



AlGaN/GaN-on-Diamond HEMT Recent Progress

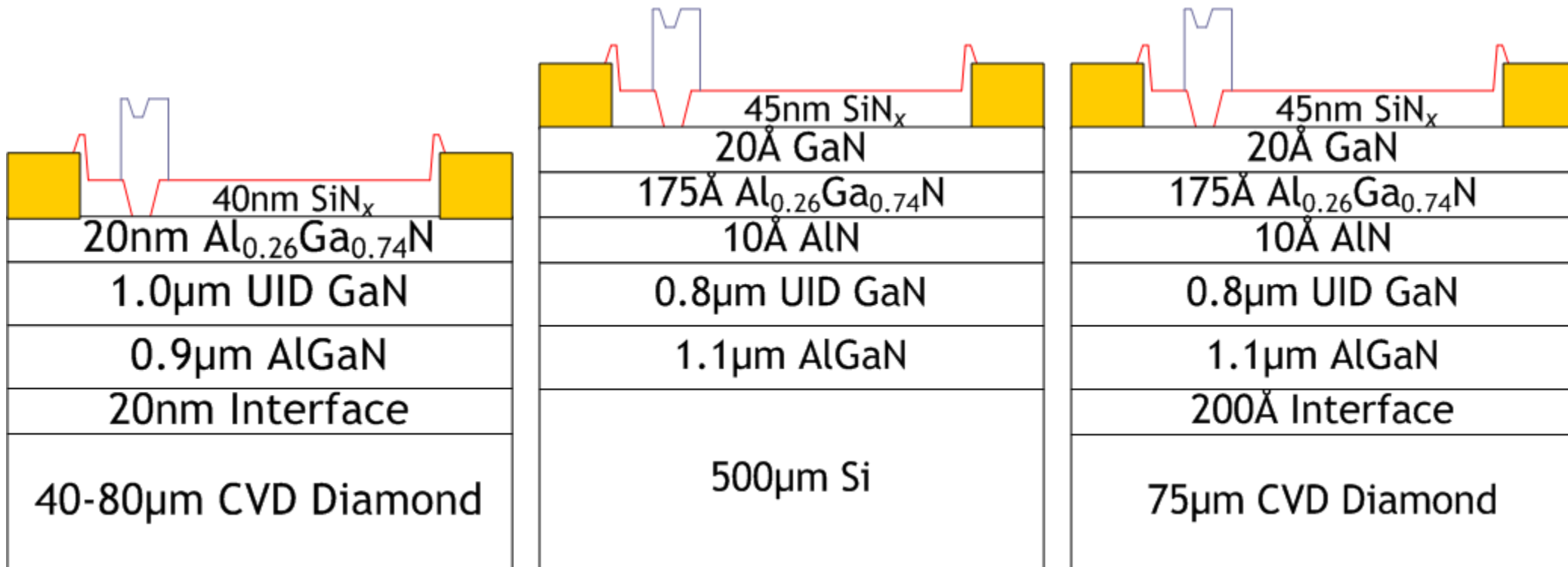
J.G. Felbinger¹, L.F. Eastman¹, J. Wasserbauer²,
F. Faili², D.I. Babić², D. Francis², F. Ejeckam²

- (1) Cornell University, Ithaca, NY
- (2) Group4 Labs, Menlo Park, CA





Material & Process



Ti/Al/Mo/Au Ohmic contacts

Ta/Ti/Al/Mo/Au Ohmic contacts

800 $^{\circ}\text{C}$ RTA

$\text{Cl}_2/\text{BCl}_3/\text{Ar}$ ICP mesa isolation

375 $^{\circ}\text{C}$ PECVD SiN_x

Ni/Au field-plated (Γ) gate with 70 $^{\circ}$ SiN_x etch angle



HEMT Dimensions 0057bb/0067a

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

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

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

source-gate spacing $L_{SG} = 700 \text{ nm}$

gate-drain spacing $L_{GD} = 1.5, 2.0, 2.5, \text{ or } 3.0 \mu\text{m}$

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

DUT Naming e.g. **1** - **200** - **.15** - **2.5** - **50**

Row $W_{G,\text{total}} (\mu\text{m})$ $L_G (\text{nm})$ $L_{GD} (\mu\text{m})$ Pitch (μm)



HEMT Dimensions 0095/0096

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

total periphery ($2 \times W_{\text{mesa}}$) $W_{G,\text{total}} = 100, 250, \text{ or } 300 \mu\text{m}$

