Contract DTRA 01-99-P-0006

Task 1. **HBT Modelling and Design**

Figure 1 shows a typical HBT structure and some of its characteristics.

**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

**Figure 1.** The HBT Structure.
The basic operating principles as shown in Figure 2.

- 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

**Figure 2.** Basic transistor operation.

To calculate the current gain, \( \beta \), we need to consider several different cases, as shown in Figure 3.
\[ \beta = \frac{I_C}{I_B} \]

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

**Ideal case**

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

**When \( I_{B,Bulk} \) dominant**

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

**Figure 3.** DC current gain \( \beta \).

**Description of the simulation**

- 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
Choice of physical parameters

- **Electron and hole mobility**
  - from a survey of 300K electron Hall mobility values
  - $\mu_E$ from 500 cm$^2$/V.s @ $10^{17}$ cm$^{-3}$ to <100 cm$^2$/V.s @ $10^{19}$ cm$^{-3}$
  - two orders of magnitude smaller for holes
  - No distinction between majority carrier and minority carrier mobility

- **Minority carrier lifetime in p-type & n-type GaN**
  by Electron Beam Induced Current (EBIC) measurements, see Z.Z. Bandic, APL 72, 3276 (1998)
  No systematic study $Vs$ carrier concentration. Results dominated by material quality
  $$\tau = 5-7 \text{ ns for } n\text{-type at } 10^{17} \text{ cm}^{-3} \quad \tau = 0.1 \text{ ns for } p\text{-type at } 10^{17} \text{ cm}^{-3}$$

- **AlGaN/GaN band offset ratio**
  $\Delta E_C = 0.7-0.75, \Delta E_G$
The initial MBE-grown structure is shown in Figure 4.

<table>
<thead>
<tr>
<th>Component</th>
<th>n/p</th>
<th>Thickness (Å)</th>
<th>μn/μp</th>
<th>τ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emitter</td>
<td>n</td>
<td>5x10^17</td>
<td>1000</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10^-9</td>
</tr>
<tr>
<td>Base</td>
<td>p</td>
<td>1x10^18</td>
<td>1500</td>
<td>50-150</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>3.5</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3-7x10^-9</td>
</tr>
<tr>
<td>Collector</td>
<td>n</td>
<td>1x10^17</td>
<td>5000</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10^-8</td>
</tr>
<tr>
<td>Sub-collector</td>
<td>n</td>
<td>1x10^18</td>
<td>8000</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5x10^-10</td>
</tr>
</tbody>
</table>

**Figure 4.** Initial MBE-grown structure.
**Gummel plot**: base & collector currents as a function of $V_{BE}$ when $V_{CB} = 0$

**Common Emitter configuration**

- Current Gain $\beta$
- Base-emitter Voltage $V_{BE}$ (V)

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

**Figure 5.** Gummel Plot of initial structure.
We then examined the effect of various parameters, including base thickness (Figure 6), the influence of a quasi E-field in the base (Figures 7 and 8) and the effect of base doping level (Figure 9).

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

Figure 6. Influence of the base thickness.

with \( X_B \) from 0.15 to 0.075 \( \mu m \)
Decreasing base transit time \( \tau_b \)
Gain up to \( \beta=6 \)
Figure 7. Influence of a quasi E-field in the base.

Electron drifts through base

Band-gap gradient in the base
Drift in addition to diffusion component
Base transit time decreases
Figure 8. 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
 quasi-field of $\sim$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
\[ \beta = \frac{I_C}{I_{B,Bulk}} = \frac{\tau_n}{\tau_b} \]

**Figure 9.** Influence of base doping level.

**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
We can accurately reproduce $I_C-V_{BE}$ characteristics using the model, as shown in Figure 10.

