Nitride Based HBT Technology

Objective:
High frequency, high power microelectronics are required for a number of navy applications including communications links and phased array radar. Target goals are devices operating at 1-5 GHz with >100W of rf power. GaN-based HBTs should be capable of this performance at temperatures >400°C and be a replacement for less efficient, low reliability, costly vacuum tubes now used to meet this need.

Technical Approach:
Develop etching and contacting techniques for fabrication of GaN/AlGaN HBTs, and optimize layer structure through 2D-modelling. In particular the base resistance is likely to be a limiting factor because of the low doping levels in p-GaN. Collaborate with Sandia National Laboratories on modelling, growth and SVT Associates on growth.

Alternative Approaches:
Traditional Si-based technologies cannot reach the desired performance.
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HBT: one of the most demanding device structures to grow
Need for -high, well confined $p$-type dopant concentration in the base layer
-very lightly doped $n$-type collector layer
-high doped $n$-type emitter layer
Requires high purity, low diffusion, abrupt switching
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Basic Transistor Operation

- Use of a wide band-gap emitter and low band-gap base provides band offsets at the hetero-interface
- Reduces the injection of base majority carrier in the emitter
- Potential step in CB permits injection of carriers with high kinetic energies in the base under the application of a forward bias, leading to a short base-transit time
- Injected carriers collected by the reverse-biased base/collector junction across which a high electric field exists
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Process Flow For GaN/AlGaN HBT

- **Emitter Mesa Dry Etching**
- **Base Metallization**
- **Base Mesa Etching**
- **Collector Metal Contact**
- **Device Isolation**

**Substrate**
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Initial Results on AlGaN/GaN HBTs

- UC Santa Barbara: MOCVD growth, RIE etching, additional p-type material re-grown to reduce extrinsic base resistance and repair etch damage using SiN sidewall

- U.of Florida/Sandia: MBE and MOCVD techniques, ICP etching

Similar results with limited current gain (β of 3 at T=30 °C and 10 at elevated temperatures > 250 °C) - High recombination rates in the base - No small signal AC results reported yet.
Confinement of Mg Base Dopant is an Issue
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- First GaN BJT Operated in Common-Base Mode
- The Common-Base Mode is Attractive for Microwave Amplifiers Because of the Possibility of Appreciable Power Gain Obtained Through the Impedance Transformation Offered by the Amplifier.
- Emitter Diameter 100 µm.
- Grown by MBE on MOCVD Buffer on Sapphire.
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- First GaN HBTs Operated in Common-base Mode
- Breakdown Characteristics Improved When Device is Grown on Thick Buffer Layers on Sapphire
- Common-emitter DC Current Gain 15-20 at 25°C
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Metal/GaAs(C)/GaN(Mg) Contacts

- Metal
- p-GaAs (C)
- p-GaN (Mg)

Energy levels:
- $\Delta E_C \sim 0.2\text{eV}$
- $\Delta E_V \sim 1.8\text{eV}$
- $E_F$ (Fermi level)

Graph showing concentration and secondary ion intensity.
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Structural and Electrical Results

Specific Contact Resistance of Ni/Au p-Ohmic Contacts
(Measured at 250°C)

<table>
<thead>
<tr>
<th>Material</th>
<th>(\rho_c,\text{(ohm}\cdot\text{cm}^2)) unannealed</th>
<th>(\rho_c,\text{(ohm}\cdot\text{cm}^2)) 800°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-GaAs(C)</td>
<td>9-14x10^{-6}</td>
<td>3-6x10^{-6}</td>
</tr>
<tr>
<td>p-GaN(Mg)</td>
<td>8x10^{-2}</td>
<td>4x10^{-3}</td>
</tr>
<tr>
<td>p-GaAs(C)/p-GaN(Mg)</td>
<td>7x10^{-3}</td>
<td>2x10^{-3}</td>
</tr>
</tbody>
</table>
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DC Current Gain $\beta$

\[ \beta = \frac{I_C}{I_B} \]

\[ I_B = I_{Bp} + I_{B,Surf} + I_{B,Cont} + I_{B,Bulk} + I_{B,SCR} \]

