Physics based modelling of next generation mm-Wave GaN technology

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Contents

Objective and Target

- To undertake a simulation study of options for future GaN technologies and benchmark their potential performance using TCAD/compact modelling approach
- Determine device scalability and ability to meet future ESA requirements.
- To propose a consistent analysis flow methodology that allows comparisons between different device concepts
- Feed device recommendations for consideration by ESA in ongoing manufacturing activities, e.g., GaNaPE, and future programmes, e.g., S2CANT.

Parameters	Minimum	Stretch Target
ft	250GHz	>300GHz
Fmax	400 GHz	500 GHz
Breakdown voltage (Vbds)	50V	
Power added efficiency at 30GHz	≥65%	
Power density @ 30GHz	3W/mm	
Linearity figure of merit OIP3/Pdc	>50	
Transistor junction temperature (Tj)	<160˚C	

Current Technology

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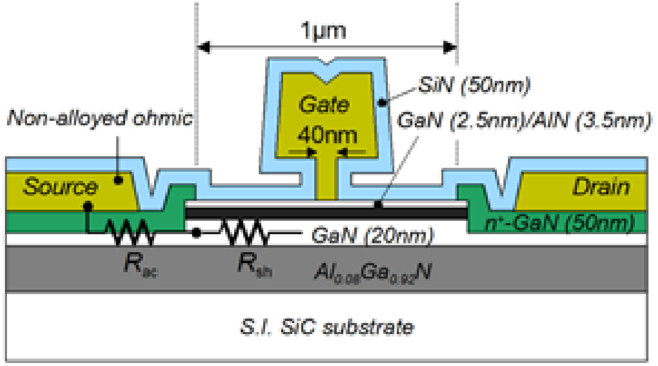
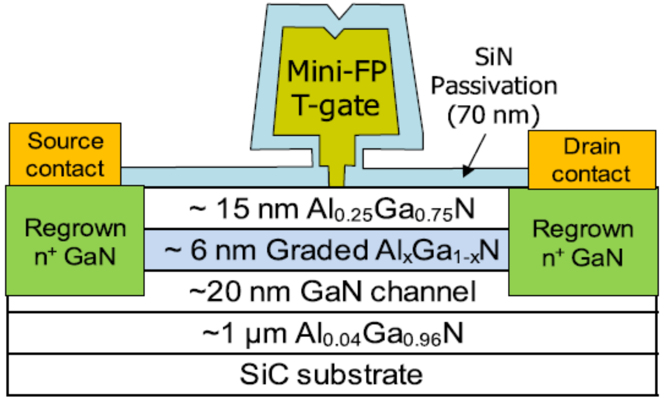
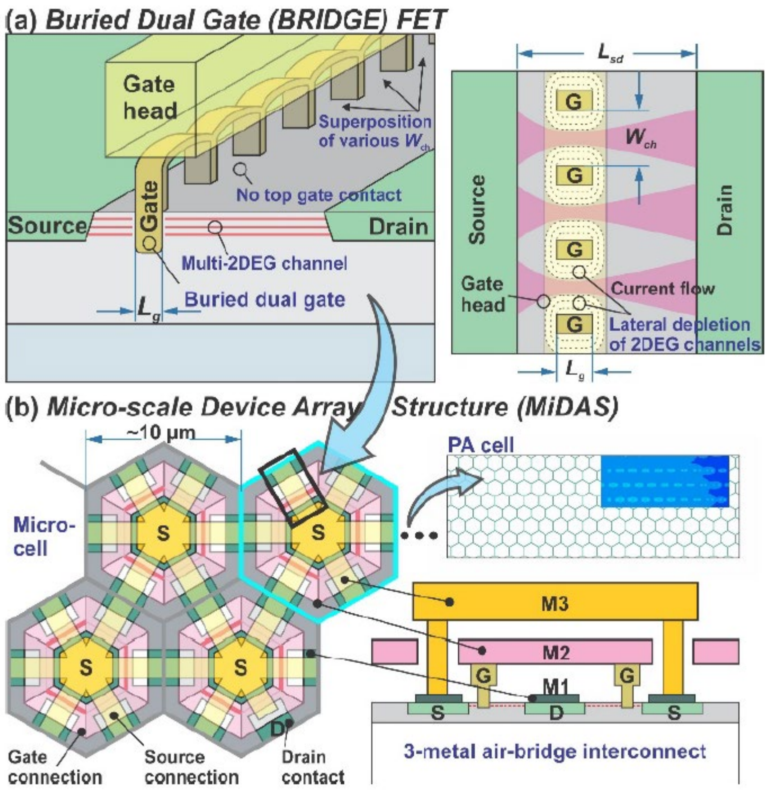


Ultra Scaled AlGaN/GaN HEMT



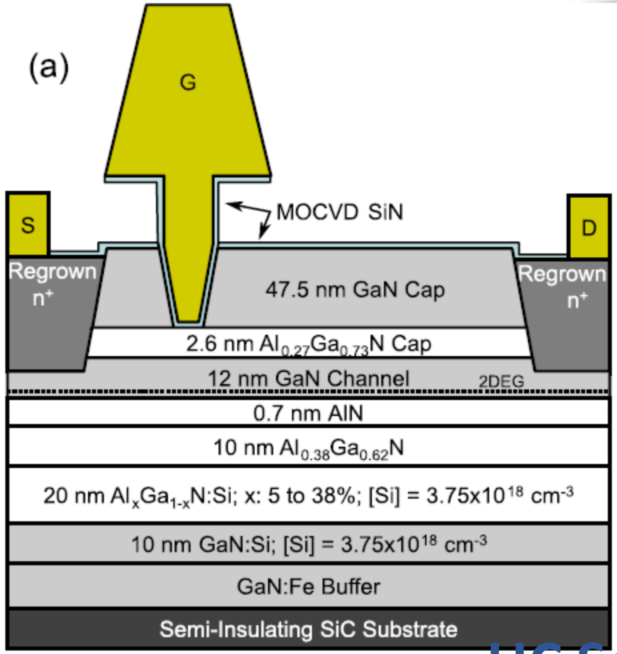
Graded channel HEMT

HRL LABORATORIES



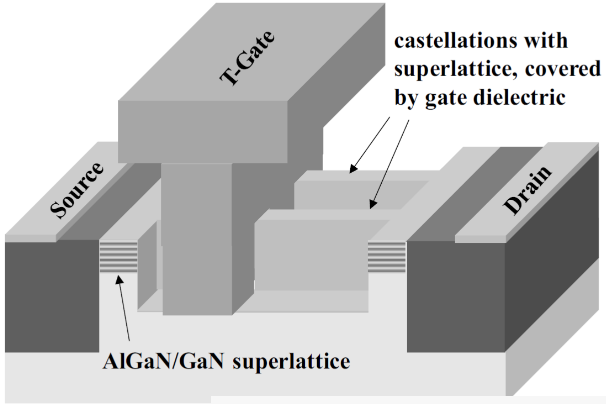
BRIDGE FET

TELEDYNE TECHNOLOGIES INCORPORATED



N-polar GaN HEMT

UC Santa Barbara



SLCFETs

NORTHROP GRUMMAN

Current Technology

Devices	L_G	F_T	F_{MAX}	BV	P_{OUT}	PD	PAE	LINEARITY		N_{Fmin}
								OIP3/ Pdc	CIM3	
HRL US HEMT	20 nm	342 GHz	518 GHz	15 V	-		-			0.5 dB at 30 GHz
	40 nm	220 GHz	400 GHz	>40 V	-		-	-		
HRL GRADED ALGAN HEMT	50 nm	170 GHz	363 GHz							
	60 nm	156 GHz	308 GHz			5.5 W/mm	70 %	17.5 dB		1.6 dB
	50 nm (mini-FP)	170 GHz	347 GHz		2.2 W	3.5 W/mm at 94 GHz	50 %			
SLCFET	100 nm	65 GHz	192 GHz		0.435 W	10.87 at 94 GHz	43 %			
BRIDGEFET	180 nm		250 GHz							
N-POLAR	75 nm	113 GHz	238 GHz			8 W/mm at 94 GHz	56 %	15 dB		

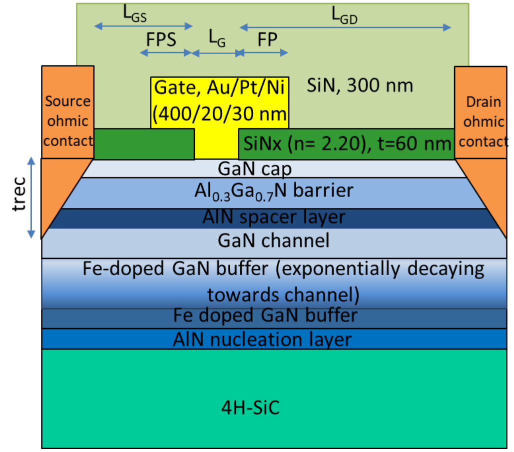
SLCFET/BRIDGEFET: × (manufacturability, technical issue with the 3D- simulation)

N-POLAR: × (lack of epitaxy in Europe, challenge in simulation with n-polar GaN)

ULTRA SCALED HEMT: ✓

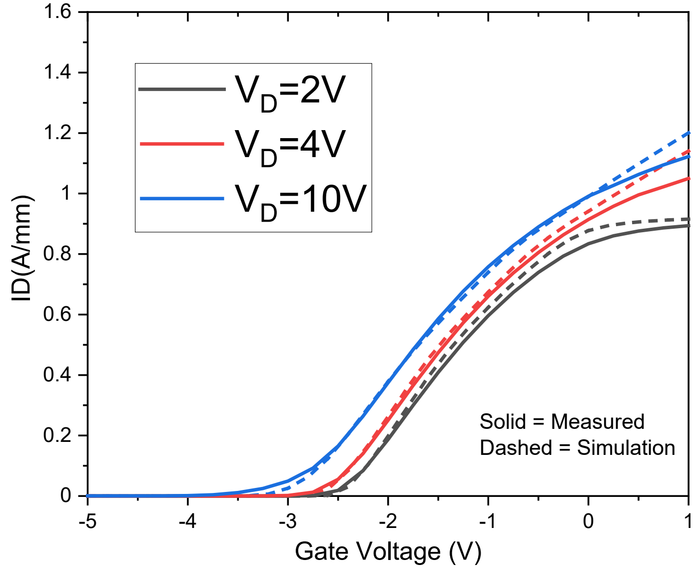
GRADED CHANNEL HEMT: ✓

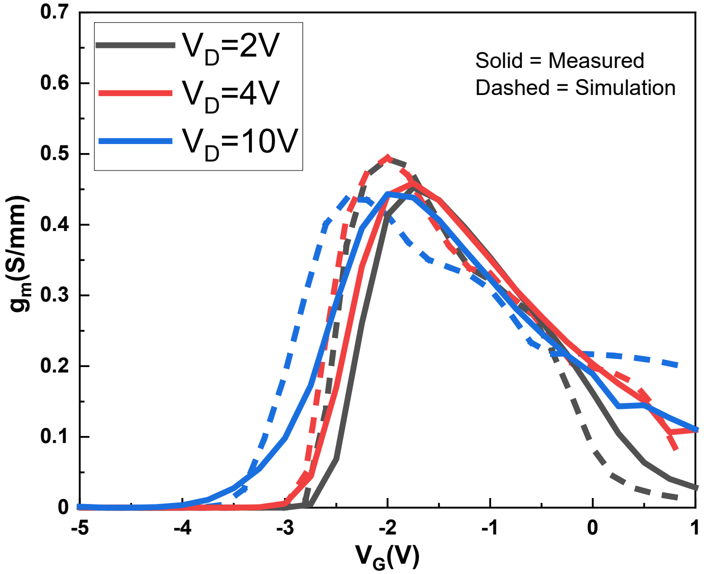
Chalmer’s Conventional AlGaN/GaN HEMT

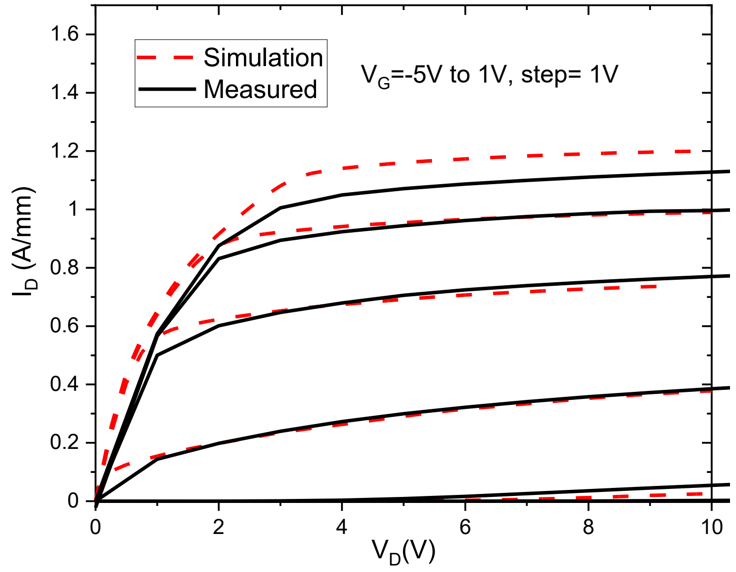


Parameters	Measured	Simulation
n_s (cm^{-2})	1.05×10^{13}	9.86×10^{12}
μ_n(cm^2.V-s)	1970	1970
R_{sh} (Ω/□)	300	290
R_c (Ω.mm)	0.3-0.35	0.3

- Source starvation model and commonly used LO phonon model are implemented to explain the gm roll-off
- Source starvation model gives a better fitting for this device, both in DC and small signal simulation

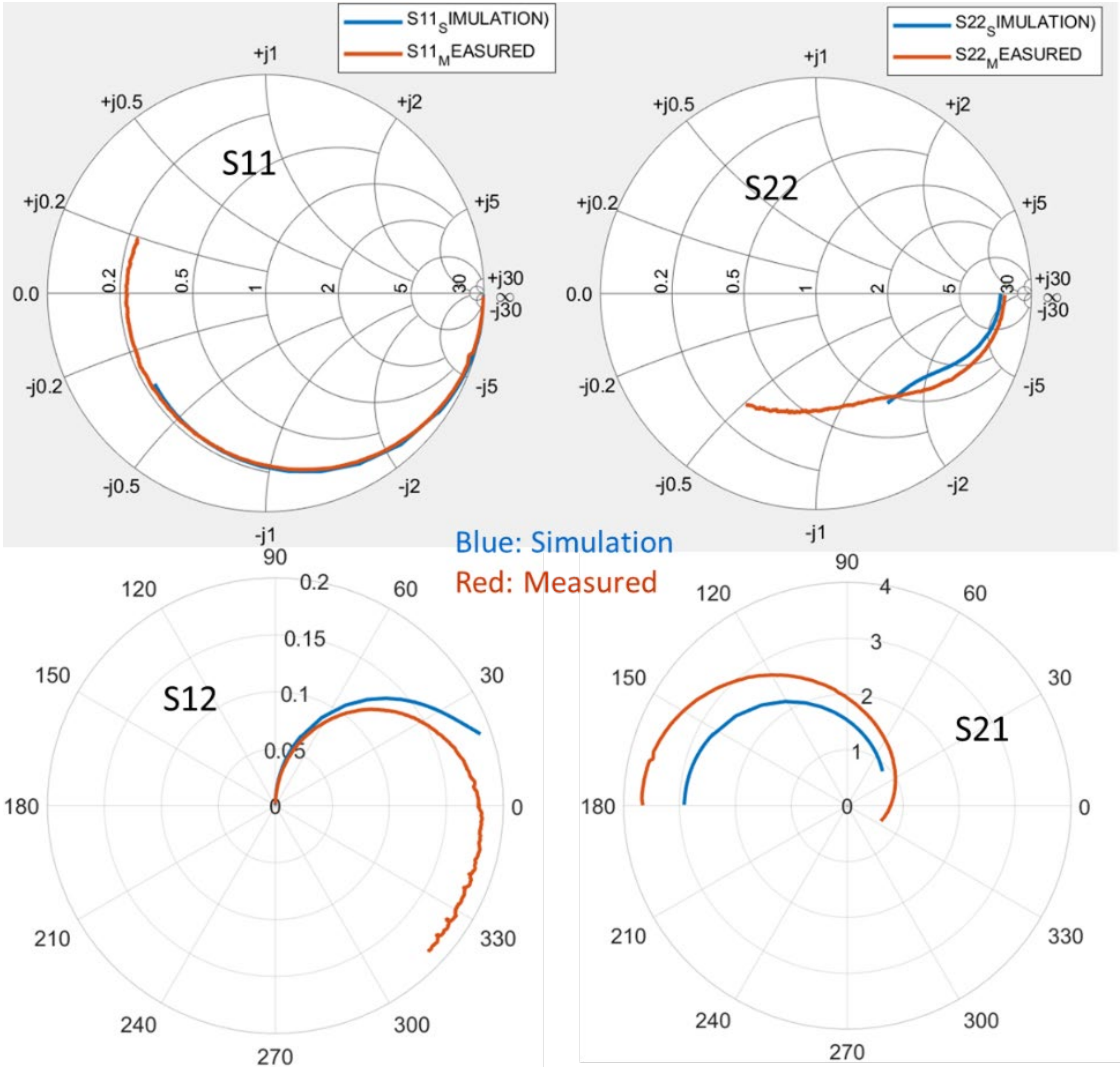


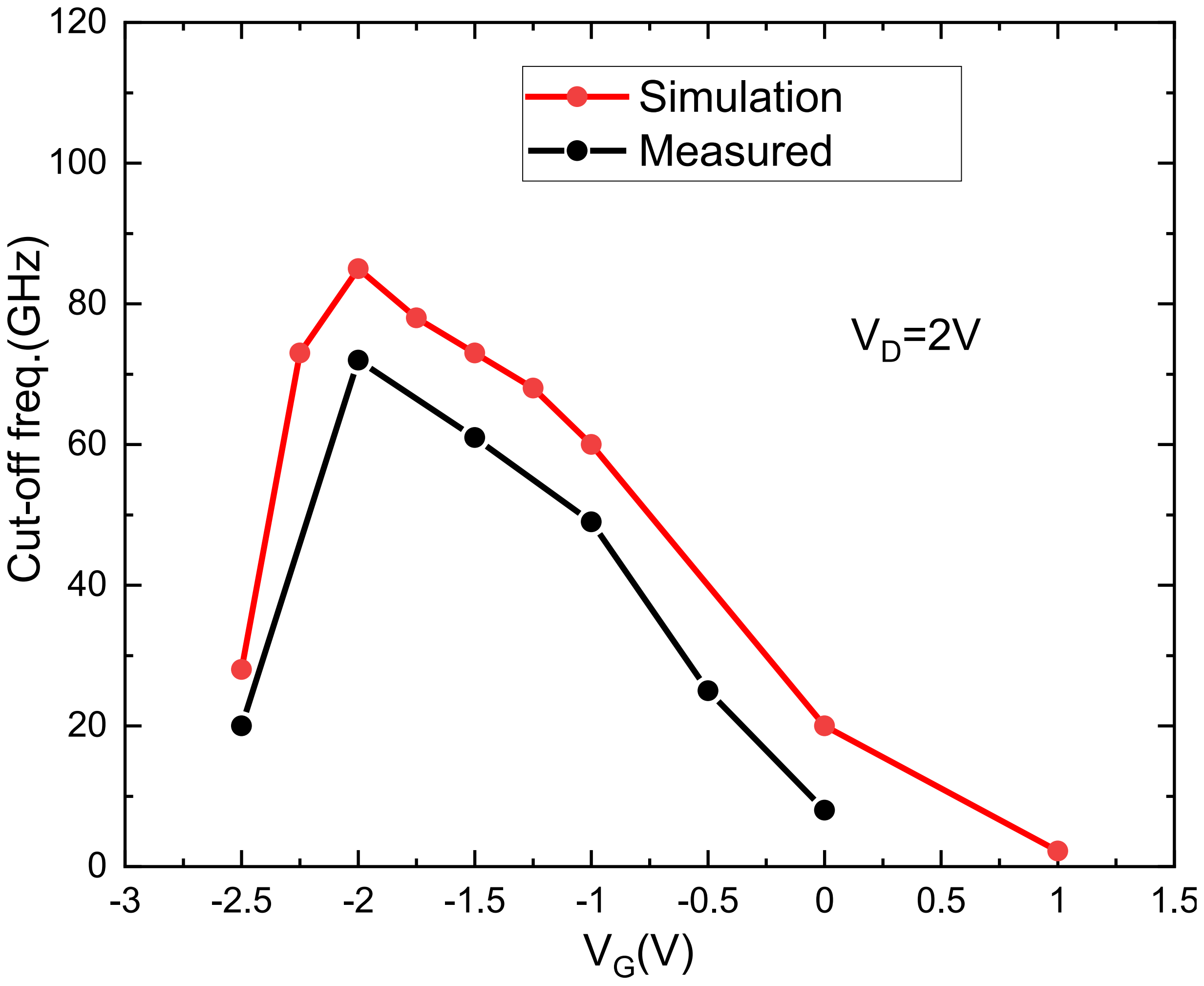




Source starvation can be dominant in this device as the contact uses MOCVD rather than MBE

