Paper 1a.3

A Hybrid Physical ASM-HEMT Model Using a Neural Network-Based Methodology

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Outline

- Motivation
- Hybrid Physical Modeling
- Model Extraction Flow
- Model Validation
- Summary

GaN Addresses High-Performance Needs

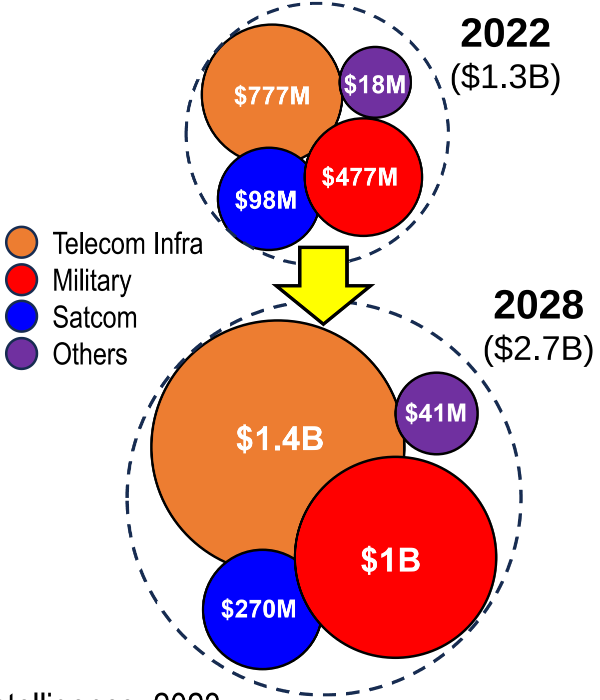
- **GaN HEMTs provide high P_{out} & PAE at mm-wave frequencies**

Properties of RF Semiconductors

Material Properties	Si	InP	GaAs	GaN
Bandgap, E_g (eV)	1.12	1.34	1.42	**3.49**
Critical Breakdown Field, E_{crit} (MV/cm)	0.3	0.5	0.4	**3.3**
Mobility, μ (cm^2 / V·s)	1500	5400	8500	**2000***
Peak Saturation Velocity, v_{sat} ($x10^7$ cm/s)	1	3.3	2.0	**2.5**
2DEG Density, n_s ($x10^{13}$ cm^{-2})	N/A	0.3	0.2	**> 1.5**
Thermal Conductivity, k (W/cm·K)	1.3	0.7	0.5	**2**
Dielectric Constant, ε_s	11.7	12.5	12.9	**9.5**
Johnson FoM Relative to Si ($E_{crit} \cdot v_{sat} / 2\pi$)	1	5.8	2.7	**28**

*2DEG Mobility

RF GaN Market Forecast



Yole Intelligence, 2023

Measurement vs. Physics-Based Models

- **Two prevalent modeling schemes at opposite ends of the spectrum**
- **Various trade-offs:** None satisfy a modeling engineer's ideal wish list ☹

Key Features	Measurement-Based	Physics-Based
CMC approved	X	✓
Good physical behavior outside extraction range	X	✓
Geometry Scalable	~	✓
Fast extraction / training time	~	~
Early availability during process development	✓	X
Does not require process information	✓	X
One-size-fit-all modeling solution	✓	X

Hybrid Physical Modeling Methodology

Physical Model

- Captures basic device physics
- Show good physical responses when simulated beyond the measurement range

ANN Model

- Early availability during process development
- Can fit complex nonlinear measured data
- Short model development time for new technologies

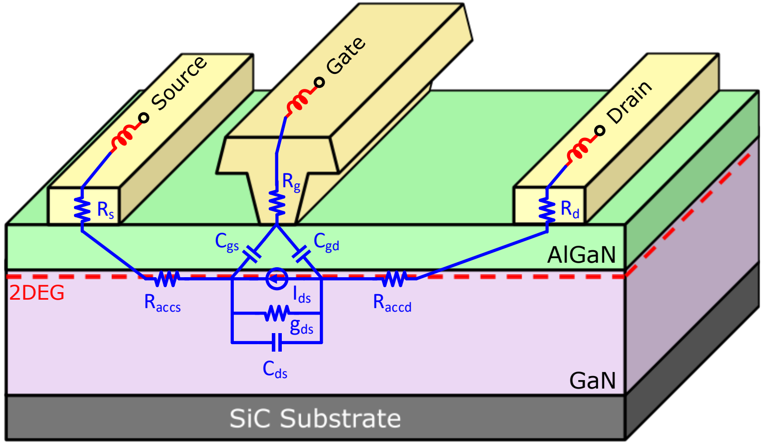
Hybrid Model:

- Combine physical model with neural networks
- Maintains physics with increased accuracy

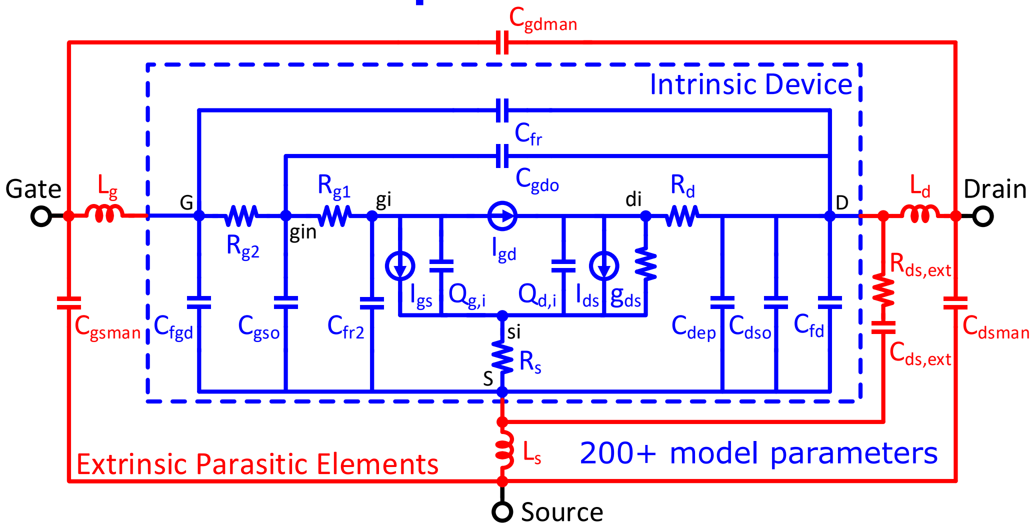
The Advanced SPICE Model for HEMTs

- **ASM-HEMT:** Surface-potential-based physical compact model
- **Model effectively captures a range of device non-idealities:**
  - Self-heating, mobility degradation, DIBL, velocity saturation, trapping, etc.

GaN Device Cross-Section

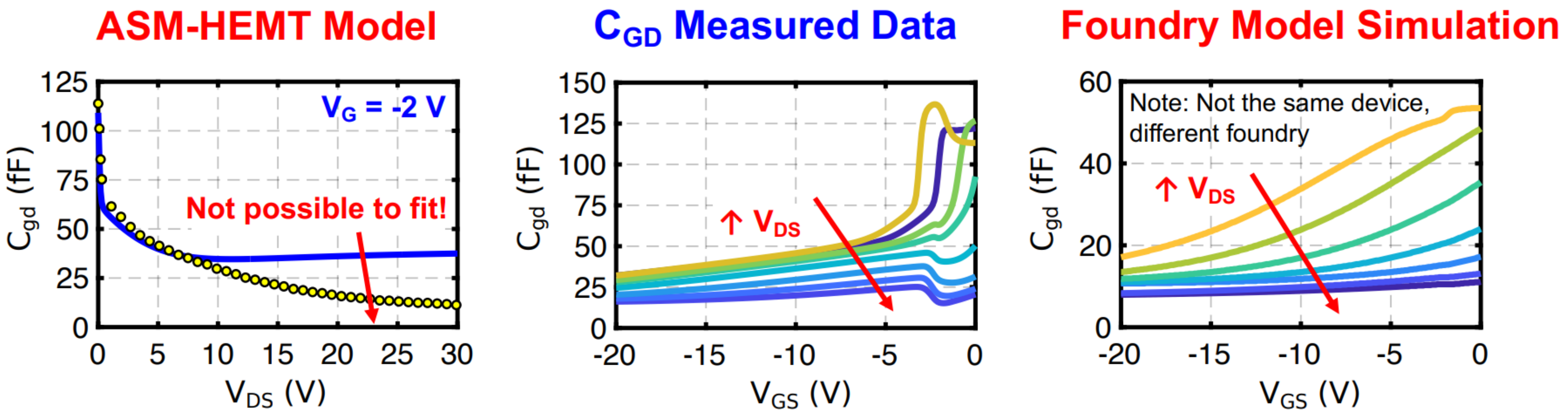


ASM-HEMT Equivalent Circuit Model



Model Limitations for C-V Characteristics

- **Problem:** ASM-HEMT fails to capture CV non-linearities of the device
  - Unable to fit measured CV curves using various approaches
- **Most results in the literature only show fitting at one V_D bias point**
  - Nonlinear behavior in HEMTs isn't modeled properly (in most models)



