电子科技大学
University of Electronic Science and Technology of China

MMT

微波毫米波集成电路与系统实验室
Microwave and Millimeter-wave Technology(MMT) Lab

Modeling the Linearity of III-V Semiconductor RF Transistors

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MOS-AK Xi'an

Outline

I. **Background**

II. EEHEMT GaAs LSM

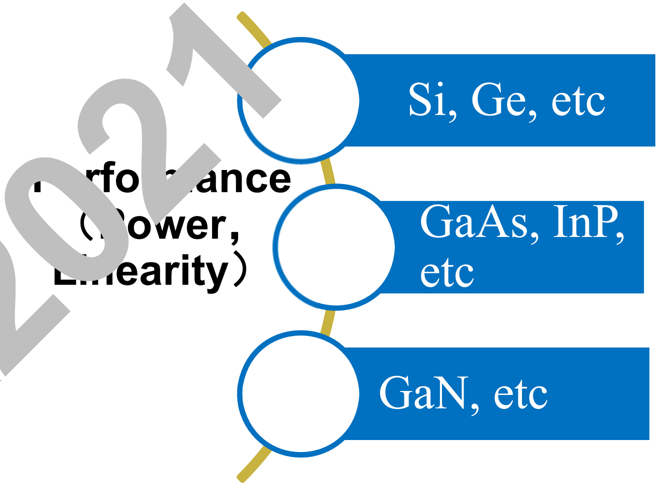
III. QPZD GaN LSM

IV. Summary

Background

RF Transistors development

Parameter	Diamond	cBN	Ga_2O_3	AlN	GaN	SiC	GaAs	Si
$\sigma_{thermal}$ (W/m•K)	2,290 - 3,450	[illegible]0 - 2,[illegible]	11 - 27	319	≤ 253	370	55	145
e^- mobility (cm²/V•s)	4,5[illegible]	8[illegible]	180	426	2,260	900	8,500	1,450
hole mobility (cm²/V•s)	3,800	500	--	--	24	120	400	480
$E_{breakdown}$ (MV/cm)	~13.0	~17.5	~10.3	~15.4	~4.9	~3.0	~0.4	~0.3
v_{sat} (10^7 cm/s)	2.3 (e^-) 1.4 (h^+)	--	1.1	1.3	1.4	2.0	1.0	1.0
Rel. permittivity	5.7	7.1	10.0	9.8	10.4	9.7	12.[illegible]	11.8



Performance (Power, Linearity)

Si, Ge, etc

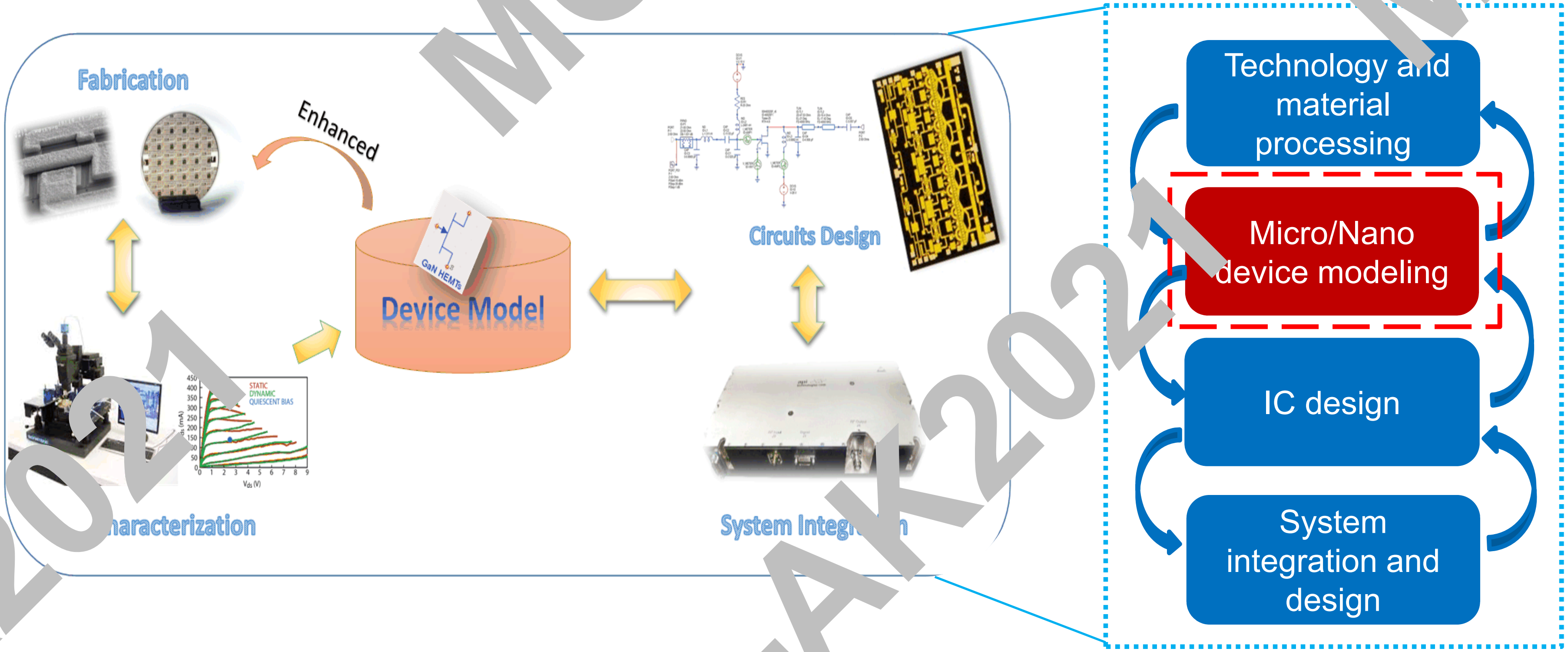
GaAs, InP, etc

GaN, etc

- ➢ **5G communication has higher requirements for linearity**
- ➢ **Device with high output power and efficiency**

