Brief CV and Research Activities

• **Affiliation:** Professor, Electrical and Computer Engineering Dept.
  Director, Solid State Electronics Lab and Device Characterization Lab
  University of Central Florida

• **Research Area:** Semiconductor device modeling/simulation, RF device/IC design, and
  semiconductor manufacturing

• **List of Sample Projects:**
  1. Study and modeling of reliability of GaAs heterojunction bipolar transistors
     (Air Force, Alcatel Space)
  2. RF CMOS reliability modeling and simulation (Intersil Corp., Conexant Systems)
  3. Design and modeling of on-chip electrostatic discharge (ESD) protection structures
     (Semiconductor Research Corp., Intersil Corp., Intel Corp., NIST)
  4. Parameter extraction of VBIC bipolar transistor model (Lucent Tech.)
  5. Statistical modeling of Si devices and ICs (Lucent Tech., Skyworks)
  6. Design and modeling of junction field-effect transistors (Texas Instruments/SRC)
  7. Development of next generation memory cell (ProMOS Technologies)
Evolution and Recent Advances in RF/Microwave Semiconductor Devices

Juin J. Liou
School of Electrical Engineering and Computer Science
University of Central Florida, Orlando, Florida, USA

OUTLINE

• Introduction
• Evolution of RF Transistors
• Some Basic Physics
• Figures of Merits
• State of the Art (2002)
• Outlook and Future Trends
Background and Evolution
The recent explosive growth in civil communication technology has created mass consumer markets for RF/Microwave electronics systems.

In general, signals with lower frequency can penetrate walls better. But antenna size varies with RF wavelength, so low-frequency RF is not practical for handheld devices. In addition, frequencies of RF noises are ranging from 50-2400 MHz, so frequencies $> 3000$ MHz is better.

Most RF systems having real mass markets operate under 5 GHz. For examples:

- Cellular phones based on global system for mobile communication (GSM), time division multiple access (TDMA), and code division multiple access (CDMA) running at 900 MHz, 1.8 and 1.9 GHz
- Future 3G cellular phones based on CDMA2000 and Wideband CDMA
- Advanced mobile communications based on global positioning systems (GPS) and general packet radio service (GPRS), running at 1.8 and 2.5 GHz, respectively
- Wireless local area network (Bluetooth) operating at 2.4 GHz
- Collision avoidance radar used in automobiles (77 GHz)
Bluetooth at Home: Wireless Connection

- Digital Camera
- Inkjet Printer
- Home Audio System
- Computer
- PDA
- Cell Phone
- Scanner
- Cordless Phone Base Station
Operating Frequencies of Widely Used RF Electronics

- 2G mobile phones: 900 M, 1.8 G, and 1.9 GHZ
- 2.5G mobile phones: 2.5 GHZ
- 3G mobile phones: 3.0 GHz
- Globe positining system: 1.8 GHz
- Wireless fidelity (Wi-Fi): 2.4 and 5.0 GHz
- Bluetooth: 2.4 GHz
- Coreless phone: 2.4 GHz
- Microwave oven: 2.4 GHz

Major problems with wireless communications: Standard and Compatibility
RF Devices are the Backbone of Advanced Communication Systems

RF: Radio Frequency, i.e. frequencies around and above 1 GHz.

Semiconductors

- III-V compounds based on GaAs and InP
- Si and SiGe
- Wide bandgap materials (SiC and III-nitrides)

Transistor Types

- MESFET - Metal Semiconductor FET
- HEMT - High Electron Mobility Transistor
- MOSFET - Metal Oxide Semiconductor FET
- HBT - Heterojunction Bipolar Transistor
- BJT - Bipolar Junction Transistor

In the past 10 years, III-V technology dominates RF market, but RF MOSFET becomes a strong contender recently!
History of RF Transistors

1980  Only two types of RF transistors available:

Si BJTs ($f_{op}$ up to 4 GHz)
GaAs MESFETs ($f_{op}$ 4-18 GHz)

