Design and Performance of Microwave and Millimeter-wave High Efficiency Power Amplifiers

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title slide

Outline

BAE SYSTEMS

- Overview and motivation
- Solid state power device technologies
  - Bipolar
    - **Si BJT**
    - **GaAs HBT**
    - **InP HBT**
  - FET
    - **GaAs MESFET**
    - **GaAs PHEMT**
    - **InP HEMT**
    - **MHEMT**
    - **SiC MESFET**
    - **GaN HEMT**
- Circuit Design
- HPAs
  - Microwave
  - Millimeter-wave
- Summary

Why Are Power Transistors So Important?

BAE SYSTEMS

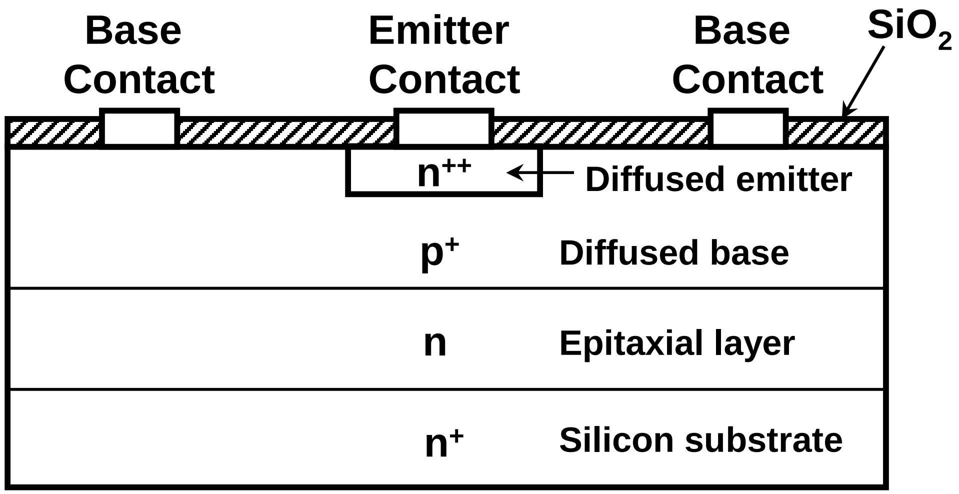
Power amplifiers typically *dominate* transmitter/system characteristics:

- **DC power consumption**
- **Power dissipation (heat) ⇨ thermal load**
- **Reliability ⇨ stressful operating conditions**
  - **High junction/channel temperature**
  - **High DC operating voltage (relative to other functions)**
  - **Large AC signals**
- **Cost**
  - **Power MMICs typically have largest chip area, highest chip count**
  - **Power MMICs typically are lowest yield, highest cost ($/chip, $/mm^2) of MMIC types due to large size, high periphery**

Silicon Bipolar Junction Transistor (BJT)

BAE SYSTEMS

- Most mature of microwave power transistors
- High power (hundreds of Watts) at up to 3.5 GHz
- Discrete transistors on conducting substrates -- parasitics limit frequency response
- 40V collector bias for typical high power device
- Reliability demonstrated: high voltage devices used in communication, navigation, DME, IFF, and radar systems

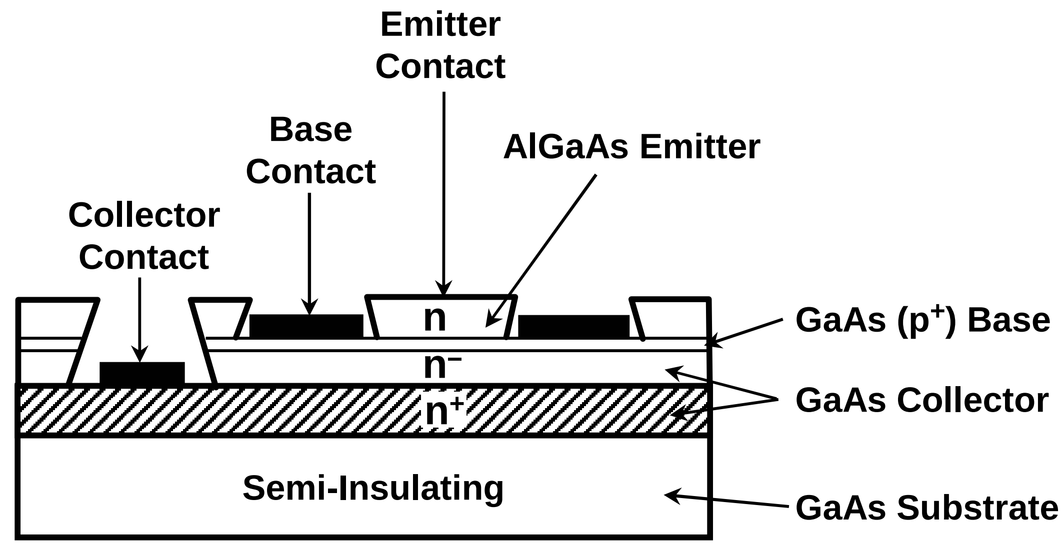


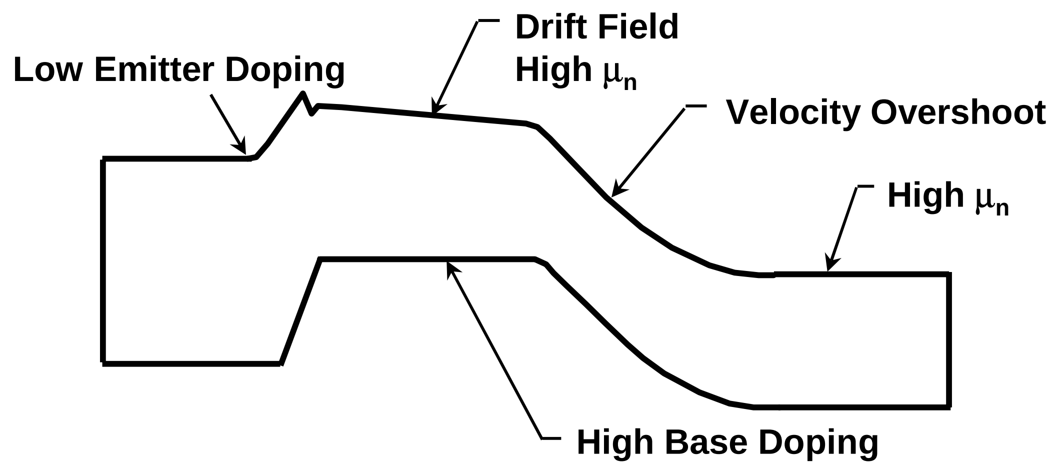
Most mature transistor, but limited frequency response

GaAs Heterojunction Bipolar Transistor (HBT)

BAE SYSTEMS

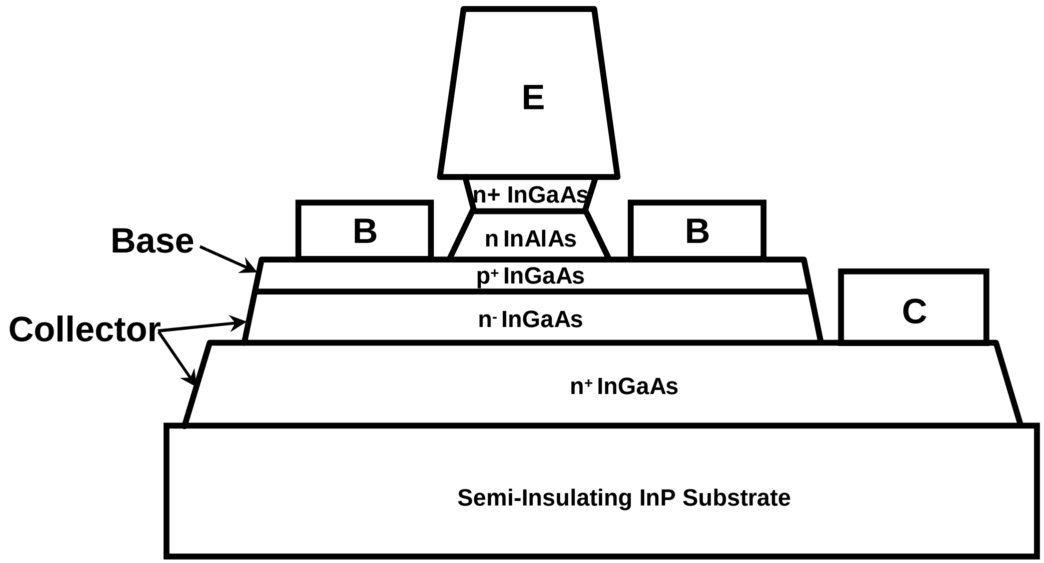
- First microwave HBTs circa 1981
- Based on AlGaAs/GaAs heterojunction
- Higher performance than Si bipolar due to:
  - Wide bandgap emitter enables high base doping, reduced base resistance
  - Emitter doping can be lowered, eliminating minority carrier storage, reducing base-emitter capacitance
  - High mobility, built-in fields and transient effects reduce electron transit times/parasitic resistances
  - Semi-insulating substrate reduces parasitics, enables MMICs
- Material grown by MBE or MOCVD
- Emitter fingers typically 0.7-2.0 µm wide
- Self-aligned base is common





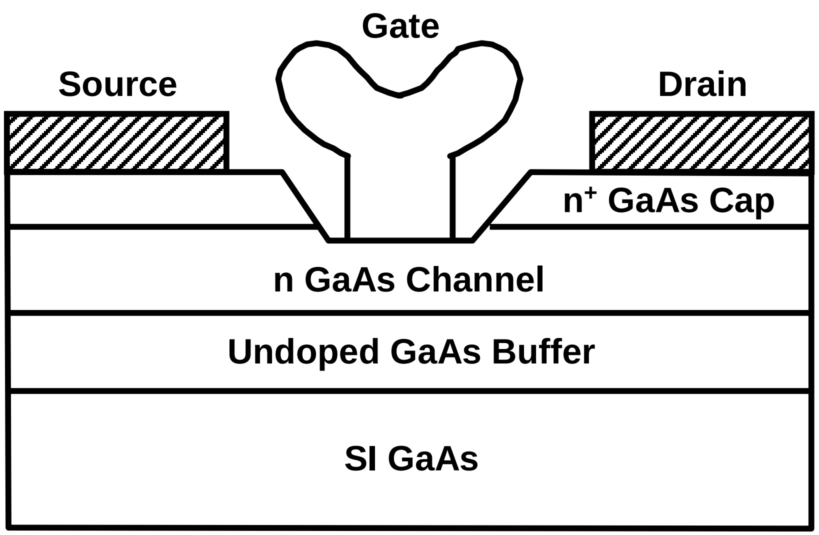
InP HBT

- Based on InGaAs/InAlAs heterojunction
- Compatible with detection of 1.30-1.55 µm light -- optoelectronic applications
- Lower turn-on voltage (0.2V) than GaAs HBT (0.8V)
- InP collector commonly used to improve breakdown (DHBT), 30-40% higher than GaAs HBT
  - Hafizi et al. (HRL), 1994 MTT Symp., pp. 671-674.
- 230 GHz f_{max}, 230 GHz f_t demonstrated
  - Yamahata et al. (NTT), 1995 GaAs IC Symp., pp. 163-166.
- Typical base layer 500-800 Å thick, doped at 3-10 $x10^{19}/cm^3$
- Emerging technology for cell-phone applications (outperforms GaAs HBT)



GaAs MESFET

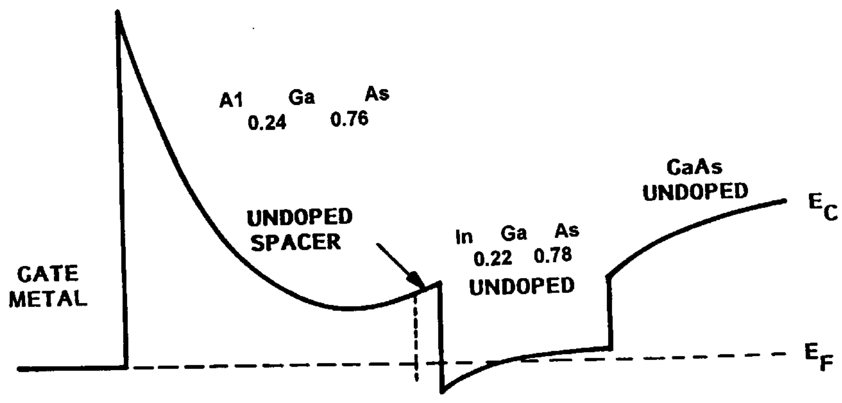
- "Grandfather" of GaAs transistors -- circa 1968
- Lowest cost of GaAs transistors
- Gate length typically 0.5 or 1.0µm -- usable for power amplifiers at up to 20 GHz
- Ion implanted or epitaxial material
- Electrons flow in doped channel region
- Planar process common -- implant isolation, no gate recess – M/A-Com SAGFET process
- Widely used since 1980's in discrete form -- internally-matched FET (IMFET)
- HFET uses low doped AlGaAs under gate to improve breakdown voltage (Saunier et al., 1992 MTT Symp., pp.635-638



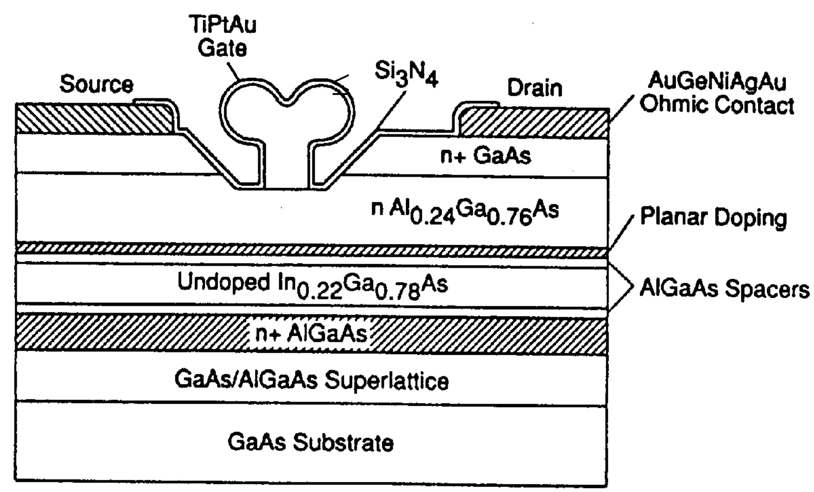
GaAs Pseudomorphic HEMT (PHEMT)

BAE SYSTEMS

- First demonstrated for microwave power in 1986
  - Henderson et al. (U. of Illinois/GE), 1986 IEDM, paper 17.7.
- $In_x Ga_{1-x}$ As channel, with $0.15 \leq x \leq 0.30$
  - Enhanced electron transport
  - Increased conduction band discontinuity, allowing higher channel current
  - Quantum well channel provides improved carrier confinement
- Power devices typically use "double heterojunction" layer structure
- Material grown by MBE or MOCVD
- Used for power amplifiers from 0.9 to 60 GHz
- Enhancement mode (E-mode) PHEMT for cell-phone PAs -- single supply voltage (Peatman et al., 2000 GaAs IC Symp., pp. 71-74)



Conduction Band Profile



Typical Power PHEMT

InP HEMT

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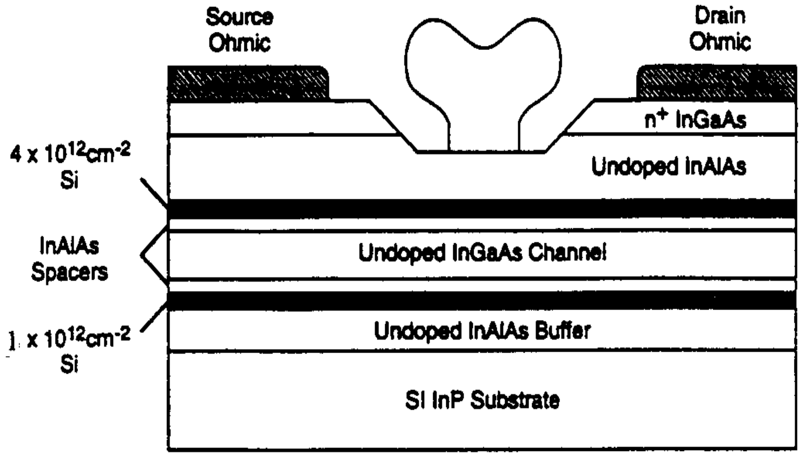
- Millimeter-wave operation first demonstrated in 1988 (low noise)
- Based on InGaAs/InAlAs material system on InP substrate
  - InGaAs channel with 53% In (lattice-matched) or up to 80% In (pseudomorphic)
  - Enhanced transport, large conduction band discontinuity
- High current (1A/mm), very high transconductance (1700 mS/mm) demonstrated
- Highest f_{tmax}, f_t of any transistor
  - 340 GHz f_t (Nguyen et al., IEEE Trans. Elec Dev., pp.2007-2014, 1992)
  - 600 GHz f_{max} (Smith et al., IEEE M&GW Lett., pp. 230-232, July 1995)
- Low breakdown for single recess devices due to low bandgap of InAlAs gate layer. Double-recess devices have been reported (S.C. Wang et al., IEEE Elec. Device Letters, pp. 335-337, July 2000)
- Superior PAE and power gain demonstrated at 20-94 GHz



InP Metamorphic HEMT (MHEMT)