Background

Importance of device modeling



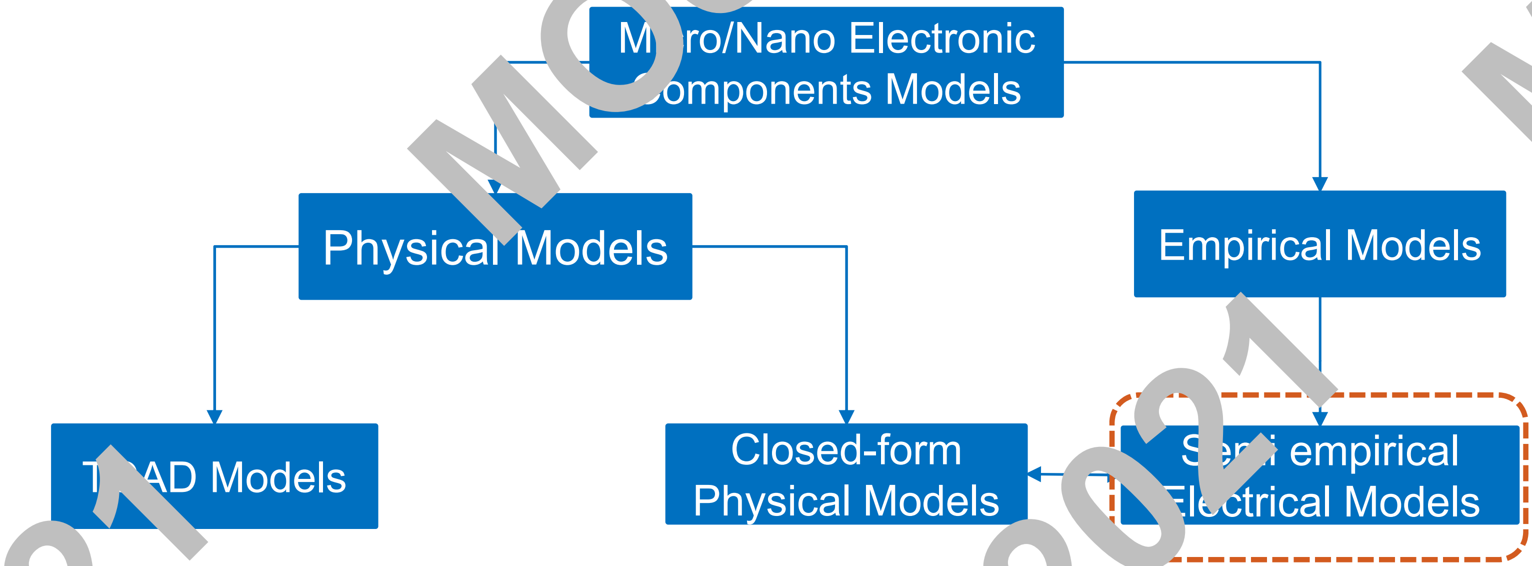
Technology and material processing

Micro/Nano device modeling

IC design

System integration and design

Background



GaN HEMT: QPZD model GaAs HEMT: EEHEMT model

QPZD：Quasi-physical zone division

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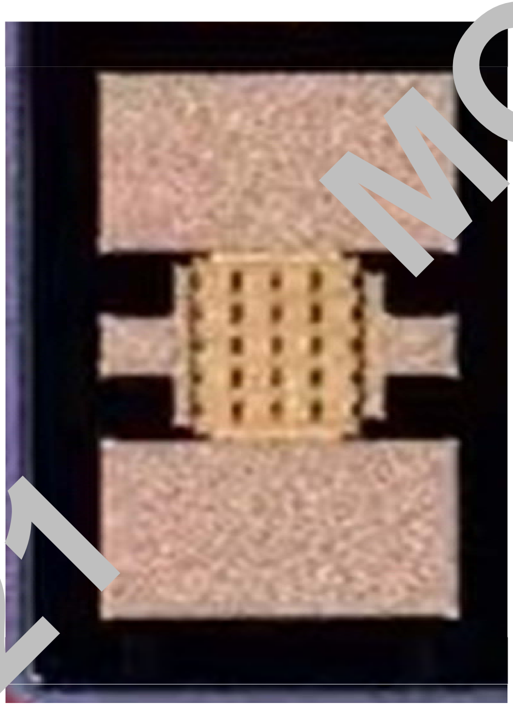
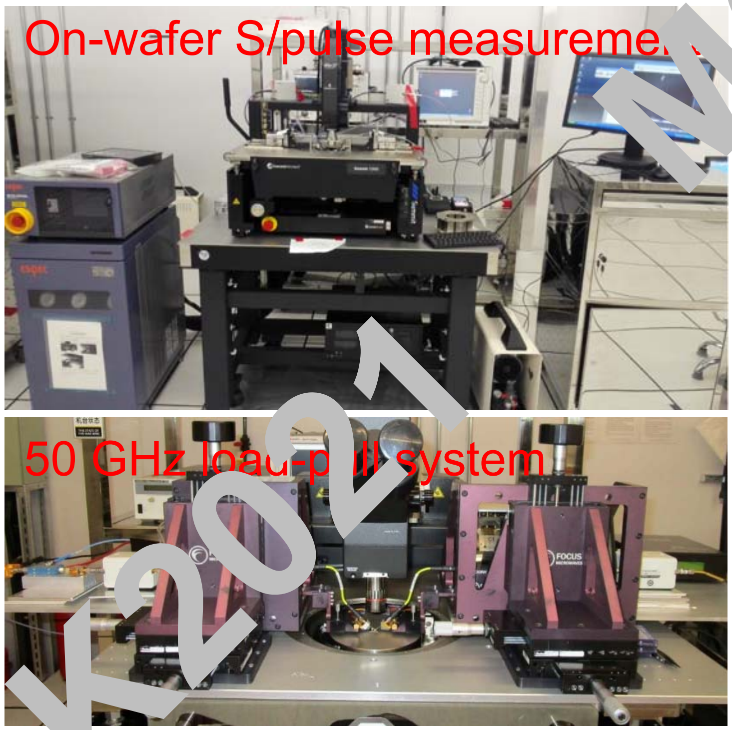
EEHEMT GaAs LSM



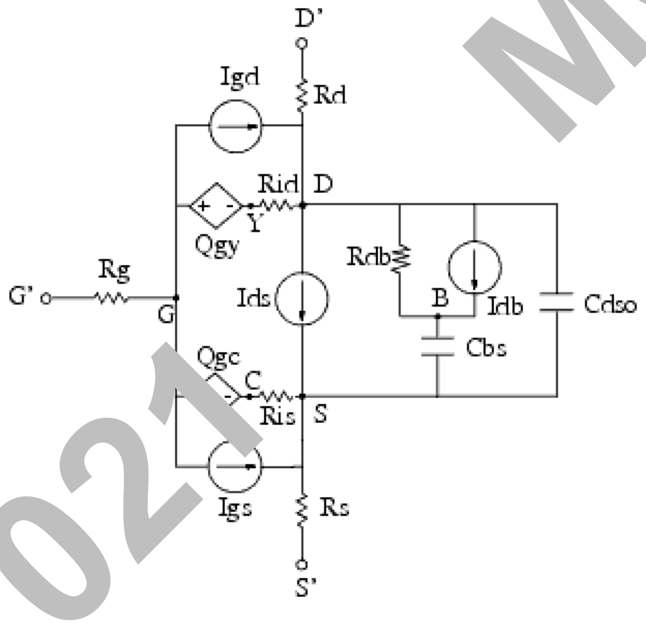
10×100 µm GaAs HEMT (0.25 µm)



