Nonlinear Capacitance Modeling for Large-Signal GaN HEMT Model

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Outline

- **Background and Motivation**
  - GaN HEMTs and Modelling Challenges
  - Nonlinear Capacitances in GaN HEMTs
  - Current Modelling Methods
- **Measurement Facilities**
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  - Continuous-Wave/Pulsed S-Parameters Measurement Setup
  - Continuous-Wave/Pulsed Load-Pull Measurement Setup
  - Specifications at A Glance
- **Outlier Detection of Capacitance Extractions**
- **Simplification of Nonlinear Capacitance**
- **Temperature Dependence of Nonlinear Capacitances**
- **ANN-Based Consistent Gate Charge Model**
- **Conclusion**

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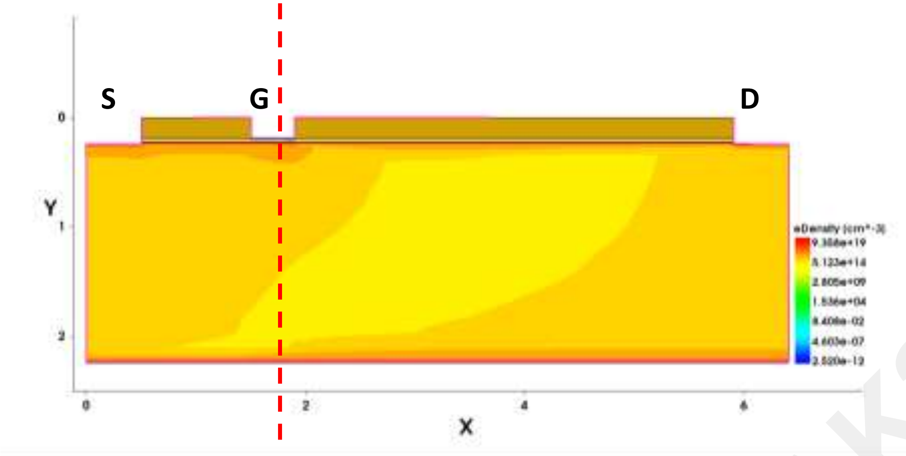
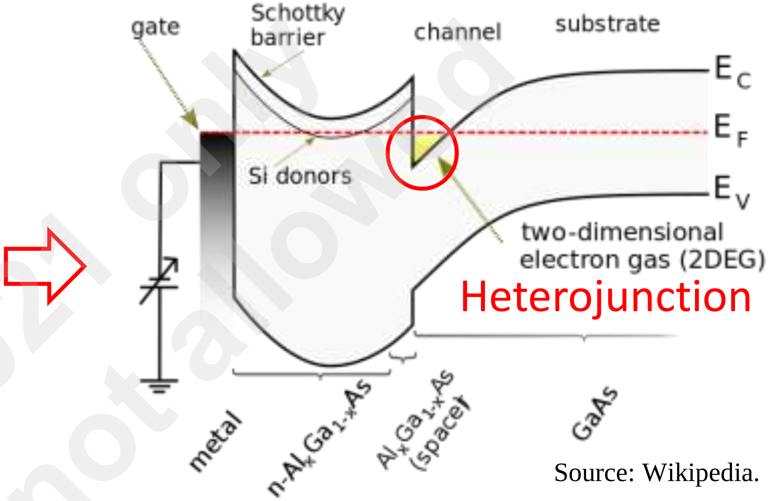
Background and Motivation

GaN HEMTs

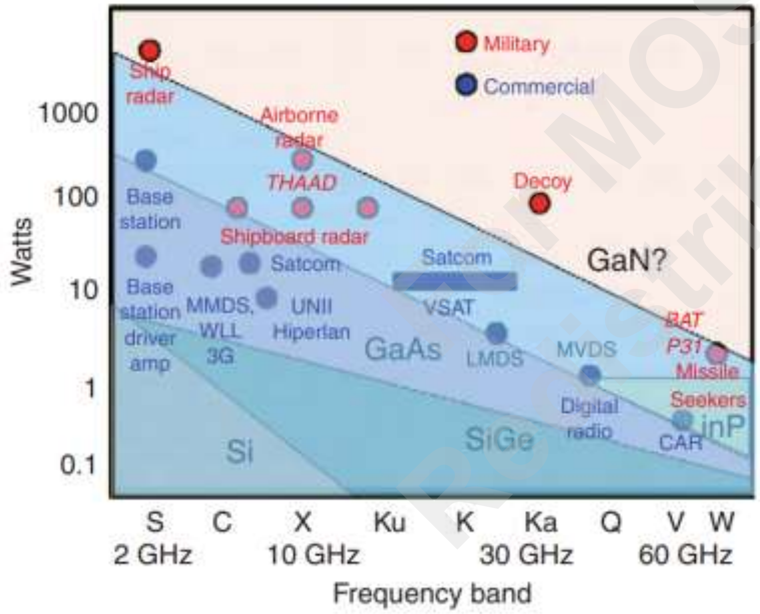
High Electron Mobility Transistors:





Source: Wikipedia.

GaN High Electron Mobility Transistors:



Advantages of GaN HEMT:

-Good linearity

-High power density

-High gain

-Good thermal conductivity

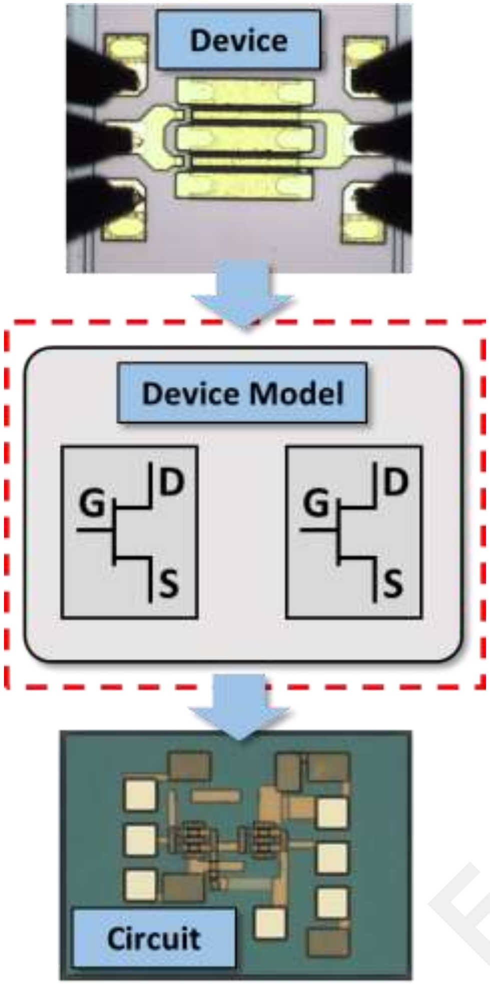
-Low parasitic capacitances and inter-terminal capacitances

-High cutoff frequency

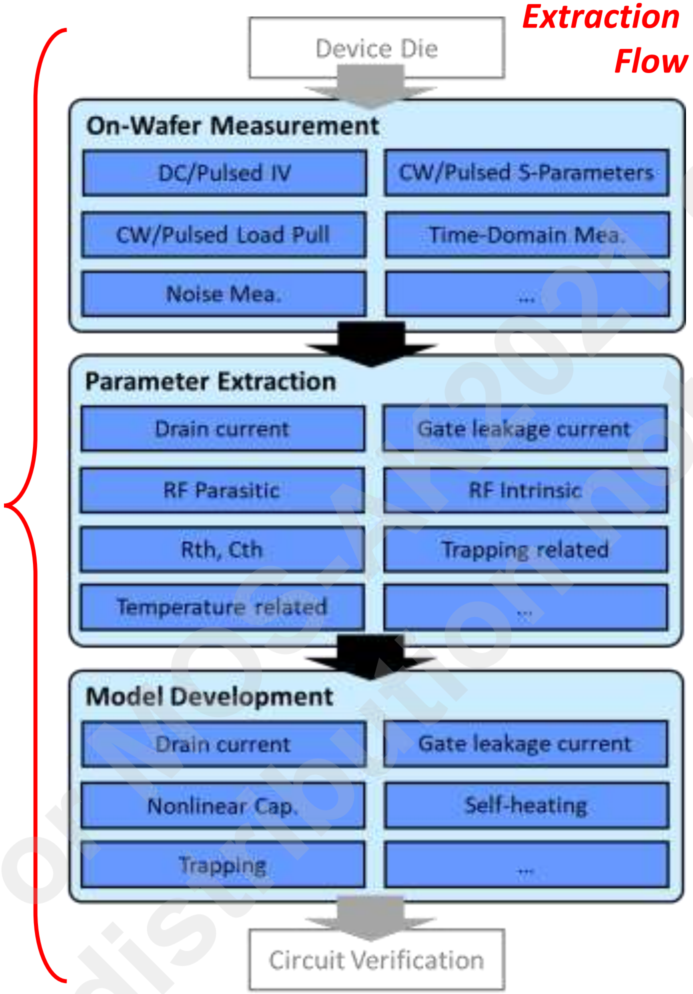
-...