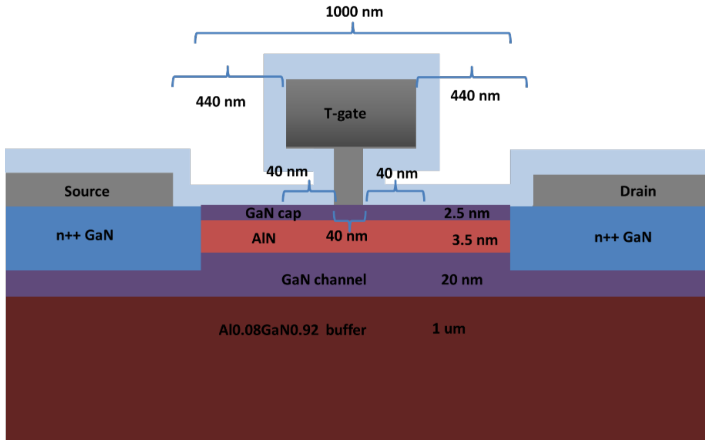
Chalmer's Conventional AlGaN/GaN HEMT

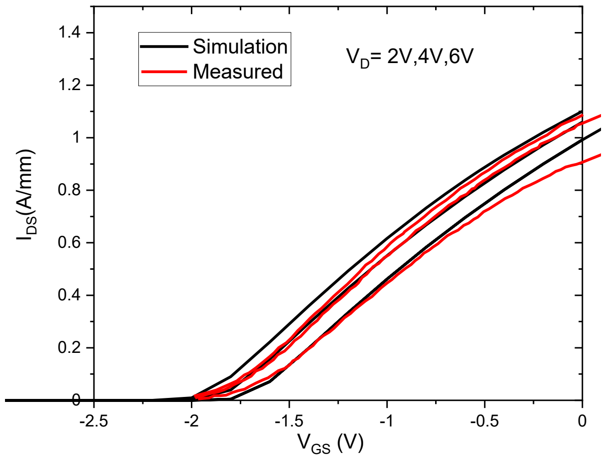


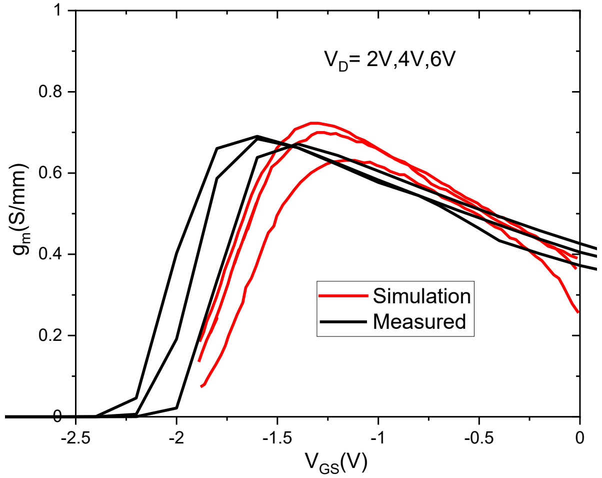


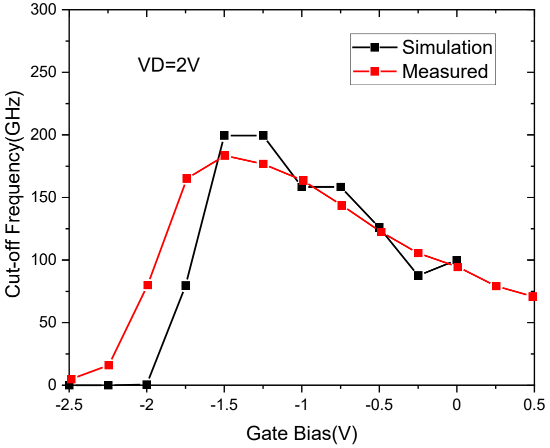
Obtained a good fitting both in the DC and small signal simulation, with the source starvation model

HRL's Ultra Scaled AlGaN/GaN HEMT

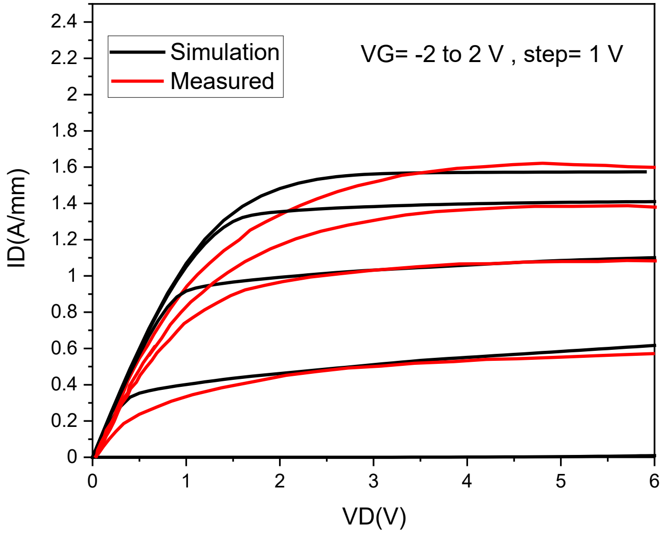


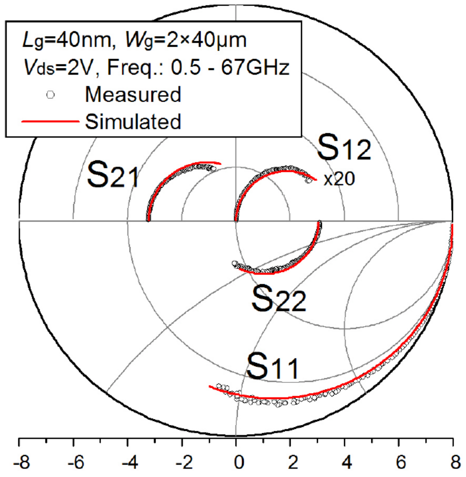


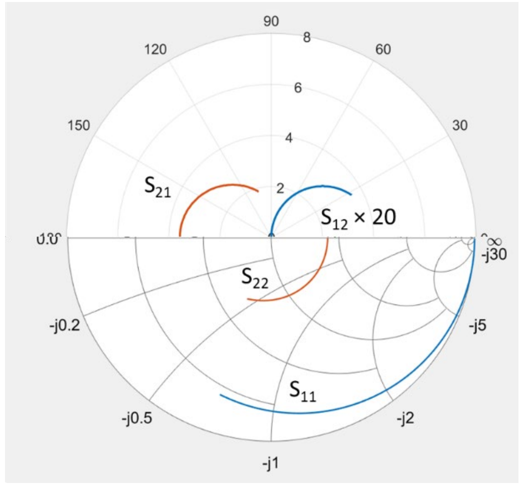




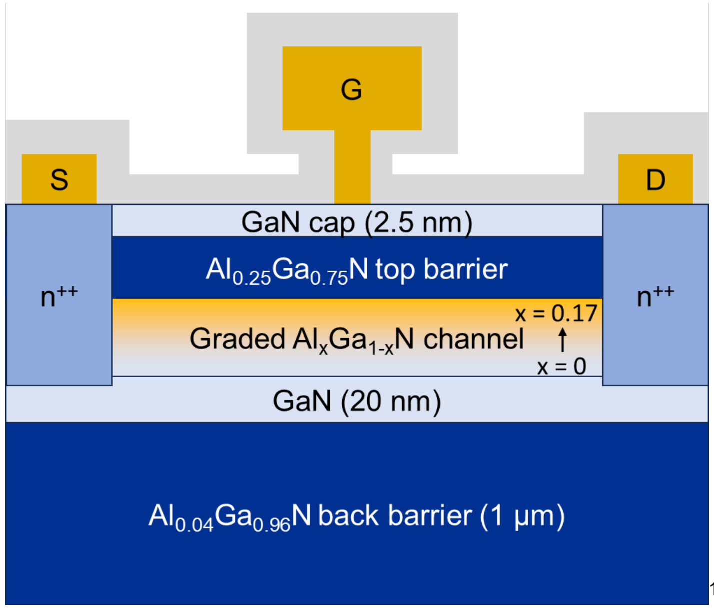
- AlGaN/GaN HEMT with 40 nm gate length.
- The structure uses MBE grown contact, Source starvation can be insignificant
- LO phonon model is used to explain the g_m roll-off.

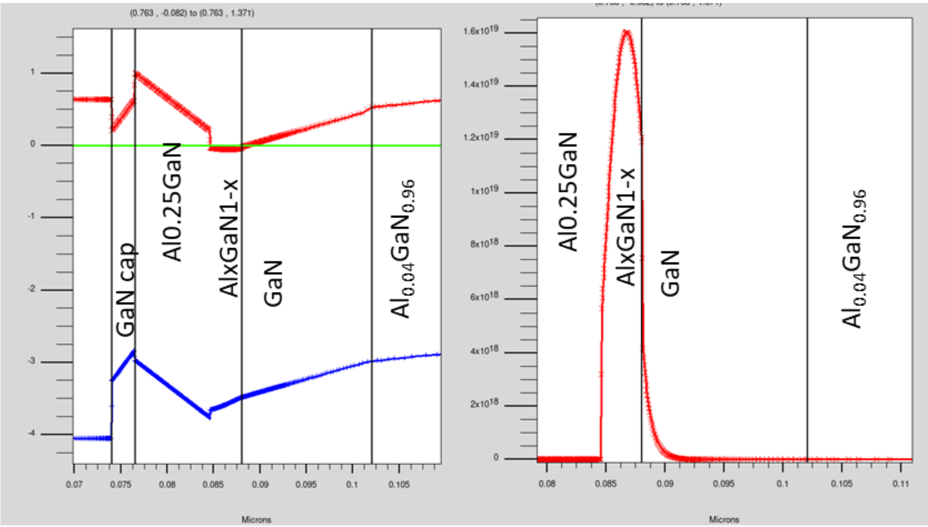


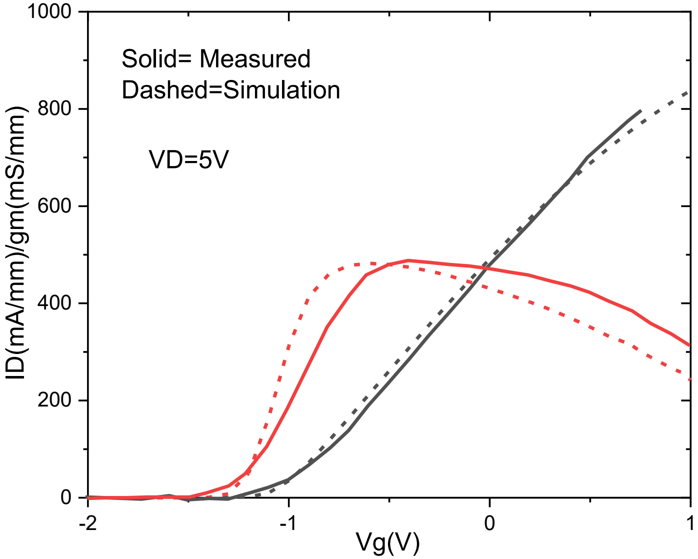




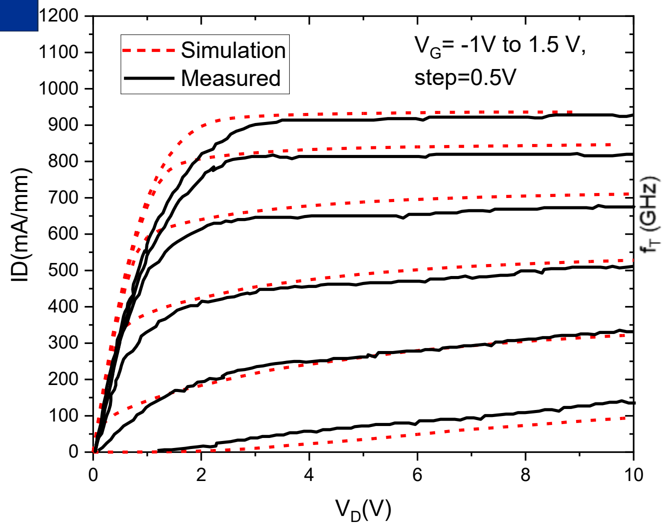
HRL's graded AlGaN HEMT(Reference for DOE)

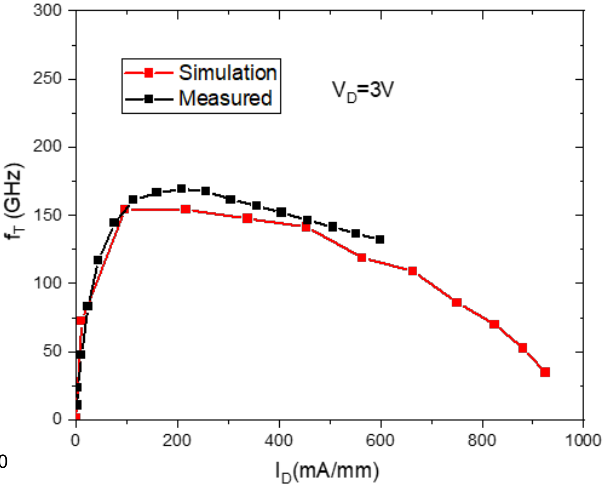


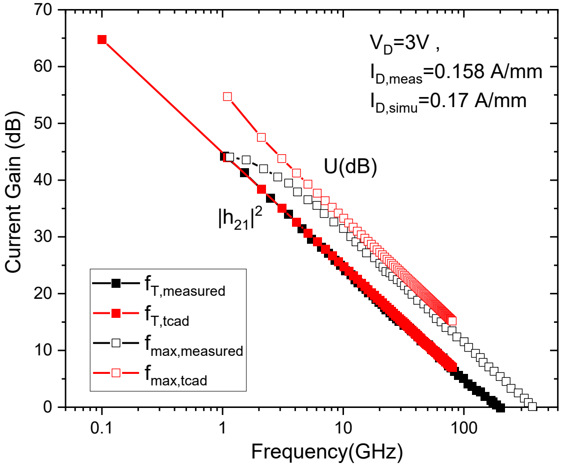




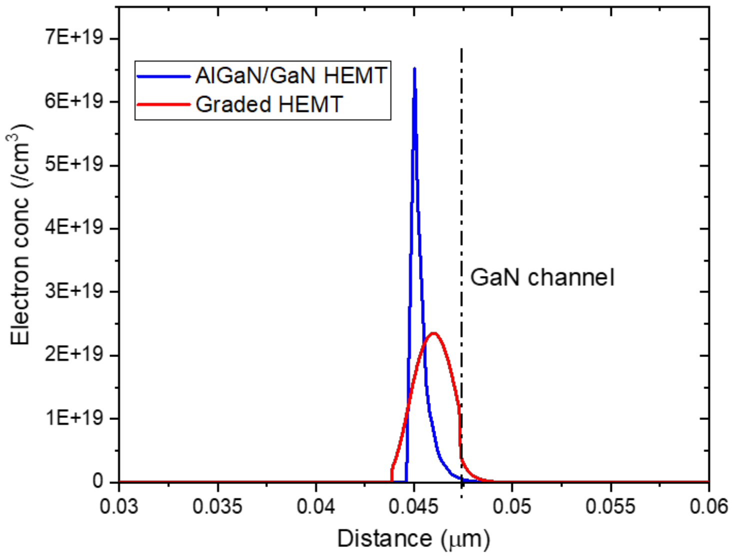
- The published graded AlGaN HEMT device gives the performance closest to the ESA targets
- Uses same process as the Ultra-scaled device
- TCAD implements LO phonon model

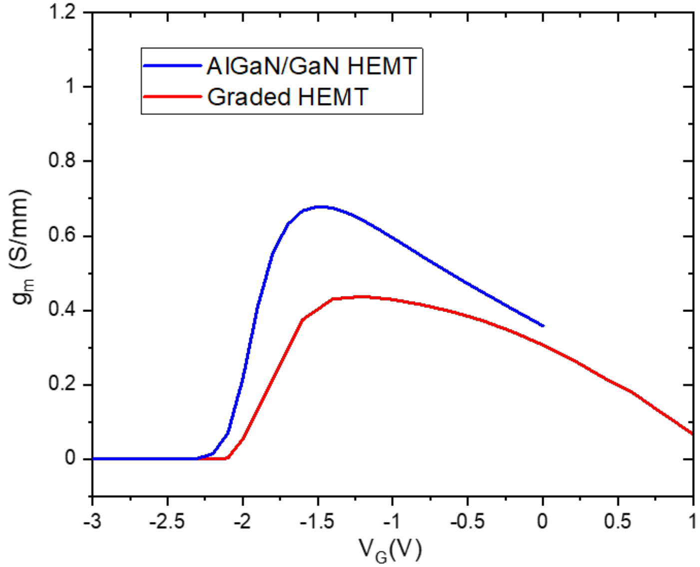


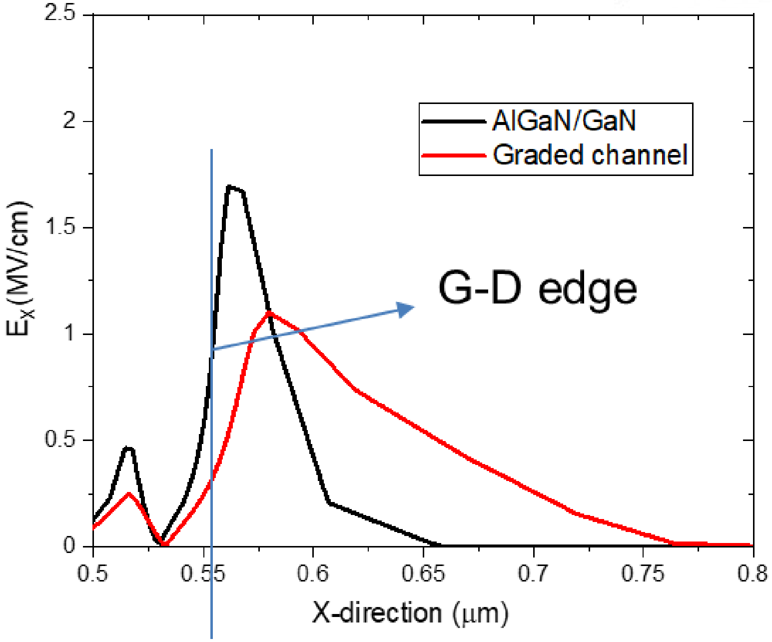


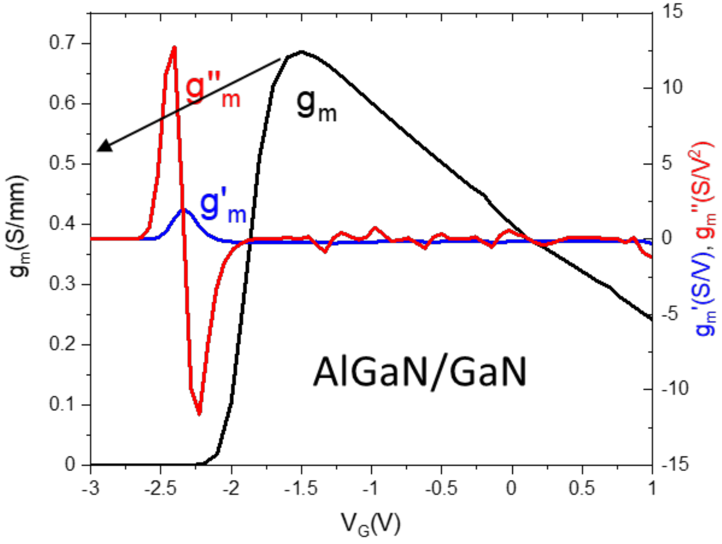


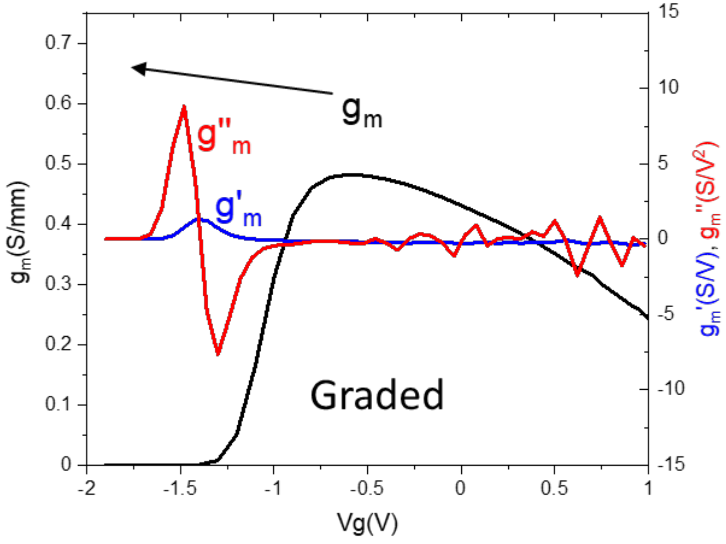
Graded AlGaN HEMT vs Conventional HEMT











- The analysis shows that graded AlGaN HEMT shows better linearity, compared to the conventional HEMT.
- Also, lower field => higher breakdown voltage for graded HEMT
- The TCAD model effectively describes and fits the data for both conventional and graded HEMT

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RF performance metrics and Assessment

Performance metrics	Parameter	Description
Maximum cut-off frequency	f_T	Extrapolation of unity current gain
Maximum freq. of oscillation	f_{MAX}	Extrapolation of unity power gain
Breakdown voltage		DIBL and the Critical EF
Power added efficiency @ 30GHz	PAE	Peak PAE
Power density @ maximum PAE	$P_{out, PAE}$	Output power density @ maximum PAE
Maximum power density @ 30GHz	P_{max}	Power density @ 3dB compression
Linearity figure of merit 1	P_{out} and PAE @ IM3=-30dBc	Output power and power added efficiency at a given IM3
Linearity figure of merit 2	OIP3	Output Third Order Intercept Point @ 30 GHz (small signal)
Linearity figure of merit 2	OIP3/P_{DC}	OIP3/P_{DC} (dB) at maximum PAE

Device Linearity from DC data

- ❑ Device Linearity Assessment from TCAD DC and small signal data for prediction and comparison