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

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

gate-drain spacing $L_{GD} = 1.5, 2.0, 2.5, \text{ or } 3.5 \mu\text{m}$

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

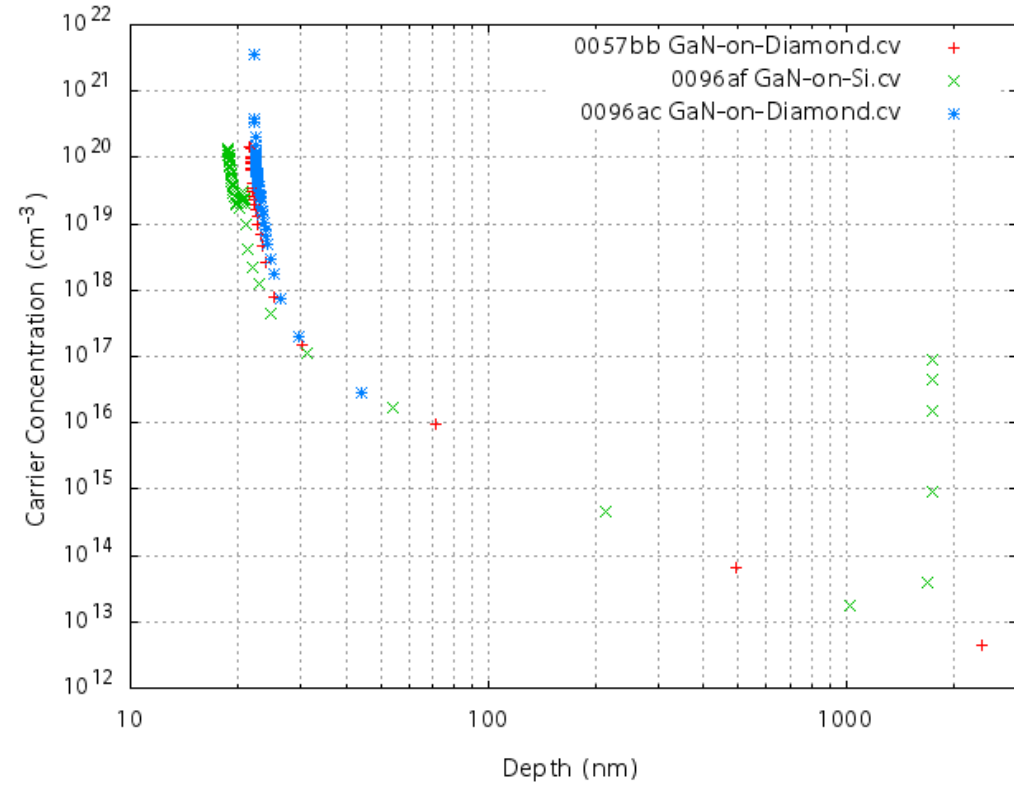
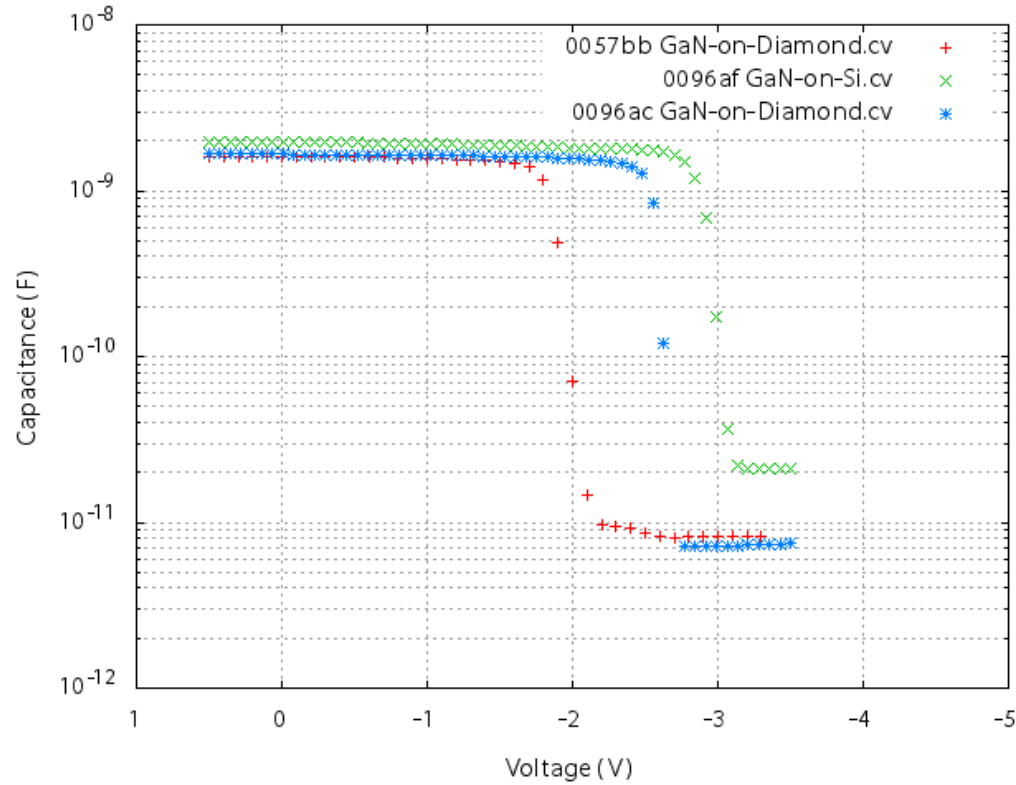
DUT Naming e.g. **100** **.3** **.06** **3.5** **50**

$W_G (\mu\text{m})$ $L_G (\text{nm})$ Pitch (μm)

$L_{SG} (\mu\text{m})$ $L_{GD} (\mu\text{m})$



C(V) & TLM Measurements

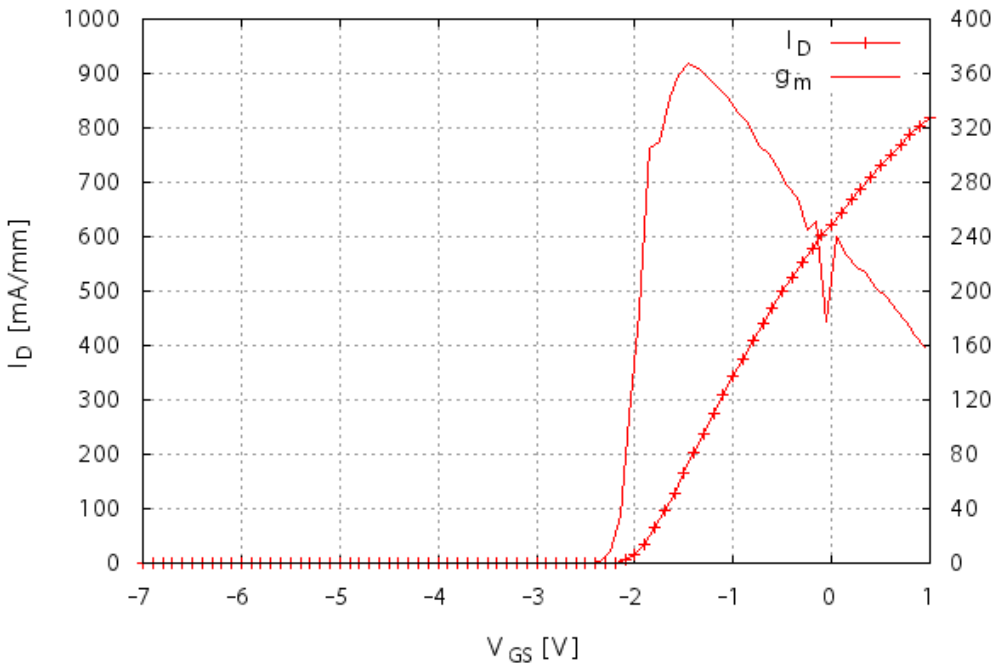


	0057bb (dia)	0096af (Si)	0096ac (dia)
R_c ($\Omega\text{-mm}$)	0.47 ± 0.07	1.12	1.14
R_{sh} (Ω/\square)	440.5 ± 13.7	364	404

