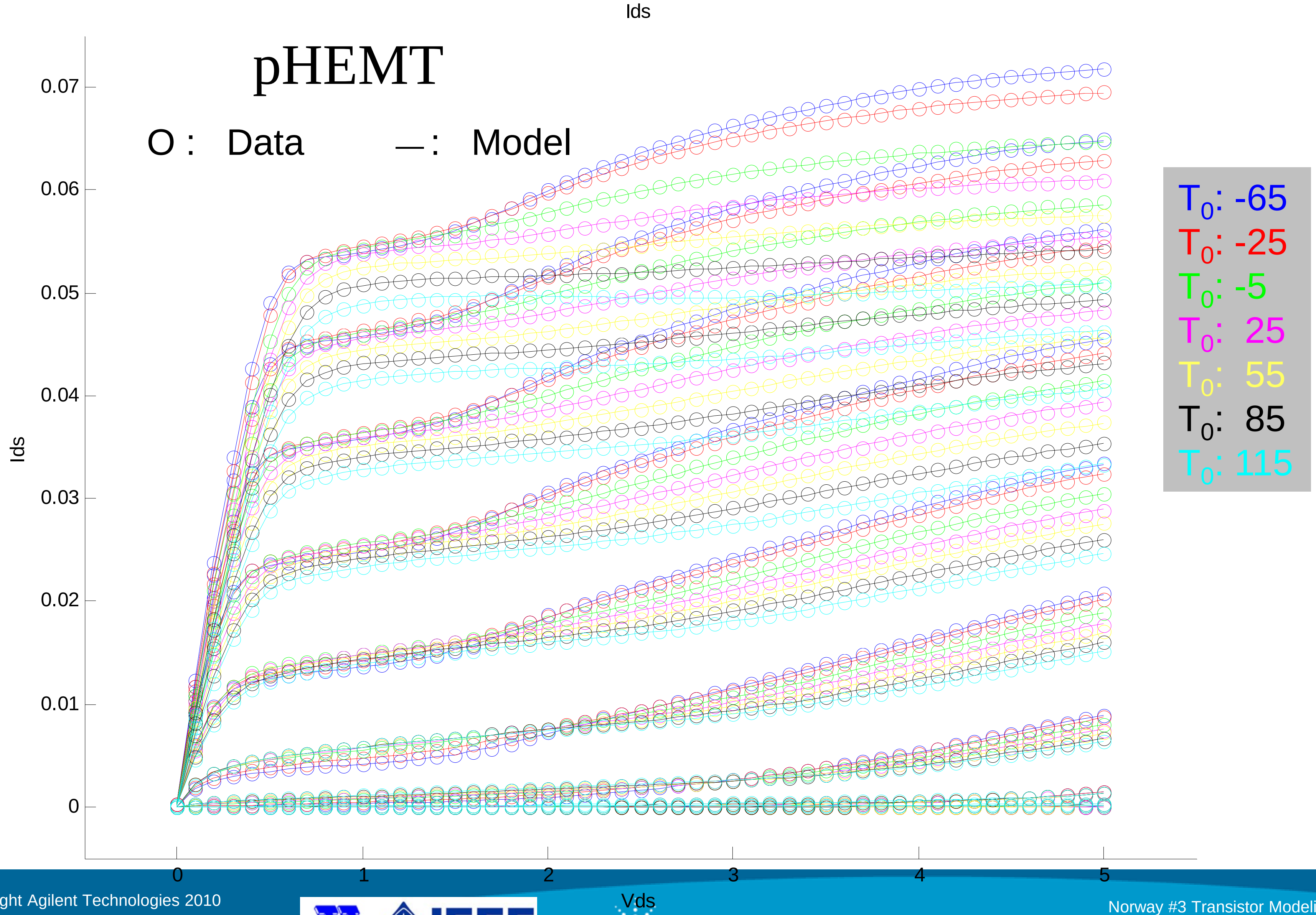








NeuroFET static self-heating

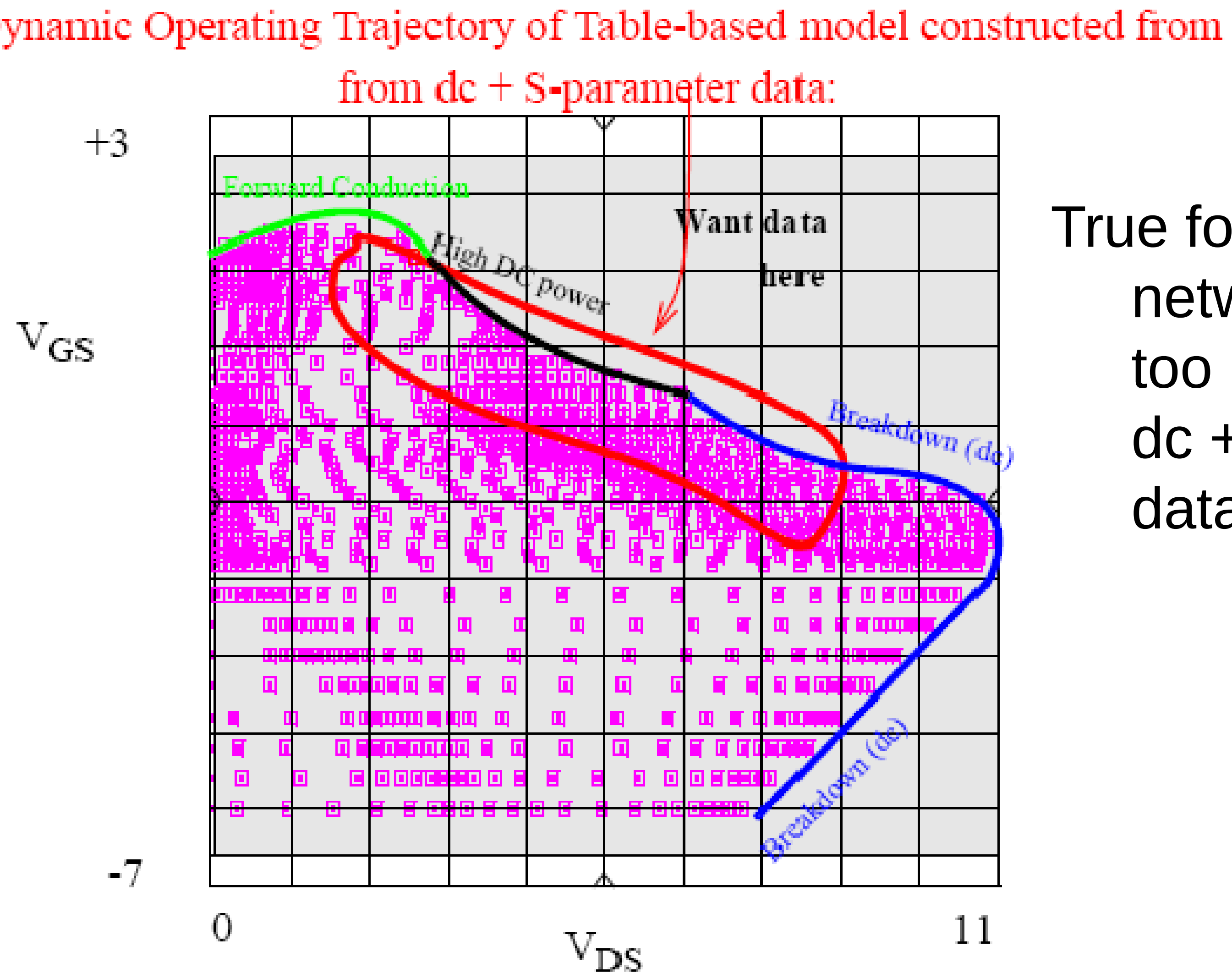


Presentation Outline

- Introduction
- I-V modeling
- Nonlinear Charge Modeling and Related Issues
- Non Quasi-Static Effects & Dispersion Modeling
- Electro-Thermal Modeling
- Advanced Measurements for Experiment Design & Model Identification
- Symmetry Considerations
- Summary & Conclusions

Artificial Neural Network applications given throughout

Need for Advanced Characterization for empirical Modeling [21]