**Ideal case**

\[ \beta = \frac{I_C}{I_{Bp}} = \frac{D n_B X_E N_E}{D p_E X_B N_B} \exp \left( \frac{\Delta E_v}{kT} \right) \]

**When $I_{B,Bulk}$ dominant**

\[ \beta = \frac{I_C}{I_{B,Bulk}} = \frac{\tau_n}{\tau_B} \]

\[ \tau_n = \left( \frac{1}{\tau_{rad.}} + \frac{1}{\tau_{SRH}} + \frac{1}{\tau_{Aug.}} \right)^{-1} \]

\[ \tau_B = \frac{X_B^2}{\frac{kT}{q} \gamma \mu_{nB}} \]
Simulation of GaN-based HBT using a commercial simulator based on the drift-diffusion model

Performance analysis achieved by self-consistent solution of the Poisson, carrier continuity and current density equations in 2D

Physical models include:

- Generation-recombination mechanisms (SRH, optical, Auger)
- Low-Field concentration-dependent mobility
- Doping dependence on minority carrier lifetime
- Ohmic contact for both $n$ and $p$-type materials
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Initial MOCVD-grown Structure

<table>
<thead>
<tr>
<th>Region</th>
<th>Charge Density</th>
<th>Thickness (Å)</th>
<th>Electron Mobility (µn)</th>
<th>Hole Mobility (µp)</th>
<th>Lifetime (τ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emitter</td>
<td>n = 5x10^{17}</td>
<td>1000</td>
<td>250</td>
<td>5</td>
<td>10^{-9} s</td>
</tr>
<tr>
<td>Base</td>
<td>p = 1x10^{18}</td>
<td>1500</td>
<td>50-150</td>
<td>3.5</td>
<td>3-7x10^{-9} s</td>
</tr>
<tr>
<td>Collector</td>
<td>n = 1x10^{17}</td>
<td>5000</td>
<td>400</td>
<td>7</td>
<td>10^{-8} s</td>
</tr>
<tr>
<td>Sub-collector</td>
<td>n = 1x10^{18}</td>
<td>8000</td>
<td>250</td>
<td>3.5</td>
<td>5x10^{-10} s</td>
</tr>
</tbody>
</table>

Emitter $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}$
$E_G=3.85 \text{ eV} @ T=300\text{K}$

Base GaN
$E_G=3.4\text{eV}$
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Gummel Plot of initial structure

**Gummel plot:** base & collector currents as a function of $V_{BE}$ when $V_{CB} = 0$
Common Emitter configuration

Current gain sensitive to transport parameters
High recombination rates in the base
Limited $\beta$ values (<3)
optimization of epitaxial/geometrical design
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Influence of the base thickness

\[ \tau_B = \frac{X_B^2}{\gamma kT q \mu_{nB}} \]

with \( X_B \) from 0.15 to 0.075 μm
Decreasing base transit time \( \tau_b \)
Gain up to \( \beta=6 \)
Influence of a quasi E-Field in the base

Band-gap gradient in the base
Drift in addition to diffusion component
Base transit time decreases

Electron drifts through base

- n$^+$ AlGaN
- p$^+$ AlGaN-GaN 0.1$\mu$m
- n GaN 0.5 $\mu$m
- n$^+$ GaN 0.8 $\mu$m

Δ$E_C$

Δ$E_V$

$\varepsilon_B$

3.75 eV
3.40 eV

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University of Florida
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Influence of a quasi E-Field in the base - II

12% grade of Al. concentration
$E_G$ from 3.75 to 3.4 eV @ 300K
$\Phi$ quasi-field of ~25 kV/cm
$x_{Al}=18\%$ in the Emitter
$(E_G=3.9eV)$

Higher turn-on voltage
Improvement of current gain from $\beta=4$ to 16
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Influence of base doping level