device measurement platform

EEHEMT GaAs LSM

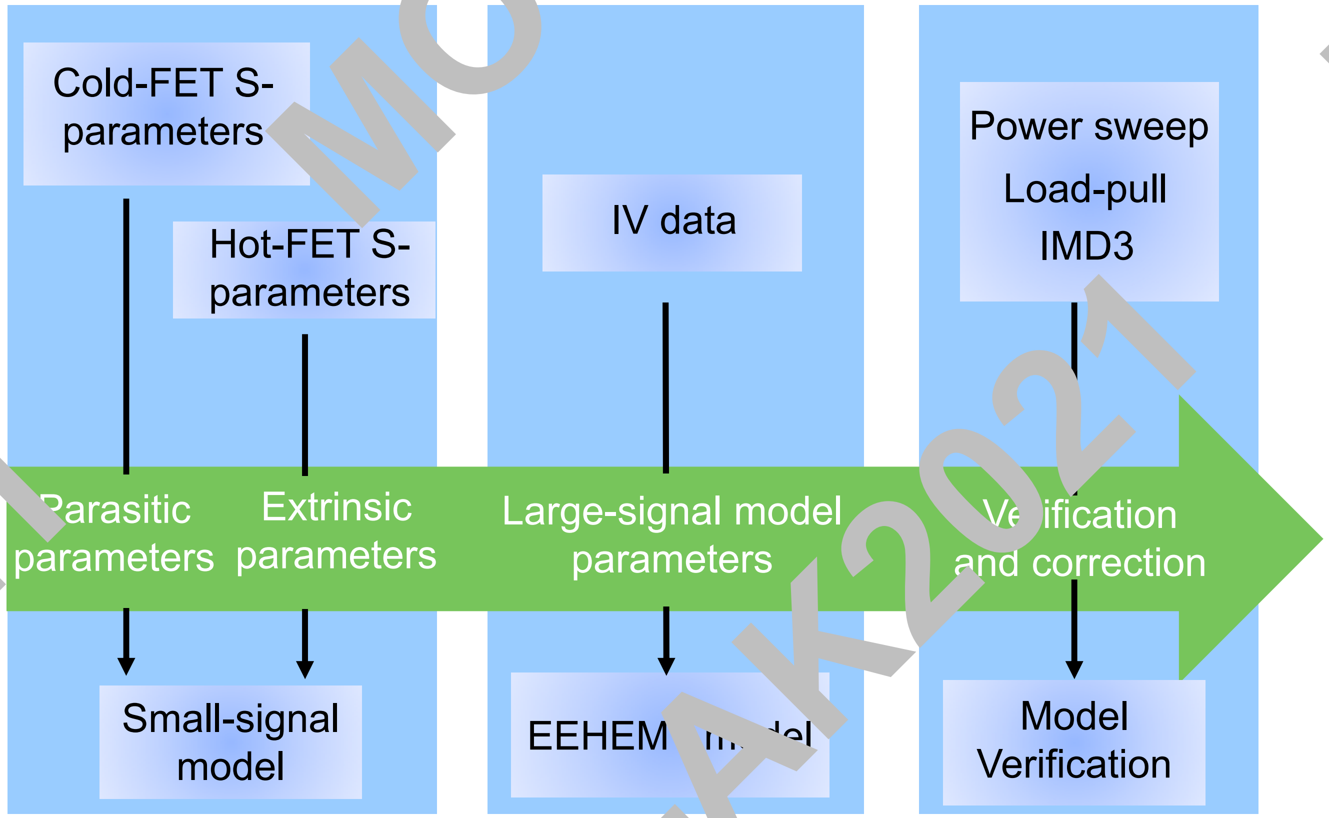
EEHEMT model introduction



- •Accurate isothermal drain-source current model
- •Flexible transconductance formulation permits accurate fitting of g_m compression found in HEMTs
- •Self-heating correction for drain-source current
- •Charge model
- •Dispersion model
- •Accurate breakdown model
- •Well-behaved (non-polynomial) expressions permit accurate extrapolations outside of the measurement range used to extract the model