Covers a wide range of applications.

GaN HEMTs Modelling



Extraction Flow



Device Die

On-Wafer Measurement

- DC/Pulsed IV
- CW/Pulsed S-Parameters
- CW/Pulsed Load Pull
- Time-Domain Mea.
- Noise Mea.
- ...

Parameter Extraction

- Drain current
- Gate leakage current
- RF Parasitic
- RF Intrinsic
- Rth, Cth
- Trapping related
- Temperature related
- ...

Model Development

- Drain current
- Gate leakage current
- Nonlinear Cap.
- Self-heating
- Trapping
- ...

Circuit Verification

Model Classifications

Empirical Models

- **Types:** Angelov [1], EEHEMT [2], Statz [3], Curtice [4]...
- **Pros:** Easy to implement, high convergence
- **Cons:** Lack physical meaning, poor scalability

Physical Models

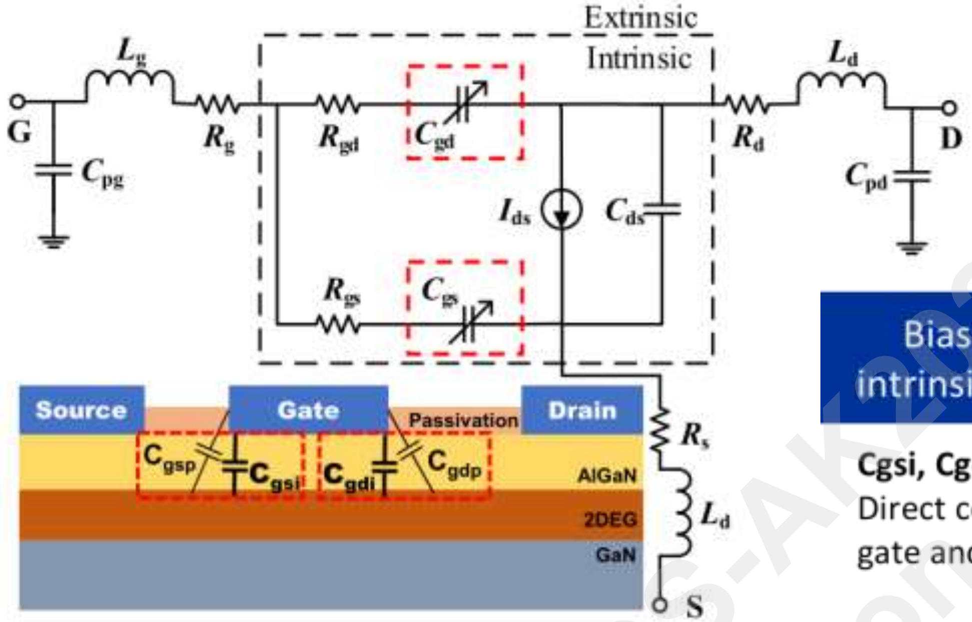
- **Types:** ASM [5], MVSG [6], QPZD [7], ...
- **Pros:** High scalability, solid physical foundation
- **Cons:** High complexity, poor flexibility

ANN Models

- **Types:** DynaFET [8], ...
- **Pros:** High accuracy, technology independent
- **Cons:** Poor convergence, poor scalability

[1] I. Angelov, H. Zirath, and N. Rosman, “A new empirical nonlinear model for hemt and mesfet devices,” IEEE Transactions on Microwave Theory and Techniques, vol. 40, no. 12, pp. 2258–2266, 1992.
[2] William Clausen. Small and large signal modeling of mm-wave mhemt devices. 2003.
[3] Hermann Statz, Paul Newman, Irl W Smith, Robert A Pucel, and Hermann A Haus. Gaas fet device and circuit simulation in spice, IEEE Transactions on Electron Devices, 34(2):160–169, 1987.
[4] Walter R Curtice and M Ettenberg. A nonlinear gaas fet model for use in the design of output circuits for power amplifiers. IEEE Transactions on Microwave Theory Techniques, 33:1383–1394, 1985.
[5] S. Khandelwal, C. Yadav, S. Agnihotri, Y. S. Chauhan, A. Curutchet, T. Zimmer, J.-C. De Jaeger, N. Defrance, and T. A. Fjeldly, “Robust surface-potential-based compact model for gan hemt ic design,” IEEE Trans. Electron Devices, vol. 60, no. 10, pp. 3216–3222, 2013.
[6] U. Radhakrishna, “Modeling gallium-nitride based high electron Mobility transistors: linking device physics to high voltage and high frequency circuit design,” PhD Thesis, Massachusetts Institute of Technology, 2016.
[7] Z. Wen et al., “A quasi-physical compact large-signal model for AlGaN/GaN HEMTs,” IEEE Trans. Microw. Theory Techn., vol. 65, no. 12, pp. 5113–5122, Dec. 2017.
[8] J. Xu, R. Jones, S. A. Harris, T. Nielsen, and D. E. Root, “Dynamic FET model-DynaFET-for GaN transistors from NVNA active source injection measurements,” in IEEE MTT-S Int. Microw. Symp. Dig., Jun. 2014, pp. 1–3.

Nonlinear Gate Capacitances in GaN HEMTs



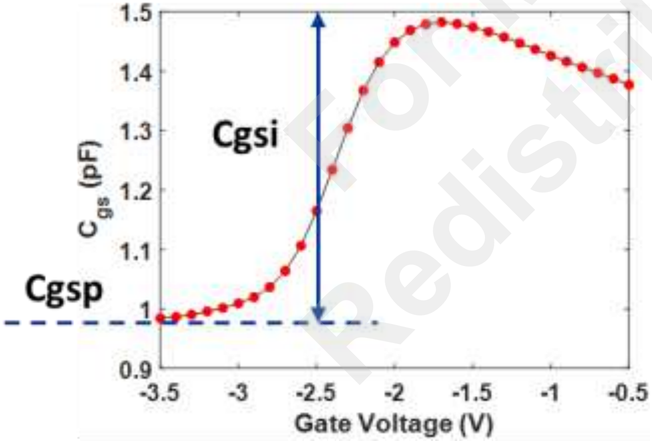
Nonlinear gate capacitance

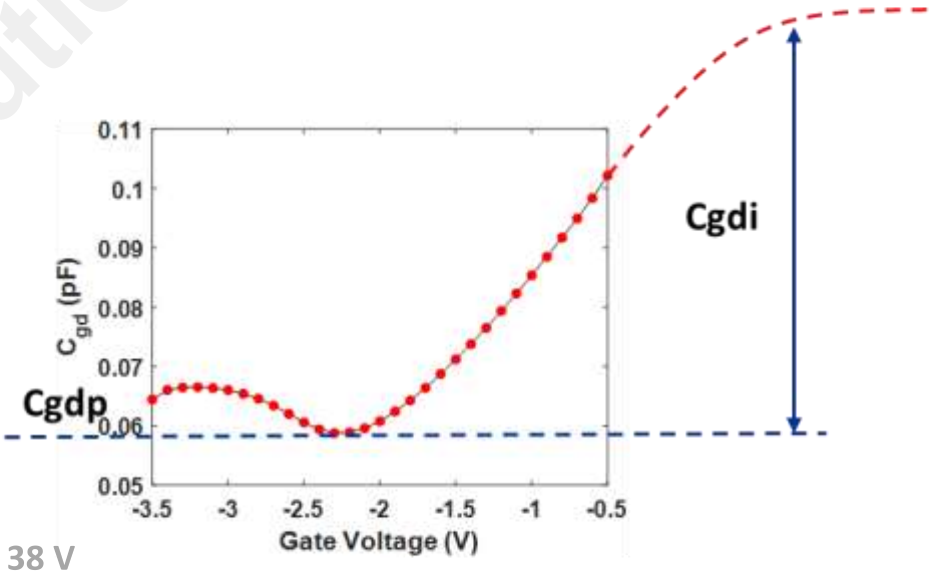
Bias-dependent intrinsic capacitances

Cgsi, Cgdi
Direct coupling between gate and 2DEG

Bias-independent parasitic capacitances

Cgsp, Cgdp
Sum of indirect coupling between gate and 2DEG (e.g., fringing capacitance)





Vds = 38 V

Nonlinear Gate Capacitances Models

- Empirical model

  - The Cgs and Cgd are independent of Ids.