True for neural network model too if built from dc + S-param data

GaN Devices

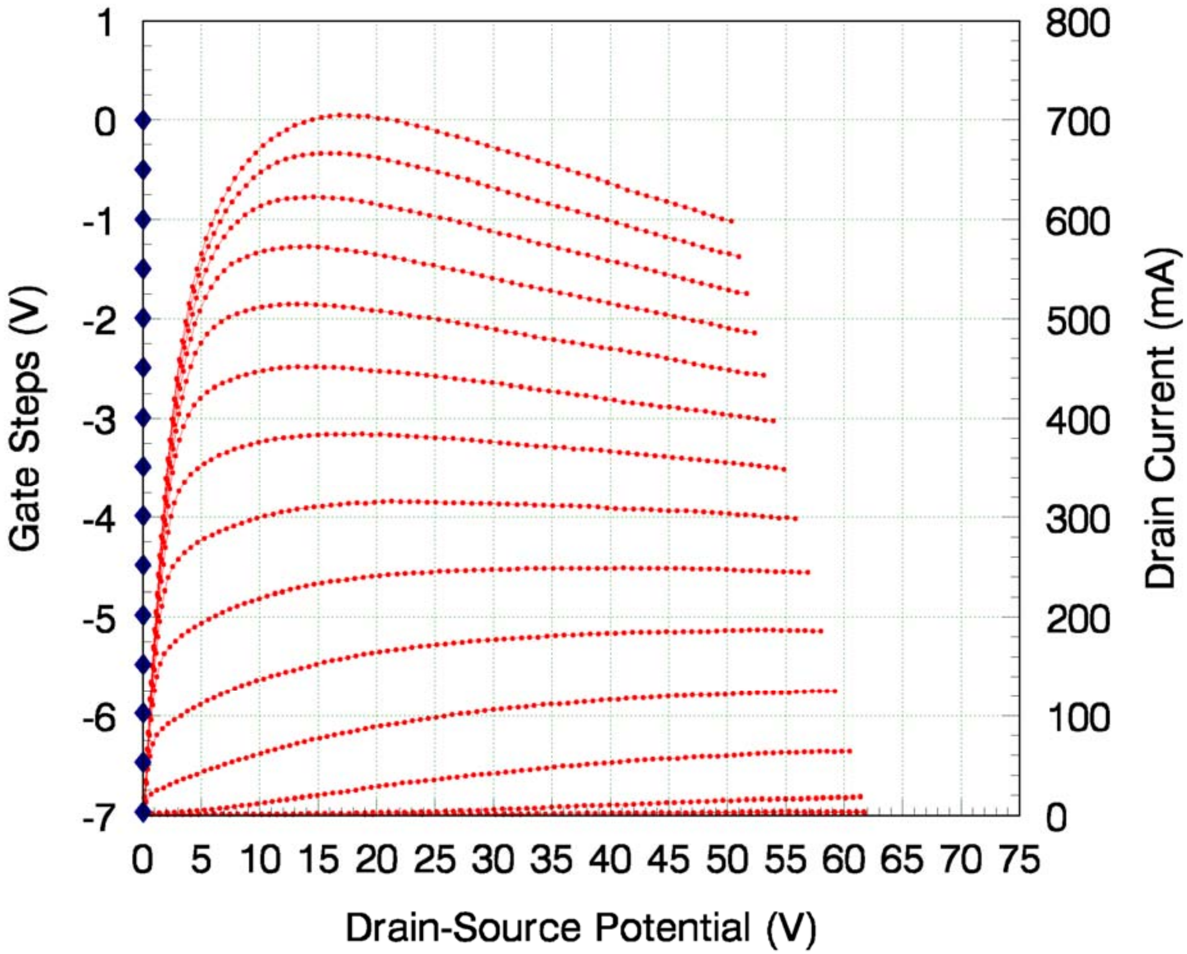
1 mm 10 fingers

GaN on Si

f_T ~ 30GHz

Pulse width 2us

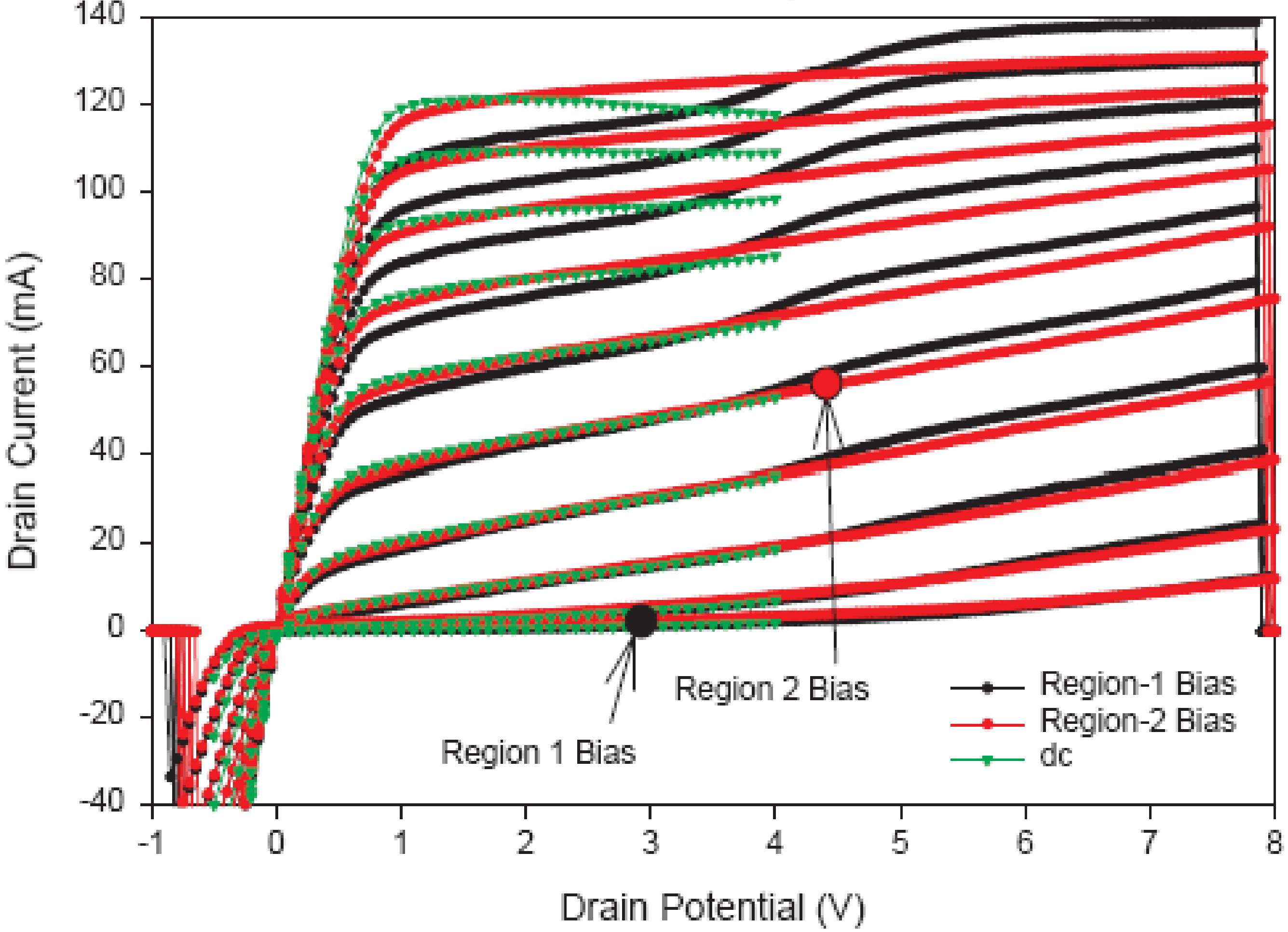
Slide courtesy J. Scott



Pulsed measurements provide much more data than can be measured under static (DC) conditions

Pulsed I-V characteristics at different quiescent points vs DC [1,21]