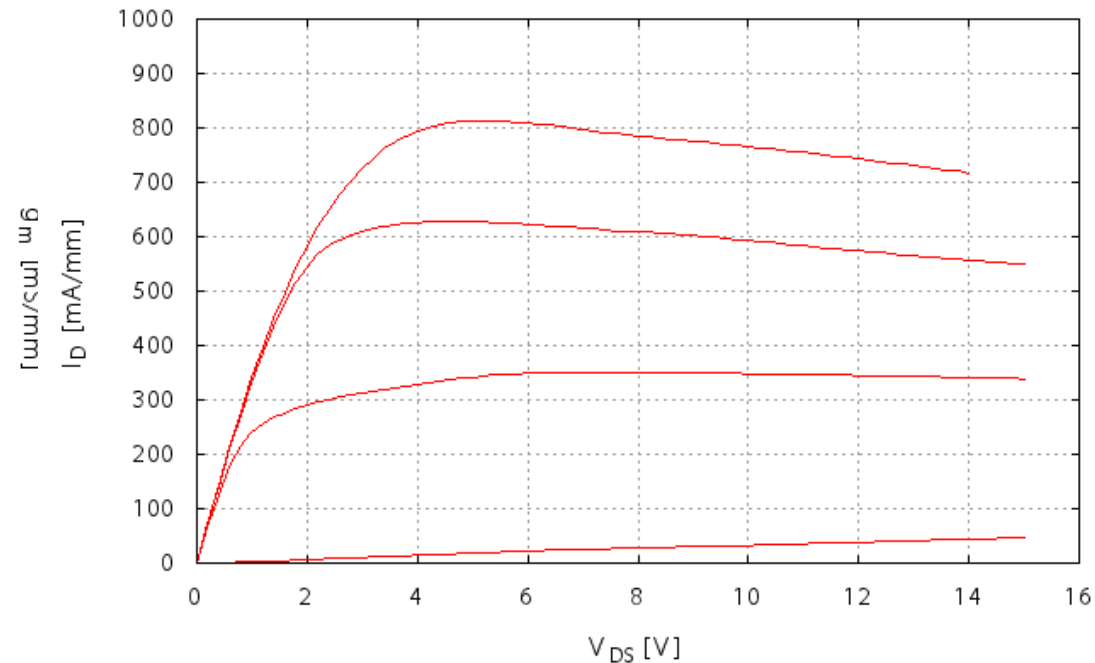


0057bb

2_200_1_2.5_25_20080714221121.xfer
Vds max 6.00 V; step 0 V; g_{m,max} = 365.15 mS/mm



2_200_1_2.5_25_20080810141723.dciiv
Vgs max 1.00 V; step -1 V; min -3.00 V



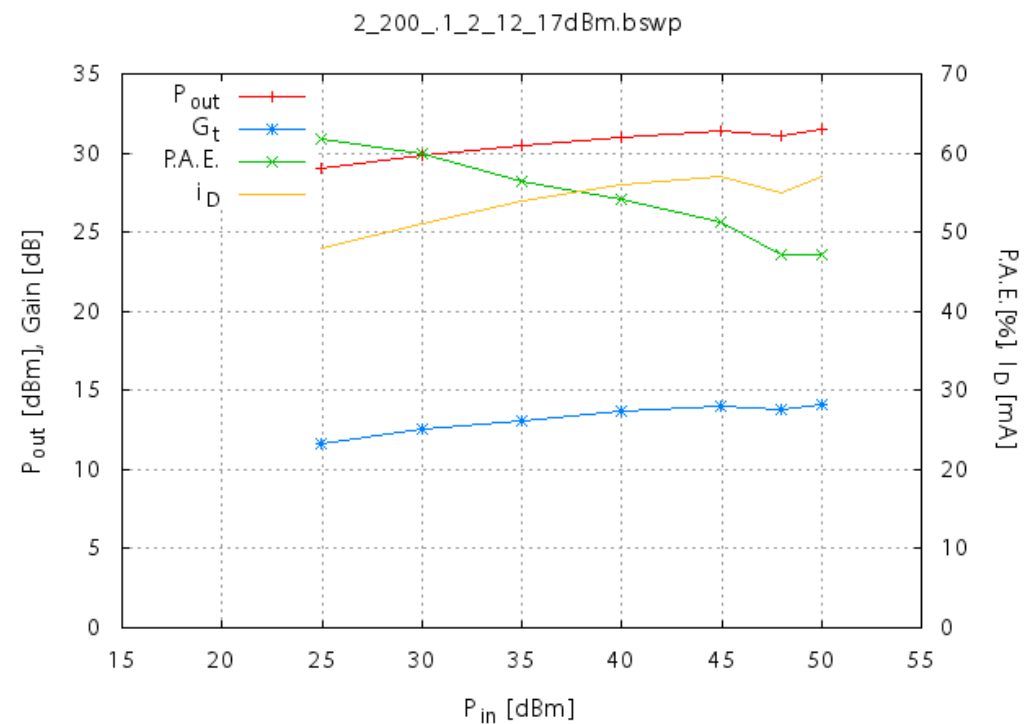
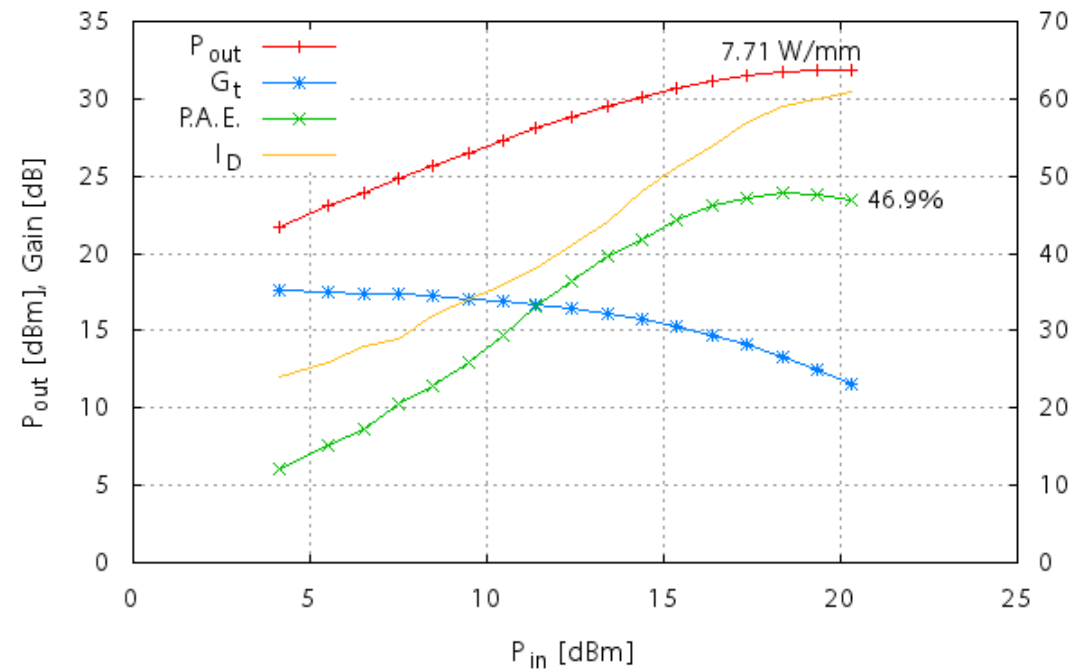
$V_{po} = -2.1 \text{ V}$ $I_{D,po} = 11 \text{ } \mu\text{A}$
 $I_{Dmax} = 813.0 \text{ mA/mm}$
 $I_{D0} = 628.3 \text{ mA/mm}$
 $g_m = 364.1 \text{ mS/mm}$
 $f_T = 58.7 \text{ GHz}$
15-20% DC-RF dispersion