Relatively lower doping in the base from $1 \times 10^{18}$ to $5 \times 10^{17}$ cm$^{-3}$

$$\beta = \frac{I_C}{I_{B,Bulk}} = \frac{\tau_n}{\tau_b}$$

Enhanced mobility & carrier lifetime € increasing gain from $\beta = 16$ to 40

BUT trade-off between gain and base contact resistance

Selective re-growth of “heavily” doped extrinsic base region to optimize both parameters
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Family of curves $I_C = f (V_{CE})$
## Summary of Simulation Results

<table>
<thead>
<tr>
<th>No</th>
<th>Structure Part I</th>
<th>Structure Part II</th>
<th>Doping</th>
<th>Lifetime</th>
<th>Mobilities $\mu n_0/\mu p_0$</th>
<th>Results</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Xe=0.1 $\mu$m, Xb=0.15 $\mu$m, Xc=0.5 $\mu$m, Xsc=0.8 $\mu$m</td>
<td>-AlGaN/GaN -Abrupt E-B interface -$E_{gg}$ = 3.9 eV -$E_{gg,C}$ = 3.4 eV</td>
<td>Ne=5.10$^{17}$ cm$^{-3}$ Nb=10$^{18}$ cm$^{-3}$ Nc=10$^{17}$ cm$^{-3}$ Nsc=10$^{15}$ cm$^{-3}$</td>
<td>$\tau_{n,p}$=10$^{-9}$ s (e) $\tau_{n,p}$=5.10$^{-11}$ s (b) $\tau_{n,p}$=10$^{-8}$ s (c) $\tau_{n,p}$=5.10$^{10}$ s (sc)</td>
<td>170/9 (e) 280/13 (b) 550/22 (c) 225/11 (sc)</td>
<td>$\beta$=2-3 (with $Q_C$=0.5) $V_{ON}$=2.7V</td>
<td>-U. of Florida’s structure -Generic design of npn HBT @ 300K -Emitter width of 100$\mu$m -All contacts supposed to be ohmic -No cap layer considered -High collector current density but too high Base current -Low $\beta$ -Turn-ON voltage ~2.7V</td>
</tr>
<tr>
<td>2</td>
<td>Xe=0.1 $\mu$m, Xb=0.05 $\mu$m, Xc=0.5$\mu$m, Xsc=0.8$\mu$m</td>
<td>- NC</td>
<td>- NC</td>
<td>- NC</td>
<td>- NC</td>
<td>$\beta$&gt;25 (with $Q_C$=0.5)</td>
<td>-Base thickness reduced to 500 Å -Improved $\beta$ due to shorter transit time -Unrealistic Xb (too thin regarding to etch control)</td>
</tr>
<tr>
<td>3</td>
<td>Xe=0.1 $\mu$m, Xb=0.10 $\mu$m, Xc=0.5$\mu$m, Xsc=0.8$\mu$m</td>
<td>- NC</td>
<td>- NC</td>
<td>- NC</td>
<td>- NC</td>
<td>$\beta$=8-9 (with $Q_C$=0.5)</td>
<td>-Base thickness reduced to 1000 Å -More realistic design of base thickness -$\beta$ increases by a factor of 3 Conclusion: a value of 800 Å might be a good candidate</td>
</tr>
<tr>
<td>4</td>
<td>Xe=0.1 $\mu$m, Xb=0.10 $\mu$m, Xc=0.5$\mu$m, Xsc=0.8$\mu$m</td>
<td>- NC</td>
<td>- NC</td>
<td>- NC</td>
<td>- NC</td>
<td>$\beta$=6-7 (with $Q_C$=0.7)</td>
<td>-Influence of the band offset ratio $Q_C$ -Current gain $\beta$ decreases because $\exp(\Delta E/kt)$ decreases -Accurate value of $Q_C$ required (not well-known parameter)</td>
</tr>
</tbody>
</table>
## Nitride Based HBT Technology

