AlGaN/GaN HEMTs and HBTs

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PART I

AlGaN/GaN HEMTs
### Materials Properties Comparison

<table>
<thead>
<tr>
<th>Material</th>
<th>$\mu$</th>
<th>$\varepsilon$</th>
<th>$E_g$</th>
<th>BFOM Ratio</th>
<th>JFM Ratio</th>
<th>$T_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1300</td>
<td>11.4</td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
<td>300 C</td>
</tr>
<tr>
<td>GaAs</td>
<td>5000</td>
<td>13.1</td>
<td>1.4</td>
<td>9.6</td>
<td>3.5</td>
<td>300 C</td>
</tr>
<tr>
<td>SiC</td>
<td>260</td>
<td>9.7</td>
<td>2.9</td>
<td>3.1</td>
<td>60</td>
<td>600 C</td>
</tr>
<tr>
<td>GaN</td>
<td>1500</td>
<td>9.5</td>
<td>3.4</td>
<td>24.6</td>
<td>80</td>
<td>700 C</td>
</tr>
</tbody>
</table>

BFOM = Baliga’s figure of merit for power transistor performance [$K\mu E_c^3$]

JFM = Johnson’s figure of merit for power transistor performance
(Breakdown, electron velocity product) [$E_b V_{br}/2\pi$]
## Advantages of WBG Devices

<table>
<thead>
<tr>
<th>Need</th>
<th>Enabling Feature</th>
<th>Performance Advantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Power/Unit Width</td>
<td>Wide Bandgap, High Field</td>
<td>Compact, Ease of Matching</td>
</tr>
<tr>
<td>High Voltage Operation</td>
<td>High Breakdown Field</td>
<td>Eliminate/Reduce Step Down</td>
</tr>
<tr>
<td>High Linearity</td>
<td>HEMT Topology</td>
<td>Optimum Band Allocation</td>
</tr>
<tr>
<td>High Frequency</td>
<td>High Electron Velocity</td>
<td>Bandwidth, $\mu$-Wave/mm-Wave</td>
</tr>
<tr>
<td>High Efficiency</td>
<td>High Operating Voltage</td>
<td>Power Saving, Reduced Cooling</td>
</tr>
<tr>
<td>Low Noise</td>
<td>High gain, high velocity</td>
<td>High dynamic range receivers</td>
</tr>
<tr>
<td>High Temperature Operation</td>
<td>Wide Bandgap</td>
<td>Rugged, Reliable, Reduced Cooling</td>
</tr>
<tr>
<td>Thermal Management</td>
<td>SiC Substrate</td>
<td>High power devices with reduced cooling needs</td>
</tr>
<tr>
<td>Technology Leverage</td>
<td>Direct Bandgap:</td>
<td>Driving Force for Technology:</td>
</tr>
<tr>
<td></td>
<td>Enabler for Lighting</td>
<td>Low Cost</td>
</tr>
</tbody>
</table>
If it ain’t good @ DC it ain’t goin’ to be good @ RF

\[ P_{\text{max}} = \frac{1}{8} V_{\text{max}} \cdot I_{\text{max}} \]

\[ I = V \cdot n_s \cdot \nu \]

- Maximize I \implies\text{Maximize } n_s, \nu
- Maximize n_s \implies\text{Maximize } P_{SP}, P_{PE}
  \implies\text{Maximize Al mole fraction without strain relaxation}
- Maximize \nu \implies\text{Minimize effective gate length}
  \implies\text{Minimize } L_g \text{ and gate length extension}
- Maximize \mu \implies\text{Minimize dislocations}
  \implies\text{Smooth interface}
Issues With Maximizing Al Mole Fraction in $\text{Al}_x\text{Ga}_{1-x}\text{N}$

- **Graph:**
  - $E_g$ vs. Lattice Constant
  - Points for $x_{\text{Al}} = 0.2$, $x_{\text{Al}} = 0.4$, $x_{\text{Al}} = 0.6$

- **Images:**
  - $x_{\text{Al}} = 0.2$
  - $x_{\text{Al}} = 0.4$
  - $x_{\text{Al}} = 0.6$

- **Explanation:**
  - Dislocations lead to premature relaxation of AlGaN and a potential reliability problem because of the metallized pits.