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



10 GHz PIPO @ AFRL

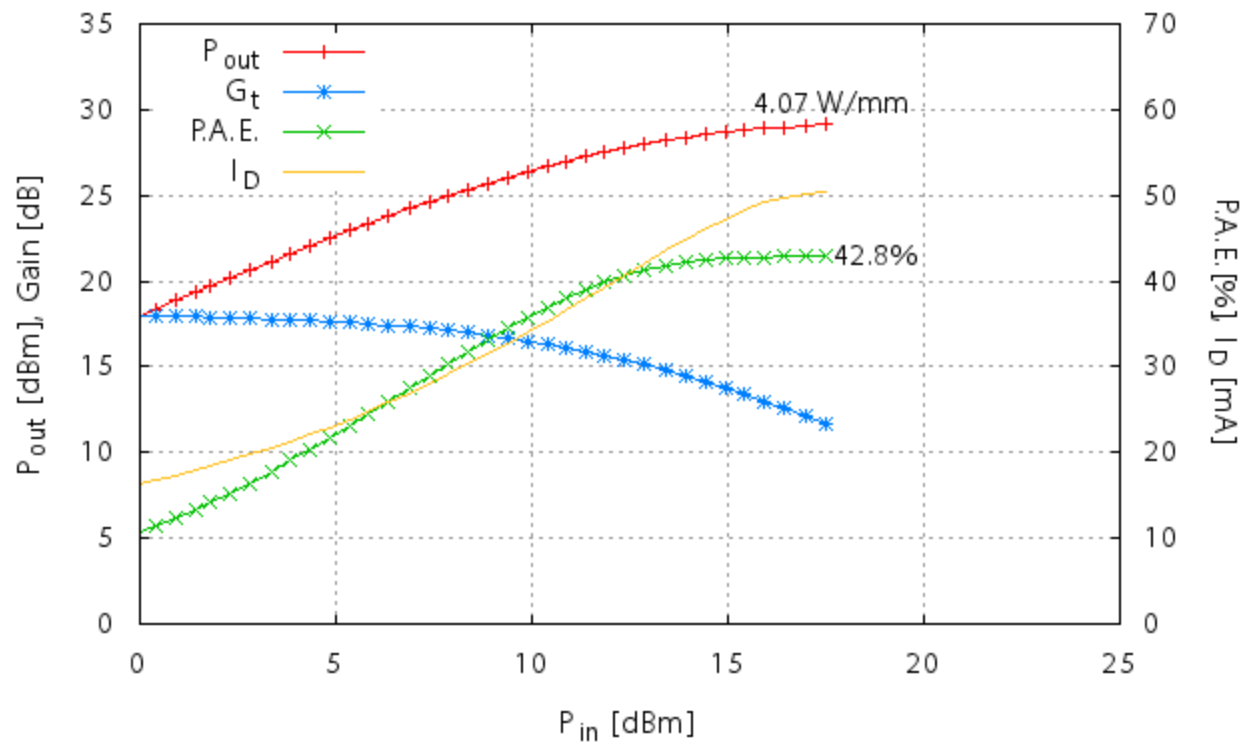
2-200-1-2-12-50n17.swp 10.0000 GHz
 $V_{DS} = 50.004 \text{ V}$; $V_{GS} = -1.700 \text{ V}$; $I_{Dq} = 105.0 \text{ mA/mm}$
 $Z_S = 69.090 + 465.921i$ $Z_L = 405.05 + 824.90i$





0057bb 10 GHz PIPO

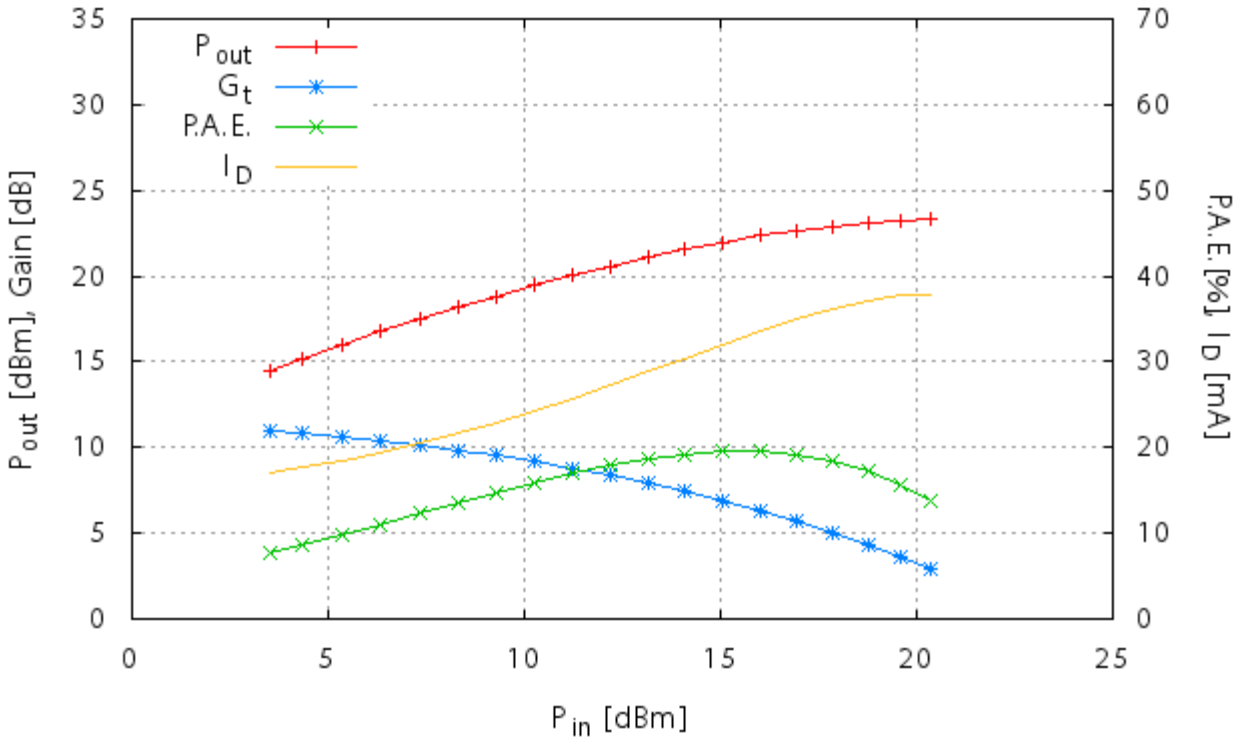
2-200-1-2.5-25-35V-10MA.SAT
 $V_{DS} = 35.003 \text{ V}; V_{GS} = -2.109 \text{ V}$
 $Z_S = 177.542 + 81.882i \quad Z_L = 454.39 + 748.18i$