2002  Many different types of RF transistors available:

Bipolar:  Si BJTs, SiGe HBTs, III-V HBTs
FET:  GaAs MESFETs, III-V HEMTs, Wide Bandgap HEMTs
Si MOSFETs

Record $f_{max}$

III-V FETs: > 600 GHz
III-V HBTs: 1.1 THz
Overview of RF Transistors and Physics of Heterostructures
Si BJT: Cross Section and Design Rules

Design Features
- Thin base
- Very high emitter doping density
- Polysilicon emitter contact
- Lightly/heavily doped collector regions
HBT: Cross Section and Design Rules

HBT Types
- GaAs HBT
- InP HBT
- SiGe HBT

Design Features
- Wide bandgap emitter
- Narrow bandgap base
- Thin base (less than 0.1 μm)
- High base doping
MESFET: Cross Section and Design Rules

**Important dimensions:**
- Gate length $L$
- Gate width $W$
- Active layer thickness

JFET

- Source (ohmic)
- Gate (ohmic)
- Drain (ohmic)
- p$^+$ gate
- Active layer (n-type)

Substrate

MESFET

- Source
- Gate (Schottky)
- Drain
- Active layer (n-type)
- Active layer thickness
- Important dimensions:
  - Gate length $L$
  - Gate width $W$
  - Active layer thickness
MOSFET: Cross Section and Design Rules

Bulk and SOI MOSFETs

Important dimensions:
- Mask gate length $L$
- Channel length $L_{ch}$
- Gate width $W$ (not shown)
- Oxide thickness $t_{ox}$
HEMT: High Electron Mobility Transistor

Cross Section

Design Features

- Deep sub-µm gate
- Mushroom gate
- Very short gate length
- High mobility channel layer
- Large conduction band offset ➔ 2DEG
Bandgap VS. Lattice Constant for Commonly Used Semiconductors

HETEROSTRUCTURES:

Lattice matched
- Al_{0.3}Ga_{0.7}As/GaAs/GaAs
- In_{0.5}Ga_{0.5}P/GaAs/GaAs
- In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/InP

Pseudomorphic (strained)
- Si/Si_{1-x}Ge_{x}/Si (x < 0.2)
- AlGaAs/In_{x}Ga_{1-x}As/GaAs (x < 0.2)
- In_{0.52}Al_{0.48}As/In_{x}Ga_{1-x}As/InP (0.3 < x < 0.7)

Metamorphic (relaxed)
- InP/In_{x}Ga_{1-x}As/GaAs (x up to 0.6) for HMET
- InP/In_{x}Ga_{1-x}As/InP/GaAs (x up to 0.6) for HBT
Lattice Matched Pseudomorphic Metamorphic

Broken Bonds
**Heterostructures Design Concept for HBT and HEMT**

HBTs are vertical devices—electrons and holes flow vertically through the heterointerface. Any defects at the heterointerface will result in a significant degradation in the device performance.

Only lattice matched (i.e., AlGaAs/GaAs HBT) or well-controlled pseudomorphic heterostructures (i.e., Si/SiGe HBT) are used in HBTs.

HEMTs, on the other hand, are horizontal devices—electrons and holes flow in parallel with the heterointerface. Defects at the heterointerface are tolerated as long as the heterointerface is separated from the free-carrier path.

All lattice matched, strained, and relaxed heterostructures can be used in HEMTs (i.e., HEMT, pHEMT, mHEMT)
Figures of Merit and State of the Art
Applications of RF Devices for Receiver and Transmitter

Important RF Circuits are LNA, Mixer, A/D-D/A, and PA
**RF Transistor Figures of Merit**

- **Cutoff Frequency** $f_T$
  Frequency at which the magnitude of the short circuit current gain $h_{21}$ rolls off to 1 (0 dB).

- **Max Frequency of Oscillation** $f_{\text{max}}$
  Frequency at which the unilateral power gain $U$ rolls off to 1 (0 dB).