Modifying the Gate Charge Framework

- **Overlap capacitances are treated as constant capacitances**
- **C_{gs}/C_{gd} formulation insufficient to model V_{DS}-dependent non-linearities**
- **Hybrid:** We compensate for unmodeled nonlinear physical behavior by incorporating additional model parameters into ASM-HEMT framework

Hybrid ASM-HEMT Gate Charge Formulation

Intrinsic **Overlap** **Fringe**

$$Q_G = Q_{\mathrm{gi}} + \int C_{\mathrm{gso}}\, dV_{\mathrm{GS}} + \int C_{\mathrm{gdo}}\, dV_{\mathrm{GD}} + Q_{\mathrm{fr}} + \int C_{\mathrm{fgd}}\, dV_{\mathrm{GS}} + \int C_{\mathrm{gs,NN}}\, dV_{\mathrm{GS}} + \int C_{\mathrm{gd,NN}}\, dV_{\mathrm{GD}}$$

"Compensating" (Uses a Neural Network)

Implemented through Verilog-A

Modifying the Drain Charge Framework

- **Overlap capacitances are treated as constant capacitances**
- **C_{ds} formulation insufficient to model V_{DS}-dependent non-linearities**
- **Hybrid:** We compensate for unmodeled nonlinear physical behavior by incorporating additional model parameters into ASM-HEMT framework

Hybrid ASM-HEMT Drain Charge Formulation

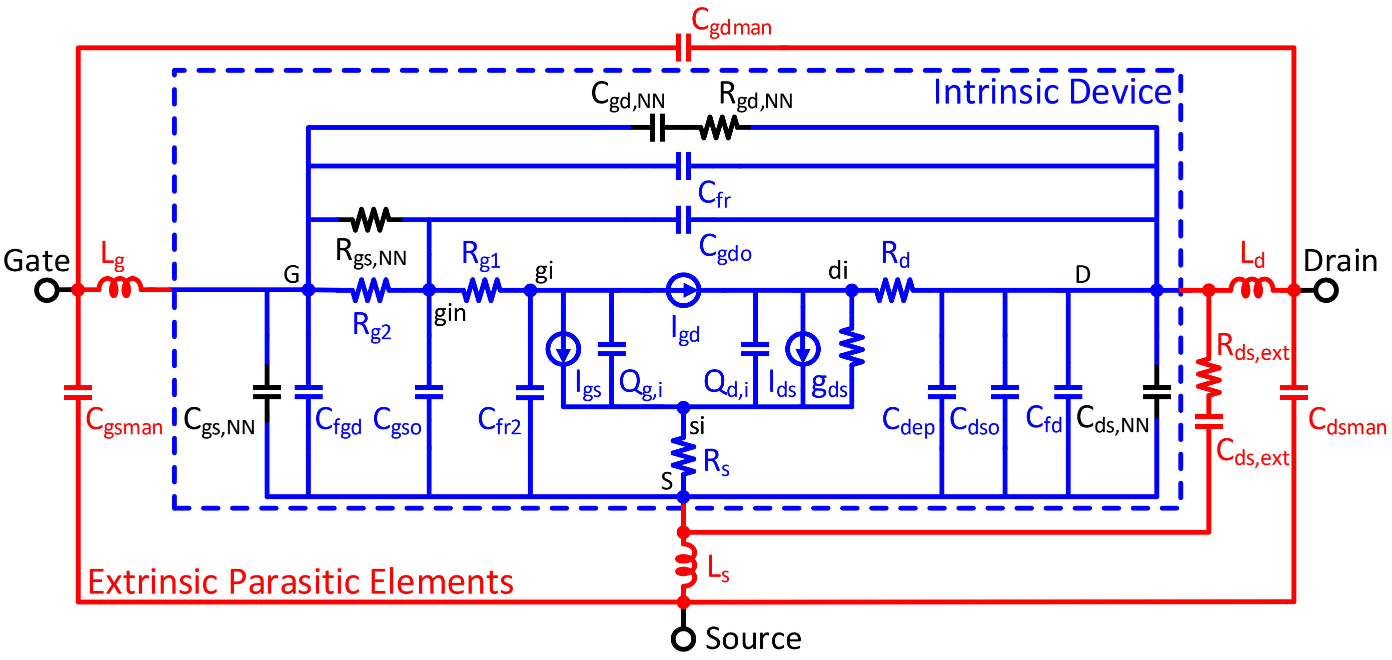
Intrinsic	Overlap	Depletion	Fringe	"Compensating"

$$Q_D = Q_{\mathrm{di}} + \int C_{\mathrm{dso}}\, dV_{\mathrm{DS}} + Q_{\mathrm{dep}} + \int C_{\mathrm{fd}}\, dV_{\mathrm{DS}} + \int C_{\mathrm{ds,NN}}\, dV_{\mathrm{DS}}$$

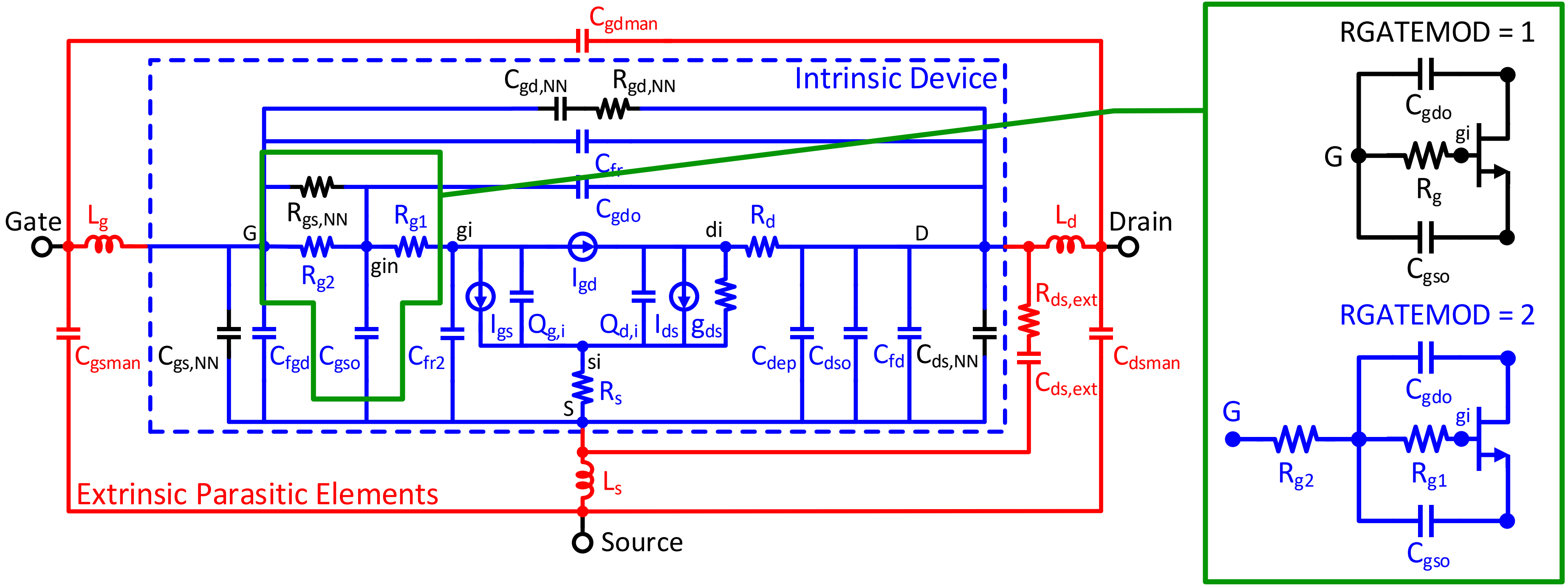
(Uses a Neural Network)

