ASM-HEMT Model for GaN RF and Power Electronic Applications: Overview and Extraction

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TECHNOLOGIES

Contents

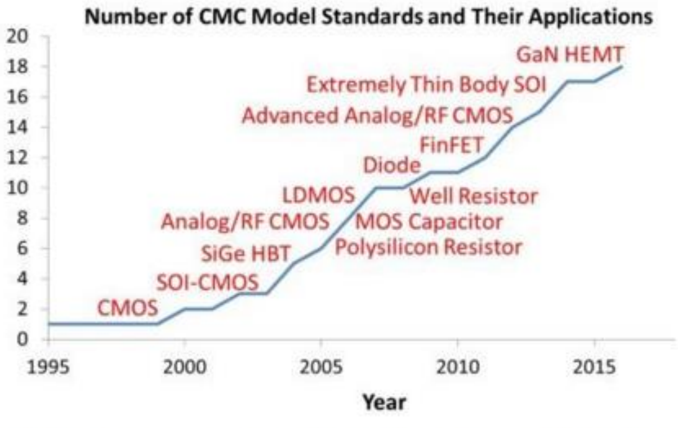
- ASM-HEMT Model Overview
- Parameter Extraction
  - DC Model
  - Field Plate Capacitance Model
  - RF Small Signal Model
- Summary

GaN HEMT Model Standardization Effort in CMC

- Compact Model Coalition – an industry body that standardizes and promotes SPICE models for semiconductor devices as well as compiled modeling interface

- Dedicated workgroup for GaN HEMT model standardization launched in Year 2011

- Standardization process
  - Phase I completed: solicitation of models and presentation to CMC.
  - Phase II completed: shortlisted candidate models being examined against fundamental requirements and being fitted to measurement data for CMC evaluation
  - **Phase III is ongoing: evaluation on runtime, convergence, operability, etc.**
    - ASM-HEMT
    - MVSG
  - Phase IV: ballot for standardization (targeting at the end of 2016)



The CMC has been developing modeling standards for nearly two decades.

[*] Compact Model Coalition, https://www.si2.org/cmc_index.php
[*] Keith Green, http://www.eetimes.com/author.asp?section_id=36&doc_id=1324925

ASM-HEMT Model Overview

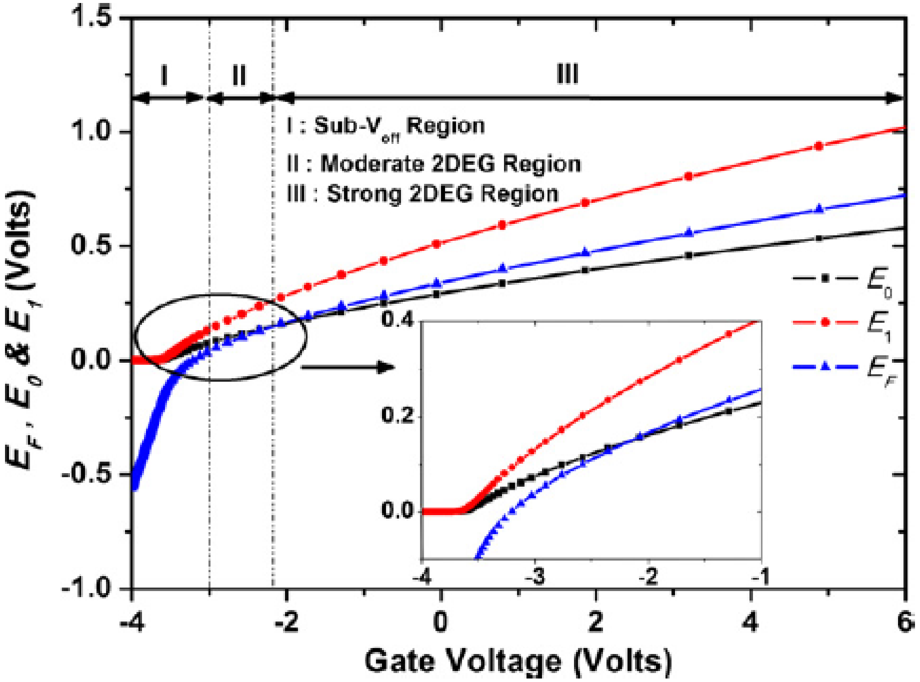
$$n_s = DV_{th}\left\{\ln\left[\exp\left(\frac{E_f - E_0}{V_{th}}\right)+1\right] + \ln\left[\exp\left(\frac{E_f - E_1}{V_{th}}\right)+1\right]\right\}$$

$$E_0 = \gamma_0 n_s^{2/3} E_1 = \gamma_1 n_s^{2/3}$$

$$n_s = \frac{\varepsilon}{qd}\left(V_{go} - E_f - V_x\right)$$

Transcendental

$$\boxed{\begin{gathered} E_{f,unified} = V_{go} - \frac{2V_{th}\ln\left(1 + e^{\frac{V_{go}}{2V_{th}}}\right)}{\frac{1}{H\left(V_{go},p\right)} + \frac{C_g}{qD}e^{-\frac{V_{go}}{2V_{th}}}} \\ \psi = E_f + V_x \end{gathered}}$$



ASM HEMT Model Overview

$$I_d(x) = \mu W N_f Q_{ch}\frac{d\psi(x)}{dx} + \mu W N_f V_{th}\frac{dQ_{ch}}{dx} \qquad Q_{ch} \;=\; -C_g(V_{go} - \psi(x))$$

$$I_d = \frac{W}{L}\mu C_g N_f\left[V_{go} - \left(\frac{\psi_s + \psi_d}{2}\right) + V_{th}\right](\psi_d - \psi_s)$$

Intrinsic Charges

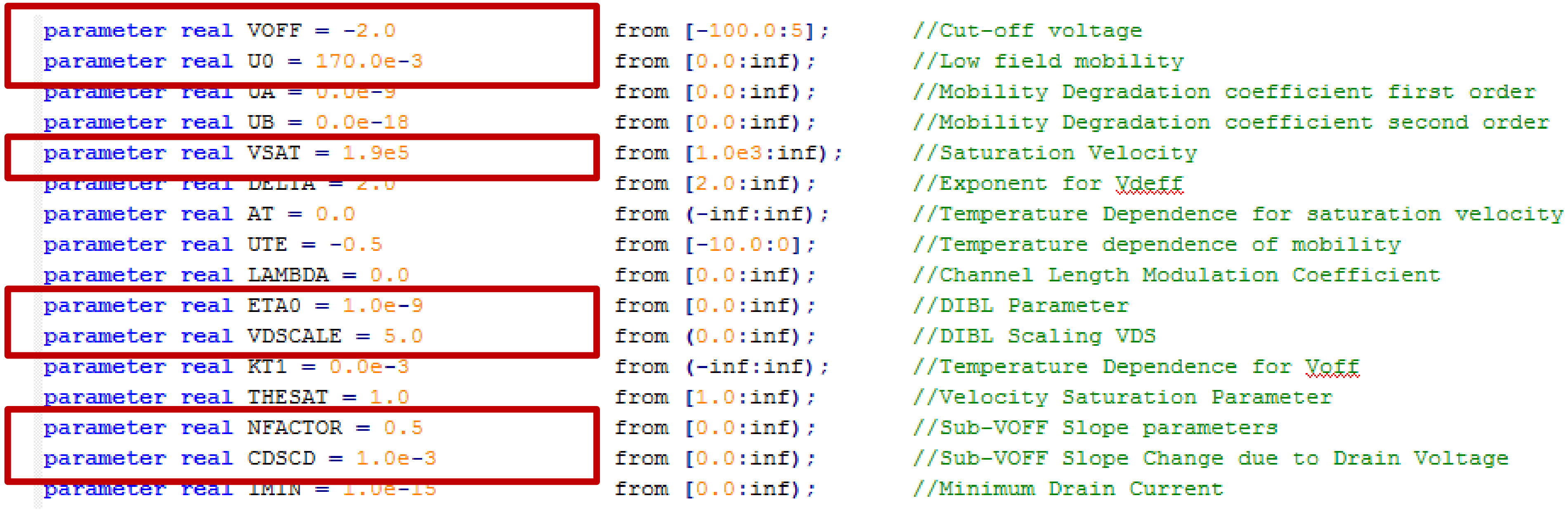
Incorporating Realistic device effects

$$\boxed{I_d = \frac{\mu_{eff}}{\sqrt{1+\theta_{sat}^2\psi_{ds}^2}}\frac{W}{L}C_g N_f\left[V_{go} - \left(\frac{\psi_s + \psi_d}{2}\right) + V_{th}\right]\psi_{ds}(1+\lambda V_{ds})}$$

$$\left.\begin{aligned} Q_{gi} &= -\int_0^L W N_f C_g(V_{go} - \psi(x))dx \\ Q_{di} &= \int_0^L (x/L) W N_f C_g(V_{go} - \psi(x))dx \\ Q_{si} &= -Q_{gi} - Q_{di} \end{aligned}\right]$$

