Cornell University
School of Electrical and Computer Engineering

GaN-on-Diamond 0057bb, 0067a, 0095 & 0096ac GaN-on-Si 0096af

Jonathan Felbinger

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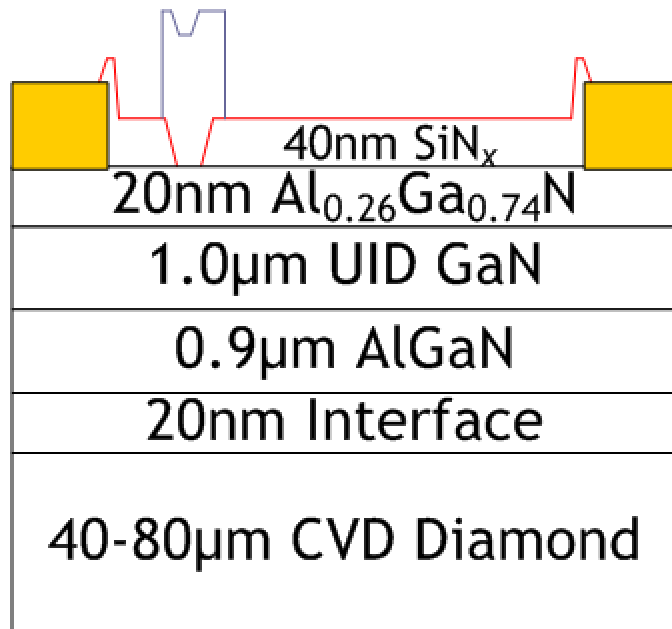
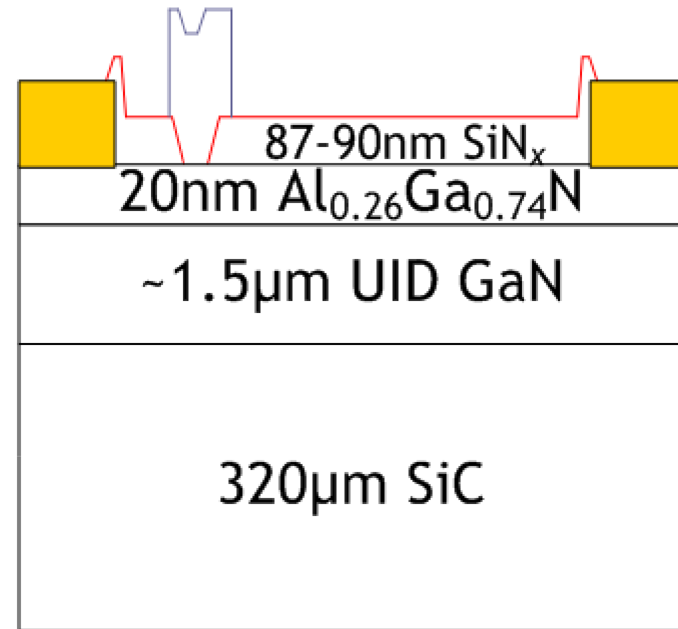
AN EXTREME MATERIALS COMPANY

HEMT Structure





Reference epi design atop SiC

Ti/Al/Mo/Au Ohmic Contacts annealed at 800°C

Ni/Au Field-Plated (FP) Gate with 70° SiN_x etch angle

375°C PECVD SiN_x

HEMT Dimensions 0057bb/0067a

360 U-shaped (C-shaped) HEMTs
with the following variations in dimension:

total periphery ($2\times W_{mesa}$) $W_{G,total}$ = 100, 150, 175, or 200 μm

Γ gate footprint L_G = 100, 150, or 250 nm
+50% field plate (FP) extension toward the drain
and compensation for the 70° SiN_x etch angle

source-gate spacing L_{SG} = 700 nm

gate-drain spacing L_{GD} = 1.5, 2.0, 2.5, or 3.0 μm

gate-center-to-gate-center pitch $L_{G\text{-}G}$ = 12.5, 25, or 50 μm

DUT Naming e.g. 1_200_.15_2.5_50

Row

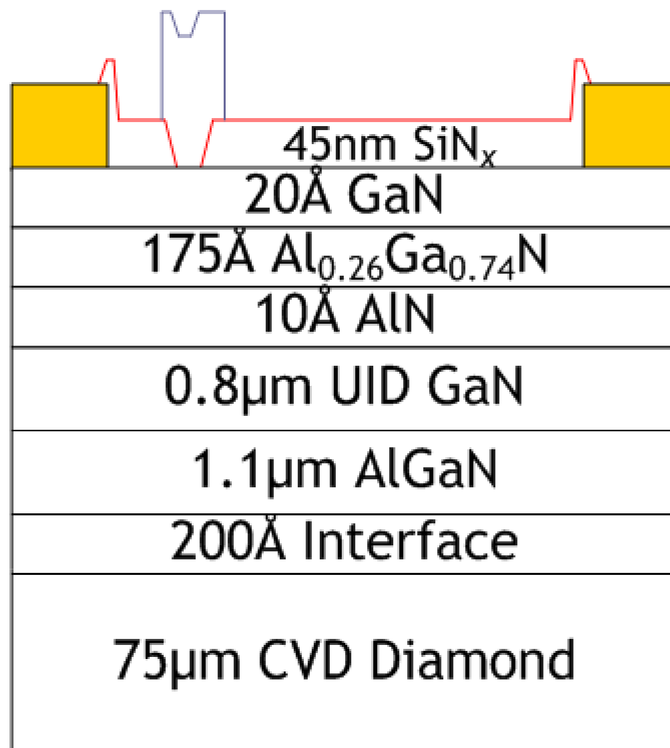
$W_{G,total}$ (μm)

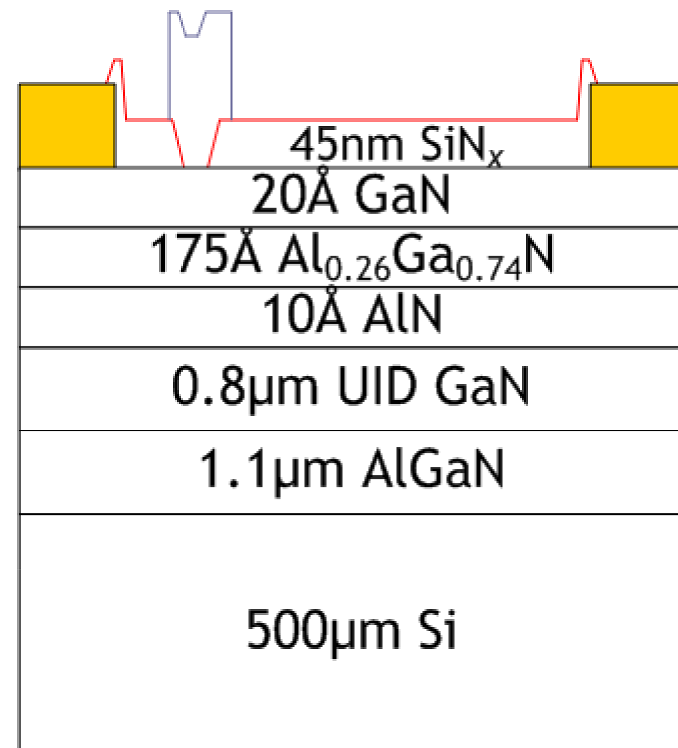
L_G (nm)

L_{GD} (μm)

Pitch (μm)

Revised HEMT Structure





Wafers 0095 & 0096 include an AlN interbarrier

Ta/Ti/Al/Mo/Au Ohmic Contacts annealed at 800°C

Ni/Au FP Gate with 70° SiN_x etch angle

375°C PECVD SiN_x

HEMT Dimensions 0095/0096

264 U-shaped HEMTs
with the following variations in dimension:

total periphery (2×W_{mesa}) $W_{G,total}$ = 100, 250, or 300 μm

Γ gate footprint L_G = 60, 80, 100, or 150 nm
+50% field plate (FP) extension toward the drain
and compensation for the 70° SiN_x etch angle

source-gate spacing L_{SG} = 300, 500, or 700 nm

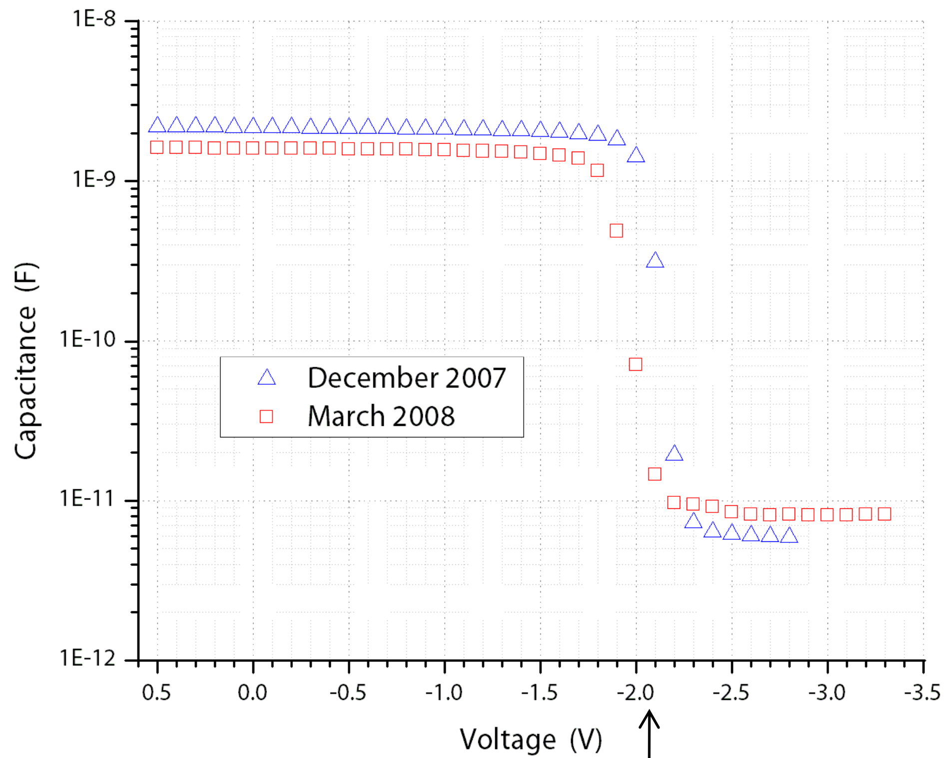
gate-drain spacing L_{GD} = 1.5, 2.0, 2.5, or 3.5 μm

