Microwave and Millimeter Wave Power Amplifiers: Technology, Applications, Benchmarks, and Future Trends

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Outline

– Overview and motivation
– Solid state power device technologies
  – Bipolar
    - Si BJT
    - GaAs HBT
    - InP HBT
  – FET
    - Si LDMOS
    - GaAs MESFET
    - GaAs PHEMT
    - InP HEMT
    - MHEMT
    - GaN HEMT
– Circuit Design
– HPAs
  – Microwave
  – Millimeter Wave
  – Sub-Millimeter Wave
– Combiners
– Summary
Why Are Power Transistors So Important?

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
• 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, limited frequency response, diminishing manufacturing sources
GaAs Heterojunction Bipolar Transistor (HBT)

- AlGaAs/GaAs heterojunction (1981)

- 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

- Self-aligned base is common

- Emitter fingers typically 0.7-2.0 µm wide

- PA of choice for wireless, led cell phone revolution, but now obsolete, replaced by InGaP HBT
InP HBT

- Based on InGaAs/InAlAs heterojunction
- Compatible with detection of 1.30-1.55 μm for 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
- Sub-Millimeter Wave frequency response $f_{max} = 600$ GHz, $f_t = 400$ GHz
- Typical base layer 500-800 Å thick, doped at $3-10 \times 10^{19}$/cm$^3$
- Diminishing Manufacturing Sources
Based on MOSFET technology
- Low cost, proven performance, reliability
- Low source inductance using p-type sinker
- Field plate for increased gain
- Multi-generation performance improvement continuously has increased frequency of operation
• “Grandfather” of GaAs transistors (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

• Widely used since 1980’s in discrete form -- internally-matched FET (IMFET)

• High Voltage variants using Field Plate

• Obsolete
GaAs Pseudomorphic HEMT (PHEMT)

- First demonstrated for microwave power in 1986
- $\text{In}_x \text{Ga}_{1-x} \text{As}$ 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 80 GHz
- Enhancement mode (E-mode) PHEMT for cell-phone PAs -- single supply voltage
InP HEMT

- 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 (3000 mS/mm) demonstrated

- Sub-Millimeter Wave frequency response
  \( f_{\text{max}} = 1500 \, \text{GHz}, \, f_t = 610 \, \text{GHz} \)

- Low breakdown for single recess (low bandgap of InAlAs gate layer)

- Double-recess devices have been reported

- Superior PAE and power gain demonstrated at 20-1000 GHz
InP Metamorphic HEMT (MHEMT)

- 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 or superior to InP HEMTs
GaN HEMT

- Grown on SiC substrates
- Heterojunction with undoped channel
- Electron mobility $\mu = 1500 \text{ cm}^2/\text{V-sec}$
- High surface defect density ($10^7$-$10^8/\text{cm}^2$)
- First GaN HEMT MMIC reported in 2000
- Millimeter Wave frequency response $f_{\text{max}}$ of 200 GHz, $f_t$ of 90 GHz
- Very high power density demonstrated $\sim 10\text{W/mm}$
- Thermally limited device
SiC MESFET (Silicon Carbide Metal Semiconductor Field Effect Transistor)

SAGFET (Self Aligned Gate Field Effect Transistor)

HFET (Heterojunction Field Effect Transistor)

PBT (Permeable Base Transistor)

SIT (Static Induction Transistor)

GaAs MESFET

AlGaAs HBT

and others
High Gain Enables High Efficiency Modes of Operation: Class AB2, Class B, Class C, Class F
Millimeter-wave Transistor Efficiencies

Gain Limited: Class AB1, Class A
Waveforms of Ideal Class A through F Power Amplifiers

High Efficiency modes square up the waveform and phase voltage and current in quadrature.
Integration to Higher Power Levels

Intrinsic Device (single finger)

Power Transistor “Cell”

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

“Building block” for higher power
Longer fingers
Characterized for power amplifier design

Hybrid Power Amplifier

Power MMIC

Module

Discrete device: all matching off-chip

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

Constrained Combining (Plumbing)

Spatial Combining (Phased Array/Quasioptics)

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

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

Full MMIC: all matching on-chip
Pre-history of Circuit Design

- Characterization:
  Simple analytical models derived from DC I-V measurements

- Simulation:
  Hand calculation of model parameters

- Models:
  Ebers-Moll
1970s Circuit Design

- **Characterization:**
  - I-V & C-V measurement;
  - S-parameters - HP8410

- **Simulation:**
  - ...increasing sophistication!