  - Flexible and easy to use. But lack physical meaning.

$$C_{\mathrm{gs}} = C_{\mathrm{gsp}} + C_{\mathrm{gs0}}\left(1 + \tanh\left(P_{\mathrm{g11}}V_{\mathrm{gs}} + P_{\mathrm{g10}}\right)\right) \times \left(1 + \tanh\left(P_{\mathrm{g21}}V_{\mathrm{ds}} + P_{\mathrm{g20}}\right)\right)$$

$$C_{\mathrm{gd}} = C_{\mathrm{gdp}} + C_{\mathrm{gd0}}\left(1 + \tanh\left(P_{\mathrm{d11}}V_{\mathrm{ds}} + P_{\mathrm{d10}}\right) - P_{\mathrm{d111}}\right) \times \left(1 + \tanh\left(P_{\mathrm{d21}}V_{\mathrm{gd}} + P_{\mathrm{d20}}\right) + 2P_{\mathrm{d111}}\right)$$

- Physical Model

  - The Cgs and Cgd are dependent on Ids.

  - Able to well reflect the physical nature of the device. But not flexible and difficult to tune.

$$C_{gs} = -\frac{\partial Q_S}{\partial V_G}$$

$$C_{gd} = -\frac{\partial Q_D}{\partial V_G}$$

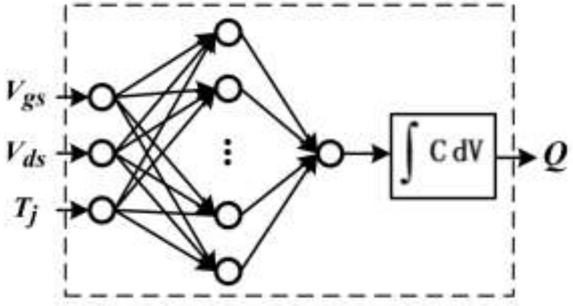
$$Q_S = \frac{2WL}{(Q_{is}^2 - Q_{id}^2)^2}\left(-Q_{id}^2\frac{Q_{id}^3 - Q_{is}^3}{3} + \frac{Q_{is}^5 - Q_{id}^5}{5}\right)$$

$$Q_D = \frac{2WL}{(Q_{is}^2 - Q_{id}^2)^2}\left(Q_{is}^2\frac{Q_{id}^3 - Q_{is}^3}{3} - \frac{Q_{is}^5 - Q_{id}^5}{5}\right)$$

- ANN based model

  - The Cgs and Cgd are built based on artificial neural networks. Independent of Ids.

  - Highly accurate. But difficult to tune (too many parameters).



Modelling Problems & Our Solutions

For the nonlinear gate capacitances:

- The abnormal results in extractions

  ⇒Outlier detection method [1].

- The complexity in building up nonlinear capacitance models

  ⇒Simplification method at large Vds [2].

- The temperature dependence of nonlinear capacitances

  ⇒Improved temperature dependence [3].

- The charge inconsistency of ANN-based gate charge model

  ⇒Novel ANN-based consistent gate charge model [1].

Ref:

[1] W. Hu, H. Luo, X. Yan and Y. -X. Guo, "An Accurate Neural Network-Based Consistent Gate Charge Model for GaN HEMTs by Refining Intrinsic Capacitances," *IEEE Trans. Microw. Theory Techn.*, vol. 69, no.7, pp. 3208-3218, July 2021.

[2] H. Luo, H. Zhang, W. Hu, and Y. Guo, “A simplification method for capacitance models in AlGaN / GaN high electron mobility transistors under large drain voltage using channel analysis,” *Int. J. RF Microw. Comput-Aid. Eng.*, vol. 31, no. 1, 2021.

[3] H. Luo, Z. Zhong, W. Hu, and Y. Guo, “Analysis and Modeling of the Temperature Dependent Nonlinearity of Intrinsic Capacitances in AlGaN/GaN HEMTs”, *IEEE Microw. Wirel. Compon. Lett.*, vol. 31, no. 4, pp. 373-376, April 2021.

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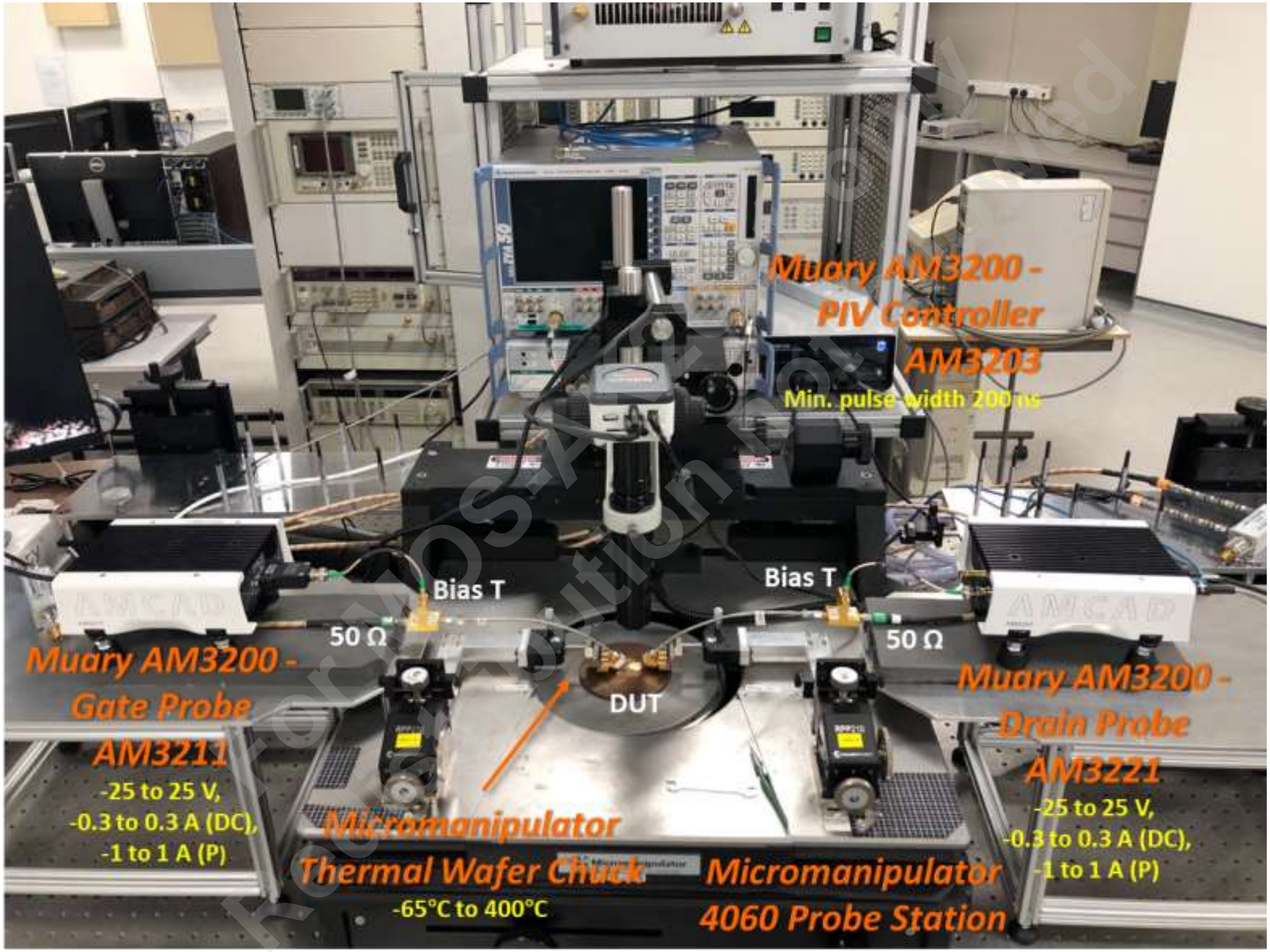
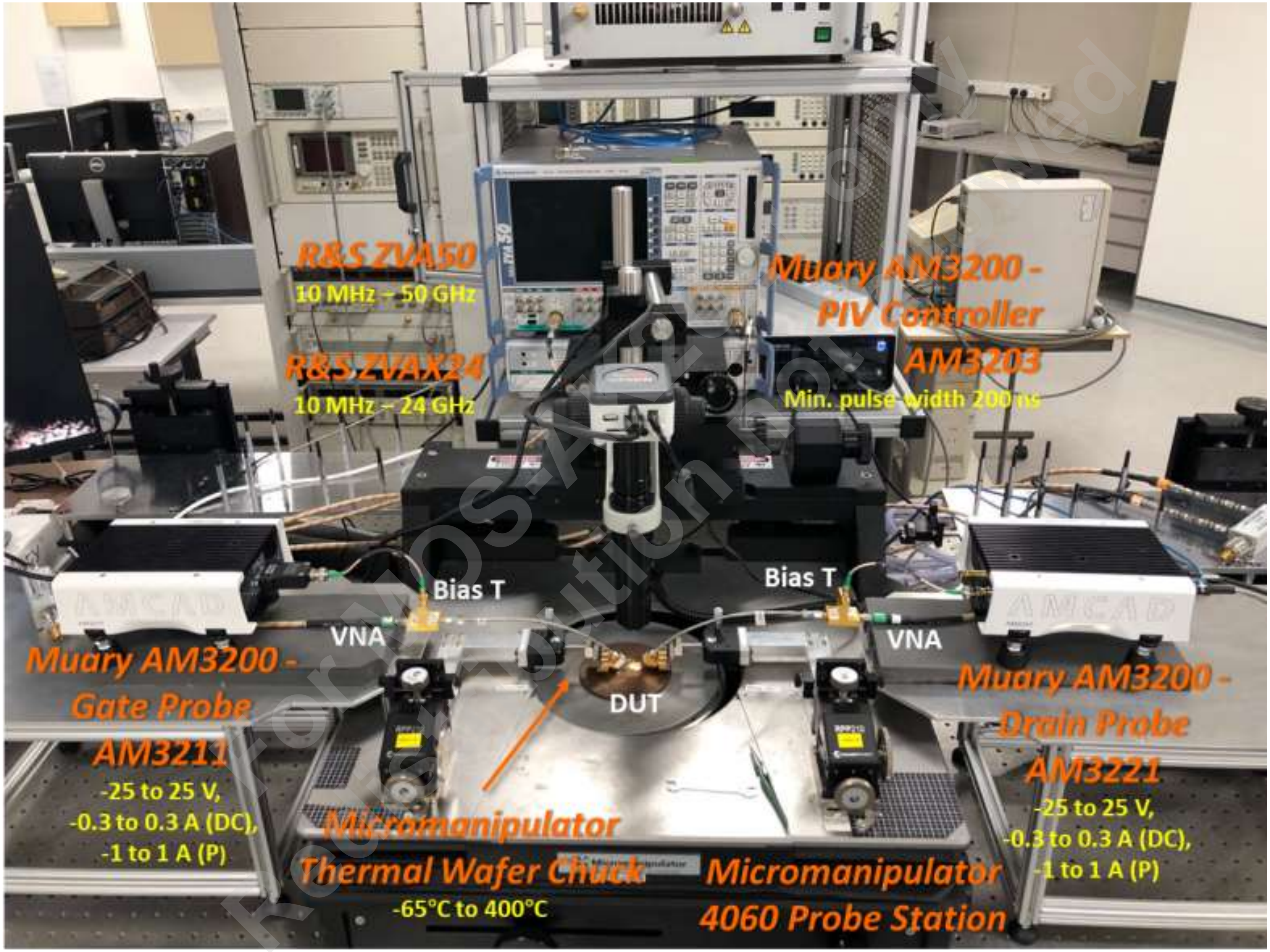
Measurement Facilities