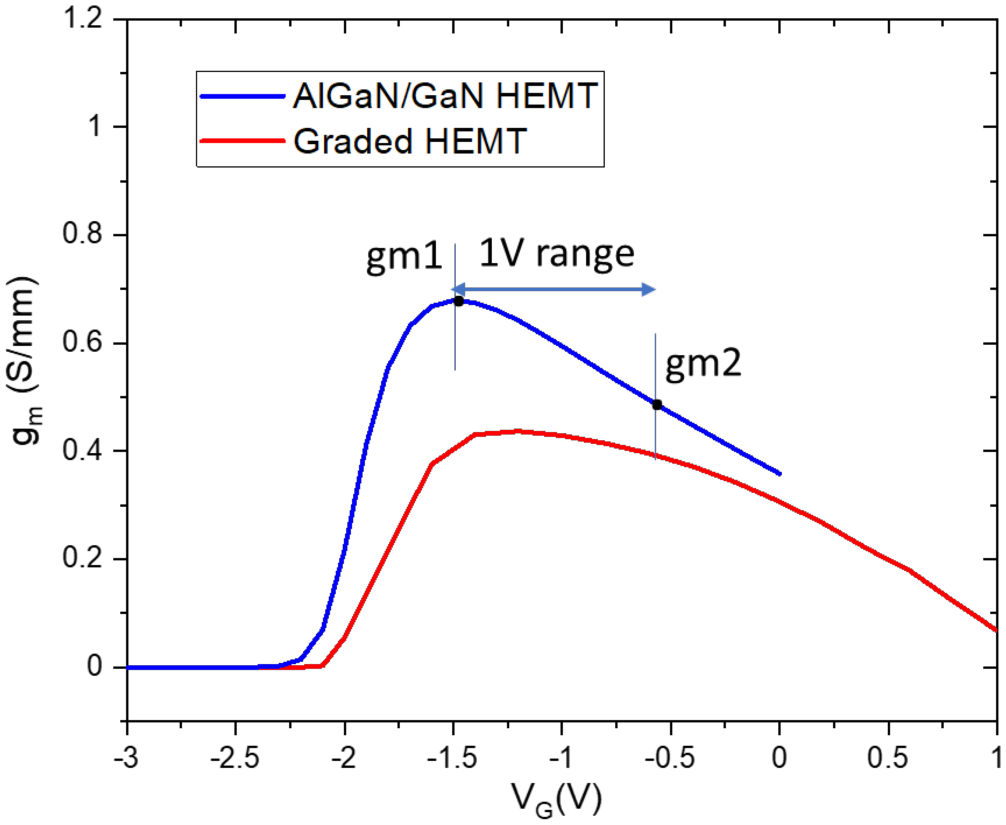
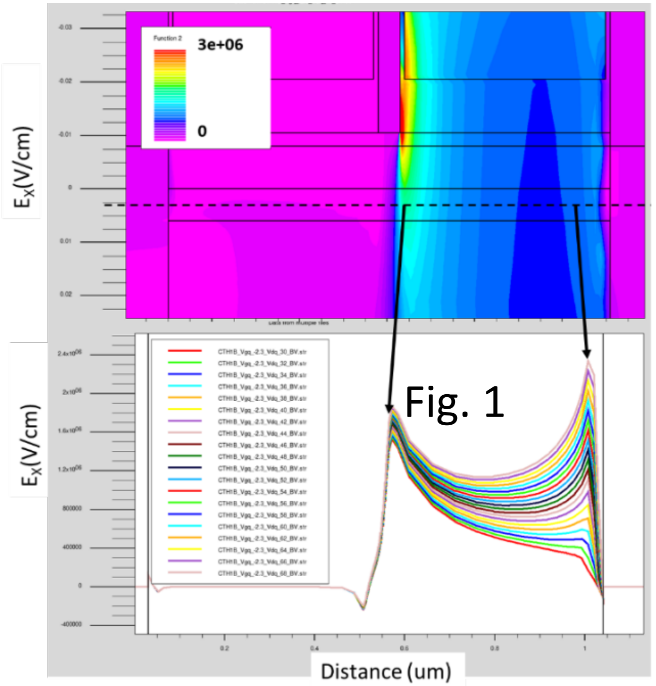


Fig. g_m vs V_{GS} curve at V_{DS}=5V

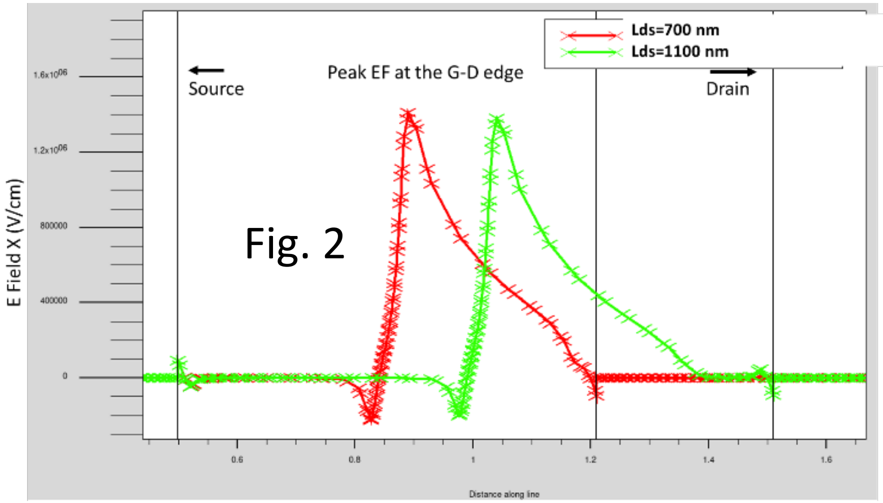
$$\Delta gm = \frac{gm1 - gm2}{\Delta Vg}$$

- A simple calculation of difference in the $g_{m,peak}$ and the g_m at a voltage range of 1 V
- The parameter can define a ‘roll-off’ factor

Breakdown Field Assessment



E_X Field along the channel Vds=30 to 68 V



E_X Field along the channel at Vds=10 for devices with different Lds (1100 nm and 700 nm)

- The following simple and transparent metrics have been chosen to allow valid device-device comparison of susceptibility to breakdown

1. **1/DIBL** : a criterion for drain breakdown susceptibility to bulk punchthrough
2. **L_{SD}*2 MV/cm:** a criterion for gate-drain breakdown. The critical field is set to 2 MV/cm and assumes no charge in the gate-drain gap

- BV is an **extrapolated** parameter
  - Errors in BV **diverge** as Vd increases
- Examples of **non-linear/device parameter dependent scaling**:
  - Second peak at the drain side is observed (Fig 1)
  - Electric Field peak doesn't scale with Lds as expected (Fig 2)
  - Uncontrolled buffer carbon doping dramatically changes BV

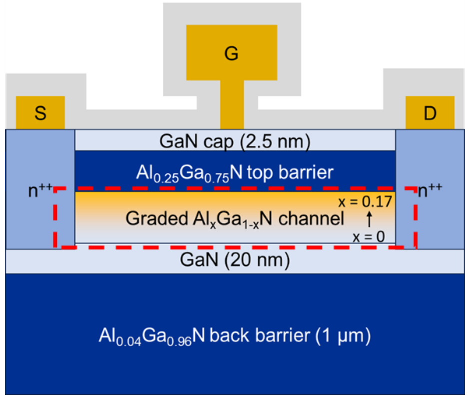
- **TCAD does not have enough information to reliably predict BV in device-device comparisons**

Device Variants for Design of Experiments

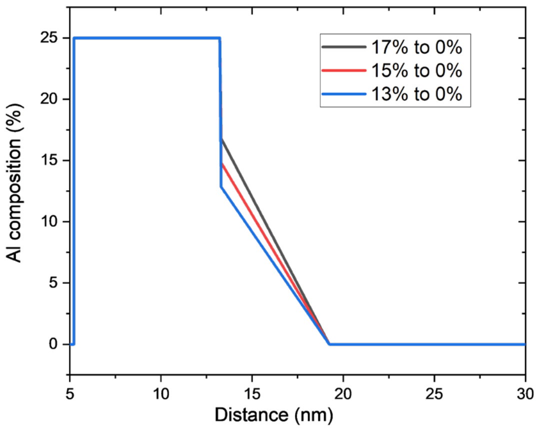
Variants	Varying Parameters and description	Value
DV_BA01	Graded AlGaN layer thickness, T_{GRAD}	8 nm
DV_BA02		4nm
DV_BB01	Top barrier AlGaN thickness, T_{TB}	15 nm
DV_BAB01	T_{GRAD}/ T_{TB}	8 nm/6 nm
DV_BAB02	T_{GRAD}/ T_{TB}	4 nm/ 10nm
DV_P01	Grading profile (Al %), varying grading profiles of the graded AlGaN layer	0% to 15%
DV_P02		0% to 13%
DV_P03		3% to 17%
DV_LA01	Varying gatelength, L_G, this also changes the drain-source spacing	25 nm
DV_LA02		40 nm
DV_LB01	Varying drain-source spacing, L_{DS} keeping the gatelength unchanged	700 nm
DV_ASYM	(Asymmetric structure) Gate position,	Lgs= 0.3 um Lgd= 0.66 um

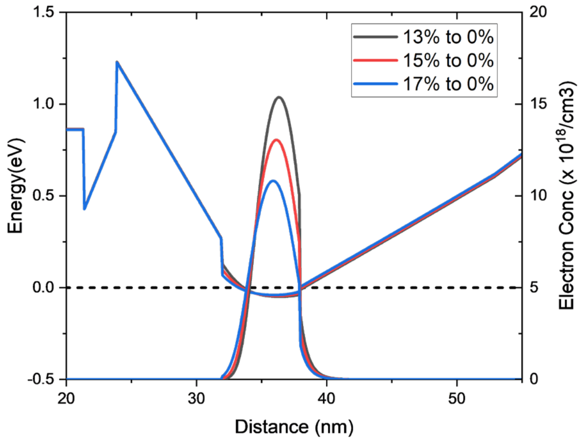
- DC and small signal simulation data from TCAD is fed to NL simulation

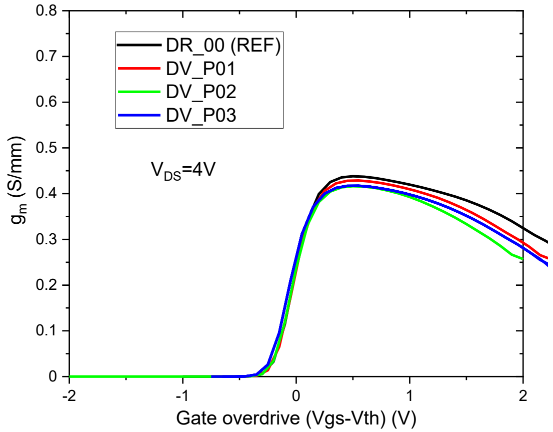
Observations from TCAD simulation



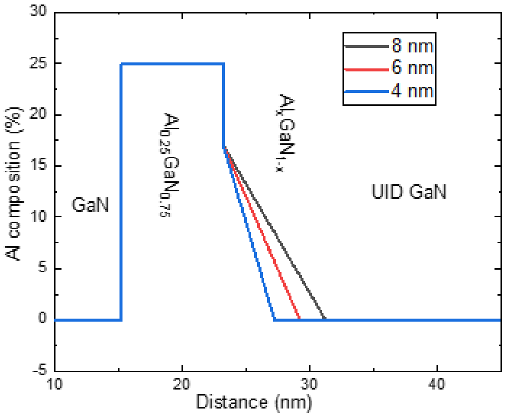
❑ Sensitivity to **Graded AlGaN layer** (Linear profile and Thickness)

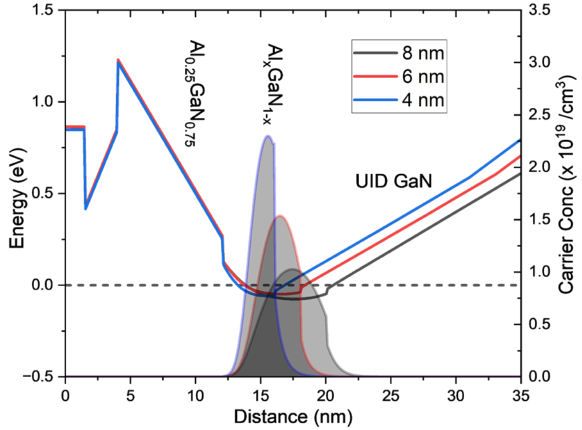


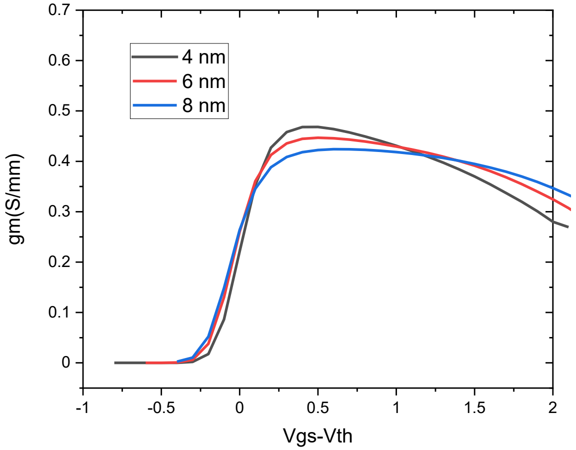




- Lower profile grading (13% to 0%) gives slight improvement in the roll-off and BV as a result of less abrupt grading but a lower carrier density, hence lower current and current gain







- Different graded layer thickness give same volumetric charge but distributed over different thickness
- Thicker layer means, more distributed carrier, higher linearity but not affect cut-off frequency

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Performance

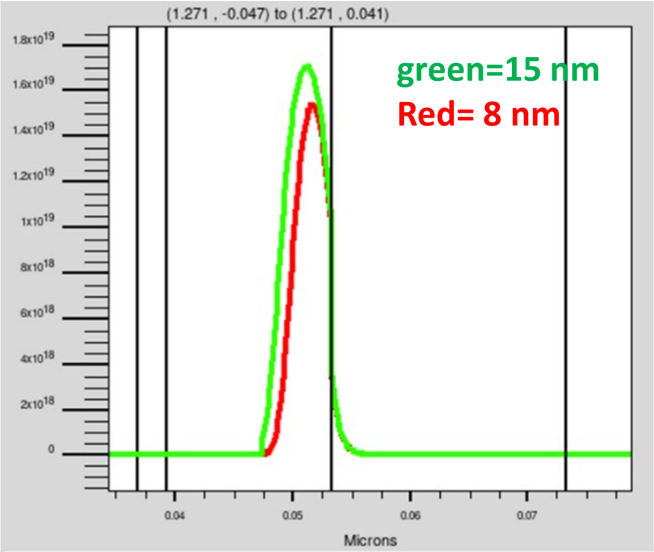
- Sensitivity to **Graded AlGaN layer** (Linear profile and Thickness)

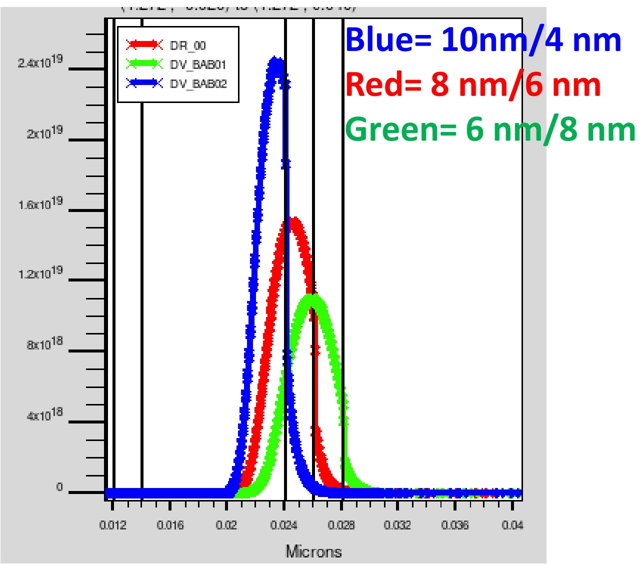
Device	Profiles (Al comp)	V_{TH} (V)	Gm,max (mS/mm)	gm roll-off (mS/mm)	DIBL (mV/V)	BV 1	BV2	f_T (GHz)
DV_00	0% to 17%	1.3	438	57	97.8	11.4	96	154
DV_P01	0% to 15%	1.1	428	70	88	12.0	96	~150
DV_P02	0% to 13%	0.9	417	84	83	11.3	96	145
DV_P03	3% to 17%	1.1	417	72	88.4	11.3	96	~150

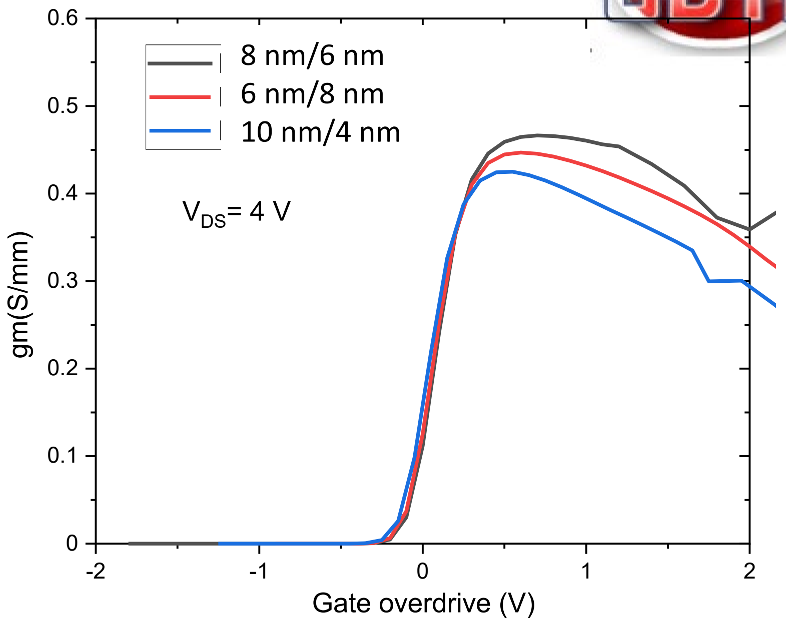
Device	T_{GRAD} (nm)	V_{TH} (V)	Gm,max (mS/mm)	gm roll-off (mS/mm)	DIBL (mV/V)	BV 1	BV2	f_T (GHz)
DV_00	6	1.3	438	57	97.8	11.4	96	154
DV_BA01	8	1.55	468	37	111	9.0	96	154
DV_BA02	4	1.1	422	96	85	11.8	96	154

- Only linearity is observed to be sensitive to the changes or Scaling of the graded AlGaN layer.

Sensitivity to the top AlGaN barrier thickness

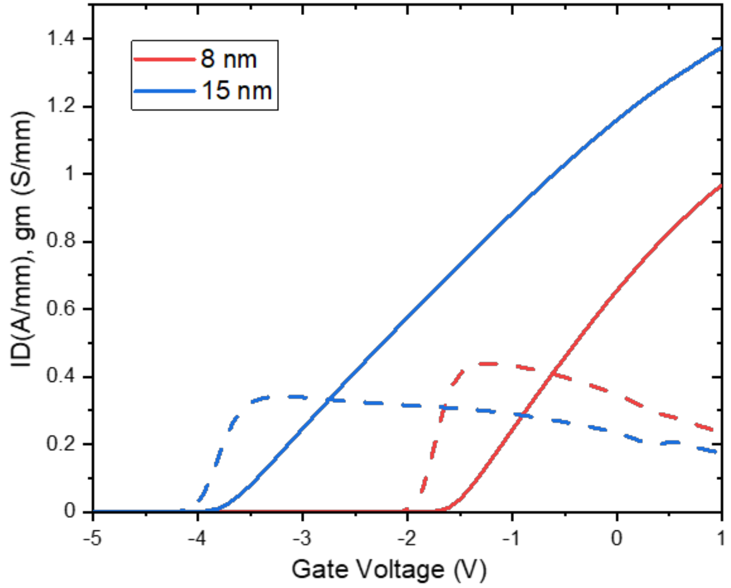




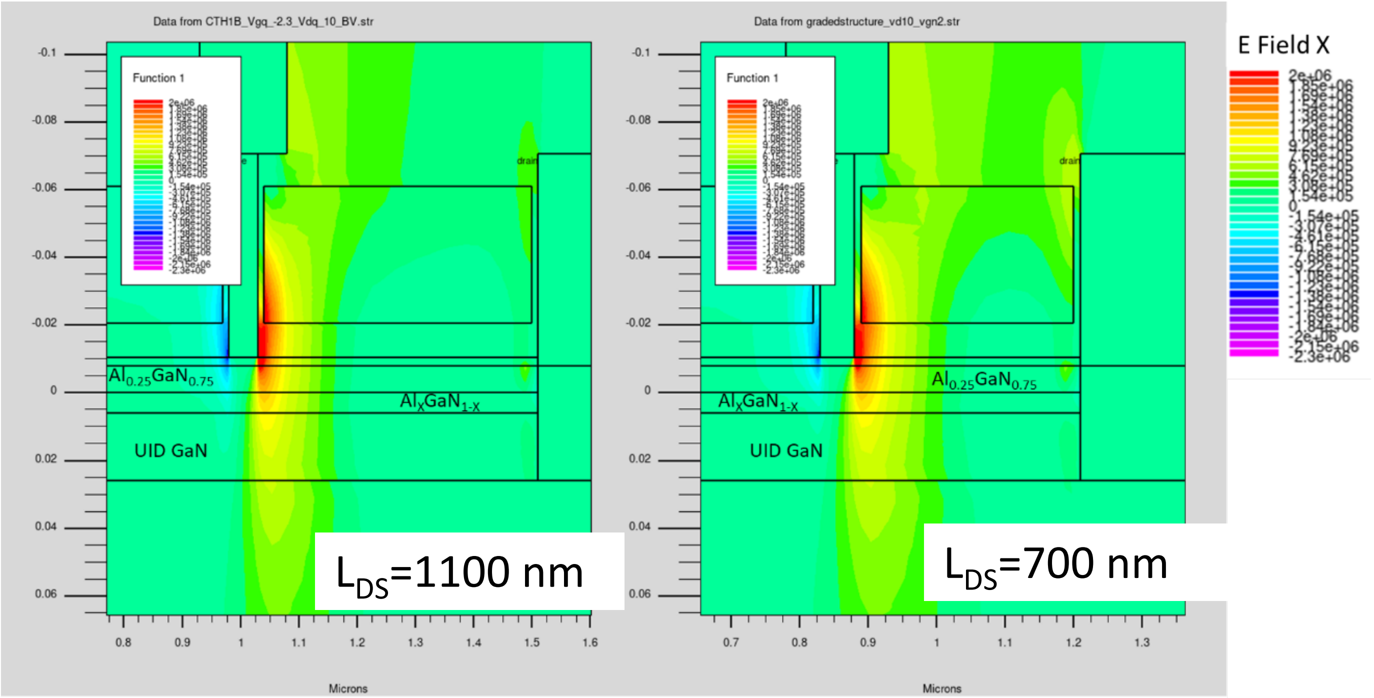


Devices	DR_00	DV_BB01	DV_BAB1	DV_BAB2
Talgan/Tgrad(nm)	8/6	15/6	6/8	10/4
n_S (x 10^{12} cm^{-2})	5.3	7.2	4.4	6.1