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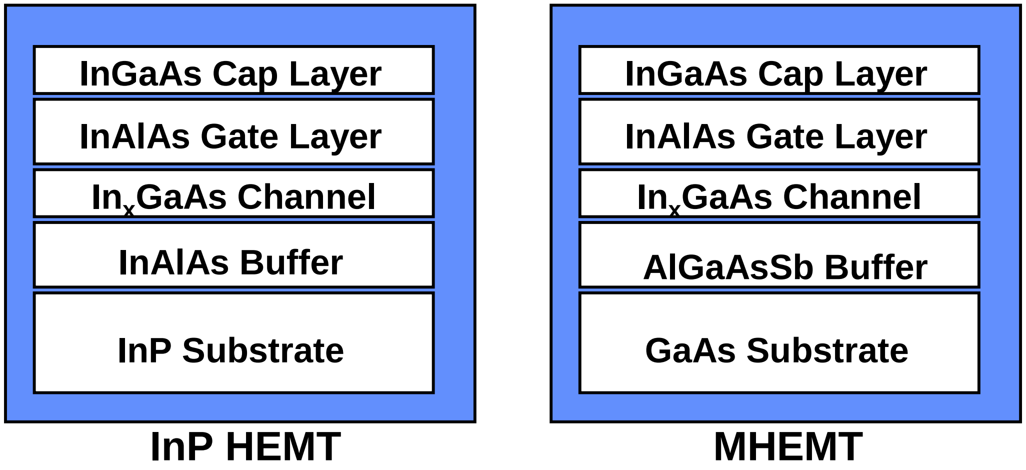
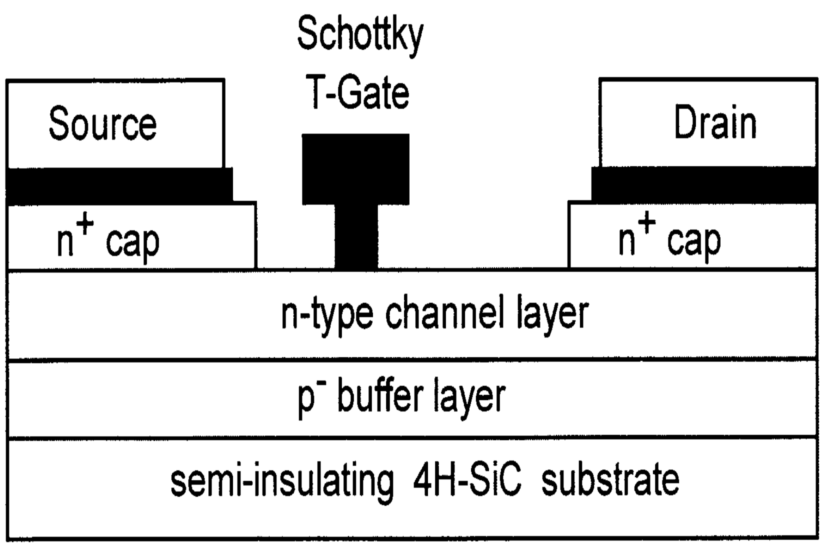


- InP HEMT on GaAs substrate for lower cost (6-inch wafer vs. 3 or 4-inch InP wafer)
- Allows GaAs backside processing/via etching (easier than InP)
- Significant lattice mismatch (4%) accommodated by thick (1µm) compositionally-graded buffer layer
- InP MHEMTs have demonstrated performance comparable to InP HEMTs:
  - DC transconductance (Higuchi et al., 1994 IEDM Tech. Dig., pp. 891-894)
  - 12 GHz noise figure -- 0.25dB for 0.1µm gate-length devices (Rohdin et al, 1995 IPRM, pp. 73-76)
  - MMIC LNA noise figure -- 2.0dB at 60 GHz, 2.8dB at 89 GHz (BAE SYSTEMS)
  - Power performance -- 41% PAE at 60 GHz for 1-stage MMIC (BAE SYSTEMS)

SiC MESFET

BAE SYSTEMS

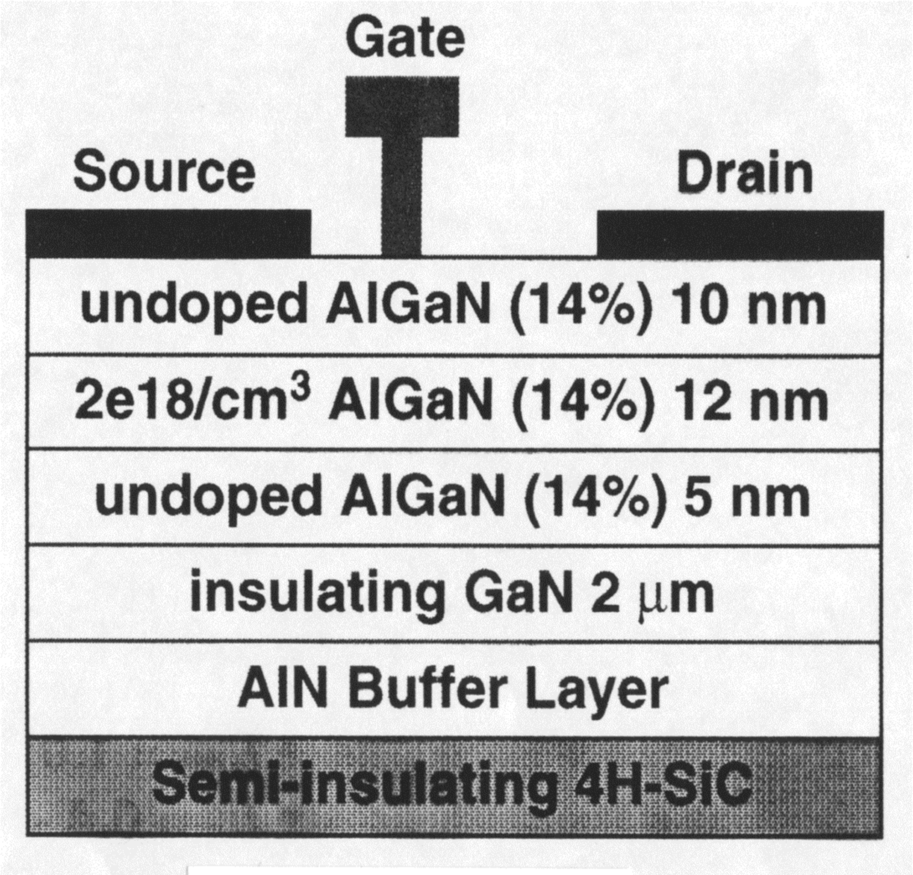
- 4H-SiC substrate with extremely high resistivity and thermal conductivity
- SiC substrates small ($\leq$ 3-inch), costly, defect density has improved significantly in last 5 years
- Typical DC characteristics for Cree SiC MESFET: V_{br} > 120V, $V_k \approx$ 10V, g_m = 50mS/mm
- 50 GHz f_{max}, 18 GHz f_t @ 40V for 0.4µm gate-length device
- Up to 3W/mm power density demonstrated
- SiC MESFET frequency response limited by low electron mobility -- 350-400 cm ^{2}/V-sec



- Commercial products offered by Cree: die or packaged 10W, 30W, 60W discrete and MMIC foundry service

GaN HEMT

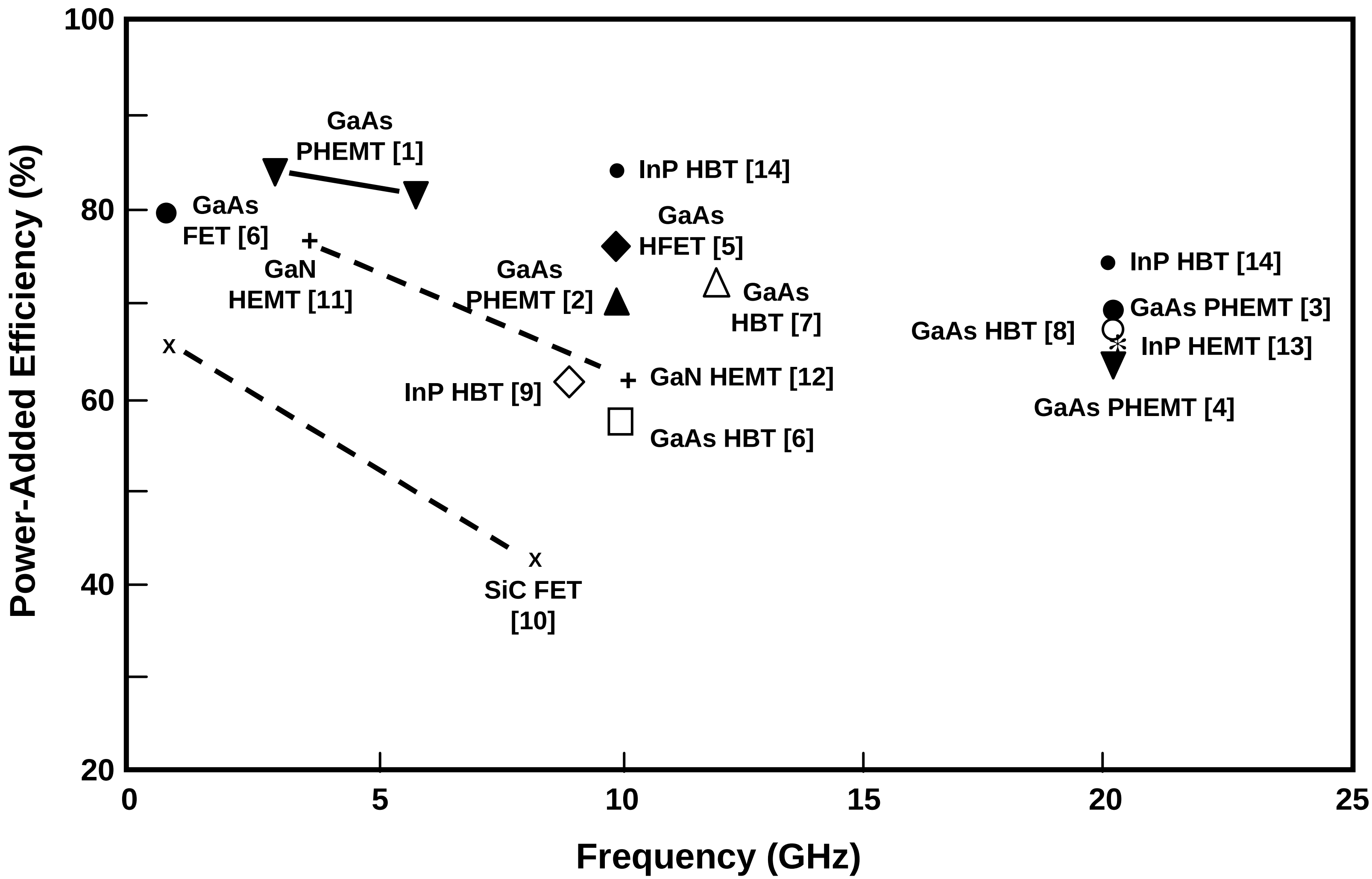
BAE SYSTEMS



- Grown on SiC or sapphire substrates, SiC preferred for thermal conductivity/ lattice mismatch (work on AlN and GaN substrates in progress)
- Heterojunction with undoped channel
- Electron mobility μ = 1500 cm^2/V-sec
- High surface defect density (10^7-10^8/cm^2)
- First GaN HEMT MMIC reported in 2000: Sheppard et al., Cornell Conf.
- Frequency response much better than SiC (due to higher mobility) f_t of 67 GHz, f_{max} of 140 GHz (Chu, 1998)
- Very high power density demonstrated -- 7W/mm with 52% PAE and 10.7dB gain at 10 GHz (Sheppard et al. (Cree), Device Research Conf., June 1988)

Best Reported Microwave Transistor Efficiencies

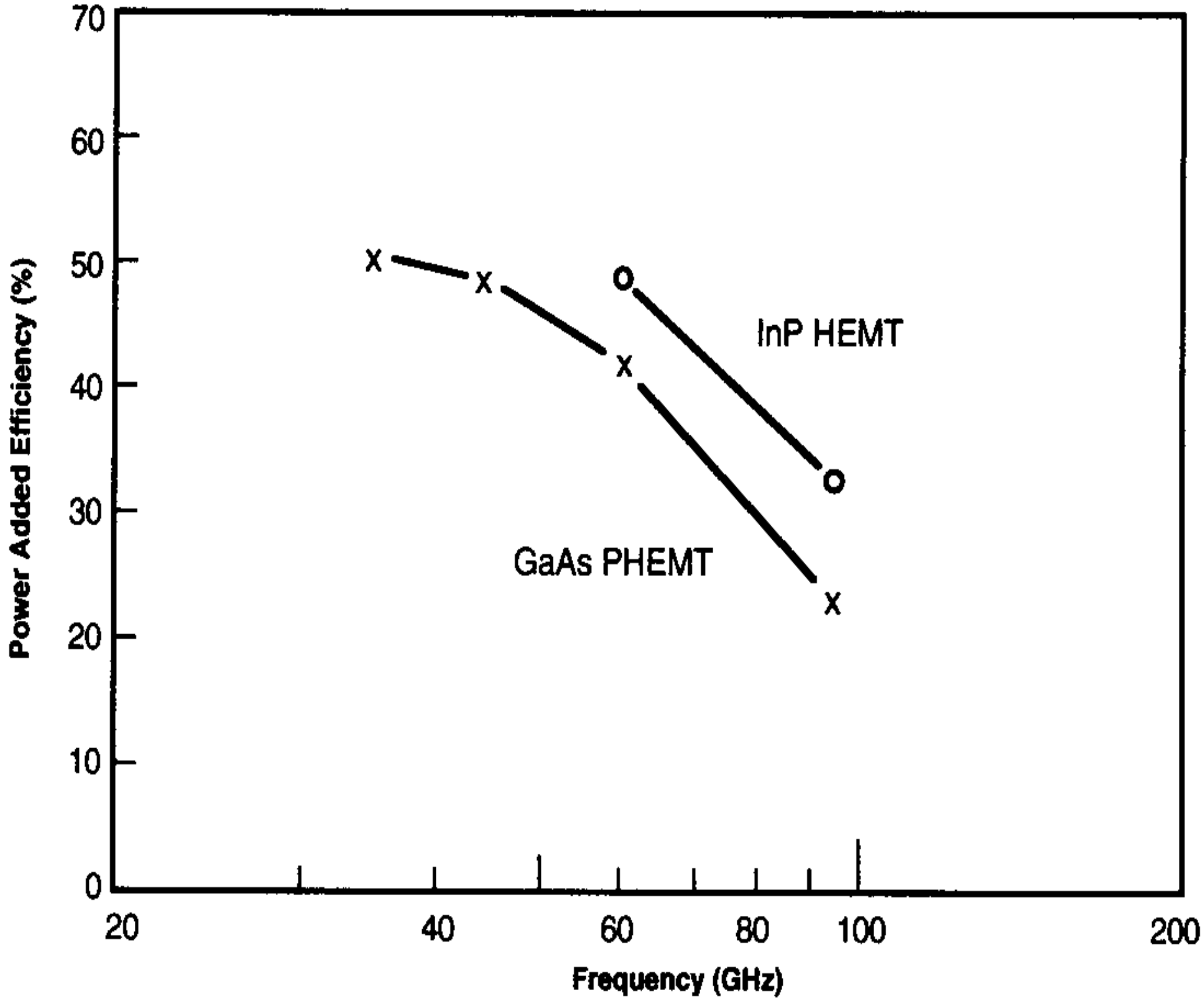
BAE SYSTEMS



High Gain Enables High Efficiency Modes of Operation: Class AB2, Class B, Class C, Class F

Millimeter-wave Transistor Efficiencies

BAE SYSTEMS



Gain Limited: Class AB1, Class A

Integration to Higher Power Levels

BAE SYSTEMS

Intrinsic Device (single finger)

Small periphery (gate/emitter)
Short gate/emitter fingers
Low parasitics

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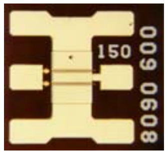
Power Transistor "Cell"



"Building block" for higher power
Longer fingers
Characterized for power amplifier design

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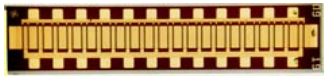
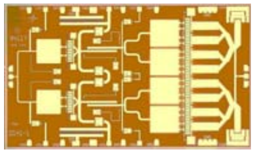


Discrete device: all matching off-chip

Hybrid Power Amplifier / **Power MMIC**



Full MMIC: all matching on-chip

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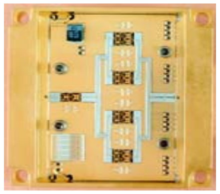
Module



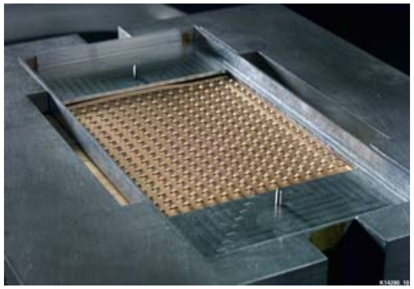
Power amplifier or T/R module
MIC power combining
(typ. 2 to 8-way)

Waveguide/Radial Combiners
W/G: 2 to 32-way
Radial: to 128-way

Constrained Combining (Plumbing)

Spatial Combining (Phased Array/ Quasioptics)

Each MMIC feeds separate radiating element
(typ. 100s-1000s of elements)