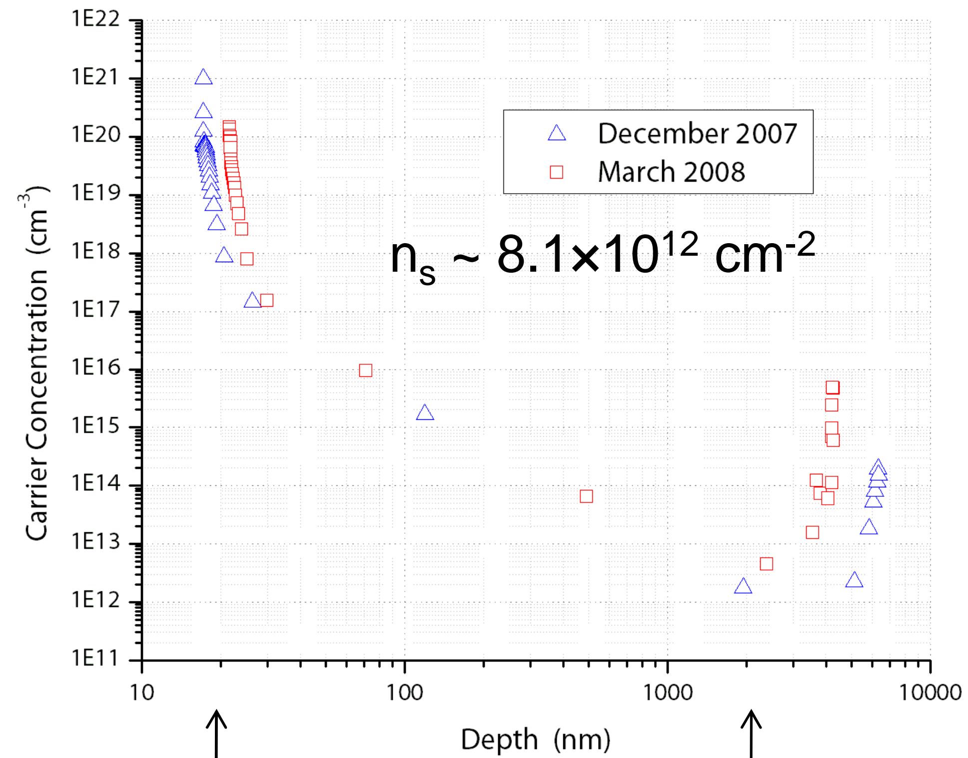
gate-center-to-gate-center pitch L_{G-G} = 12.5, 25, or 50 μm

DUT Naming e.g. 100_.3_.06_3.5_50

W_G (μm)
L_{SG} (μm)
L_G (nm)
L_{GD} (μm)
Pitch (μm)