- Background and Motivation
- Measurement Facilities
- Outlier Detection of Capacitance Extractions
- Simplification of Nonlinear Capacitance
- Temperature Dependence of Nonlinear Capacitances
- ANN-Based Consistent Gate Charge Model
- Conclusion

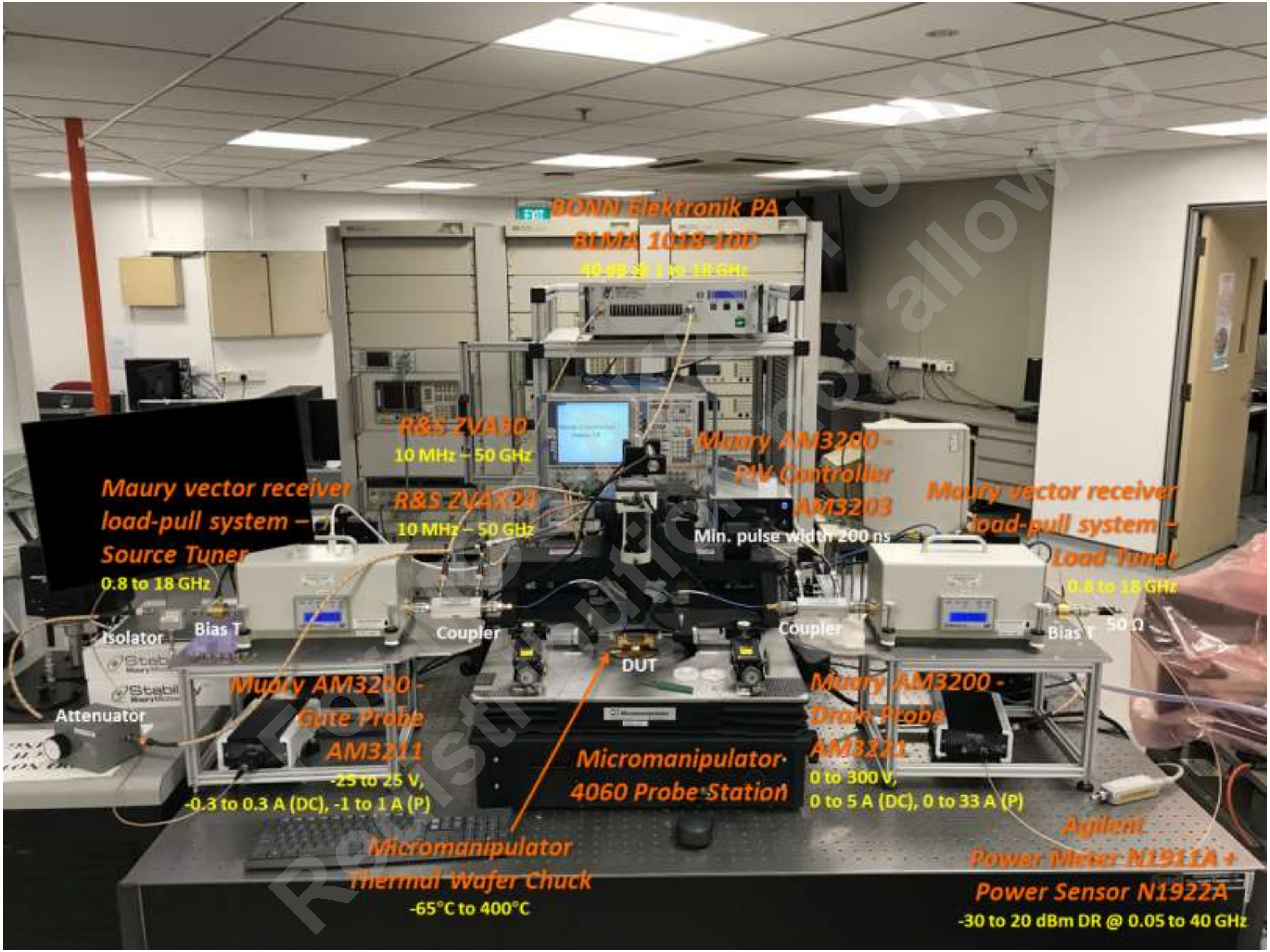
DCIV/PIV Measurement Setup



CW/Pulsed S-Parameters Measurement Setup



CW/Pulsed Load-Pull Measurement Setup



Specifications at A Glance

Equipment	Specification			
Maury AM 3200 PIV System (AM3203 Pulse IV Controller) (AM3211 Gate/Input Probe) (AM3221 Drain/Output Probe)	Min. pulse width 200ns from the generator.			
		DC & Pulsed Voltage	DC Current	Pulsed Current
	Input	-25 - 25 V	-0.3 - 0.3 A	-1 - 1 A
	Output	0 - 250 V	0 - 5 A	0 - 33 A
Maury Vector Receiver Load-Pull System (7mm Automated Tuners)	Frequency Range	Power Capacity		Insertion Loss
	0.8 GHz - 18.0 GHz	50 W (CW)	0.5 kW (PEP)	0.5 dB
ROHDE & SCHWARZ ZVA 50	Frequency Range		10 MHz - 50 GHz	
R&S ZVAX 24 Extension Unit	Frequency Range		10 MHz - 24 GHz	
BONN Elektronik Power Amplifier (BLMA 1018-10D)	Frequency Range	Output Power PN min / typ	Gain min / typ	Harmonics 2nd / 3rd
	1-18 GHz	10 / 12 W	40 / 43 ± 3 dB	15 / 20 dBc
Agilent P-Series Single Channel Power Meter (N1911A)	Power requirement		≤30W	
Agilent wideband power Sensor (N1922A)	Frequency Range		Dynamic range	
	0.05 - 40 GHz		-35 - 20 dBm (≥0.5 GHz) -30 - 20 dBm (0.05 - 0.5 GHz)	
Micromanipulator 4060 High Performance Manual Probe Station with Computer Controlled Thermal Chuck	X and Y Axis Range		Temperature	
	8” × 8” (200mm × 200mm)		-65 - 400 °C	