List of Parameters I

Core Model Parameters



```
parameter real VOFF = -2.0          from [-100.0:5];      //Cut-off voltage
parameter real U0 = 170.0e-3        from [0.0:inf);       //Low field mobility
parameter real UA = 0.0e-9          from [0.0:inf);       //Mobility Degradation coefficient first order
parameter real UB = 0.0e-18         from [0.0:inf);       //Mobility Degradation coefficient second order
parameter real VSAT = 1.9e5         from [1.0e3:inf);     //Saturation Velocity
parameter real DELTA = 2.0          from [2.0:inf);       //Exponent for Vdeff
parameter real AT = 0.0             from (-inf:inf);      //Temperature Dependence for saturation velocity
parameter real UTE = -0.5           from [-10.0:0];       //Temperature dependence of mobility
parameter real LAMBDA = 0.0         from [0.0:inf);       //Channel Length Modulation Coefficient
parameter real ETA0 = 1.0e-9        from [0.0:inf);       //DIBL Parameter
parameter real VDSCALE = 5.0        from (0.0:inf);       //DIBL Scaling VDS
parameter real KT1 = 0.0e-3         from (-inf:inf);      //Temperature Dependence for Voff
parameter real THESAT = 1.0         from [1.0:inf);       //Velocity Saturation Parameter
parameter real NFACTOR = 0.5        from [0.0:inf);       //Sub-VOFF Slope parameters
parameter real CDSCD = 1.0e-3       from [0.0:inf);       //Sub-VOFF Slope Change due to Drain Voltage
parameter real IMIN = 1.0e-15       from [0.0:inf);       //Minimum Drain Current
```

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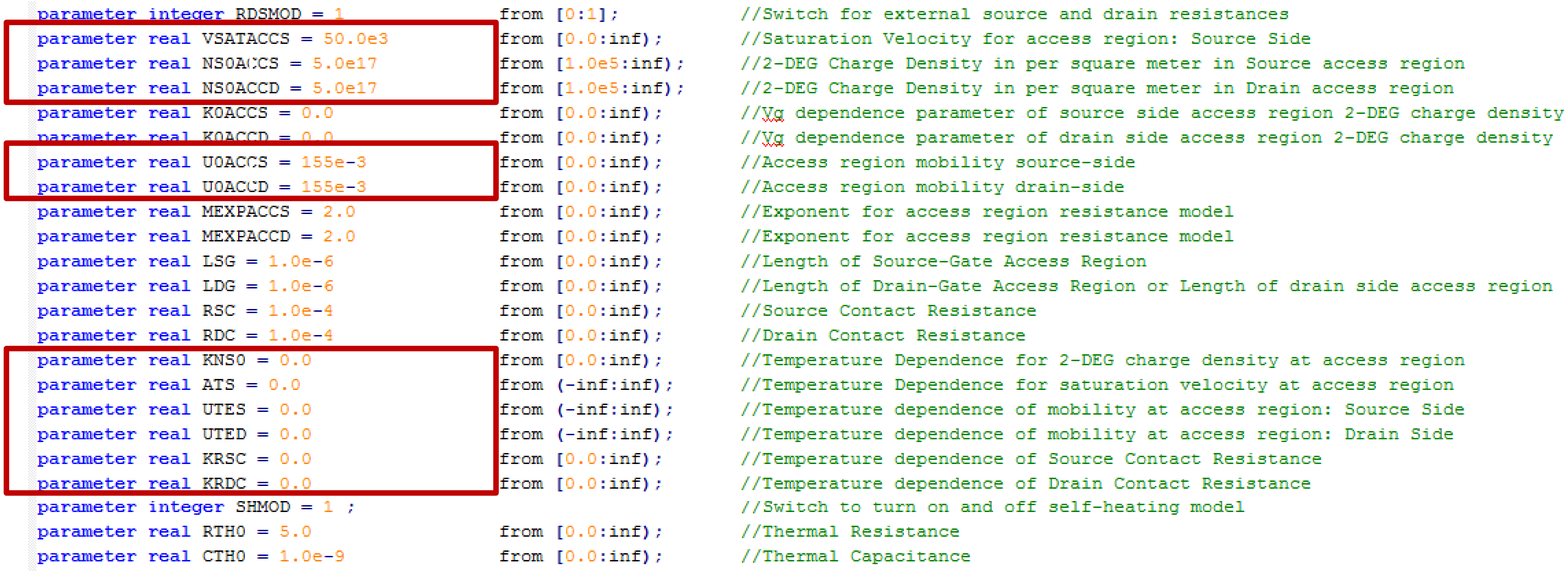
List of Parameters II

Access Region and Temperature Parameters



```
parameter integer RDSMOD = 1              from [0:1];           //Switch for external source and drain resistances
parameter real VSATACCS = 50.0e3          from [0.0:inf);       //Saturation Velocity for access region: Source Side
parameter real NS0ACCS = 5.0e17           from [1.0e5:inf);     //2-DEG Charge Density in per square meter in Source access region
parameter real NS0ACCD = 5.0e17           from [1.0e5:inf);     //2-DEG Charge Density in per square meter in Drain access region
parameter real K0ACCS = 0.0               from [0.0:inf);       //Vg dependence parameter of source side access region 2-DEG charge density
parameter real K0ACCD = 0.0               from [0.0:inf);       //Vg dependence parameter of drain side access region 2-DEG charge density
parameter real U0ACCS = 155e-3            from [0.0:inf);       //Access region mobility source-side
parameter real U0ACCD = 155e-3            from [0.0:inf);       //Access region mobility drain-side
parameter real MEXPACCS = 2.0             from [0.0:inf);       //Exponent for access region resistance model
parameter real MEXPACCD = 2.0             from [0.0:inf);       //Exponent for access region resistance model
parameter real LSG = 1.0e-6               from [0.0:inf);       //Length of Source-Gate Access Region
parameter real LDG = 1.0e-6               from [0.0:inf);       //Length of Drain-Gate Access Region or Length of drain side access region
parameter real RSC = 1.0e-4               from [0.0:inf);       //Source Contact Resistance
parameter real RDC = 1.0e-4               from [0.0:inf);       //Drain Contact Resistance
parameter real KNS0 = 0.0                 from [0.0:inf);       //Temperature Dependence for 2-DEG charge density at access region
parameter real ATS = 0.0                  from (-inf:inf);      //Temperature Dependence for saturation velocity at access region
parameter real UTES = 0.0                 from (-inf:inf);      //Temperature dependence of mobility at access region: Source Side
parameter real UTED = 0.0                 from (-inf:inf);      //Temperature dependence of mobility at access region: Drain Side
parameter real KRSC = 0.0                 from [0.0:inf);       //Temperature dependence of Source Contact Resistance
parameter real KRDC = 0.0                 from [0.0:inf);       //Temperature dependence of Drain Contact Resistance
parameter integer SHMOD = 1 ;                                   //Switch to turn on and off self-heating model
parameter real RTH0 = 5.0                 from [0.0:inf);       //Thermal Resistance
parameter real CTH0 = 1.0e-9              from [0.0:inf);       //Thermal Capacitance
```

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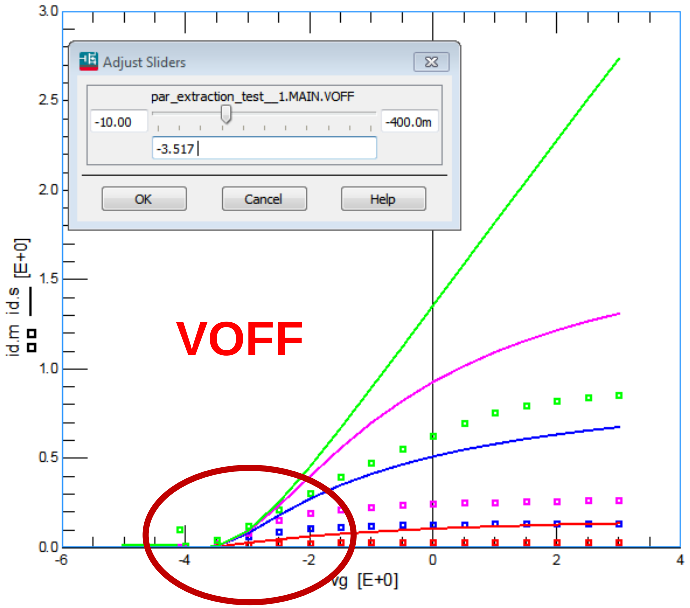
Parameter Extraction I

Id-Vg Linear and Log Scale (Linear Vd Condition)



VOFF

par_extraction_test__1.MAIN.VOFF

-10.00 | -400.0m

-3.517

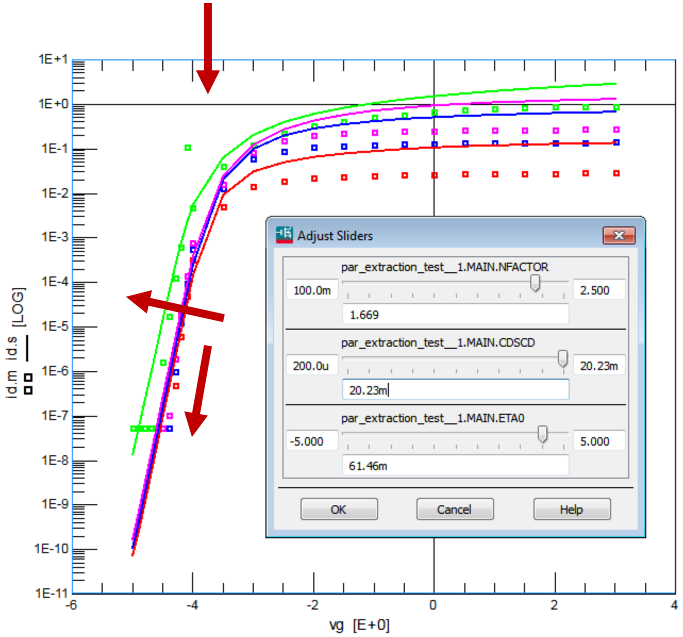
Id-Vgs (Linear)