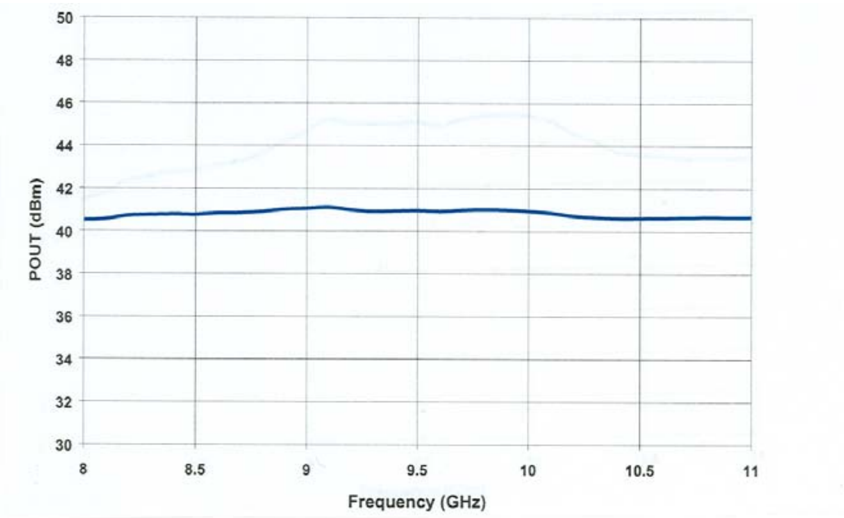


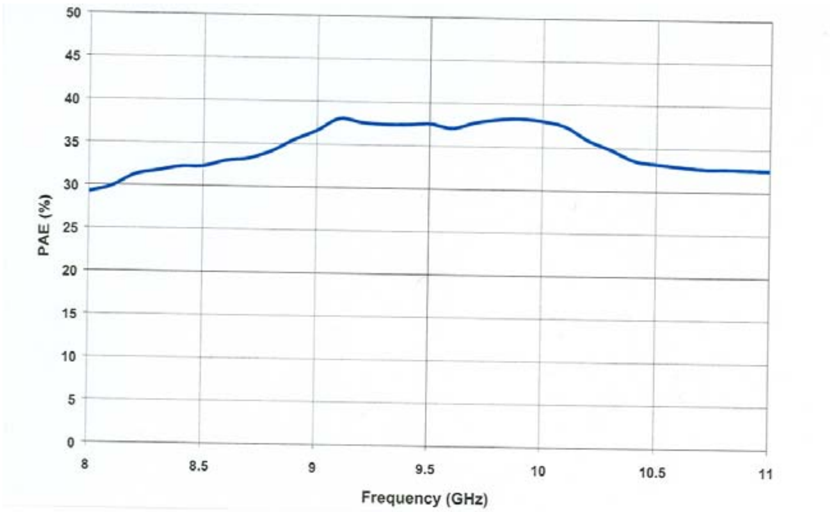
Power Amplifier Design Process

BAE SYSTEMS

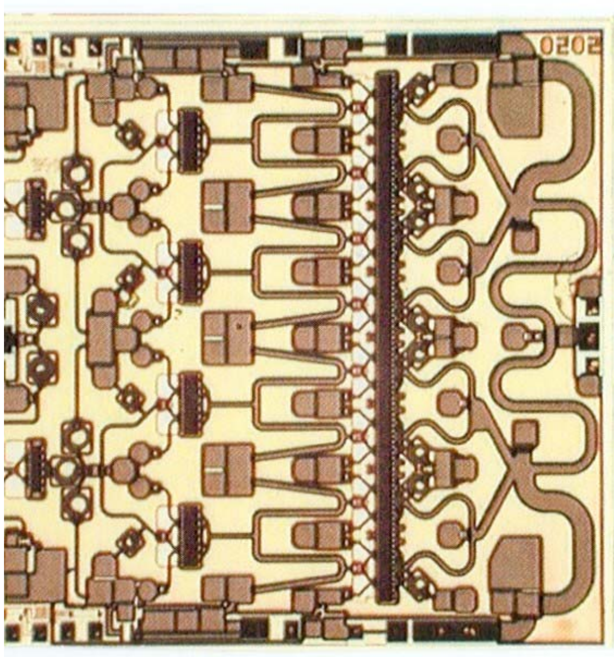
- Device Cell Characterization & Modeling
  - DC & Pulse IV
  - Small Signal S-parameters
  - Load Pull (Optimum Load)
  - Non-linear Model
- Circuit Design
  - Select Topologies & Implementation
  - Output Match & Harmonic Terminations
  - Interstage Match (Gain/Power Transfer Compromise)
  - Input Match (VSWR/Flatten Gain)
  - Stability (Even, Odd, Parametric)
  - Harmonic Balance
  - Repeat as necessary

X-Band High Power Amplifier (MA08509D)





- **Process:** **MSAG MESFET**
- **Applications:** **Radar**
- **Frequency Range: 8 to 11 GHz**
  22 dB Power Gain
  +41 dBm Psat
  32% PAE (3.9 A @ Psat)
  10 V @ 2.7 A Bias
- **Chip Size:**
  4.58 mm x 4.58 mm x 0.075 mm



GaAs MESFET HPAs

BAE SYSTEMS

Frequency (GHz)	Discrete/ MMIC	Output Power (W)	PAE (%)	Power Gain (dB)	Reference
1.5	Discrete	17	68	14	Tsutsui et al., 1998 MTT Symp., pp. 715-718
1.5	Discrete	51	54	12.3	Ono et al., 1996 GaAs IC Symp., pp.103-106
2.1	Discrete	240	54%	7.8	Inoue et al., 2000 MTT Symp., pp. 1719-1722
2.2	Discrete	102	47	11	Ebihara et al., 1998 MTT Symp., pp. 703-706
2.5	Discrete	31	60	13	Takenaka et al., 1997 MTT Symp., pp. 1417-1420
3-6	MMIC	15-29	23-35	10-13.5	Komiak et al., 1992 GaAs IC Symp., pp. 187-190
4.3-5.4	MMIC	12-14	50-60	-	Pribble et al., 1996 Monolithic Symp., pp. 25-28
14	Discrete	20	30	7	Saito et al., 1995 MTT Symp., pp. 343-346

Very high power (up to 240W), but limited to 14 GHz and below

GaAs HBT HPAs

BAE SYSTEMS

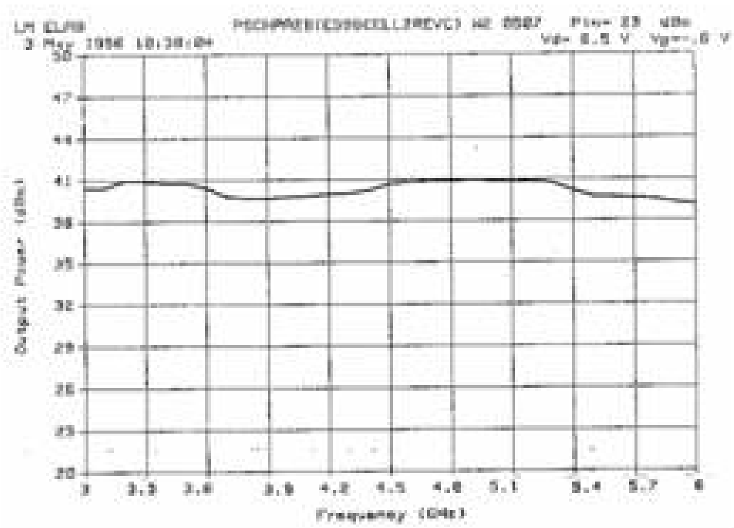
- High intrinsic device efficiency demonstrated at up to 20 GHz
- High-power MMICs with good efficiency demonstrated at up to 20 GHz

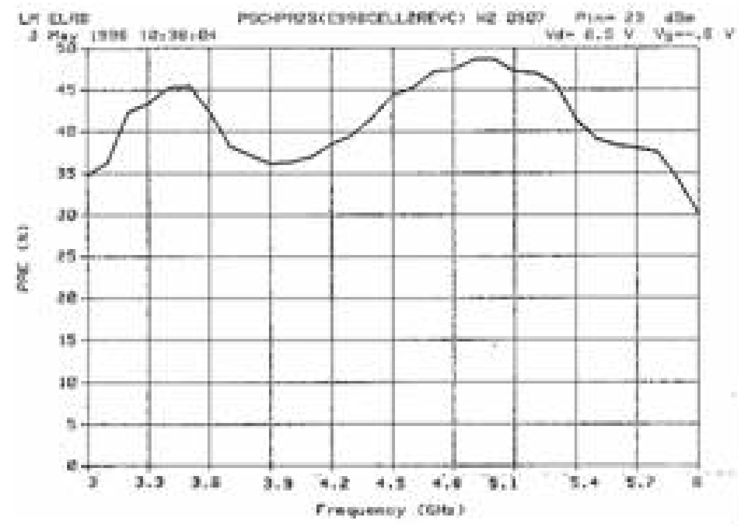
Frequency (GHz)	Power (W)	PAE (%)	Reference
8-14	2.8-3.8	37-51	Salib et al. (NG), 1998 MTT Symp., pp.581-584.
7-11	4.5-7.3	38-56	Komiak and Yang (LM), 1995 Monolithic Symp., pp. 17-20
8.3-10	9.0-12.5	38-51	Khatibzadeh et al. (TI), 1994 Monolithic Symp., pp.117-120
6-18	1.3-2.5	18-37	Salib et al. (NG), M&GW Letters, pp. 325-326, Sept. 1998

- Excellent linearity for low-voltage phone application:
  - 2-stage PA with 63% PAE, 1.3W P_{out}, -52 dBC ACP at 50 KHz offset at 1.5GHz, 3.5V (Iwai et al. (Fujitsu), 1998 MTT Symposium, pp. 435-438)
  - WCDMA -- 0.5W P_{out}, 42% PAE, 30dB gain, -38dBC ACP at 1.95 GHz (Iwai et al. (Fujitsu), 2000 MTT Symposium, pp. 869-872.)
- High-volume commercial product for handsets -- TRW/RFMD

S/C-Band High Power Amplifier

BAE SYSTEMS

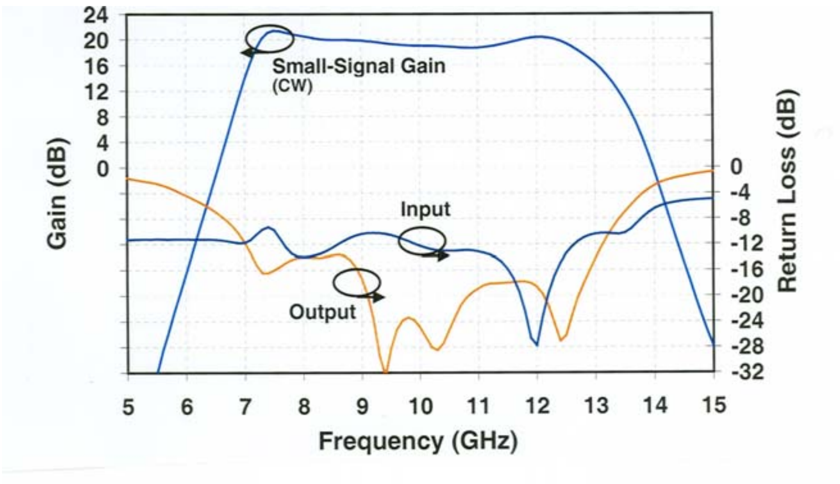


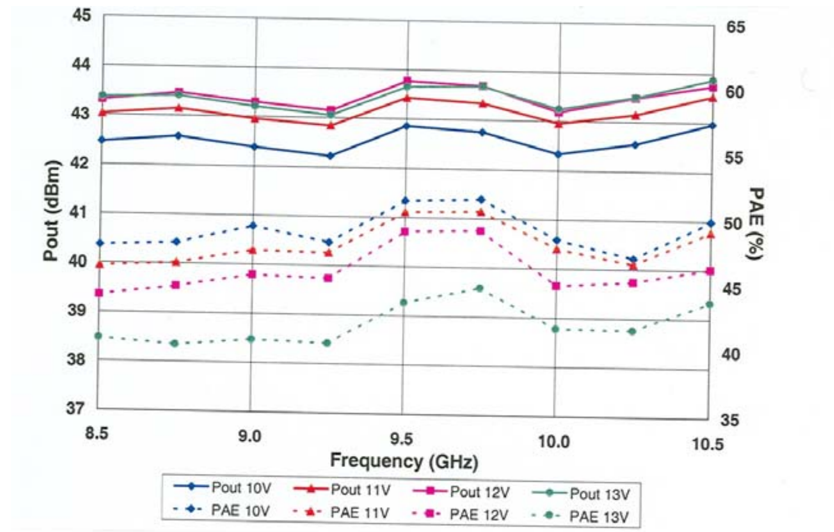


- **Process:** **0.25 um DR PHEMT**
- **Applications:** **EW, Radar**
- **Frequency Range: 3 to 6 GHz**
  - **18 dB Power Gain**
  - **+41 dBm Psat**
  - **31 to 55% PAE**
  - **6.5 V @ 4 A Bias**
- **Chip Size:**
  - **4.65 mm x 6.15 mm x 0.1 mm**

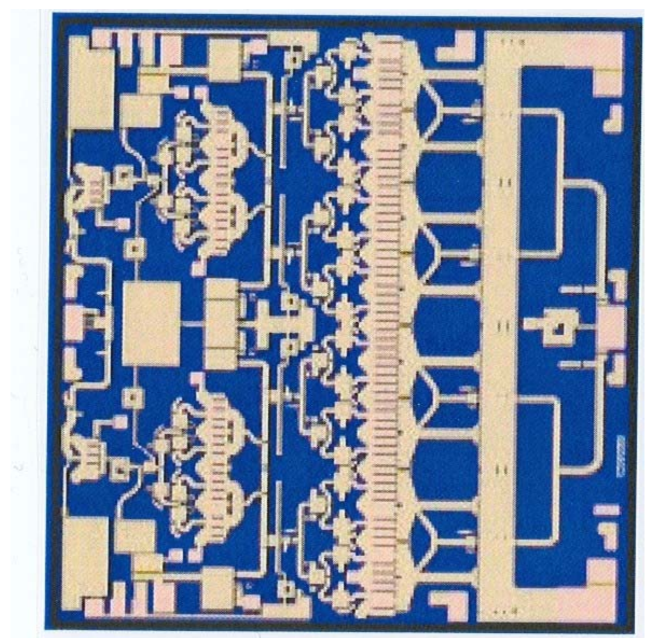
8 mm - 32 mm

X-Band High Power Amplifier (TGA2517)





- **Process:** **0.35 μm 3MI Double Recess PHEMT**
- **Applications:** **Radar**
- **Frequency Range: 8.5 to 10.5 GHz**
  19 dB Gain
  +43 dBm Psat
  >40% PAE
  12 V @ 3 A Bias
- **Chip Size:**
  4.07 mm x 4.33 mm x 0.1 mm



2 x 0.6 mm – 2 x 2.4 mm – 19.2 mm

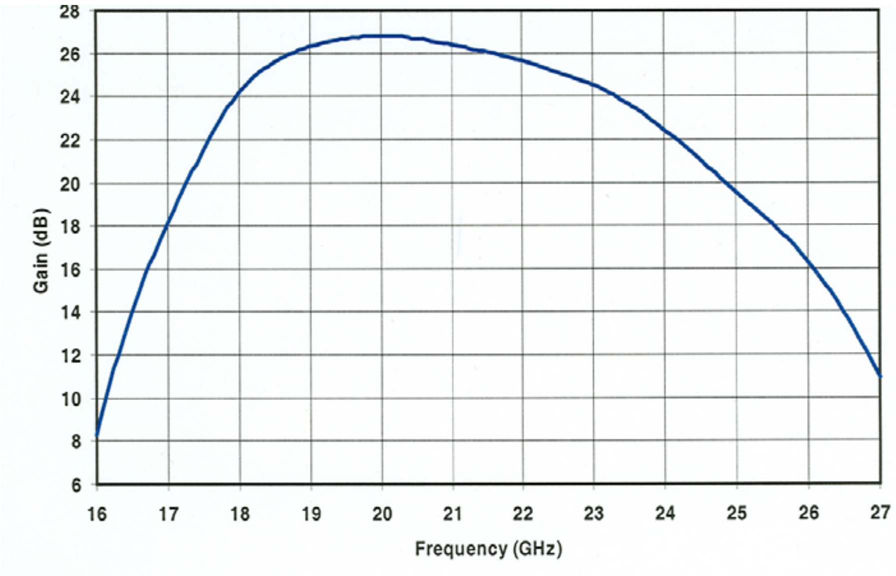
Microwave GaAs PHEMT HPAs

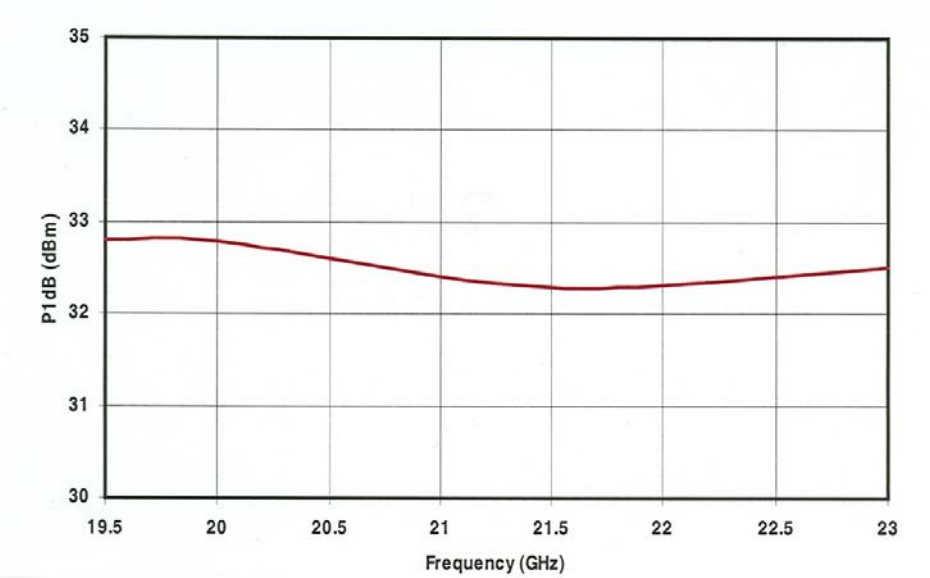
BAE SYSTEMS

Frequency (GHz)	Discrete/ MMIC	Output Power (W)	PAE (%)	Power Gain (dB)	Reference
0.85	Discrete	1.4	72	12	Nair et al., 1996 Monolithic Symp., pp. 17-20
2.1	Discrete	140	51	10	Takenaka et al., 2000 MTT Symp., pp. 1711-1714
2.2	Discrete	20	66	14	Pusl et al., 1998 MTT Symp., pp . 711-714
2.6-3.3	MMIC	21-24	40-43	26	Murae et al., 2000 MTT Symp., pp. 943-946
3-6	MMIC	8.9-17	31-55	16.5-19.3	Komiak et al., 1997 MTT Symp., pp. 1421-1424
5.4	MMIC	7.4	50	24dB	Butel et al., 2000 GaAs IC Symp., pp. 215-218
7-11	MMIC	3-6	31-60	11.8-14.8	Wang et al., 1996 GaAs IC Symp. pp. 111-114
7.4-8.4	MMIC	3.2	50-60	24	Chu et al., 2000 MTT Symp., pp. 947-950
8-14	MMIC	2.5-4.0	31-50	17-21	Cardullo et al., 1996 Monolithic Symp.,pp. 163-166
12	Discrete	15.8	36	7.6	Matsunaga et al., 1996 MTT Symp, pp. 697-700
6-18	MMIC	2.3-4.5	10-30	20.5-27.5	Barnes et al., 1997 MTT Symp., pp. 1429-1432