0057bb C(V) Measurement





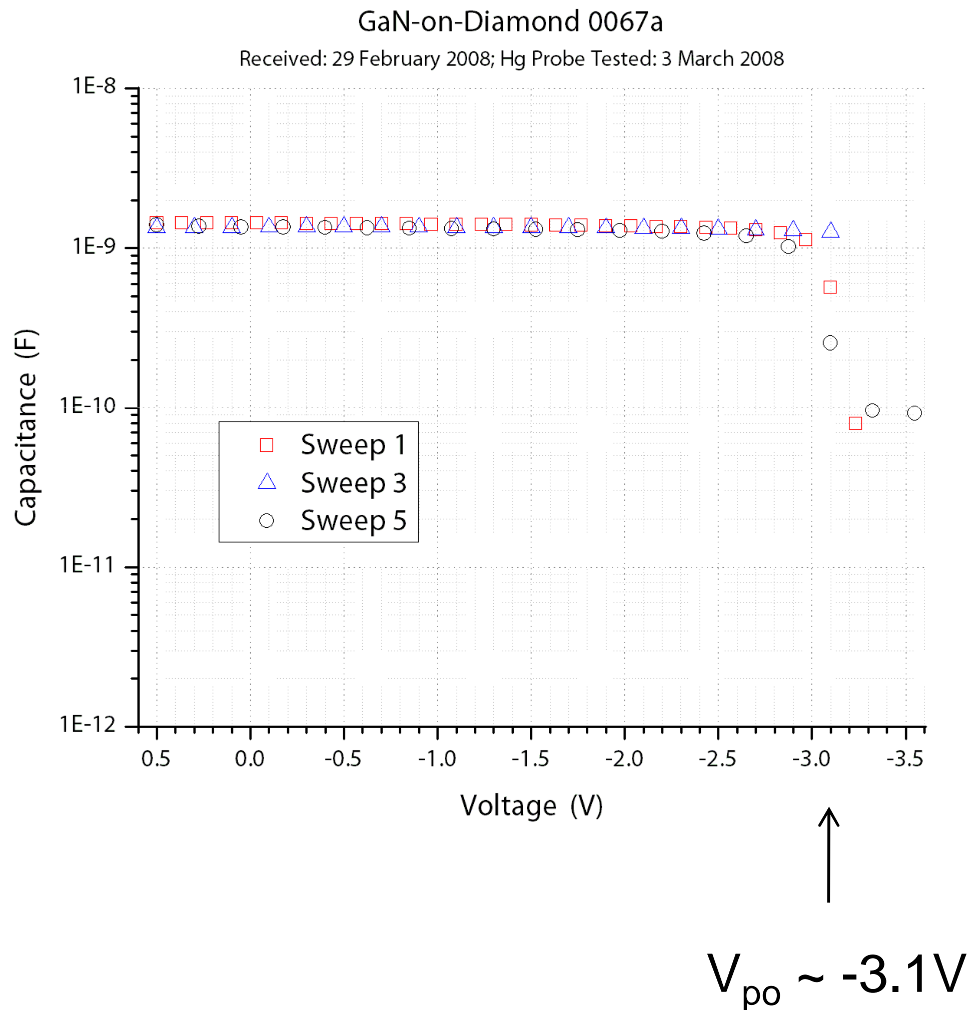
$n_s \sim 8.1\times10^{12}\ cm^{-2}$

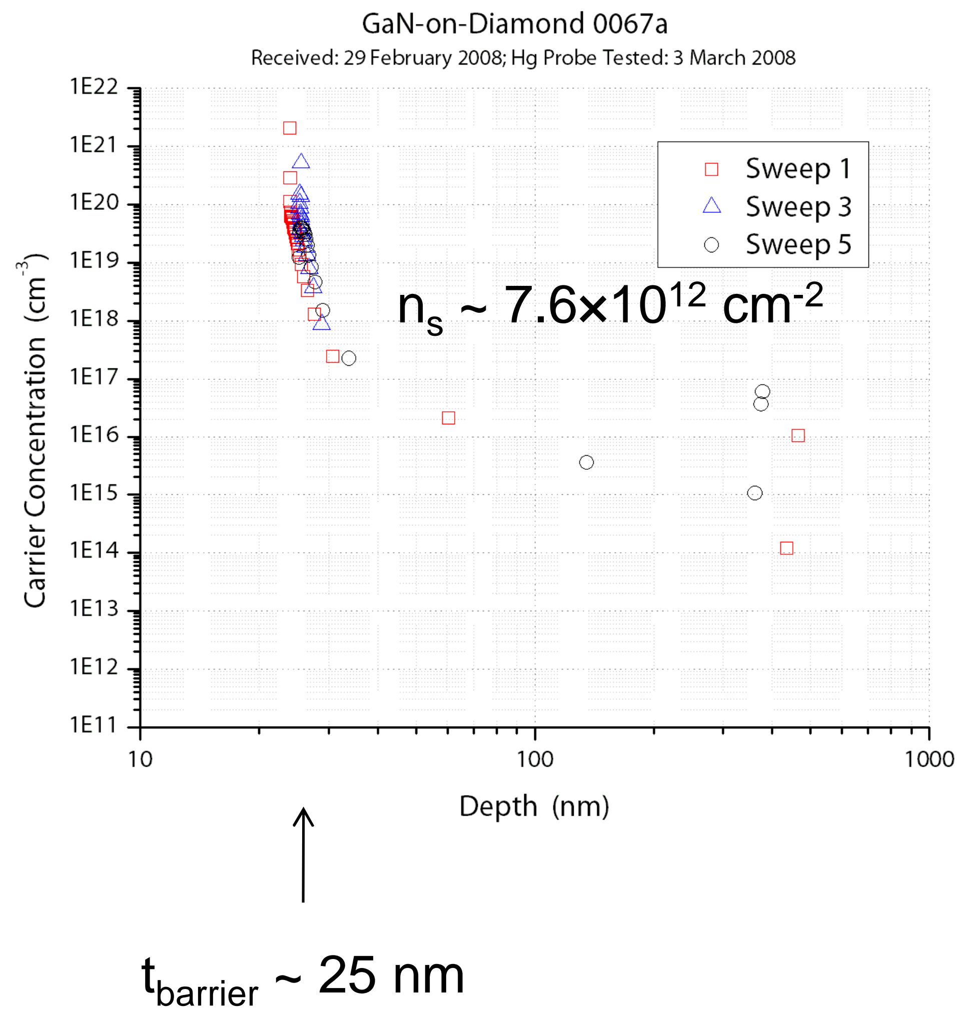
$V_{po} \sim -2.1V$

$t_{barrier} \sim 20\ nm$

$t_{buffer} \sim 2\ \mu m$

0067a C(V) Measurement





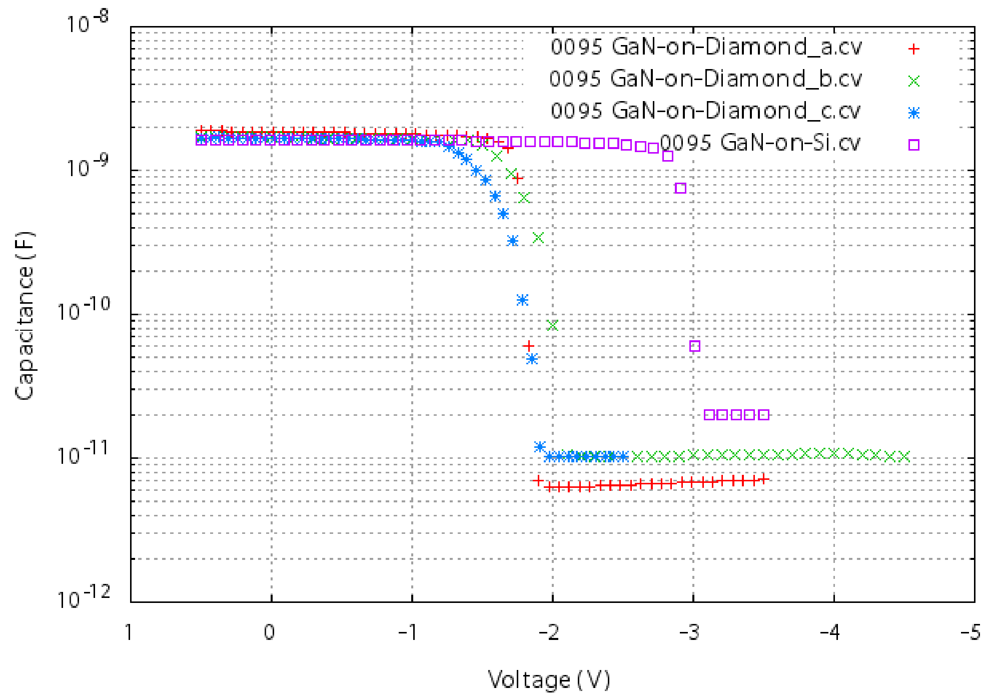
$n_s \sim 7.6\times10^{12}\ cm^{-2}$

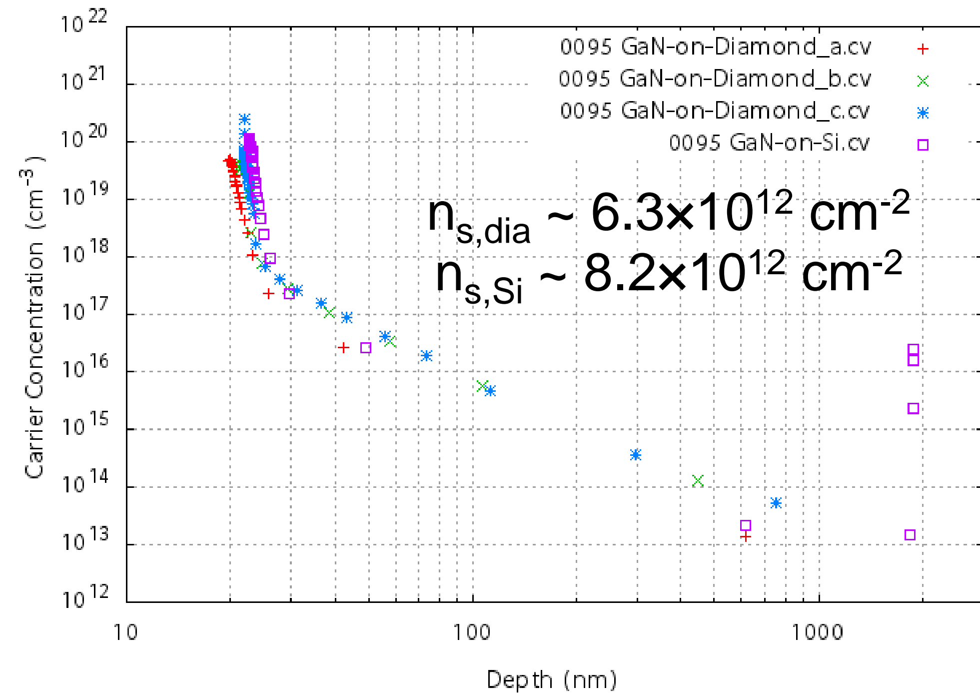
$V_{po} \sim -3.1V$

$t_{barrier} \sim 25$ nm

Obs. high buffer charge density

0095 C(V) Measurement

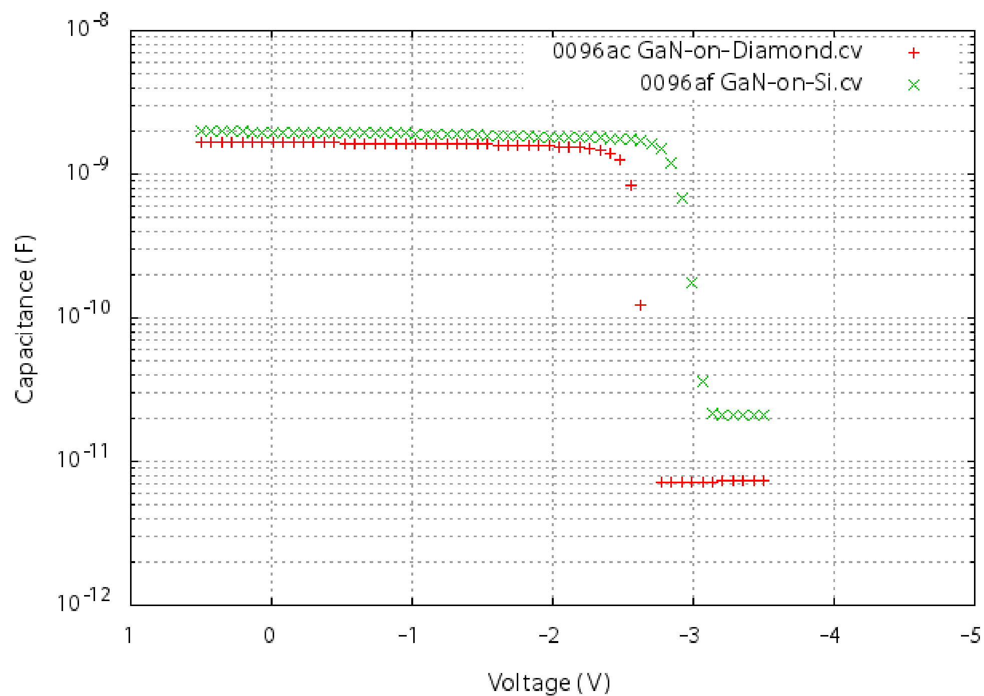


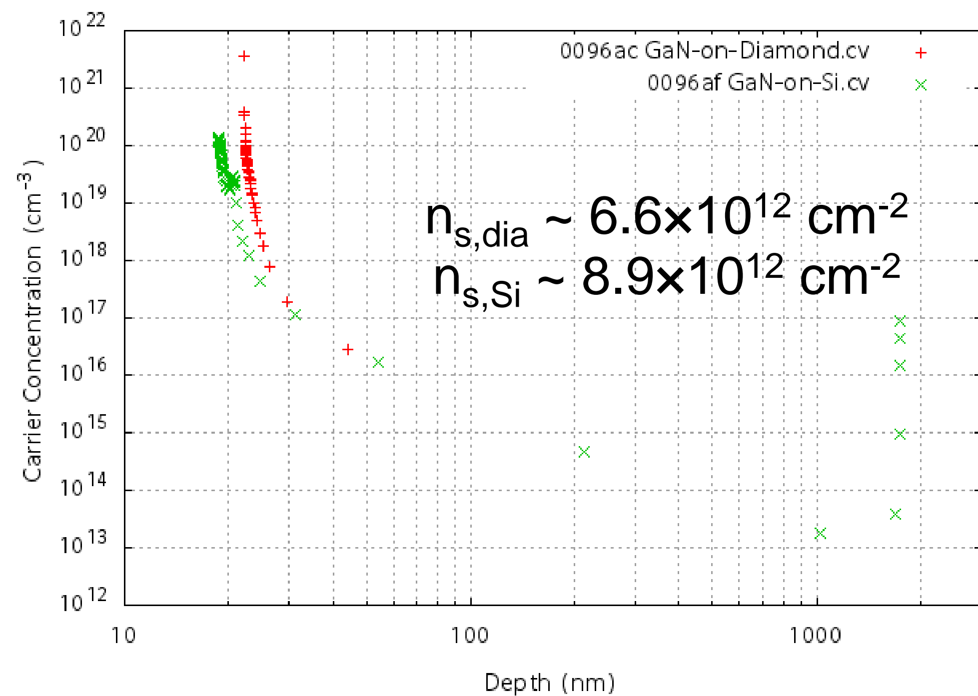


V_{po} ~ -1.8V

$t_{barrier}$ ~ 22 nm

0096 C(V) Measurement





V_{po} ~ -2.8V

$t_{barrier}$ ~ 22 nm

TLM Measurements

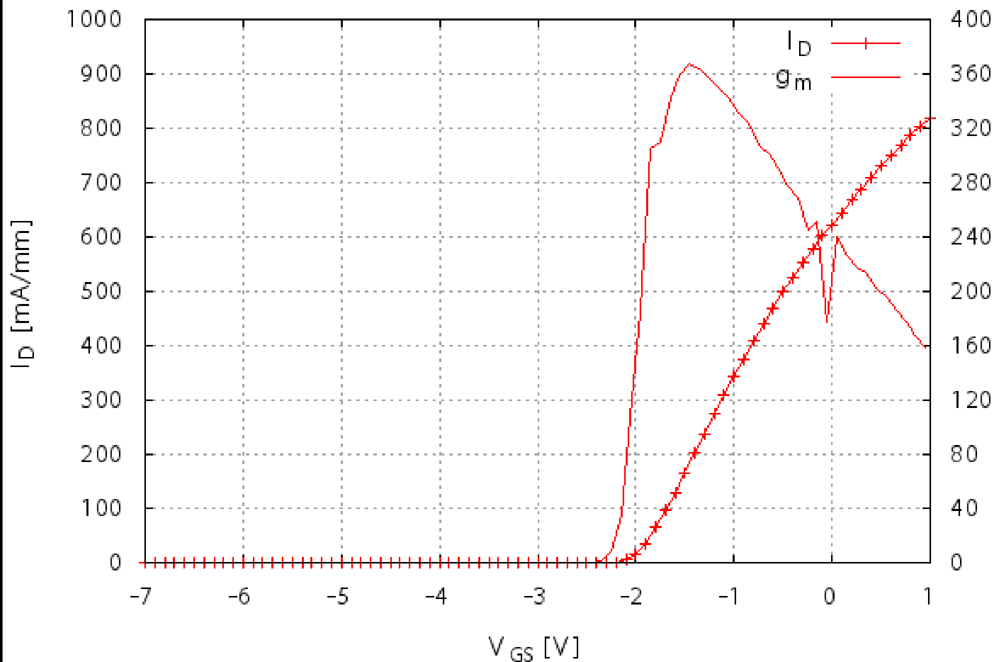
	0057bb (dia)	0067a (dia)	C540-4 (SiC)
R_c (Ω-mm)	0.47 ± 0.07	0.56 ± 0.03	0.19 ± 0.04
R_{sh} (Ω/□)	440.5 ± 13.7	476.7 ± 6.2	423.7 ± 8.6
R_{sc} ($\times 10^{-6}$ Ω-cm^2)	5.1 ± 1.5	6.7 ± 0.9	0.9 ± 0.4
L_t (µm)	1.06 ± 0.18	1.18 ± 0.08	0.46 ± 0.11