NFACTOR

ETA0

VDSCALE

CDSCD



par_extraction_test__1.MAIN.NFACTOR

100.0m | 2.500

1.669

par_extraction_test__1.MAIN.CDSCD

200.0u | 20.23m

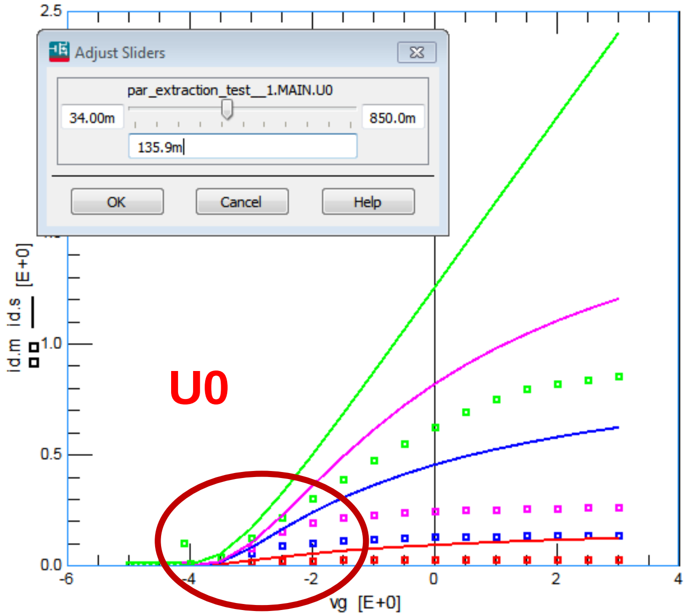
20.23m

par_extraction_test__1.MAIN.ETA0

-5.000 | 5.000

61.46m

Id-Vgs (Log)



U0

par_extraction_test__1.MAIN.U0

34.00m | 850.0m

135.9m

Id-Vgs (Linear)

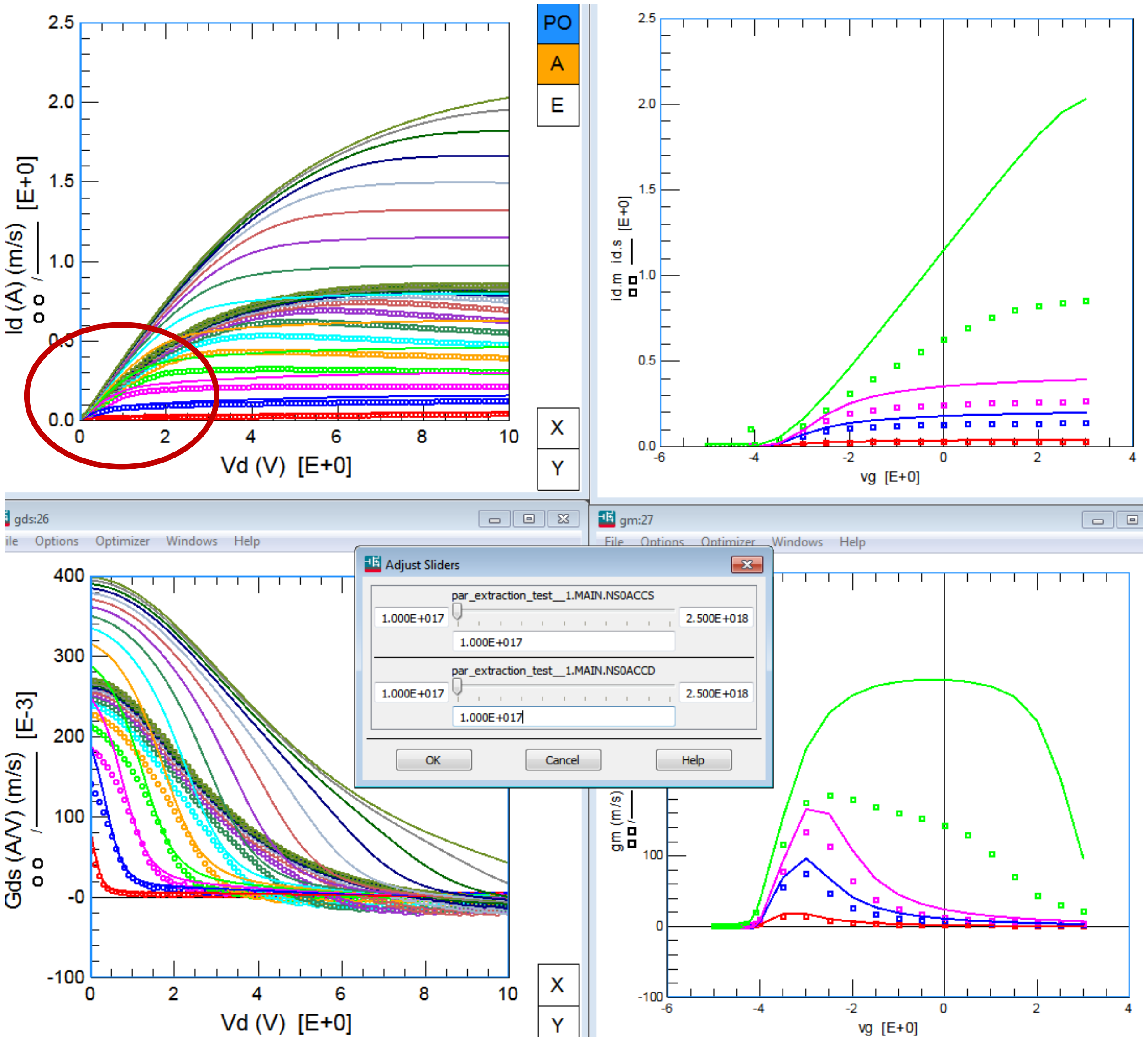
Parameter Extraction II

Id-Vgs, gm-Vgs and Id-Vds, gds-Vds

Adjust Ron using

NS0ACCS

NS0ACCD



Adjust Sliders

par_extraction_test__1.MAIN.NS0ACCS
1.000E+017 | 2.500E+018
1.000E+017

par_extraction_test__1.MAIN.NS0ACCD
1.000E+017 | 2.500E+018
1.000E+017

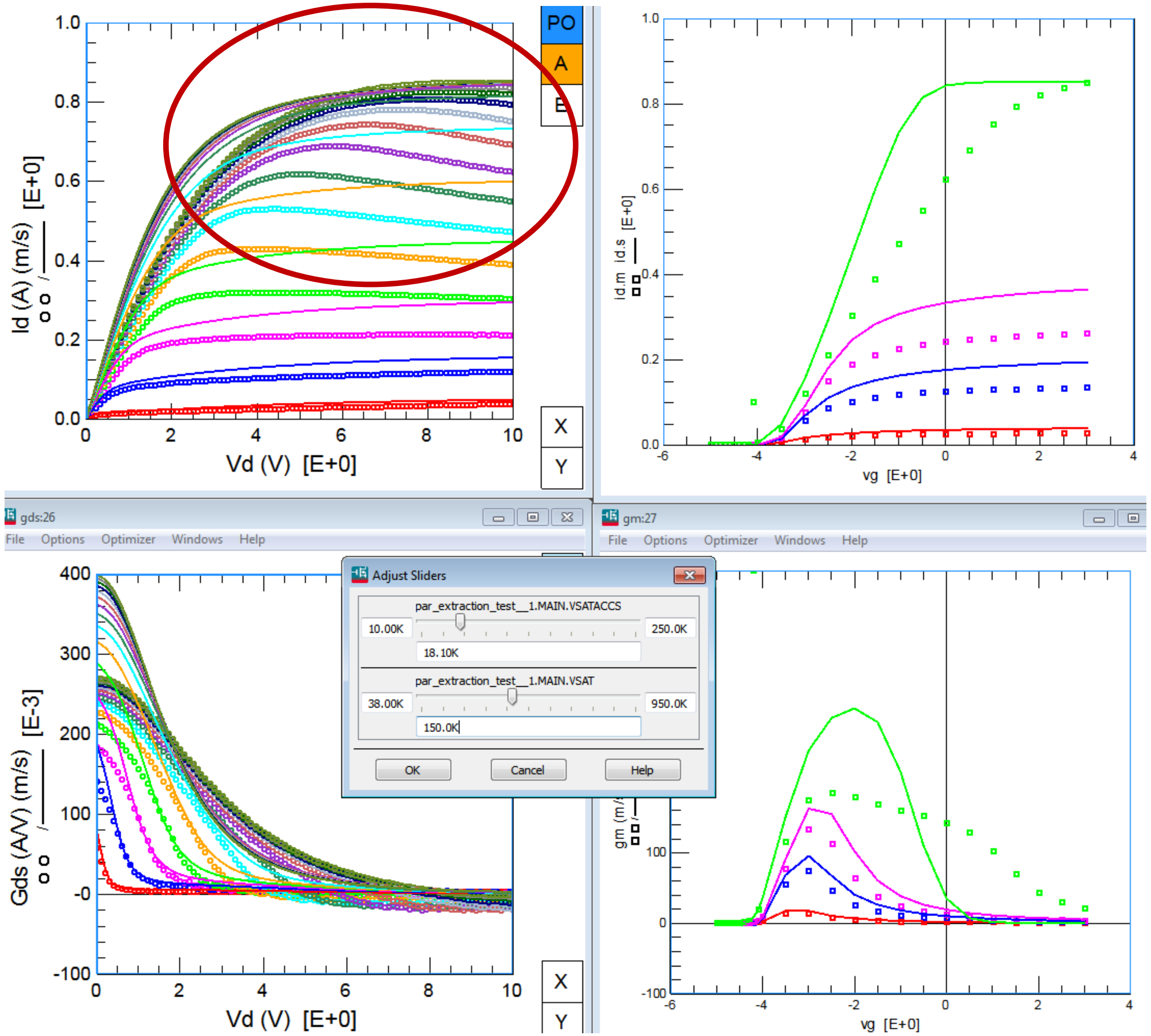
Parameter Extraction III

Id-Vgs, gm-Vgs and Id-Vds, gds-Vds

Fit Saturation Current by adjusting

VSATACCS

VSAT should remain more or less the same since it is a material dependent parameter and should not vary much for different GaN Technologies