- **Models:**
  - “hybrid-π”

![Image of circuit diagram and equipment]
1980s Circuit Design

- Characterization:
  S-parameters over bias
  - HP8510

- Simulation Tools:
  Touchstone, Compact

- Models appear in the simulators:

Small-signal bias-dependent equivalent-circuit FET model
1990s Circuit Design

- **Characterization:**
  Pulsed I-V and S-parameters

- **Simulation Tools:**
  Harmonic Balance enables large-signal simulation in HP ‘MDS’, EEsof ‘Libra’

- **Models:**
  Large-signal models: ‘Root’ FET model

![Graph and Diagrams]
2000s to now

- **Characterization:** X-Parameters – PNAX
- **Simulation Tools:**
  - HB, Circuit Envelope
  - Agilent ‘ADS’
  - AWR ‘Microwave Office’

Vector Signal Analysis
Modern Power Amplifier Design Process

- Device Cell Characterization & Modeling
  - DC & Pulse IV
  - Small Signal S-parameters
  - Load Pull (Optimum Load)
  - Non-linear Model (User Defined Angelov with Charge Conservation)
- 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
  - Layout
  - EM Simulation
  - Repeat as necessary
EM Simulation of Drain Inductor - HFSS Model

EM Simulation widely recognized as a necessary CAD tool

Port 1
Port 2

TR Metal: T=1.35 um, Cond=3e7 S/m

Full Metal: T=7 um, Cond=3e7 S/m

Airbridge Metal: T=5.65 um, Cond=3e7 S/m

GaN: H=4 mil, Er=9.7, Tand=0.005
The MMIC Amplifier, 3 to 6 GHz, off-chip network
- Power: 11 W ± 1 dB
- Gain: 10 to 13 dB
- Efficiency: ~10 to 17%
- Yield: 67% dc / visual yield

The discussion on thermal performance

Stage design methodology

- Comprehensive device characterization including both measurement and modeling
- Measured small-signal S parameters, equivalent circuit models, and measurements augmented with optimum load/contour data obtained via load pull, are used to derive a consistent nonlinear model

- Synthesis techniques consisting of transforming the 50Ω load required optimum large-signal load impedance
- As a result, a value of $R_{opt}$ derived from $I_{dss}$ and the $V_{ds}$, and small-signal model parameters $C_{ds}$ and $L_d$, determines an approximation to the optimum class A load.

- Enhanced version of the Cripps technique takes into account the effect of the full-channel current $I_{max}$ and the nonunilateral nature of the device by large-signal conductance substitution of a load line into the complete small-signal model
- Use of the load-pull measurements with variable tuners, simulated to search for optimum conditions

S/C-Band PHEMT High Power Amplifier (1997)

- **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
- **Class F/Inverse F**

8 mm - 32 mm
1995 State of the Art Amplifier

- A fully monolithic HBT power amplifier
  - 2400 μm consisting of 8 - 300 μm unit cells in a cascode configuration
  - Power-added efficiencies of 56% max / 38% min, 44.4% average across 7 to 11 GHz band
  - Output power levels of up to 7.3 Watts with a gain of 11 to 14.1 dB
    - Under long pulse (500 usec) and high duty cycle (25%) conditions.

1999 State of the Art Amplifier

- Two stage MMIC Amplifier, 29 to 31 GHz
  - Output Power 35.5 dBm ± 1 dBm
  - Large signal gain > 14 dB
  - PAE in the range of 25 to 31%
  - RF/DC yield of 30% to 50%
  - Design emphasis on stability, particularly related to bias networks
- Output stage design methodology
  - Considered small signal response and power transfer to the optimum source or load impedance simultaneously.