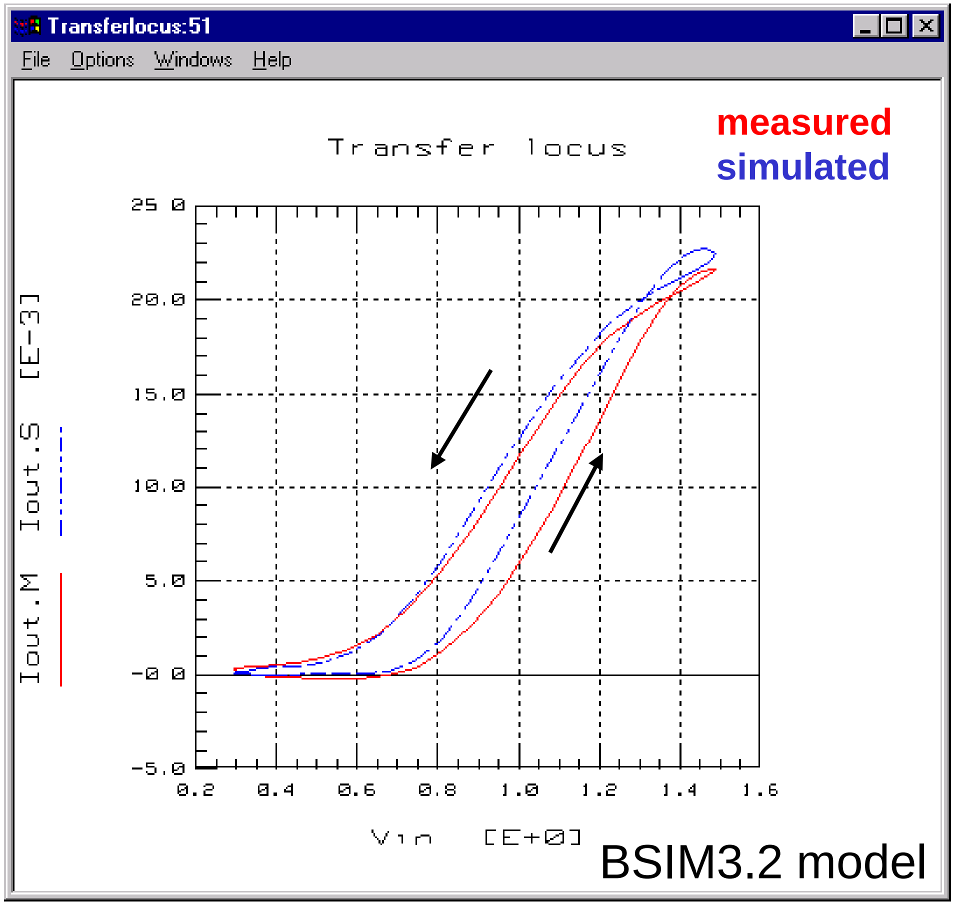
pHEMT device



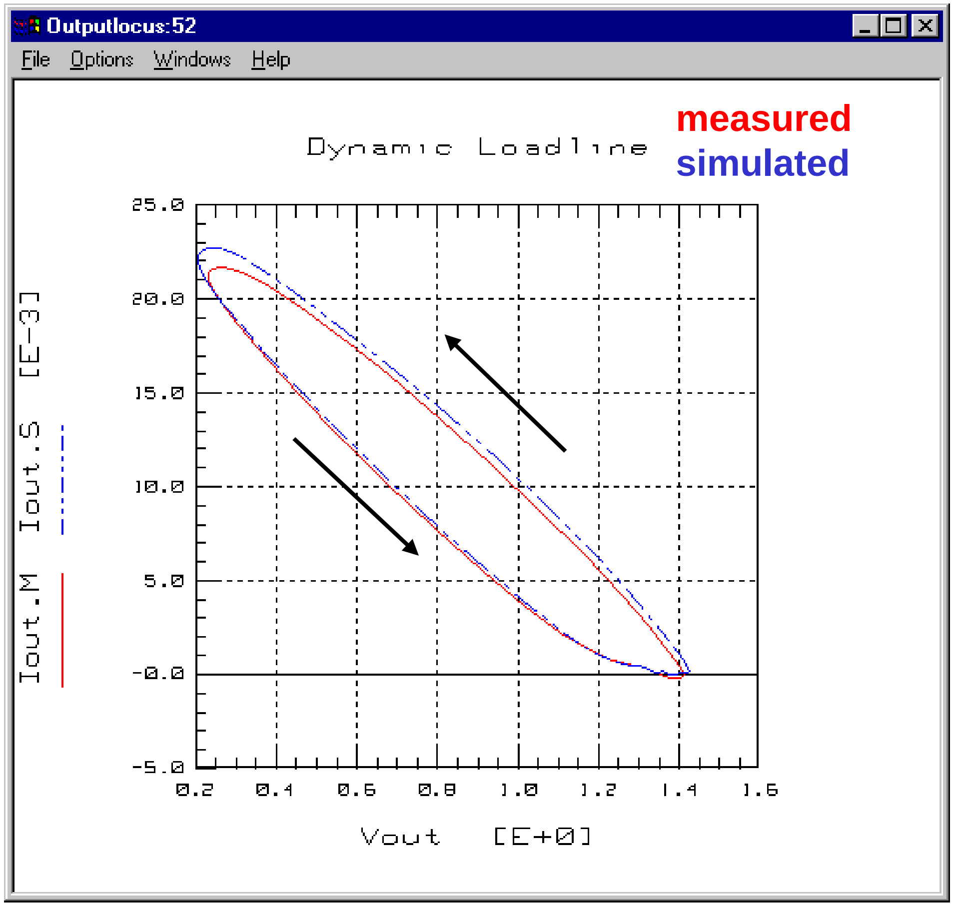
Nonlinear Vector Network Analyzer (NVNA) Measurements for Transistor Modeling:

- These measurements will compliment and eventually totally replace small-signal measurements for large-signal device model experiment design and model identification [36-38]. Such systems are also useful for *model validation.*
    - Stimulates device with more realistic signals
    - Reduce degradation of device characteristics from static measurements