- Thinner the AlGaN layer, the more the sheet charge density
- This is due to the stronger EF introduced by the thinner AlGaN which depletes the charge in the channel more.
- A wider gm is obtained with 15 nm top barrier but degrades ft and DIBL



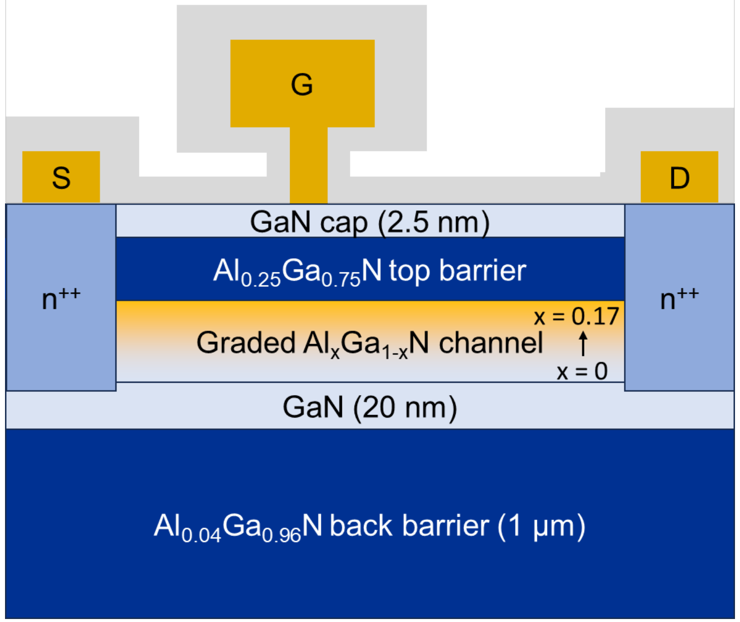
Device Variants with different S-D distance

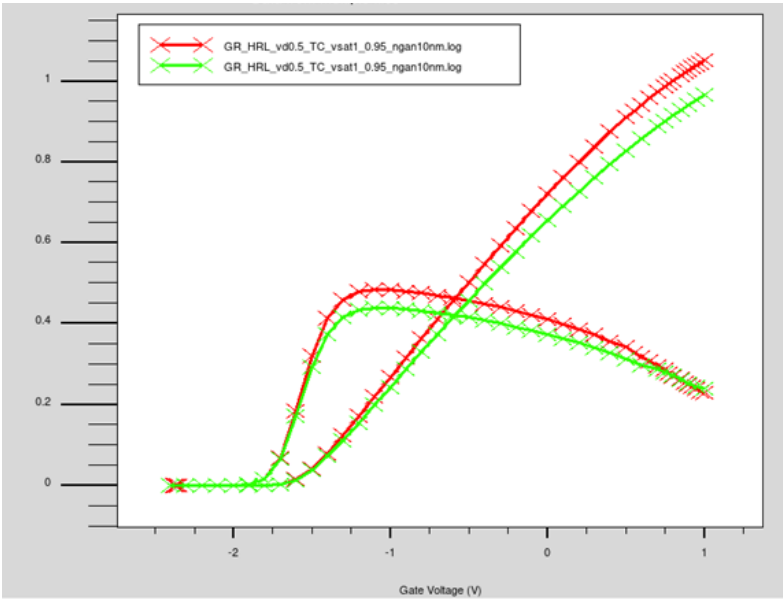


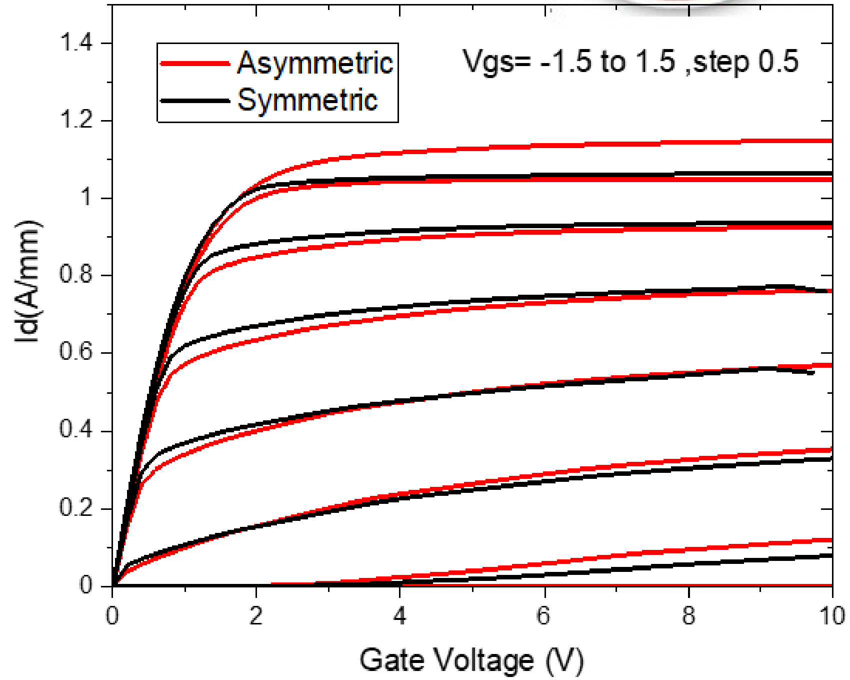
- Scaling the S-D distance decreases BV
- Scaling gatelength, keeping the Lgs and Ldg same enhanced cut-off frequency significantly but at the expense of DIBL and hence BV

Device	Parameters varied Lg/Lds (nm)	V_{TH} (V)	Gm,max (mS/mm)	gm roll-off (mS/mm)	DIBL	BV1	BV2	f_T
DV_00	50/1100	-1.3	438	57	97.8	96	96	154
DV_LA01	25/1025	-1.8	395	53	300	3.3	93.5	175
DV_LA02	40/1060	-1.65	421	62	117	8.5	95	160
DV_LB01	50/700	-1.25	475	51	93.3	7.65	65	160

Asymmetric Structure







Device	Parameters varied Lg/Lds (nm)	V_{TH} (V)	Gm,max (mS/mm)	gm roll-off (mS/mm)	DIBL	BV2	f_T	fmax
DV_00	50/1100	-1.3	438	57	97.8	96	154	
DV_ASM	50/1100	-1.3	485	73	93.3	**132**	154	

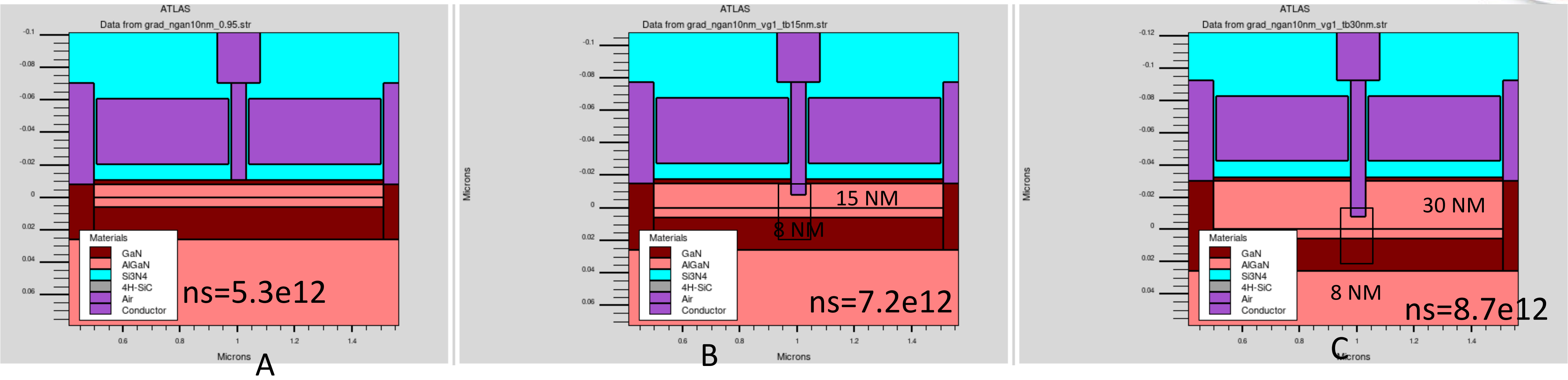
- Asymmetric structure increases the BV significantly as G-D distance is longer

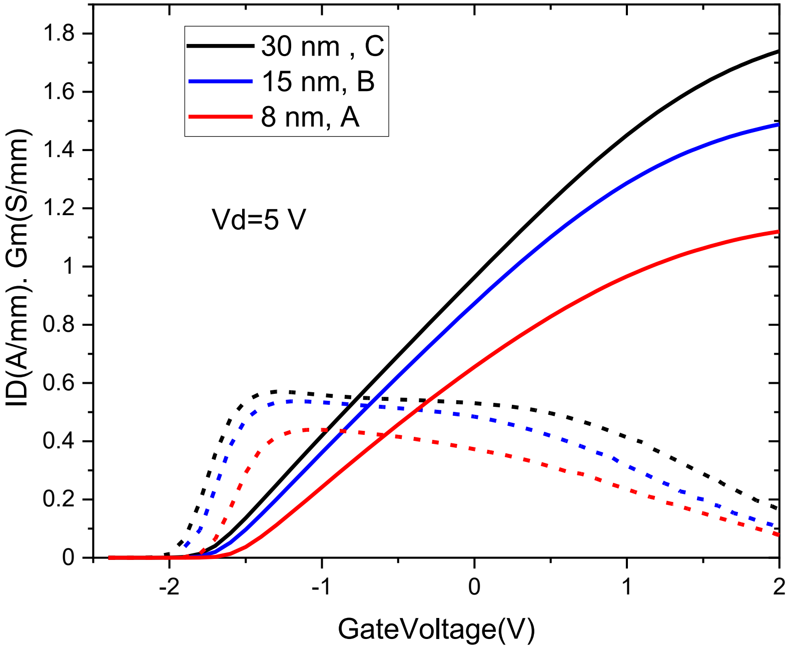
Performance Summary

Device	DESCRIPTION (Varied parameter w.r.t reference)	$g_{m,max}$ (mS/mm)	Ft (GHz)	DIBL (mV/V)	Gm roll off mS/V	BV1 1/dibl	BV2 (Lgd*2 MV/cm)
DR_00	L_G=50, T_{TB}=8, T_{GRAD}=6, L_{DS}=1100 Profile =17%-0%	440	154	97.8	57	10.2	96
DV_BB01	T_{TB}=15	340	140	148.8	25	6.7	96
DV_BA01	T_{GRAD}=8	420	154	111	37	9.0	96
DV_BA02	T_{GRAD}=4	470	154	85	96	11.8	96
DV_BAB01	T_{GRAD}/ T_{TB}=8/6	460	154	92.4	46	10.8	96
DV_BAB02	T_{GRAD}/ T_{TB}=4/10	420	154	93	70	10.7	96
DV_P01	Profile= 0%-15%	416	~150	88	71	11.4	96
DV_P02	Profile= 0%-13%	400	145	83	85	12.0	96
DV_P03	Profile= 3%-17%	400	~150	88.4	77	11.3	96
DV_LA01	L_G=25	395	175	300.4	53	3.3	93.5
DV_LA02	L_G=40	430	160	117	62	8.5	95
DV_LB01	L_{DS}=700	475	160	130.6	51	7.65	65
DV_ASM	L_{GS}= 0.3 um L_{GD}= 0.66 um	485	154	93.3	73	10.7	132

- Trade-off in performance metrics is observed

Suggested Structure





- Increasing carrier density in the access region can improve linearity
- Increasing Al% is also an option but not very feasible
- Maintaining a thinner AlGaN under the gate can improve the gate controllability

Conclusion

- The TCAD model successfully fits the simulation very well to the measured/reported data
- Different approaches (implementation of source starvation or LO phonon model) were needed depending on the contact regrowth (MOCVD/MBE)
- Graded AlGaN Layer is important for improved Linearity and BV
- Breakdown field assessment could be not be done accurately as it depends strongly on divergent extrapolated quantities
- Performance **not super sensitive** to changes in the epitaxy (upto the degree considered in this work)

THANK YOU

ESA Contract No. 4000135857/21/NL/GLC/my

Physics Based Modelling of Next Generation mm-Wave GaN Technology

Chalmers University of Technology

2023-10-25

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CHALMERS

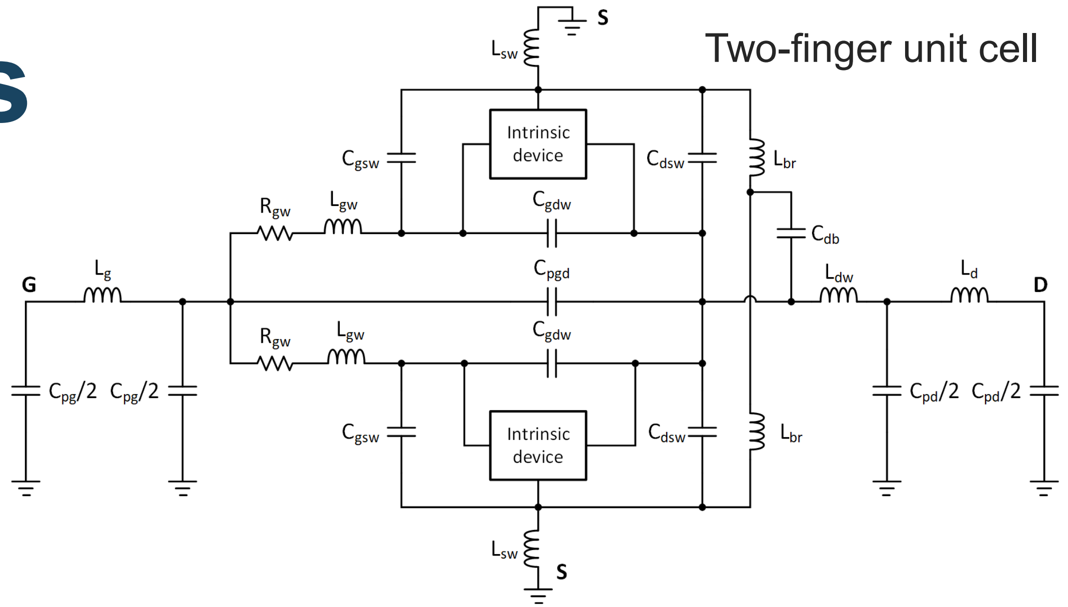
Outline

- EM simulation of parasitics
- Angelov (Chalmers) model
- Validation of methodology
  - DC
  - Charge model
  - S-parmeters
  - Large-signal
- Results of experiments
  - Barrier thickness
  - Grading profile (Al concentration in the graded channel)
  - Thickness of graded channel
  - Gate position
- Conclusion and future work

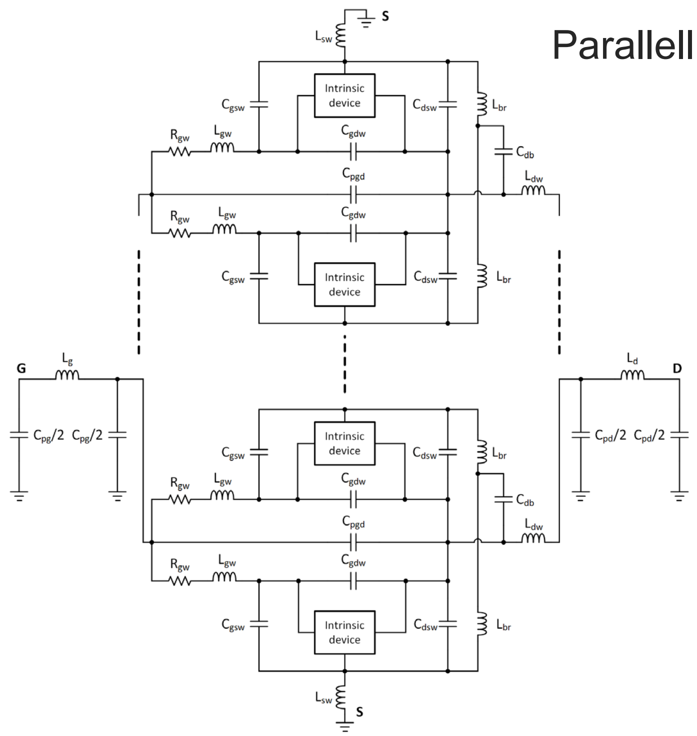
EM simulation of parasitics

- Extraction of parasitic capacitances and inductances using
  - Direct extraction from ColdFET models [1,2,3]
  - Utilizing scaling to extract parasitic elements [3]
- Simulation using both EM in ADS (pads and manifolds) and HFSS (gate-finger)
- Demonstration of lumped network capable of modeling parasitic circuit up to at least 100 GHz

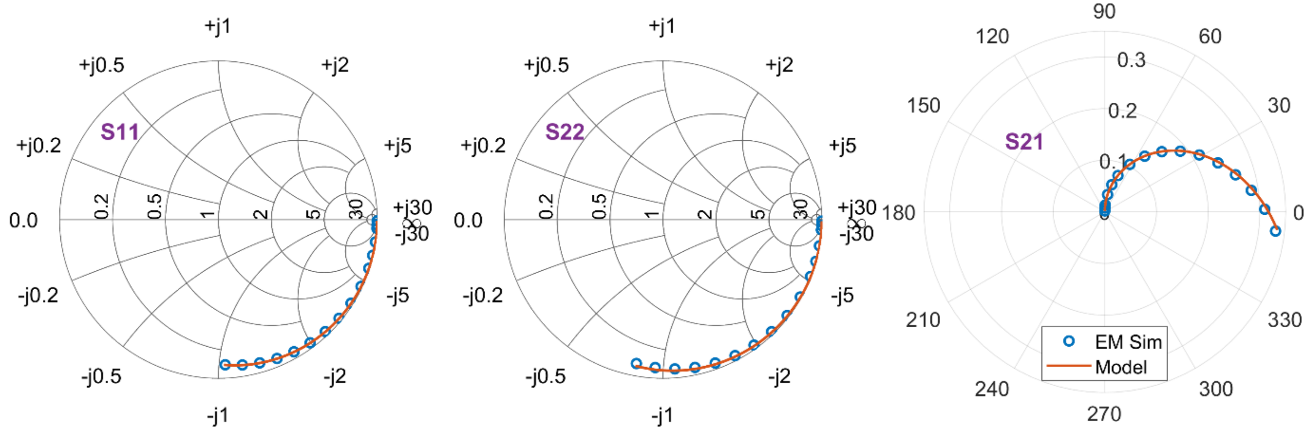
Two-finger unit cell



Parallelling unit cells



Chalmers HEMT layout: S-parameters from EM simulation and lumped parasitic model (0.5-100 GHz)



Non-linear transistor model

- Angelov (Chalmers) model
  - Current model
  - Charge (capacitance) model
  - Thermal model
  - Dispersive effects
    - Back gating
    - Frequency dispersion
  - Soft breakdown

$$I_{ds}[V_{gs},V_{ds}] = I_{pk} \cdot (1+\tanh(\psi)) \cdot (1+\lambda V_{ds}) \cdot \tanh(\alpha V_{ds})$$

$$C_{gs} = C_{gsp} + C_{gs0} \cdot (1+\tanh(\psi_1)) \cdot (1+\tanh(\psi_2))$$

$$C_{gs} = C_{gsp} + C_{gs0} \cdot (1+\tanh(\psi_1)) \cdot (1+\tanh(\psi_2))$$

$$V_{pk}(V_{ds}) = V_{pks} - \Delta V_{pks} + \Delta V_{pks} \cdot \tanh\left(\alpha V_{ds} + K_{BG} \cdot V_{bgate}\right)$$

$$I_{pk0} = I_{pk0} \cdot (1 + T_{CIPK0} \cdot (Tj - T_{nom}))$$

$$I_{ds}[V_{gs},V_{ds}] = I_{pk} \cdot (1+\tanh(\psi)) \cdot \left(1+\lambda V_{ds} + L_{sb0} \cdot e^{V_{dg}-V_{tr}}\right) \cdot \tanh(\alpha V_{ds})$$

- Angelov (Chalmers) model implemented in Keysight's ADS

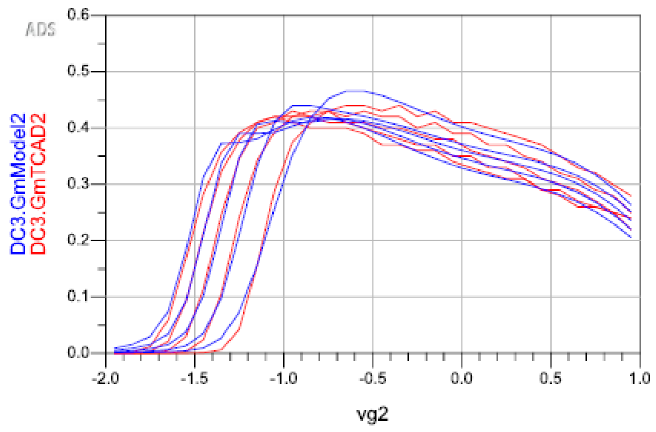
Non-linear transistor model: Parameter extraction

1. Extraction of the current model from DC-data
   - I_{ds} vs. V_{ds}
   - I_{ds} and V_{gs} vs. V_{gs}
2. Extraction of charge model from low-frequency s-parameters
   - C_{gs} and C_{gs} vs. V_{gs}
   - C_{gs} and C_{gs} vs. V_{gs}
   - C_{ds} = const.
3. Extraction of frequency dispersion and back-gating paramers and Schottky series resistances
4. Comparison with large signal measurements
   1. Power spectrum (low frequency)
   2. Current and voltage waveforms
   3. Load- and source pull and power sweep