Adjust Sliders

par_extraction_test__1.MAIN.VSATACCS

10.00K

250.0K

18.10K

par_extraction_test__1.MAIN.VSAT

38.00K

950.0K

150.0K

Parameter Extraction IV

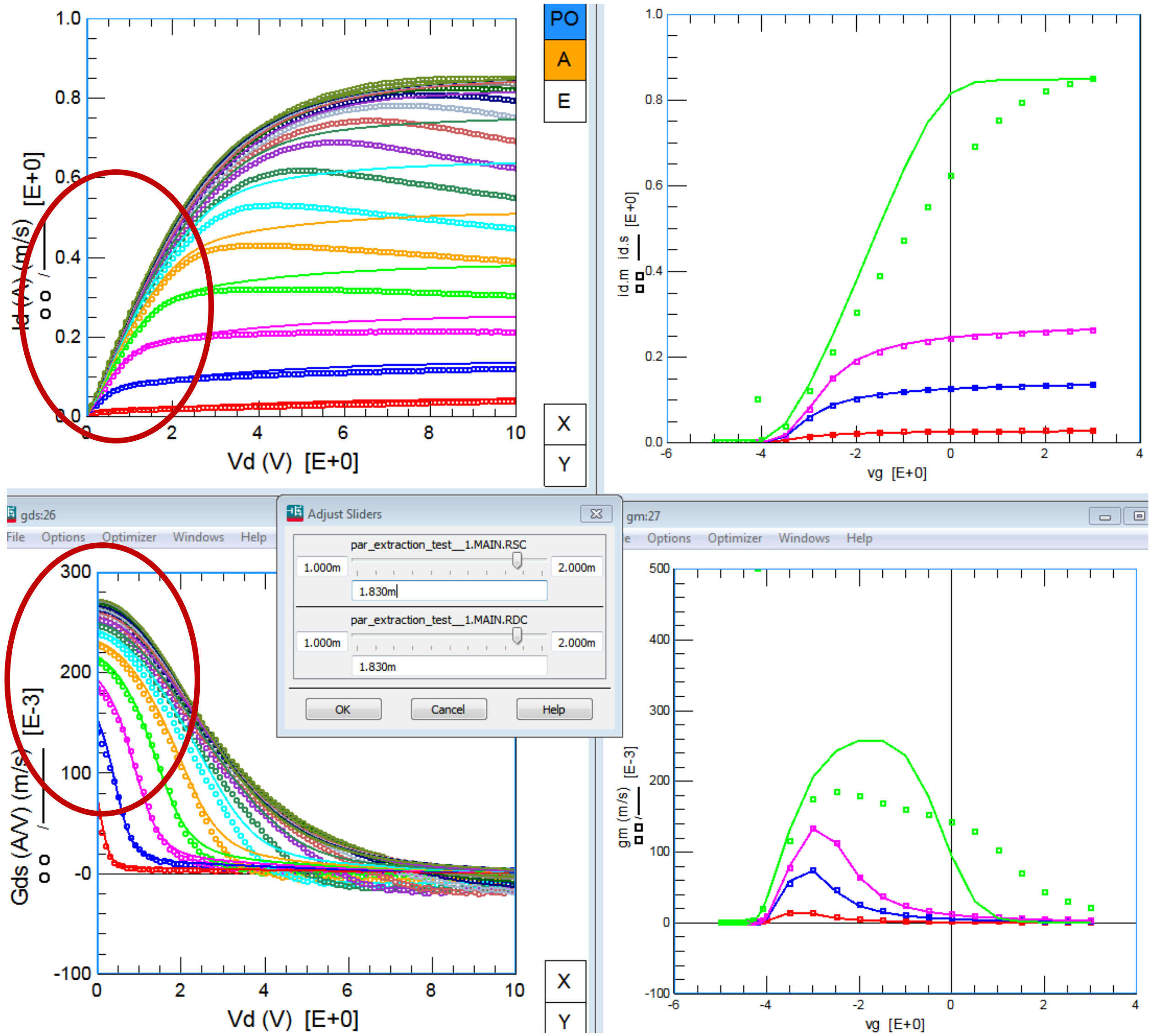
Id-Vgs, gm-Vgs and Id-Vds, gds-Vds

Fine tune Contact Resistance parameters

RDC

RSC

To further fit the Ron



Adjust Sliders

par_extraction_test__1.MAIN.RSC

1.000m 2.000m

1.830m

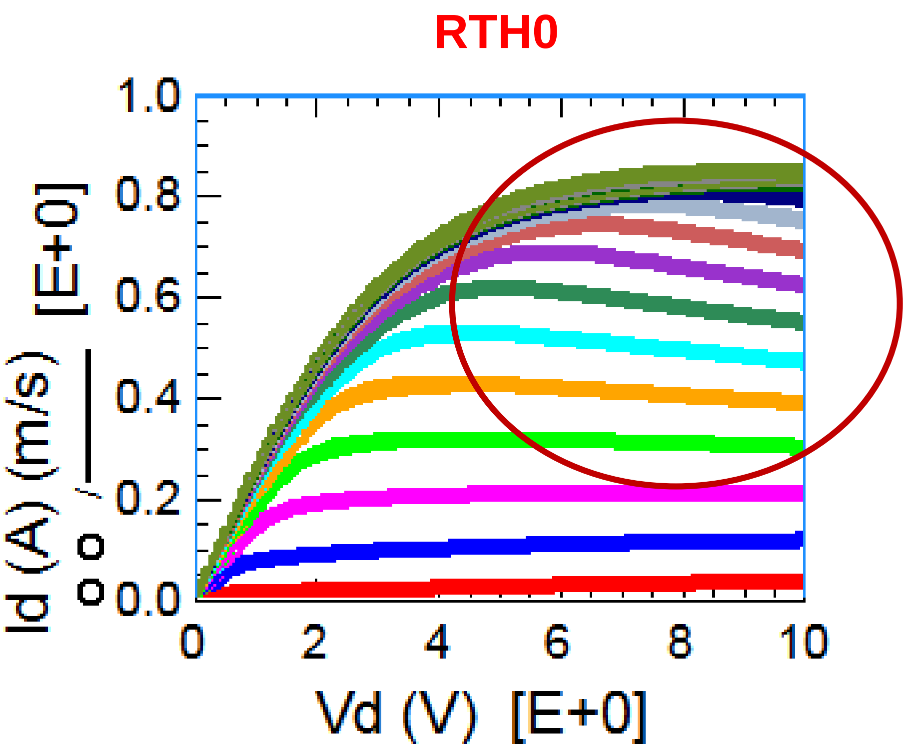
par_extraction_test__1.MAIN.RDC

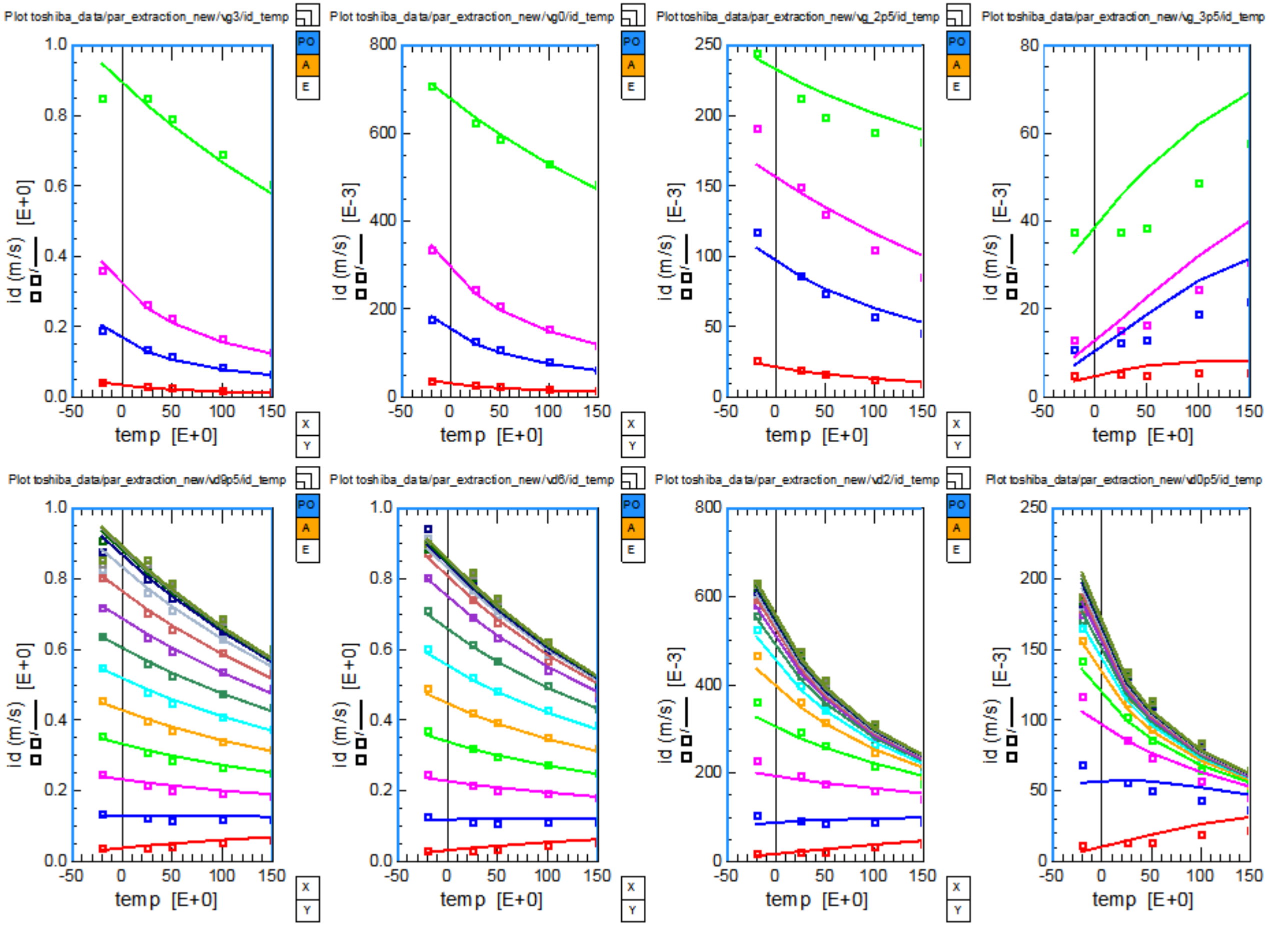
1.000m 2.000m

1.830m

OK Cancel Help

Self Heating and Temperature Related Parameters





KT1

AT

ATS

KRSC

KRDC

UTE

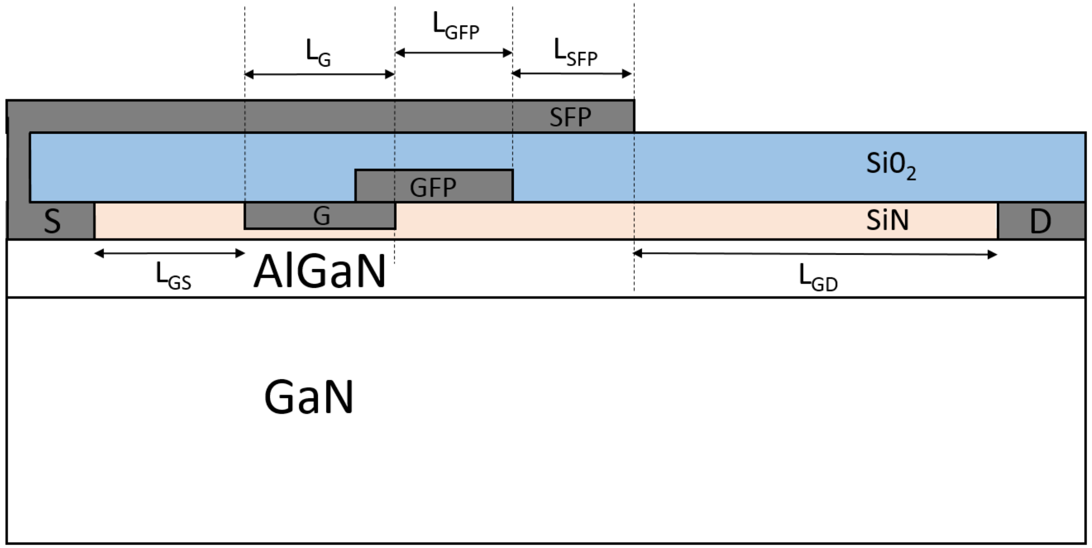
Field Plate Capacitance Model

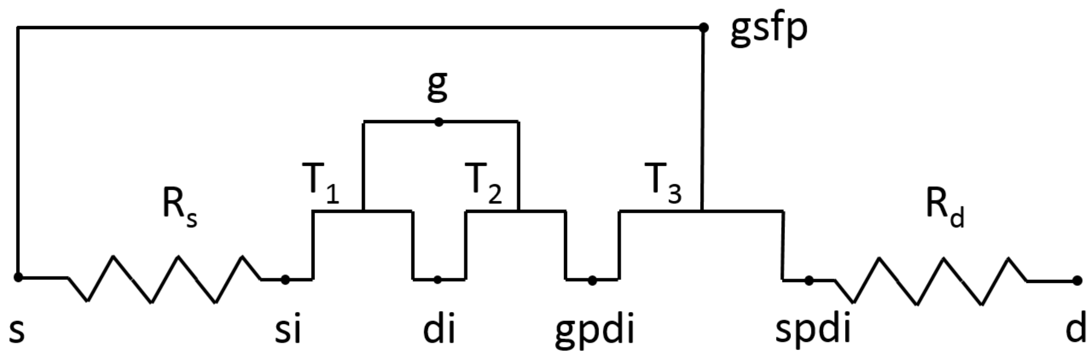
Terminal Capacitances

- Ciss = Cgs + Cgd
- Crss = Cgd
- Coss = Cds + Cgd

FP Modeled as an intrinsic HEMT

- Each HEMT governed by ψ Calc.