Implemented through Verilog-A

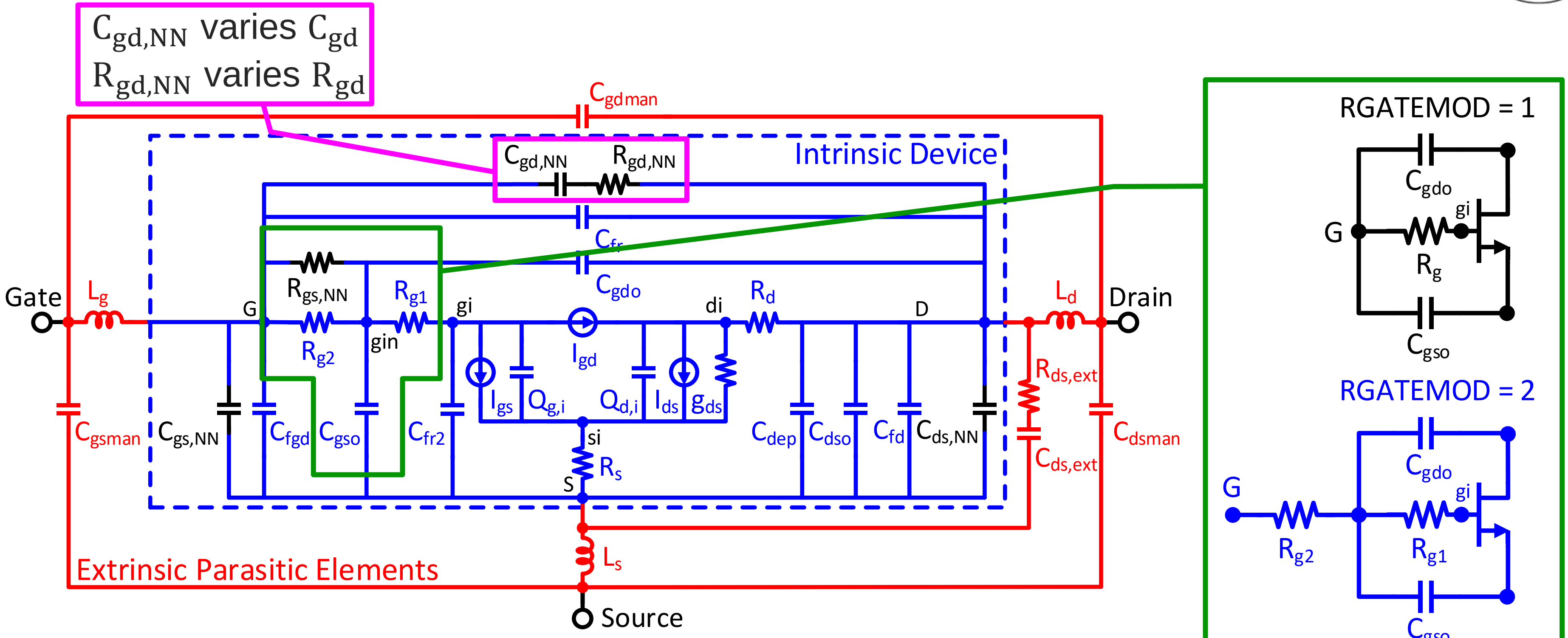
Hybrid ASM-HEMT Model Equivalent Circuit



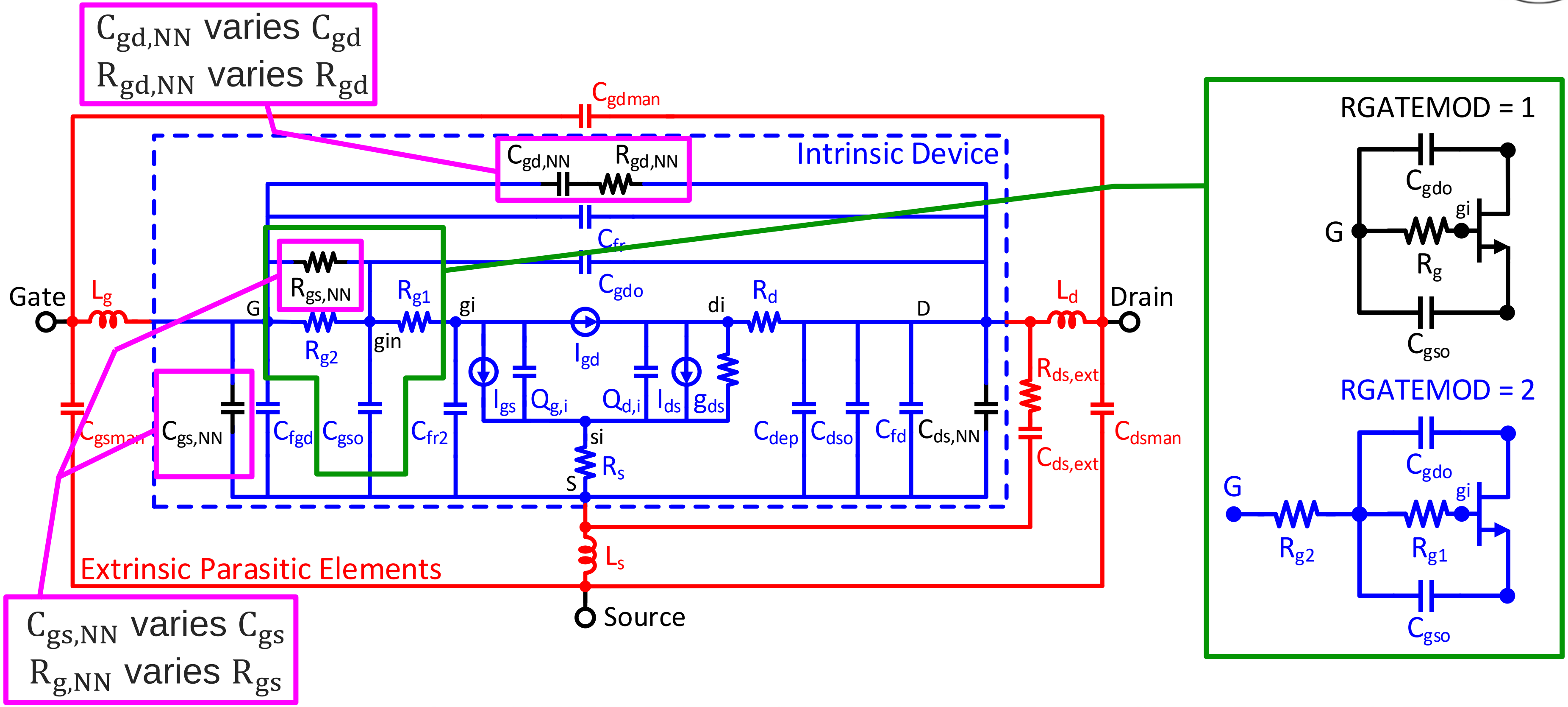
Hybrid ASM-HEMT Model Equivalent Circuit



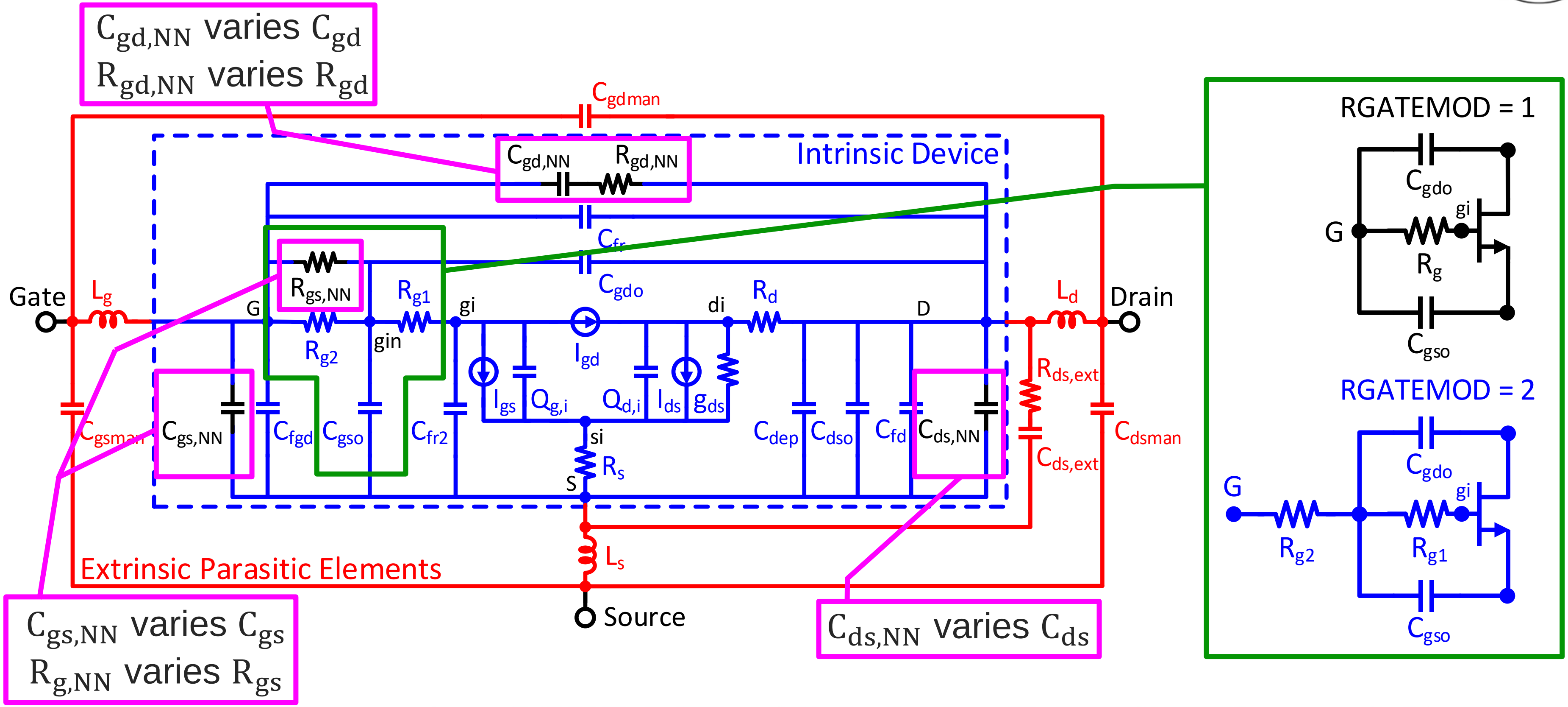
Hybrid ASM-HEMT Model Equivalent Circuit