Validation of methodology

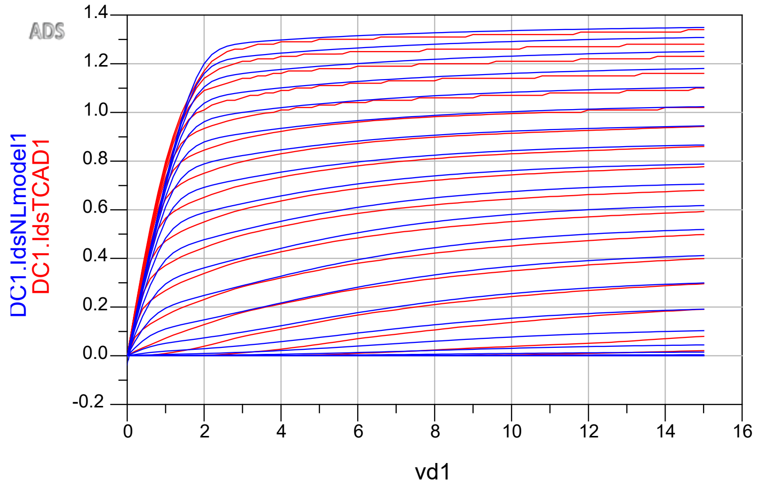
- Methodology verified against published data on GaN HEMTs with graded channel and thick barrier
  1. DC
  2. S-parameters and small-signal model
  3. Gain and PAE vs. P_{out} (Z_L)
  4. P_{out}, IMD3 and OIP3 vs. P_{in}

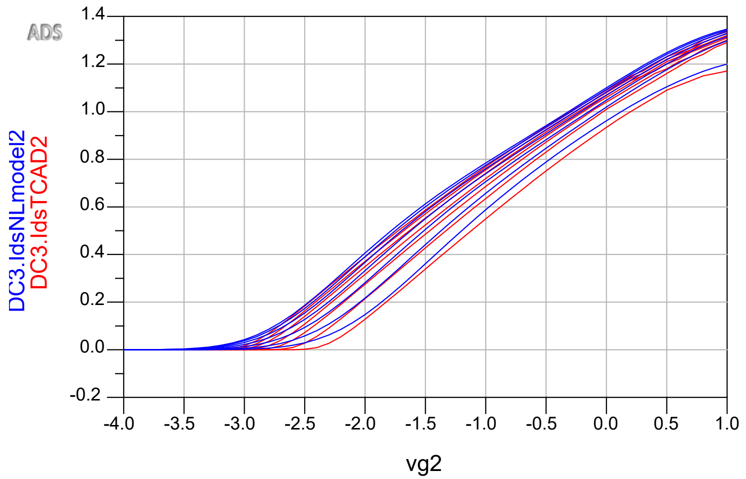
Usually better fit of g_m vs. V_{gs} (short channel effect)

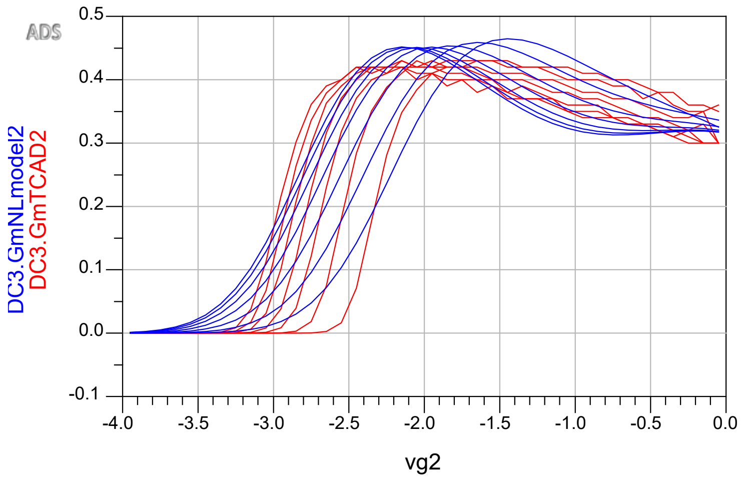


Demonstration of extraction of current model

Comparison of I_{ds} vs. V_{ds}, I_{ds} vs. V_{gs}, g_m vs. V_{gs} (red - TCAD, blue - NL model)



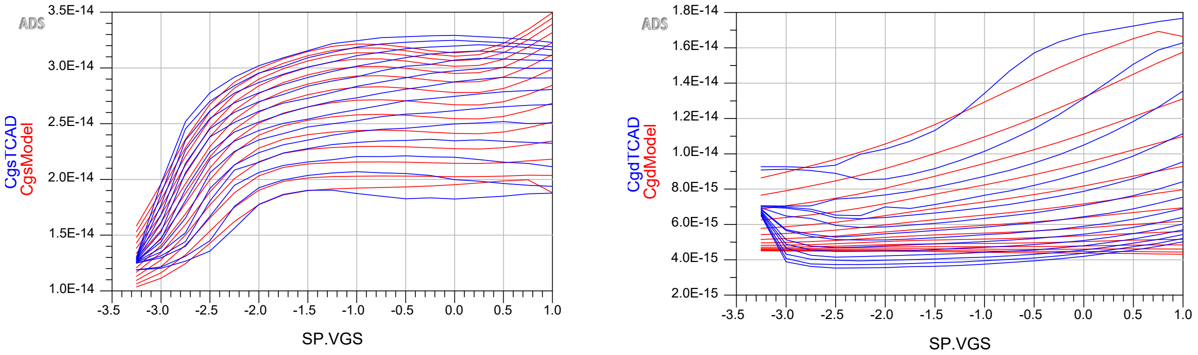




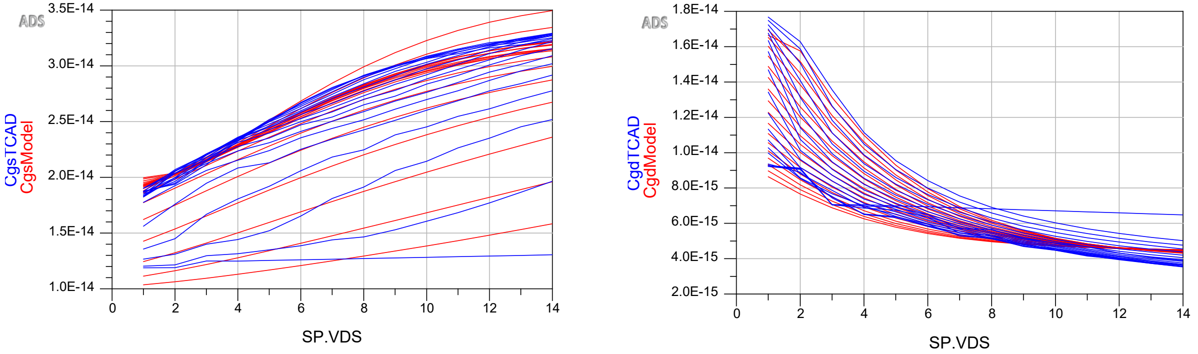
Validation of methodology

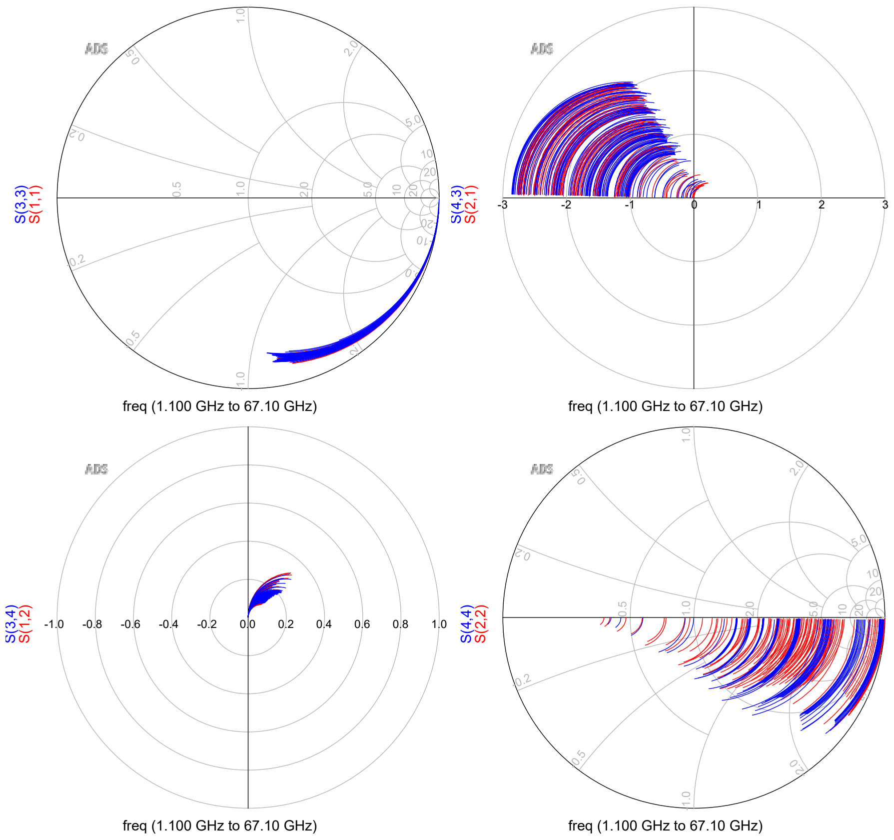
- Extraction of charge model and frequency dispersion / backgating DC

Demonstration of C_{gs} and C_{gd} vs V_{gs} from non-linear model (blue - TCAD, red - NL model)



Demonstration of C_{gs} and C_{gd} vs V_{ds} from non-linear model (blue - TCAD, red - NL model)



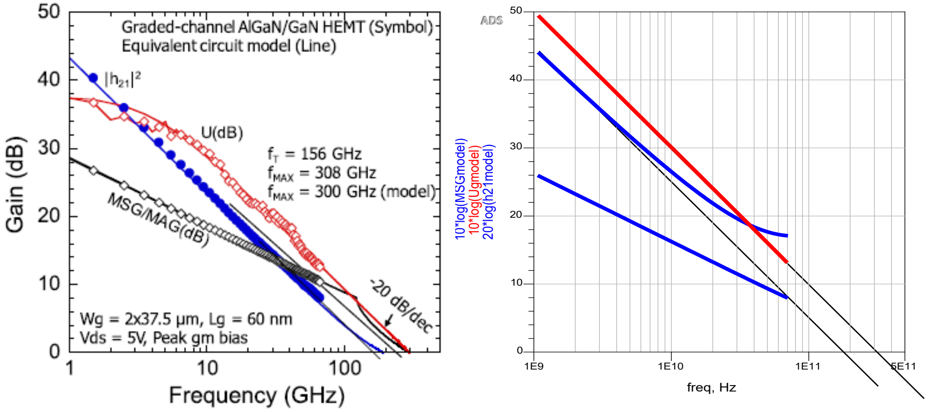


Demonstration of bias dependent s-parameters from non-linear model (red - TCAD, blue - NL model)

Validation of methodology

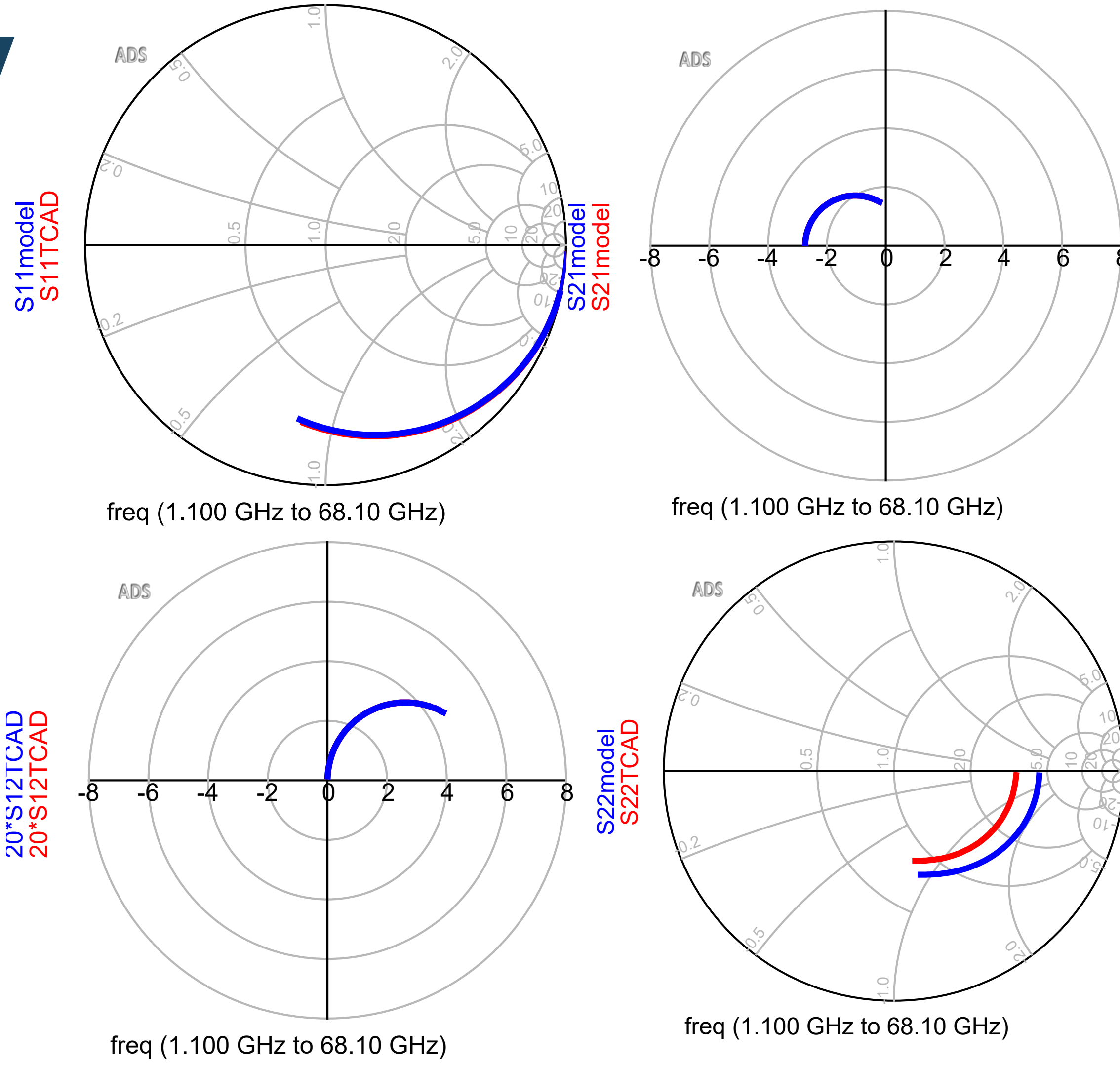
- Comparison of s-parameters and f_T and f_{max} at high gain bias
  - V_{ds}=5 V and I_{ds}=320 mA/mm (V_{gs}=-1.85 V) (from ref)

Comparison of h_{21}, U, and MSG at V_{ds}=5 V and I_{ds}=320 mA/mm from non-linear model with parasitics from EM-simulations added for the TCAD and non-linear model



Comparison of f_T and f_{max} at V_{ds}=5 V and I_{ds}=320 mA/mm from non-linear model with parasitics from EM-simulations added for the TCAD and non-linear model

	f_T [GHz]	f_{max} [GHz]
Measured [from ref]	156	308
TCAD	181	294
Non-linear model	180	314

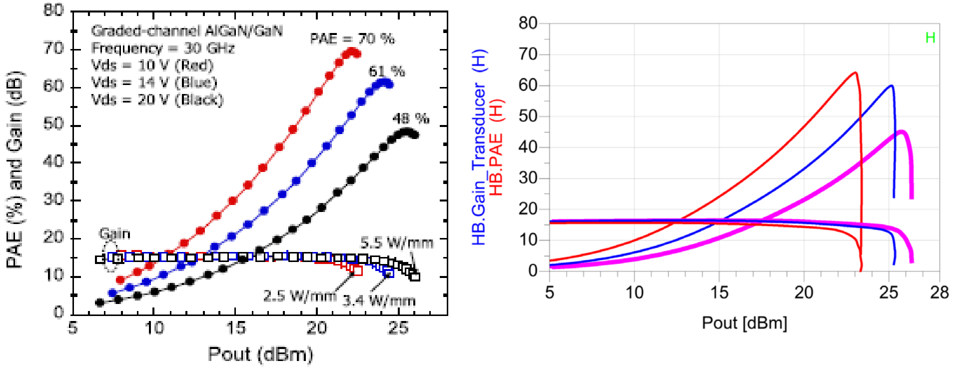


Comparison of s-parameters from non-linear model and TCAD (red - TCAD, blue - NL model)

Validation of methodology

- Comparison of PAE and gain vs. Pout
  - Z_L= 0.7 ∠39° (from ref)
  - Z_S tuned for equal gain

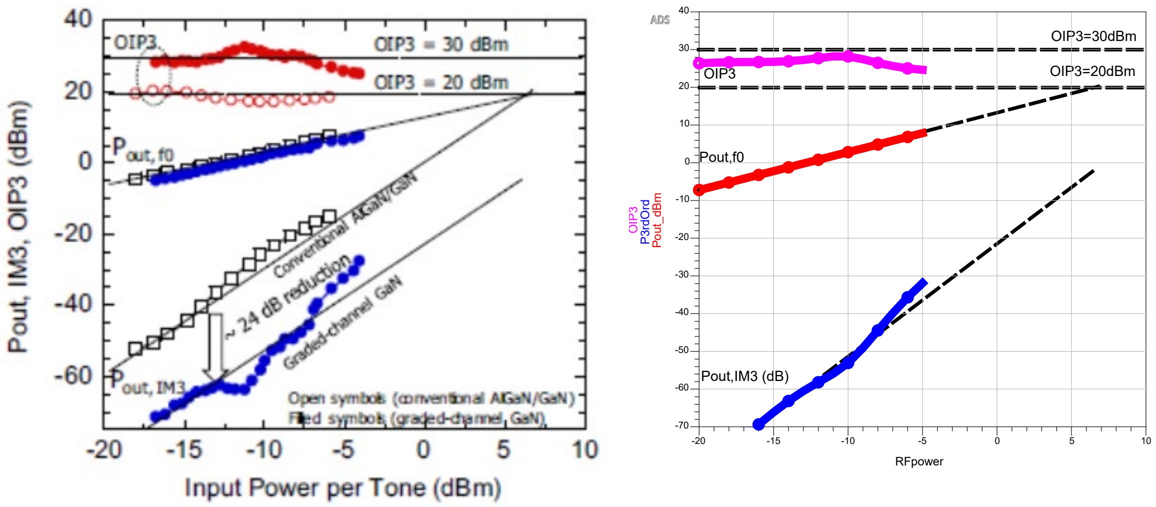
Comparison of h_{21}, U, and MSG at V_{ds}=5 V and I_{ds}=320 mA/mm from non-linear model with parasitics from EM-simulations added for the TCAD and non-linear model



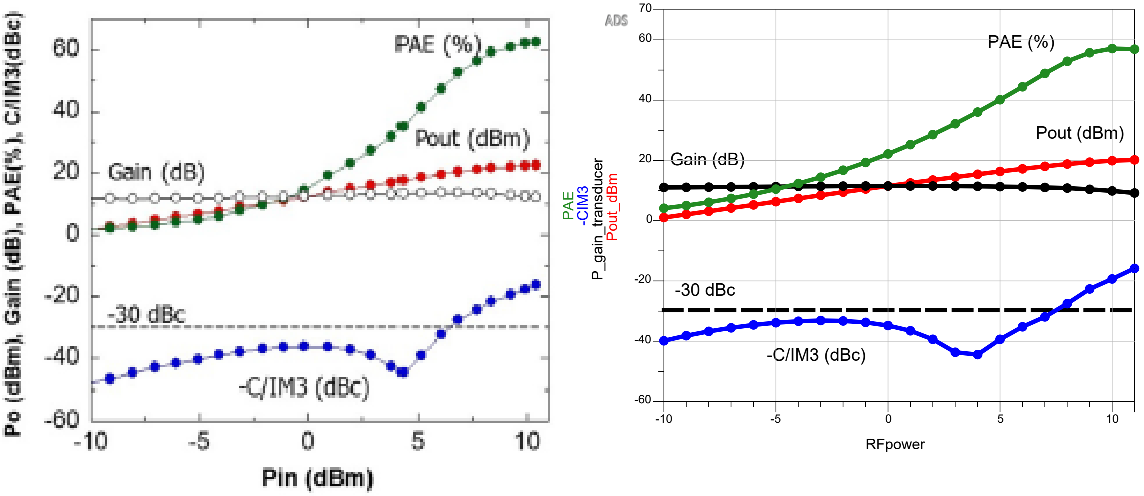
Comparison of P_{out} and PAE at V_{ds}=10, 14 and 20 V from non-linear model with parasitics from EM-simulations and published data

	Measured [2]		Simulated	
V_{ds} [V]	P_{out} [W/mm]	PAE [%]	P_{out} [W/mm]	PAE [%]
10	2.5	70	2.9	64
14	3.4	61	4.6	60
20	5.5	48	5.7	45

Comparison of Pout, IMD3 and OIP3 from non-linear model and published data



Comparison of, Pout Gain and –C/IM3 from non-linear model and published data



Barrier thickness

- Varying the thickness of the barrier
  - $Al_{0.25}Ga_{0.75}N$-barrier
  - 2 different thicknesses
    - 8 nm
    - 15 nm

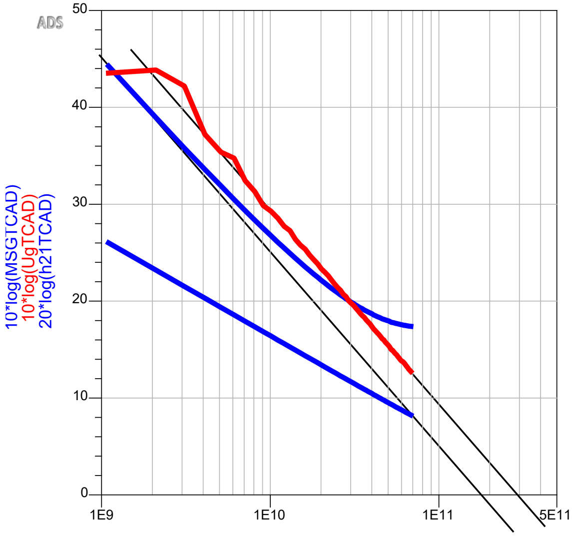
	Variations
Cap	2 nm, GaN
Barrier	**8 nm**, $Al_{0.25}Ga_{0.75}N$ **15 nm**, $Al_{0.25}Ga_{0.75}N$
Graded channel	6 nm Graded $Al_xGa_{1-x}N$ (x=0 to 17%)
Channel	20 nm, GaN
Back-barrier	1000 nm, $Al_{0.04}Ga_{0.96}N$
Substrate	SiC