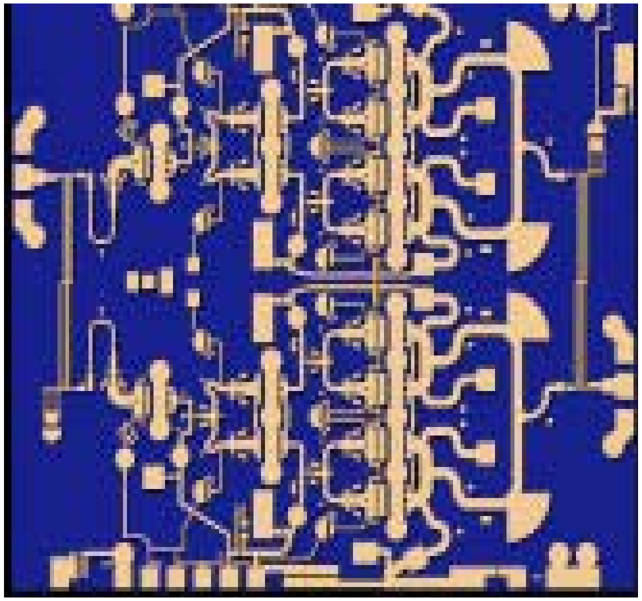
K-Band High Power Amplifier (TGA4022)

TriQuint SEMICONDUCTOR



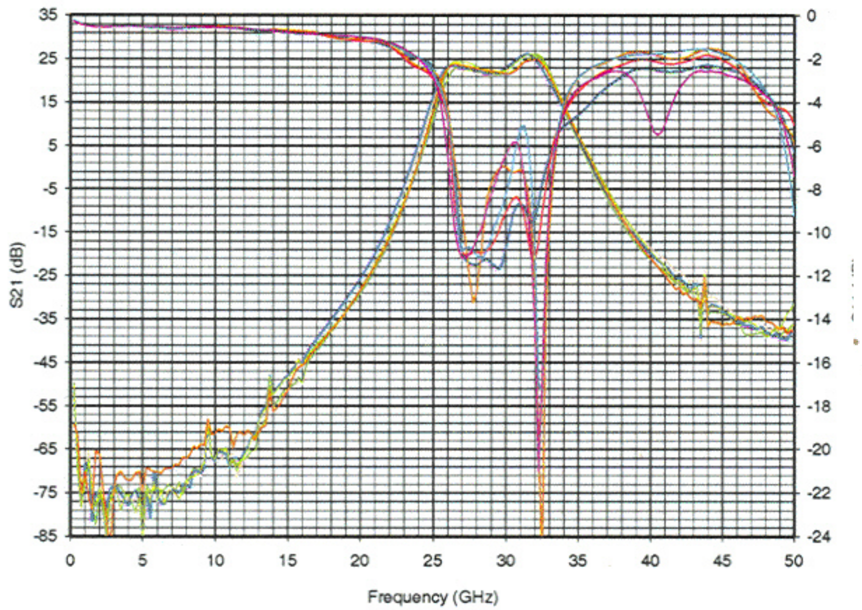


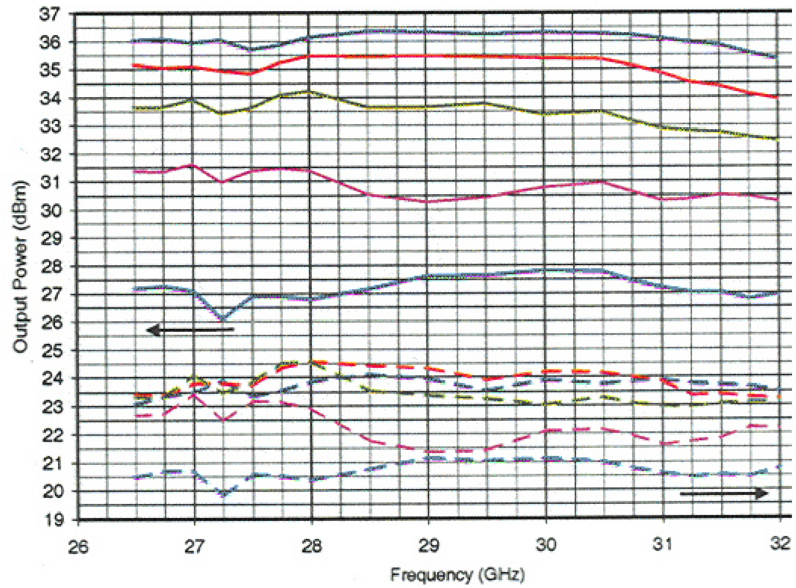
- **Process:** **0.25 µm 2MI Double Recess PHEMT**
- **Applications:** **Point-to-Point Comm, K-Band SatCom**
- **Frequency Range: 18 to 23 GHz**
  - **26 dB Gain**
  - **+32.5 dBm P1dB**
  - **15 dB Return Loss**
  - **38 dBc @ +20 dBm SCL**
  - **7 V @ 840 mA Bias**
- **Chip Size:**
  - **3.65 mm x 3.14 mm x 0.1 mm**



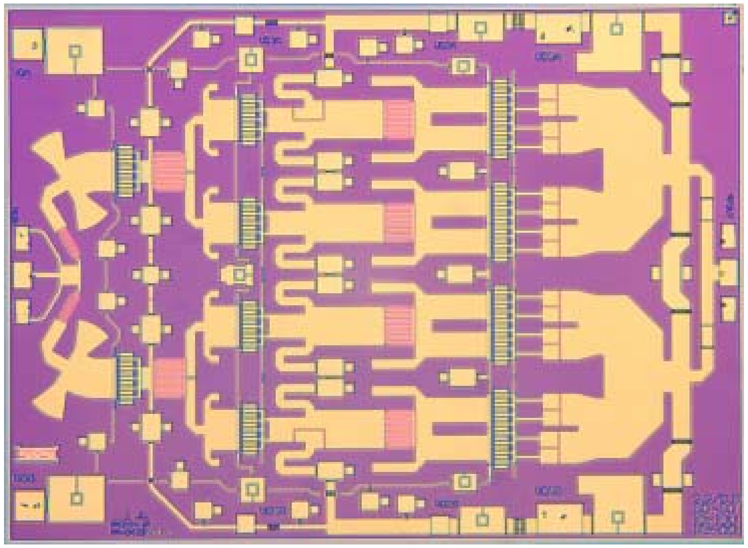
2 x [0.6 mm - 1.2 mm - 2.4 mm]

4 Watt Ka-Band PHEMT Power Amplifier MMIC





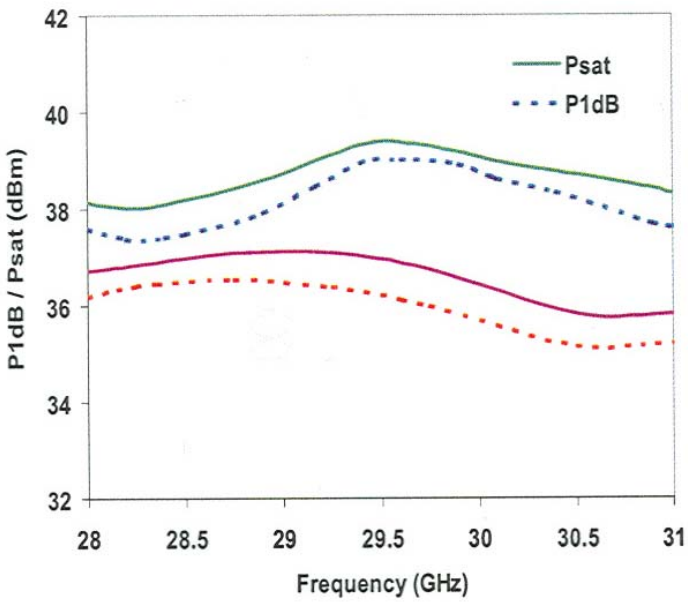
- **Process:** **0.2 μm Double Recess PHEMT**
- **Applications:** **Point-to-Point Comm, Ka-Band SatCom**
- **Frequency Range: 26.5 to 31.5 GHz**
  - **22 dB Gain**
  - **+36 dBm Psat**
  - **28% PAE (2.4 A @ Psat)**
  - **40 dBc @ +20 dBm SCL**
  - **6 V @ 1.8 A Bias**
- **Chip Size:**
  - **4.8 mm x 3.4 mm x 0.05 mm**

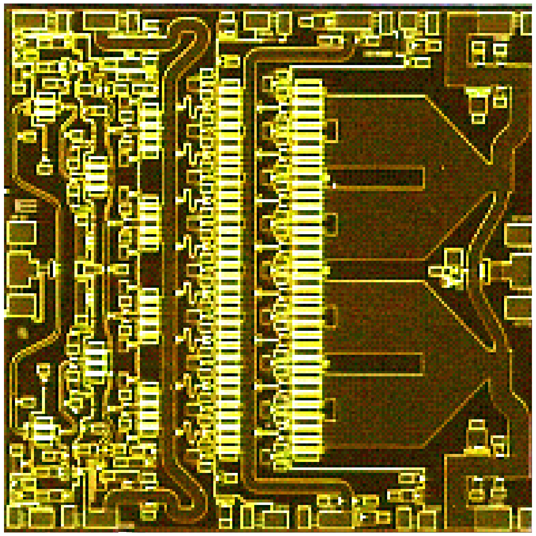


2 mm – 4 mm - 6.4 mm

4 & 6 Watt Ka-Band Power Amplifier MMICs

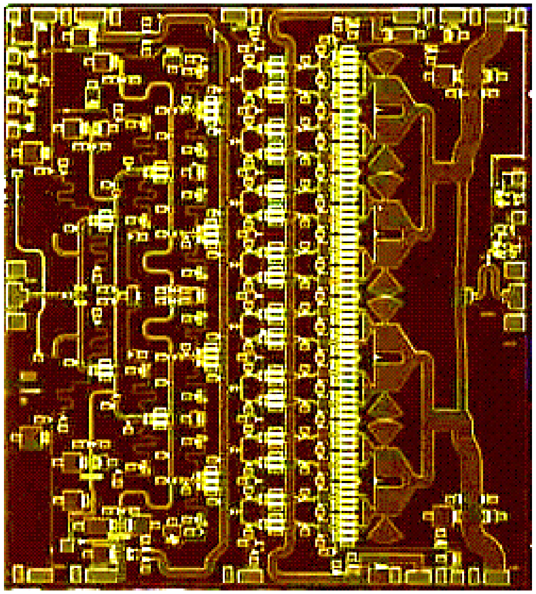
US Monolithics®





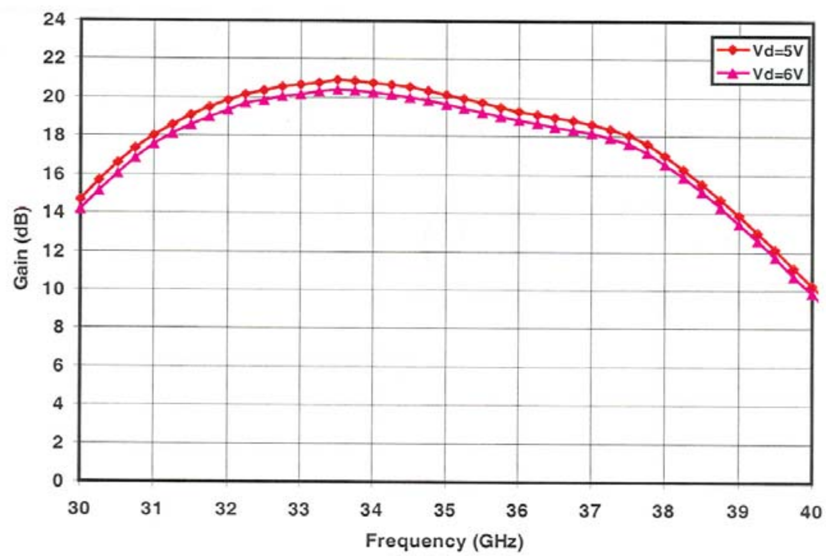
0.8 mm – 1.2 mm - 2.88 mm – 7.04 mm – 9.6 mm

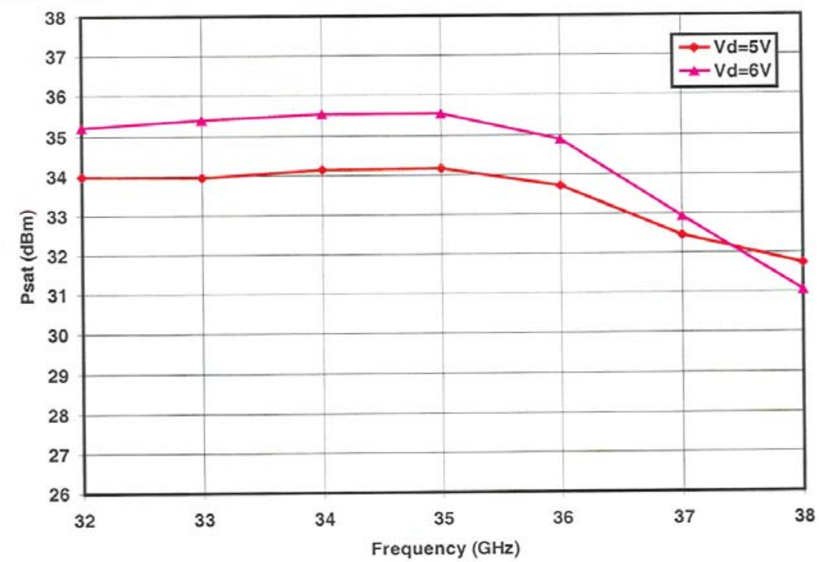
- **Process:** **0.15 µm Double Recess PHEMT**
- **Applications:** **Point-to-Point Comm, Ka-Band SatCom**
- **Frequency Range: 28 to 31 GHz**
  30 dB Gain
  +36 and +38 dBm Psat
  5 V @ 150 mA/mm Bias
- **Chip Area:**
  9.86 mm² (4 Watt)
  21 mm² (6 Watt)



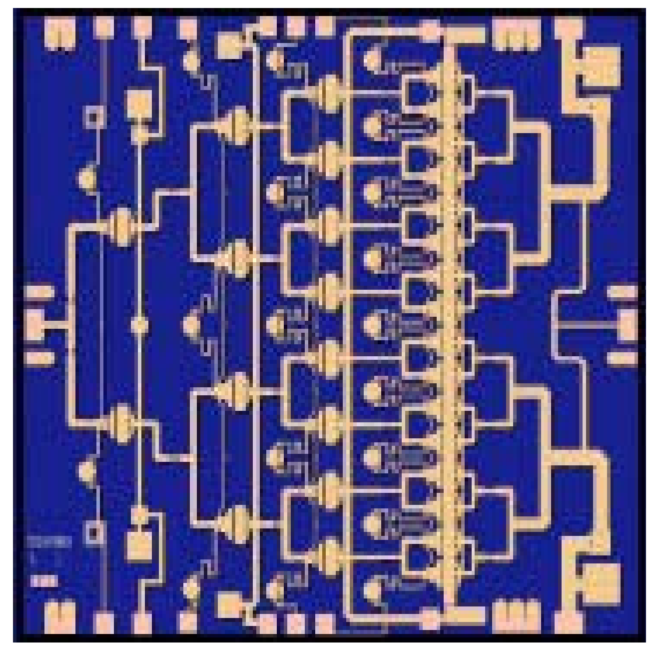
0.8 mm – 0.8 mm – 2.4 mm – 7.2 mm – 14.72 mm

Ka-Band Power Amplifier (TGA4517)