Hybrid ASM-HEMT Model Equivalent Circuit



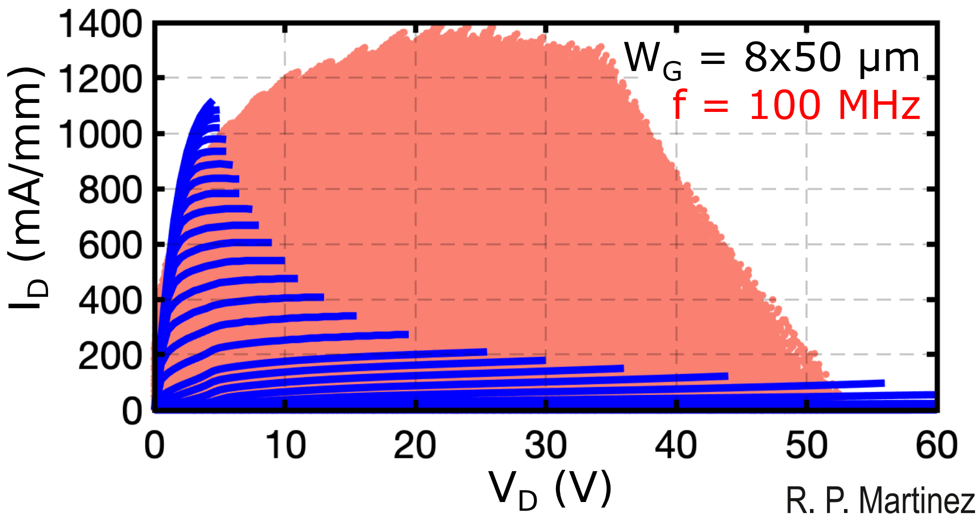
Hybrid ASM-HEMT Model Equivalent Circuit



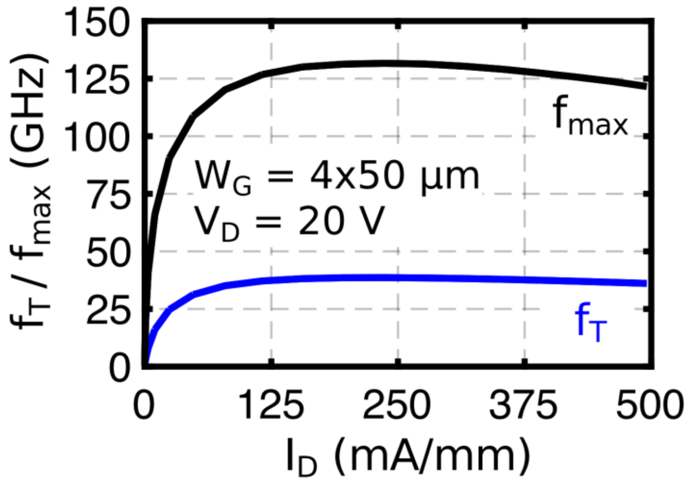
Modeling a 150-nm GaN HEMT

- **High-performance GaN HEMT process on a SiC substrate**
  - Primarily targets 5G and mm-wave applications (Ku, Ka, Q-band)
- **Device Geometry:** 4x50 µm GaN HEMT (L_G = 150 nm)

DC Characteristics & NVNA Data



Small-Signal Metrics

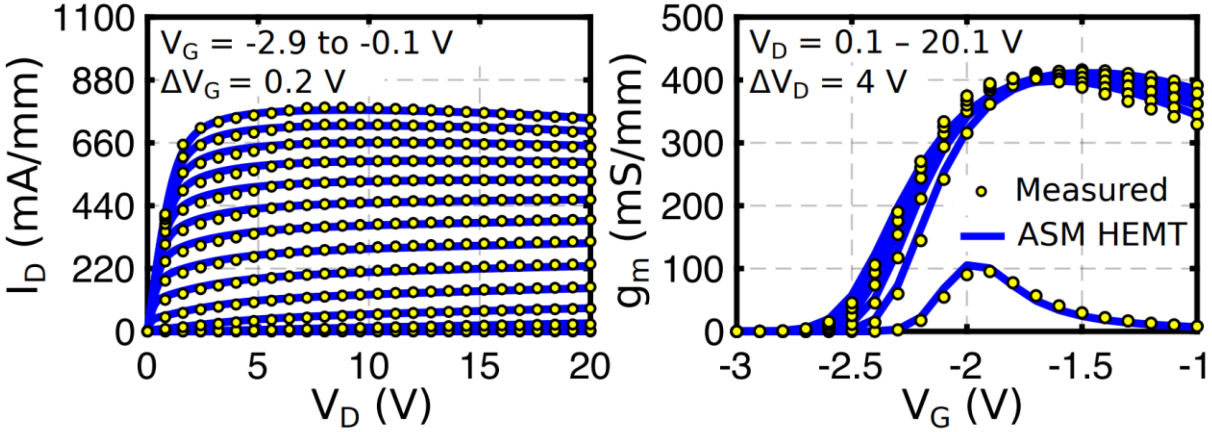


R. P. Martinez et al., *IEEE TMTT*, 2024.

Extracting the ASM-HEMT DC Model

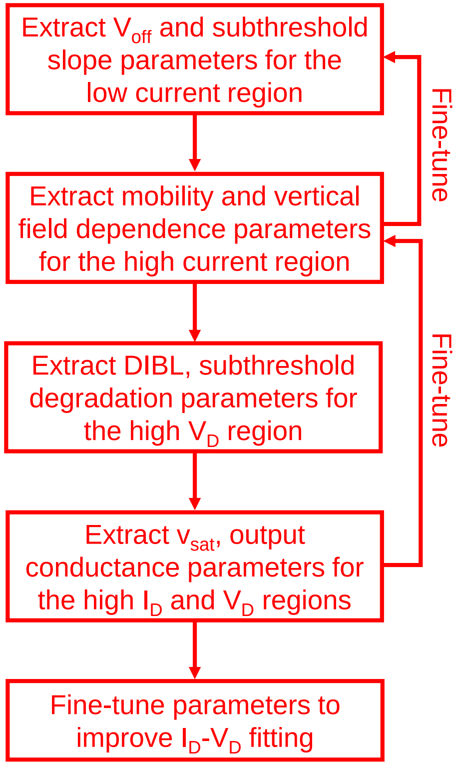
1) **Follow the manual flow of ASM-HEMT RF extraction package in IC-CAP (<u>this work</u>)**
   - Divide the parameter set into smaller subsets

2) **Extract the DC model via derivative-free optimization (no manual efforts)**



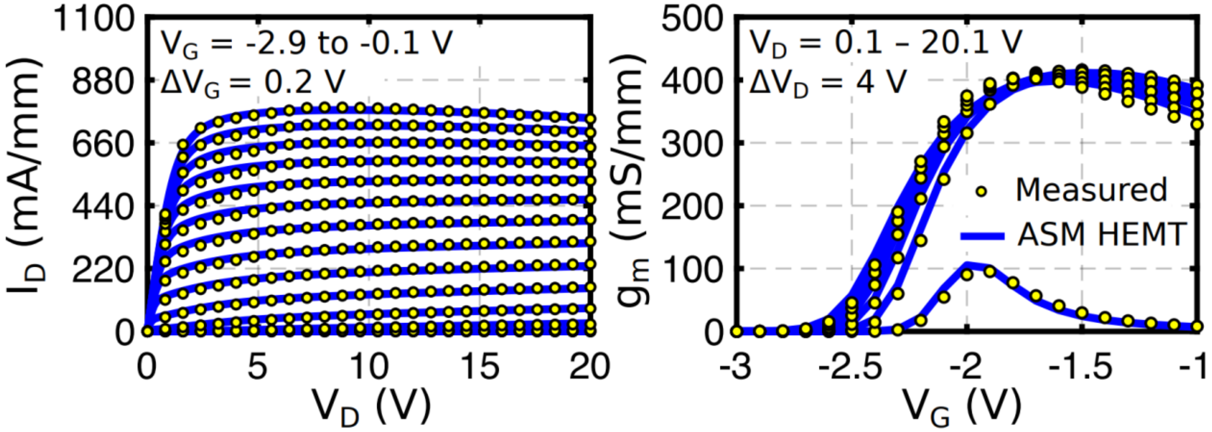
S. A. Ahsan et al., *IEEE JEDS*, 2017.

Manual Extraction Flow



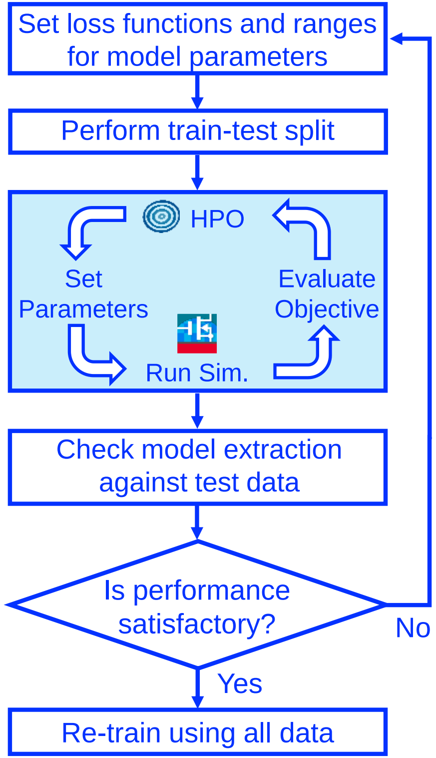
Extracting the ASM-HEMT DC Model

1) **Follow the manual flow of ASM-HEMT RF extraction package in IC-CAP**
2) **Extract the DC model via derivative-free optimization (no manual efforts)**
   – Reduce extraction time from weeks to hours!