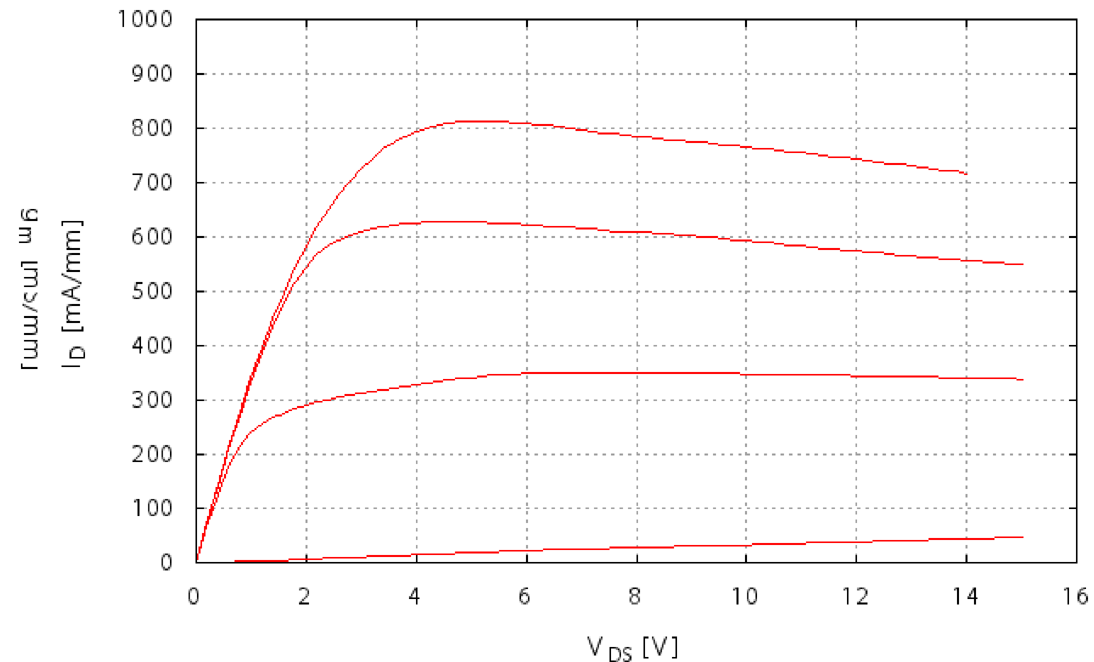
4-point-probe measurements completed at AFRL

6-8 sites measured per wafer

Wafers 0057bb and 0067a processed in parallel
(RTA calibration found to have drifted 20%
shortly after process completion)

0057bb

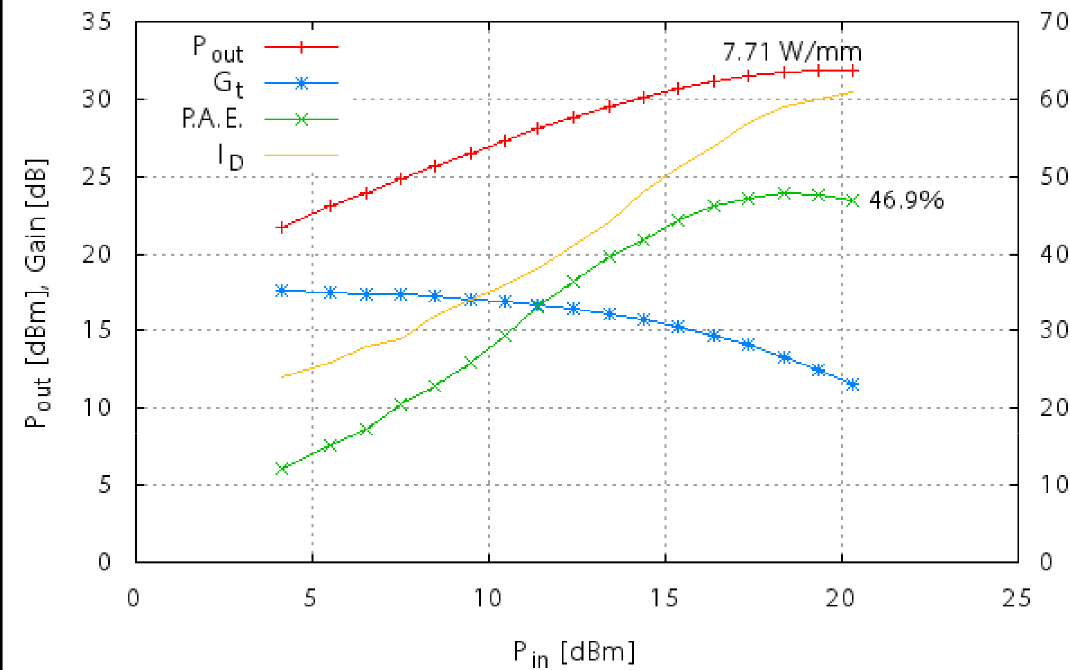


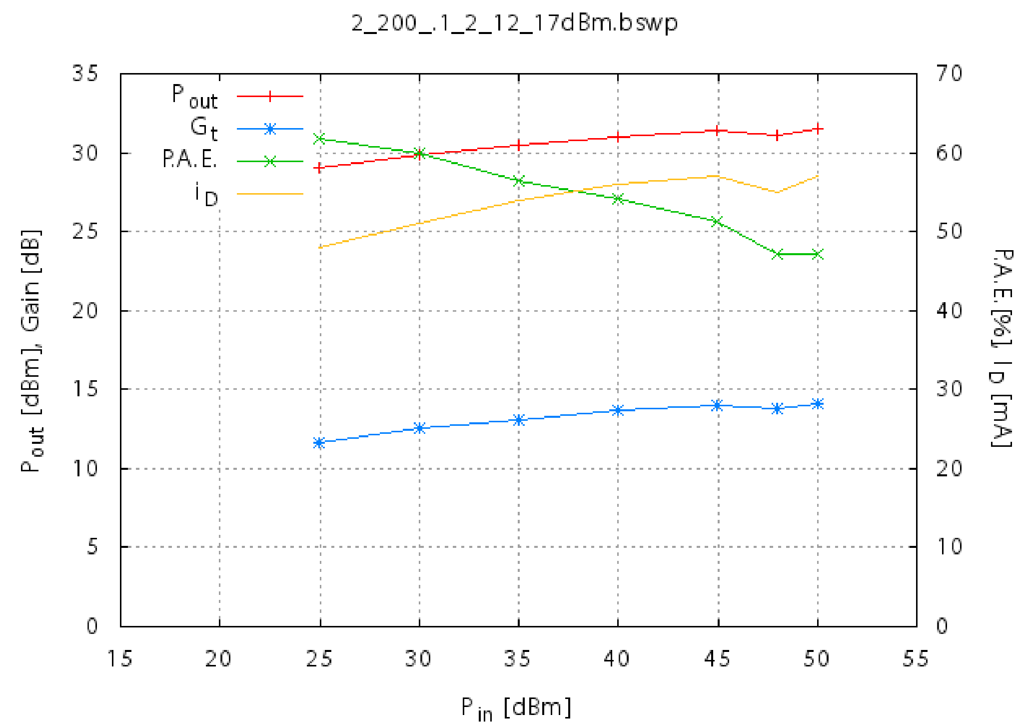


V_{po} = -2.1 V $I_{D,po}$ = 11 μA
I_{Dmax} = 813.0 mA/mm
I_{D0} = 628.3 mA/mm
g_m = 364.1 mS/mm
f_T = 58.7 GHz
15-20% DC-RF dispersion

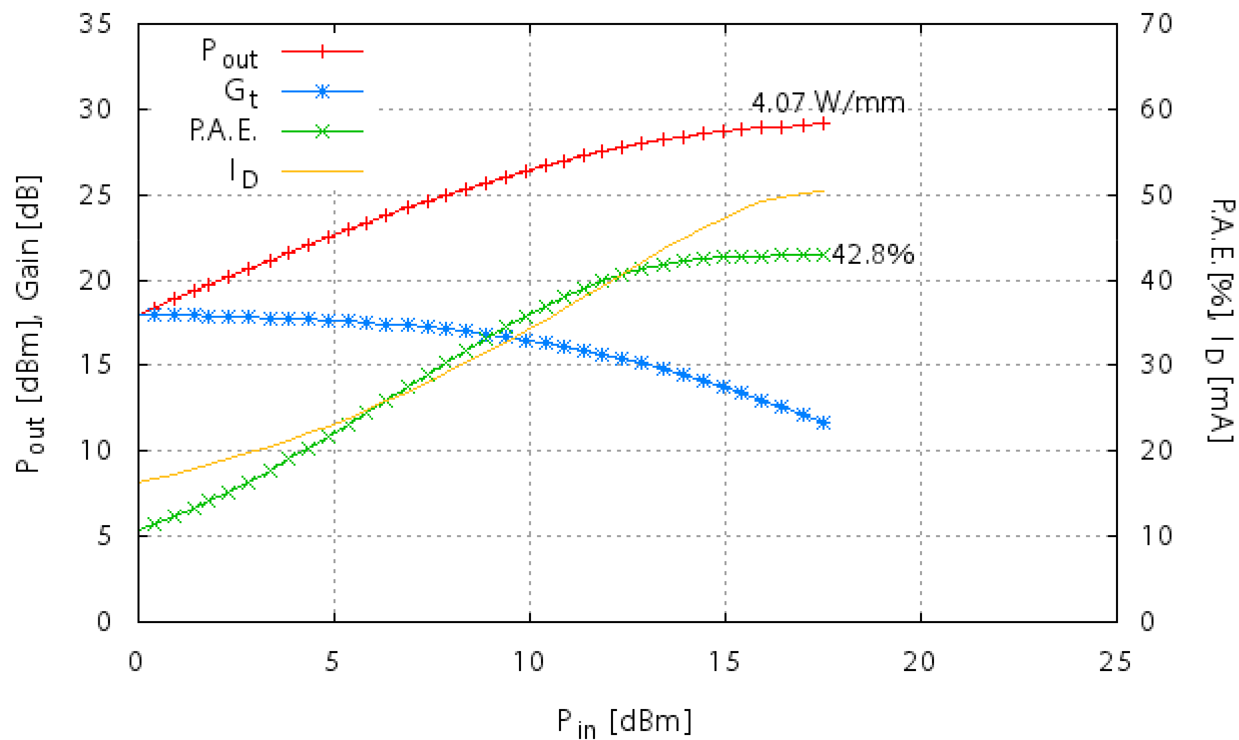
Consider a 2×100 μm HEMT
Lg = 100nm, $f_{T,avg}$ = 57 GHz
(with std. dev. of 2 GHz)
Lg = 150nm, $f_{T,avg}$ = 48 GHz
$V_{po,\ avg}$ = -2.0 Vgs
$I_{Dmax,avg}$ = 791 mA/mm
$I_{D0,avg}$ = 597 mA/mm