- $f_T$ and $f_{\text{max}}$ can be extracted from $h_{21}$ and $U$ roll off at higher frequencies at a slope of $-20$ dB/dec.
Further RF Transistor FOMs:

- **Minimum Noise Figure** $\text{NF}_{\text{min}}$
  
  Given in dB at a certain frequency. Most important for low-noise applications.

- **Output Power** $P_{\text{out}}$
  
  Given in W or dBm at a certain frequency. Important for power transistors.

- **Power Added Efficiency** PAE and Maximum Available Power Gain MAG
  
  MAG is the power gain when the device is unconditional stable and conjugately matched to the source and load.

Useful Rules of Thumb:

- $f_T$ and $f_{\text{max}}$ should be as high as possible.

- The operating frequency of a RF transistor should not be higher than 1/10 of $f_T$.

- $P_{\text{out}}$, PAE, and MAG should be as high as possible.

- $\text{NF}_{\text{min}}$ should be as low as possible but is always larger than 0 dB in real transistors.

- Cost and reliability may also be factors in selecting RF devices.
RF Low Noise Amplifier (LNA)

Criterion for transistors in LNA:

A sufficiently high $f_T$ or $f_{\text{max}}$ and a sufficiently low $N_{\text{F min}}$
A Few Comments on On-Chip Spiral Inductor

\[ \Omega = \frac{R}{2nHLg} \]

\[ L_s = 6nH \]

\[ L_c = 0.5nH \]

\[ \text{RFC} \]

\[ \text{Term} 1 \]

\[ \text{Term} 2 \]

- Impressed device currents
- Magnetically induced eddy currents
- Electrically induced conduction and displacement currents

- Metal Layer
- Oxide Layer
- Substrate

Substrate loss mechanisms

### Noise Figure (dB)

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>NF (dB)</th>
<th>QF</th>
</tr>
</thead>
<tbody>
<tr>
<td>m1: Freq=2.4 GHz</td>
<td>0.898</td>
<td>25</td>
</tr>
<tr>
<td>m2: Freq=2.4 GHz</td>
<td>2.057</td>
<td>5</td>
</tr>
</tbody>
</table>

### S21 (dB)

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>S21 (dB)</th>
<th>QF</th>
</tr>
</thead>
<tbody>
<tr>
<td>m1: Freq=2.4 GHz</td>
<td>12.001</td>
<td>25</td>
</tr>
<tr>
<td>m2: Freq=2.4 GHz</td>
<td>10.487</td>
<td>5</td>
</tr>
</tbody>
</table>
Important Trends:

- Continuous increase of the frequency limits, i.e. $f_T$ and $f_{max}$
- Development of low-cost RF transistors for mass consumer markets

InP HBT and HMET possess the best frequency performance
Wide Bandgap MESFETs

Today only 4H SiC MESFET play a role worth mentioning. First commercial SiC MESFETs became available in 1999!

<table>
<thead>
<tr>
<th>Material</th>
<th>Cutoff Frequency, GHz</th>
<th>Gate Length, µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>4H SiC MESFET</td>
<td>22 GHz</td>
<td>upper limit 4H SiC MESFET</td>
</tr>
<tr>
<td>6H SiC MESFET</td>
<td>10 GHz</td>
<td>upper limit 6H SiC and GaN MESFET</td>
</tr>
<tr>
<td>GaN MESFET</td>
<td>8 GHz</td>
<td></td>
</tr>
</tbody>
</table>

Record $f_T$
- 4H SiC MESFET: 22 GHz
- 6H SiC MESFET: 10 GHz
- GaN MESFET: 8 GHz

Record $f_{max}$
- 4H SiC MESFET: 50 GHz
- 6H SiC MESFET: 25 GHz
AlGaN/GaN HEMTs

AlGaN/GaN HEMTs: Both $f_T$ and $f_{\text{max}}$ in excess of 100 GHz!
Design Rules for Low-Noise FETs According to the Formula

\[ NF \approx 10 \times \log \left( 1 + 2 \pi f K_f C_{GS} \sqrt{\frac{R_G + R_S}{g_m}} \right) \]
Noise Performance of RF Bipolar Devices