Field Plate MOD Parameter Extraction I

Ciss – Vgs

-150V < Vgs < 0V

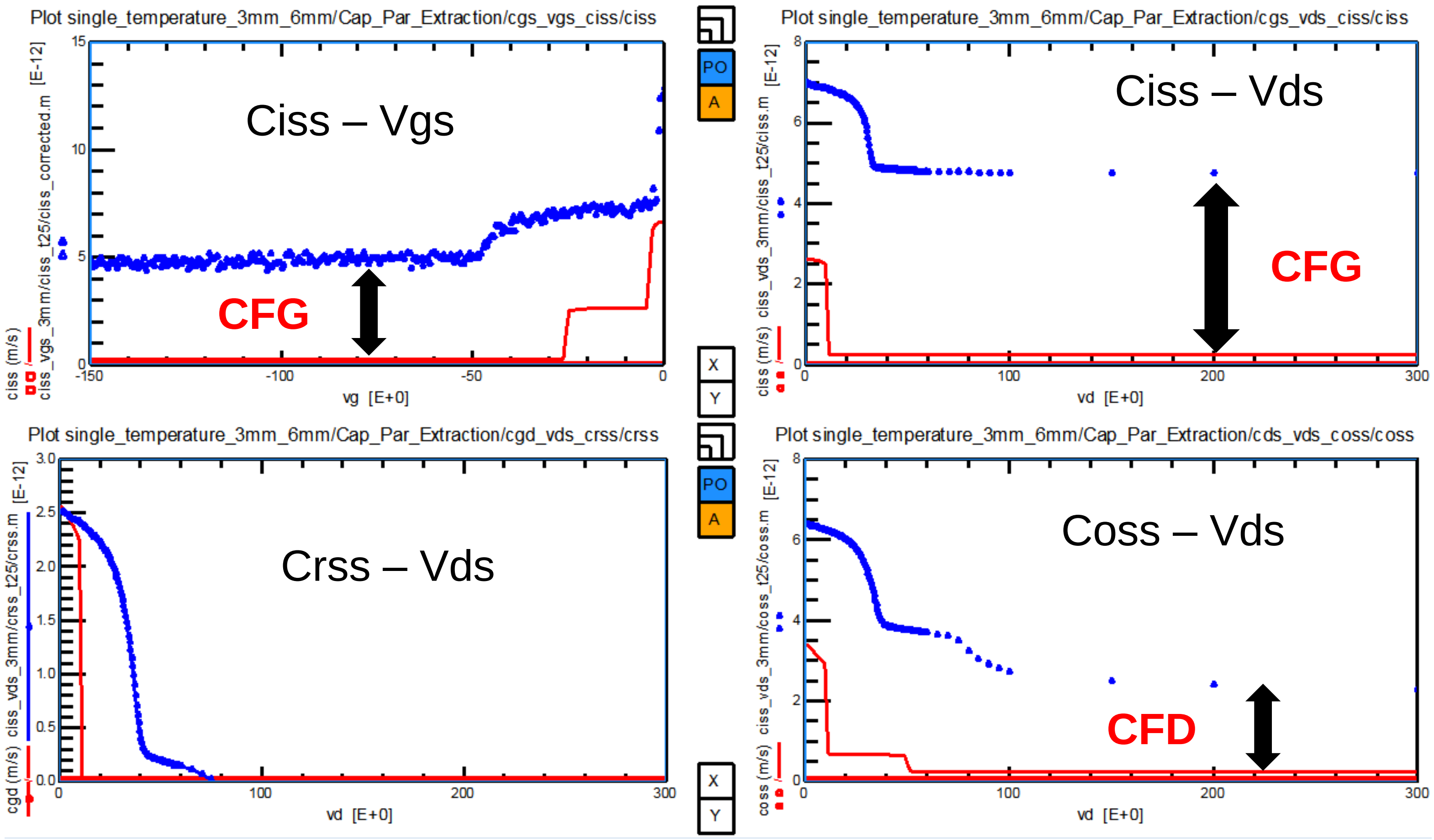
Vds = 0

Crss, Ciss, Coss versus Vds

0V < Vds < 300V

Vgs = -15V

GFPMOD = SFPMOD = 1



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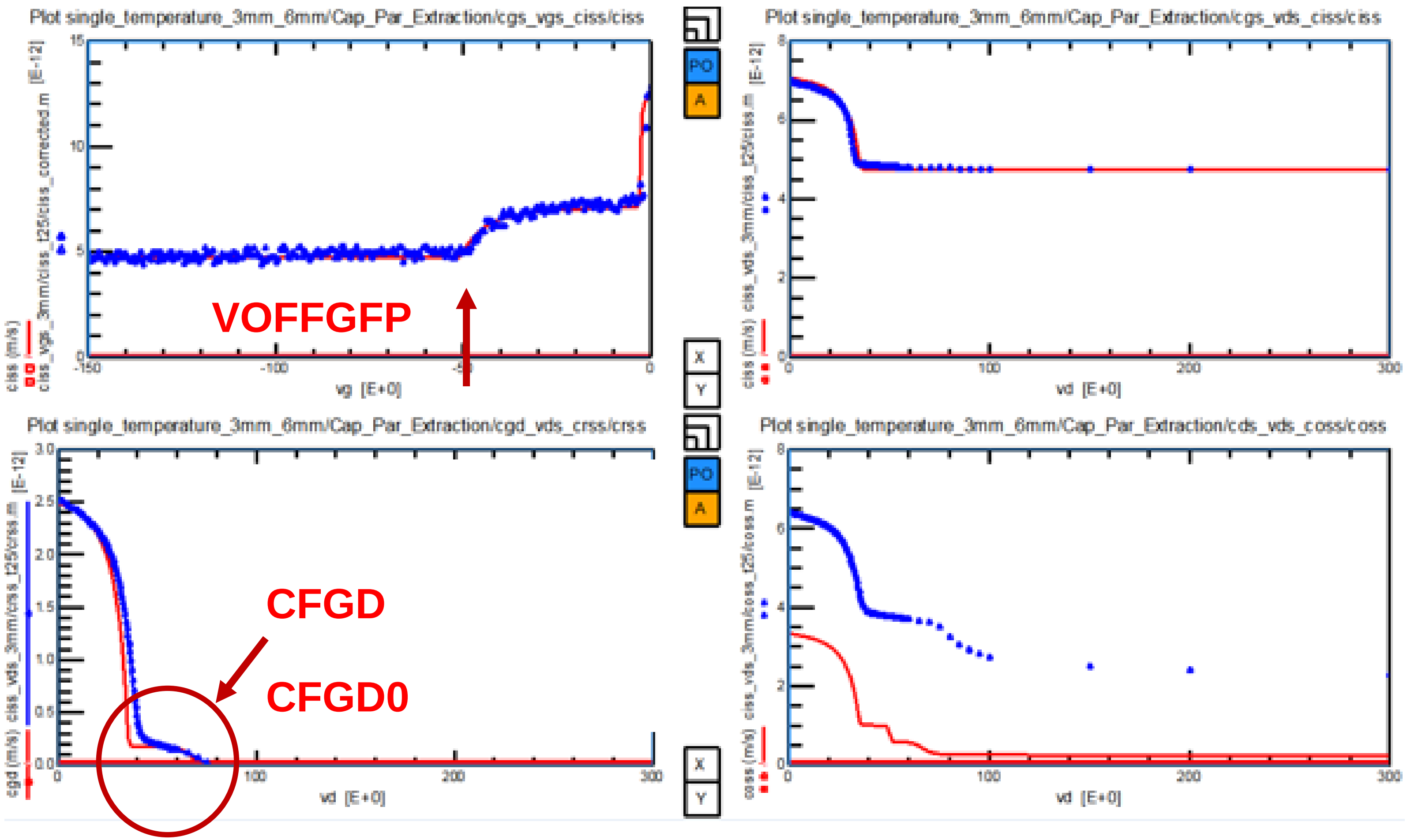
Field Plate MOD Parameter Extraction II

VOFFGFP – sets the rise of the hump

ADOS – Smoothens the hump

CFGD
CFGD0 } Gate FP - Drain Fringing capacitance



VOFFGFP

CFGD

CFGD0

KEYSIGHT TECHNOLOGIES

Field Plate MOD Parameter Extraction III

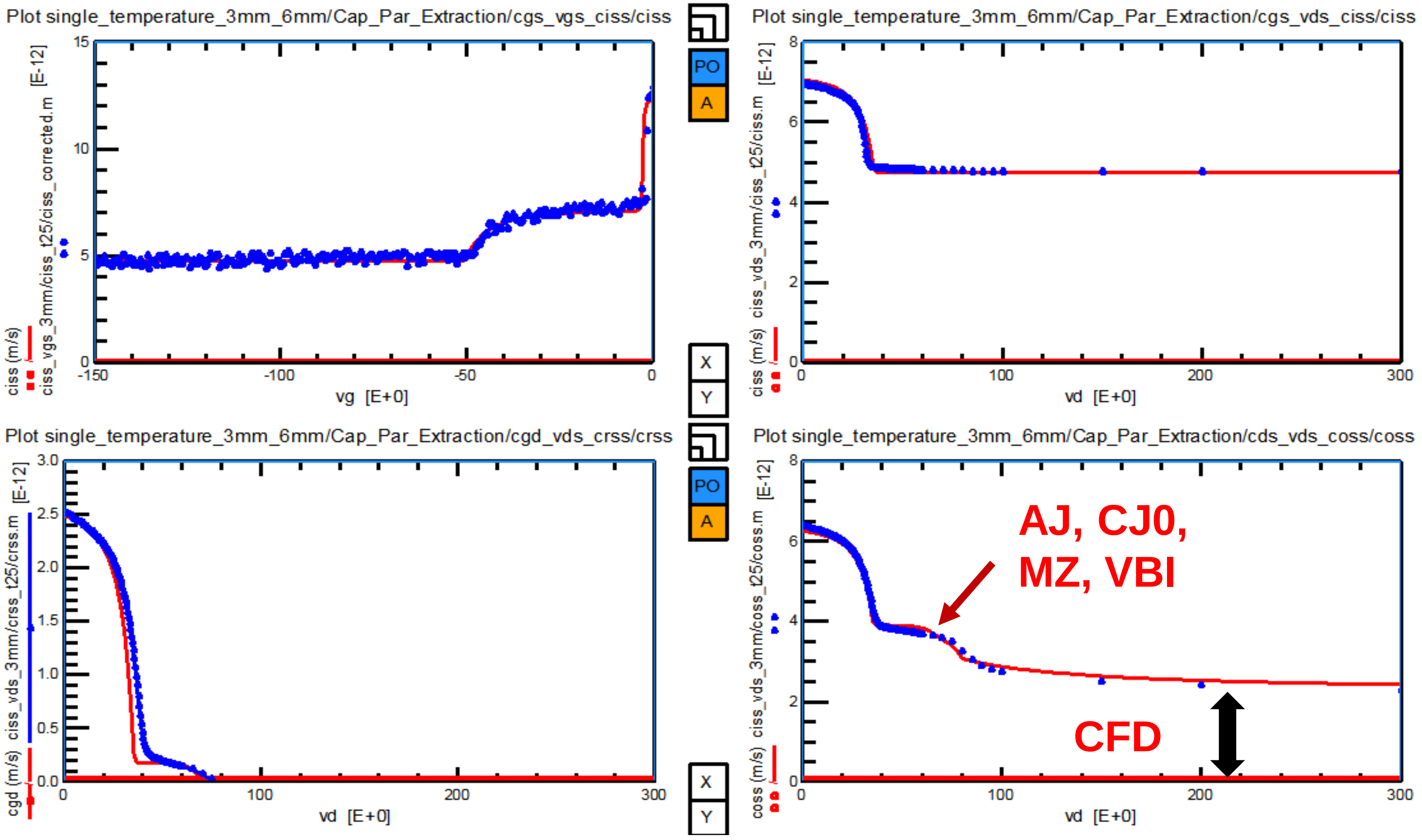
Optimize the following

AJ

CJ0

MZ

VBI



AJ, CJ0, MZ, VBI

CFD

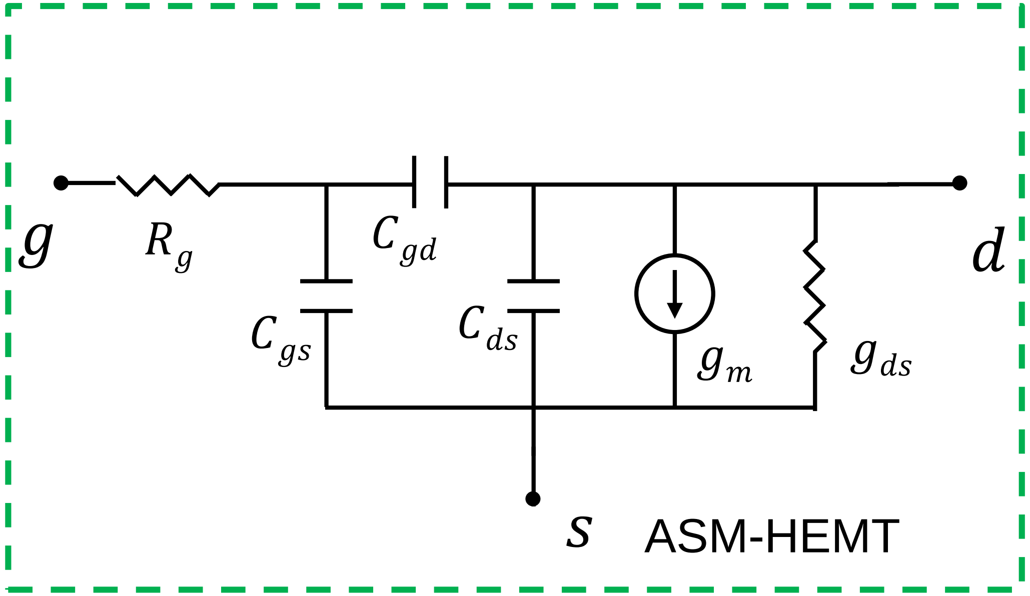
ASM HEMT - Small Signal Representation

$$Y_{11} = \frac{j\omega\left(C_{gs} + C_{gd}\right)}{1 + \omega^2\left(C_{gs} + C_{gd}\right)^2 R_g^2} + \frac{\omega^2\left(C_{gs} + C_{gd}\right)^2 R_g}{1 + \omega^2\left(C_{gs} + C_{gd}\right)^2 R_g^2}$$