10 GHz PIPO @ AFRL

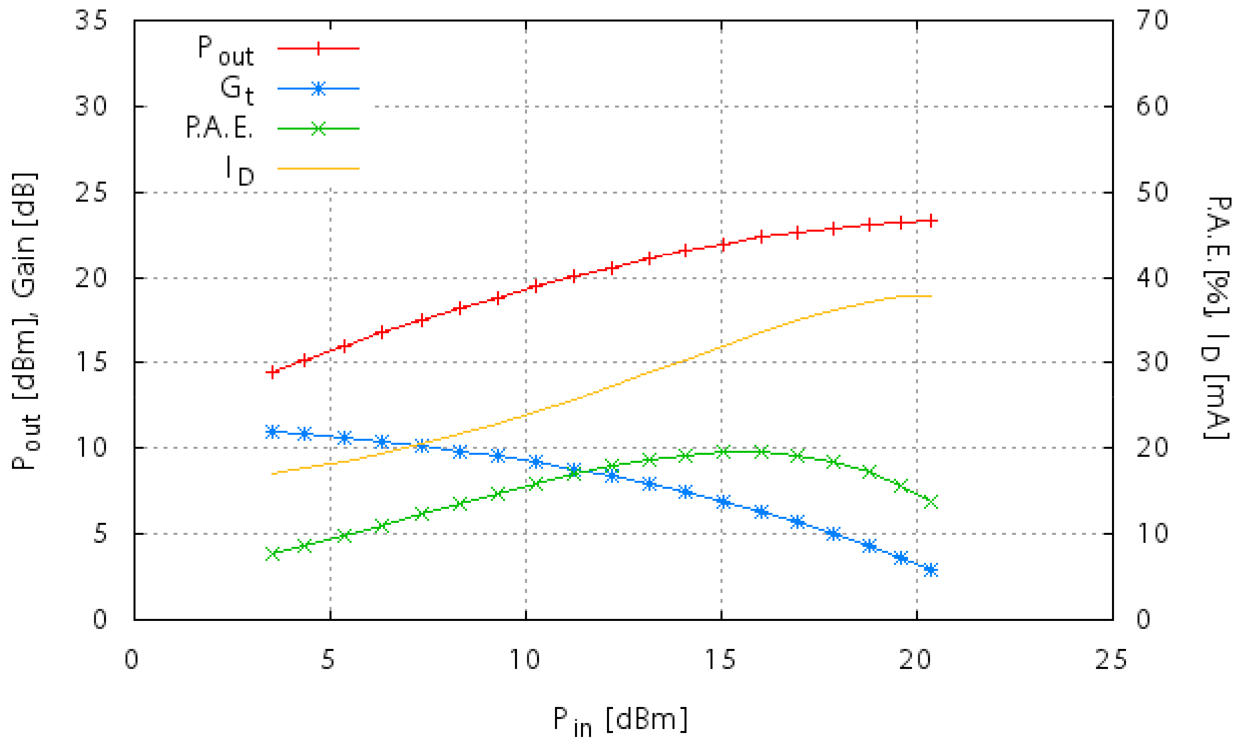




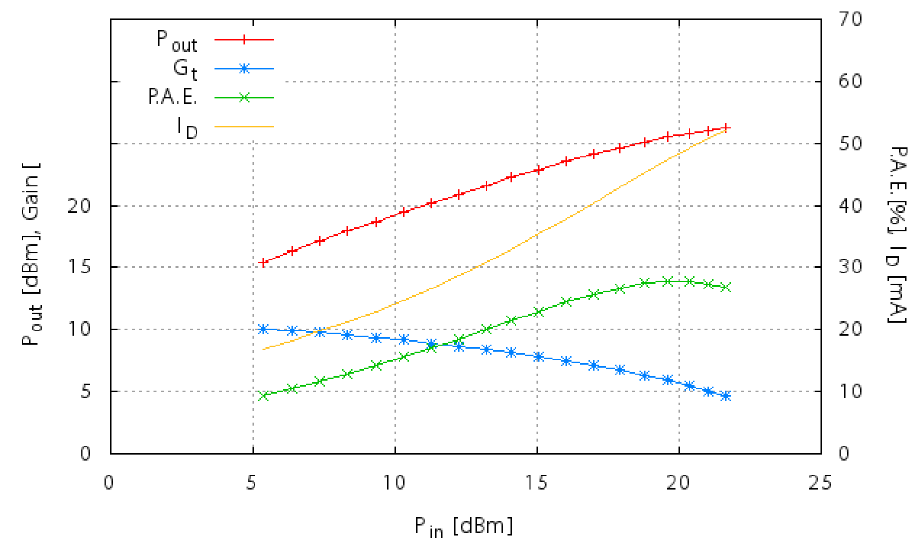
0057bb 10 GHz PIPO



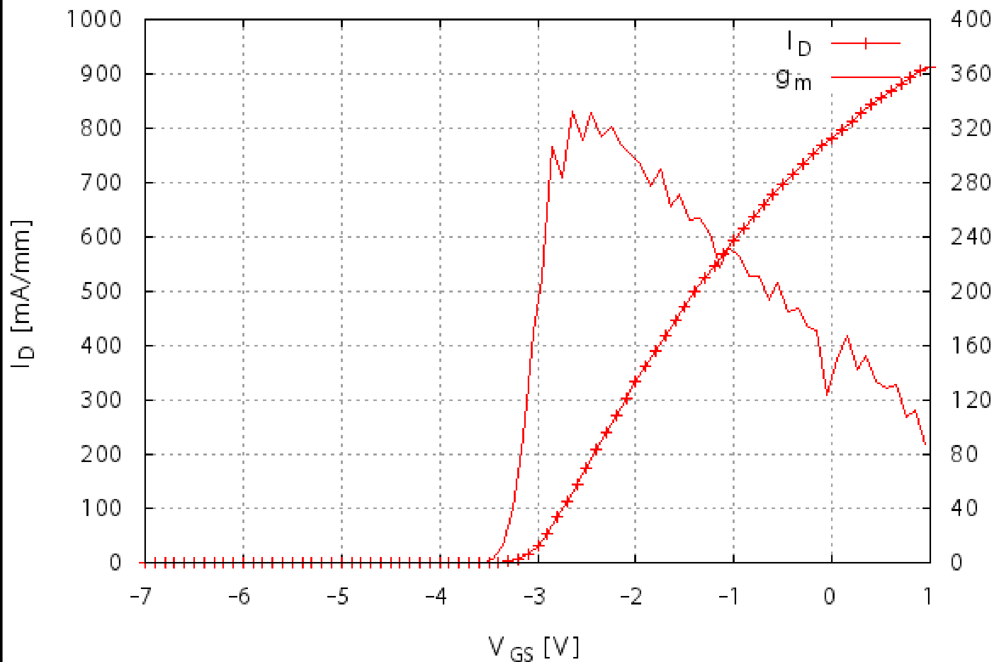
30 GHz PIPO

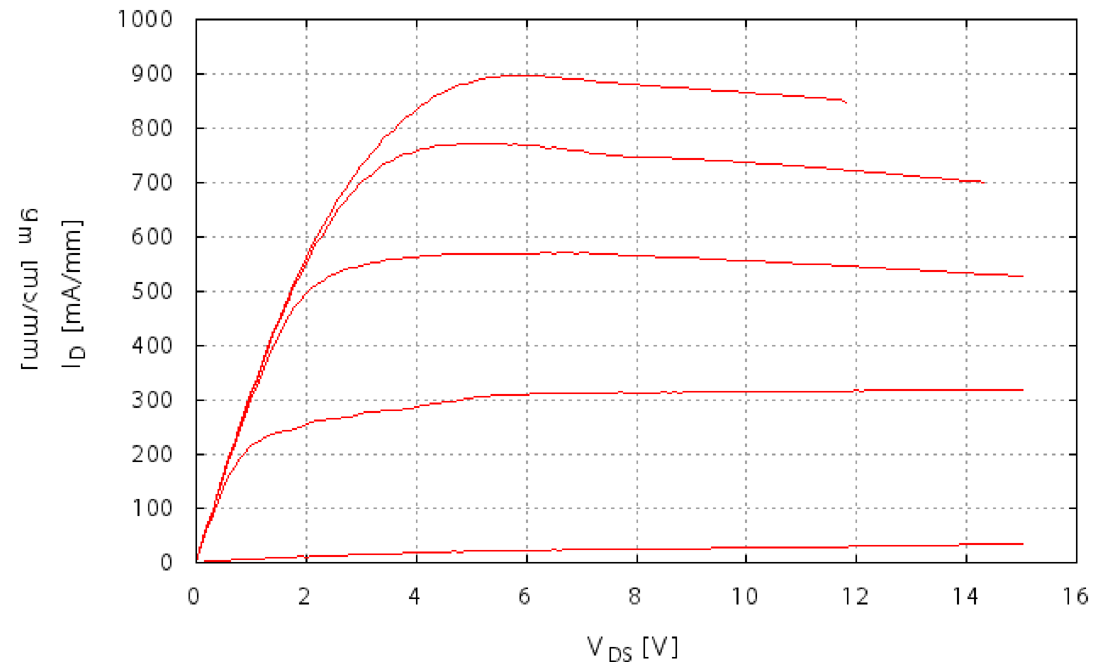


For comparison…



0067a





V_{po} = -3.1 V $I_{D,po}$ = 12 μA

I_{Dmax} = 898.3 mA/mm

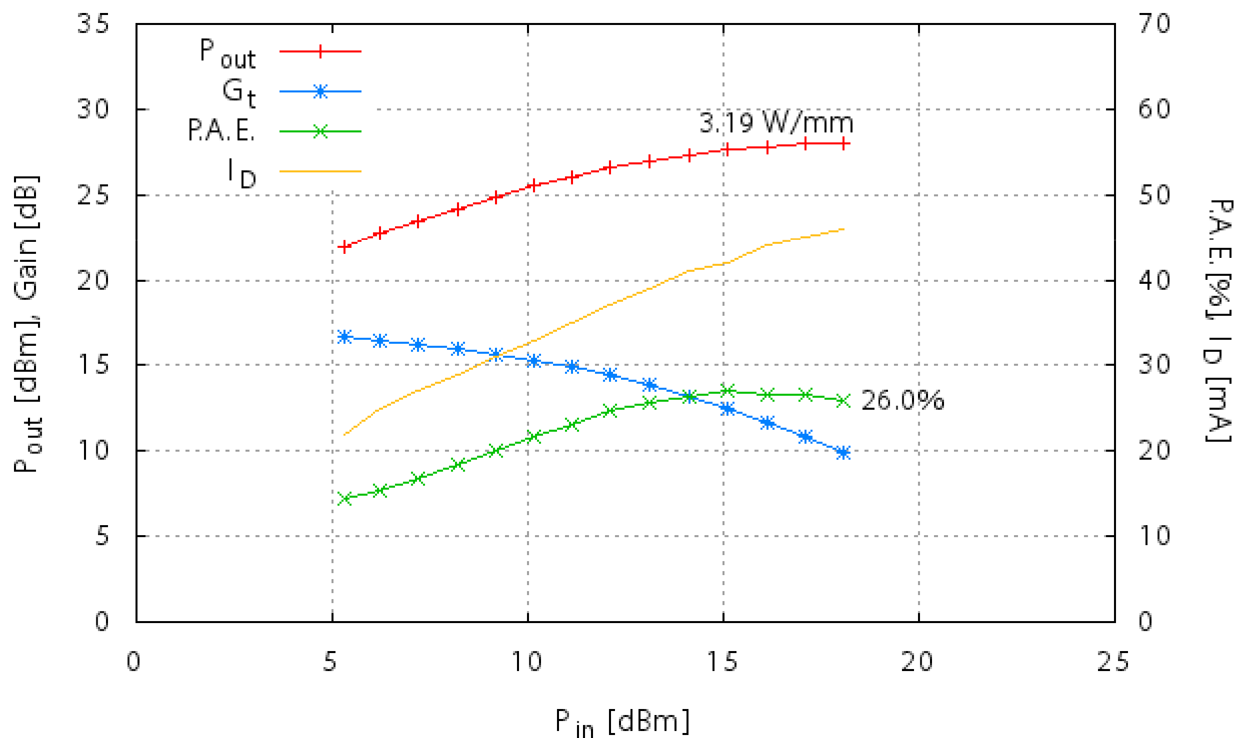
I_{D0} = 773.4 mA/mm

g_m = 322.7 mS/mm

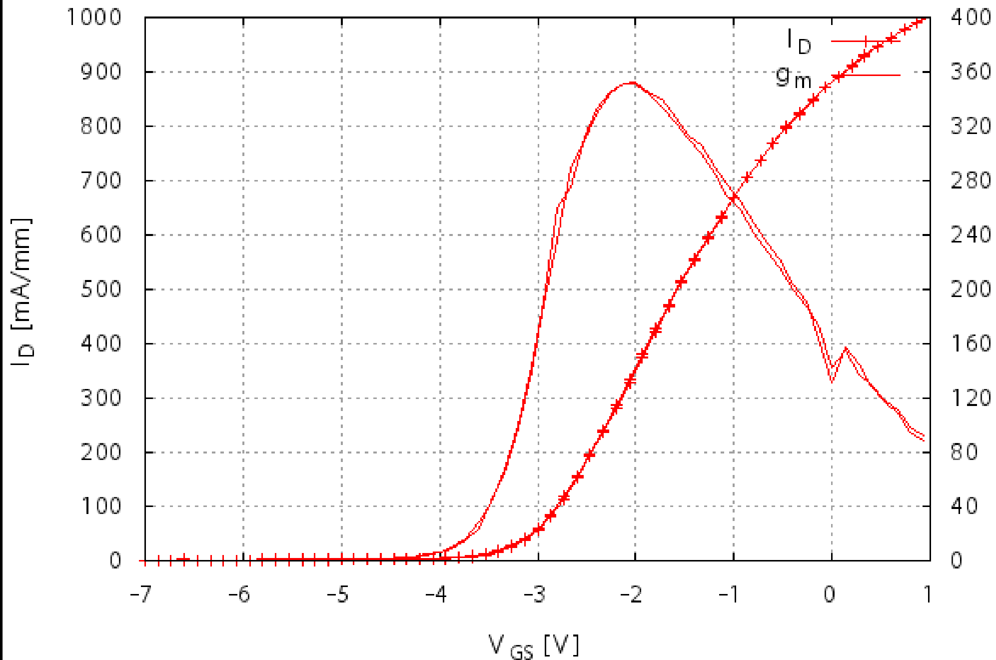
f_T = 55.7 GHz

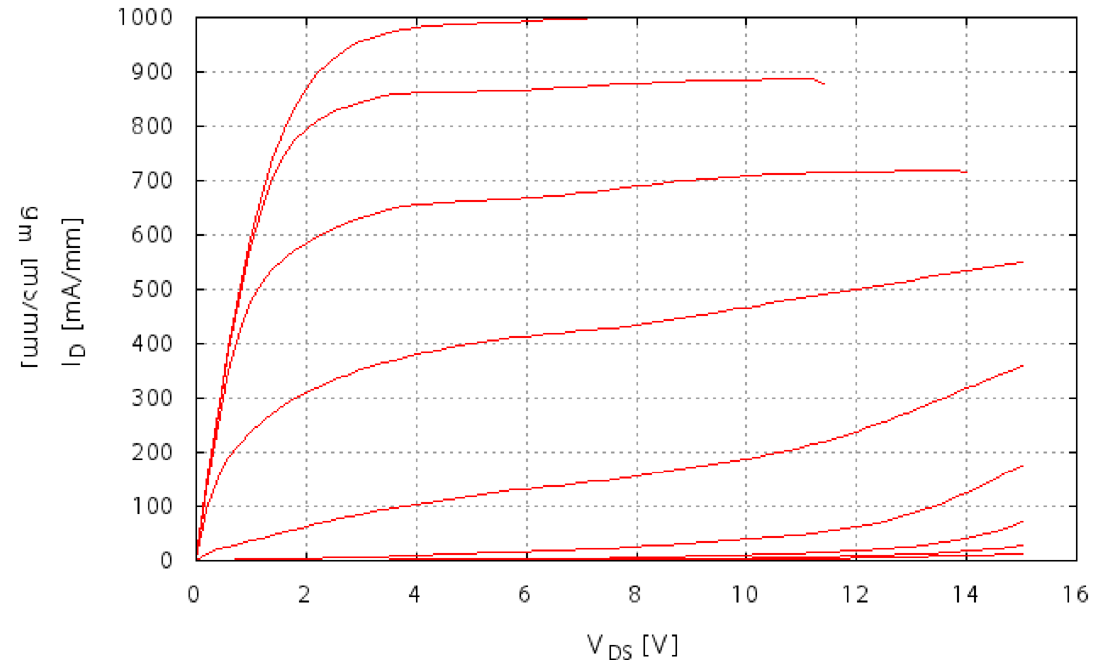
15-20% DC-RF dispersion

0067a 10 GHz PIPO



0095 DC Characteristics





Short Device, Lg = 60nm

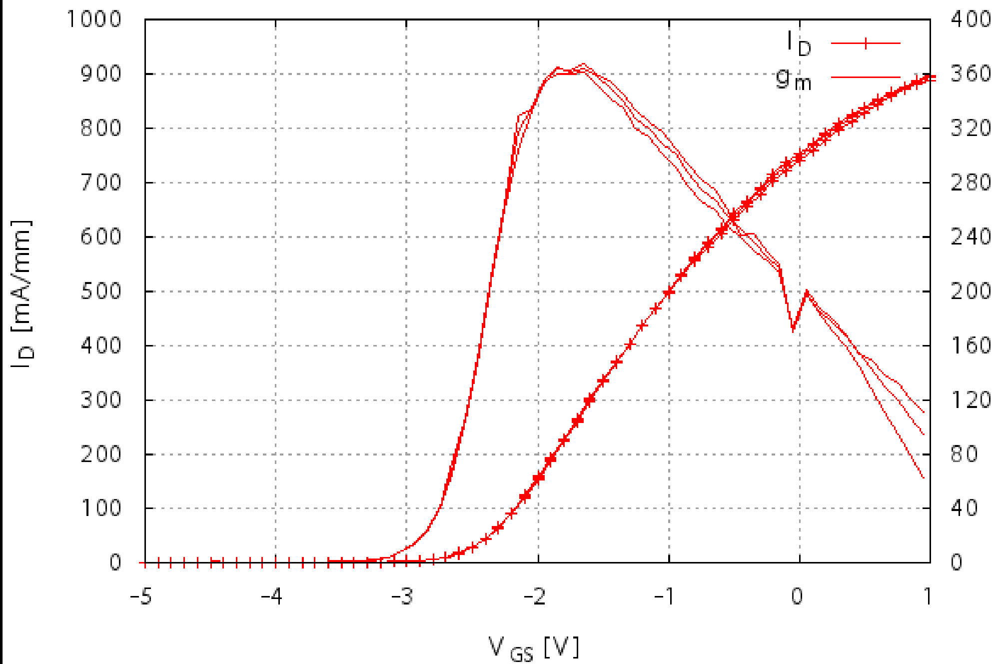
I_{Dmax} = 1007.8 mA/mm

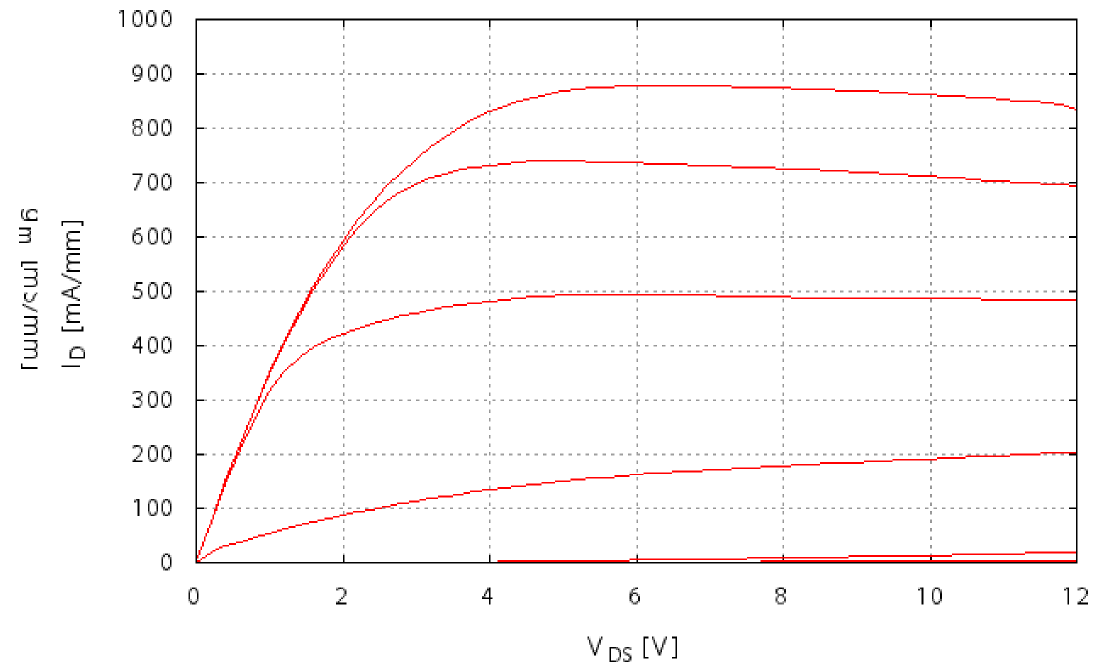
I_{D0} = 886.2 mA/mm

g_m = 351.6 mS/mm

f_T = 61.6 GHz

0095 DC Characteristics