    - Less reliance on inferring large-signal dynamic behavior from *linear small- signal measurements*
    - Some device properties may very different (breakdown, Ig, …)
    - Use to identify parametric (empirical) models or even train (generate) data-based models directly

(1a) NVNA data for compact model validation



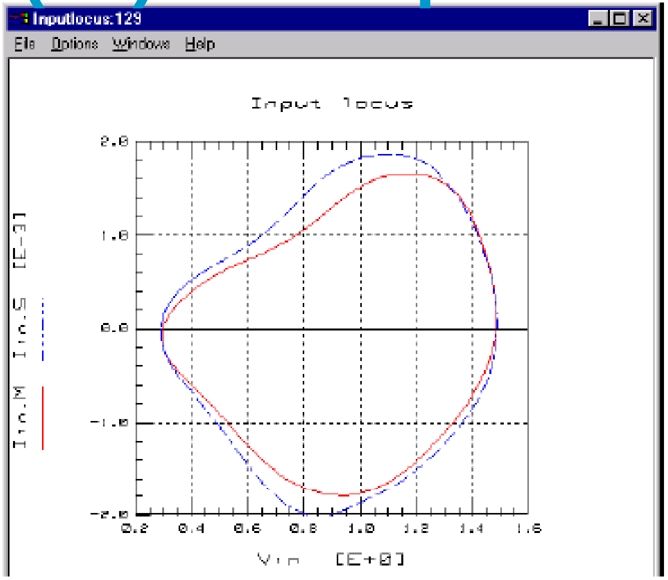
BSIM3.2 model



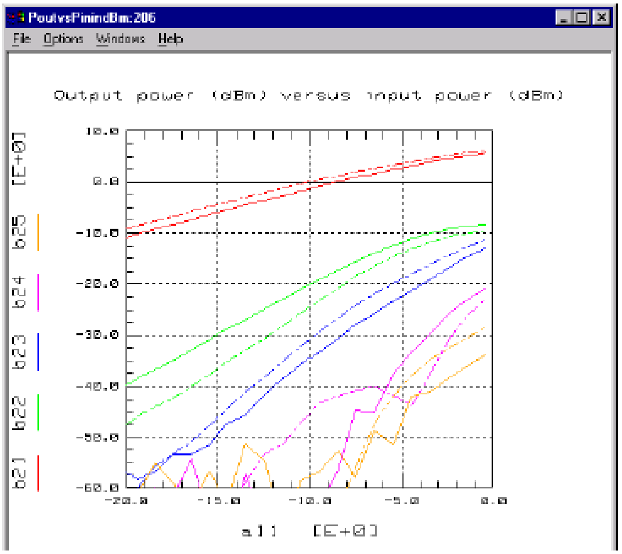
- Parameters extracted from DC and S-parameters (or CV)
- BSIM3 model simulated in Harmonic balance (HB) analysis
- Results compared with NVNA data

