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

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Outline

• 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?

Power amplifiers typically *dominate* transmitter/system characteristics:

- DC power consumption
- Power dissipation (heat) $\Rightarrow$ thermal load
- Reliability $\Rightarrow$ 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, but limited frequency response
GaAs Heterojunction Bipolar Transistor (HBT)

- 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

• 230 GHz $f_{\text{max}}$, 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 $\times 10^{19}$/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 1.0 µm -- 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)

- First demonstrated for microwave power in 1986
  - Henderson et al. (U. of Illinois/GE), 1986 IEDM, paper 17.7.
- $\ln_x \text{Ga}_{1-x} \text{As}$ 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 60 GHz
- Enhancement mode (E-mode) PHEMT for cell-phone PAs -- single supply voltage (Peatman et al., 2000 GaAs IC Symp., pp. 71-74)
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 (1700 mS/mm) demonstrated

- Highest $f_{\text{max}}$, $f_t$ of any transistor
  - 600 GHz $f_{\text{max}}$ (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)

- 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

- 4H-SiC substrate with extremely high resistivity and thermal conductivity

- SiC substrates small (≤3-inch), costly, defect density has improved significantly in last 5 years

- Typical DC characteristics for Cree SiC MESFET: \( V_{br} > 120\text{V} \), \( V_k \approx 10\text{V} \), \( g_m = 50\text{mS/mm} \)

- 50 GHz \( f_{\text{max}} \), 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 cm²/V-sec

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

- 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 $\mu = 1500 \text{ cm}^2/\text{V-sec}$
- 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, $f_{\text{max}}$ 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)

<table>
<thead>
<tr>
<th>Source</th>
<th>Gate</th>
<th>Drain</th>
</tr>
</thead>
<tbody>
<tr>
<td>undoped AlGaN (14%) 10 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2e18/cm$^3$ AlGaN (14%) 12 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>undoped AlGaN (14%) 5 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>insulating GaN 2 $\mu$m</td>
<td></td>
<td></td>
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<tr>
<td>AIN Buffer Layer</td>
<td></td>
<td></td>
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<tr>
<td>Semi-insulating 4H-SiC</td>
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</tbody>
</table>
Best Reported Microwave Transistor Efficiencies

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
Integrate to Higher Power Levels

Intrinsic Device (single finger)

Power Transistor “Cell”

Hybrid Power Amplifier

Power MMIC

Module

Spatial Combining (Phased Array/Quasioptics)

Spatial Combining (Phased Array/Quasioptics)

Constrained Combining (Plumbing)

Waveguide/Radial Combiners

Full MMIC: all matching on-chip

Power amplifier or T/R module

MIC power combining (typ. 2 to 8-way)

Small periphery (gate/emitter)

Short gate/emitter fingers

Low parasitics

“Building block” for higher power

Longer fingers

Characterized for power amplifier design

Discrete device: all matching off-chip

Each MMIC feeds separate radiating element

(typ. 100s-1000s of elements)

Waveguide/Radial Combiners

W/G: 2 to 32-way

Radial: to 128-way

slide 14
Power Amplifier Design Process

- 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
<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>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>Discrete</td>
<td>17</td>
<td>68</td>
<td>14</td>
<td>Tsutsui et al., 1998 MTT Symp., pp. 715-718</td>
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<tr>
<td>1.5</td>
<td>Discrete</td>
<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>
<td>Discrete</td>
<td>240</td>
<td>54%</td>
<td>7.8</td>
<td>Inoue et al., 2000 MTT Symp., pp. 1719-1722</td>
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<td>2.2</td>
<td>Discrete</td>
<td>102</td>
<td>47</td>
<td>11</td>
<td>Ebihara et al., 1998 MTT Symp., pp. 703-706</td>
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<tr>
<td>2.5</td>
<td>Discrete</td>
<td>31</td>
<td>60</td>
<td>13</td>
<td>Takenaka et al., 1997 MTT Symp., pp. 1417-1420</td>
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<tr>
<td>3-6</td>
<td>MMIC</td>
<td>15-29</td>
<td>23-35</td>
<td>10-13.5</td>
<td>Komiak et al., 1992 GaAs IC Symp., pp. 187-190</td>
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<tr>
<td>4.3-5.4</td>
<td>MMIC</td>
<td>12-14</td>
<td>50-60</td>
<td>-</td>
<td>Pribble et al., 1996 Monolithic Symp., pp. 25-28</td>
</tr>
<tr>
<td>14</td>
<td>Discrete</td>
<td>20</td>
<td>30</td>
<td>7</td>
<td>Saito et al., 1995 MTT Symp., pp. 343-346</td>
</tr>
</tbody>
</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

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Power (W)</th>
<th>PAE (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<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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<tr>
<td>7-11</td>
<td>4.5-7.3</td>
<td>38-56</td>
<td>Komiak and Yang (LM), 1995 Monolithic Symp., pp. 17-20</td>
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<tr>
<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>
</tr>
<tr>
<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, -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

- **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

![Graphs and diagrams showing performance characteristics of the amplifier.](image-url)
# 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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<tbody>
<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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<tr>
<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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<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>
K-Band High Power Amplifier (TGA4022)

- **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

- **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 – 1.2 mm - 2.88 mm – 7.04 mm – 9.6 mm

0.8 mm – 0.8 mm – 2.4 mm – 7.2 mm – 14.72 mm
Ka-Band Power Amplifier (TGA4517)

- **Process:** 0.15 \( \mu m \) 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**

- **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

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

- 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

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
Q-Band PHEMT Power MMIC

- **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

- 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

<table>
<thead>
<tr>
<th>Power-Added Efficiency (%)</th>
<th>MMIC Output Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>10</td>
</tr>
<tr>
<td>50</td>
<td>20</td>
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<td>40</td>
<td>30</td>
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<td>30</td>
<td>40</td>
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<tr>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>10</td>
<td>60</td>
</tr>
</tbody>
</table>

[1] BAE SYSTEMS unpublished data (InP HEMT)
[4] BAE SYSTEMS unpublished data
[5] 1999 GaAs IC Symposium, pp. 141-143
[7] Raytheon data sheet--RMPA39200
[8] TRW data sheet--APH309C
V-Band InP HEMT Power Amplifier MMIC

- 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

- 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
W-Band InP HEMT Power Amplifier MMIC

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

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

GaN potential -- 10X increase in MMIC and SSPA power, 1-45 GHz
BAE GaN Device Power Results at K-Band

A322 B2T56 2x100um GaN HEMT
22 GHz Power Sweep

22 GHz CW @ 25 V
Class AB

P_out (dBm), Gain (dB)

PAE (%)

P_in (dBm)

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

A322 B2T56 2x100um GaN HEMT
26 GHz Power Sweep

26 GHz CW @ 25 V
Class AB

P_out (dBm), Gain (dB)

PAE (%)

P_in (dBm)

3.2 W/mm, 21% PAE, 10 dB gain
6 Watt Ka-Band AlGaN/GaN HFET

REFERENCES
Summary

- 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


MMIC State of the Art at ~30 GHz References

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