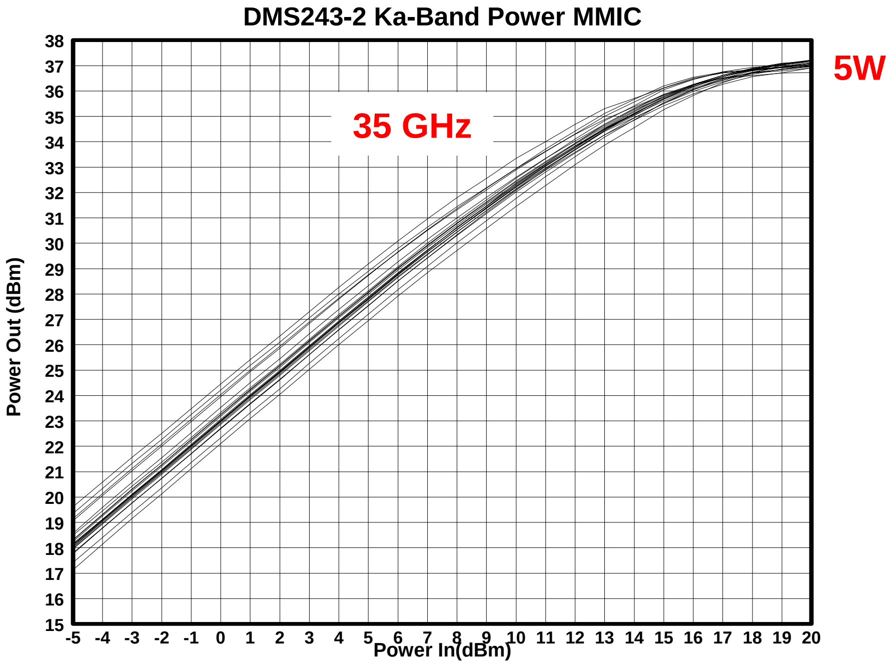
- **Process:** **0.15 µm 3MI Double Recess PHEMT**
- **Applications:** **Point-to-Point Comm, Ka-Band SatCom, Radar**
- **Frequency Range: 31 to 36 GHz**
  - **17 dB Gain**
  - **+35 dBm Psat**
  - **12% PAE (4.4 A @ Psat)**
  - **6 V @ 2A Bias**
- **Chip Size:**
  - **4.35 mm x 3.9 mm x 0.05 mm**

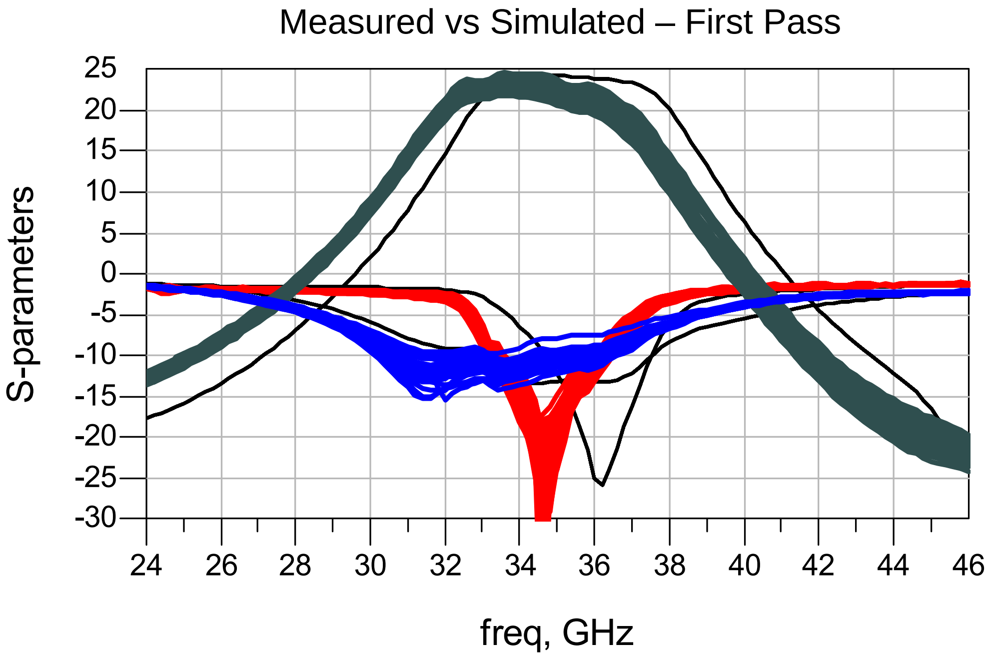


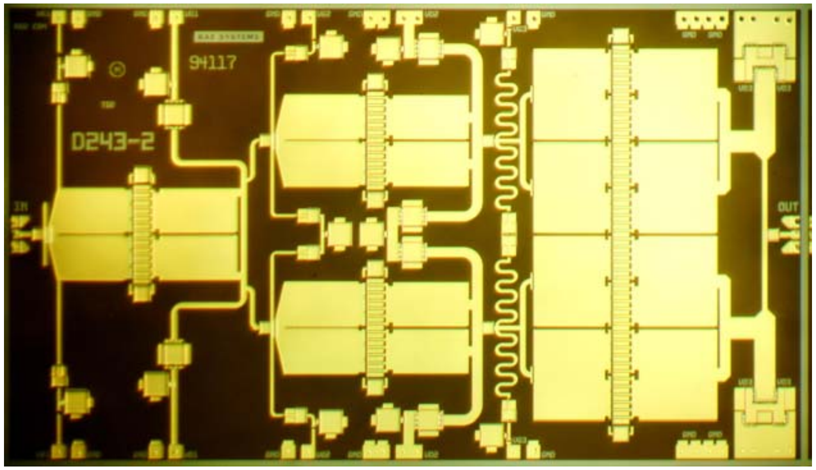
1.5 mm – 3 mm – 6 mm – 12 mm

Ka-Band PHEMT Power MMIC

BAE SYSTEMS





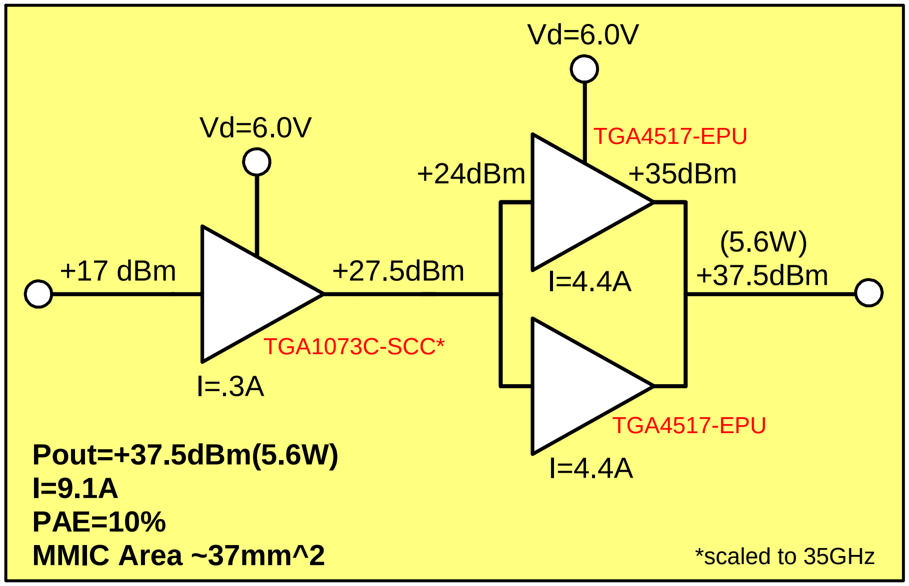


- **Process: 0.1 µm Single Recess PHEMT (2 mil)**
- **Application: Ka-Band seekers/radar**
- **MMIC measured performance:**
  5W @ 16% PAE (on wafer)
  6W @ 20% PAE (on carrier)

0.15 um DR vs 0.1 um SR PHEMT Comparison

BAE SYSTEMS

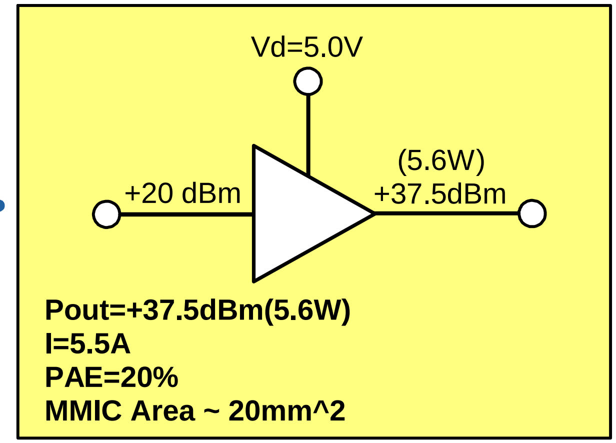
Triquint 35GHz



TGA4517-EPU is highest power Triquint 35GHZ MMIC

3 MMIC's into 1

BAE SYSTEMS 35GHz MMIC



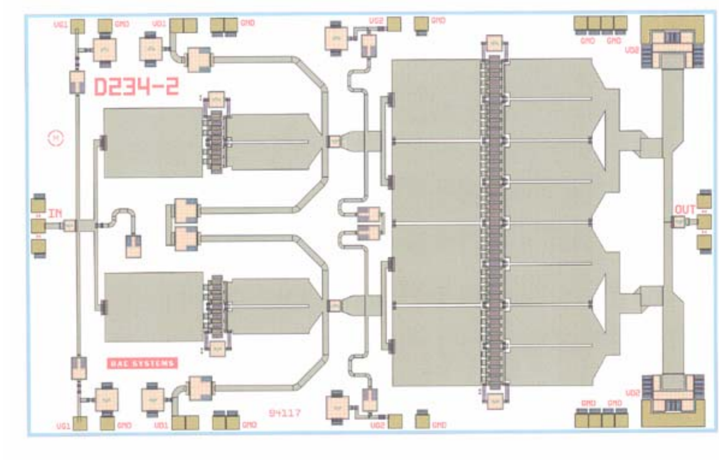
.1um Space Qualified pHEMT Process

Same output power, 2X overall efficiency, 46% less GaAs, reduced module complexity--no combiner/divider, fewer substrates and reduced assembly/tune time

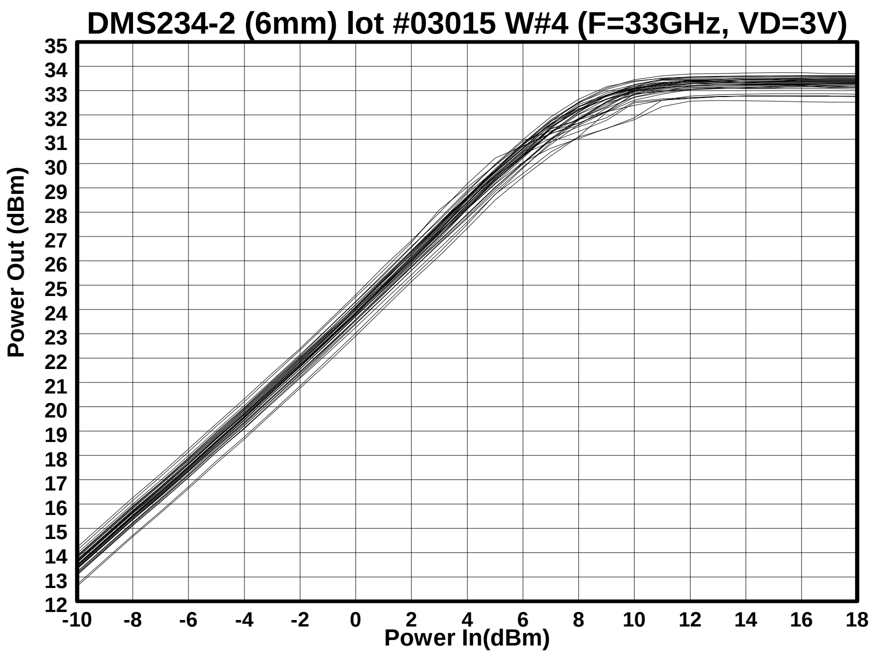
0.1 um SR MMIC enables significant cost savings, reduced size/weight/DC power

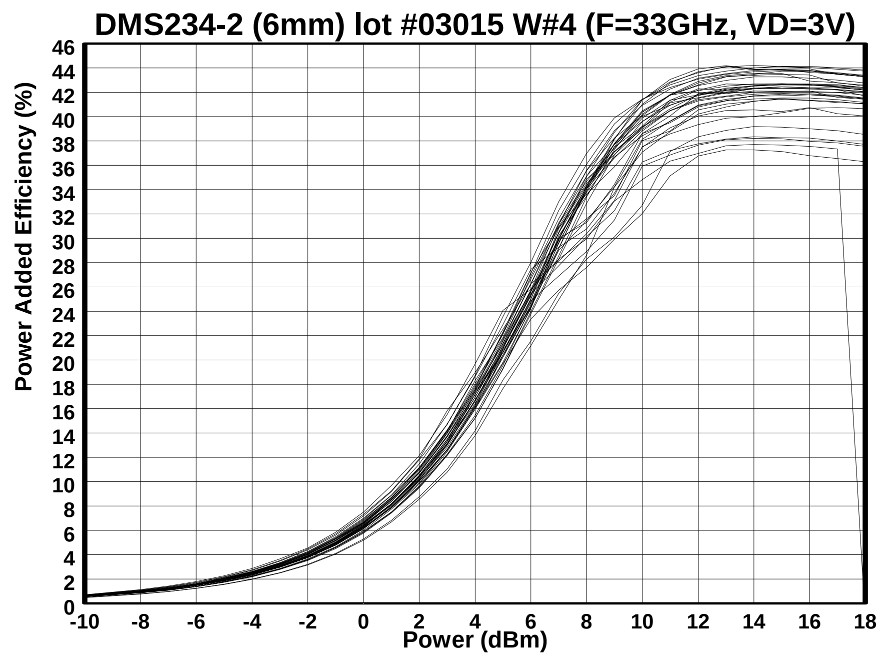
32-35 GHz 2W MHEMT MMIC

BAE SYSTEMS



- 0.1µm power MHEMT process (2 mil)
- 2-stage design
- Chip size: 3.1mm x 5.1mm
- Measured Performance:
  - 23-27dB small-signal gain, 30.5-35GHz
  - 33-33.7dBm (2.0-2.3W) Psat with 21-22dB power gain, 42-44% PAE