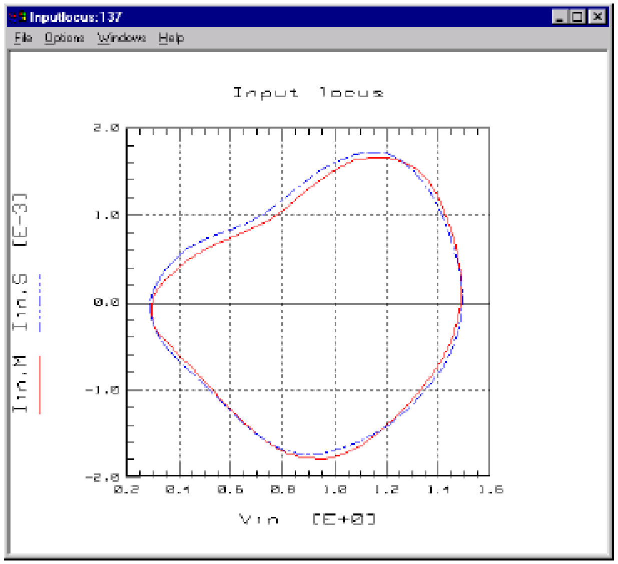
Slide courtesy of Franz Sischka, data from [51]

(1b) Model parameter extraction from NVNA Data [51]



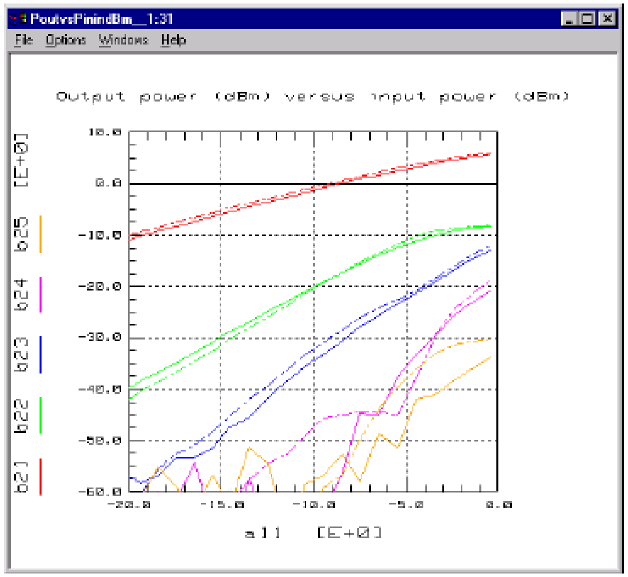
NVNA data vs HB simulation using initial parameter values extracted from DC + CV



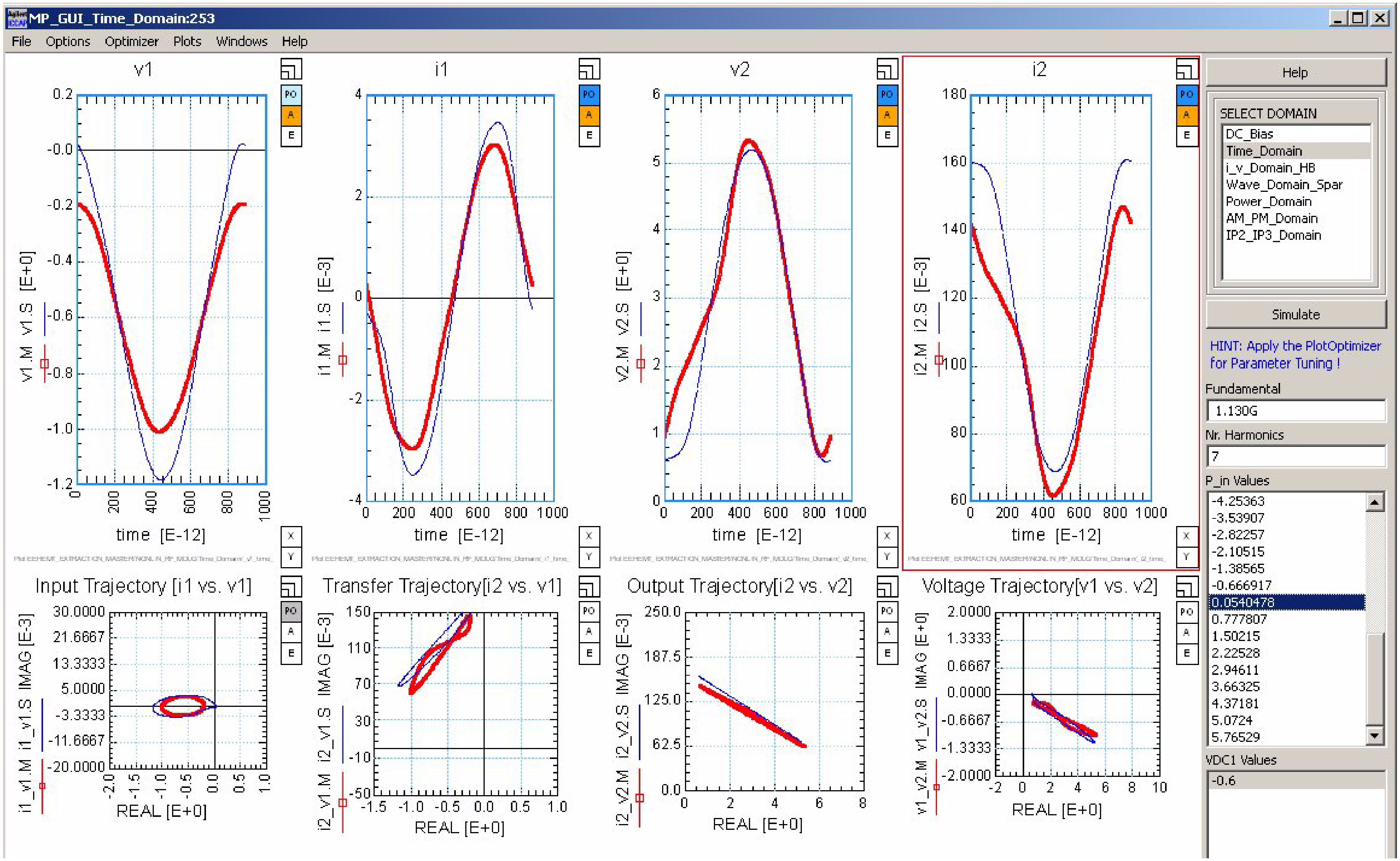


Modify parameter values (optimize) to *better fit* large-signal NVNA data

- Get optimal parameter set for given model
- trade-off DC, SP, for nonlinear performance
- App-dependent tuning
- Explore model limits