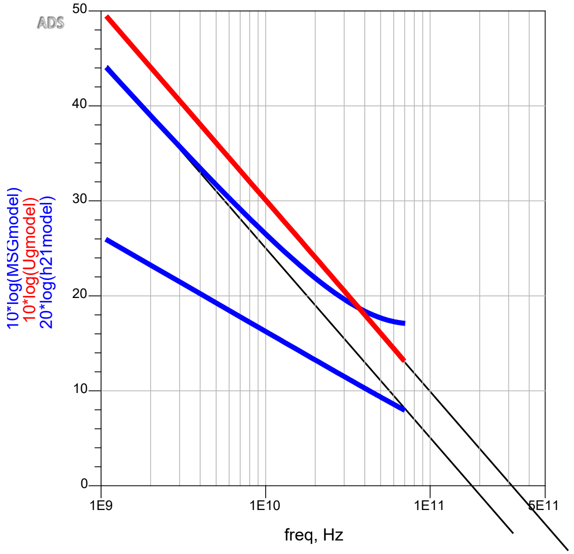
Barrier thickness: small signal

- Bias for maximum intrinsic f_T
- Parasitics added from EM-simulations

- f_T and f_{max} increase with thinner barrier
- Trends different for TCAD (and non-linear model)

	8 nm		15 nm	
	f_T [GHz]	f_{max} [GHz]	f_T [GHz]	f_{max} [GHz]
Measured	170	363	156	308
TCAD	169	325	181	294
Non-linear model	171	332	180	314
V_{ds} [V]	3		5	
I_{ds} [mA/mm]	158		320	

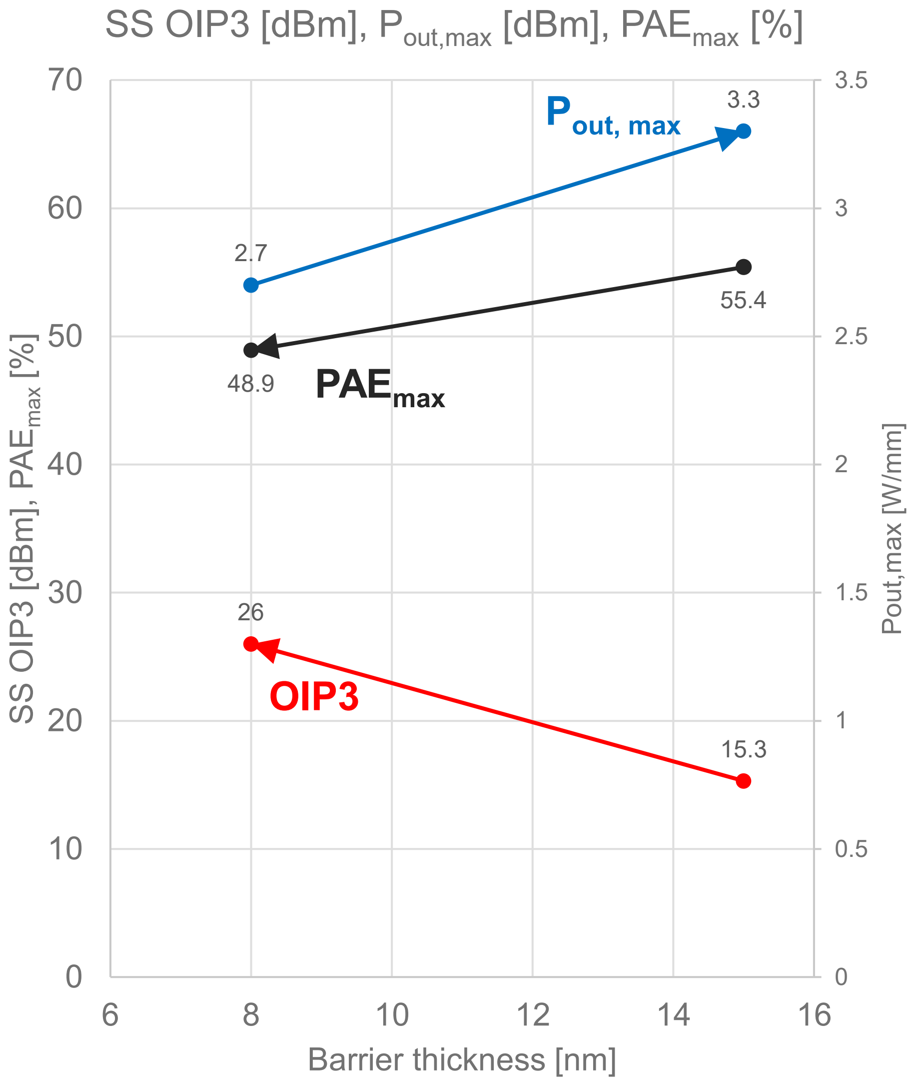




Barrier thickness: Large-signal performance

- Frequency 30 GHz
- Gate periphery: 2x37.5 µm
- Class AB (15% of I_{max}), V_{ds}=10 V
- Matched for maximum P_{out}

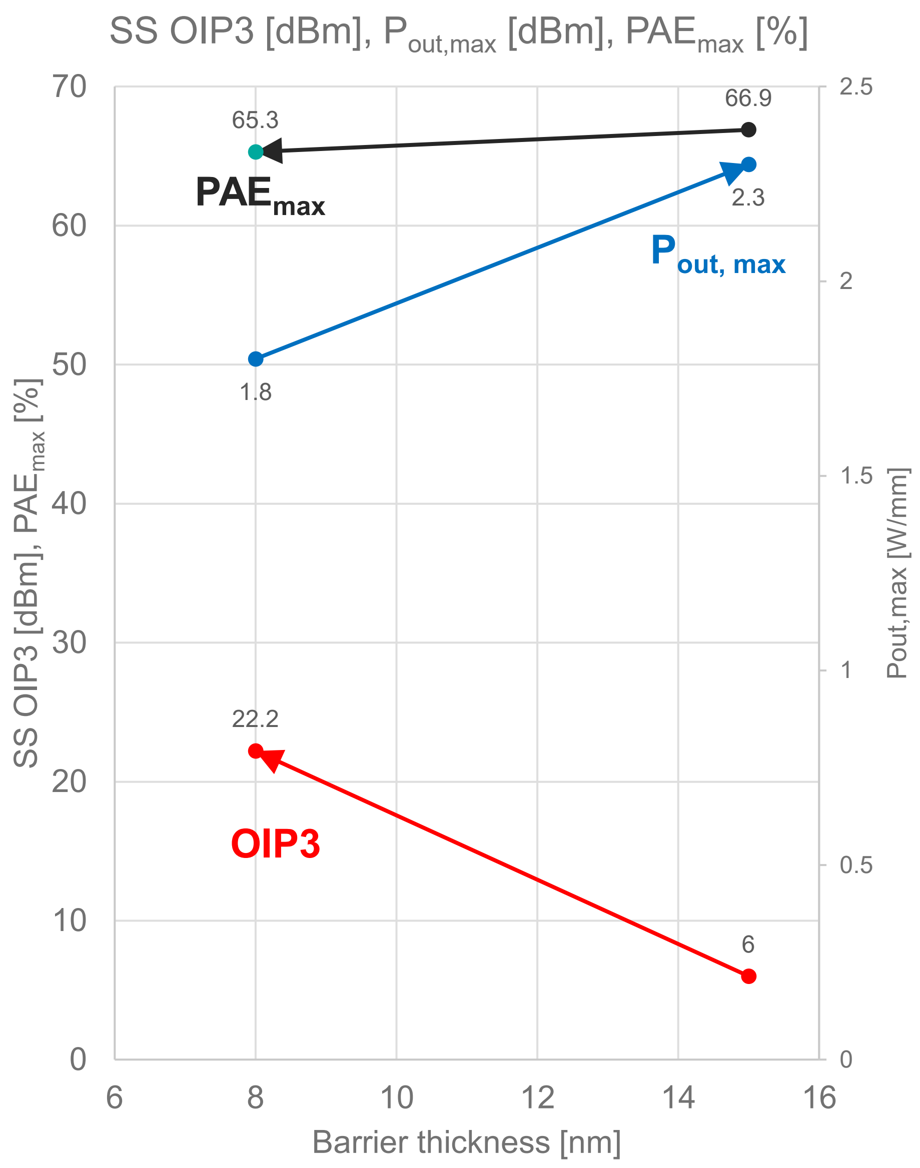
- P_{out} increases with a thicker barrier
  - Max Pout=3.3 W/mm
- OIP3 decreases with a thicker barrier
  - OIP3 extracted from small-signal
  - Max OIP3=26 dBm
- PAE increases with a thicker barrier
  - Max PAE=55.4%



Barrier thickness

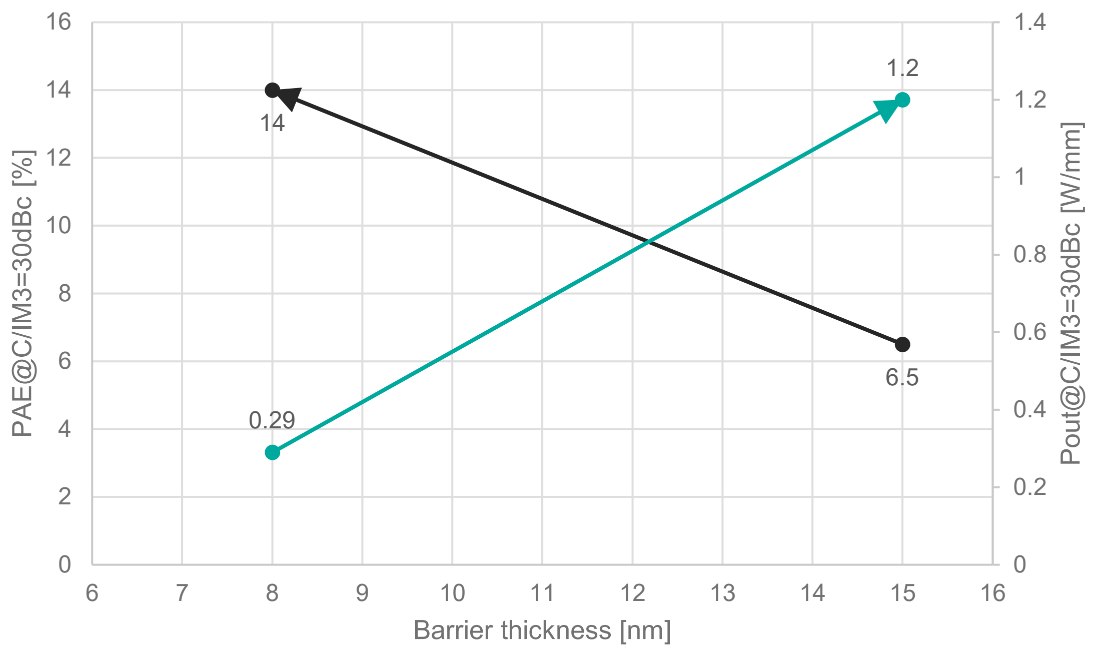
- Frequency 30 GHz
- Gate periphery: 2x37.5 µm
- Class AB (15% of I_{max}), V_{ds}=10 V
- Matched for maximum PAE

- P_{out} increases with a thicker barrier
  - Max Pout=2.3 W/mm
- OIP3 decreases with a thicker barrier
  - OIP3 extracted from small-signal
  - Max OIP3=22.2 dBm
- PAE increases with a thicker barrier
  - Max PAE=66.9%



Barrier thickness: Linearity

- Frequency 30 GHz
- Gate periphery: 2x37.5 µm
- Class A, V_{ds}=10 V
- Matched for maximum PAE



- P_{out} @ C/IM3=30dBc increases with a thicker barrier
  - Max Pout=1.2 W/mm
- PAE @ C/IM3=30dBc decreases with a thicker barrier
  - Max PAE=14

‘Hero numbers’ for each barrier thickness

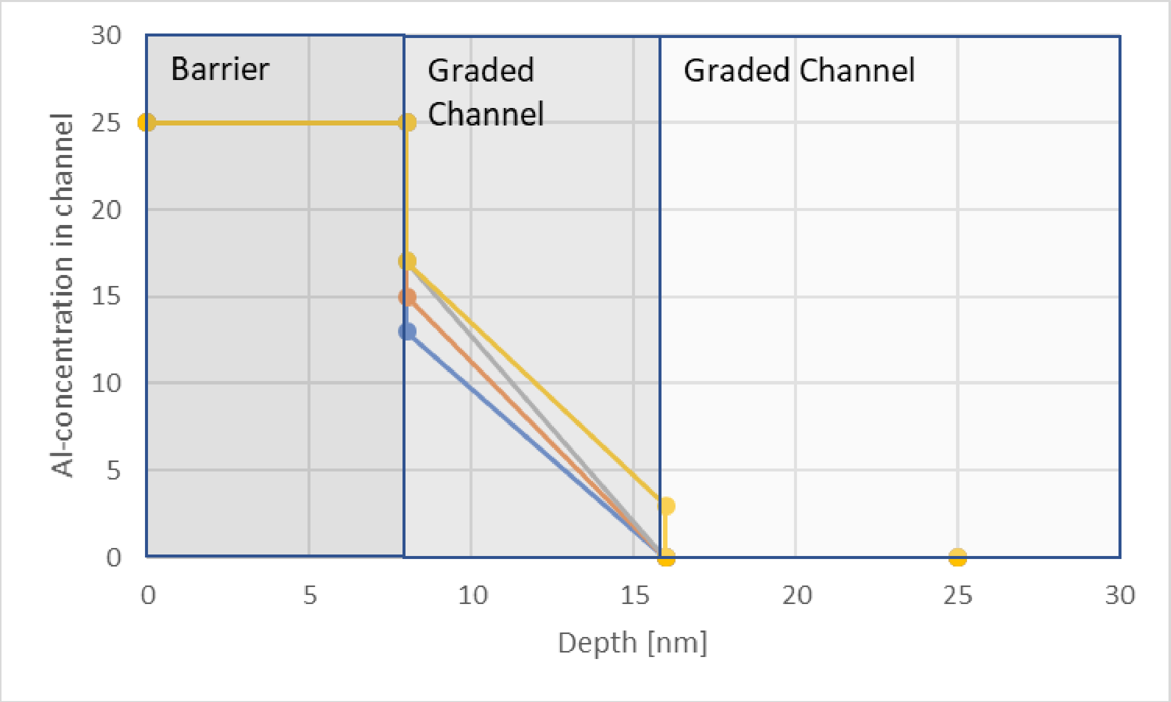
- Maximum values of the large-signal parameters
  - not simultaneous, i. e. different classes (Class A or AB and optimized parameter (Pout or PAE)

	$P_{out, max}$	PAE_{max}	OIP3	P_{out}@C/IM3=30dBc	PAE@C/IM3=30dBc
8 nm	2.7	65.3	26.0	13.4	15.4
15 nm	3.3	66.9	15.3	19.6	19.4

Grading profile: Al-concentration in channel

- Varying the Al-concentration in the graded channel
  - Linear grading
  - 4 different profiles
    - Grading from 0 to 13%
    - Grading from 0 to 17%
    - Grading from 0 to 17%
    - Grading from 3 to 17%

	Variations
Cap	2 nm, GaN
Barrier	8 nm, $Al_{0.25}Ga_{0.75}N$
Graded channel	6 nm Graded $Al_xGa_{1-x}N$ (x=0 to 13%) 6 nm Graded $Al_xGa_{1-x}N$ (x=0 to 15%) **6 nm Graded $Al_xGa_{1-x}N$ (x=0 to 17%)** 6 nm Graded $Al_xGa_{1-x}N$ (x=3 to 17%)
Channel	20 nm, GaN
Back-barrier	1000 nm, $Al_{0.04}Ga_{0.96}N$
Substrate	SiC



Grading profile: small-signal

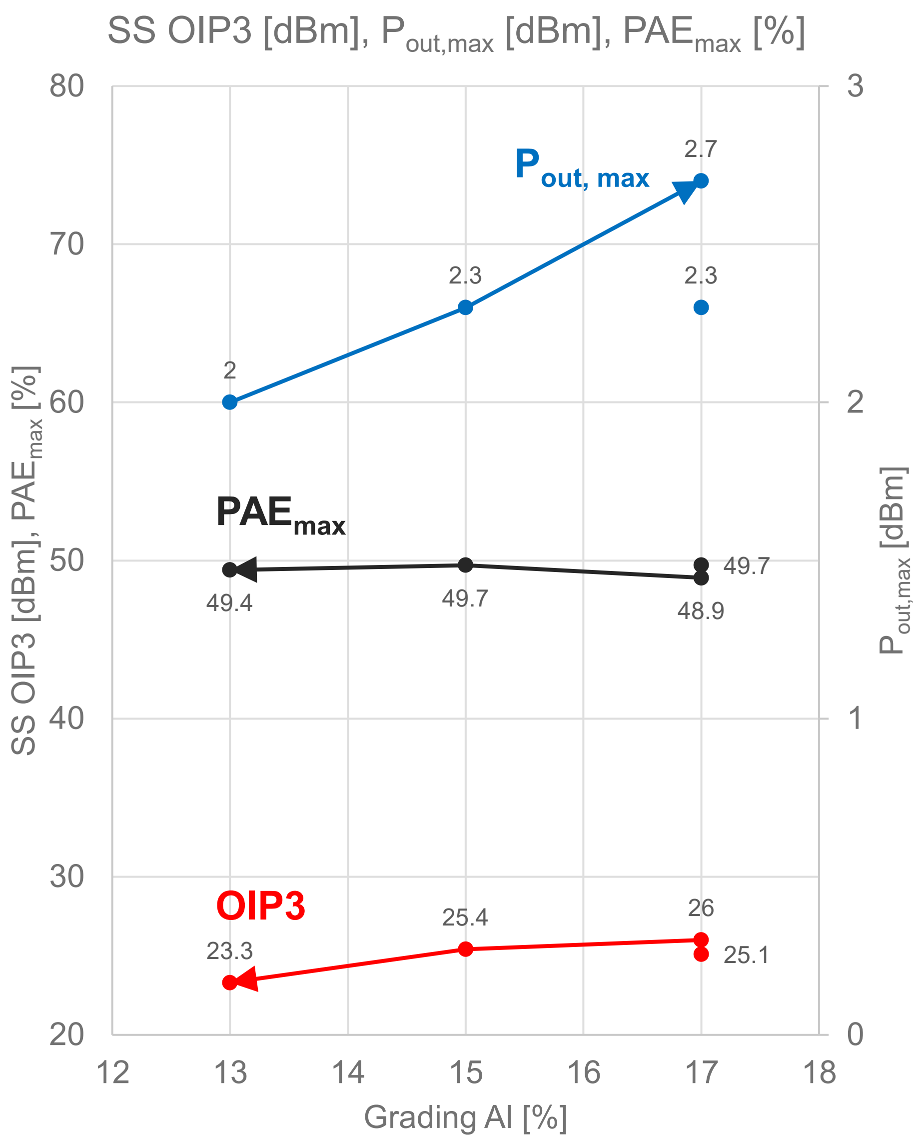
- Bias for maximum intrinsic f_T
- Parasitics added from EM-simulations
- f_T increase with higher Al-concentration
  - Better confinement in the GaN-channel
- f_{max} increases with higher Al-concentration

	$f_{T,int}$ [GHz]	$f_{T,NL}$ ($f_{T,TCAD}$) [GHz]	$f_{max,NL}$ ($f_{max,TCAD}$) [GHz]	V_{ds} [V]	V_{gs} [V]
Graded to 13%	165	171 (165)	244 (220)	2	-0.500
Graded to 15%	193	171 (159)	314 (303)	4	-1.00
Graded to 17% (ref)	199	171 (171)	358 (338)	4	-1.25
Graded to 3 to17%	184	165 (159)	314 (303)	4	-1.00

Grading profile: Large-signal

- Frequency 30 GHz
- Gate periphery: 2x37.5 µm
- Class AB (15% of I_{max}), V_{ds}=10 V
- Matched for maximum P_{out}

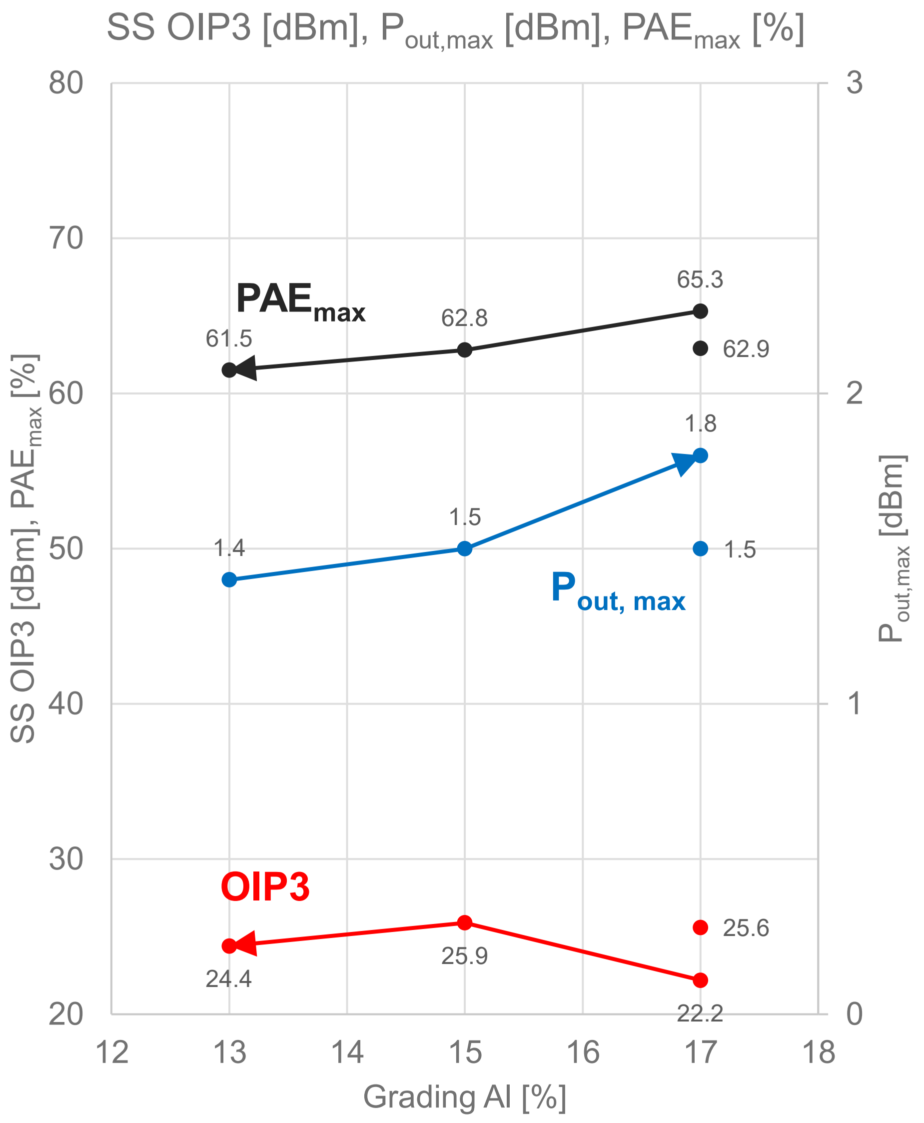
- P_{out} increases with higher Al-concentration
  - Max Pout=2.7 W/mm
- OIP3 increases with higher Al-concentration
  - OIP3 extracted from small-signal
  - Max OIP3=26 dBm
- PAE insensitive to Al-concentration
  - Max PAE=49.7%