EEHEMT GaAs LSM

EEHEMT parameters extraction flow



Cold-FET S-parameters

Hot-FET S-parameters

IV data

Power sweep

Load-pull

IMD3

Parasitic parameters

Extrinsic parameters

Large-signal model parameters

Verification and correction

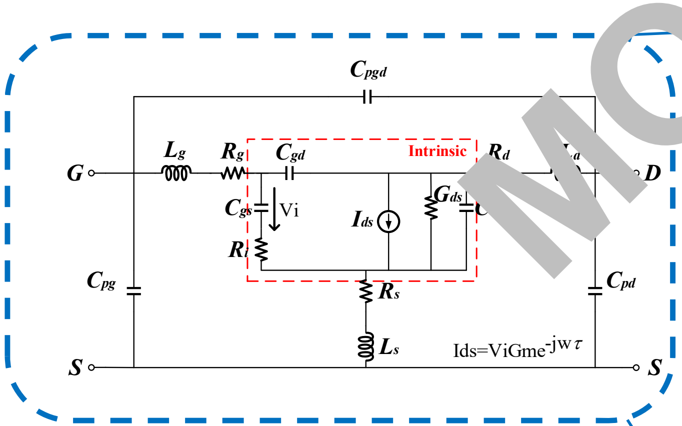
Small-signal model

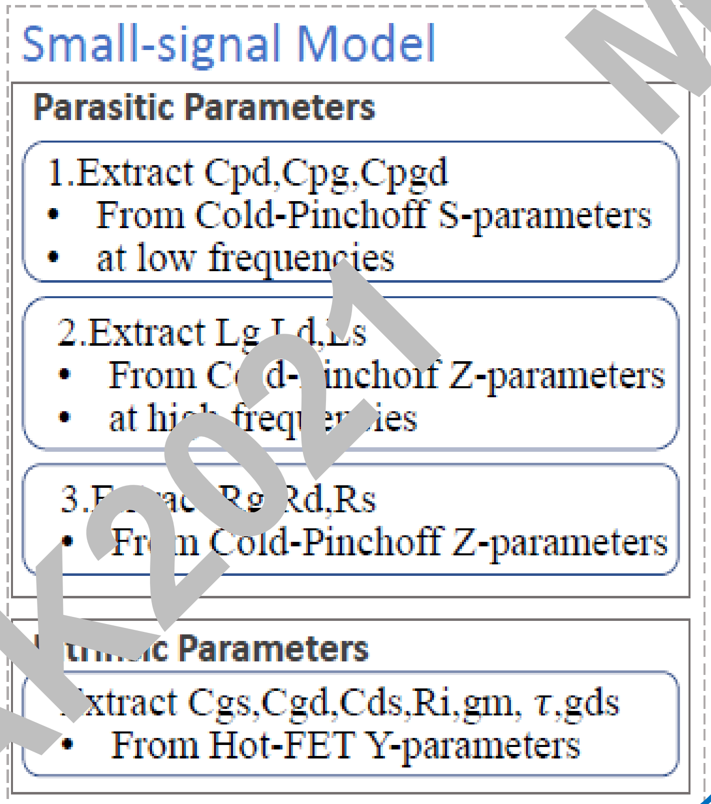
EEHEMT model

Model Verification

EEHEMT GaAs LSM

Small-signal model parameters extraction





Small-signal Model

Parasitic Parameters

1.Extract Cpd,Cpg,Cpgd
- From Cold-Pinchoff S-parameters
- at low frequencies

2.Extract Lg,Ld,Ls
- From Cold-Pinchoff Z-parameters
- at high frequencies

3.Extract Rg,Rd,Rs
- From Cold-Pinchoff Z-parameters

Intrinsic Parameters

Extract Cgs,Cgd,Cds,Ri,gm, τ,gds
- From Hot-FET Y-parameters

➢ **Parasitic Parameters**

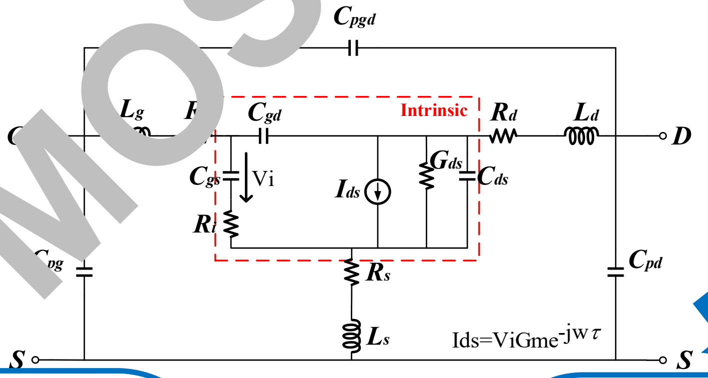
- **Parasitic capacitance Cpg, Cpd, Cpgd**
- **Parasitic inductance Lg, Ld, Ls**
- **Parasitic resistance Rg, Rd, Rs**

➢ **Intrinsic Parameters**

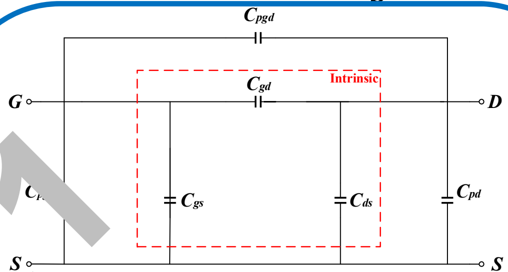
- **Cgs, Cgd, Cds, Ri, gm, tau, gds**

EEHEMT GaAs LSM

Parasitic parameters extraction



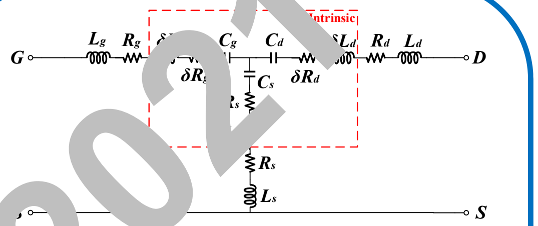
Low-frequency



$$C_{gdo} = C_{pgd} + C_{gd}$$
$$C_{gso} = C_{pg} + C_{gs}$$
$$C_{dso} = C_{pd} + C_{ds}$$
$$Y_{11} = j\omega(C_{gso} + C_{gdo})$$
$$Y_{22} = j\omega(C_{dso} + C_{gdo})$$
$$Y_{12} = Y_{21} = -j\omega C_{gdo}$$

- ***assuming C_{pg}=C_{pd}***
- ***scanning C_{pg} and C_{pgd}***

De-embedding Capacitance



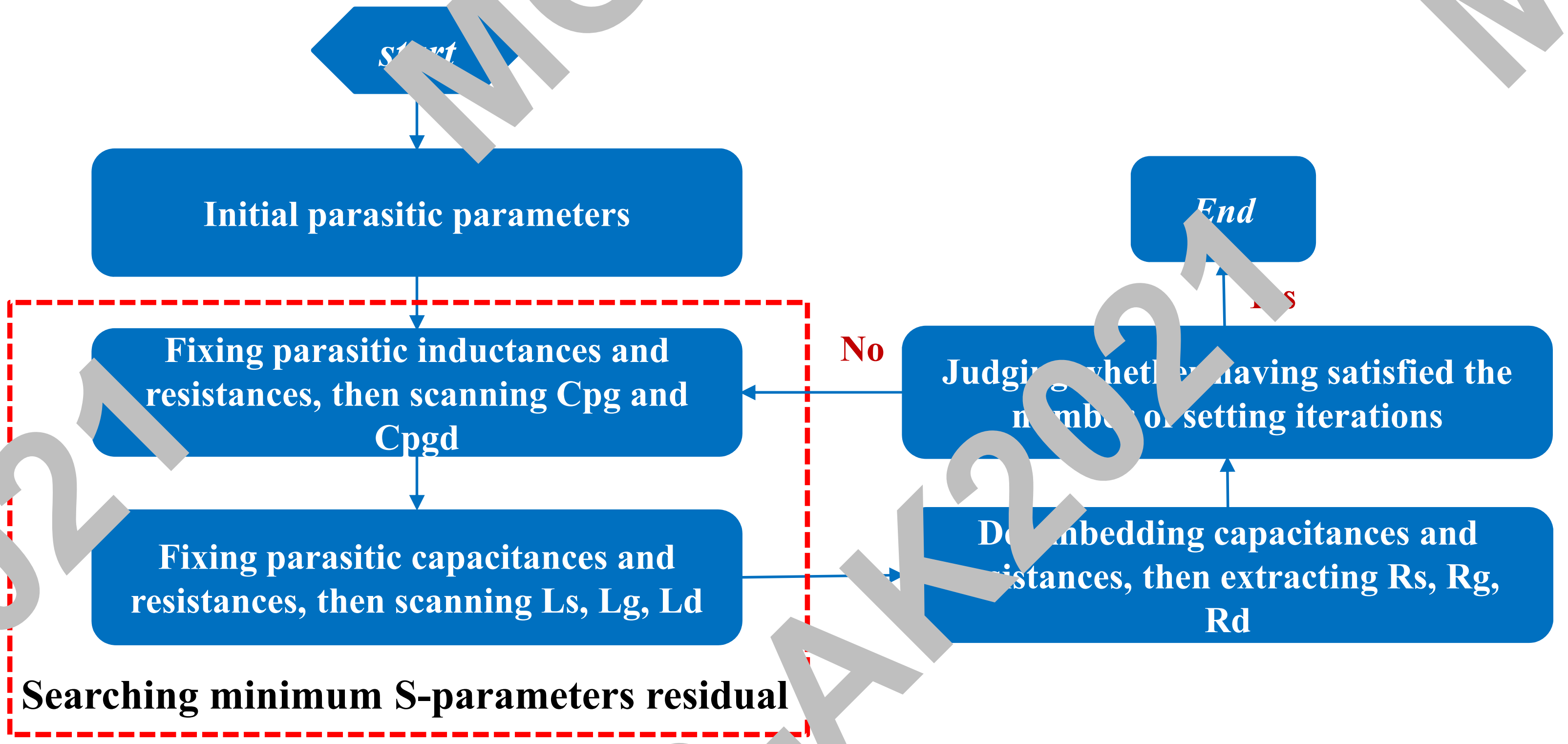
$$Im(\omega Z_{11}) = (L_g + L_s)\omega^2 - (\frac{1}{C_g} + \frac{1}{C_s})$$
$$Im(\omega Z_{22}) = (L_d + L_s)\omega^2 - (\frac{1}{C_d} + \frac{1}{C_s})$$
$$Im(\omega Z_{11}) = L_s\omega^2 - \frac{1}{C_s}$$
$$\omega^2 Re(Z_{11}) = \omega^2 (R_g + R_s)$$
$$\omega^2 Re(Z_{22}) = \omega^2 (R_d + R_s)$$
$$\omega^2 Re(Z_{12}) = \omega^2 R_s$$