Longer Device, Lg = 60nm

I_{Dmax} = 877.9 mA/mm

I_{D0} = 740.2 mA/mm

g_m = 364.8 mS/mm

f_T = 65.0 GHz

0095 DC & SS Characteristics

Wg	Lsg	Lg	Lgd	Pitch	gm	V(gm)	Vt	Idpo	ft	Id,max	Id0,max
um	*um*	*um*	*um*	*um*	*mS/mm*	*V*	*V*	*uA*	*GHz*	*mA/mm*	*mA/mm*
100	0.3	0.06	0.3	50	351.6	-2.1	-3.6	126	61.6	1007.8	886.2
100	0.3	0.1	0.3	50	366.6	-1.8	-3.6	86	53.8	992.0	855.1
100	0.3	0.1	0.3	50	366.0	-2.0	-3.8	98	53.9	1002.0	876.7
100	0.5	0.08	0.5	50	340.2	-1.9	-3.1	83	57.8	943.4	816.2
100	0.5	0.1	0.5	50	345.6	-2.0	-3.1	97	53.8	903.2	768.0
100	0.5	0.1	0.5	50	344.4	-1.9	-3.1	104	54.2	922.3	783.8
100	0.7	0.08	0.7	50	324.3	-1.9	-3.2	333	57.5	898.3	764.9
100	0.7	0.1	0.7	50	338.6	-1.8	-2.8	89	53.0	854.0	693.1
100	0.7	0.1	0.7	50	329.8	-1.9	-2.9	95	53.4	846.0	716.2
100	0.3	0.1	0.3	50	367.9	-2.0	-3.2	94	54.2	1006.0	878.3