- **Note:**
  - $x_{\text{HC}} = 0.3$ relaxed
Issues With Increasing Mobility

INCREASING Al MOLE FRACTION DECREASES MOBILITY

High Mobility AlGaN/GaN Structures
Grown by RF Plasma Assisted MBE

Mobility v. Al Fraction Plot

U.S. Department of Defense
ELECTRONS IN SURFACE STATES AND/OR BUFFER TRAPS DEPLETE THE CHANNEL CAUSING GATE LENGTH EXTENSION

SEVERE CONSEQUENCE: DISPERSION BETWEEN SMALL SIGNAL AND LARGE SIGNAL BEHAVIOR BECAUSE OF THE LARGE TRAP TIME CONSTANTS

WHY DO THESE TRAPS ARISE?
Example of Advantage of WBG Devices

- 10-x power density (> 10 W/mm)
- 10-x reduction in power-combining
- Improved efficiency (> 60 %)
- Improved reliability
- Compact size
- Superior Performance at reduced cost
Application Space

The diagram illustrates the application space for various technologies, categorized by frequency bands and power levels. Key technologies include Shipboard Radar, Airborne Radar, THAAD, Decoy, Satcom, VSAT, Base Station Driver Amp, MMDS, WLL, 3G, UNII, Hiperlan, LMDS, Digital Radio, VSAT, LMDS, Military, Commercial, BAT, P31, Missile Seekers, and CAR.

The frequency bands are divided into S, C, X, Ku, K, Ka, Q, V, and W, with corresponding power levels ranging from 0.1 to 1000 watts. The diagram highlights the overlap and distribution of these technologies across different applications and frequencies.
Schematic of Device Structure

- **SOURCE**
- **DRAIN**
- **GATE**
- **2DEG**
- **GaN**
- **AlGaN**

- **SiN Passivation**
- **Nucleation Layer**
  - GaN, AlGaN or AlN
- **Substrate**: Typically Sapphire or SiC

**UCSB**
Ball and Stick Diagram of the GaN Crystal
How does the electron gas form in AlGaN/GaN structures? - A

$Q_\pi$ includes the contribution of spontaneous and piezo-electric contributions

$P(x) = (Q_{\pi,\text{AlGaN}}) + (-Q_{\pi,\text{GaN}})$
How does the electron gas form in AlGaN/GaN structures?

$Q_{\pi}$ includes the contribution of spontaneous and piezo-electric contributions

$P(x) = (-Q_{\pi,GaN}) + (Q_{\pi,InGaN})$
How does the electron gas form in AlGaN/GaN structures? - C

\[ V_{AlGaN} \approx E_{g,GaN} + \Delta E_v = \text{Maximum Dipole Moment} \]
How does the electron gas form in AlGaN/GaN structures?
Dispersion in AlGaN/Ga HEMTs
Electrons in Surface States

Depletion of 2DEG caused by occupied surface states
Performance of Passivated AlGaN/GaN HEMT on Sapphire
Performance of AlGaN/GaN HEMT on SiC (CLC)

f = 8 GHz, Tuned for Power

\[ P_{\text{out}} = 10.3 \text{ W/mm} \]

PAE = 42\%

- Pout
- Gain
- PAE
- Id

\[ P_{\text{out}} (dB), \text{Gain(dB)}, \text{PAE} (\%) \]

\[ P_{\text{in}} (dB) \]

\[ I_d (mA) \]
Drain Bias Dependence of Rf Power (CLC)