R. P. Martinez et al., *IEEE Access*, 2024.

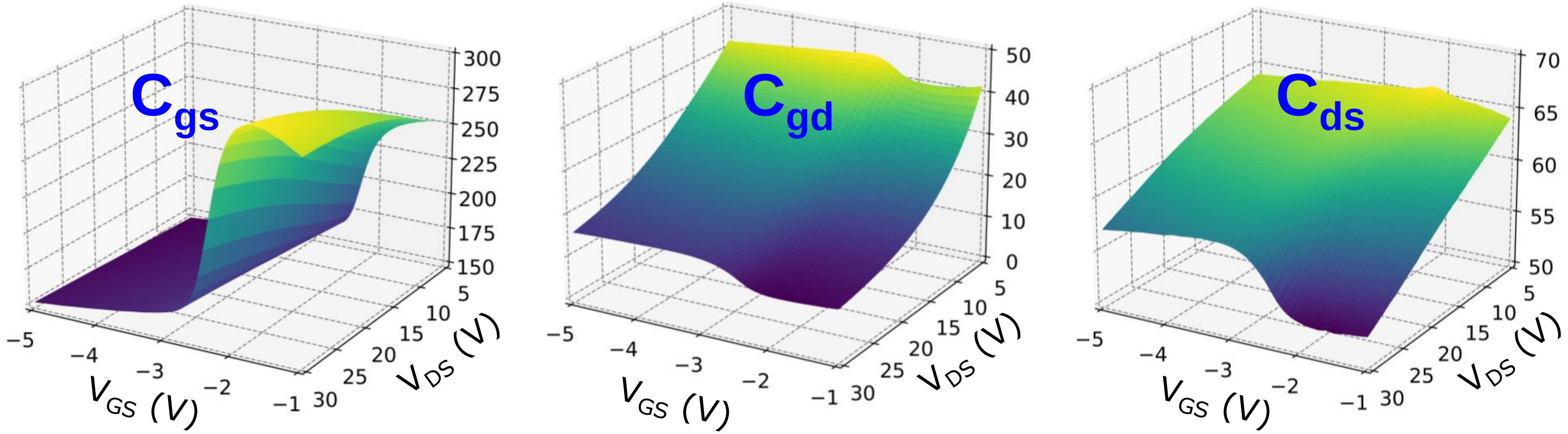
Automatic Extraction Flow



Measurements Needed for Hybrid Model

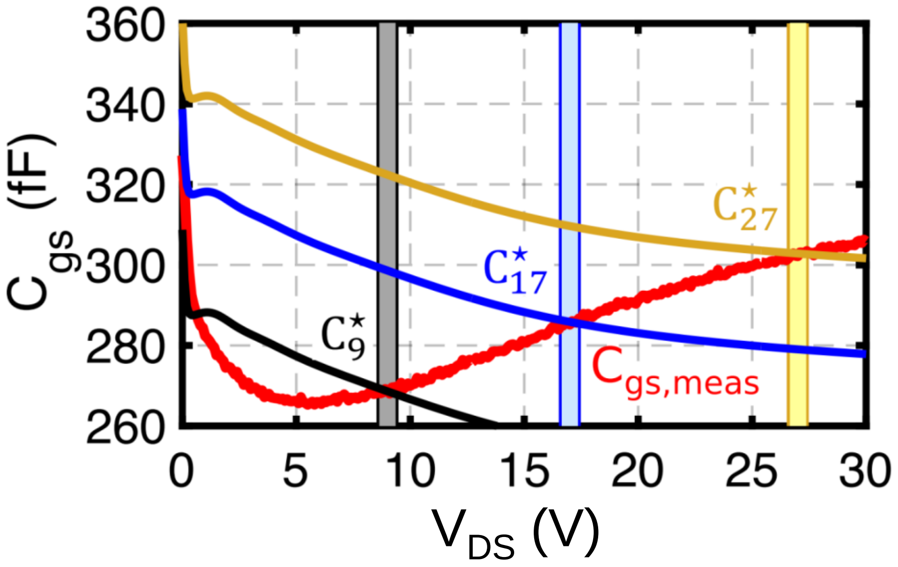
- **S-parameters were measured for a wide range of bias conditions**
  - $V_D = 0 - 30$ V ($\Delta V_D = 200$ mV) , $V_G = -5$ to -1 V ($\Delta V_G = 100$ mV) at f = 10 GHz
- **Dataset used to extract model parameters in the hybrid model**

Nonlinear Junction Capacitances of 4x50 µm GaN HEMT



Obtaining Training Data for Hybrid Model

- **Goal:** Identify best model parameter value that aligns simulated results with measured device characteristics at each bias condition
- **Logical sequence was established:** $C_{GD} \rightarrow C_{GS} \rightarrow C_{DS}$

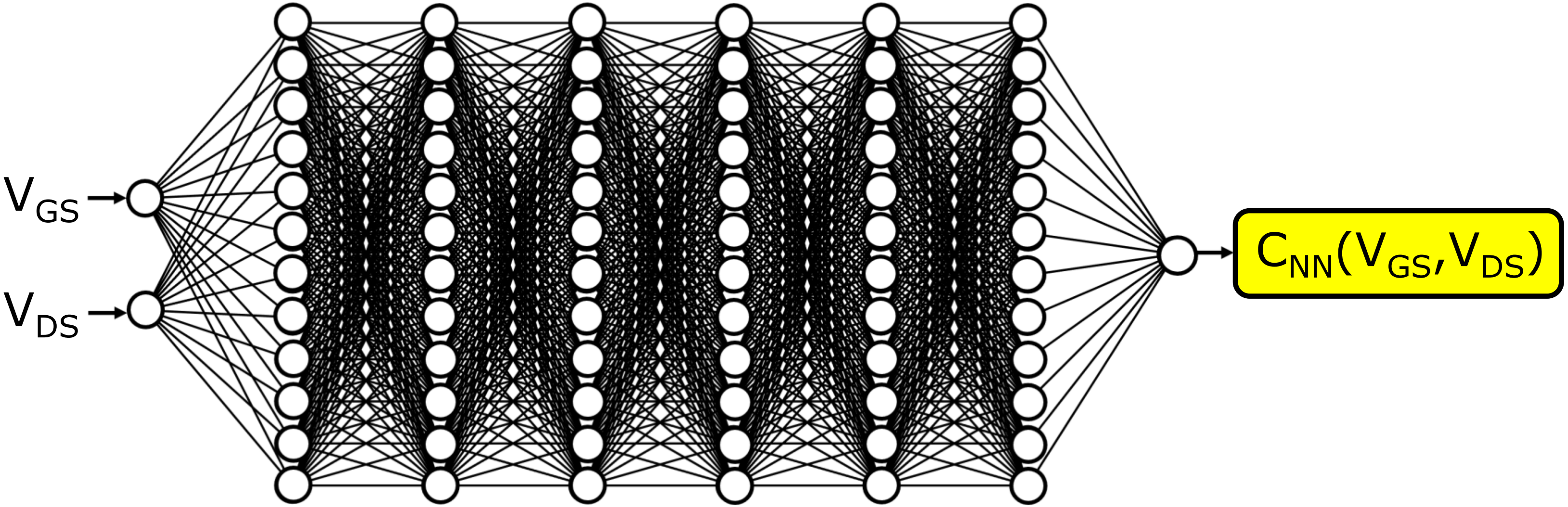


- **Minimize relative error at each bias using Levenberg-Marquardt:**

$$\underset{C_{ASM,param}}{\text{minimize}} \left| \frac{C_{sim}(V_{GS}^{(i)}, V_{DS}^{(j)}, C_{ASM,param}) - C_{meas}(V_{GS}^{(i)}, V_{DS}^{(j)})}{C_{meas}(V_{GS}^{(i)}, V_{DS}^{(j)})} \right|$$