2011 State of the Art Amplifier

- Decade Bandwidth 2 to 20 GHz GaN HEMT Power Amplifier MMICs in DFP and No FP Technology
  - With Dual Field Plate [DFP] Technology
    - $P_{3db}$ of 26.3 Watts max, 15.4 Watts average, 7.1 Watts min.
    - PAE of 38.3 % max, 19.8 % average, 5.9 % min.
    - Power gain of 11.2 dB max, 8.6 dB average, 5.0 dB
  - No Field Plate [FP] Technology
    - $P_{3db}$ of 21.6 Watts max, 16.0 Watts average, 9.9 Watts min.
    - PAE of 35.7 % max, 25.9 % average, 15.3 % min.
    - Power Gain of 11.1 dB max, 9.7 dB average, 8.0 dB

<table>
<thead>
<tr>
<th>Freq (GHz)</th>
<th>Power (Watts)</th>
<th>Gain (dB)</th>
<th>PAE (%)</th>
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Komiak, J.J.; Kanin Chu; Chao, P.C.; , "Decade bandwidth 2 to 20 GHz GaN HEMT power amplifier MMICs in DFP and No FP technology," Microwave Symposium Digest (MTT), 2011 IEEE MTT-S International , vol., no., pp.1-4, 5-10 June 2011
2011 State of the Art Amplifier

- Wideband 1 to 6 GHz Ten and Twenty Watt Balanced GaN HEMT Power Amplifier MMICs
- The balanced amplifier achieved a
  - P3dB of 14.5 Watts max, 11.1 Watts average, 8.2 Watts min
  - PAE 46.1 % max, 31.8 % average, 18.1 % min

Komiak, J.J.; Lender, R.J.; Kanin Chu; Chao, P.C.,
Bypassing and Gate Switching

Envelope Elimination and Restoration Technique

Bypasses a highly efficient, but nonlinear RF Power Amplifier with a highly efficient envelope detector to implement a high-efficiency linear RF Amplifier.

Phase Tracking

Supply voltage is varied dynamically to conserve power, but with sufficient excess ("headroom") to allow the RF PA to operate in a linear mode near saturation at high efficiency.

Mixing

Mixes an amplitude-modulated signals that are combine the outputs of two amplifier signals of different time-varying phases. The resulting output is the instantaneous sum of the two amplifier outputs to follow the desired signal amplitude. In a modern implementation, a DSP and synthesizer produce the inverse-sine modulations of the carrier.

Hybrid Technique

Architecture combines two amplifiers of equal capacity through quarter-wavelength networks. The “carrier” (main) amplifier is biased in class B, while the “peaking” (auxiliary) amplifier is biased in class C. Only the carrier PA is active when the lower signal amplifiers contribute output power when the input signal amplitude is approaching near saturation of the main amplifier.

Amplifier Linearization Techniques

Back

The RF-output signal from the amplifier is fed back and subtracted from the RF input signal without detection or down-conversion. The delays involved must be small to ensure some loss of gain at RF is a more significant design issue.

Forward

The output signal is split into two paths, with one path going to the high-power main amplifier, and the other signal path goes to a delay element. The output signal from the main amplifier contains the desired signal and distortion. This signal is sampled and scaled using attenuators before being added with the delayed portion of the input signal, which is regarded as distortion free. The resulting “error signal” ideally contains only the distortion components in the output of the main amplifier. The error signal is then amplified by the low-power high-linearity error amplifier, amplified with a delayed version of the main amplifier output. This second combination ideally cancels distortion components in the main-amplifier output while leaving the desired signal unaltered.

Predistortion

It is the insertion of a nonlinear element prior to the RF PA such that the combined transfer characteristic of both is linear.

Predistortion

It is the considerable processing power available from DSP devices, which allows both to update the required predistortion characteristic.

150 Watt 110-450 MHz Si LDMOS Power Amplifier

Push-Pull with Ferrite Loaded Coax Baluns

Power Gain at 150 Watts ~ 12.5 dB
S-Band GaN HEMT High Power Amplifier

- Frequency = 2.9 GHz
- Pout ~ 800 Watts
- Bandwidth > 2.9 to 3.3 GHz
- Vds = 65 V
- Idsq = 2 A
- PW = 200 usec
- Duty Cycle = 10 %
X-Band GaN HEMT High Power Amplifier

- **Process**: 0.25 μm GaN HEMT
- **Application**: X-band radar
- **Frequency Range**: 9 to 10 GHz
  - $V_{ds} = 24$ V
  - $I_{dsq} = 2.4$ A
  - 60 W @ 38% PAE
- **Package Size**: 17.4 mm x 24 mm x 3.9 mm
**Ka-Band 0.1 \( \mu \text{m} \) PHEMT MMIC HPA**