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Outlier Detection of Capacitance Extractions

- Background and Motivation
- Measurement Facilities
- **Outlier Detection of Capacitance Extractions**
- Simplification of Nonlinear Capacitance
- Temperature Dependence of Nonlinear Capacitances
- ANN-Based Consistent Gate Charge Model
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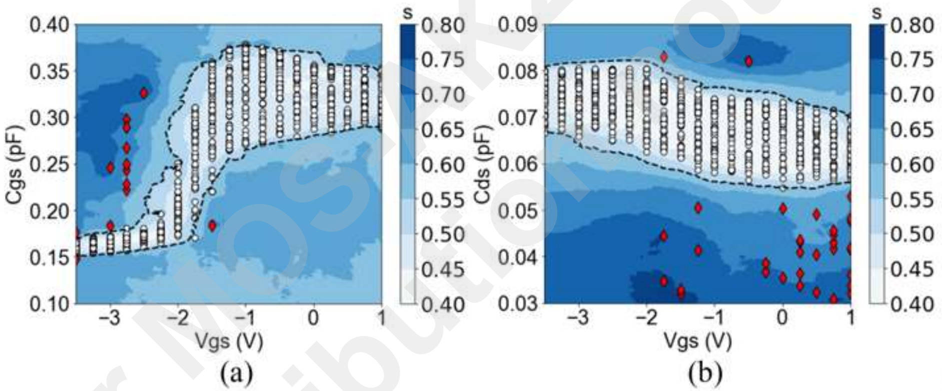
Problem and Method

- The extracted capacitances data may have abnormal results (outliers), which may not be conducive to parameter extraction and fitting

$$C_{\mathrm{gs}} = C_{\mathrm{gsp}} + C_{\mathrm{gs0}}\left(1 + \tanh\left(P_{\mathrm{g11}}V_{\mathrm{gs}} + P_{\mathrm{g10}}\right)\right) \times \left(1 + \tanh(P_{\mathrm{g21}}V_{\mathrm{ds}} + P_{\mathrm{g20}})\right)$$

$$C_{\mathrm{gd}} = C_{\mathrm{gdp}} + C_{\mathrm{gd0}}\left(1 + \tanh(P_{\mathrm{d11}}V_{\mathrm{ds}} + P_{\mathrm{d10}}) - P_{\mathrm{d111}}\right) \times \left(1 + \tanh(P_{\mathrm{d21}}V_{\mathrm{gd}} + P_{\mathrm{d20}}) + 2P_{\mathrm{d111}}\right)$$

- We use the iForest algorithm to detect and remove the outliers [1]



(a) (b)

Figure 2. *Outlier detection results of the extracted (a) C_{gs} and (b) C_{ds}, including the normal points (circle symbols), outliers (diamond symbols), and decision boundary (dashed lines).*

- The outliers (red diamonds) can be successfully detected and removed

Ref:

[1] W. Hu, H. Luo, X. Yan and Y. -X. Guo, "An Accurate Neural Network-Based Consistent Gate Charge Model for GaN HEMTs by Refining Intrinsic Capacitances," *IEEE Trans. Microw. Theory Techn.*, vol. 69, no.7, pp. 3208-3218, July 2021.

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Simplification of Nonlinear Capacitances

Problem

- The original Angelov Cgs and Cgd model has 13 parameters to fit at both Vgs and Vds direction.

$$C_{gs} = C_{gsp} + C_{gso}\left(1 + \tanh\left(P_{g11}V_{gs} + P_{g10}\right)\right) \times (1 + \tanh(P_{g21}V_{ds} + P_{g20}))$$

$$C_{gd} = C_{gdp} + C_{gd0}(1 + \tanh(P_{d11}V_{ds} + P_{d10}) - P_{d111}) \times (1 + \tanh(P_{d21}V_{gd} + P_{d20}) + 2P_{d111})$$

- Difficult to fit. Complex expression is also easier to lead to convergence issue.

- It is common for GaN HEMT to work at high Vds to provide a high output power.

- Solution: We cancel the Vds dependence of Cgs and Cgd at high Vds. Parameter number is reduced from 13 to 8 [1].

$$C_{gs} = C_{gsp} + C_{gs0}\left(1 + \tan h\left(P_{g11}V_{gs} + P_{g10}\right)\right)$$

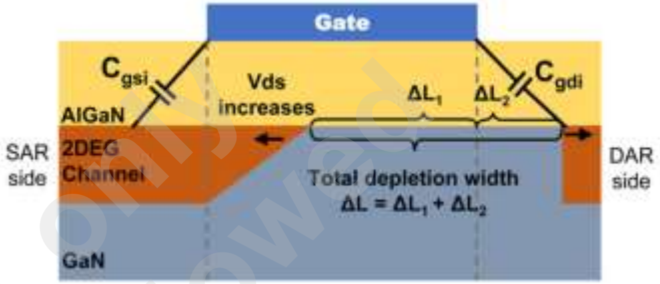
$$C_{gd} = C_{gdp} + C_{gd0}\left(1 + \tan h\left(P_{d11}V_{gs} + P_{d10}\right)\right)$$

Ref:

[1] H. Luo, H. Zhang, W. Hu, and Y. Guo, “A simplification method for capacitance models in AlGaN / GaN high electron mobility transistors under large drain voltage using channel analysis,” *Int. J. RF Microw. Comput-Aid. Eng.*, vol. 31, no. 1, 2021.

Method

The Vds dependence of Cgs and Cgd can be attributed to the Vds dependence of channel.

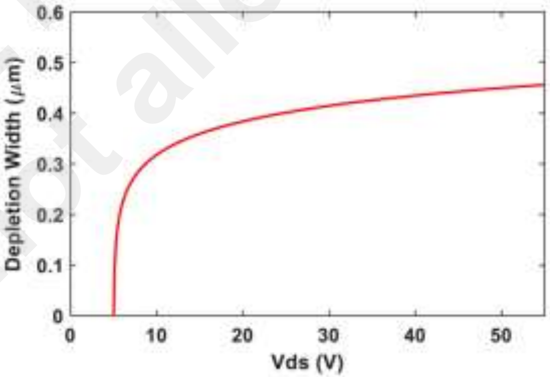


It is formulated and plotted as follows.

$$\Delta L = \Delta L_1 + \Delta L_2 \qquad (1)$$

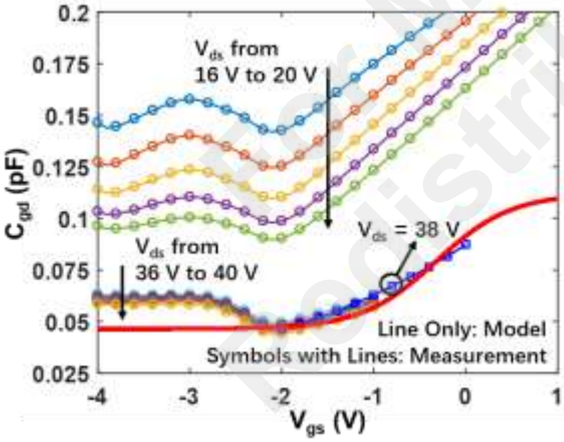
$$\Delta L_1 = \gamma \ln\left(\left(\frac{V_{\mathrm{ds}} - F_{\mathrm{sat}} V_{\mathrm{ds(sat)}}}{E_{\mathrm{sat}}\gamma}\right) + \sqrt{\left(\frac{V_{\mathrm{ds}} - F_{\mathrm{sat}} V_{\mathrm{ds(sat)}}}{E_{\mathrm{sat}}\gamma}\right)^2 + 1}\right) \qquad (2)$$

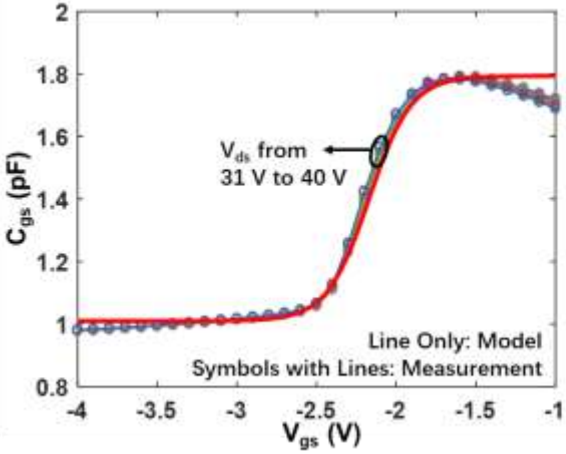
$$\Delta L_2 = k \cdot \Delta L_1 \qquad (3)$$



The increase of depletion width becomes slow when Vds is high.