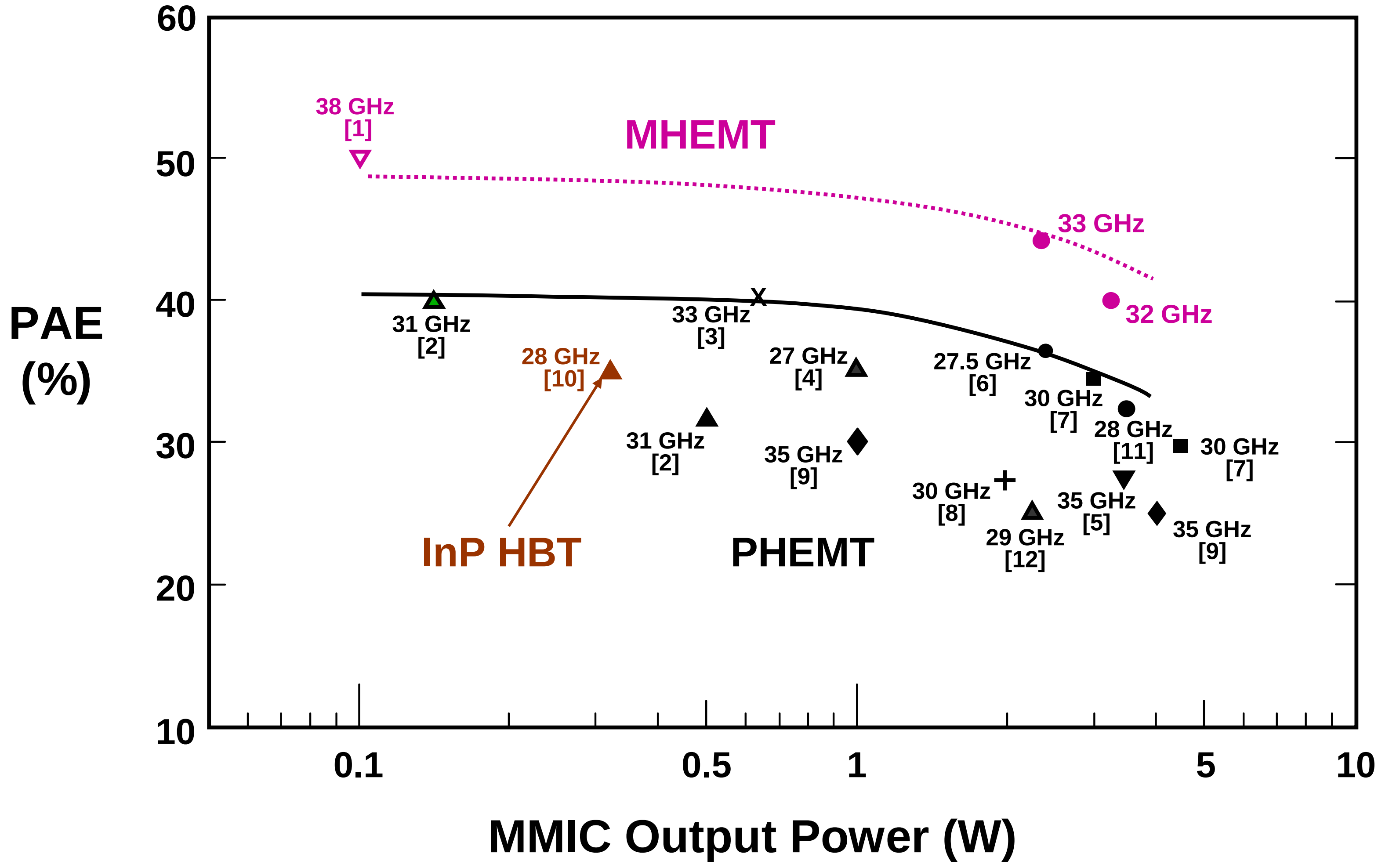




higher gain, power, and PAE

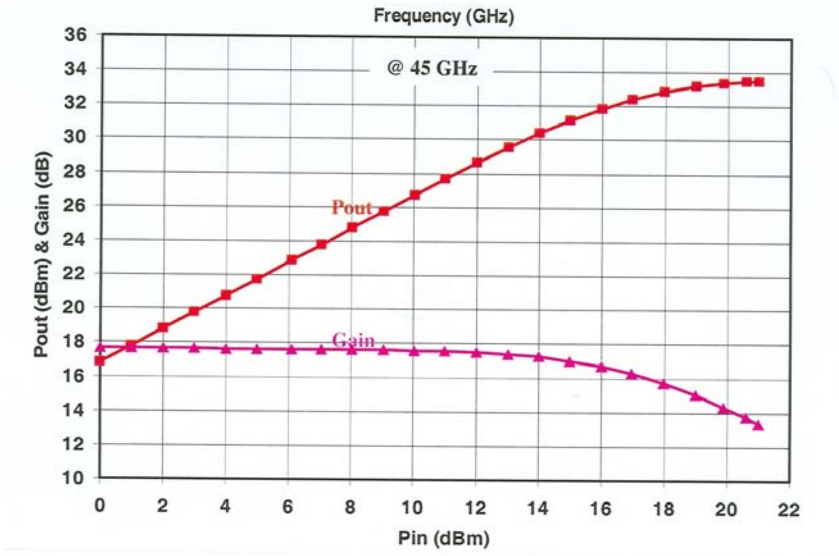
MMIC State of the Art at ~30 GHz

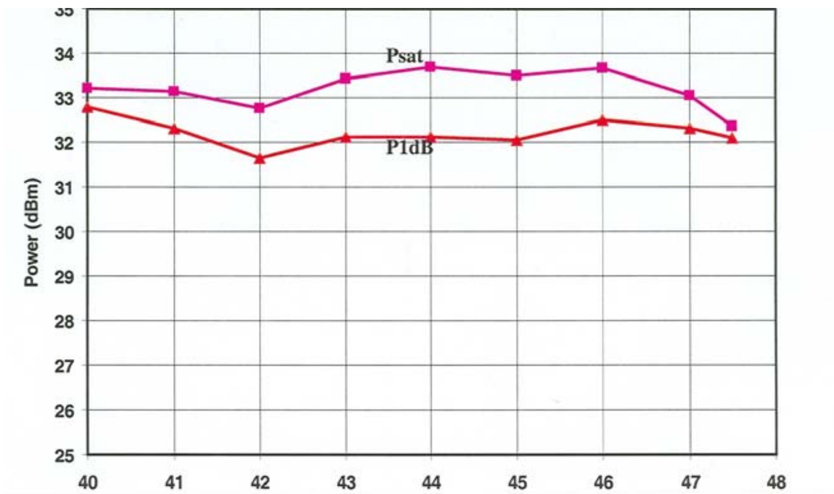
BAE SYSTEMS



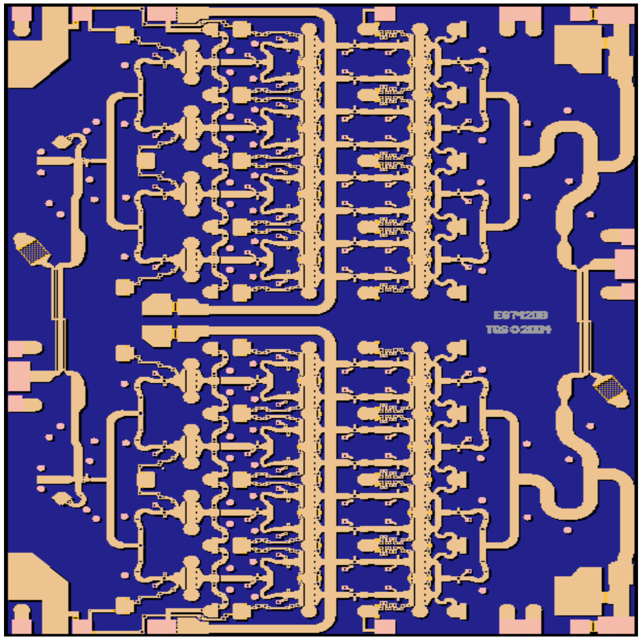
MHEMT MMICs outperform best reported PHEMT MMICs at ~30 GHz

2 W Q-Band High Power Amplifier (TGA4046)





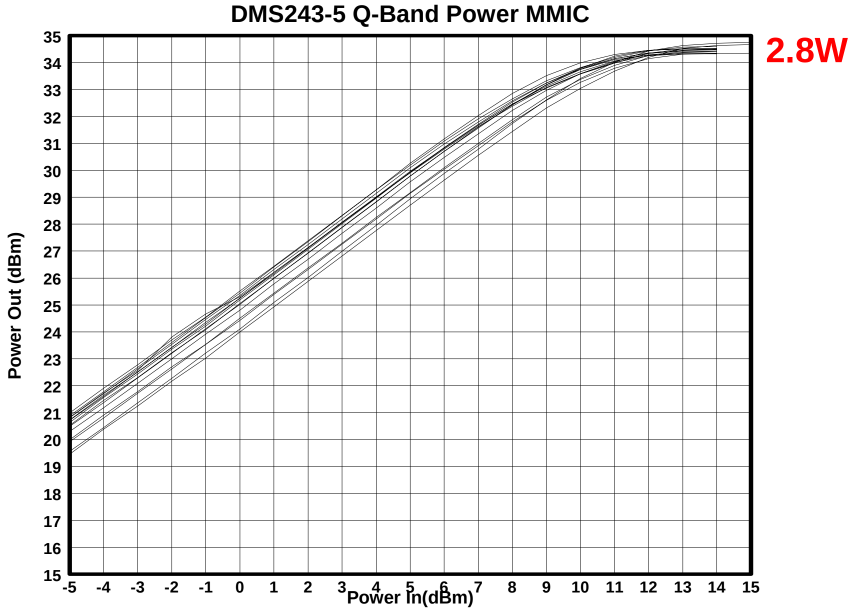
- **Process:** **0.15 μm 3MI Double Recess PHEMT**
- **Application:** **Q-Band SatCom**
- **Frequency Range: 41 to 46 GHz**
  15 dB Gain
  +33 dBm Psat
  14% PAE (2.6 A @ Psat)
  6 V @ 2A Bias
- **Chip Size:**
  3.45 mm x 4.39 mm x 0.10 mm

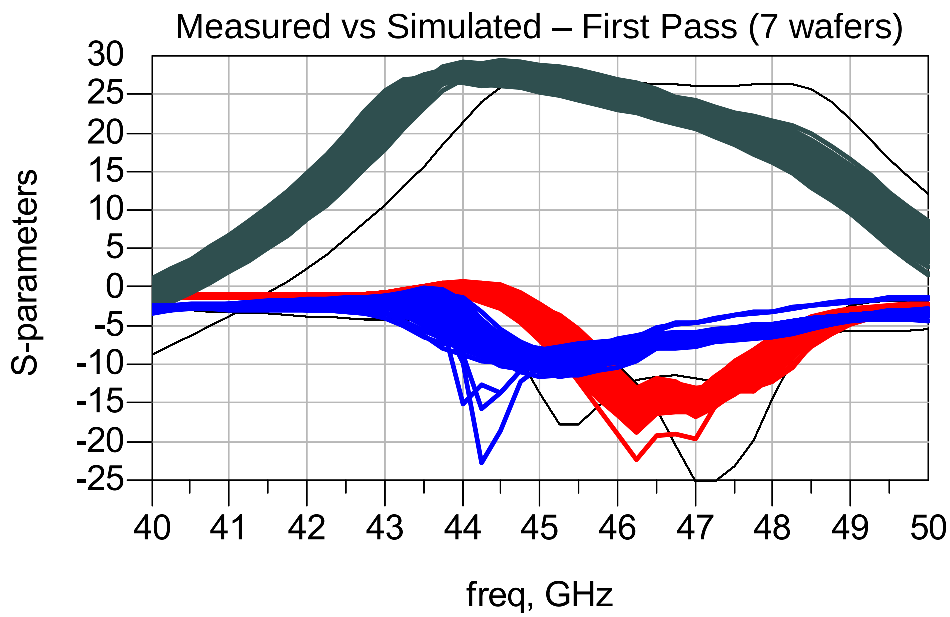


2.56 mm – 5.12 mm - 5.12 mm

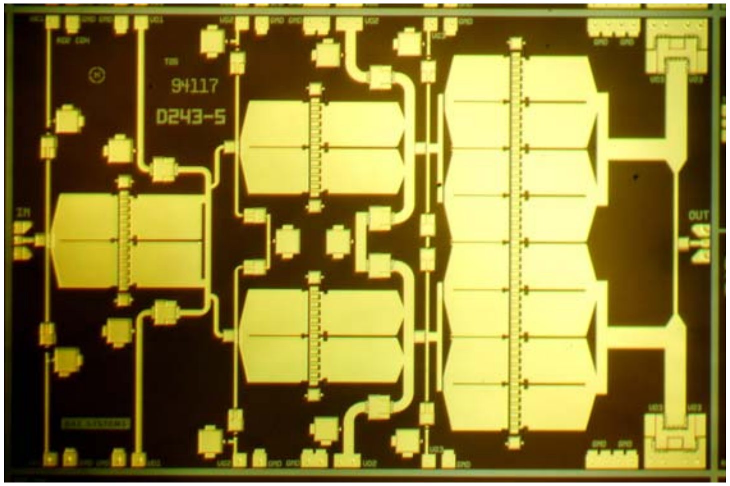
Q-Band PHEMT Power MMIC

BAE SYSTEMS



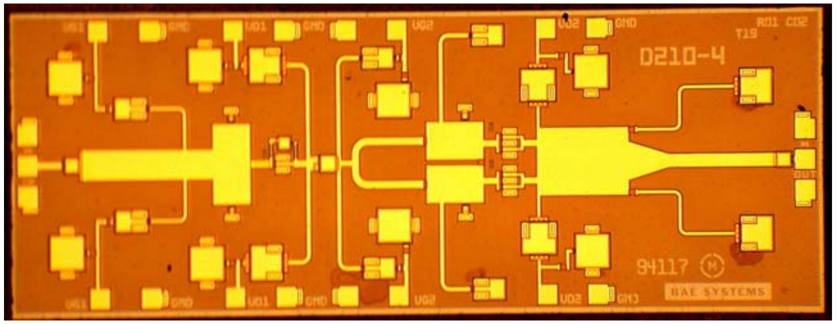


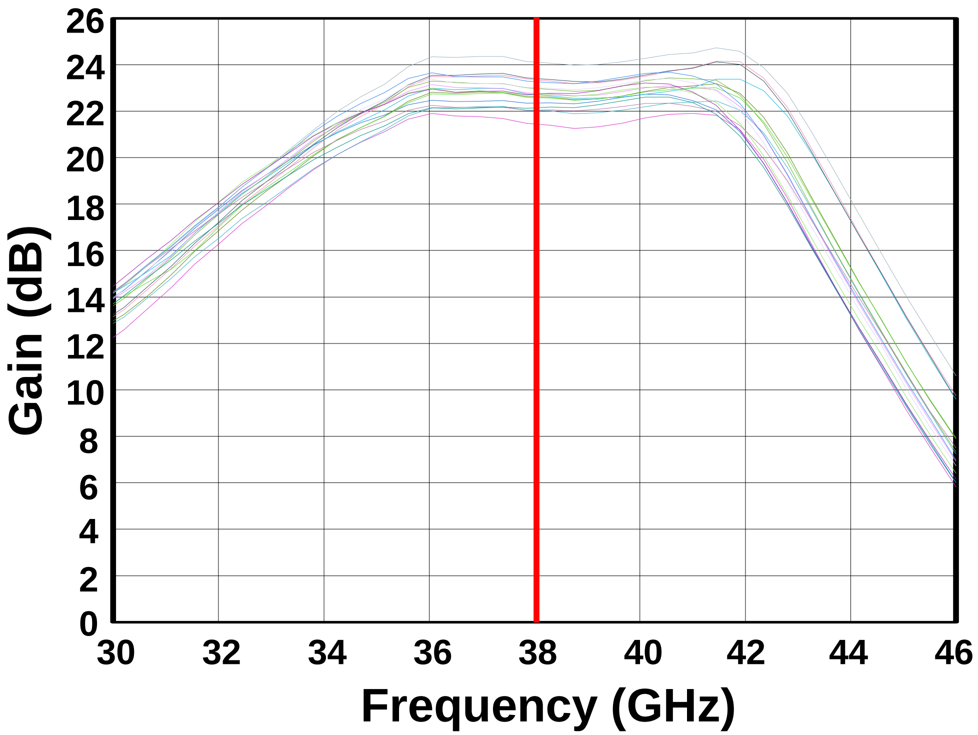
- **Process: 0.1 µm Single Recess PHEMT (2 mil)**
- **Application: Q-Band SatCom**
- **Measured Performance:**
  2.8W @ 20% PAE (on wafer)
  3.0W @ 25% PAE (on carrier)
- **Chip Size:**
  3.5 mm x 5.3 mm



38 GHz 100mW MHEMT MMIC

BAE SYSTEMS



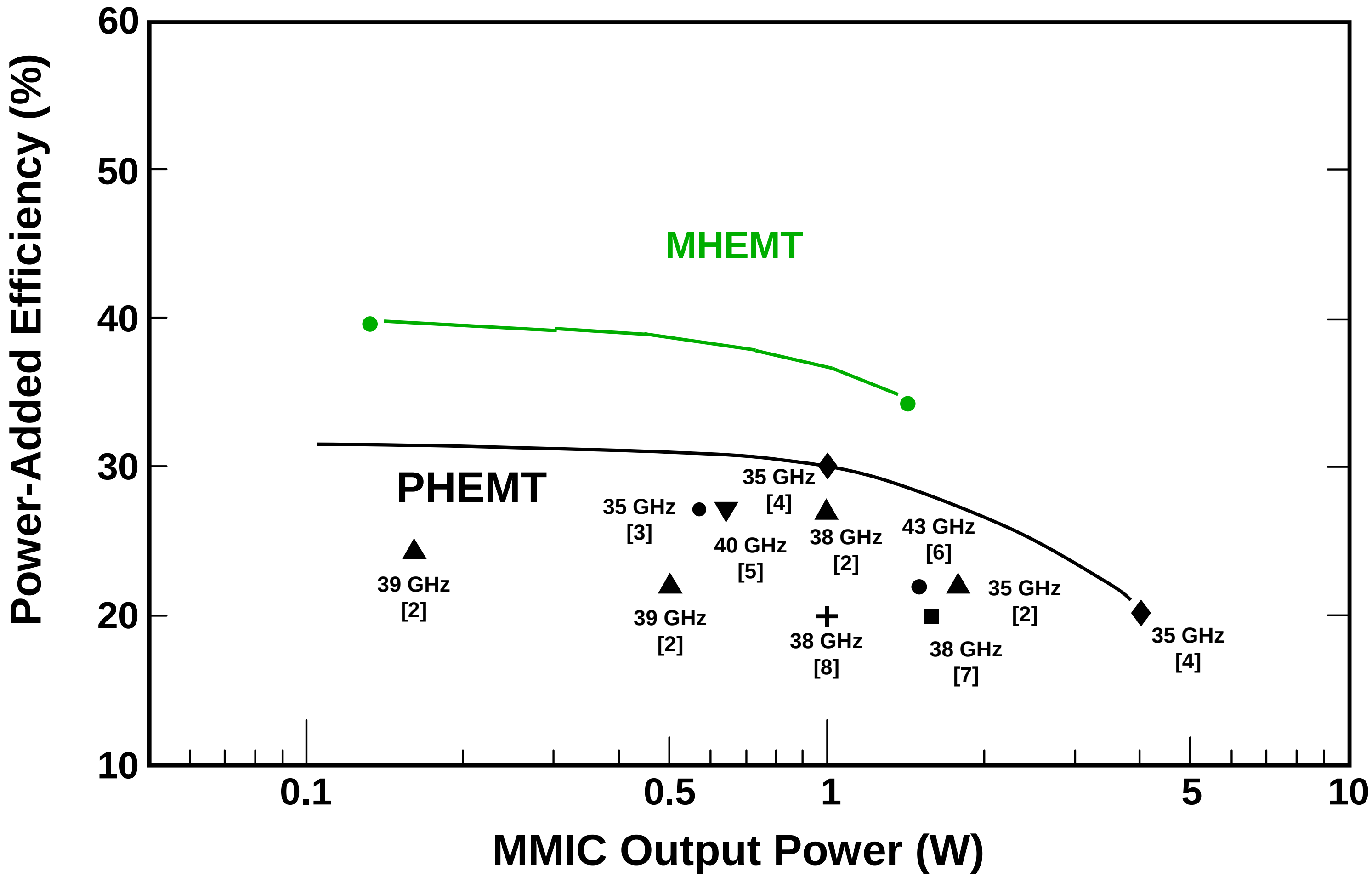


- **Application: Phased Arrays**
- **23 dB small-signal gain**
- **6 GHz bandwidth**
- **120mW P_{out} with 20dB power gain and 40% PAE**

high gain, good flatness, and high PAE

Best Reported Fully Monolithic PAs, ~40 GHz

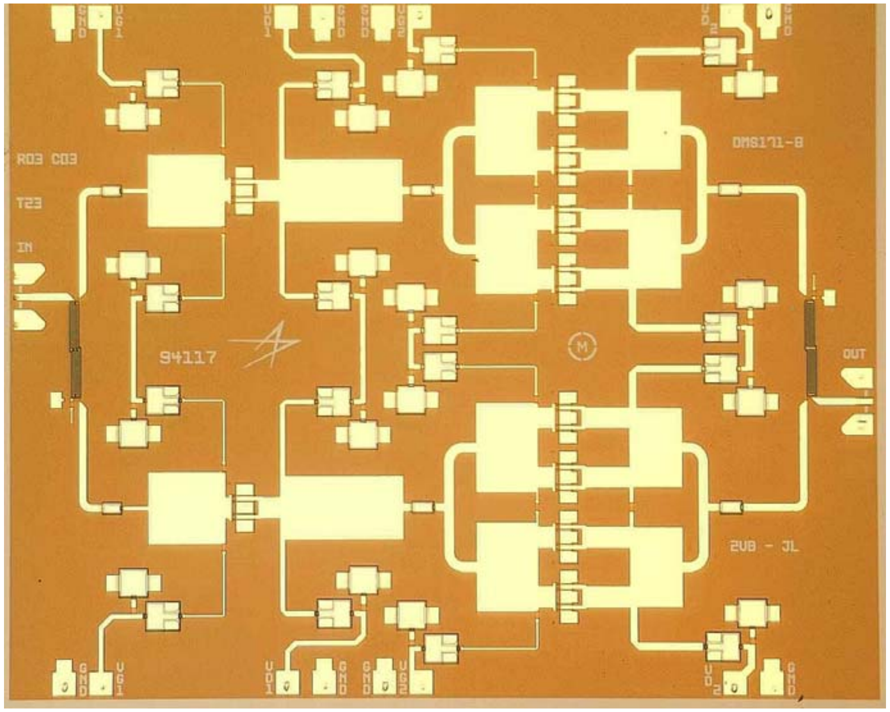
BAE SYSTEMS



[1] BAE SYSTEMS unpublished data (InP HEMT)
[2] Triquint data sheets--TGA1071-EPU, TGA1073-SCC, TGA1171-SCC, TGA1141-EPU
[3] *1997 MTT Symposium,* pp. 1183-1186 (TRW)
[4] BAE SYSTEMS unpublished data
[5] *1999 GaAs IC Symposium,* pp. 141-143
[6] *1997 GaAs IC Symposium,* pp. 283-286
[7] Raytheon data sheet--RMPA39200
[8] TRW data sheet--APH309C