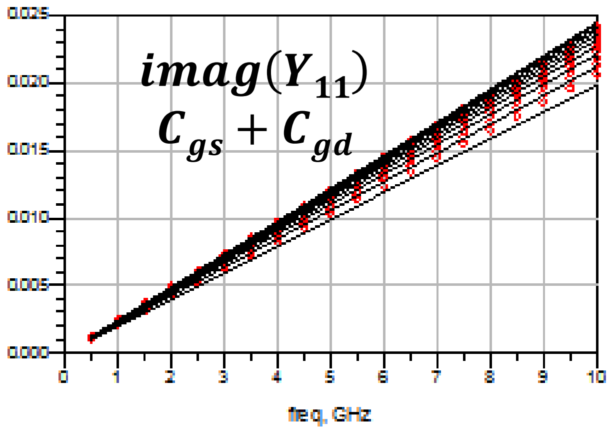
$$Y_{12} = -j\omega C_{gd} - \omega^2 C_{gd}(C_{gs} + C_{gd})R_g$$

$$Y_{21} = \left[g_m - \omega^2 C_{gd}\left(C_{gs} + C_{gd}\right)R_g\right] - j\omega\left\{C_{gd} + g_m\left(C_{gs} + C_{gd}\right)R_g\right\}$$

$$Y_{22} = g_{ds} + j\omega\left\{C_{ds} + C_{gd}(1 + g_m R_g)\right\}$$

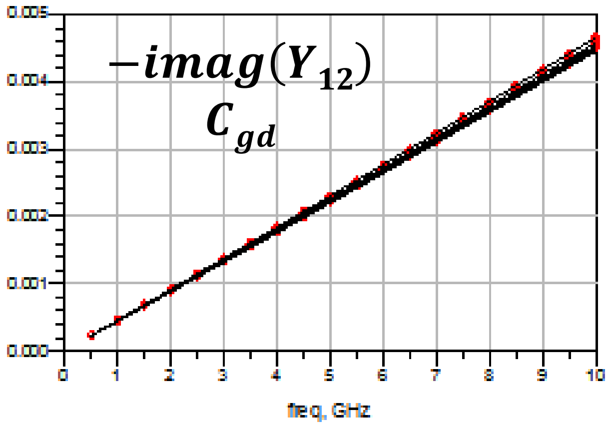


De-embedded Y-Parameters (0.5-10 GHz)