The extracted Cgs and Cgd also indicate a slow increase when Vds is high.





Therefore, we cancel the Vds dependence of Cgs and Cgd for simplification

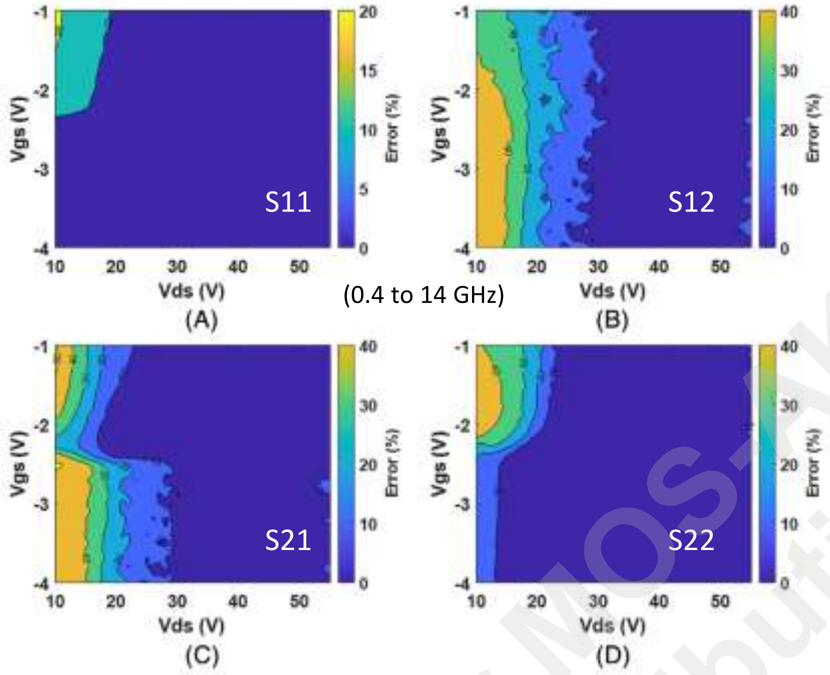
Validations

With the simplified equations and parameters extracted at 38V

$$C_{gs} = C_{gsp} + C_{gs0}\left(1 + \tan h\left(P_{g11}V_{gs} + P_{g10}\right)\right)$$

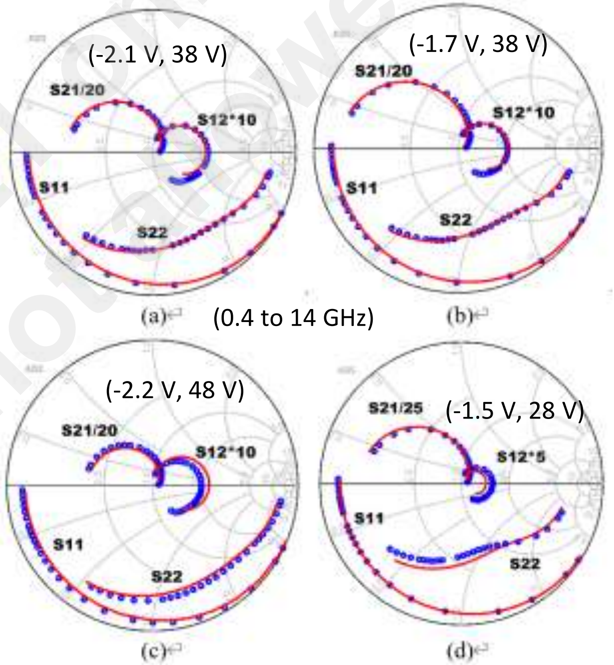
$$C_{gd} = C_{gdp} + C_{gd0}\left(1 + \tan h\left(P_{d11}V_{gs} + P_{d10}\right)\right)$$

The RMS error of recovered small signal S-parameters



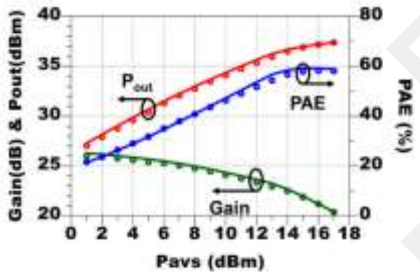
(0.4 to 14 GHz)

S-Parameters

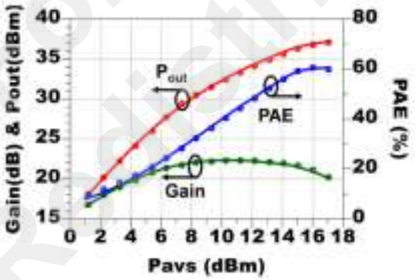


(0.4 to 14 GHz)

Power sweeps

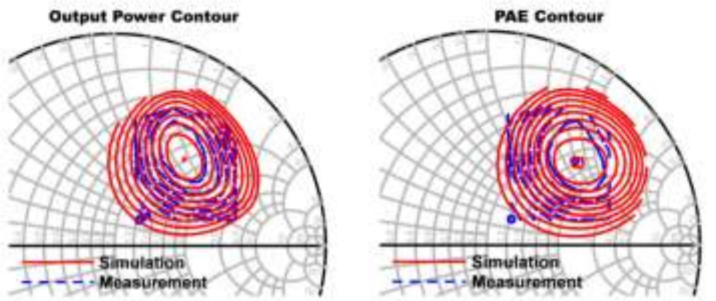


Vdsq = 38 V, Vgsq = -2.1 V, f = 2.7 GHz



Vdsq = 38 V, Vgsq = -2.5 V, f = 2.7 GHz

Load pull



(Vdsq = 38 V, Vgsq = -2.1 V, f= 2.7 GHz, Pin = 17 dBm)

5

Temperature Dependence of Nonlinear Capacitances

- Background and Motivation
- Measurement Facilities
- Outlier Detection of Capacitance Extractions
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Problem

- The original temperature dependence of Cgs and Cgd: linear scaling

$$C_{\mathrm{X}} = C_{\mathrm{Xp}} + \alpha_{T\mathrm{X}} C_{\mathrm{Xi}} \tag{1}$$

- This may not be accurate as the evidence of this relationship in many literatures came from the single bias Cgs and Cgd.

- Previous extractions on EDL (H.-H. Hu, 08) also showed that the Cgs and Cgd has a more complex temperature dependence at Vgs direction.

- We analyzed and characterized the previously unconsidered temperature dependent nonlinearity based on device physics [1]

$$k_{\mathrm{TX}} = k_{\mathrm{TX0}} \cdot (1 + \gamma_{\mathrm{kX1}} / (\gamma_{\mathrm{kX2}} + (T - T_0))) \tag{2}$$

$$V_{\mathrm{sTX}} = V_{\mathrm{sTX0}} + \gamma_{\mathrm{VX}} (T - T_0) \tag{3}$$

$$\begin{aligned} C_{\mathrm{gs}} = {} & C_{\mathrm{gsp}} + \alpha_{T\mathrm{gs}} C_{\mathrm{gs0}} \cdot \left(\tanh\left(k'_{\mathrm{gs}}\left(V_{\mathrm{ds}} + V'_{\mathrm{sgs}}\right)\right) + 1\right) \\ & \cdot \left(\tanh\left(\boldsymbol{k_{gs}}\left(V_{\mathrm{gs}} + \boldsymbol{V_{sgs}}\right)\right) + P_{222} V_{\mathrm{ds}} + 1\right) \end{aligned} \tag{4}$$

$$\begin{aligned} C_{\mathrm{gd}} = {} & C_{\mathrm{gdp}} + \alpha_{T\mathrm{gd}} C_{\mathrm{gd0}} \cdot \left(\tanh\left(k'_{\mathrm{gd}}\left(V_{\mathrm{ds}} + V'_{\mathrm{sgd}}\right)\right) + 1 - P_{111}\right) \\ & \cdot \left(\tanh\left(\boldsymbol{k_{gd}}\left(V_{\mathrm{gs}} + \boldsymbol{V_{sgd}}\right) - P_{111} V_{\mathrm{ds}}\right) + 1 + 2P_{111}\right) \end{aligned} \tag{5}$$

$$\alpha_{\mathrm{TX}} = 1 + \alpha_{\mathrm{TX0}} (T - T_0) \tag{6}$$

- A higher accuracy of device model is achieved.

Ref:

[1] H. Luo, Z. Zhong, W. Hu, and Y. Guo, “Analysis and Modeling of the Temperature Dependent Nonlinearity of Intrinsic Capacitances in AlGaN/GaN HEMTs”, *IEEE Microw. Wirel. Compon. Lett.*, vol. 31, no. 4, pp. 373-376, April 2021.