Grading profile: Large-signal

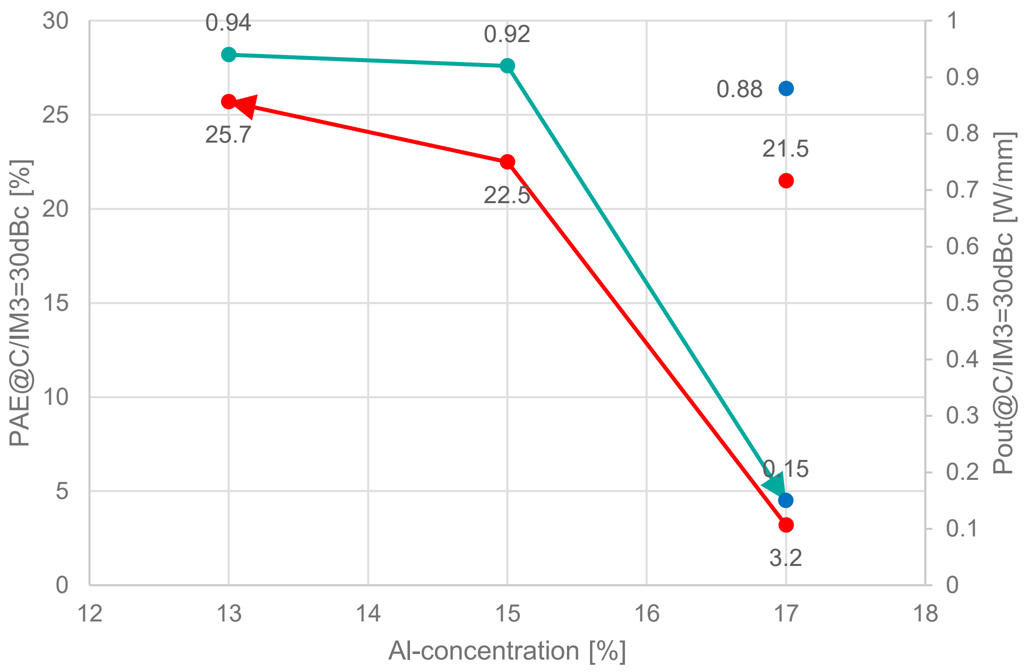
- Frequency 30 GHz
- Gate periphery: 2x37.5 µm
- Class AB (15% of I_{max}) , V_{ds}=10 V
- Matched for maximum PAE

- P_{out} increases with higher Al-concentration
  - Max Pout=1.8 W/mm
- OIP3 increases with higher Al-concentration (?)
  - OIP3 extracted from small-signal
  - Max OIP3=25.6 dBm
- PAE increases with higher Al-concentration
  - Max PAE=65.3%



Grading profile: Linearity

- Frequency 30 GHz
- Gate periphery: 2x37.5 µm
- Class A, V_{ds}=10 V
- Matched for maximum PAE



- P_{out} C/IM3=30dBc decreases with higher Al-concentration
  - Max Pout=0.94 W/mm
- PAE decreases with higher Al-concentration
  - Max PAE=25.7
- In general Class A exhibits sweep spots in IMD3
  - Potential improvement in P_{out} and PAE@C/IM3=30dBc

Graded 0 to 15%	P_{out}@C/IM3=30dBc [dBm] / [W/mm]	PAE@C/IM3=30dBc [%]	SS OIP3 [dBm]	OIP3/P_{dc}@PAE_{max} [dB]
Class A (P_{out} opt.)	17.8 / 0.80	18.8	13.3	-0.70
Class A (PAE opt.)	18.4 / 0.92	22.5	10.6	-1.2
Class AB (P_{out} opt.)	8.4 / 0.09	6.6	25.4	1.4
Class AB (PAE opt.)	12.4 / 0.23	17.2	25.9	0.61

‘Hero numbers’ for each grading profile

- Maximum values of the large-signal parameters
  - not simultaneous, i. e. different classes (Class A or AB and optimized parameter (Pout or PAE)

	$P_{out,\ max}$	PAE_{max}	OIP3	P_{out}@C/IM3=30dBc	PAE@C/IM3=30dBc
Graded to 13%	2.0	61.5	23.3	0.94	25.7
Graded to 15%	2.3	62.8	25.9	0.92	22.5
Graded to 17%	2.7	65.3	26.0	0.29	15.4
Graded to 3 to17%	2.3	62.9	25.6	0.88	21.5

Thickness of graded channel

- Varying the thickness of graded channel
  - 3 thicknesses
    - 4 nm
    - 6 nm
    - 8 nm
  - Grading profile fixed to 0 to 17 % Al-concentration

	Variations
Cap	2 nm, GaN
Barrier	8 nm, $Al_{0.25}Ga_{0.75}N$
Graded channel	**4 nm** Graded $Al_xGa_{1-x}N$ (x=0 to 17%) **6 nm** Graded $Al_xGa_{1-x}N$ (x=0 to 17%) **8 nm** Graded $Al_xGa_{1-x}N$ (x=0 to 17%)
Channel	20 nm, GaN
Back-barrier	1000 nm, $Al_{0.04}Ga_{0.96}N$

Thickness of graded channel: small-signal

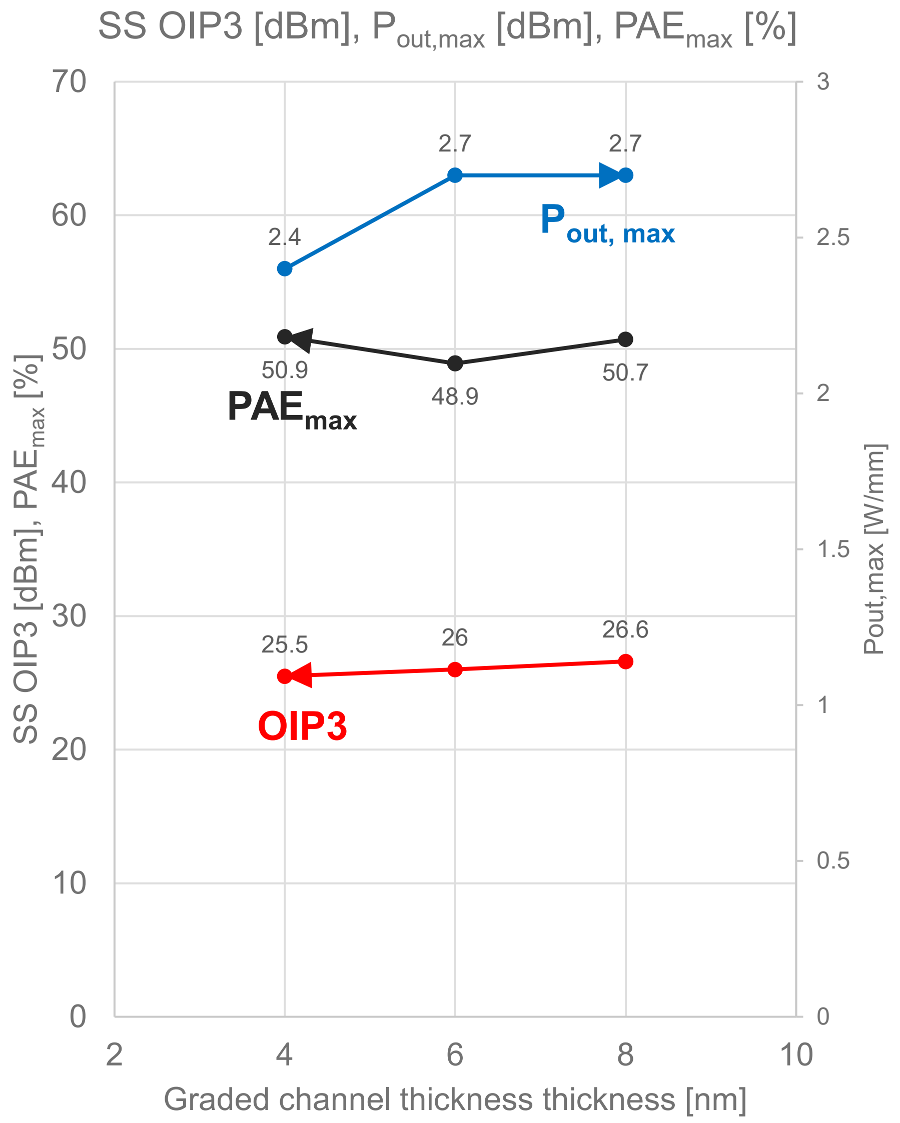
- Bias for maximum intrinsic f_T
- Parasitics added from EM-simulations
- No clear trends for f_T or f_{max}

	$f_{T,int}$ [GHz]	f_T ($f_{T,TCAD}$) [GHz]	f_{max} ($f_{max,TCAD}$) [GHz]	V_{ds} [V]	V_{gs} [V]
Graded 4nm	216	167 (173)	257 (266)	2	-0.75
Graded 6nm	199	171 (171)	358 (338)	4	-1.25
Graded 8nm	205	167 (161)	275 (265)	3	-1.25

Thickness of graded channel: Large-signal

- Frequency 30 GHz
- Gate periphery: 2x37.5 µm
- Class AB (15% of I_{max}), V_{ds}=10 V
- Matched for maximum P_{out}

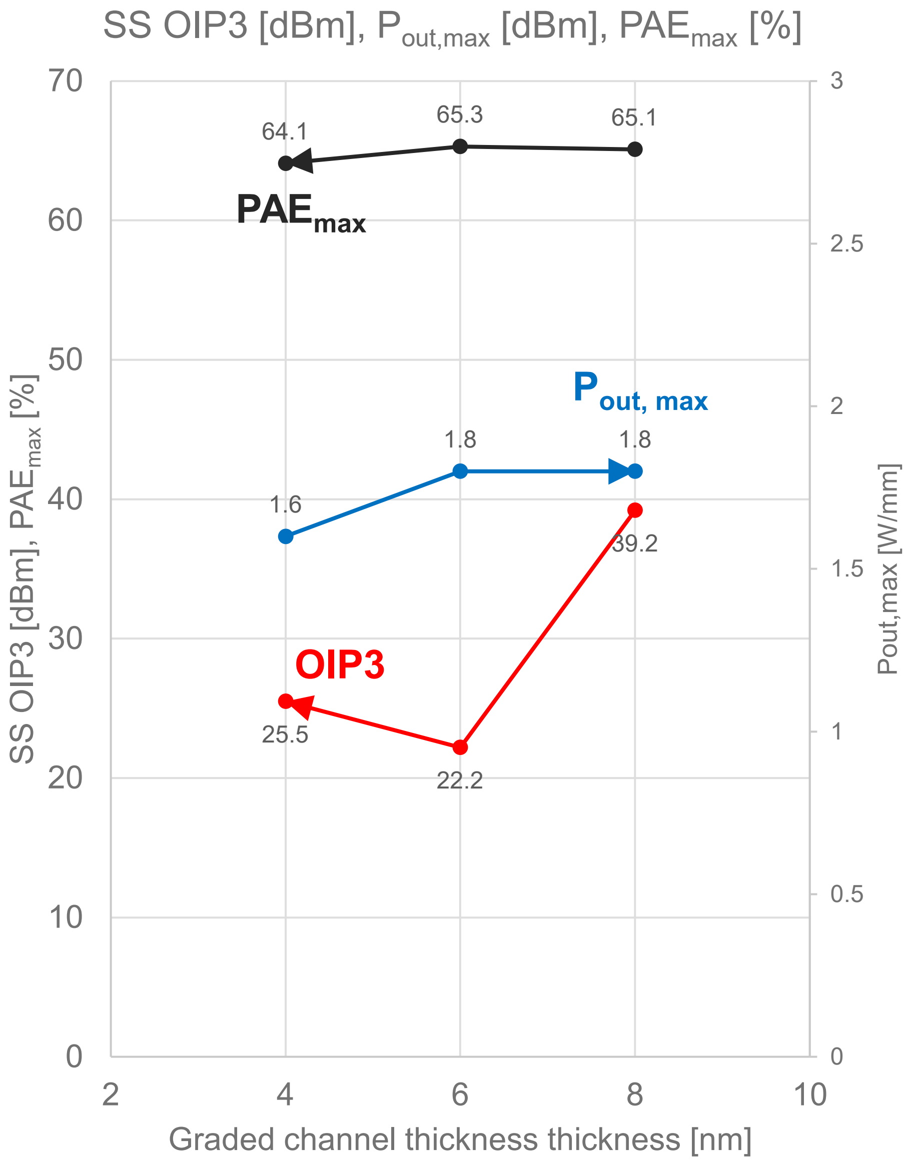
- P_{out} increases with a thicker channel
  - Max Pout=2.7 W/mm
- OIP3 increases with a thicker channel
  - OIP3 extracted from small-signal
  - Max OIP3=26.6 dBm
- PAE insensitive to Al-concentration
  - Max PAE=50.9%



Thickness of graded channel: Large-signal

- Frequency 30 GHz
- Gate periphery: 2x37.5 µm
- Class AB (15% of I_{max}) , V_{ds}=10 V
- Matched for maximum PAE

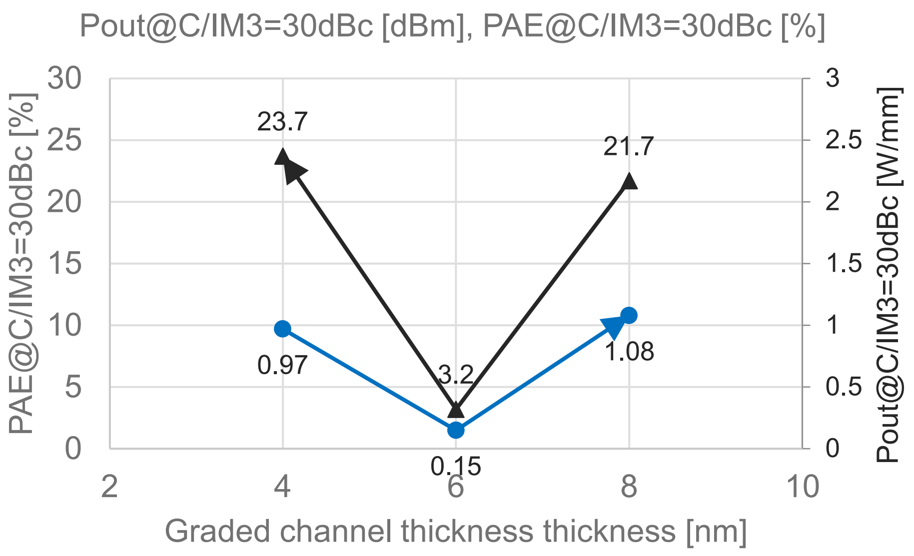
- P_{out} increases with a thicker channel
  - Max Pout=1.8 W/mm
- OIP3 increases with a thicker channel(?)
  - OIP3 extracted from small-signal
  - Max OIP3=39.2 dBm
- PAE increases a thicker channel
  - Max PAE=65.3%



Thickness of graded channel: Linearity

- Frequency 30 GHz
- Gate periphery: 2x37.5 µm
- Class A, V_{ds}=10 V
- Matched for maximum PAE

- No clear trend of P_{out} @ C/IM3=30dBc with channel thickness
  - Max Pout=0.94 W/mm
- No clear trend of PAE @ C/IM3=30dBc decreases with channel thickness
  - Max PAE=25.7%



‘Hero numbers’ for each channel thickness

- Maximum values of the large-signal parameters
  - not simultaneous, i. e. different classes (Class A or AB and optimized parameter (Pout or PAE)

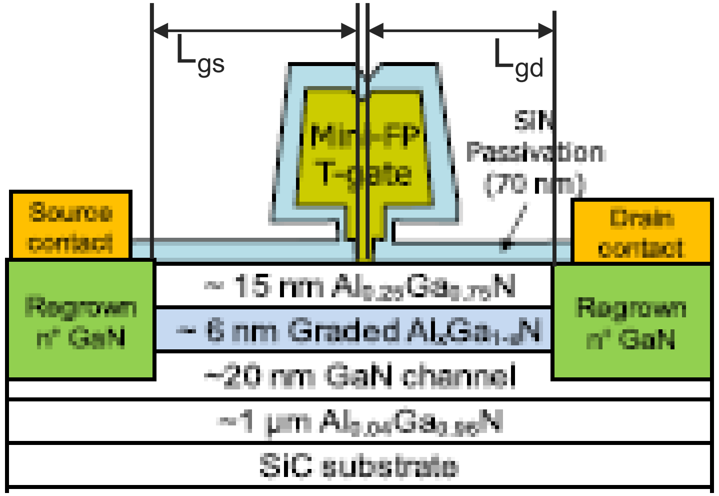
Channel thickness [nm]	$P_{out, max}$ [W/mm]	PAE_{max} [%]	OIP3 [dBm]	P_{out}@C/IM3=30dBc [W/mm]	PAE@C/IM3=30dBc [%]
4	2.4	64.1	25.5	18.6	23.7
6	2.7	65.3	26.0	13.4	15.4
8	2.7	65.1	26.6	19.1	21.7

Gate position on epistruture with graded channel

- Varying the position of the gate
  - Asymmetric: L_{gs}=0.3 µm, L_{gd}=0.66 µm
  - Symmetric: L_{gs}=0.3 µm, L_{gd}=0.66 µm

- Epitaxial structure identical

	Variation	
Cap	2 nm, GaN	
Barrier	8 nm, $Al_{0.25}Ga_{0.75}N$	
Graded channel	6 nm Graded $Al_xGa_{1-x}N$ (x=0 to 17%)	
Channel	20 nm, GaN	
Back-barrier	1000 nm, $Al_{0.04}Ga_{0.96}N$	
Substrate	SiC	
L_{gs} [µm]	**0.5**	**0.3**
L_{gd} [µm]	**0.5**	**0.66**



Gate position : small-signal

- Bias for maximum intrinsic f_T
- Parasitics added from EM-simulations

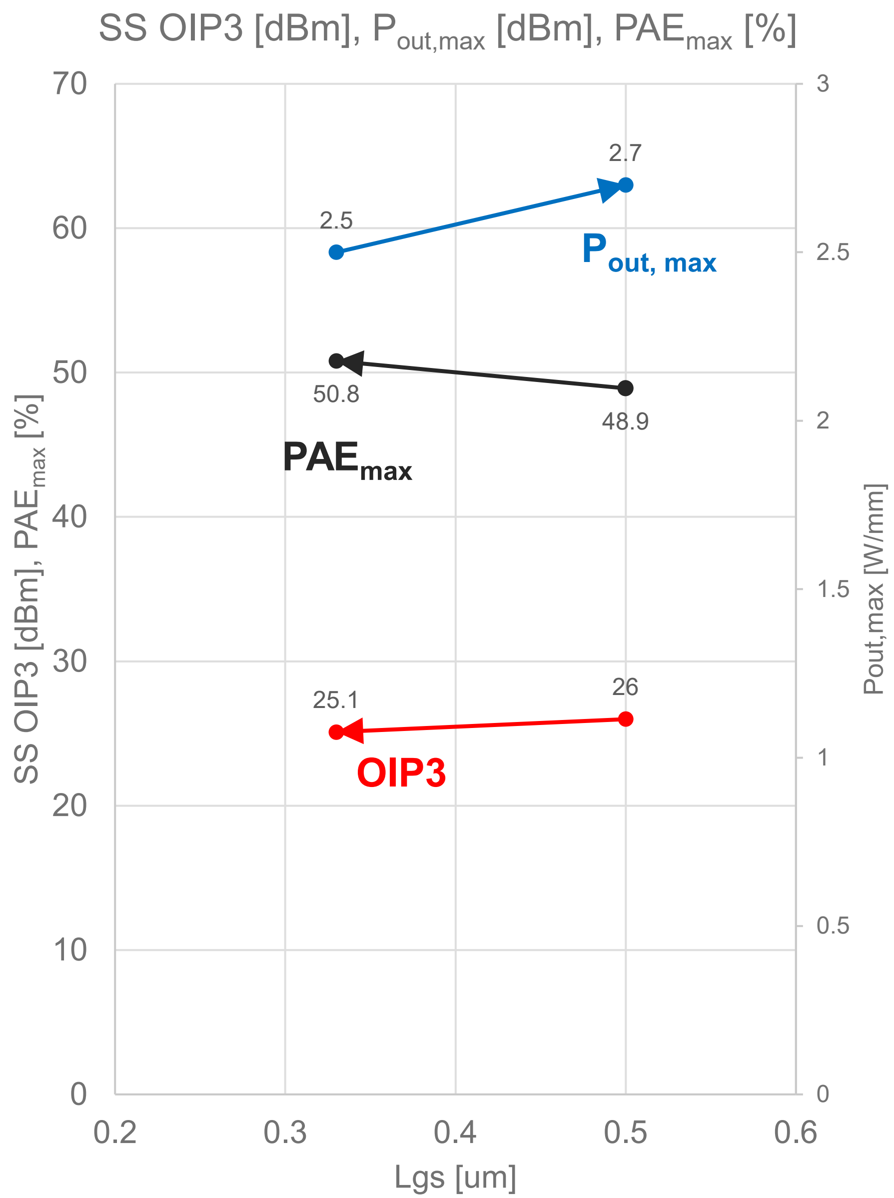
	$f_{T,int}$ [GHz]	f_T ($f_{T,TCAD}$) [GHz]	f_{max} ($f_{max,TCAD}$) [GHz]	V_{ds} [V]	V_{gs} [V]
Asymmetric	185	177 (-)	277 (-)	3	-1
Symmetric	199	171 (-)	358 (-)	4	-1.25