Increasing $V_{ds}$
Flip-chip AlGaN/GaN HEMT for Thermal Management
I-V Curves from 8mm-wide HEMT

\( V_g \) start: +2V, Step: -2 V

\( I_d \) (A/division)

\( V_{ds} \) (V/division)

U.S. Department of Defense
Low Flip-chip Wide Bandwidth Amplifier
Pulse Power Performance of mm-flipped Device
• Includes ALL LEADING players in the field
• CREE = Cree Lighting + Cree-Durham
Part II

High Voltage Operation (> 330 V) of AlGaN/GaN HBTs
Bipolar transistor key issues

- **Injection**
  - $\gamma \Rightarrow 1$
  - $n \Rightarrow 1$
  
  \[ I = I_0 \exp(\frac{qv}{nkt}) \]

- **Transport**
  - $\alpha \Rightarrow 1$

- **Collection**
  - $C_{bc} \Rightarrow 0$
  - $\nu \Rightarrow \nu_{\text{sat}} \left[2 \times 10^7 \, \text{cm/s}\right]$ \textit{(Kolnik et. al.)}
  - $V_{br} \Rightarrow E_{\text{crit}} \, W_C \left[E_{\text{crit}} \sim 2 \, \text{MV/cm}\right]$ \textit{(Bhapkar and Shur.)}

- **Output Conductance**
  - $\Delta I_C/\Delta V_{CE} \Rightarrow 0$
  - $(\Delta W_B/\Delta V_{CE} \Rightarrow 0)$
Hurdles with GaN bipolar transistors

- Lack of low damage etch to reveal base
  - Leaky E/B junction
  - Bad base contact
  - No etch stop
- High $R_B$
  - Poor p-GaN base contact
  - Low p-GaN base conductivity
    - Deep acceptor (~160 meV)

- Hard to control junction placement in MOCVD due to memory effect of p-dopant Mg

Surface leakage due to etch damage

Low minority carrier lifetime

Dislocation causes leakage

U.S. Department of Defense
Demonstration of dislocation enhanced leakage

**LEO used to investigate leakage of devices without dislocations. (Lee McCarthy et al.)**

![Graph showing leakage current vs applied bias](graph)

**Leakage from Collector to Emitter, Wing vs Window**

**Results:** LEO device demonstrated
- Reduction in Leakage
- Stable operation past 20V
- Gain unchanged
- Devices on dislocated material also functional

**Explanation**
- Thick substrate sufficiently reduces dislocations to prevent C/E short in window region
- Gain ($\tau_e$) not currently limited by dislocation density
Strategy: Thick Collector

- Decent dislocation density
  - High quality MOCVD templates achieved
    \textit{Dislocation density} \sim 5e8 \text{ cm}^2

- Low background doping
  - \( N_D < 1e16 \text{ cm}^{-3} \) (Assuming uniform doping \( N_D \) and \( E_{\text{critical}} = 2 \text{ MV/cm} \), requires 10 \( \mu \text{m} \) to achieve 1 KV breakdown voltage.)
Selectively grow MOCVD emitter on base-collector structures.

1. Pattern regrowth mask
2. Regrow emitter layer by MOCVD
3. Remove mask and contact base and etch to collector
4. Contact collector, emitter
Severe memory effect observed in non-interrupted MOCVD growth
Slow decay tail into GaN:Si regrown on as-grown GaN:Mg layer

Memory effect

Slow decay tail in regrowth
- Regrown in Mg-free reactor and all grown by MOCVD
- Presence of an excessive amount of Mg on the surface, which can be removed by acid etch
- Occurrence of Mg diffusion, ~ 40 nm/decade sharpness achieved

![Graph showing Mg concentration vs. depth with labels C, D, and E explaining the conditions: C: as grown, ~100 nm/decade, D: etch in HF and HCl for 5 min, ~ 50 nm/decade, E: etch in BHF (1:20) for 15 sec and HCl for 20 sec, ~40 nm/decade. The graph includes a detection limit and a regrowth surface marker.]
Selectively regrown n/p diodes

- Mask enhanced growth complicates the analysis
  - Regrowth rate depends on the mask layout, diode size etc
  - “Bunny ear” regrowth profile is often seen
  - Only the emitter edge is active in device operation due to highly resistive base layer
  - The junction quality depends on how the regrowth is initiated, e.g. Temp, P, flows, presence of Si and Al etc.