V-Band InP HEMT Power Amplifier MMIC

BAE SYSTEMS



- Dual channel PA MMIC combined with low loss Lange Coupler
- Process: 0.1 um InP HEMT (2 mil)
- Measured performance @ 60 GHz +27.5 dBm (562 mW) output power, 32% PAE, 13.5 dB power gain
- 3.60 mm x 2.91 mm

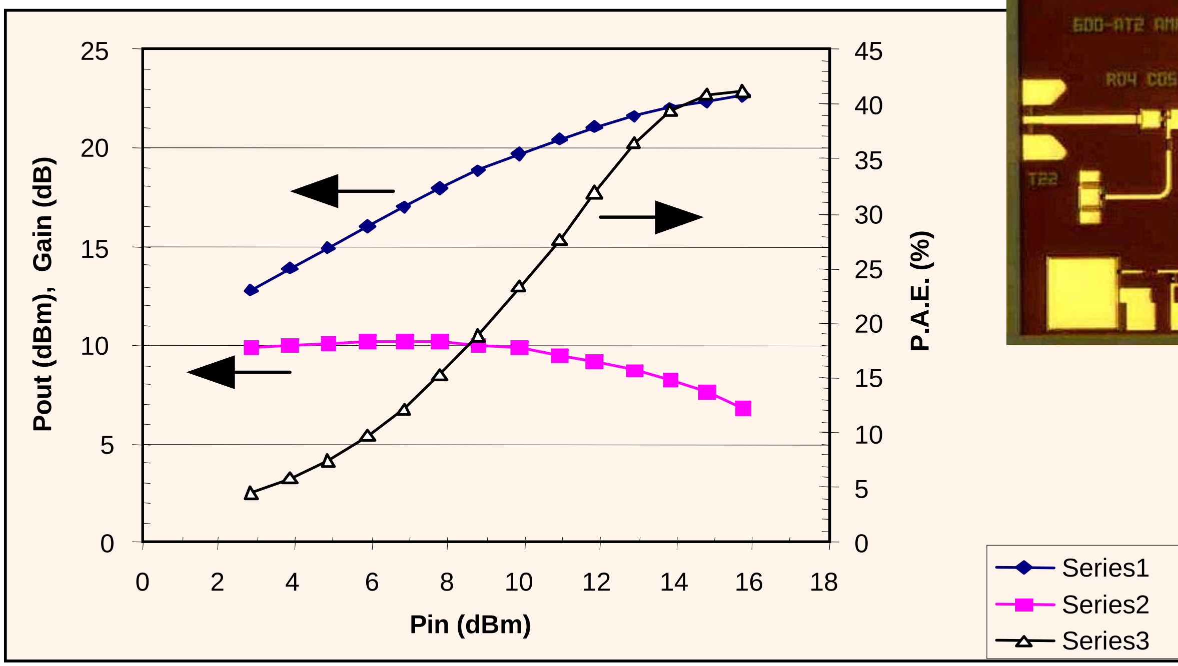
Comparable 0.1 um SR PHEMT MMIC +27.5 dBm (562 mW), 21% PAE with 9.8 dB power gain @ 60 GHz

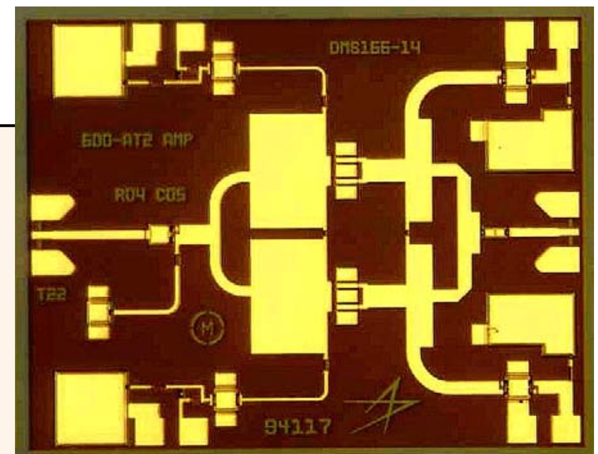
higher gain and efficiency

60 GHz MHEMT Power MMIC

BAE SYSTEMS

- Single-stage 0.1μm SR MHEMT MMIC
- Design based on 0.1μm InP HEMT, not modified for MHEMT
- Measured performance at 60 GHz: 185 mW with 41% PAE and 7dB power gain



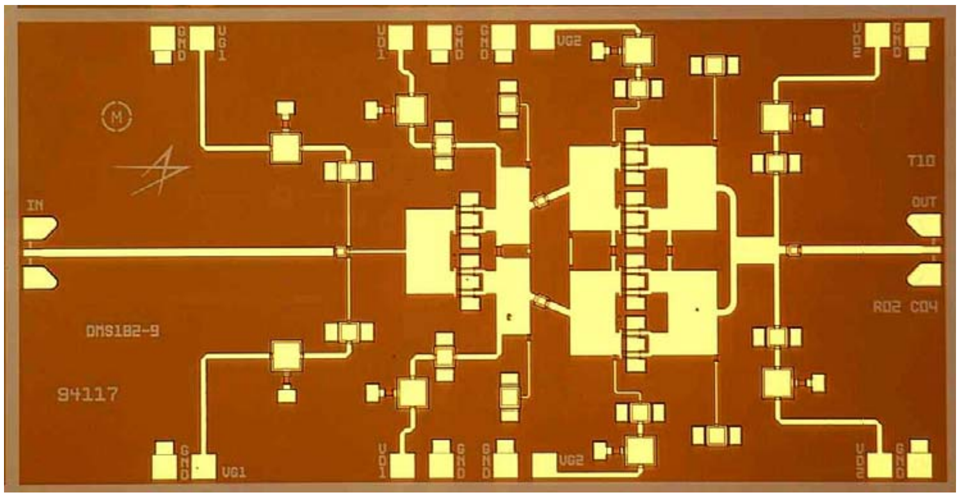


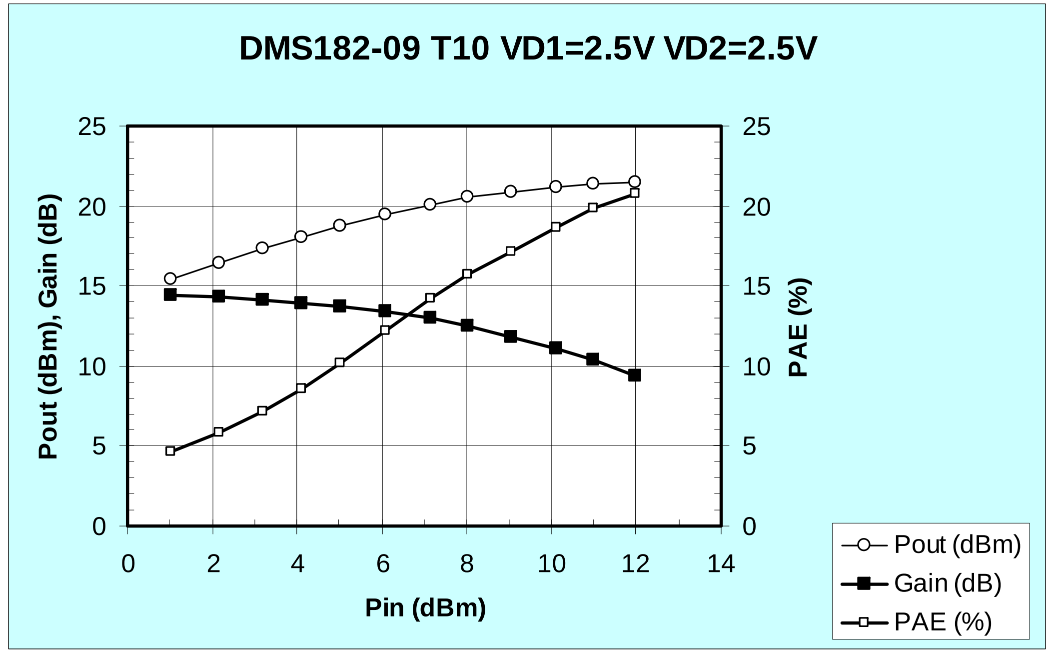
Performance of InP HEMT at lower cost

W-Band InP HEMT Power Amplifier MMIC

BAE SYSTEMS

400 um – 800 um





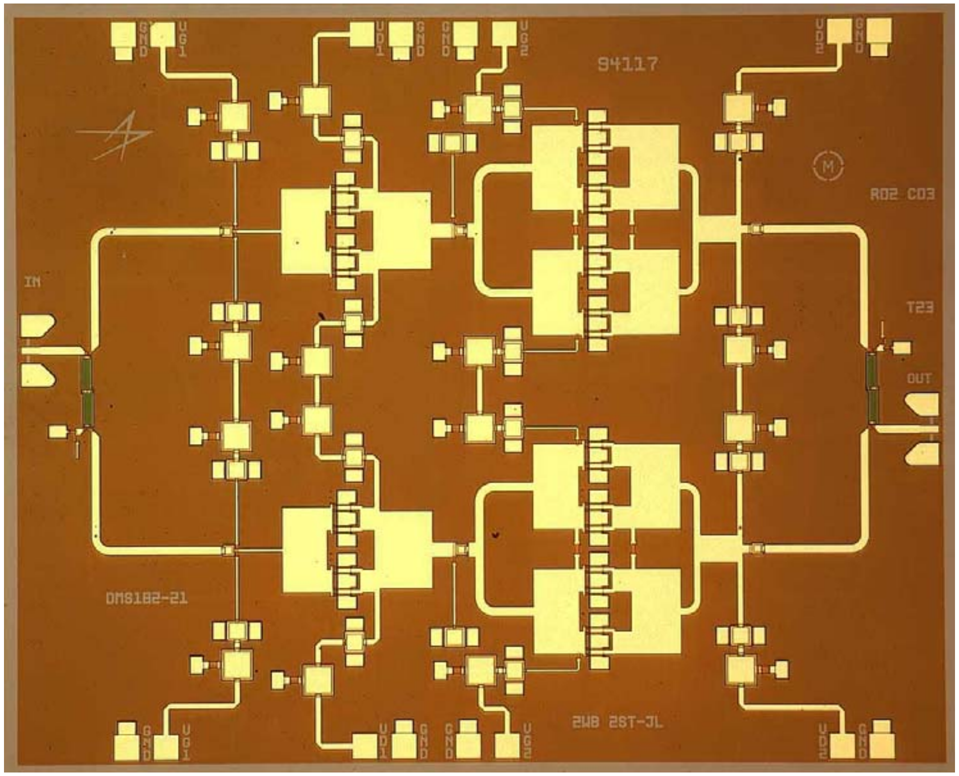
Process: 0.1 um InP HEMT (2 mil)

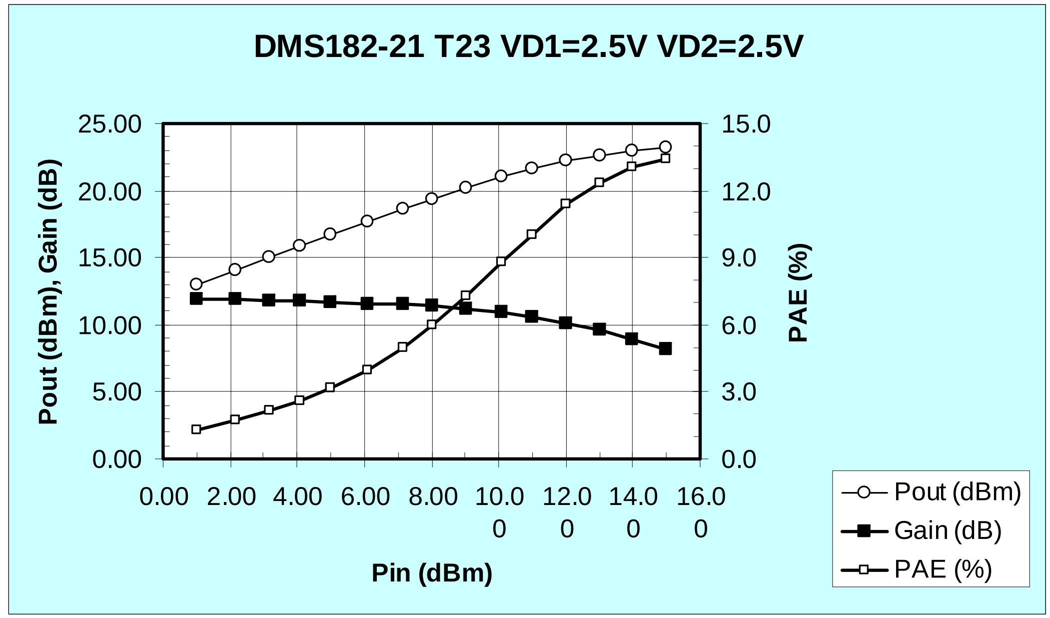
+21.5 dBm (140mW), 21% PAE, 9.5 dB gain at 94GHz

W-Band InP HEMT Power Amplifier MMIC

BAE SYSTEMS

2 x [400 um – 800 um]



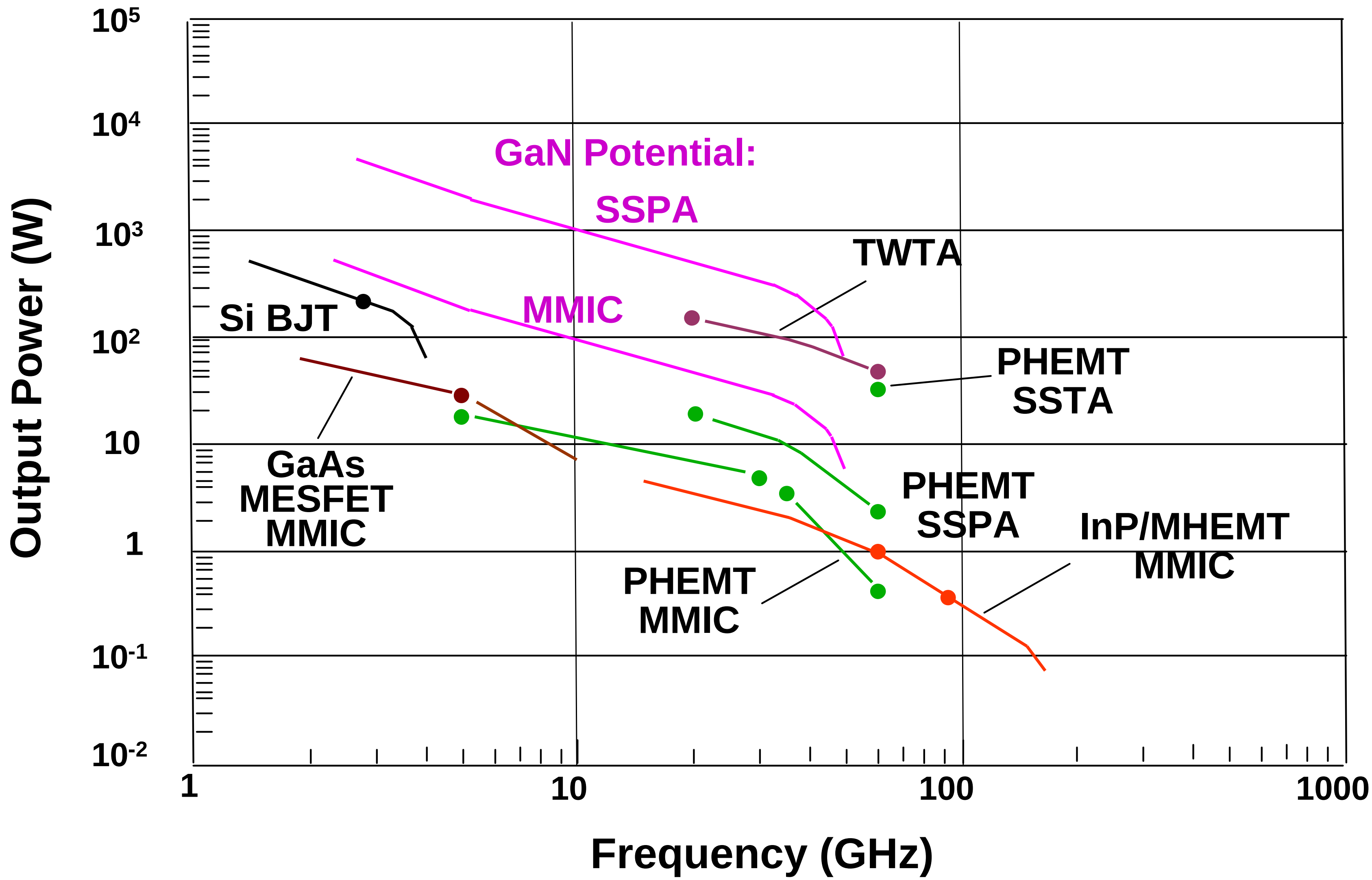


Process: 0.1 um InP HEMT (2 mil)