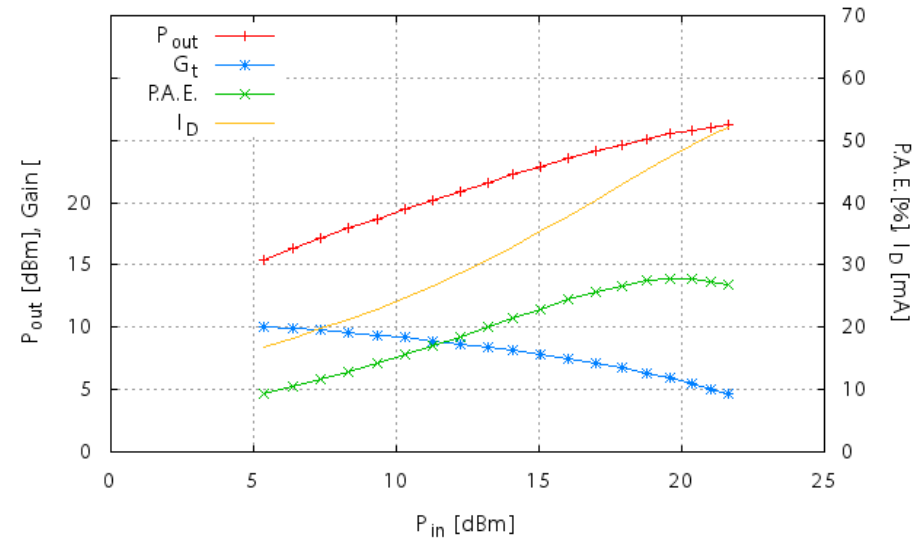
30 GHz PIPO

P-20V15MA-2-100-.1-1.5-50-DIA1-30G.SAT
 $V_{DS} = 20.018 \text{ V}; V_{GS} = -1.518 \text{ V}$
 $Z_S = 113.393 + 51.788i \quad Z_L = 185.34 + 360.48i$



For comparison...

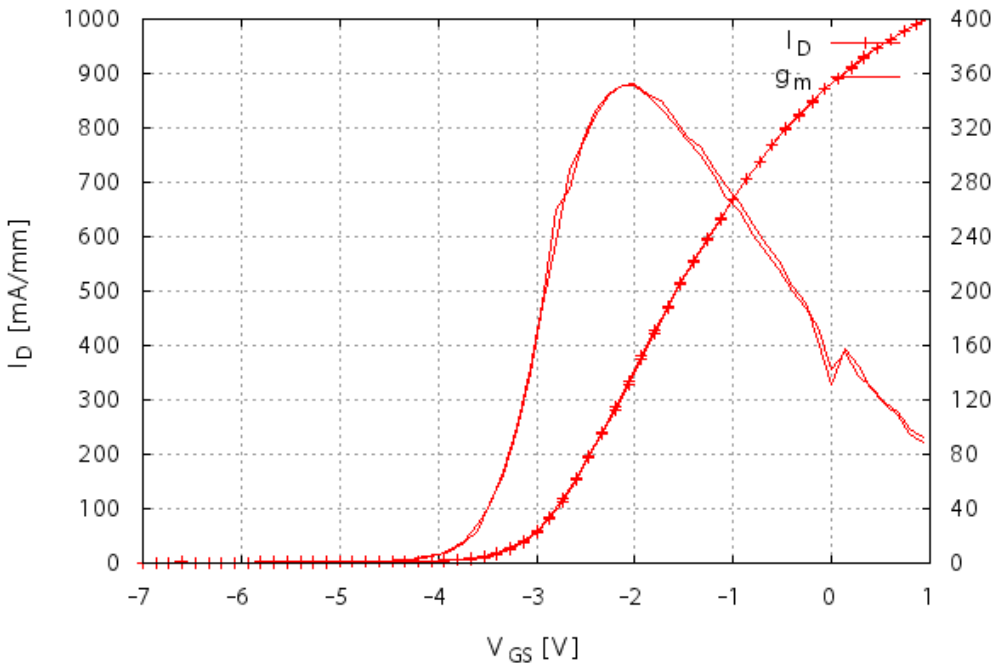
P2-20V10MA-2-100-.1-1.5-50-P1-30G.SAT
 $V_{DS} = 20.008 \text{ V}; V_{GS} = -5.552 \text{ V}$
 $Z_S = 109.797 + 49.794i \quad Z_L = 180.77 + 137.72i$



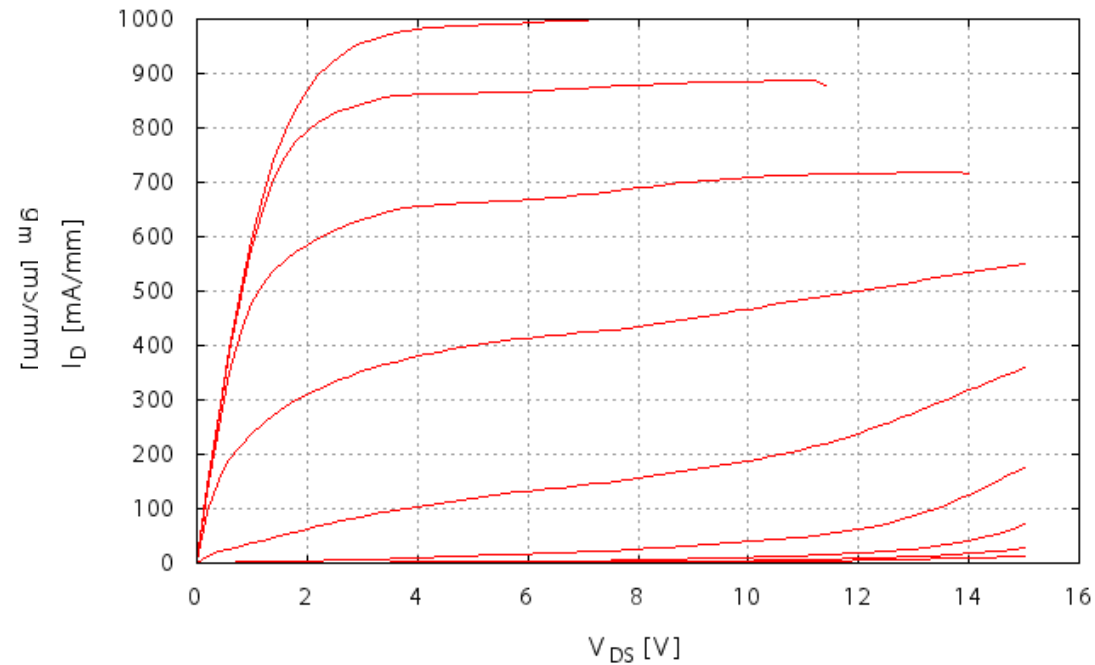


0095 DC Characteristics

100_3_06_3_50L_20081212111538.xfer
Vds max 6.00 V; step -1 V; g_{m,max} = 351.60 mS/mm