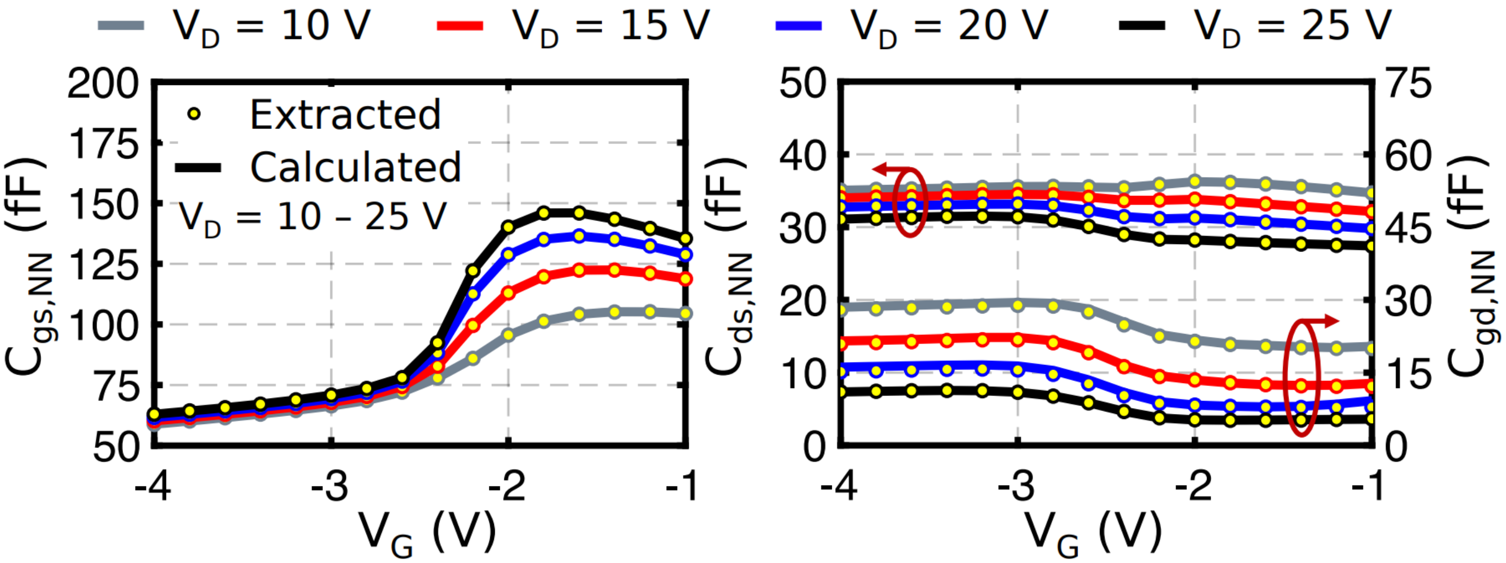
Neural Network Training for Hybrid Model

- **Neural network predicts hybrid model parameter at each bias**
  - Incorporated in Verilog-A model (replaces constant model parameter)
  - 6 hidden layers, 12 neurons each; Root Mean Square Error as loss function
- **Keysight's ANN Toolkit in IC-CAP is used to train neural network**



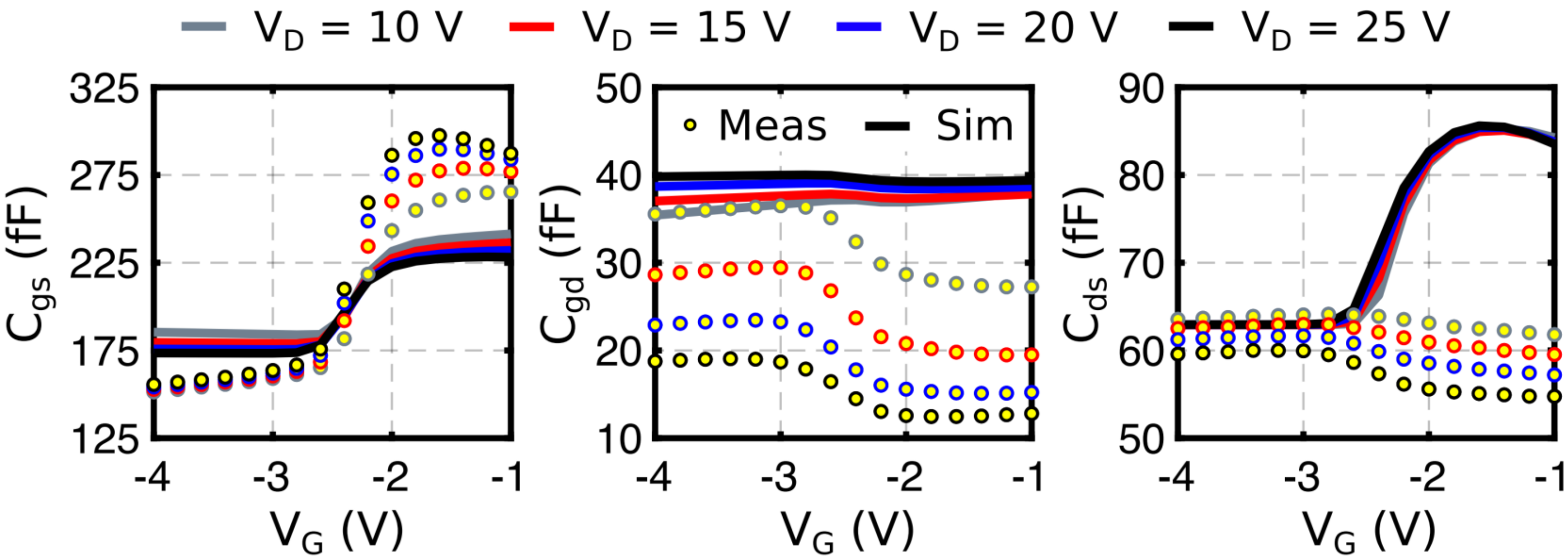
Neural Network Output for Hybrid Model

- **Extracted capacitance model parameters that minimize error between simulated and measured C-V characteristics**
- **Neural network output shows good agreement as a function of bias**



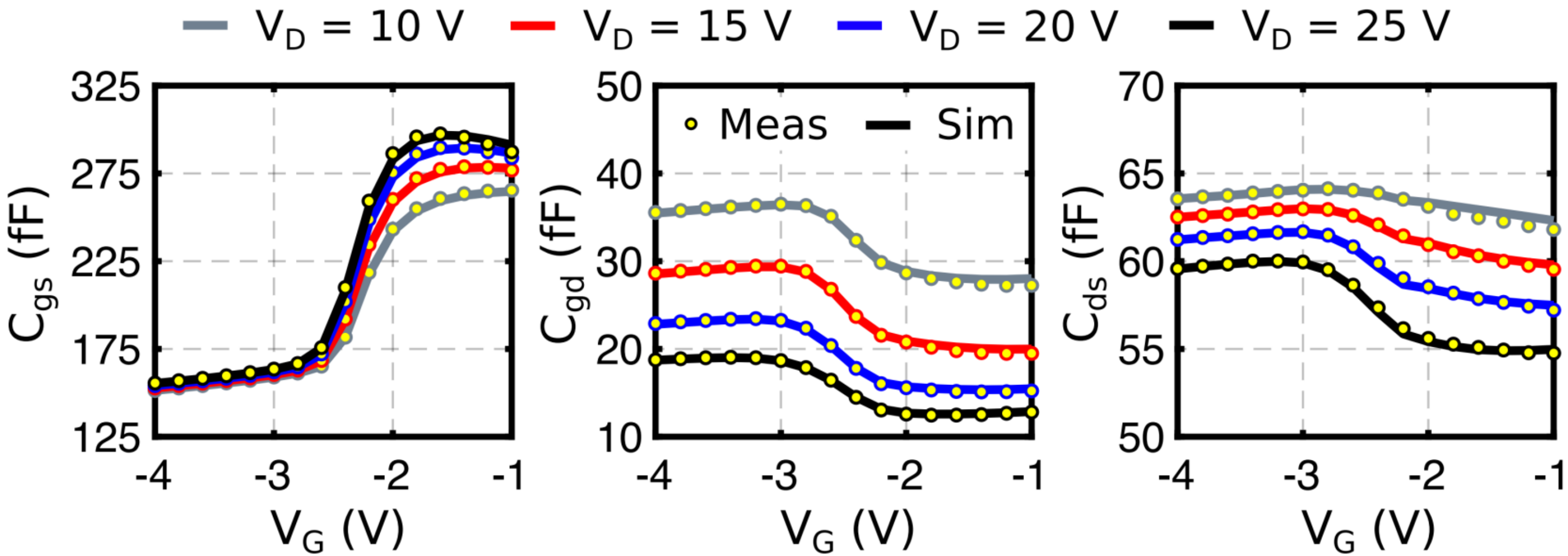
Baseline Model Fails to Model Capacitances

- **Baseline Model:** Unmodified model tailored to fit CV characteristics starting at V_{DS} = 0 V
- **Unable to fit V_{DS}-dependence for all three CV curves (<u>limited range</u>)**