- **Process**: 0.1 \( \mu \text{m} \) Single Recess PHEMT
- **Application**: Ka-Band seekers/radar
- **Frequency Range**: 34 to 36 GHz
  - 5 W @ 19.5 % PAE (on wafer)
- **Chip Size**: 3.5 mm x 6.1 mm x 0.055 mm

3.2 mm – 6.4 mm – 12.8 mm
Ka-Band 0.2 μm NFP GaN HEMT MMIC HPA

- **Process:** 0.2 μm NFP GaN HEMT
- **Application:** Ka-Band seekers/radar
- **Frequency Range:** 30 to 33 GHz
  - 10-12 W @ 25% PAE (on wafer)
- **Chip Size:**
  - 4.587 mm x 3.925 mm x 0.1016 mm

1.8 mm – 3.6 mm
Q-Band 0.1 μm PHEMT MMIC HPA

- **Process:** 0.1 μm Single Recess PHEMT
- **Application:** Q-Band SatCom
- **Frequency Range:** 43 to 45 GHz
  - 2.8 W @ 21.5 % PAE (on wafer)
- **Chip Size:**
  - 3.5 mm x 5.3 mm x 0.055 mm

1.8 mm – 3.6 mm – 7.2 mm
W-Band 0.15 μm GaN HEMT MMIC HPA

- **Process:** 0.15 μm GaN HEMT
- **Application:** W-Band Radar, Com
- **Frequency Range:** 84 to 95 GHz
  - 0.5 to 0.8 W @ 10-15 % PAE (module)
Eight stage InP HEMT PA MMIC with integral waveguide transitions

- **Process:** 30 nm InP HEMT
- **Application:** THz
- **Frequency Range:** 628 to 643 GHz
  - mW (module)
- **Chip Size:**
  - 655 um x 375 um x 25 um

Pout vs Pin at 643 GHz

- **20 um transistor cell**
- **4 fingers x 5 um**
- **CPW MMIC**
Coaxial Waveguide Spatial Power Combiner
V-Band PHEMT SSTA

304 Dipole Radiating Element
19 Tray Modules

6 Output MMIC Power

W-Band Combiners

- 4-way septum combiner
- 12-way radial combiner
  - 12-way Radial
  - Pout: 5.2 W at 95 GHz
  - Bandwidth: 94 to 98 GHz

Phased Array

An array of antennas in which the relative phases of the respective signals feeding the antennas are varied in such a way that the effective radiation pattern of the array is reinforced in a desired direction and suppressed in undesired directions.

\[ \text{EIRP} = G_e \times P_e \times N^2 \]
High Power Solid State Transmit Technologies
(not including Phased Arrays)

GaN potential -- 10X increase in MMIC and SSPA power, 1-100 GHz
Summary

• Silicon BJT in a niche market (high power IFF and Link 16)
• LDMOS faces challenges from GaN in base station market
• HBT holds on to the wireless market with challenges from E-PHEMT
• PHEMT is a mature workhorse technology (S-band to V-band)
• 0.1 um/70 nm 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 is the SSPA leader (MHz to W-band)
Future Trends

- Circuit Technique Development & Implementation
  - Multi-tone with controlled distortion
  - STAR: Simultaneous Transmit and Receive

- Sub-Millimeter Wave Applications

- Thermal
  - Near Junction Thermal Transport (NJTT) – GaN on Diamond
  - Thermal Ground Plane (TGP) -- alloy heat spreader
  - IntraChip/InterChip Enhanced Cooling (ICECOOL) -- convective or evaporative microfluidic cooling built directly into devices or packaging
  - Microtechnologies for Air Cooled Exchangers (MACE) – enhanced heatsinks
  - Active Cooling Module (ACM) – miniature refrigeration systems based on thermoelectric or vapor-compression technologies

- Semiconductor Devices
  - Evolutionary
  - Diamond
  - Graphene, Carbon Nanotube
  - Boron Nitride
  - ???
Best Reported Transistor Efficiencies References