+23.5 dBm (225mW), 13.5% PAE, 8.5 dB gain at 94 GHz

High Power Solid State Transmit Technologies

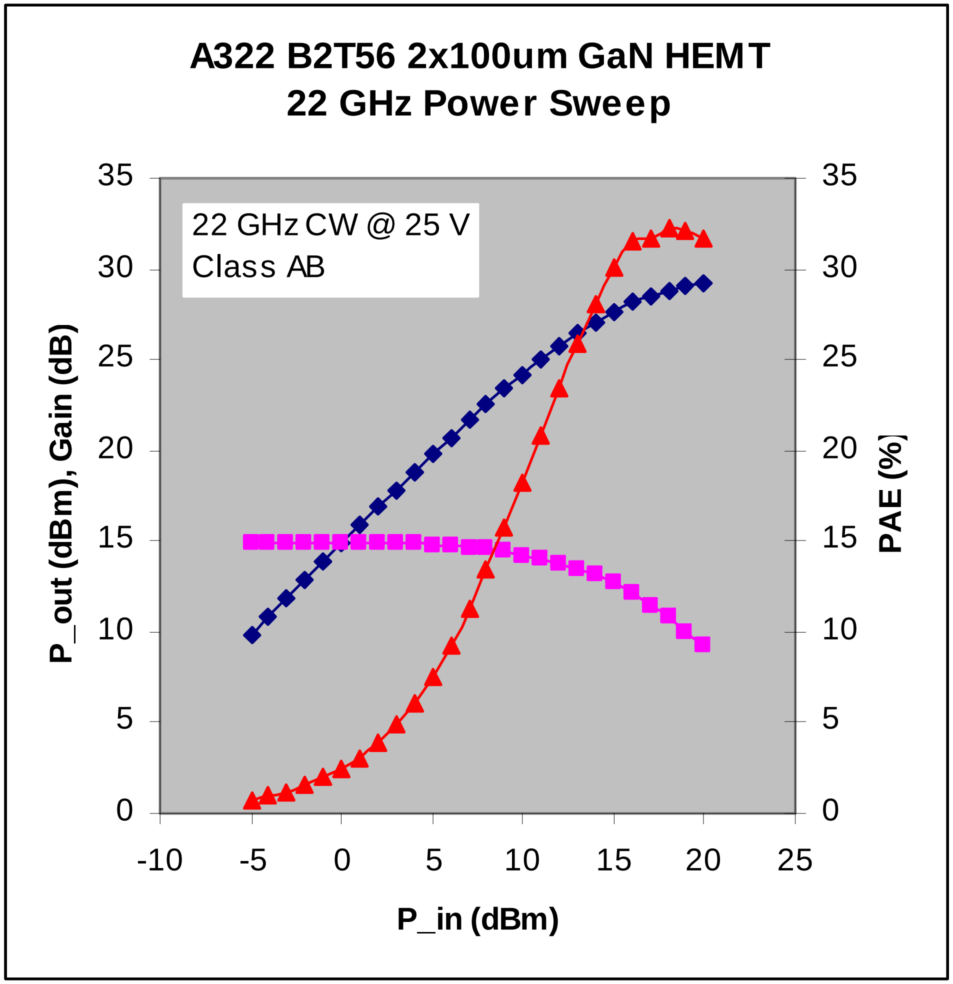
BAE SYSTEMS

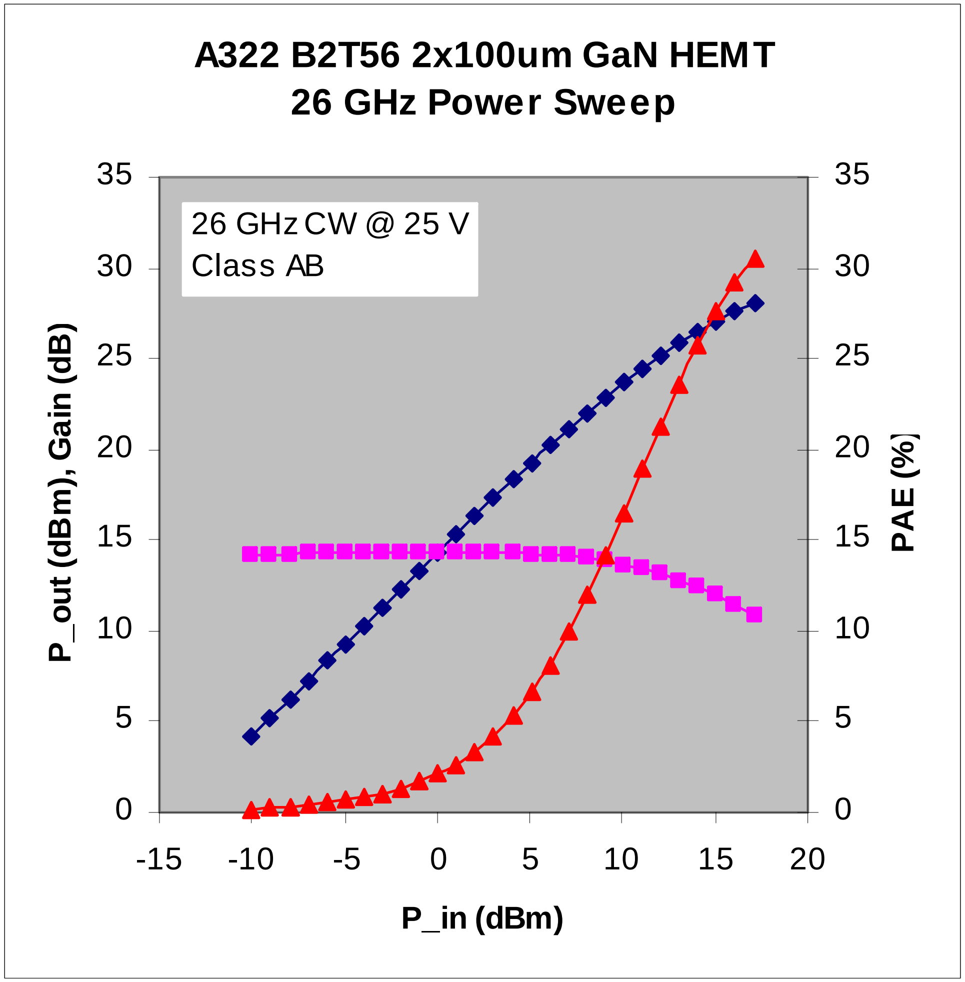


GaN potential -- 10X increase in MMIC and SSPA power, 1-45 GHz

BAE GaN Device Power Results at K-Band

BAE SYSTEMS

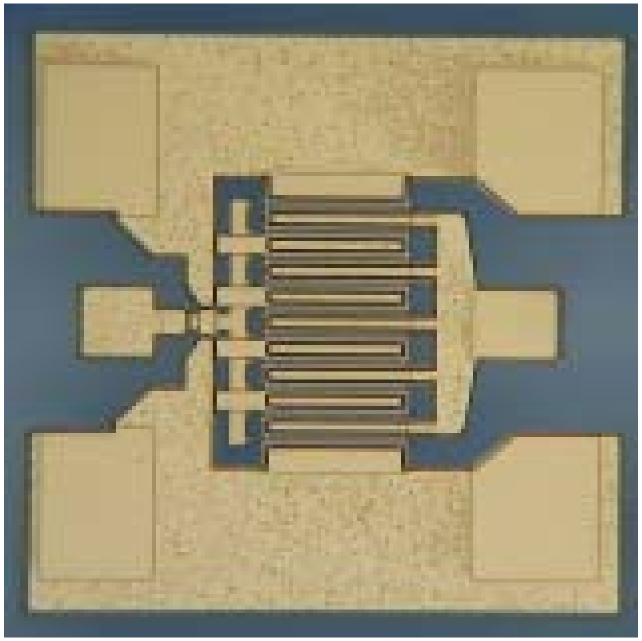




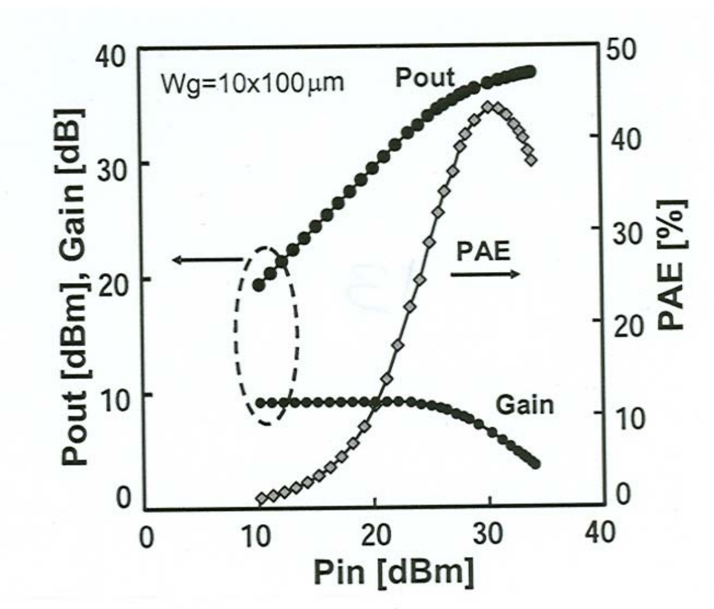
4.4 W/mm, 32% PAE, 10 dB gain

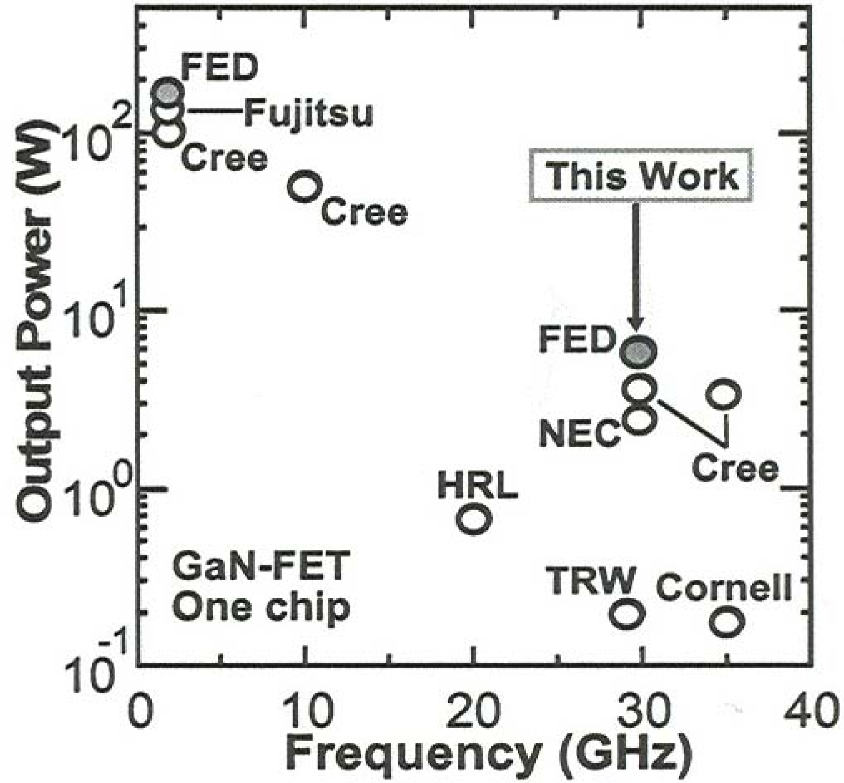
3.2 W/mm, 21% PAE, 10 dB gain

6 Watt Ka-Band AlGaN/GaN HFET



0.25 um x 10 x 100 um





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[1] T. Inoue, et al, “30 GHz Band 5.8W High Power AlGaN/GaN Hetrojunction FET”, 2004 IEEE MTT-S Digest, pp 1649-1652.

[2] Y. Ando, et al, “3.5 Watt AlGaN/GaN HEMTs and Amplifiers at 35GHz”, 2003 IEDM Technical Digest, pp 579-581.

[3] K. Kasahara, et al, “Ka-band 2.3W Power AlGaN/GaN Heterojunction FET”, 2002 IEDM Technical Digest, pp 677-680.

Summary

BAE SYSTEMS

- Silicon (BJT and LDMOS) dominate high power L-band and below
- HBT holds on to the wireless market
- SiC MESFET has a niche L-band to S-band
- PHEMT is a mature workhorse technology (S-band to V-band)
- At mm-wave 0.1 um PHEMT outperforms 0.15 - 0.25 um PHEMT
- InP HEMT offers improved PAE/gain at expense of power density
- MHEMT has the performance of InP HEMT at lower cost
- GaN HEMT will emerge as power density leader within 3 to 5 years

Best Reported Transistor Efficiencies References

BAE SYSTEMS

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[2] S. Shanfield et al., “1W, Very High Efficiency 10 and 18 GHz PHEMTs Fabricated by Dry First Recess Etching,” *1992 MTT-S Digest* , pp. 639-641.

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[4] R. Actis et al., “High-Performance 0.15 µm Gate-Length PHEMTs Enhanced with a Low-Temperature-Grown GaAs Buffer Layer,” *1995 MTT-s Digest*, pp. 445-448.

[5] P. Saunier et al., “A Heterostructure FET with 75.8% PAE at 10 GHz, “ *1992 MMT-S Digest*, pp. 635-638.

[6] N.L. Wang et al., “0.7W X-Ku-Band High-Efficiency common Base Power HBT,” *IEEE Microwave and Guided Wave Letters*, pp. 258-260, Sept. 1991.

[7] T. Shimura et al., “1W Ku-Band AlGaAs/GaAs Power HBT’s with 72% Peak PAE, “ *IEEE Trans. Elec. Devices*, pp. 1890-1895, Dec. 1995

[8] H.-F. Chau et al., “1W, 65% PAE K-Band AlGaAs HBTs Using Emitter Air-Bridge Technology.” *1997 RFIC Symp. Digest*, pp. 219-222.

[9] M. Hafizi et al., “Microwave Power Performance of InP-Based Double Heterojunction Bipolar Transistors for C- and X-Band Applications,” *1994 MTT-S Digest*, pp. 671-674.

[10] R.A. Sadler, “SiC MESFET with Output Power of 50 W CW at S-Band,” *Device Research Conference*, June 1998.

[11] J. Komiak, private communication.

[12] S.T. Sheppard, “High Power Microwave GaN/AlGaN HEMTs on Silicon Carbide, “ *Device Research Conference*, June 1998.

[13] S.C. Wang et al., "High Performance Fully Selective Double-Recess InAlAs/InGaAs/InP HEMTs," *IEEE Electron Device Letters,* vol. 21, no. 7, pp. 335-337, July 2000.

[14] W. Okamura et al., "K-Band 76% PAE InP Double Heterojunction Bipolar Power Transistors and a 23 GHz Compact Linear Power Amplifier MMIC," *2000 IEEE GaAs IC Symposium Digest, pp. 219-222.*

MMIC State of the Art at ~30 GHz References

BAE SYSTEMS

[1] BAE SYSTEMS unpublished data for 1-stage InP HEMT MMIC.

[2] H.Q. Tserng et al., "High Efficiency Broadband Monolithic Pseudomorphic HEMT Amplifiers at Ka-Band," *1992 Monolithic Circuits Symposium,* pp. 51-54.

[3] J.M. Schellenberg, "A High Voltage, Ka-Band Power MMIC with 41% Efficiency," *1995 IEEE GaAs IC Symposium,* pp. 284-287.

[4] R. Yarborough et al., "Performance Comparison of 1 Watt Ka-Band MMIC Amplifiers Using Pseudomorphic HEMTs and Ion-Implanted MESFETs," *1996 IEEE Monolithic Circuits Symposium,* pp. 21-24.

[5] D.L. Ingram et al., "A 6 Watt Ka-Band MMIC Power Module Using MMIC Power Amplifiers," *1997 IEEE MTT Symposium,* pp. 1183-1186.

[6] M. Siddiqui et al., "A High Power and High Efficiency Monolithic Power Amplifier for Local Multipoint Distribution Service," *1998 IEEE MTT Symposium,* pp. 569-572.

[7] J.J. Komiak et al., "Fully Monolithic 4 Watt High Efficiency Ka-Band Power Amplifier," *1999 IEEE MTT-Symposium,* pp. 947-950.

[8] M. Siddiqui et al., "A High Power Broadband Monolithic Power Amplifier for Ka-Band Ground Terminals," *1999 IEEE MTT Symposium,* pp. 951-954.

[9] BAE SYSTEMS unpublished data.

[10] T. Quach et al., "Ultra-Efficient X-Band and Linear-Efficient Ka-Band Power Amplifiers using Indium Phosphide Double Heterojunction Bipolar Transistors," *International Conf. on InP and Related Materials,* pp. 501-504, 2001.

[11] F. Colomb and A. Platzker, "2 and 4 Watt Ka-Band GaAs PHEMT Power Amplifier MMICs," *2003 IEEE International Microwave Symposium,* pp. 843-846.

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