Parameter extraction from NVNA data



SELECT DOMAIN
- DC_Bias
- Time_Domain
- i_v_Domain_HB
- Wave_Domain_Spar
- Power_Domain
- AM_PM_Domain
- IP2_IP3_Domain

HINT: Apply the PlotOptimizer for Parameter Tuning !

Fundamental: 1.130G

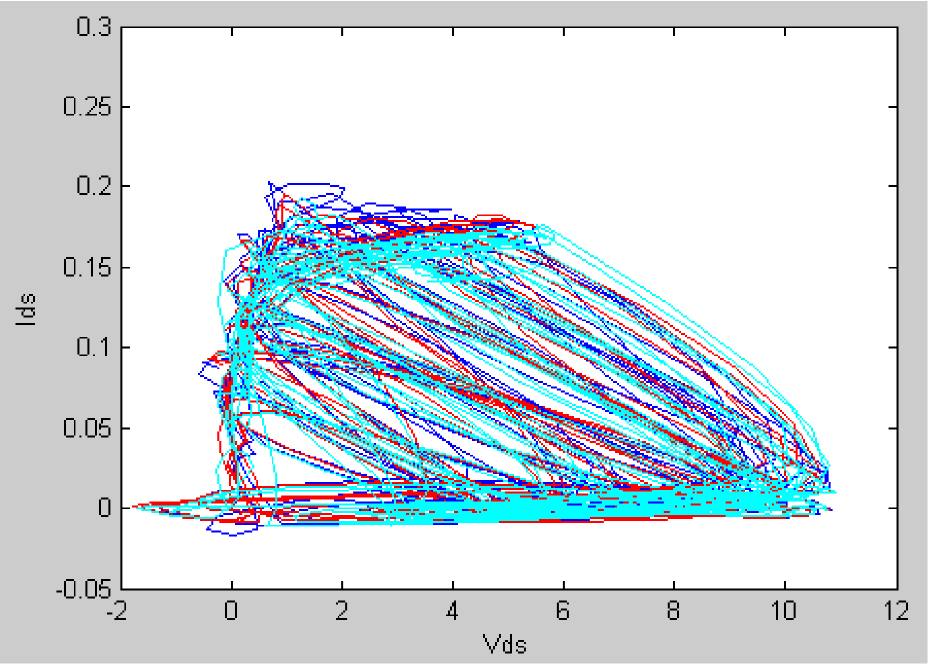
Nr. Harmonics: 7

P_in Values
-4.25363
-3.53907
-2.82257
-2.10515
-1.38565
-0.666917
0.0540478
0.777807
1.50215
2.22528
2.94611
3.66325
4.37181
5.0724
5.76529

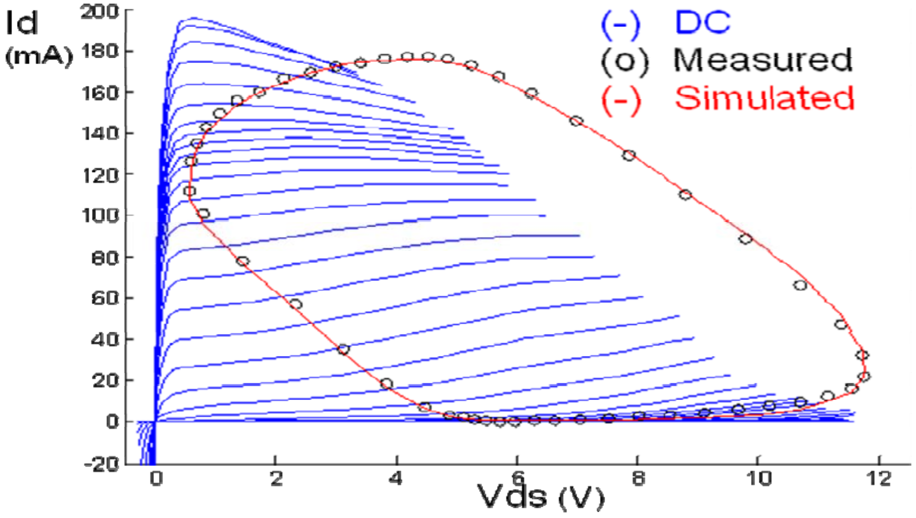
VDC1 Values: -0.6

Slide courtesy Franz Sischka

Examples of measured dynamic load-lines using NVNA for advanced FET model construction



Root et al INMMiC2010 [52]
Xu et al IMS2010 [53]

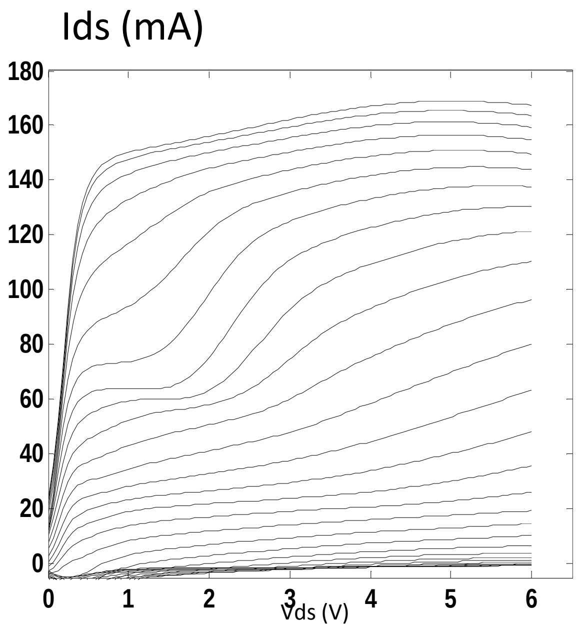


- Entire operating range covered
- Can measure into limiting operating regions
- Get data under realistic operating conditions