![Graph showing collector current vs. base-emitter voltage](image)

**Figure 10.** Family of curves $I_C = f(V_{CE})$

**Perspectives**

- Demonstrator device to confirm theoretical prediction
- $Pnp$ structures as an alternative
  - Larger emitter-base energy band-gap difference and band discontinuities
  - Heavy base doping level easier to achieve with n-type
  - High electron mobility to reduce base resistance
  - Preliminary results demonstrated
- Influence of specific resistance for $n$- and $p$-type contacts
  (including the introduction of cap layers)
- Thermal effects for High-power applications
- Dependence of material and transport properties to be analyzed
- Small-signal properties for high-frequency applications
- No electronics devices demonstrated
  - With the use of LEO/Pendel/Cantilever Substrates
Table 1 shows results of a 3D simulation of different AlGaN/GaN HBTs. Structure 1 was our initial conservative design, while structures 2 and 3 show the effect of varying base thickness. An aggressive design with a 500Å thick base can increase the dc current gain to 25. The largest gains are expected to be obtained with a graded bandgap in the base (structures 5 and 6).
<table>
<thead>
<tr>
<th>N°</th>
<th>Structure Part I</th>
<th>Structure Part II</th>
<th>Doping</th>
<th>Lifetime</th>
<th>Mobilities $\mu_0/\mu_0$</th>
<th>Results</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Xe=0.1 $\mu$m</td>
<td>AlGaN/GaN</td>
<td>Ne=5.10$^{17}$ cm$^{-3}$</td>
<td>$\gamma_{n,p}=10^{-9}$ s (e)</td>
<td>$\beta=\gamma$-3 (with $Q_C=0.5$)</td>
<td>-U. of Florida’s structure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Xb=0.15 $\mu$m</td>
<td>Abrupt E-B</td>
<td>Nb=10$^{18}$ cm$^{-3}$</td>
<td>$\gamma_{n,p}=5.10^{-11}$ s (b)</td>
<td>$V_{ON}≈2.7V$</td>
<td>-Generic design of nnp HBT @ 300K</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Xc=0.5 $\mu$m</td>
<td>interface</td>
<td>Nc=10$^{17}$ cm$^{-3}$</td>
<td>$\gamma_{n,p}=10^{-8}$ s (c)</td>
<td>-Emitter width of 100$\mu$m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Xsc=0.8 $\mu$m</td>
<td>E$_c$=3.9 eV</td>
<td>Nsc=10$^{18}$ cm$^{-3}$</td>
<td>$\gamma_{n,p}=5.10^{-10}$ s (sc)</td>
<td>-All contacts supposed to be ohmic</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-No cap layer considered</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-High collector current density</td>
<td></td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>but too high Base current</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>□ Low $\beta$</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-Turn-ON voltage ~2.7V</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Xe=0.1 $\mu$m</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</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Xb=0.05 $\mu$m</td>
<td></td>
<td>- NC</td>
<td>- NC</td>
<td></td>
<td>-Improved $\beta$ due to shorter transit time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Xc=0.5 $\mu$m</td>
<td></td>
<td>- NC</td>
<td>- NC</td>
<td></td>
<td>-Unrealistic Xb (too thin regarding to etch control)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Xsc=0.8 $\mu$m</td>
<td></td>
<td>- NC</td>
<td>- NC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Xe=0.1 $\mu$m</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</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Xb=0.10 $\mu$m</td>
<td></td>
<td>- NC</td>
<td>- NC</td>
<td></td>
<td>-More realistic design of base thickness</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Xc=0.5 $\mu$m</td>
<td></td>
<td>- NC</td>
<td>- NC</td>
<td>$\beta$ increases by a factor of 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Xsc=0.8 $\mu$m</td>
<td></td>
<td>- NC</td>
<td>- NC</td>
<td>Conclusion: a value of 800 Å might be a good candidate</td>
<td></td>
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</tr>