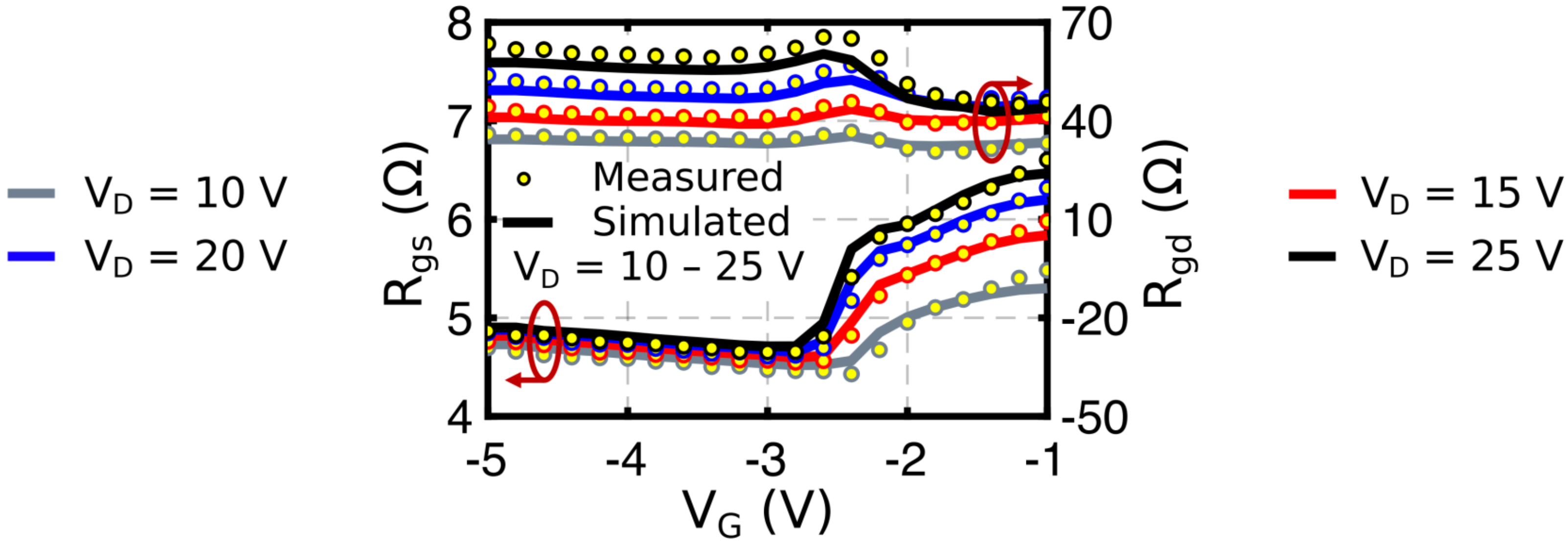
Improved Fitting Using Hybrid Approach

- **Hybrid Model:** Incorporates "compensating" circuit elements to fit capacitances through a neural network (6 hidden layers, 12 neurons)
- **Fitting of capacitances improved greatly as a function of V_G and V_D**



Improved Fitting Using Hybrid Approach

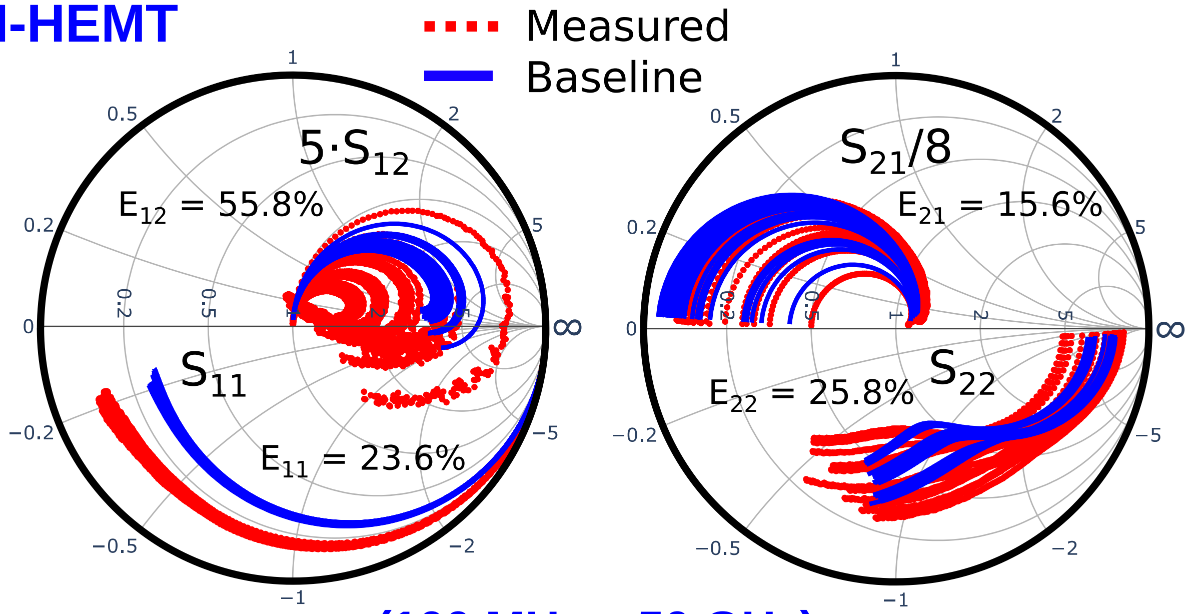
- **Hybrid Model:** Incorporates "compensating" circuit elements to fit resistances through a neural network (6 hidden layers, 12 neurons)
- **Fitting of resistances improved greatly as a function of V_G and V_D**



S-parameter Model Validation

- **Mismatch between measured and simulated S-parameters**
  - V_D = 5 – 25 V (ΔV_D = 5 V), V_G = -2.2 to -1 V (ΔV_G = 0.2 V), I_D = 15 – 500 mA/mm

Baseline ASM-HEMT

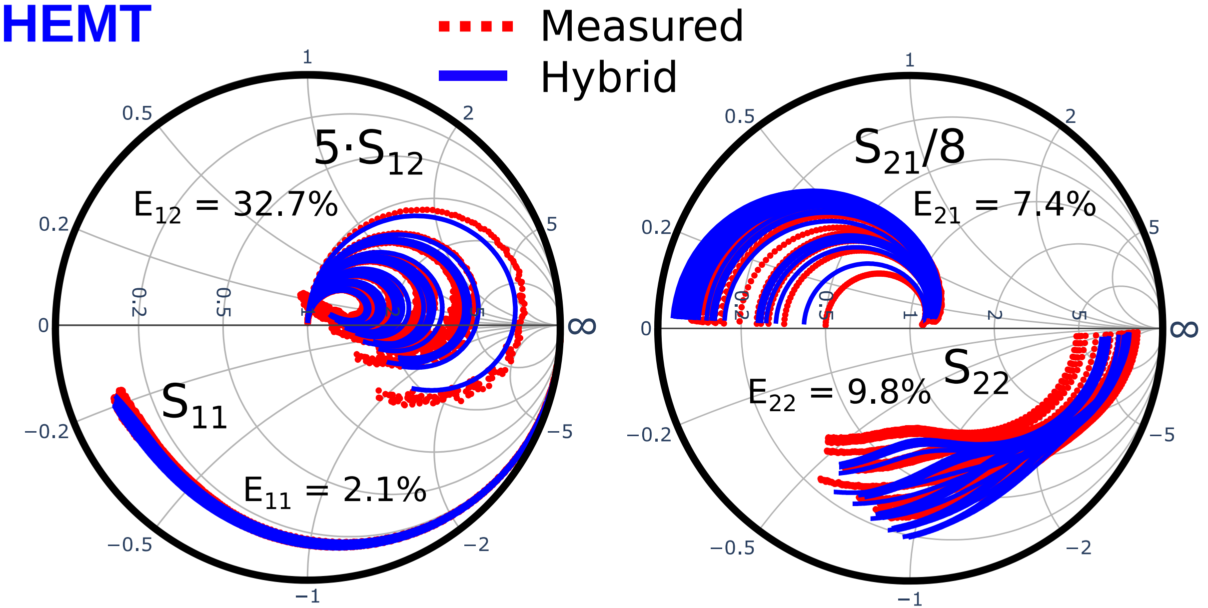


(100 MHz – 50 GHz)

S-parameter Model Validation

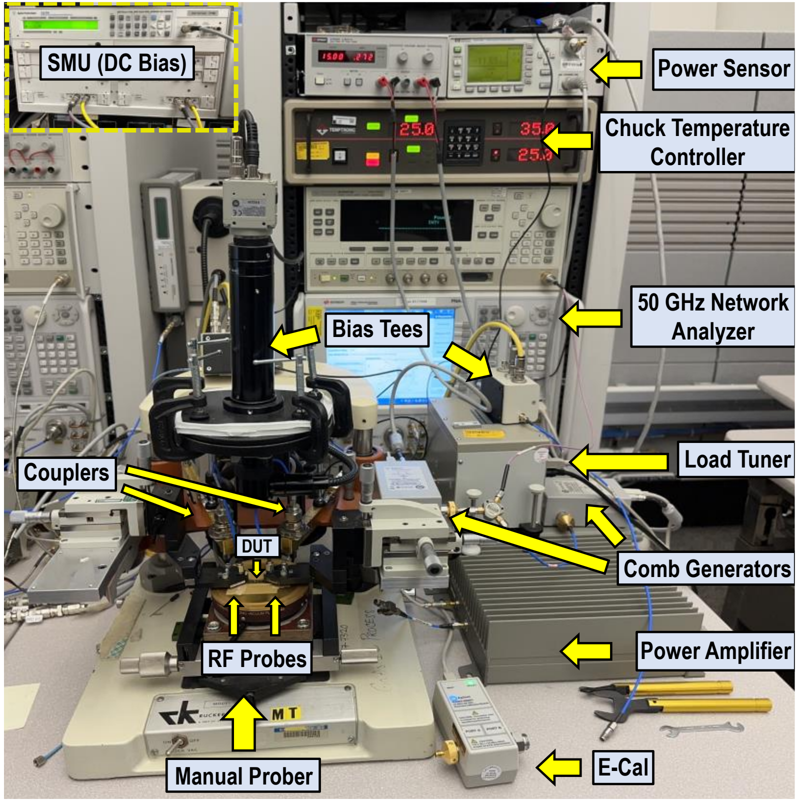
- **Good agreement between measured and simulated S-parameters**
  - V_D = 5 – 25 V (ΔV_D = 5 V), V_G = -2.2 to -1 V (ΔV_G = 0.2 V), I_D = 15 – 500 mA/mm