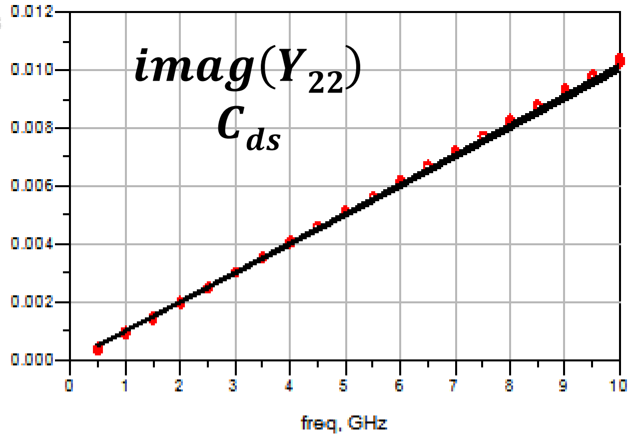
$imag(Y_{11})$

$C_{gs} + C_{gd}$



$-imag(Y_{12})$

C_{gd}

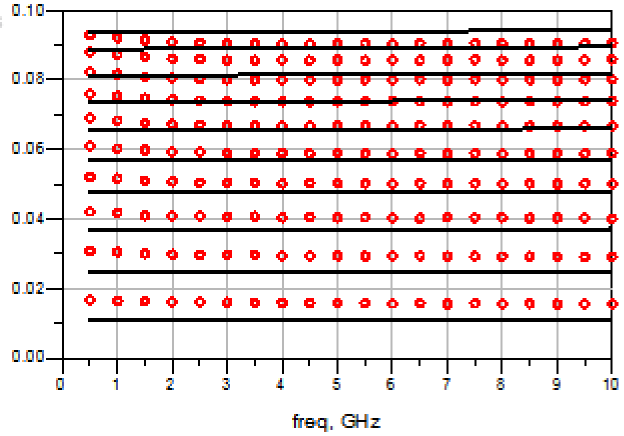


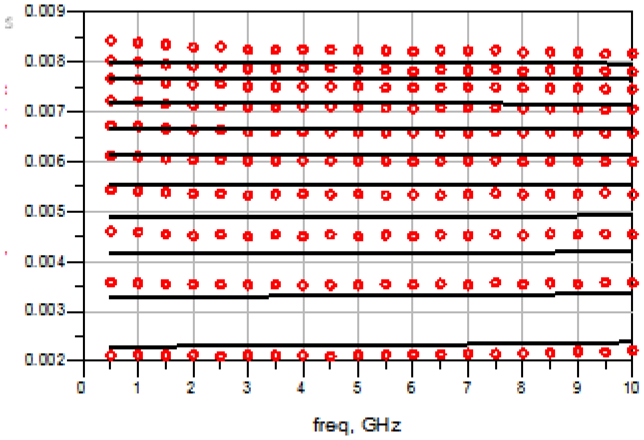
$imag(Y_{22})$

C_{ds}

$real(Y_{21})$

g_m

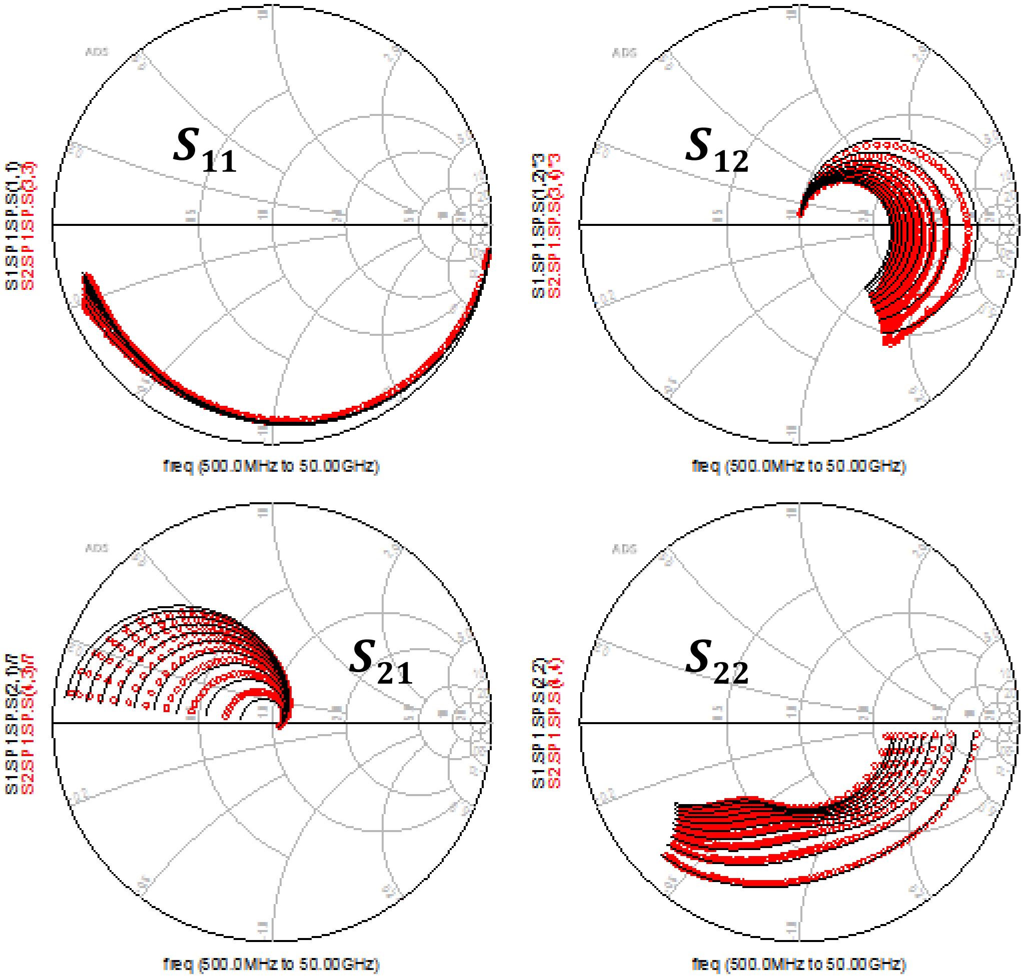


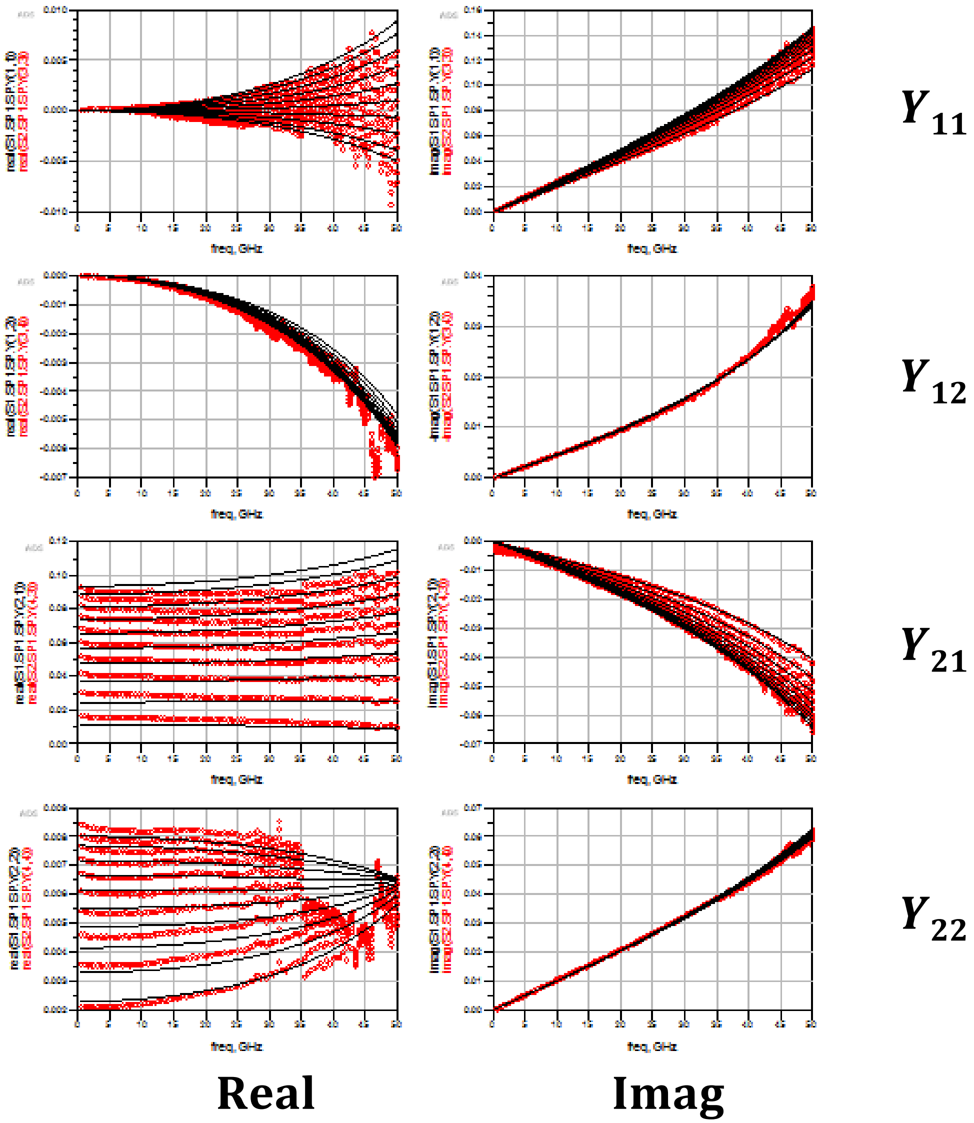


$real(Y_{22})$

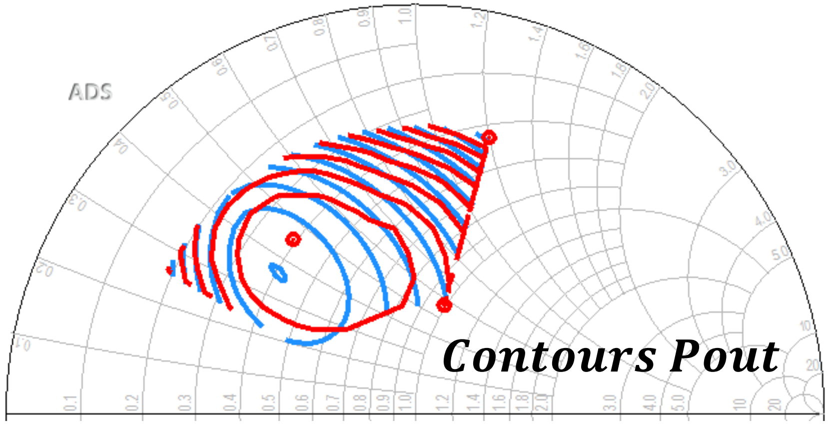
g_{ds}

Broadband S-Parameters (0.5-50 GHz)

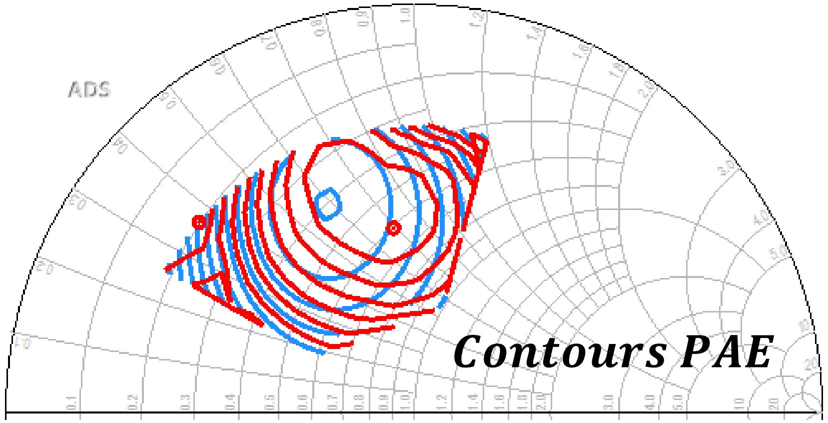


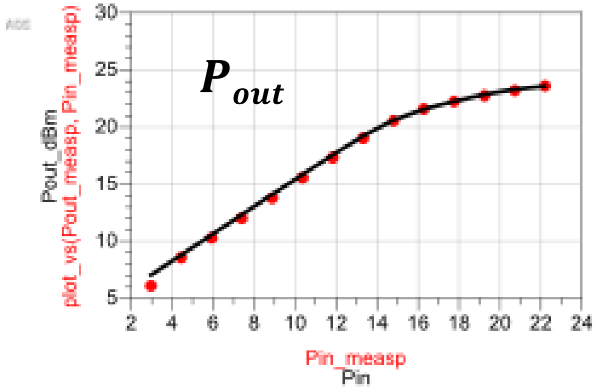


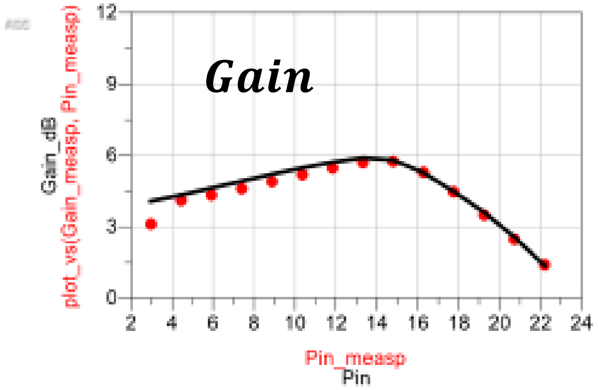
Load-Pull and Harmonic Balance Simulations

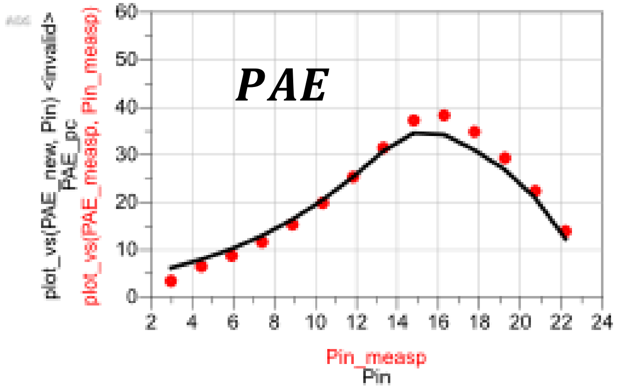