- ***L-the slope of Im(wZ)-w²***
- ***R-the slope of w² Re(Z)-w²***

EEHEMT GaAs LSM

Parasitic parameters extraction

- Optimization algorithm



start

Initial parasitic parameters

Fixing parasitic inductances and resistances, then scanning Cpg and Cpgd

Fixing parasitic capacitances and resistances, then scanning Ls, Lg, Ld

Searching minimum S-parameters residual

De-embedding capacitances and resistances, then extracting Rs, Rg, Rd

Judging whether having satisfied the number of setting iterations

No

Yes

End

EEHEMT GaAs LSM

Intrinsic parameters extraction

- **De-embedding extrinsic parameters including Cpg, Cpd, Cpgd, Lg, Ld, Ls,Rg, Rd and Rs**
- **Using following equations to extract intrinsic parameters**

$$d(\omega_i)=\frac{Re(Y_{11}(\omega_i)+Y_{12}(\omega_i))}{Im(Y_{11}(\omega_i)+Y_{12}(\omega_i))}$$

$$c(\omega_i)=(Y_{21}(\omega_i)-Y_{12}(\omega_i))(1+jd(\omega_i))$$

$$R_i(\omega_i)=\frac{d^2(\omega_i)}{(1+d^2(\omega_i))Re(Y_{11}(\omega_i)+Y_{12}(\omega_i))}$$

$$g_m(\omega_i)=|c(\omega_i)|$$

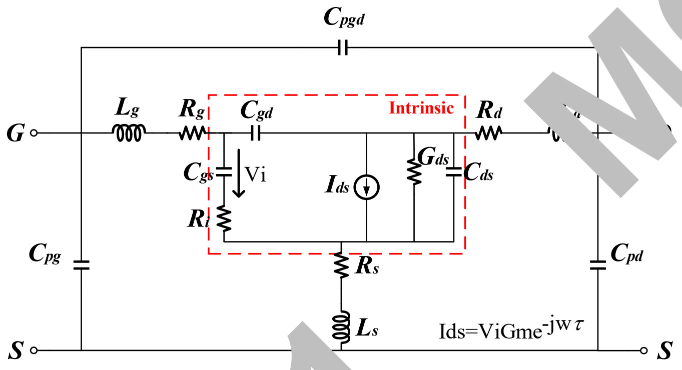
$$\tau(\omega_i)=-\frac{1}{\omega_i}\arctan(\frac{Im(c(\omega_i))}{Re(c(\omega_i))})$$

$$G_{ds}(\omega_i)=Re(Y_{22}(\omega_i)+Y_{12}(\omega_i))$$

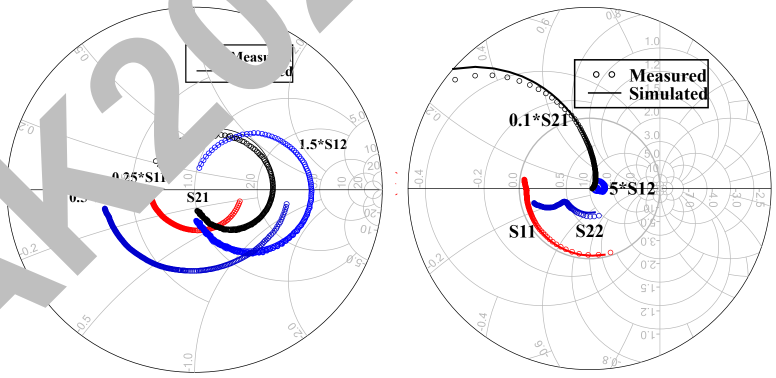
$$C_{ds}(\omega_i)=\frac{Im(Y_{22}(\omega_i)+Y_{12}(\omega_i))}{\omega_i}$$

$$C_{gd}(\omega_i)=-\frac{Im(Y_{12}(\omega_i))}{\omega_i}$$

$$C_{gs}(\omega_i)=\frac{1+d^2(\omega_i)}{\omega_i}Im(Y_{11}(\omega_i)+Y_{12}(\omega_i))$$



Result

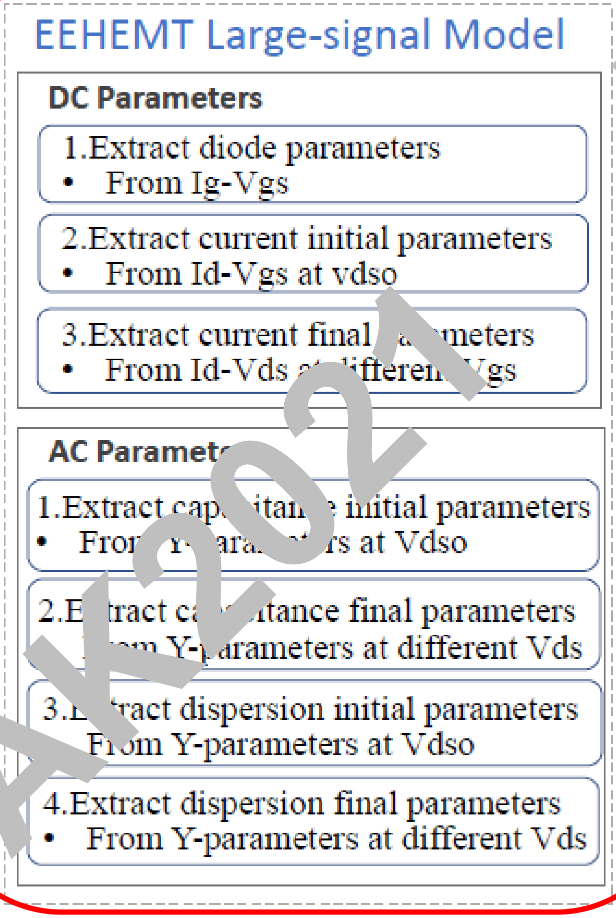


Vds=2V,Vgs=0.2V   Vds=4V,Vgs=0.5V

EEHEMT GaAs LSM

EEHEMT large-signal model parameters extraction

- **DC Parameters**
  - **Diode parameters**
  - **Drain-source current parameters**
- **AC Parameters**
  - **Capacitance parameters**
  - **Dispersion parameters**