![Graph showing the noise performance of different types of RF bipolar devices.](image)
**Power Performance of State-of-Art RF FETs**

**GaAs MESFET, AlGaAs HEMT**
Moderate output power densities. Power amplification up to 60 GHz.

**pHEMT on GaAs, InP HEMT**
Moderate output power densities. Power amplification up to 100 GHz.

**Wide Bandgap FETs**
AlGaN/GaN HEMT, SiC MESFET. Highest output power densities up to 20 GHz.

---

[Graph showing power density vs. frequency for different types of FETs]
Wide bandgap FETs show the highest output power densities of all RF FETs in the frequency range important for current mobile communication systems (up to 5 GHz).
Cutoff Frequency vs. Gate Length for Different Types of RF FETs

<table>
<thead>
<tr>
<th>FET Type</th>
<th>$f_{\text{max}}$</th>
<th>$L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs MESFET</td>
<td>177</td>
<td>0.12</td>
</tr>
<tr>
<td>AlGaAs/GaAs HEMT</td>
<td>151</td>
<td>0.24</td>
</tr>
<tr>
<td>pHEMT on GaAs</td>
<td>350</td>
<td>0.1</td>
</tr>
<tr>
<td>mHEMT on GaAs</td>
<td>400</td>
<td>0.1</td>
</tr>
<tr>
<td>InP HEMT</td>
<td>$&gt; 600$</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Record $f_{\text{max}}$ Values for Different Types of RF FETs, $f_{\text{max}}$ in GHz, $L$ in $\mu$m
State of the Art (RF Bipolars)

<table>
<thead>
<tr>
<th>Transistor Type</th>
<th>$f_T$, GHz</th>
<th>$f_{\text{max}}$, GHz</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs HBT</td>
<td>60</td>
<td>350</td>
<td>1992</td>
</tr>
<tr>
<td>GaAs HBT</td>
<td>156</td>
<td>255</td>
<td>1998</td>
</tr>
<tr>
<td>InP HBT</td>
<td>154</td>
<td>478</td>
<td>2003</td>
</tr>
<tr>
<td>InP HBT</td>
<td>377</td>
<td>230</td>
<td>2003</td>
</tr>
<tr>
<td>InP HBT (TS)</td>
<td>204</td>
<td>1080</td>
<td>2000</td>
</tr>
<tr>
<td>SiGe HBT</td>
<td>350</td>
<td>170</td>
<td>2002</td>
</tr>
<tr>
<td>SiGe HBT</td>
<td>180</td>
<td>338</td>
<td>2003</td>
</tr>
<tr>
<td>SiGe HBT</td>
<td>270</td>
<td>260</td>
<td>2002</td>
</tr>
<tr>
<td>Si BJT</td>
<td>100</td>
<td>?</td>
<td>1996</td>
</tr>
<tr>
<td>Si BJT</td>
<td>72</td>
<td>101</td>
<td>1996</td>
</tr>
</tbody>
</table>
Silicon Advantages

• For God made earth with 25.7% of silicon

• For the greatest and most mature technology available (As fine as nanometer and as great as Giga scale)

• For the largest and least expensive substrate available. (for mass production with excellent uniformity and reproducibility)

• For the most compact and reliable devices available
SiGe HBTs – State of the Art 2003

<table>
<thead>
<tr>
<th>Performance Metric</th>
<th>Specification</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutoff Frequency</td>
<td>350GHz (IBM)</td>
<td></td>
</tr>
<tr>
<td>Max. Frequency of Oscillation</td>
<td>338GHz (IBM)</td>
<td></td>
</tr>
<tr>
<td>Minimum Noise Figure (at 2GHz)</td>
<td>&lt; 0.2dB (DaimlerChrysler)</td>
<td></td>
</tr>
<tr>
<td>Minimum Noise Figure (at 20GHz)</td>
<td>1.1dB (IBM)</td>
<td></td>
</tr>
</tbody>
</table>