100	0.3	0.1	0.3	50	369.5	-2.0	-3.0	97	53.5	993.5	860.0
100	0.5	0.1	0.5	50	344.3	-1.9	-3.1	89	54.4	923.5	790.5
100	0.5	0.1	0.5	50	355.5	-1.9	-2.9	101	53.5	942.7	798.7
100	0.7	0.06	0.7	50	315.4	-2.2	-3.8	100	60.9	935.1	815.0
100	0.7	0.08	0.7	50	333.2	-1.9	-3.0	75	58.1	912.4	778.2
100	0.7	0.1	0.7	50	332.1	-1.9	-2.9	91	54.4	880.3	740.9
100	0.7	0.1	0.7	50	335.1	-1.9	-2.8	90	54.0	881.9	739.8

0095 Small-Signal Response

0095 Lg=60nm Extrinsic SS

f (GHz)

0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75

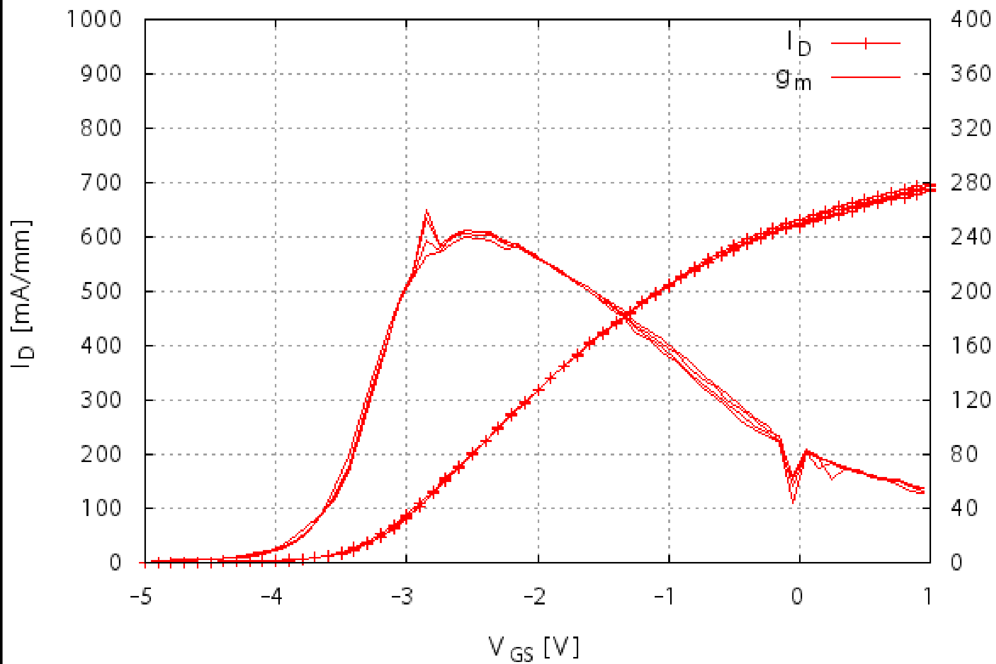
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5

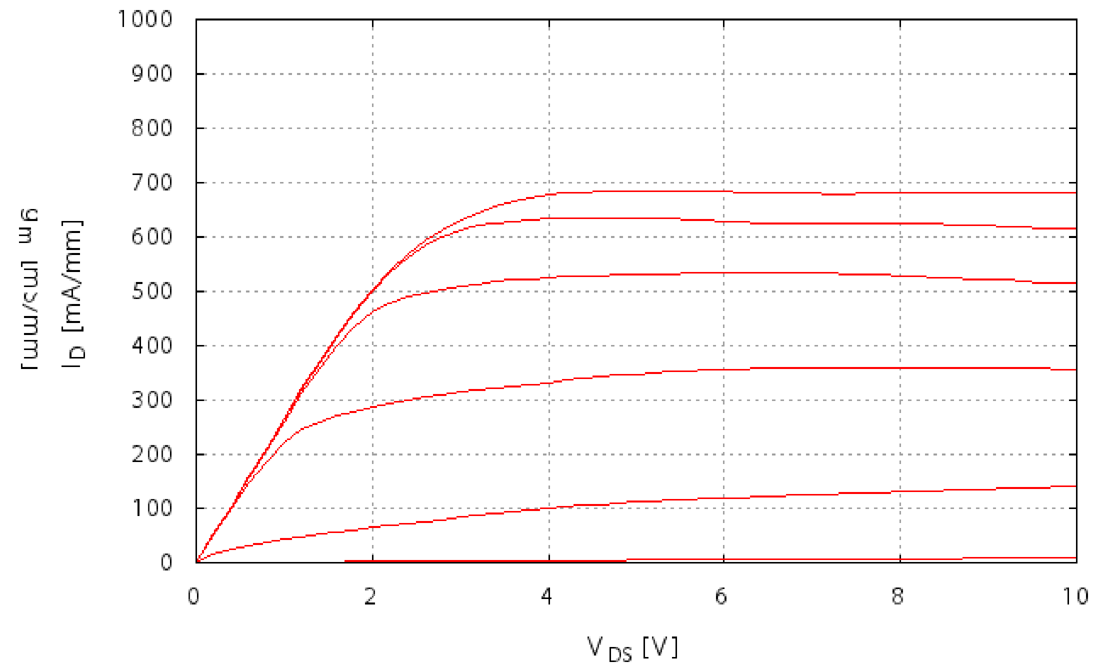
Lsd (um)

fT
fMAX

Emperically, f_T is invariant w.r.t. L_{sd} over lengths of interest
Extrapolated beyond 26.5GHz, so f_{max} may be inaccurate