EEHEMT Large-signal Model

DC Parameters

1.Extract diode parameters
- From Ig-Vgs

2.Extract current initial parameters
- From Id-Vgs at vdso

3.Extract current final parameters
- From Id-Vds at different Vgs

AC Parameters

1.Extract capacitance initial parameters
- From Y-parameters at Vdso

2.Extract capacitance final parameters
- From Y-parameters at different Vds

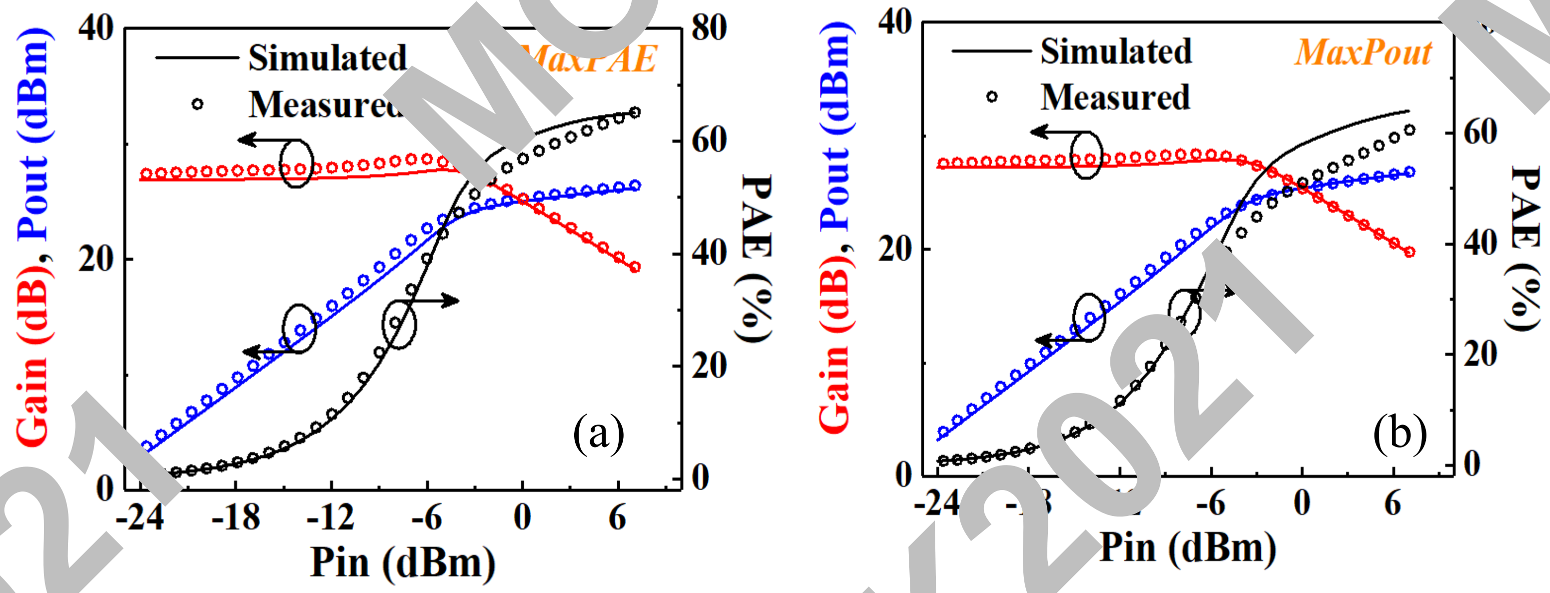
3.Extract dispersion initial parameters
- From Y-parameters at Vdso

4.Extract dispersion final parameters
- From Y-parameters at different Vds

EEHEMT GaAs LSM

Model verification

- RF performance(one-tone excitation)



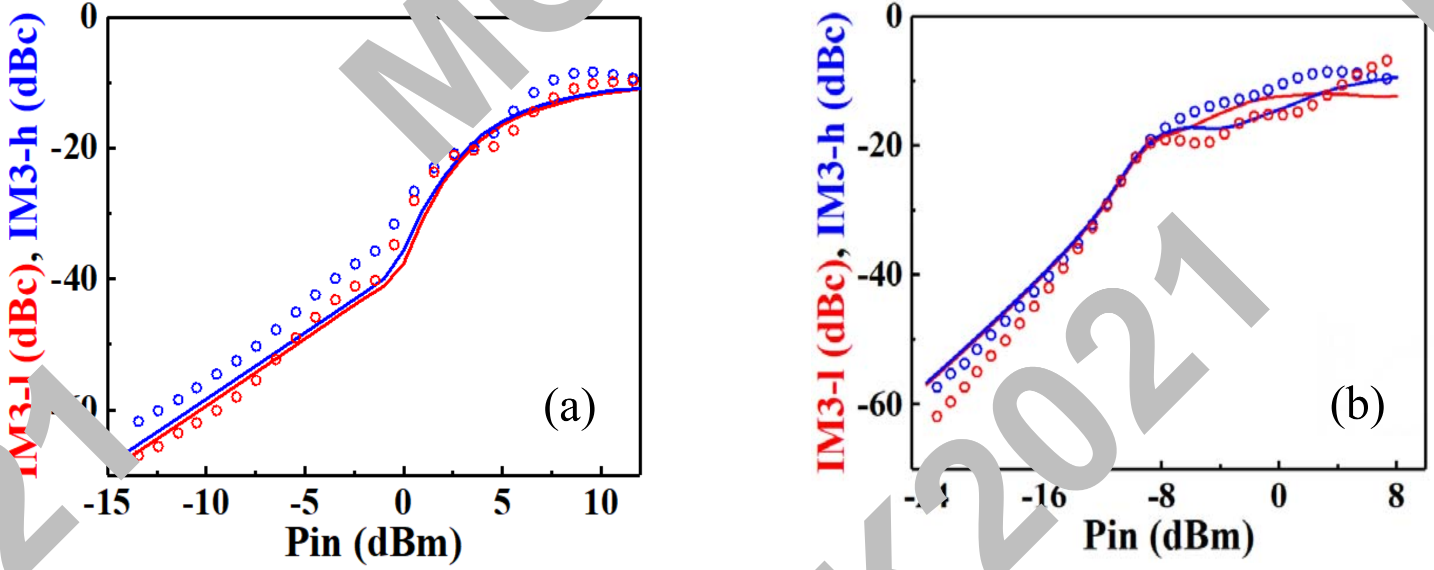
(a) at maximum PAE matching (b) at maximum Pout mathcing

(V_{ds}=5V;V_{gs}=0.5V; *freq*=1.8 GHz)

EEHEMT GaAs LSM

Model verification

- RF performance(two-tone excitation)



(a) at 50Ohm impedances matching (b) at maximum Pout matching

(V_{ds}=5V;V_{gs}=0.5V, *freq*=1.8 GHz ± 5 MHz)