GE Aerospace

S/C-band MMIC HPA
Chip Size is 5.8 mm x 4.3 mm x 0.127 mm

Design and Performance of an Octave Band 11 Watt Power Amplifier MMIC
J.J. Komiak
### GaAs MESFET HPAs

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Discrete/ MMIC</th>
<th>Output Power (W)</th>
<th>PAE (%)</th>
<th>Power Gain (dB)</th>
<th>Reference</th>
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<td>1.5</td>
<td>Discrete</td>
<td>17</td>
<td>68</td>
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<td>Tsutsui et al., 1998 MTT Symp., pp. 715-718</td>
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<td>1.5</td>
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<td>51</td>
<td>54</td>
<td>12.3</td>
<td>Ono et al., 1996 GaAs IC Symp., pp.103-106</td>
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<td>2.1</td>
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<td>240</td>
<td>54%</td>
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<td>Inoue et al., 2000 MTT Symp., pp. 1719-1722</td>
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<td>102</td>
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<td>Ebihara et al., 1998 MTT Symp., pp. 703-706</td>
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<td>31</td>
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<td>Takenaka et al., 1997 MTT Symp., pp. 1417-1420</td>
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<td>3-6</td>
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<td>Komiak et al., 1992 GaAs IC Symp., pp. 187-190</td>
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<td>Pribble et al., 1996 Monolithic Symp., pp. 25-28</td>
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<td>14</td>
<td>Discrete</td>
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<td>30</td>
<td>7</td>
<td>Saito et al., 1995 MTT Symp., pp. 343-346</td>
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</table>

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

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

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<th>Reference</th>
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<td>8-14</td>
<td>2.8-3.8</td>
<td>37-51</td>
<td>Salib et al. (NG), 1998 MTT Symp., pp.581-584.</td>
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<td>7-11</td>
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<td>Komiak and Yang (LM), 1995 Monolithic Symp., pp. 17-20</td>
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<td>8.3-10</td>
<td>9.0-12.5</td>
<td>38-51</td>
<td>Khatibzadeh et al. (TI), 1994 Monolithic Symp., pp.117-120</td>
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<td>6-18</td>
<td>1.3-2.5</td>
<td>18-37</td>
<td>Salib et al. (NG), M&amp;GW Letters, pp. 325-326, Sept. 1998</td>
</tr>
</tbody>
</table>

- 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, -38dB ACP at 1.95 GHz  (Iwai et al. (Fujitsu), 2000 MTT Symposium, pp. 869-872.)

- High-volume commercial product for handsets -- TRW/RFMD
## Microwave GaAs PHEMT HPAs

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

MHEMT MMICs outperform best reported PHEMT MMICs at ~30 GHz
[1] BAE SYSTEMS unpublished data for 1-stage InP HEMT MMIC.


Best Reported Fully Monolithic PAs, ~40 GHz

- **MMIC Output Power (W)**
  - 60
  - 50
  - 40
  - 30
  - 20
  - 10
  - 0.1
  - 0.5
  - 1
  - 5
- **Power-Added Efficiency (%)**
  - MHEMT
  - PHEMT

- ** Frequencies and References:**
  - 35 GHz [4]
  - 39 GHz [2]
  - 38 GHz [2]
  - 40 GHz [5]
- **Devices and Data Sheets:**
  - BAE SYSTEMS unpublished data (InP HEMT) [1]
  - 1997 MTT Symposium, pp. 1183-1186 (TRW) [3]
  - 1999 GaAs IC Symposium, pp. 141-143 [5]
  - 1997 GaAs IC Symposium, pp. 283-286 [6]
  - Raytheon data sheet--RMPA39200 [7]
  - TRW data sheet--APH309C [8]
### Millimeter and Sub-millimeter Wave MMIC Power Amplifiers (Samoska)