Model I-V characteristics at different trap-states

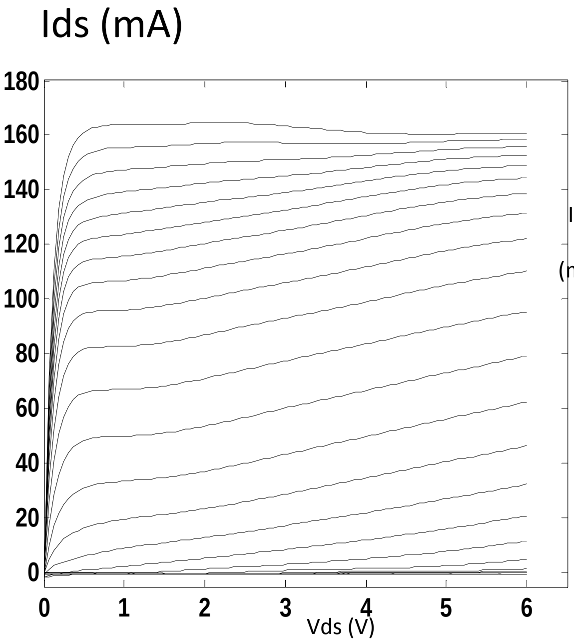
$$I_D(V_{gs}(t), V_{ds}(t), T_j, \varphi_1, \varphi_2)$$

Xu et al IMS2010 [53]



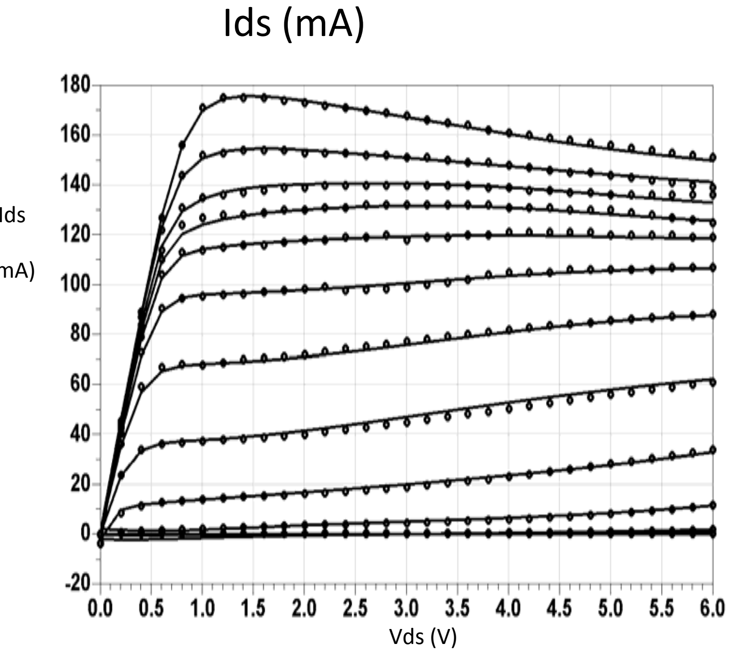
Corresponds to *drain-lag* (knee walk-out) (intrinsic)