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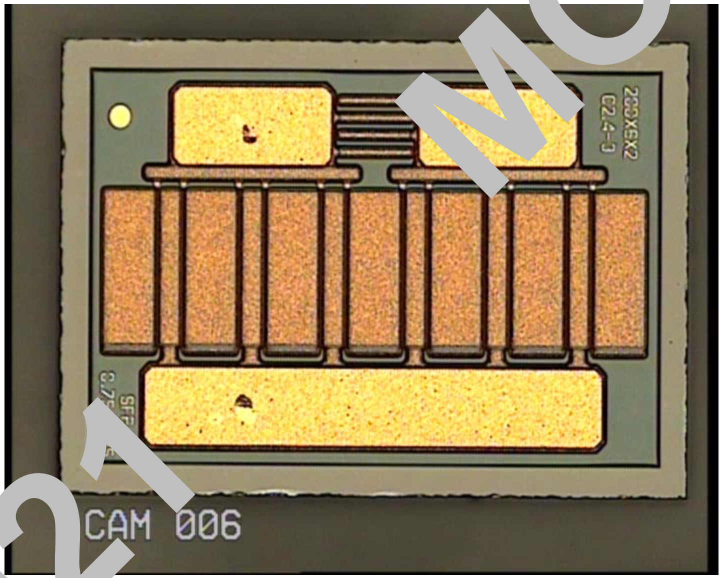
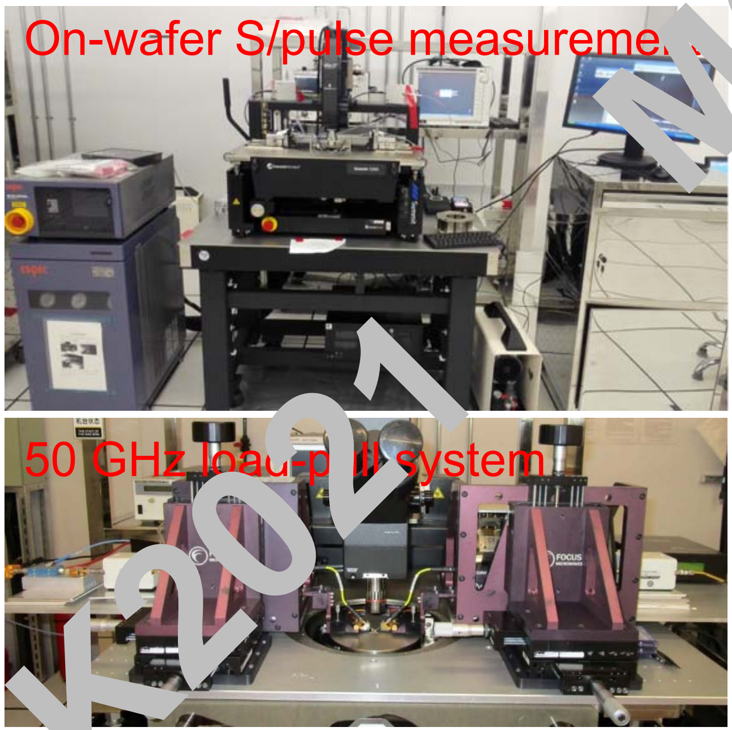
QPZD GaN LSM



12×200 μm GaN HEMT (0.4 μm)



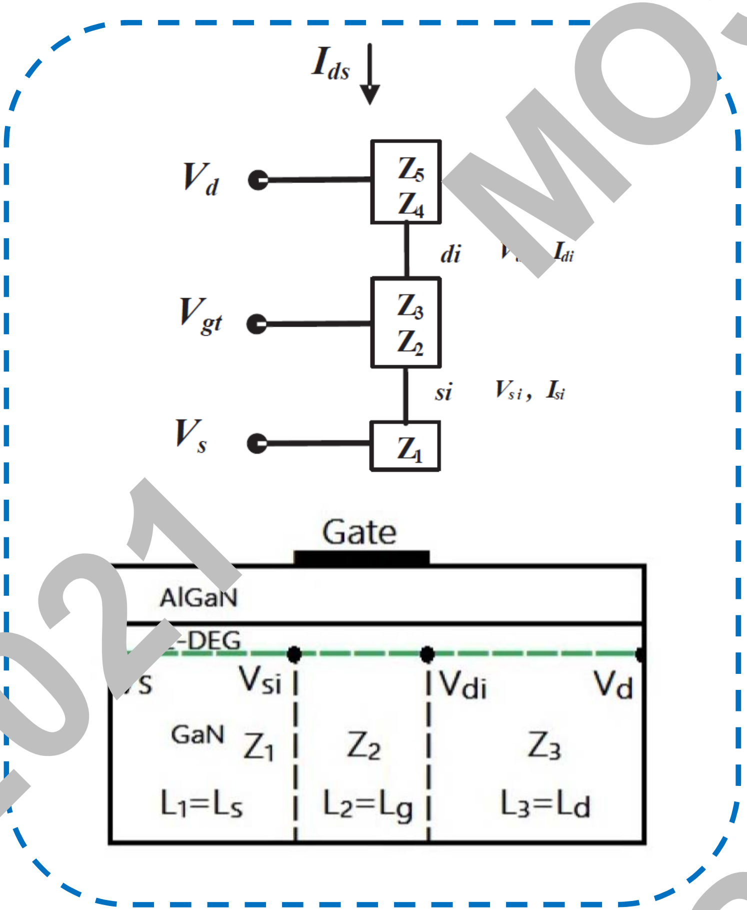
On-wafer S/pulse measurement

50 GHz load-pull system

device measurement platform

QPZD GaN LSM

QPZD(Quasi-physical zone division) model introduction



- **Less fitting parameters (i.e. Angelov model)**

$$I_{\mathrm{ds}} = \frac{I_{\max} V_{\mathrm{ds}}(1+\lambda V_{\mathrm{ds}})}{\sqrt[\beta]{E_c^{\beta}(l_s+l_d)^{\beta} + (E_c l_g + V_{\mathrm{ds}})^{\beta}}}$$

$$I_{\max} = W q n_s(V_{\mathrm{gs}}) \upsilon_{\max}$$

$$n_s = 0.5 n_{smax} \cdot tanh(\alpha_3 \cdot (V_{gs} - V_{off})^3 + \alpha_2 \cdot (V_{gs} - V_{off})^2 + \alpha_1 \cdot (V_{gs} - V_{off}) + \beta_v) + 0.5 n_{smax}$$

$$\mu = \left(a_0 + a_1 V_{gs}\right)\left(b_0 + b_1 T_{ch} + b_2 T_{ch}^2\right)$$