100_3_06_3_50L_20081212112200.dcv
Vgs max 1.00 V; step -1 V; min -7.00 V



Short Device, $L_g = 60$ nm

$$I_{Dmax} = 1007.8 \text{ mA/mm}$$

$$I_{D0} = 886.2 \text{ mA/mm}$$

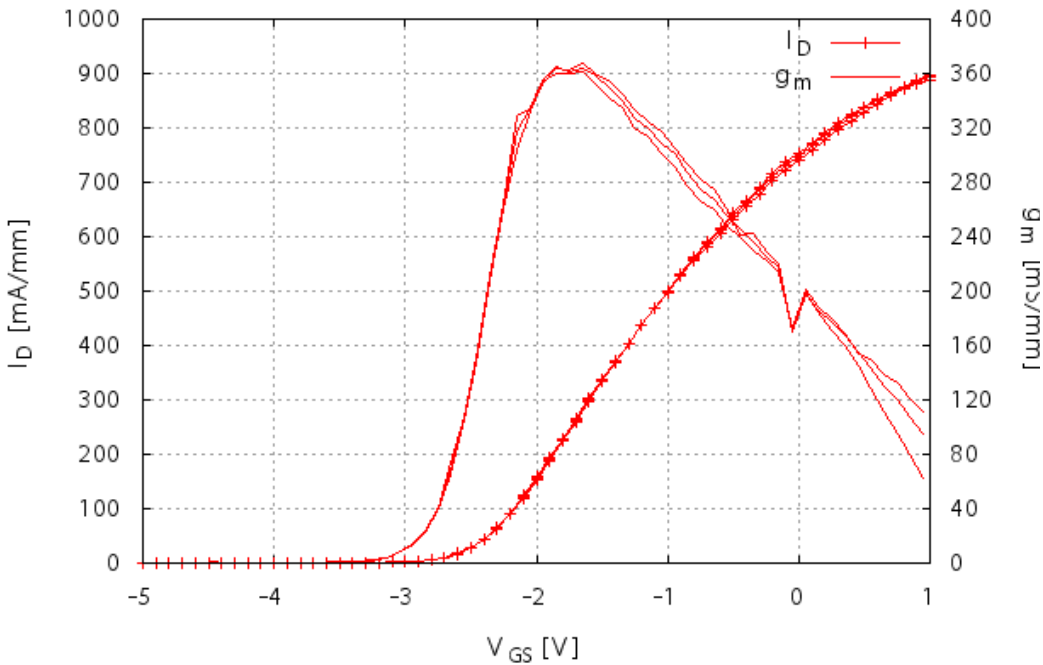
$$g_m = 351.6 \text{ mS/mm}$$

$$f_T = 61.6 \text{ GHz}$$

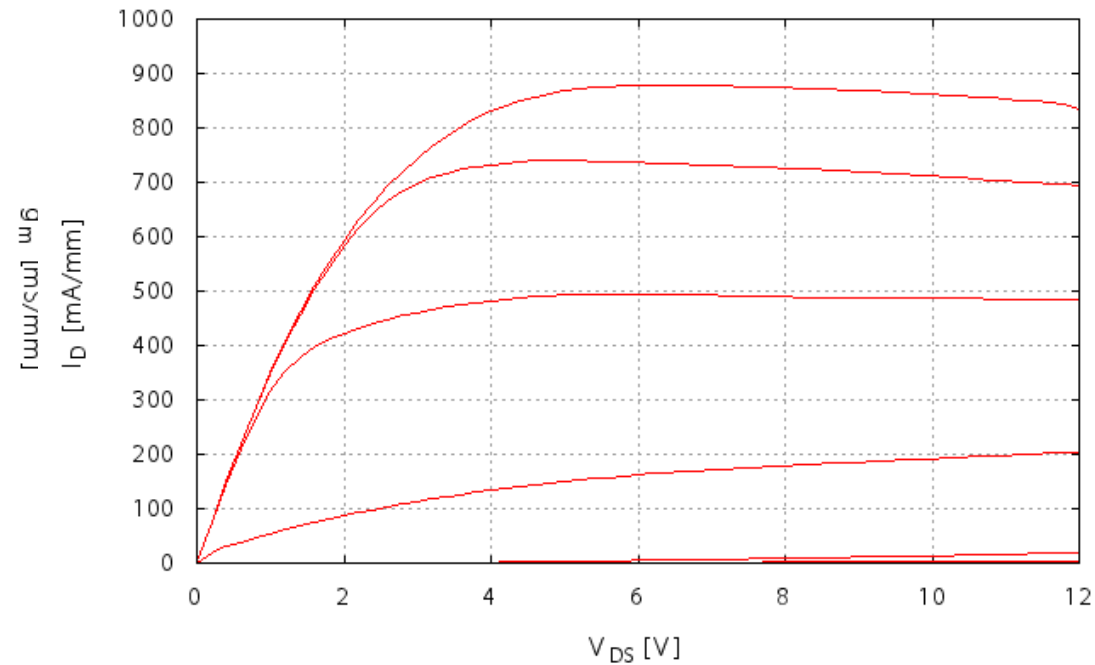


0095 DC Characteristics

100_5_06_2.5_50_20081214175913.xfer
Vds max 7.00 V; step -1 V; g_m,max = 364.80 mS/mm