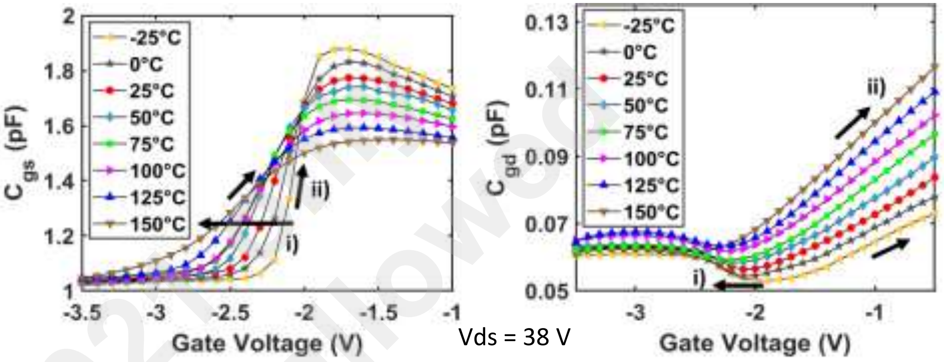
Method

The extracted Cgs and Cgd are given on the right.

In addition to the traditional relationship

$$C_X = C_{Xp} + \alpha_{TX} C_{Xi} \qquad (1)$$

The horizontal shift (i) and slope flattening (ii) can be observed.



The horizontal shift (i) is caused by the temperature dependence of threshold voltage (Vth).
The slope flattening (ii) is caused by the temperature dependence of subthreshold swing (SS).

The **constant** kgs, kgd, Vsgs and Vsgd in the Angelov capacitance model is modified to be **temperature dependent**.

Modification

$$k_{TX} = k_{TX0} \cdot (1 + \gamma_{kX1}/(\gamma_{kX2} + (T - T_0))) \qquad (2)$$

⇒ In accordance with the temperature dependence of Vth

$$V_{sTX} = V_{sTX0} + \gamma_{VX}(T - T_0) \qquad (3)$$

⇒ In accordance with the temperature dependence of SS

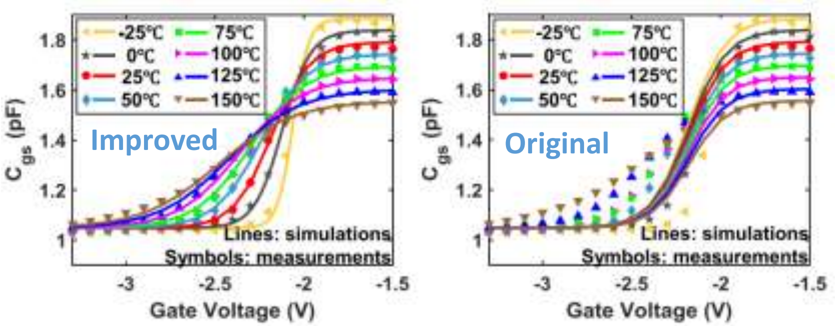
where X can be either gs or gd

Angelov capacitance model

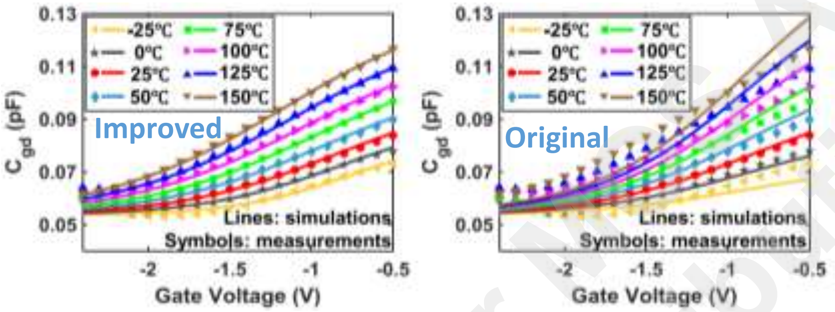
$$\begin{aligned} C_{gs} = {} & C_{gsp} + \alpha_{Tgs} C_{gs0} \cdot \left(\tanh\left(k'_{gs}\left(V_{ds} + V'_{sgs}\right)\right) + 1\right) \\ & \cdot \left(\tanh\left(\boldsymbol{k_{gs}}\left(V_{gs} + \boldsymbol{V_{sgs}}\right)\right) + P_{222} V_{ds} + 1\right) \qquad (4) \\ C_{gd} = {} & C_{gdp} + \alpha_{Tgd} C_{gd0} \cdot \left(\tanh\left(k'_{gd}\left(V_{ds} + V'_{sgd}\right)\right) + 1 - P_{111}\right) \\ & \cdot \left(\tanh\left(\boldsymbol{k_{gd}}\left(V_{gs} + \boldsymbol{V_{sgd}}\right) - P_{111} V_{ds}\right) + 1 + 2P_{111}\right) \qquad (5) \\ \alpha_{TX} = {} & 1 + \alpha_{TX0}(T - T_0) \qquad (6) \end{aligned}$$

Validations

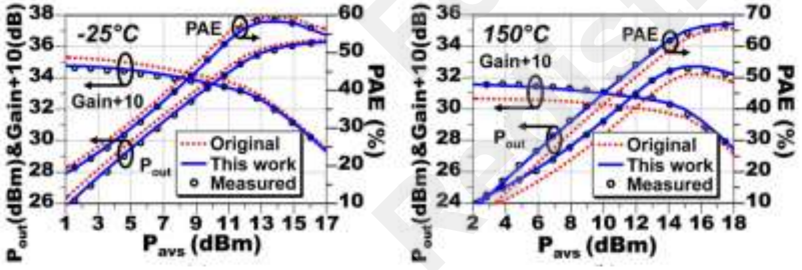
Comparison of the original Cgs and improved Cgs



Comparison of the original Cgd and improved Cgd

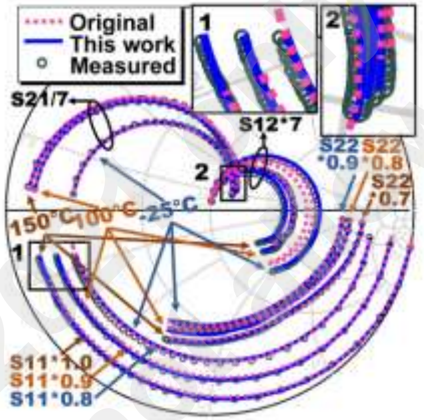


Power sweeps

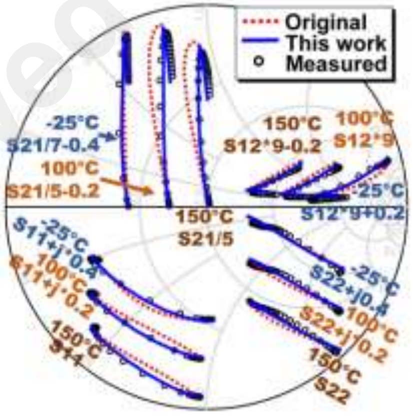


Vgsq = -2.1 V, Vdsq = 38 V, f = 3.5 GHz

S-Parameters

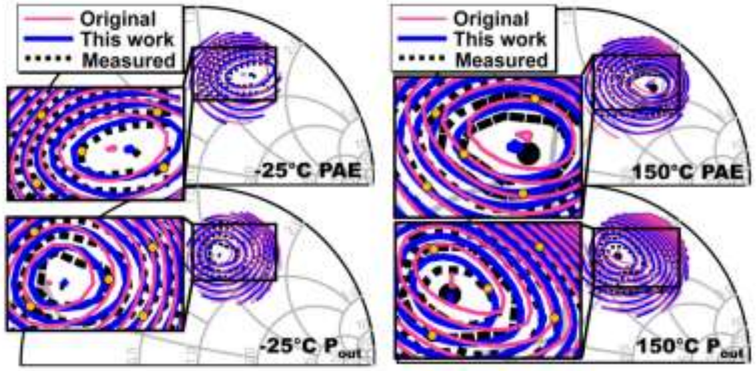


Vgs = -2.3 V, Vds = 38 V,
f = 0.2 to 10 GHz



f = 3.4 GHz, Vds = 38 V,
Vgs = -3.5 to -0.5 V

Load pulls



Vgsq = -2.1 V, Vdsq = 38 V, f = 3.5 GHz

6

ANN-Based Consistent Gate Charge Model

- Background and Motivation
- Measurement Facilities
- Outlier Detection of Capacitance Extractions
- Simplification of Nonlinear Capacitance
- Temperature Dependence of Nonlinear Capacitances
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Problem and Method

- The ANN capacitance model is not charge-conservative, which may have convergence issue
- The gate charge can be used to avoid charge-conservation issue, i.e.,