$$T_{ch} = T_0 + I_{ds} V_{ds} P_{diss}$$

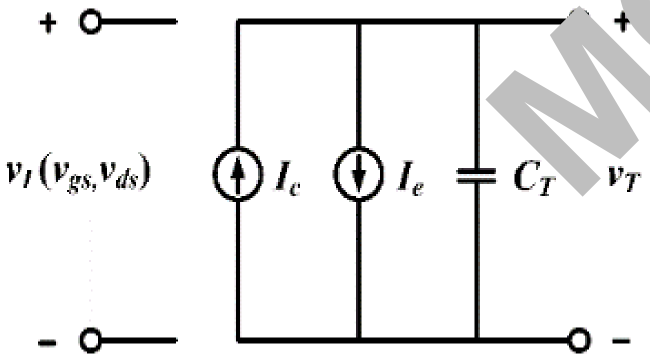
$$E_c = \frac{v_{sat}}{\mu}$$

- **Natural scale**

Zhang wen, Yuehang Xu*， et al.， *IEEE T-MTT*, 2017, 65(12):5113-5122

QPZD GaN LSM

Modeling trapping effect using SRH model



$$v_T = \frac{Vo}{1+\exp(\frac{v_i}{kT})}$$

$$v_i = AV_{GS} + BV_{DS} + C$$

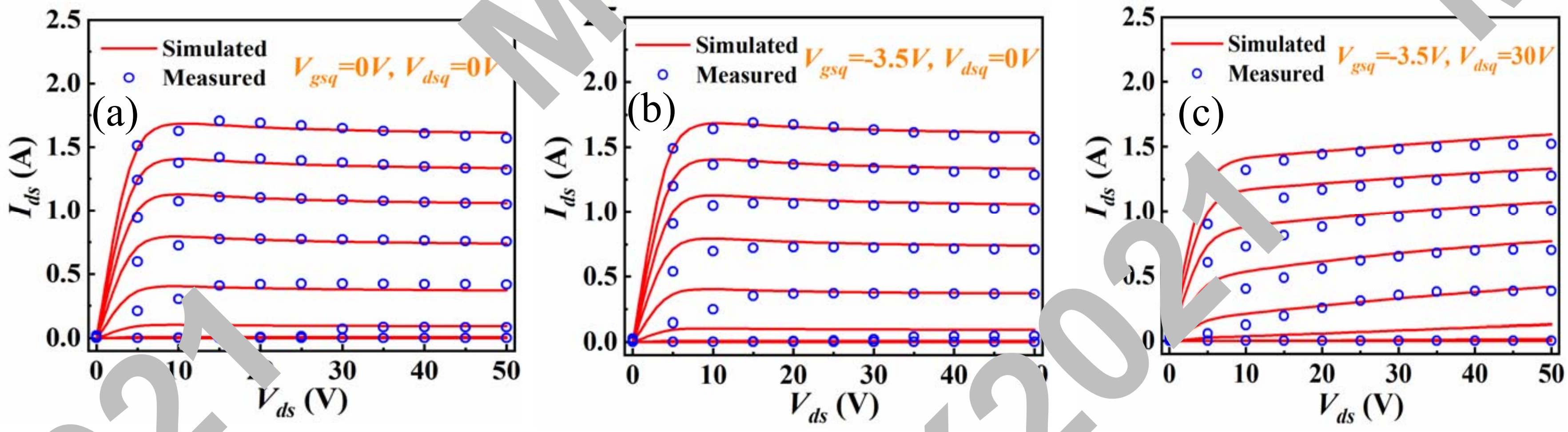
Vo [V]: trap potential when it is fully ionized
T [K]: temperature
K [eV/K]: the Boltzmann constant
v_i [V]: the trap-control potential
v_T [V]: the calculated effective trap potential

- **Using SRH(Shockley-Read-Hall) to model the trapping effect**
  - **characterizing the electron capture and emission in the trap center**
  - **dynamic trapping effect can be considered**
- **A sub-network is used for describing the dynamic process**

QPZD GaN LSM

Model verification

- Pulse IV

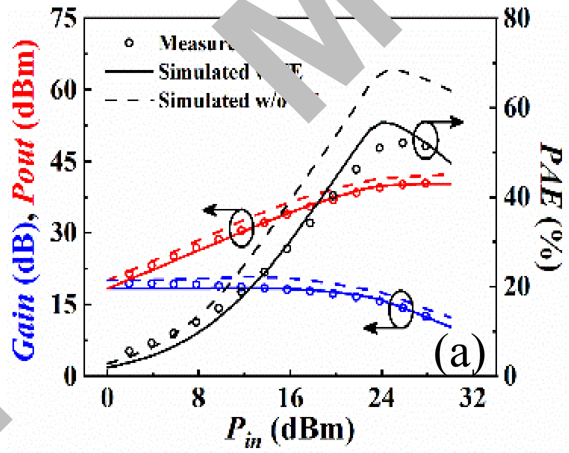


(a) V_{gsq}=0 V, V_{dsq}=0 V (b) V_{gsq}=-3.5 V, V_{dsq}=0 V (c) V_{dsq}=-3.5 V, V_{dsq}=30 V

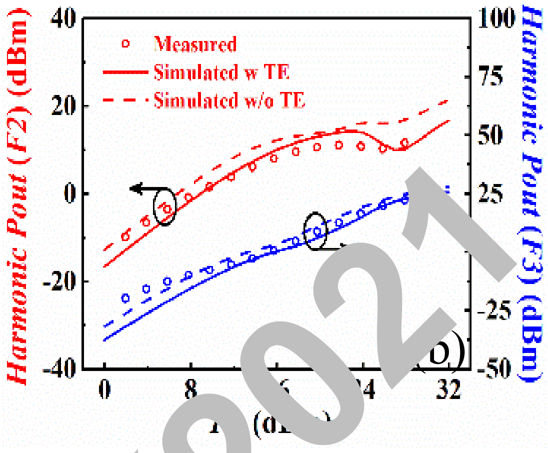
QPZD GaN LSM

Model verification

- RF performance(one-tone excitation)



(a)Fundamental output performance

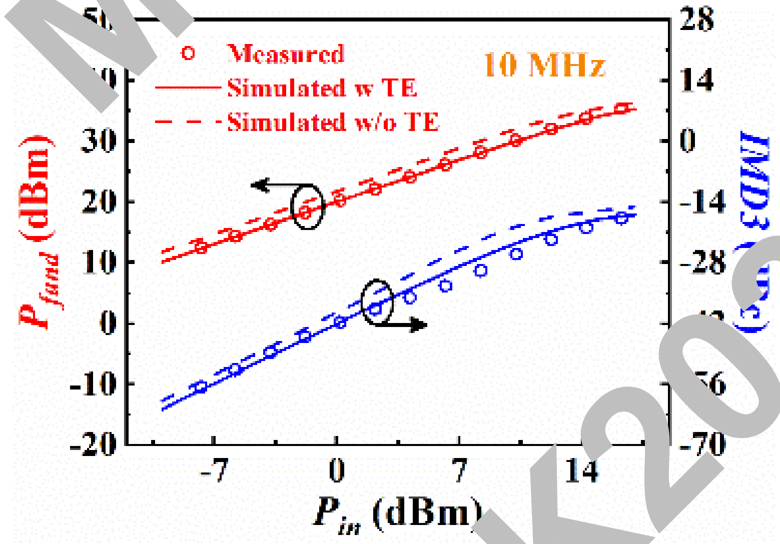


(b) second and third harmonic output performance

QPZD GaN LSM

Model verification

- RF performance(two-tone excitation)



Pout and IMD3 characteristics

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Summary

- Present an improved small-signal model parameters extraction method and establish the EEHEMT large-signal model . Results show it accurately characterize the radio frequency characteristics of GaAs HEMT

- Introduce an improved QPZD large-signal model using the SRH trap model to model the trapping effect for GaN HEMT. Model validation results show that it can accurately characterize RF performance

Thank you！