**Drawback:** Very low breakdown voltage (2-3 V compared to 10-15 V of GaAs-based HBT)

**SiGe HBT became commercially available in the late 90s!**
RF Si MOSFET – State of the Art 2002

- $f_T$
  - 240 GHz (70 nm bulk nMOSFET)
  - 178 GHz (125 nm SOI nMOSFET)

- $f_{\text{max}}$
  - 198 GHz (5 nm SOI nMOSFET)

- $\text{NF}_{\text{min}}$
  - 0.25 dB @ 2 GHz, 0.5 dB @ 4 GHz, 1.2 dB @ 12 GHz

- $P_{\text{out}}$
  - 120 W @ 2 GHz (LDMOSFET)

The SOI MOSFET seems to be more promising in RF applications due to the ease of integration with III-V devices fabricated also on insulators.

Problems:
- High resistance of the poly Si gate (low $f_{\text{max}}$)
- Low breakdown voltage of extremely scaled Si MOSFETs
- Significant RF substrate noise due to the non-insulating Si substrate

Si power MOSFET operating up to 2.5 GHz are commercially available!
State of the Art MOSFET 2002

Intel MOSFET with 70 nm gate length

More than 40 Mio. transistors of this type are integrated on a single Intel Pentium 4 chip

The cutoff frequency of this device is 20-50 GHz, and the MOSFET is capable for low-end RF applications

Is the MOSFET size reduction approaching its limitation?
## Prediction of downsizing limit

<table>
<thead>
<tr>
<th>Period</th>
<th>Expected Limit (size)</th>
<th>Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late 1970’s</td>
<td>1 µm:</td>
<td>Short channel effect</td>
</tr>
<tr>
<td>Early 1980’s</td>
<td>0.5 µm:</td>
<td>S/D resistance</td>
</tr>
<tr>
<td>Early 1980’s</td>
<td>0.25 µm:</td>
<td>Direct-tunneling of gate SiO₂</td>
</tr>
<tr>
<td>Late 1980’s</td>
<td>0.1 µm:</td>
<td>Various</td>
</tr>
<tr>
<td>Early 2000’s</td>
<td>50 nm:</td>
<td>Various</td>
</tr>
<tr>
<td>Today</td>
<td>10 nm:</td>
<td>Fundamental limit?</td>
</tr>
</tbody>
</table>

H. Iwai, EDMO 2003
Ultimate limitation

There is a practical limit before the ultimate limit is reached. But no one knows the practical limit!

H. Iwai, EDMO 2003
Limiting factor for sub-10 nm CMOS

- Depletion layer formation
- Direct-tunneling current
- Fringing capacitance
- High S/D extension resistance
- Direct-tunneling current
- Inversion layer capacitance
- Impurity non-uniformity

H. Iwai, EDMO 2003
Future MOS Technologies

- Silicon dioxide gate insulation will be replaced by material with higher dielectric constant.
- Polysilicon gate will be replaced by metal.
- Silicon substrate will be replaced by strained silicon.
- Single gate will be replaced by double gate and basic transistor structure will change.

The Coming Thing in Transistors
Future generations of transistors will not only be smaller than today’s, but will also have to be different in more fundamental ways, as indicated above, to maintain acceptable performance levels.
Metallic overlay gate to reduce the gate resistance
Measured gains. Note: the reported $f_T$ and $f_{max}$ are simulated!
## Choice of high-k