<table>
<thead>
<tr>
<th>Freq [GHz]</th>
<th>Technology</th>
<th>Output Power</th>
<th>PAE %</th>
<th>Power Density</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>76</td>
<td>0.12 μm GaN HEMT</td>
<td>347 mW</td>
<td>-</td>
<td>434 mW/mm</td>
<td>Masuda [77]</td>
</tr>
<tr>
<td>84</td>
<td>0.15 μm GaN HEMT</td>
<td>500 mW</td>
<td>17%</td>
<td>1670 mW/mm</td>
<td>Micovic [76]</td>
</tr>
<tr>
<td>88</td>
<td>0.15 μm GaN HEMT</td>
<td>842 mW</td>
<td>14.7%</td>
<td>1400 mW/mm</td>
<td>Micovic [74]</td>
</tr>
<tr>
<td>90</td>
<td>0.15 μm mHEMT</td>
<td>267 mW</td>
<td>17%</td>
<td>222 mW/mm</td>
<td>Herrick [89]</td>
</tr>
<tr>
<td>94</td>
<td>0.1 μm mHEMT</td>
<td>214 mW</td>
<td>8%</td>
<td>148 mW/mm</td>
<td>Tessmann [88]</td>
</tr>
<tr>
<td>94</td>
<td>0.15 μm InP HEMT</td>
<td>427 mW</td>
<td>19%</td>
<td>266 mW/mm</td>
<td>Ingram [82]</td>
</tr>
<tr>
<td>94</td>
<td>0.15 μm GaN HEMT</td>
<td>933 mW</td>
<td>13.3%</td>
<td>1550 mW/mm</td>
<td>Micovic [75]</td>
</tr>
<tr>
<td>95</td>
<td>0.15 μm GaN HEMT</td>
<td>560 mW</td>
<td>-</td>
<td>930 mW/mm</td>
<td>Micovic [74]</td>
</tr>
<tr>
<td>75-110</td>
<td>0.1 μm GaAs pHEMT</td>
<td>200 mW</td>
<td>4-9%</td>
<td>160 mW/mm</td>
<td>Wang [80]</td>
</tr>
<tr>
<td>75-110</td>
<td>0.1 μm InP HEMT</td>
<td>40 mW</td>
<td>6%</td>
<td>133 mW/mm</td>
<td>Samoska [85]</td>
</tr>
<tr>
<td>115</td>
<td>70 nm GaAs pHEMT</td>
<td>25 mW</td>
<td>-</td>
<td>200 mW/mm</td>
<td>Morgan [81]</td>
</tr>
<tr>
<td>120</td>
<td>0.1 μm InP HEMT</td>
<td>29 mW</td>
<td>4%</td>
<td>96 mW/mm</td>
<td>Samoska [84]</td>
</tr>
<tr>
<td>150</td>
<td>0.1 μm InP HEMT</td>
<td>20 mW</td>
<td>3%</td>
<td>66 mW/mm</td>
<td>Samoska [83]</td>
</tr>
<tr>
<td>190</td>
<td>70 nm InP HEMT</td>
<td>20 mW</td>
<td>9.5%</td>
<td>166 mW/mm</td>
<td>Huang [38]</td>
</tr>
<tr>
<td>192</td>
<td>0.1 μm mHEMT</td>
<td>8.9 mW</td>
<td>4%</td>
<td>55 mW/mm</td>
<td>Kallfass [87]</td>
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<tr>
<td>208</td>
<td>InP HBT</td>
<td>35.6 mW</td>
<td>-</td>
<td>1.5 mW/μm²</td>
<td>Reed [72]</td>
</tr>
<tr>
<td>217.5</td>
<td>&lt; 50 nm InP HEMT</td>
<td>51 mW</td>
<td>2.3%</td>
<td>63 mW/mm</td>
<td>Radisic [69]</td>
</tr>
<tr>
<td>270</td>
<td>&lt; 50 nm InP HEMT</td>
<td>6.1 mW</td>
<td>5.2%</td>
<td>50 mW/mm</td>
<td>Deal [70]</td>
</tr>
<tr>
<td>324</td>
<td>InP HBT</td>
<td>1.3 mW</td>
<td>0.6%</td>
<td>~0.5 mW/μm²</td>
<td>Hacker [34]</td>
</tr>
<tr>
<td>330</td>
<td>&lt; 50 nm InP HEMT</td>
<td>2 mW</td>
<td>-</td>
<td>25 mW/mm</td>
<td>Deal [86]</td>
</tr>
<tr>
<td>338</td>
<td>&lt; 50 nm InP HEMT</td>
<td>10 mW</td>
<td>-</td>
<td>62 mW/mm</td>
<td>Radisic [71]</td>
</tr>
</tbody>
</table>

*HBT power density reported as mW/(emitter area)