Hybrid ASM-HEMT



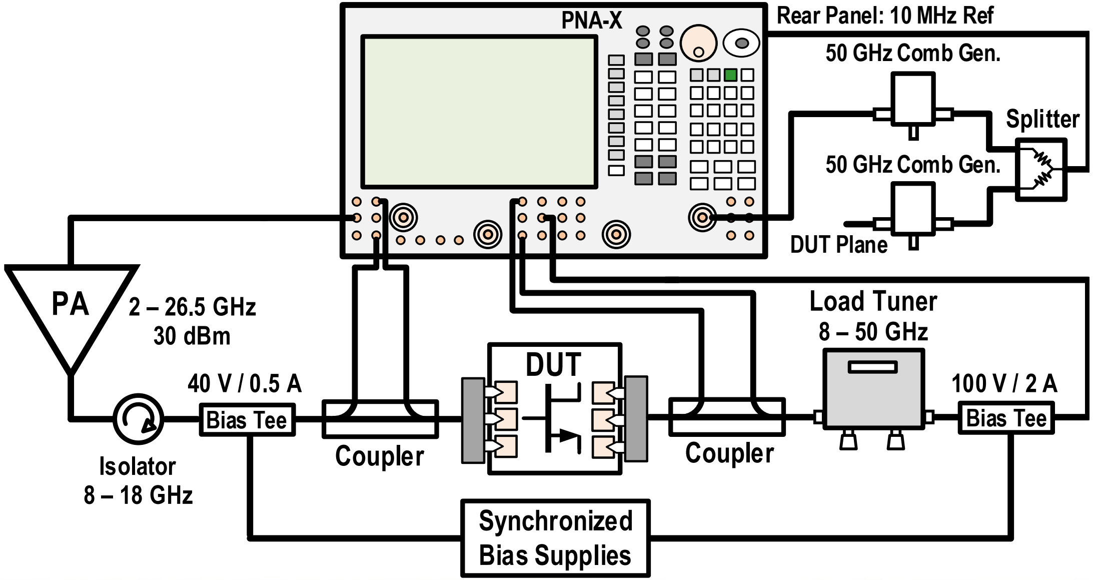
(100 MHz – 50 GHz)

Set-up for Non-linear Validation



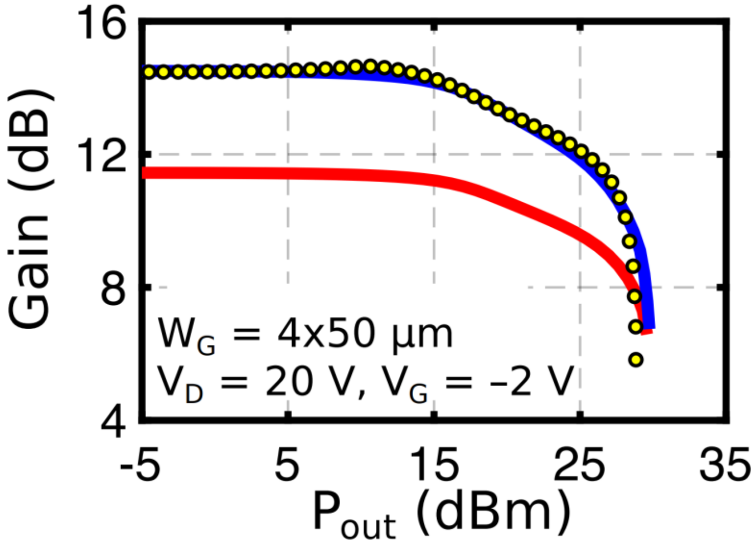
R. P. Martinez et al., *IEEE TMTT*, 2024.

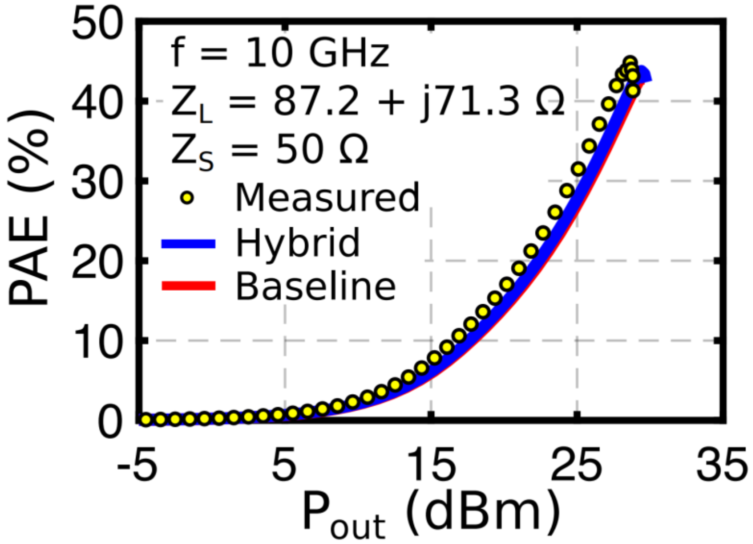
- **Fundamental load-tuner and NVNA set measurement frequency range**
- **Driver amplifier + isolator limit how much power we can present to the DUT**



Large-Signal Non-linear Validation

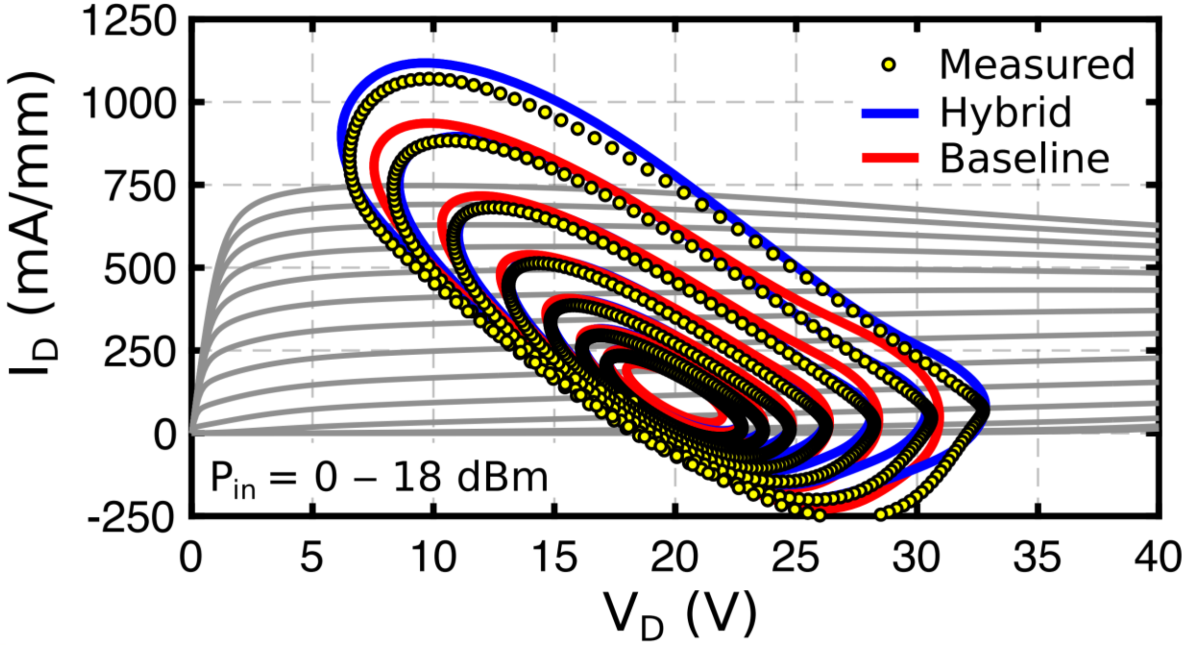
- **Hybrid model accurately predicted gain compression and PAE**
- **Baseline model resulted in a poor fit for gain compression**
  - Baseline model confined to a narrow V_{DS} range due to existing limitations





Dynamic Load-Line Validation

- Dynamic load-lines accurately predicted by hybrid ASM-HEMT model
- Baseline model yields poor results due to poor fitting of capacitances



Summary

- Introduced GaN technology and modeling schemes
- Evaluated strengths and limitations of measurement and physics-based models
- Proposed hybrid physical approach using ASM-HEMT model to improve fitting of capacitances and resistances
- Model validated against S-parameters, X-parameters, and dynamic load lines

Code and detailed documentation to be available in IC-CAP 2025 to benefit the device modeling community