Trap state $\varphi_1 = -2 \quad \varphi_2 = 8$



Static “Iso-thermal” intrinsic I-V

$\varphi_1 = Vgs \quad \varphi_2 = Vds \quad T_j = 65$

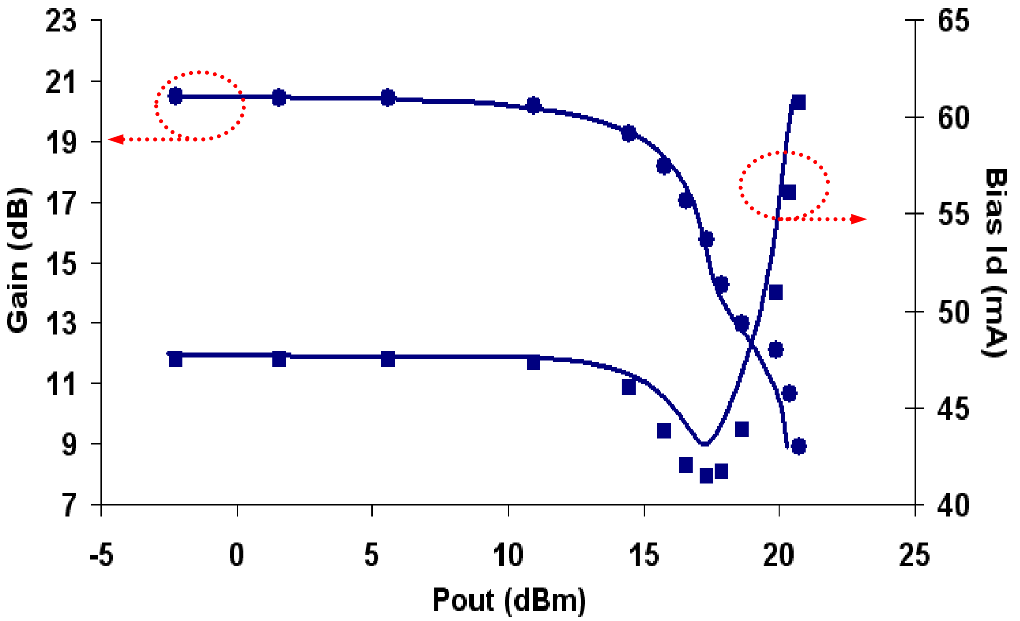


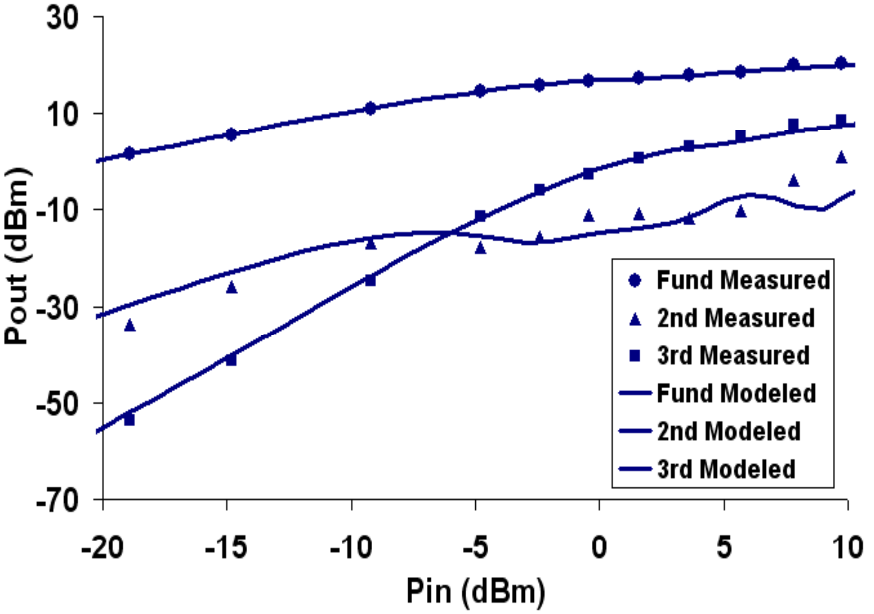
Measured and simulated extrinsic DC - IV

Bias-dependent small-signal admittances fit better everywhere

Nonlinear validation of advanced GaAs FET model (using NVNA data)

Xu et al IMS2010 [53]

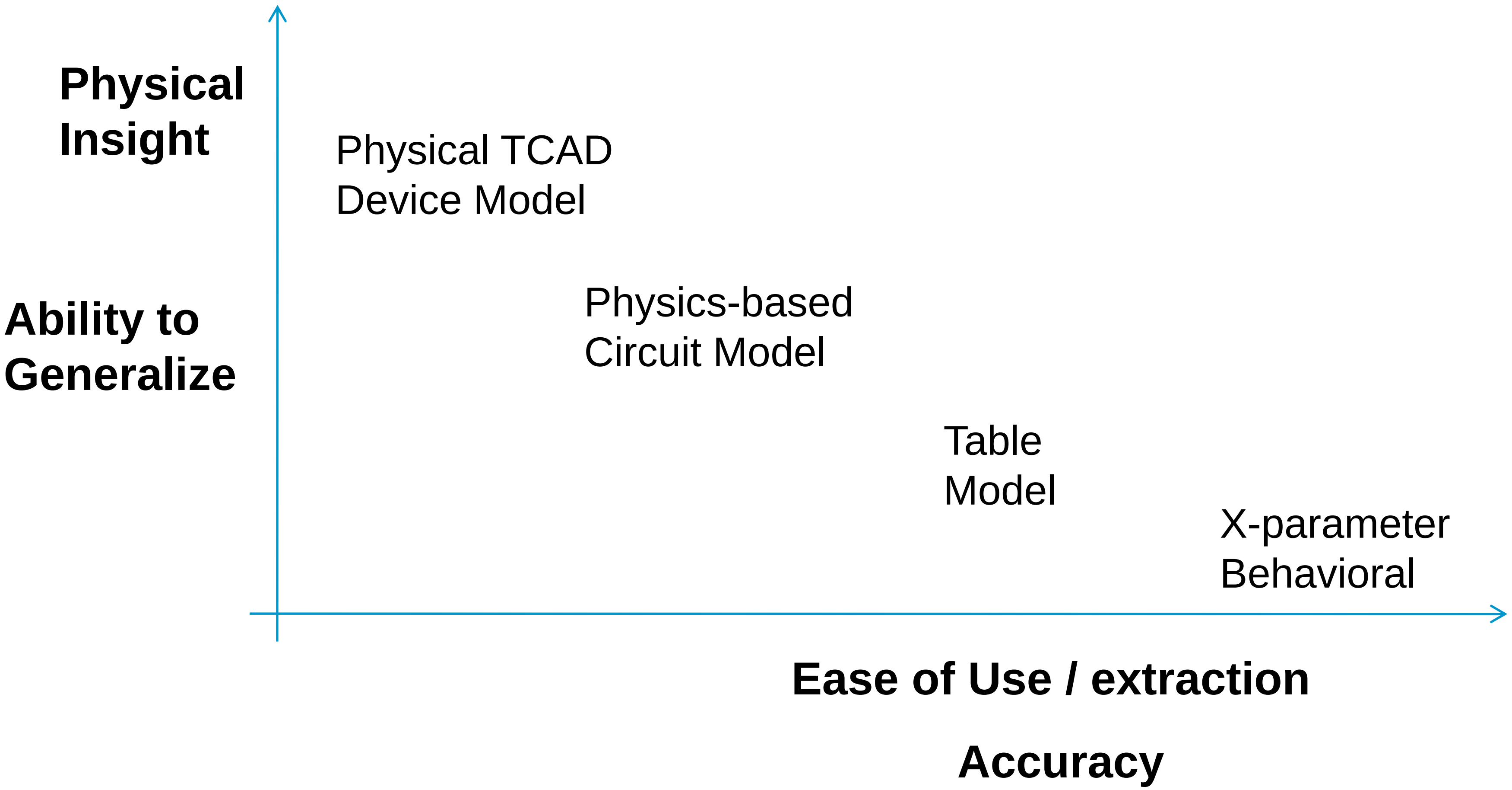




Simulated (—)
Measured data (symbols)

With NVNA, Nonlinear validation ***comes for free***

Tradeoffs



Physical Insight

Ability to Generalize

Physical TCAD
Device Model

Physics-based
Circuit Model

Table
Model

X-parameter
Behavioral

Ease of Use / extraction

Accuracy

Conclusions

- Physical, Empirical, Table-based, and Behavioral models (e.g. X-parameters) of transistors all have their place in device modeling
- Advanced characterization techniques and instruments (e.g. NVNA) will change the paradigm for nonlinear device modeling and validation. This is a key industry trend.
- Modeling is a rigorous and complex process. Good results take time, expertise, good measurements, and care.

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