### Summary of Simulation Results (continued)

| 5 | Xe=0.1 µm  
Xb=0.10 µm  
Xc=0.5µm  
Xsc=0.8µm  | -Graded Band Gap in base from 3.9 to 3.4 eV.  
- Emitter E_{G} @4.1 eV  | - NC  
| - NC  
| - NC  | β=60  
(with $Q_{C}=0.5$)  
β=55  
(with $Q_{C}=0.6$)  
β=50  
(with $Q_{C}=0.7$)  | -Graded Al composition in the base for the establishment of a “base quasi E. Field”  
- Base thickness of 1000 Å  
- Higher turn-ON voltage ~2.9V  
- Drift component in addition to diffusion in Base  
- $\tau_{b}$ base transit time decreases  |
| 6 | Xe=0.1 µm  
Xb=0.10 µm  
Xc=0.5µm  
Xsc=0.8µm  | -Graded Band Gap in base from 3.9 to 3.4 eV.  
- Emitter E_{G} @4.1 eV  | Nb=5.10^{17} cm^{-3}  
$\tau_{n,p}$=6.10^{-11} s (b)  
300/17 (b)  | β=80  
(with $Q_{C}=0.7$)  | -GaN=poor transport properties for minority carrier. Higher lifetime & mobilities by considering lower Base doping level Nb  
- lower base current  
- improvement of $\beta$  
- Strong Influence of $\tau_{n,p}$ on simulation results  
- Higher sheet resistance expected (not compatible with AC optimization)  |
| 7 | Xe=0.1 µm  
Xb=0.10 µm  
Xc=0.5µm  
Xsc=0.8µm  | -AlGaN/GaN  
-Abrupt E-B interface  
-E_{st} = 4.1 eV  
-E_{E_B,C}=3.4 eV  | $\beta=8.9$  
(with $Q_{C}=0.5$)  
$V_{ON}$~2.9V  | - Influence of Emitter band gap  
- Comparison with # 3  
- No modification of current gain  
- Higher turn-On voltage  |

Legend:  
e-emitter  
b-base  
c-collector  
sc-sub-collector  
$Q_{C}$-Conduction Band offset

Numerical values of current gain displayed in this table must be considered carefully because of the lack of reliable and systematic characterization of minority carrier lifetime and mobility, especially for p-type doped materials. The band offset ratio is also subject to speculation (most likely around 0.70). The investigation gives us an idea of how the design of HBT devices might be modified to increase $\beta$. Basically, an approach with a thin (less than 1000 Å) base layer with a graded composition ($E_{G}$ from 3.9 near the emitter side to 3.4 eV near the collector side) and a not too high doping level might have a significant impact on the current gain $\beta$. 


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Conclusion

Simulation of DC performances of existing \textit{Npn} AlGaN/GaN HBTs Structures

Current gain ($\beta < 3$) limited by high recombination rates in the base

Investigation of geometrical and epitaxial design in order to decrease the transit time $\tau_b$ in the base

An approach with
- a thin ($X_b < 1000$ Å) base layer
- a base graded composition ($E_G$ from 3.75 near E to 3.4 eV near C)
- a not too high base doping level

might have a significant impact on the current gain $\beta$. 
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Technical Accomplishments:
(i) GaN/AlGaN HBTs with gain of 10 at 300°C
(ii) Demonstrated GaN BJT
(iii) Improved p-contact resistance through GaAs(C) regrowth
(v) Initial modelling of layer structure to optimize gain
(vi) Developed technologies for damage removal in dry etched p-GaN

Future Plans:
(i) Improved modelling to include spontaneous and piezoelectric polarization effects (6/2000)
(ii) Optimized layer structures (6/2000)
(iii) Optimized p-contact for base (6/2000)
(iv) Power devices (9/2000)
(v) rf measurements (9/2000)
(vi) pnp HBT (12/2000)

Navy, DOD Impact: Improved satellite and terrestrial radar and communications links.

Funding Level: $360,000/3 years