“Bunny ear” regrowth profile of two different square diodes
Regrown n/p Diodes Characteristics

- Comparison of various structures regrown on 0.5 μm GaN:Mg

<table>
<thead>
<tr>
<th>Run #</th>
<th>Layer structure</th>
<th>Growth Parameter</th>
<th>G.R. (nm/min)</th>
<th>Temp/Press (C/Torr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0005 10GF</td>
<td>400 nm GaN:Si (4e18 cm⁻³)</td>
<td>~30</td>
<td>1140/760</td>
<td></td>
</tr>
<tr>
<td>0007 14AE</td>
<td>250 nm Al₀.₀₆GaN:Si (1e18)</td>
<td>~30</td>
<td>1100/300</td>
<td></td>
</tr>
<tr>
<td>0007 14AF</td>
<td>xₚ≈ 5%</td>
<td>~30</td>
<td>1100/300</td>
<td></td>
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<tr>
<td></td>
<td>250 nm AlGaN:Si (1e18)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>75 nm GaN-&gt;AlGaN:Si (1e18)</td>
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<td></td>
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<tr>
<td>0105 13GC</td>
<td>450 nm GaN:Si (1e18)</td>
<td>~40</td>
<td>1100/300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30 nm GaN</td>
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<td>0105 17AA</td>
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<td>30 nm GaN:Si</td>
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<td>30 nm AlGaN-&gt;GaN:Si</td>
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<td>750 nm AlGaN:Si</td>
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<td>60 nm GaN-&gt;AlGaN</td>
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<tr>
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<td>60 nm GaN</td>
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</tr>
</tbody>
</table>

![Graph of I density vs V (Volts)]

- Year 2000
- Year 2001
HBT with 8 mm GaN collector

- Current gain ($\beta$) > 20
- Common emitter operation > 300 V
- Non-passivated
- Base thickness 1000 Å
- Al$_{0.05}$GaN emitter

$V_{br} \sim 330$ V
Device structure

- Utilization of uid GaN spacer and grading layer
  - HBTs with high emitter injection coefficient
- Etch damage and current mask layout limits V_{br}

\[
\begin{align*}
4 \text{ nm GaN:Si (1e18 cm}^{-3}\text{) contact} \\
4 \text{ nm Al}_{0.05} \text{ GaN->GaN:Si (1e18 cm}^{-3}\text{) grading} \\
105 \text{ nm Al}_{0.05} \text{ GaN:Si (1e18 cm}^{-3}\text{) emitter} \\
8 \text{ nm GaN->Al}_{0.05} \text{ GaN (?3e18 cm}^{-3}\text{) grading} \\
8 \text{ nm uid GaN spacer} \\
100 \text{ nm GaN:Mg (2e19 cm}^{-3}\text{) base} \\
8 \mu\text{m uid GaN (4e15 cm}^{-3}\text{) collector} \\
2 \mu\text{m GaN:Si (1e18 cm}^{-3}\text{) subcollector} \\
\text{Sapphire}
\end{align*}
\]
I-V Characteristics

- reasonable base contacts
- Improved B/E diodes
- Rectifying B/C diodes, Vbr > 300 V
• Conclusion

– In selective emitter regrowth, a sharp Mg profile, ~ 40 nm/decade, enables the precise junction placement

– Improvement of regrown-emitter/base diodes

– Demonstration of high Vbr (> 300 V) with high $\beta$ (DC common emitter operation up to 35)