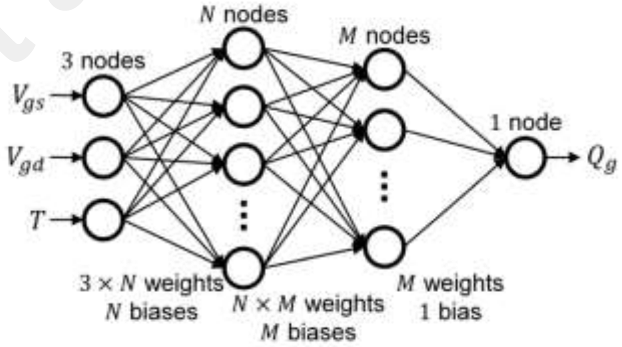
$$\frac{\partial C_{\mathrm{gs}}}{\partial V_{\mathrm{gd}}}=\frac{\partial^2 Q_g}{\partial V_{\mathrm{gd}}\partial V_{\mathrm{gs}}}=\frac{\partial^2 Q_g}{\partial V_{\mathrm{gs}}\partial V_{\mathrm{gd}}}=\frac{\partial C_{\mathrm{gd}}}{\partial V_{\mathrm{gs}}}$$

- We construct the gate charge ANN model directly

$$Q_g(V_{\mathrm{gs}},V_{\mathrm{gd}},T)=b_3+\sum_{i=1}^{M}w_{3i}\tanh(\varphi_{2i})$$

$$\varphi_{2i}=b_{2i}+\sum_{j=1}^{N}w_{2ij}\tanh(\varphi_{1j})$$

$$\varphi_{1j}=b_{1j}+w_{1j1}V_{\mathrm{gs}}+w_{1j2}V_{\mathrm{gd}}+w_{1j3}T$$



- Then the Cgs and Cgd is naturally charge conservative

$$C_{\mathrm{gs}}=\sum_{i=1}^{M}\left[w_{3i}\mathrm{sech}^2(\varphi_{2i})\left(\sum_{j=1}^{N}w_{2ij}w_{1j1}\mathrm{sech}^2(\varphi_{1j})\right)\right]$$

$$C_{\mathrm{gd}}=\sum_{i=1}^{M}\left[w_{3i}\mathrm{sech}^2(\varphi_{2i})\left(\sum_{j=1}^{N}w_{2ij}w_{1j2}\mathrm{sech}^2(\varphi_{1j})\right)\right]$$

Ref:

[1] W. Hu, H. Luo, X. Yan and Y. -X. Guo, "An Accurate Neural Network-Based Consistent Gate Charge Model for GaN HEMTs by Refining Intrinsic Capacitances," *IEEE Trans. Microw. Theory Techn.*, vol. 69, no.7, pp. 3208-3218, July 2021.

Validations

Extracted and modelled Qg, Cgs and Cgd

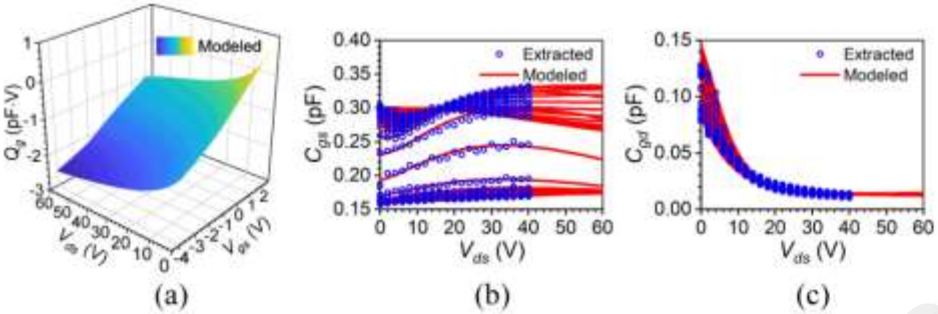


Figure 5. *The Extracted results with V_{gs} from -3.5 V to 1 V and V_{ds} from 0 V to 40 V and modeled results with V_{gs} from -4 V to 2 V and V_{ds} from 0 V to 60 V at 125 ℃. (a) Q_g. (b) C_{gs}. (c) C_{gd}.*

S-Parameters

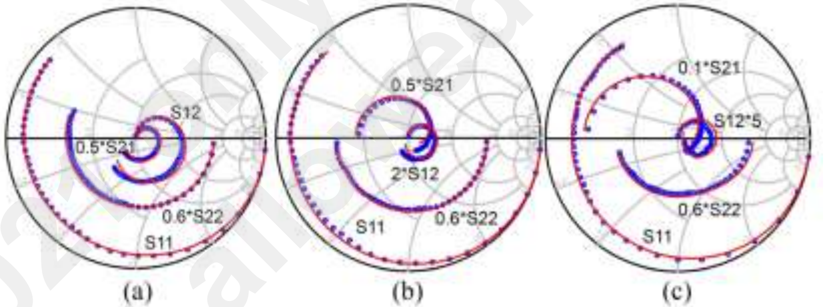


Fig. 17. Measured (symbols) and simulated (lines) CW S-parameters from 0.5 to 40 GHz at 25 °C with the reference plane at the probe tips. (a) $V_{gs} = -3$ V and $V_{ds} = 0$ V. (b) $V_{gs} = -2$ V and $V_{ds} = 20$ V. (c) $V_{gs} = -1$ V and $V_{ds} = 20$ V.

Load pulls:

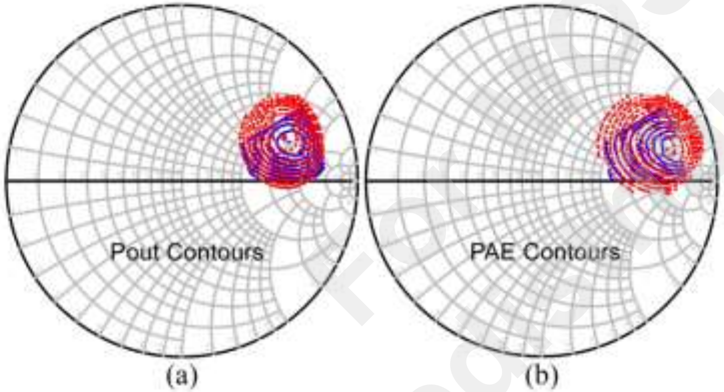


Fig. 19. Measured (solid lines) and simulated (dashed lines) CW load—pull results at a Class-AB operating point ($V_{gsq} = -1.68$ V, $V_{dsq} = 20$ V, and $I_{dsq} = 10$ mA) with the operating frequency $f_0 = 2.8$ GHz, the input power $P_{in} = 6.8$ dBm, and the source impedance $Z_S = 56.768 + j129.46\ \Omega$. (a) P_{out} contours in steps of 0.25 dBm. (b) PAE contours in steps of 4%.

Power sweeps:

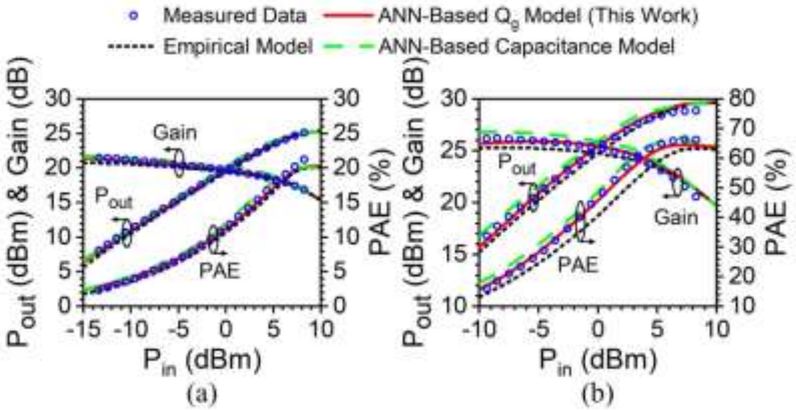


Fig. 20. Measured (symbols) and simulated (lines) P_{out}, Gain, and PAE at a Class-AB operating point with $V_{dsq} = 20$ V, $I_{dsq} = 10$ mA, and $f_0 = 2.8$ GHz. (a) $Z_S = 61.03 + j134\ \Omega$ and $Z_L = 50.02 + j0.418\ \Omega$. (b) $Z_S = 56.77 + j129.5\ \Omega$ and $Z_L = 146 + j110.7\ \Omega$ (optimum source and load impedances).

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Conclusion

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Conclusion

This presentation includes:

- **A quick review of GaN HEMT and its nonlinear capacitance modelling methods**
- **Introduction of our on-wafer measurement facilities**
- **The latest progress of our group on GaN HEMT nonlinear capacitance modeling. Including**
  - A method to detect capacitance extraction outliers
  - A simplification method of nonlinear capacitances
  - An improvement method of temperature dependence of nonlinear capacitances
  - An ANN-based consistent gate charge model