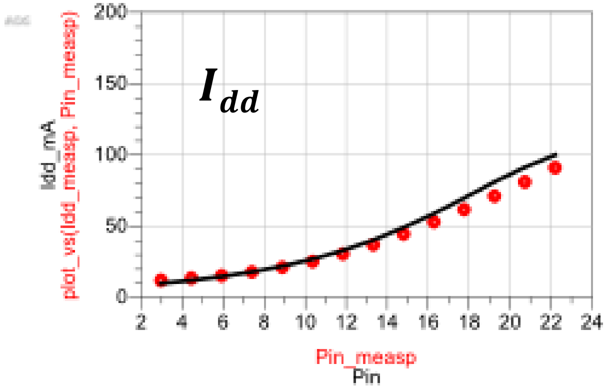
Measured Model











Summary

- As one of the candidates for CMC GaN HEMT, ASM-HEMT is a physical model base on surface potential analytical calculation
- Model extraction procedure
  - DC parameter extraction – Focused on key parameters
  - Model field plate as a transistor and perform capacitance parameter extraction
  - RF modeling
    - Broadband S-Parameters and Y-Parameters
    - Large signal load pull and harmonic balance power sweeps
- The model is developed by using Keysight’s IC-CAP and ADS software. Good fitting is achieved with industry measured data.

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