- f_T increase with a symmetric gate position
  - Better confinement in the GaN-channel
- f_{max} increases with a symmetric gate position

Gate position : Large-signal

- Frequency 30 GHz
- Gate periphery: 2x37.5 µm
- Class AB (15% of I_{max}), V_{ds}=10 V
- Matched for maximum P_{out}

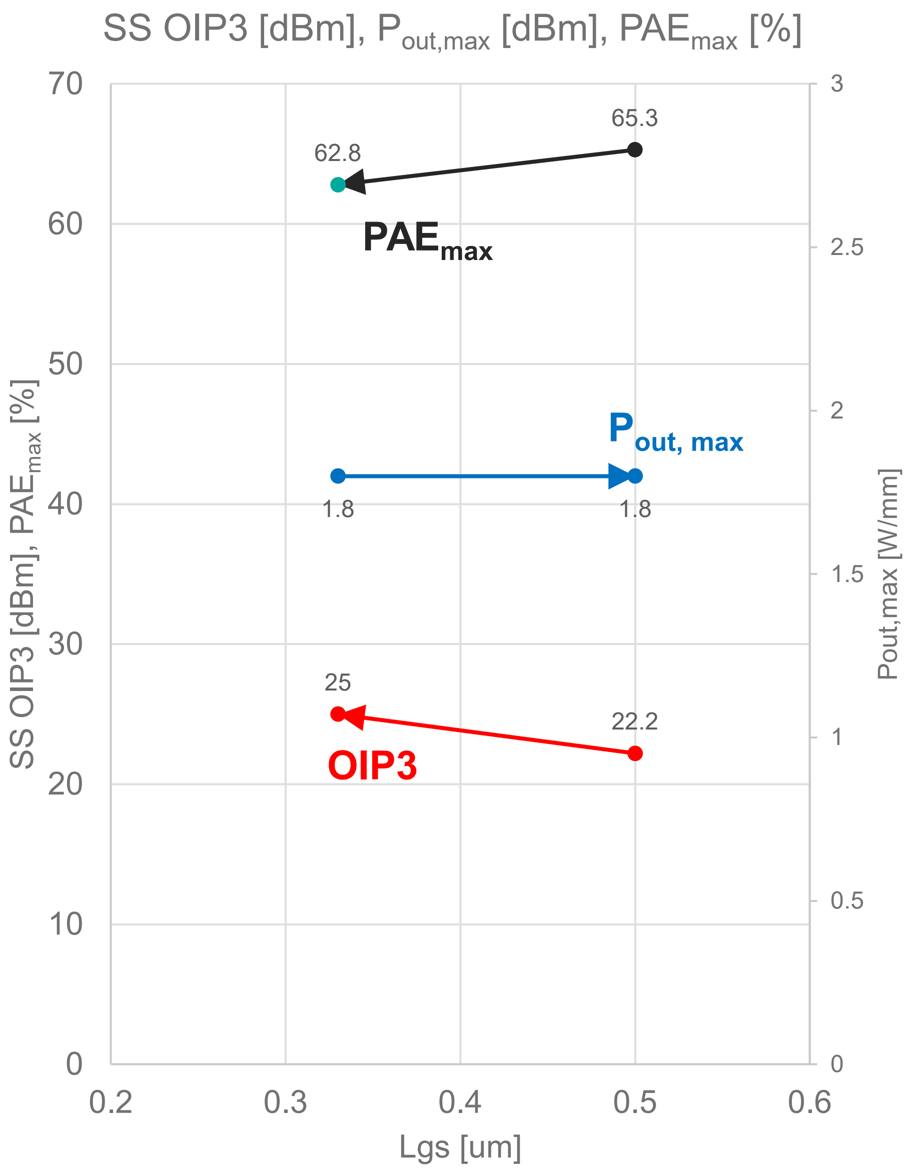
- P_{out} decreases with an asymmetric gate position
  - Max Pout=2.7 W/mm
- OIP3 decreases with an asymmetric gate position
  - OIP3 extracted from small-signal
  - Max OIP3=26.0 dBm
- PAE increases with an asymmetric gate position
  - Max PAE=50.8%



Gate position : Large-signal

- Frequency 30 GHz
- Gate periphery: 2x37.5 µm
- Class AB (15% of I_{max}) , V_{ds}=10 V
- Matched for maximum PAE

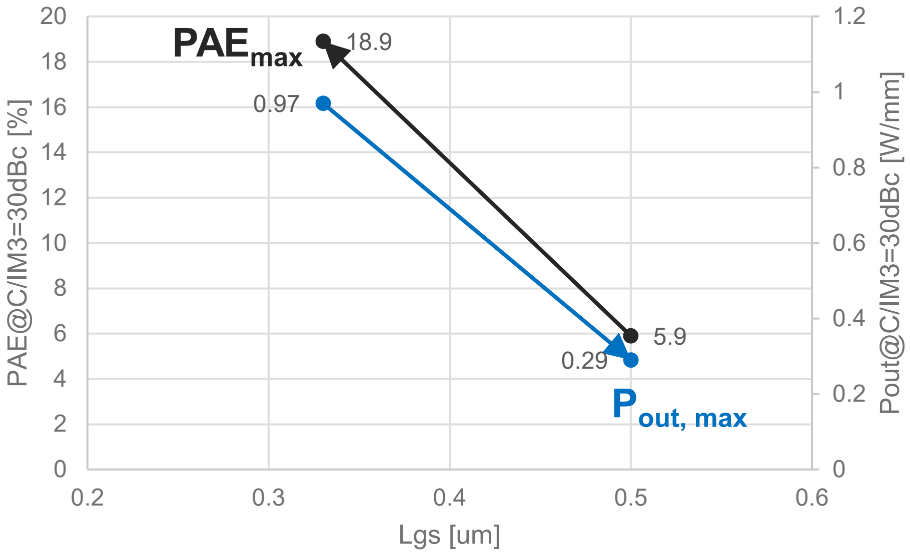
- P_{out} does not change with gate position
  - Max Pout=1.8 W/mm
- OIP3 increases with an asymmetric gate position
  - OIP3 extracted from small-signal
  - Max OIP3=25.0 dBm
- PAE decreases with an asymmetric gate position
  - Max PAE=65.3%



Gate position : Linearity

- Frequency 30 GHz
- Gate periphery: 2x37.5 μm
- Class A, V_{ds}=10 V
- Matched for maximum P_{out}

- P_{out} @ C/IM3=30dBc increases for an asymmetric gate position
  - Max Pout=0.97 W/mm
- PAE @ C/IM3=30dBc increases for an asymmetric gate position
  - Max PAE=18.9%



‘Hero numbers’ for each gate position

- Maximum values of the large-signal parameters
  - not simultaneous, i. e. different classes (Class A or AB and optimized parameter (P_{out} or PAE)

Channel thickness [nm]	$P_{out, max}$ [W/mm]	PAE_{max} [%]	OIP3 [dBm]	P_{out}@C/IM3=30dBc [W/mm]	PAE@C/IM3=30dBc [%]
Assymmetric	2.5	62.8	25.1	0.97	19.1
Symmetric	2.7	65.3	26.0	0.29	15.4

Conclusions and future work

- Parasitics extracted from EM-simulations
  - Combination of EM in ADS and HFSS
  - Lumped model able to describe parasitic circuit at least to 100 GHz
- Validation of a methodology to predict DC, s-parameters, and large-signal performance of GaN HEMT designs from DC and s-parameters from physical simulations
  - Verified on graded-channel HEMT with thick barrier
- Variations in epi-design to optimize PAE and linearity at 30 GHz
  - Barrier thickness
  - Grading profile
  - Thickness of graded channel
  - Gate position

	P_{out}	PAE	OIP3
Thicker barrier	↑	↑	↓
Higher Al-conc in channel profile	↑	↔	↑
Thicker channel	↑	↑	↑ ?
Asymmetric gate position	↓↔	↑↓	↑↓

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Barrier thickness

Table 4-5: Small-signal Transducer gain, maximum out power (Pout), peak power added efficiency (PAE), P_{out}@PAEmax, load and source impedance of a 2x37.5 HEMT for HEMTs with 8nm and 15 nm barrier thickness

	SS Gain [dB]	$P_{out,max}$ [dBm] / [W/mm]	PAE_{max} [%]	$P_{out}@PAE_{max}$ [dBm] / [W/mm]	Z_L (Ω)	Z_S (Ω)
Barrier thickness: 8 nm						
Class A (P_{out} opt.)	12.7	22.8 / 2.5	44.8	22.7 / 2.5	88+j110	26+j58
Class A (PAE opt.)	11.7	22.1 / 2.2	52.1	22.0 / 2.1	46+j120	38+j63
Class AB (P_{out} opt.)	11.7	23.0 /2.7	48.9	22.5 / 2.4	96+j110	24+j71
Class AB (PAE opt.)	15.3	21.3 / 1.8	65.3	21.1 /1.7	36+j124	22+j56
Barrier thickness: 15 nm						
Class A (P_{out} opt.)	13.9	24.0 / 3.3	49.6	23.9 /3.3	98+j90	28+j72
Class A (PAE opt.)	13.9	23.2 / 2.8	56.0	23.1 /2.7	54+j116	40+j70
Class AB (P_{out} opt.)	13.5	24.0 / 3.3	55.4	23.7 / 3.1	90+j86	26+j92
Class AB (PAE opt.)	17.7	22.3 / 2.3	66.9	22.0 / 2.1	38+j120	38+j54

Barrier thickness

Table 4-6: P_{out} and PAE@C/IM3=30dBc, small-signal OIP3, and OIP3/P_{dc}@PAEmax of GaN HEMTs with graded channel and barrier thicknesses of 8nm and 15 nm.

	P_{out}@C/IM3=30dBc [dBm] / [W/mm]	PAE@C/IM3=30dBc [%]	SS OIP3 [dBm]	OIP3/P_{dc}@PAE_{max} [dB]
Barrier thickness: 8 nm				
Class A (P_{out} opt.)	13.4 / 0.29	5.9	14.0	-0.21
Class A (PAE opt.)	10.6 / 0.15	3.2	11.9	0.36
Class AB (P_{out} opt.)	10.6 / 0.15	9.6	26.0	3.4
Class AB (PAE opt.)	12.2 / 0.22	15.4	22.2	-0.2
Barrier thickness: 15 nm				
Class A (P_{out} opt.)	19.6 / 1.2	19.4	6.5	-1.7
Class A (PAE opt.)	18.6 / 0.97	16.2	4.0	-2.1
Class AB (P_{out} opt.))	12.3 / 0.23	10.7	15.3	1.5
Class AB (PAE opt.))	13.4 /0.29	15.3	6.0	-0.063

Grading profile: Power FoM

Table 4-10: Small-signal transducer gain, maximum out power (P_{out}), peak power added efficiency (PAE), P_{out}@PAEmax, load and source impedance of a 2x37.5 HEMT for HEMTs with different Al-concentration in the grading profile

	SS Gain [dB]	$P_{out,max}$ [dBm] / [W/mm]	PAE_{max} [%]	$P_{out}@PAE_{max}$ [dBm] / [W/mm]	Z_L (Ω)	Z_S (Ω)
Graded 0 to 13%						
Class A (P_{out} opt.)	11.1	21.6 / 1.9	41.3	21.3 / 1.8	96+j140	42+j40
Class A (PAE opt.)	11.1	21.3 / 1.8	46.0	21.1 / 1.7	65+j140	48+j38
Class AB (P_{out} opt.)	12.4	21.8 / 2.0	49.4	21.3 / 1.8	94+j131	29+j67
Class AB (PAE opt.)	11.6	20.3 / 1.4	61.5	20.0 / 1.3	39+j146	33+j67
Graded 0 to 15%						
Class A (P_{out} opt.)	12.2	22.1 / 2.2	42.0	21.8 / 2.0	102+j128	27+j41
Class A (PAE opt.)	12.8	21.8 / 2.0	47.1	21.5 / 1.9	64+j136	17+j31
Class AB (P_{out} opt.)	12.4	22.3 / 2.3	49.7	21.8 / 2.0	99+j119	31+j73
Class AB (PAE opt.)	11,8	20.6 / 1.5	62.8	20.3 / 1.4	39+j143	24+j71
Graded 0 to 17% (ref.)						
Class A (P_{out} opt.)	12.7	22.8 / 2.5	44.8	22.7 / 2.5	88+j110	26+j58
Class A (PAE opt.)	11.7	22.1 / 2.2	52.1	22.0 / 2.1	46+j120	38+j63
Class AB (P_{out} opt.)	11.7	23.0 /2.7	48.9	22.5 / 2.4	96+j110	24+j71
Class AB (PAE opt.)	15.3	21.3 / 1.8	65.3	21.1 /1.7	36+j124	22+j56
Graded 3 to 17%						
Class A (P_{out} opt.)	12.1	22.2 / 2.2	42.4	21.8 / 2.0	102+j128	32+j52
Class A (PAE opt.)	12.4	21.6 /1.9	48.0	21.4 /1.8	58+j136	20+j30
Class AB (P_{out} opt.)	12.3	22.3 / 2.3	49.7	21.9 / 2.1	99+j119	31+j73
Class AB (PAE opt.)	11.8	20.6 /1.5	62.9	20.4 / 1.5	39+j143	24+j71

Grading profile: Linearity FoM

Table 4-11: P_{out} and PAE@C/IM3=30dBc, small-signal OIP3, and OIP3/P_{dc}@PAEmax of GaN HEMTs with graded channel different Al-concentration in the grading profile.

	P_{out}@C/IM3=30dBc [dBm] / [W/mm]	PAE@C/IM3=30dBc [%]	SS OIP3 [dBm]	OIP3/P_{dc}@PAE_{max} [dB]
Graded 0 to 13%				
Class A (P_{out} opt.)	17.7 / 0.79	20.3	13.4	-0.41
Class A (PAE opt.)	18.5 / 0.94	25.7	12.2	-0.95
Class AB (P_{out} opt.)	8.3 / 0.09	7.2	23.3	2.1
Class AB (PAE opt.)	12.6 / 0.24	19.1	24.4	0.59
Graded 0 to 15%				
Class A (P_{out} opt.)	17.8 / 0.80	18.8	13.3	-0.70
Class A (PAE opt.)	18.4 / 0.92	22.5	10.6	-1.2
Class AB (P_{out} opt.)	8.4 / 0.09	6.6	25.4	1.4
Class AB (PAE opt.)	12.4 / 0.23	17.2	25.9	0.61
Graded 0 to 17% (ref.)				
Class A (P_{out} opt.)	13.4 / 0.29	5.9	14.0	-0.21
Class A (PAE opt.)	10.6 / 0.15	3.2	11.9	0.36
Class AB (P_{out} opt.)	10.6 / 0.15	9.6	26.0	3.4
Class AB (PAE opt.)	12.2 / 0.22	15.4	22.2	-0.2
Graded 3 to 17%				
Class A (P_{out} opt.)	17.8 / 0.80	18.6	14.0	-0.63
Class A (PAE opt.)	18.2 / 0.88	21.5	10.6	-1.0
Class AB (P_{out} opt.)	9.2 / 0.11	7.8	25.1	1.7
Class AB (PAE opt.)	12.5 / 0.24	17.2	25.6	-0.26

Thickness of graded channel

Table 4-15: Small-signal transducer gain, maximum out power (P_{out}), peak power added efficiency (PAE), P_{out}@PAEmax, load and source impedance of a 2x37.5 HEMT for HEMTs with graded channel thickness

	SS Gain [dB]	$P_{out,max}$ [dBm] / [W/mm]	PAE_{max} [%]	P_{out}@PAE_{max} [dBm] / [W/mm]	Z_L (Ω)	Z_S (Ω)
Graded 4nm						
Class A (P_{out} opt.)	12.3	22.4 / 2.3	43.8	22.0 / 2.1	102+j124	34+j52
Class A (PAE opt.)	11.9	21.7 / 2.0	50.0	21.5 / 1.9	56+j137	44+j42
Class AB (P_{out} opt.)	12.6	22.5 / 2.4	50.9	22.0 / 2.1	99+j117	28+j69
Class AB (PAE opt.)	14.0	20.9 / 1.6	64.1	20.7 / 1.6	40+j138	24+j58
Graded 6nm (ref.)						
Class A (P_{out} opt.)	12.7	22.8 / 2.5	44.8	22.7 / 2.5	88+j110	26+j58
Class A (PAE opt.)	11.7	22.1 / 2.2	52.1	22.0 / 2.1	46+j120	38+j63
Class AB (P_{out} opt.)	11.7	23.0 /2.7	48.9	22.5 / 2.4	96+j110	24+j71
Class AB (PAE opt.)	15.3	21.3 / 1.8	65.3	21.1 /1.7	36+j124	22+j56
Graded 8nm						
Class A (P_{out} opt.)	12.3	23.0 / 2.7	43.4	22.7 / 2.5	100+j108	28+j58
Class A (PAE opt.)	11.5	22.5 / 2.4	48.	22.3 / 2.3	62+j126	40+j61
Class AB (P_{out} opt.)	12.5	23.1 / 2.7	50.7	22.7 / 2.5	102+j102	26+j74
Class AB (PAE opt.)	15.6	21.3 / 1.8	65.1	21.0 / 1.7	40+j132	22+j52

Thickness of graded channel

Table 4-16: P_{out} and PAE@C/IM3=30dBc, small-signal OIP3, and OIP3/P_{dc}@PAEmax of GaN HEMTs with different graded channel thicknesses.

	P_{out}@C/IM3=30dBc [dBm] / [W/mm]	PAE@C/IM3=30dBc [%]	SS OIP3 [dBm]	OIP3/P_{dc}@PAE_{max} [dB]
Graded 4nm				
Class A (P_{out} opt.)	18.0 / 0.84	19.5	13.0	-0.87
Class A (PAE opt.)	18.6 / 0.97	23.7	10.3	-1.2
Class AB (P_{out} opt.)	9.6 / 0.12	8.4	25.5	1.5
Class AB (PAE opt.)	11.4 / 0.18	13.7	25.5	0.30
Graded 6nm (ref.)				
Class A (P_{out} opt.)	13.4 / 0.29	5.9	14.0	-0.21
Class A (PAE opt.)	10.6 / 0.15	3.2	11.9	0.36
Class AB (P_{out} opt.)	10.6 / 0.15	9.6	26.0	3.4
Class AB (PAE opt.)	12.2 / 0.22	15.4	22.2	-0.2
Graded 8nm				
Class A (P_{out} opt.)	19.0 / 1.06	20.3	14.9	-1.0
Class A (PAE opt.)	19.1 / 1.08	21.7	13.1	-0.98
Class AB (P_{out} opt.)	10.3 / 0.14	8.6	26.6	2.7
Class AB (PAE opt.)	11.4 / 0.18	12.3	39.2	0.17

Gate position

Table 4-20: Small-signal Transducer gain, maximum out power (P_{out}), peak power added efficiency (PAE), Pout@PAEmax, load and source impedance of a 2x37.5 HEMT for different gate positions

	SS Gain [dB]	$P_{out,max}$ [dBm] / [W/mm]	PAE_{max} [%]	$P_{out}@PAE_{max}$ [dBm] / [W/mm]	Z_L (Ω)	Z_S (Ω)
Asymmetric						
Class A (P_{out} opt.)	12.9	22.7 / 2.5	43.7	22.4 / 2.3	88+j110	24+j58
Class A (PAE opt.)	10.8	22.0 / 2.1	46.7	21.9 / 2.1	52+j128	38+j63
Class AB (P_{out} opt.)	12.2	22.8 /2.5	50.8	22.4 / 2.3	94+j110	24+j73
Class AB (PAE opt.)	15.3	21.2 / 1.8	62.8	21.0 /1.7	38+j130	26+j54
Centred (ref.)						
Class A (P_{out} opt.)	12.7	22.8 / 2.5	44.8	22.7 / 2.5	88+j110	26+j58
Class A (PAE opt.)	11.7	22.1 / 2.2	52.1	22.0 / 2.1	46+j120	38+j63
Class AB (P_{out} opt.)	13.9	23.0 /2.7	48.9	22.5 / 2.4	96+j110	24+j71
Class AB (PAE opt.)	15.3	21.3 / 1.8	65.3	21.1 /1.7	36+j124	22+j56

Gate position

	P_{out}@C/IM3=30dBc [dBm] / [W/mm]	PAE@C/IM3=30dBc [%]	SS OIP3 [dBm]	OIP3/P_{dc}@PAE_{max} [dB]
Asymmetric				
Class A (P_{out} opt.)	18.6 / 0.97	18.9	16.8	-1.7
Class A (PAE opt.)	18.4 / 0.92	19.1	14.8	-1.4
Class AB (P_{out} opt.)	10.2 / 0.14	8.3	25.1	1.1
Class AB (PAE opt.)	11.6 / 0.19	12.5	25.0	-0.13
Centred (ref.)				
Class A (P_{out} opt.)	13.4 / 0.29	5.9	14.0	-0.21
Class A (PAE opt.)	10.6 / 0.15	3.2	11.9	0.36
Class AB (P_{out} opt.)	10.6 / 0.15	9.6	26.0	3.4
Class AB (PAE opt.)	12.2 / 0.22	15.4	22.2	-0.2

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