0096ac DC Characteristics



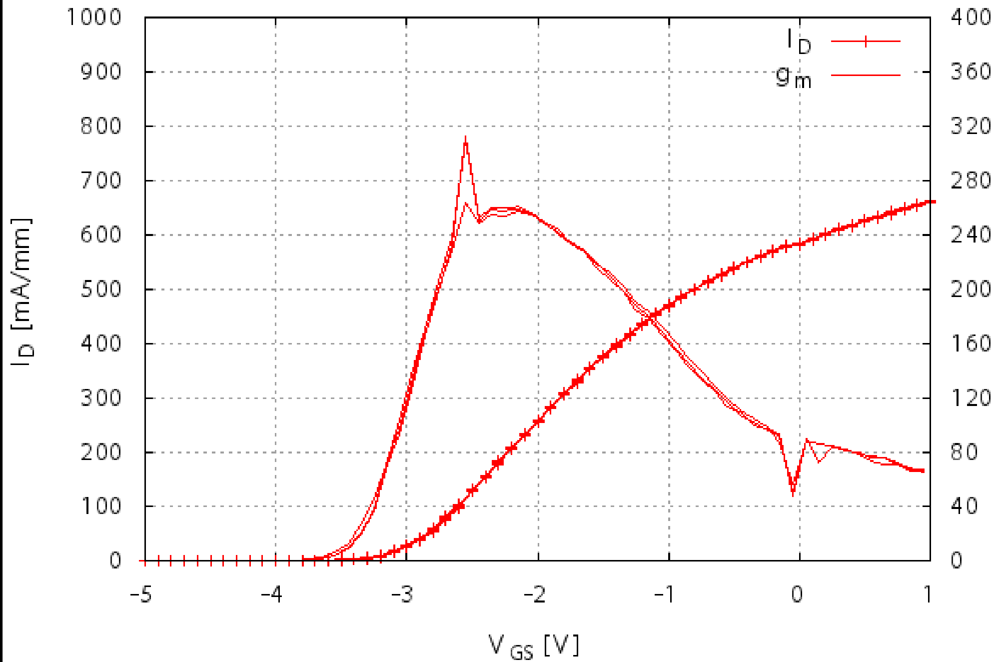


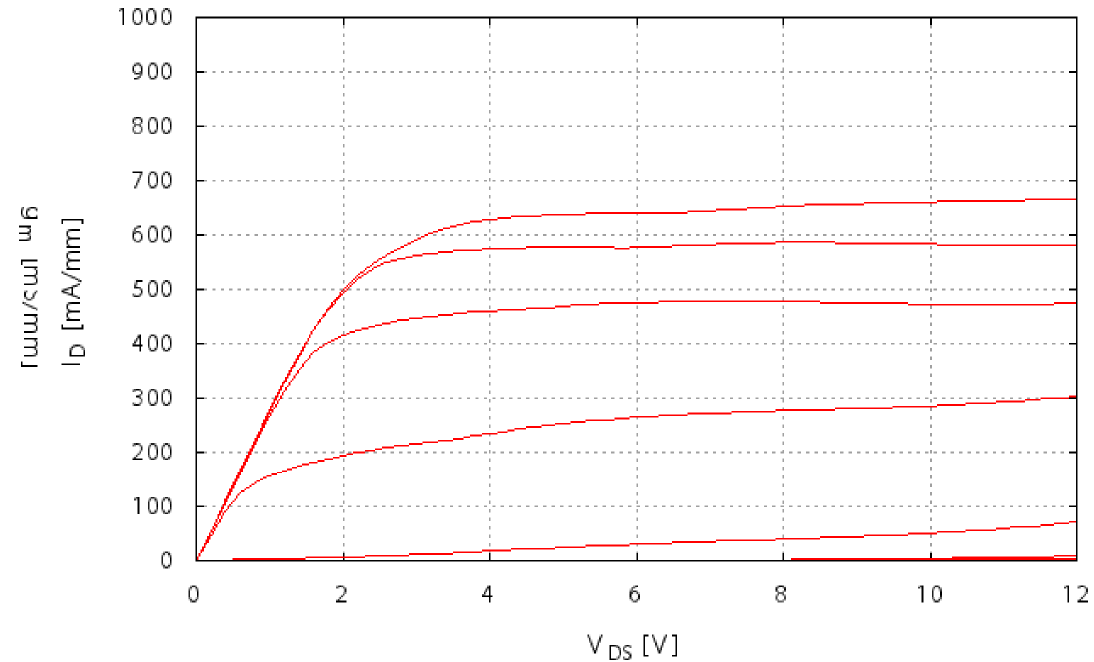
I_{Dmax} = 685.5 mA/mm
I_{D0} = 635.8 mA/mm
g_m = 245.9 mS/mm
f_T = 70.0 GHz

0096ac DC & SS Characteristics

Wg	Lsg	Lg	Lgd	Pitch	gm	V(gm)	Vt	Idpo	ft	Id,max	Id0,max
um	*um*	*um*	*um*	*um*	*mS/mm*	*V*	*V*	*uA*	*GHz*	*mA/mm*	*mA/mm*
100	0.3	0.08	0.3	50	258.6	-2.5	-3.4	85	64.0	704.3	639.3
100	0.3	0.1	0.3	50	266.6	-2.5	-3.2	47	58.9	691.8	636.9
100	0.3	0.1	0.3	50	274.4	-2.5	-3.1	64	59.5	730.4	648.2
100	0.3	0.1	0.3	50	284.6	-2.5	-3.1	52	58.2	735.6	677.4
100	0.5	0.06	0.5	50	240.7	-2.4	-3.4	48	67.7	640.4	590.4
100	0.5	0.06	0.5	50	257.2	-2.6	-3.6	31	69.2	707.8	655.5
100	0.5	0.08	0.5	50	244.6	-2.4	-3.2	62	64.3	663.9	605.7
100	0.5	0.08	0.5	50	276.0	-2.5	-3.2	56	66.2	712.5	662.8
100	0.5	0.1	0.5	50	256.8	-2.4	-3.1	56	59.2	690.4	628.2
100	0.5	0.1	0.5	50	253.2	-2.4	-3.1	60	57.5	695.2	625.1
100	0.5	0.1	0.5	50	279.0	-2.4	-3.2	75	57.8	724.7	666.4
100	0.5	0.1	0.5	50	278.7	-2.5	-3.1	60	58.8	721.2	665.9
100	0.7	0.06	0.7	50	245.9	-2.6	-3.8	119	70.0	685.5	635.8
100	0.7	0.06	0.7	50	259.8	-2.5	-3.4	68	68.9	706.5	652.5
100	0.7	0.08	0.7	50	249.0	-2.5	-3.3	68	64.3	682.3	630.5
100	0.7	0.08	0.7	50	256.3	-2.4	-3.2	70	62.9	699.9	642.0
100	0.7	0.1	0.7	50	246.7	-2.5	-3.3	74	58.3	692.9	630.9
100	0.7	0.1	0.7	50	254.5	-2.4	-3.2	85	56.9	691.6	625.0
100	0.7	0.1	0.7	50	268.5	-2.5	-3.2	61	59.2	715.4	657.4
100	0.7	0.1	0.7	50	265.4	-2.5	-3.2	67	58.2	719.2	660.9

0096af AlGaN/GaN-on-Si





I_{Dmax} = 639.4 mA/mm
I_{D0} = 576.8 mA/mm
g_m = 260.1 mS/mm
f_T = 55.3 GHz

Output conductance issue appears innate to source epi layers

0096af DC & SS Characteristics

Wg	Lsg	Lg	Lgd	Pitch	gm	V(gm)	Vt	Idpo	ft	Id,max	Id0,max
um	*um*	*um*	*um*	*um*	*mS/mm*	*V*	*V*	*uA*	*GHz*	*mA/mm*	*mA/mm*
100	0.3	0.06	0.3	50	259.5	-2.4	-3.1	63	54.5	653.4	575.2
100	0.3	0.06	0.3	50	260.1	-2.3	-3.1	68	55.3	639.4	576.8
100	0.3	0.08	0.3	50	249.4	-2.3	-3.1	57	50.5	616.6	565.6
100	0.3	0.08	0.3	50	267.1	-2.3	-3.2	93	50.3	659.4	597.1
100	0.3	0.1	0.3	50	256.1	-2.2	-3.1	82	45.8	628.0	566.1
100	0.3	0.1	0.3	50	267.4	-2.1	-3.0	81	46.5	635.8	570.9
100	0.3	0.1	0.3	50	260.7	-2.2	-3.3	60	46.2	629.5	573.0
100	0.5	0.06	0.5	50	246.2	-2.7	-3.5	62	53.5	656.5	598.0
100	0.5	0.06	0.5	50	258.7	-2.6	-3.4	61	53.8	658.1	598.0
100	0.5	0.08	0.5	50	254.4	-2.5	-3.3	69	49.5	658.2	591.7
100	0.5	0.1	0.5	50	240.2	-2.6	-3.3	56	45.4	605.2	558.0
100	0.5	0.1	0.5	50	244.0	-2.4	-3.1	61	45.5	637.6	580.4
100	0.5	0.1	0.5	50	256.8	-2.5	-3.3	62	45.3	661.7	599.0
100	0.7	0.06	0.7	50	244.8	-2.6	-3.2	211	52.8	676.0	609.5
100	0.7	0.06	0.7	50	251.6	-2.5	-3.4	66	52.5	653.0	601.2
100	0.7	0.08	0.7	50	244.2	-2.6	-3.3	51	48.0	636.2	575.6
100	0.7	0.08	0.7	50	244.4	-2.4	-3.1	59	48.4	625.0	570.1
100	0.7	0.1	0.7	50	237.4	-2.4	-3.2	55	45.0	630.7	569.7
100	0.7	0.1	0.7	50	246.6	-2.6	-3.3	62	44.6	645.7	582.0
100	0.7	0.1	0.7	50	252.7	-2.4	-3.3	65	44.5	649.6	587.0
100	0.7	0.1	0.7	50	253.1	-2.5	-3.3	52	44.76	663.8	593.92

Future Work

- 2-port pulsed characterization of 0095 & 0096
- SThM measurement of 0108, 0095, & 0096
- Optimize epitaxial layer design for higher carrier density and lower leakage
- Develop e-beam air-bridging process for multi-finger X-band power devices
- In future processes, continue using as-grown, on-Si epi layers from the same wafer as those transferred onto diamond