<table>
<thead>
<tr>
<th>Material</th>
<th>k</th>
<th>$\text{HfAl}_x\text{O}_y$</th>
<th>10-15</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO stack</td>
<td>5-6</td>
<td>$\text{HfSi}_x\text{O}_y\text{N}_z$</td>
<td>10-15</td>
</tr>
<tr>
<td>$\text{Al}_2\text{O}_3$</td>
<td>8-9</td>
<td>$\text{ZrO}_2$, $\text{HfO}_2$</td>
<td>20-30</td>
</tr>
<tr>
<td>$\text{HfSi}_x\text{O}_y$</td>
<td>10-15</td>
<td>Lanthanide Oxides</td>
<td>15-30</td>
</tr>
</tbody>
</table>

Today, $\text{HfO}_2$ and its nitrides are mainstream for R & D

H. Iwai, EDMO 2003
Mobility Enhancement in Strained Si

K. Goodson et al., Stanford University
New MOSFET Structures for VLSI

Example: Trigate MOSFET (Intel)
Other groups call this device FinFET, Gate-All-Around FET, etc.
AlGaN/GaN HEMTs – State of the Art 2002

Frequency Limits
Record $f_T$: 121 GHz
Record $f_{max}$: 195 GHz

Noise Behavior
$NF_{min} = 0.3 \, \text{dB} \, @ \, 8 \, \text{GHz}$
$0.7 \, \text{dB} \, @ \, 12 \, \text{GHz}$
$1.0 \, \text{dB} \, @ \, 18 \, \text{GHz}$

Output Power
12.1 W/mm @ 3.5 GHz
105 W @ 2 GHz
51 W @ 6 GHz (W = 8 mm)
50 W @ 10 GHz (W = 12 mm)
Highest output power density of all RF FETs up to 20 GHz!

AlGaN/GaN HEMTs vs. SiC MESFETs
Higher frequency limits
Higher output power densities, but less total output power
GaN technology less mature, and reliability is still an open question
Up to now commercial AlGaN/GaN HEMTs are not available while commercial SiC MESFETs came to market in 1999
Future Trends and Summary
Trend 1

During the last 10 years: Shift of the applications of RF systems from defense and space applications to commercial mass markets.

RF is becoming mainstream!

Most commercial applications are in the lower GHz range (up to about 6 GHz).
Trend 2

Over the years, the performance of RF transistors has been improved continuously

Origins of the progress
• Scaling of the intrinsic device dimensions related to transistor speed
• Minimizing the external parasitics
• Introduction of heterostructures
• Using new materials, which offer better carrier transport properties, better carrier confinement and/or higher breakdown fields
Trend 3

Growing role of Si-based RF transistors (Si RF CMOS, Si LDMOSFET, SiGe HBT)

For mass markets, cost is an extremely important issue – and Si technology is less expensive than any other semiconductor technology.
## Active Device Comparison Matrix

<table>
<thead>
<tr>
<th></th>
<th>CMOS</th>
<th>LDMOS</th>
<th>SiGe HBT</th>
<th>GaAs MESFET</th>
<th>GaAs/Inp HEMT</th>
<th>GaAs/Inp HBT</th>
<th>SiC MESFET/GaN HEMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_T$</td>
<td>+</td>
<td>-</td>
<td>++</td>
<td>-</td>
<td>+</td>
<td>++</td>
<td>-</td>
</tr>
<tr>
<td>$f_{MAX}$</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>$NF_{MIN}$</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Linearity/$P_{DC}$</td>
<td>-</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Gain $g_m/g_0$</td>
<td>-</td>
<td>+</td>
<td>++</td>
<td>-</td>
<td>+</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Breakdown</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+++</td>
</tr>
<tr>
<td>Collector efficiency</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Device count</td>
<td>+++</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Thermal</td>
<td>+++</td>
<td>+++</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Cost</td>
<td>+++</td>
<td>+++</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
### Status of Different Semiconductor Technologies for RF Transistors