100_5_06_2.5_50_20081214175919.dciw
Vgs max 1.00 V; step -1 V; min -6.00 V



Longer Device, $L_g = 60\text{nm}$

$$I_{Dmax} = 877.9 \text{ mA/mm}$$

$$I_{D0} = 740.2 \text{ mA/mm}$$

$$g_m = 364.8 \text{ mS/mm}$$

$$f_T = 65.0 \text{ GHz}$$

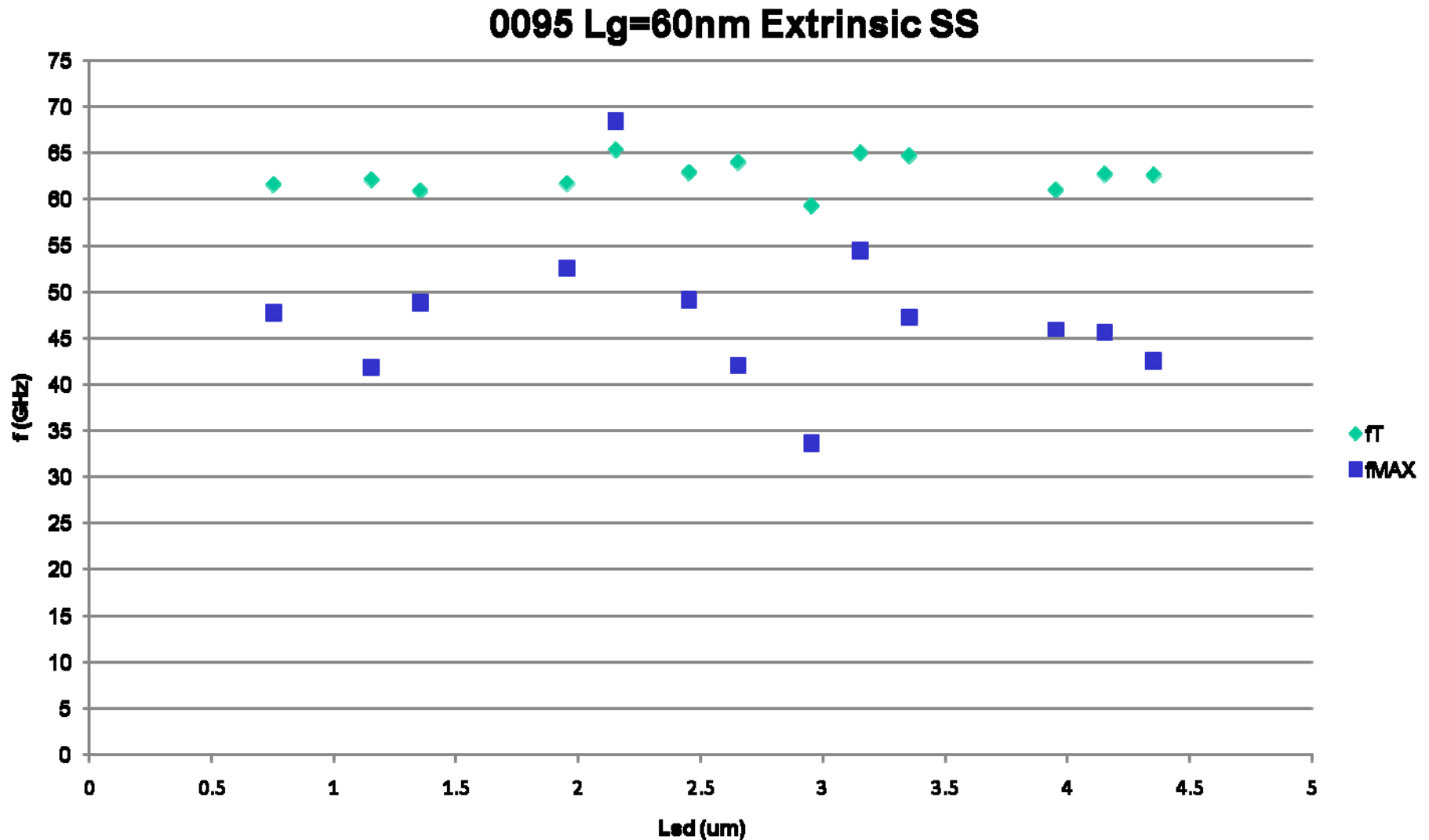


0095 DC & SS Characteristics

Wg	Lsg	Lg	Lgd	Pitch	gm	V(gm)	Vt	Idpo	ft	Id,max	Id0,max
<i>um</i>	<i>um</i>	<i>um</i>	<i>um</i>	<i>um</i>	<i>mS/mm</i>	<i>V</i>	<i>V</i>	<i>uA</i>	<i>GHz</i>	<i>mA/mm</i>	<i>mA/mm</i>
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

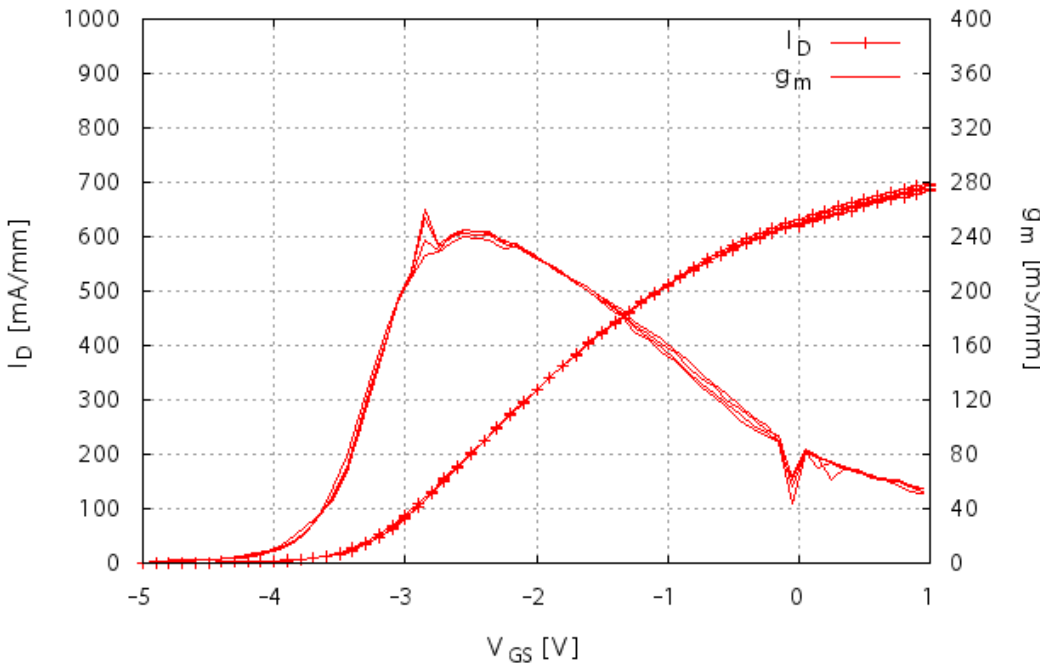


Empirically, f_T is invariant w.r.t. L_{sd} over lengths of interest
Extrapolated beyond 26.5GHz, so f_{max} may be inaccurate

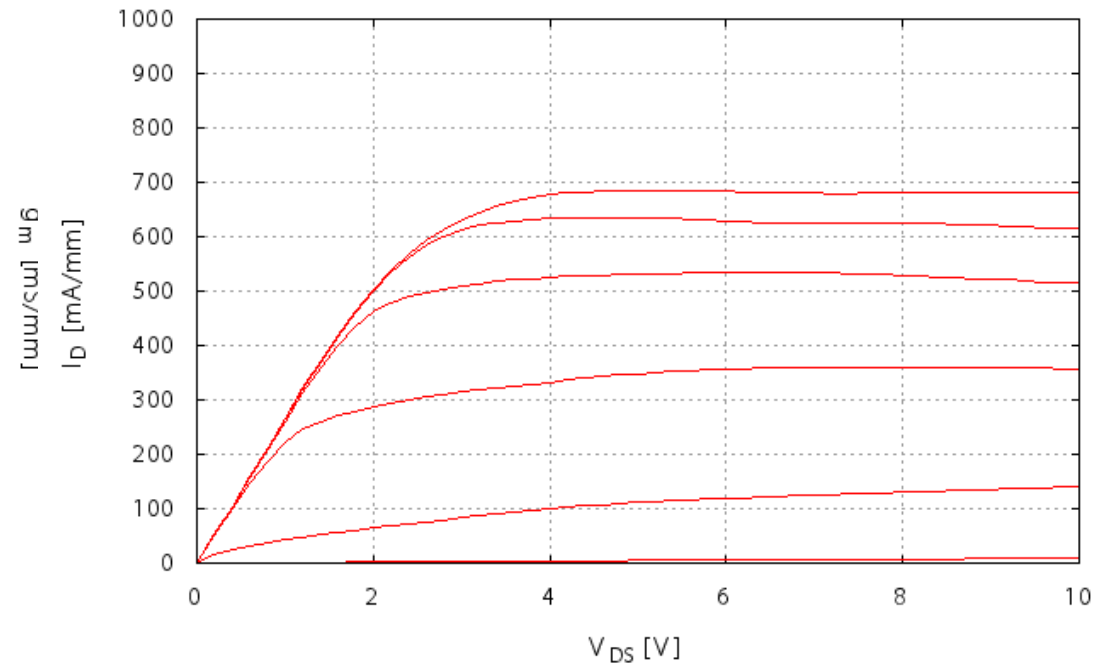


0096ac DC Characteristics

100_7_06_7_50L_20081212170452.xfer
Vds max 6.00 V; step -0.5 V; g_{m,max} = 247.29 mS/mm



100_7_06_7_50L_20081212170226.dciw
Vgs max 1.00 V; step -1 V; min -5.00 V



$$\begin{aligned} I_{Dmax} &= 685.5 \text{ mA/mm} \\ I_{D0} &= 635.8 \text{ mA/mm} \\ g_m &= 245.9 \text{ mS/mm} \\ f_T &= 70.0 \text{ GHz} \end{aligned}$$



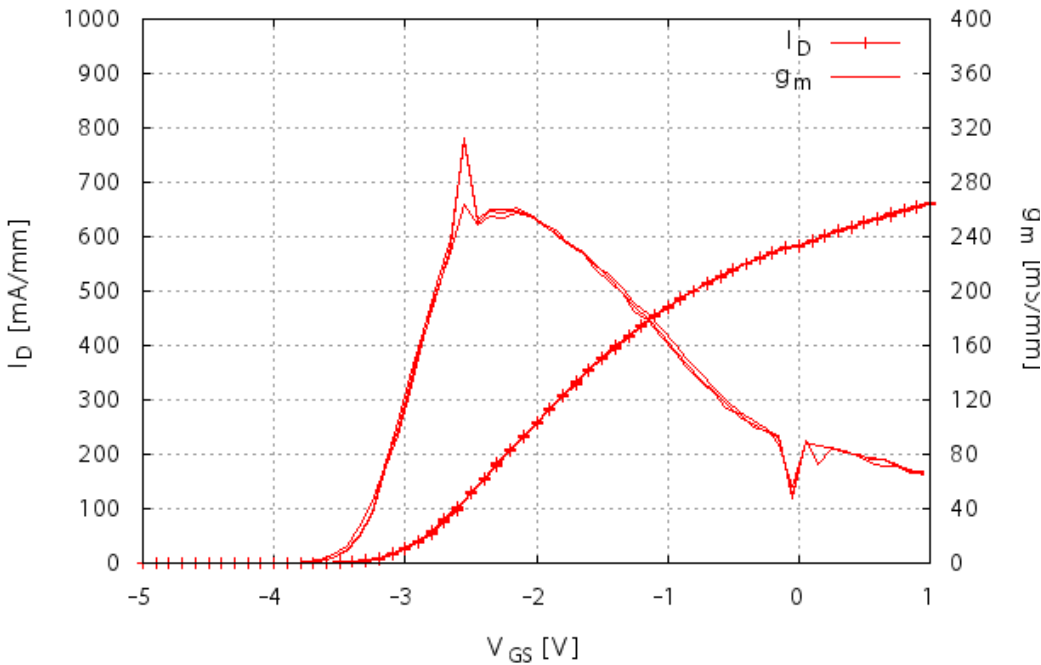
0096ac DC & SS Characteristics

Wg	Lsg	Lg	Lgd	Pitch	gm	V(gm)	Vt	ldpo	ft	Id,max	Id0,max
<i>um</i>	<i>um</i>	<i>um</i>	<i>um</i>	<i>um</i>	<i>mS/mm</i>	<i>V</i>	<i>V</i>	<i>uA</i>	<i>GHz</i>	<i>mA/mm</i>	<i>mA/mm</i>
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

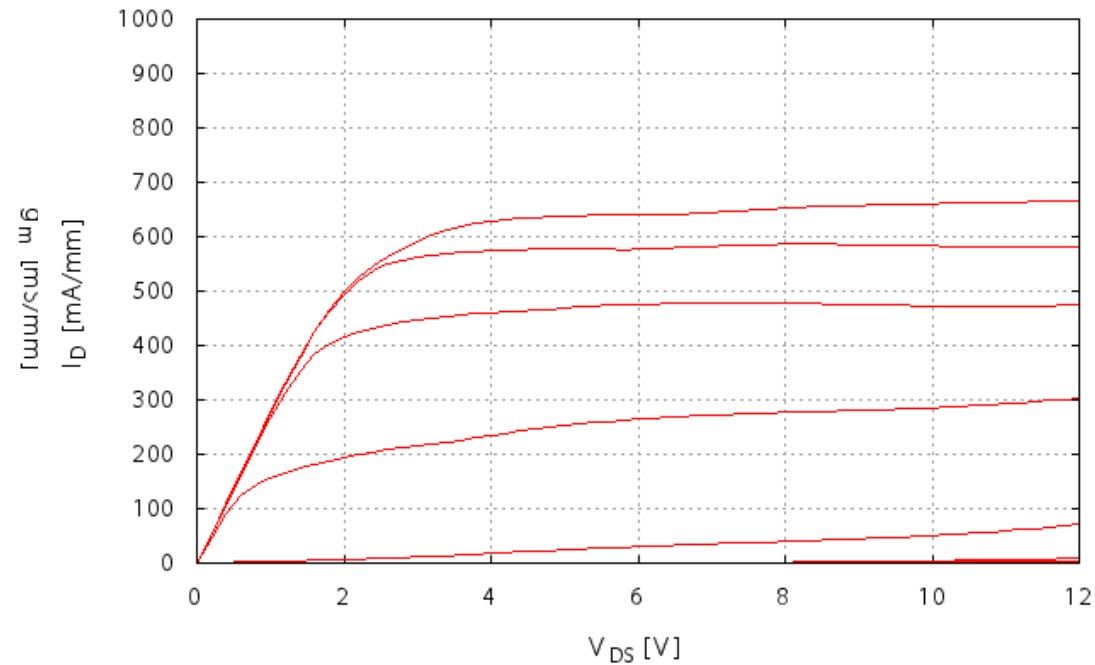


0096af AlGaN/GaN-on-Si

100_3_06_3_50R_20081213172905.xfer
Vds max 6.00 V; step -0.5 V; g_m,max = 281.61 mS/mm



100_3_06_3_50R_20081213172909.dciw
Vgs max 1.00 V; step -1 V; min -5.00 V



$$\begin{aligned} I_{Dmax} &= 639.4 \text{ mA/mm} \\ I_{D0} &= 576.8 \text{ mA/mm} \\ g_m &= 260.1 \text{ mS/mm} \\ f_T &= 55.3 \text{ GHz} \end{aligned}$$

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
<i>um</i>	<i>um</i>	<i>um</i>	<i>um</i>	<i>um</i>	<i>mS/mm</i>	<i>V</i>	<i>V</i>	<i>uA</i>	<i>GHz</i>	<i>mA/mm</i>	<i>mA/mm</i>
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



Ongoing Work

- Optimize device dimensions for large-signal performance
- Optimize epitaxial layer design for higher carrier density
- Develop gate recess process and ALD surface passivation
- Continue using as-grown, on-Si epi layers alongside those transferred onto diamond