<table>
<thead>
<tr>
<th>Technology</th>
<th>max. $f_{op}$</th>
<th>Status</th>
<th>Preferred Appl.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si CMOS</td>
<td>5</td>
<td>R&amp;D, P</td>
<td>D/A, A/D</td>
</tr>
<tr>
<td>Si LDMOS</td>
<td>3</td>
<td>P</td>
<td>PA</td>
</tr>
<tr>
<td>Si BJT</td>
<td>5</td>
<td>P</td>
<td>LN, PA</td>
</tr>
<tr>
<td>SiGe HBT</td>
<td>50</td>
<td>P, R&amp;D</td>
<td>LN, PA (?)</td>
</tr>
<tr>
<td>GaAs MESFET</td>
<td>20</td>
<td>P</td>
<td>LN, PA</td>
</tr>
<tr>
<td>GaAs HEMT</td>
<td>60</td>
<td>P</td>
<td>LN, PA</td>
</tr>
<tr>
<td>GaAs HBT</td>
<td>30</td>
<td>P</td>
<td>PA, LN (?)</td>
</tr>
<tr>
<td>InP HEMT</td>
<td>200</td>
<td>R&amp;D, P</td>
<td>LN, PA</td>
</tr>
<tr>
<td>InP HBT</td>
<td>150</td>
<td>R&amp;D, P</td>
<td>PA</td>
</tr>
<tr>
<td>SiC MESFET</td>
<td>10</td>
<td>R&amp;D, P</td>
<td>PA</td>
</tr>
<tr>
<td>AlGaN/GaN HEMT</td>
<td>20</td>
<td>R&amp;D</td>
<td>PA, LN (?)</td>
</tr>
</tbody>
</table>
Market Share of Semiconductor Devices

- **Market Share of MOS**: Dominant share increasing over the years.
- **Market Share of Bipolar**: Decreasing share over the years.
- **Market Share of III-V**: Stable share over the years.

Year:

Market Share, %:
- 0 to 100

Graph shows the market share distribution of MOS, Bipolar, and III-V semiconductor devices from 1980 to 2005.
Market Share of III-V Technologies

Share of GaAs MESFETs, GaAs HEMTs, and GaAs HBTs on the total GaAs RF IC market
Summary

• Prior to 1980, only two RF transistor types (Si BJT and GaAs MESFET) existed. In 2001, a large variety of different devices are available, including Si CMOS, SiGe HBT, GaAs HBT, GaAs HEMT, InP HBT, InP HEMT, and wide bandgap FETs.

• Si CMOS devices have a clear cost advantage and are typically used for frequencies up to 2.5 GHz. Most applications above 2.5 GHz belong to GaAs-based transistors. High-performance applications above 40 GHz are dominated by InP-based transistors.

• InP-based HBTs and HEMTs possess the best $f_T$ and $f_{max}$, but the technology for InP-based devices is not yet mature. These devices also have poorer power performance.

• GaAs-based HBT has been the most widely used HBT in RF design, but SiGe HBT has gained popularity recently due to its superior noise performance and its compatibility with existing Si CMOS technology.
Wide bandgap devices have great potential because of their relatively high operating frequency and superior power performance. Difficulties with their processing, however, have hampered their progress toward becoming mainstream devices.

Cost study in 1998 suggested $0.12/mm^2, 0.5/mm^2, and 1.2/mm^2 for SiGe, GaAs, and InP HBTs, respectively, based on the use of 6” Si, 4” GaAs ($170), and 3” InP ($700) wafers.

Mass production GaAs- and InP-based devices with $f_T$ and $f_{\text{max}}$ over 300 GHz can become available in the next few years, and the operating frequency of next-generation MOSFET with 0.07 μm feature size can reach 20-30 GHz.
To Probe Further

Text Books

• J. J. Liou, Principles and Analysis of AlGaAs/GaAs Heterojunction Bipolar Transistors, Artech House 1996.


• F. Ali and A. Gupta (eds.), HEMTs & HBTs, Artech House 1991.


• J. J. Liou et al., CMOS RF Devices: Test Structure, Modeling, and Characterization, J. Wiley 2004?

Review Papers