<tr>
<td>4</td>
<td>Xe=0.1 $\mu$m</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 $Q_C$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Xb=0.10 $\mu$m</td>
<td></td>
<td>- NC</td>
<td>- NC</td>
<td></td>
<td>-Current gain $\beta$ decreases because</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Xc=0.5 $\mu$m</td>
<td></td>
<td>- NC</td>
<td>- NC</td>
<td>exp($\Delta E$V/kT) decreases</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Xsc=0.8 $\mu$m</td>
<td></td>
<td>- NC</td>
<td>- NC</td>
<td>-Accurate value of $Q_C$ required (not well-known parameter)</td>
<td></td>
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<tr>
<td>5</td>
<td>Xe=0.1 $\mu$m</td>
<td>Graded</td>
<td>- NC</td>
<td>- NC</td>
<td>$\beta=60$ (with $Q_C=0.5$)</td>
<td>-Graded Al composition in the base for the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Xb=0.10 $\mu$m</td>
<td>Band Gap in</td>
<td>- NC</td>
<td>- NC</td>
<td>$\beta=55$ (with $Q_C=0.6$)</td>
<td>establishment of a “base quasi E. Field”</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Xc=0.5 $\mu$m</td>
<td>base from 3.9</td>
<td>- NC</td>
<td>- NC</td>
<td></td>
<td>-Base thickness of 1000 Å</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Xsc=0.8 $\mu$m</td>
<td>to 3.4 eV, 4.1 eV</td>
<td>- NC</td>
<td>- NC</td>
<td></td>
<td>-Higher turn-ON voltage ~2.9V</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>E$_G$ @4.1 eV</td>
<td></td>
<td></td>
<td></td>
<td>-Drift component in addition to diffusion in Base</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(X_e=0.1 , \mu m)</td>
<td>(X_b=0.10 , \mu m)</td>
<td>(X_c=0.5 , \mu m)</td>
<td>(X_{sc}=0.8 , \mu m)</td>
<td>(\beta=50) (with (Q_C=0.7))</td>
<td>base transit time decreases</td>
<td></td>
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<td>---</td>
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<td></td>
</tr>
<tr>
<td>6</td>
<td>- Graded Band Gap in base from 3.9 to 3.4 eV. - Emitter (E_G) @ 4.1 eV</td>
<td>(N_b=5.10^{17} , cm^{-3})</td>
<td>(\tau_{n,p}=6.10^{-11} , s) (b)</td>
<td>300/17 (b)</td>
<td>(\beta=80) (with (Q_C=0.7))</td>
<td>- GaN=poor transport properties for minority carrier. Higher lifetime &amp; 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)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>- AlGaN/GaN - Abrupt E-B interface - (E_{g_E}=4.1 , eV) - (E_{g_B,C}=3.4 , eV)</td>
<td></td>
<td></td>
<td>(\beta=8.9) (with (Q_C=0.5))</td>
<td>(V_{ON}\sim2.9V)</td>
<td>- Influence of Emitter band gap - Comparison with # 3 - No modification of current gain - Higher turn-On voltage</td>
<td></td>
</tr>
</tbody>
</table>

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 a significant impact on the current gain \(\beta\).
Conclusions

♦ Simulation of DC performances of existing 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 (Xb <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 \(\beta\).
We have also begun to develop the packaging technology for power GaN/AlGaN HBTs. On the device mask we have included a capability for clearing the silicon nitride passivation layer to accept solder bumps (Figure 11). Eventually we will flip-chip bond the HBTs using the technology available at Unitive Electronics (a spin-off of MCNC). As shown in Figure 12, they have the capability for producing 80µm solder bumps on metallized alumina substrates. The solder bumps provide electrical contact to the HBT, while the substrate provides probe contact and connection to ground. The device assembly consists of placement and alignment, temporary backing, solder reflow, testing and rework if necessary (Figure 13). The solder bumps are refloowed for device attachment to the substrate, with a gap of approximately 50µm. Finally there are several possibilities for thermal management systems and interfaces, as shown in Figure 14.

![GaN Device](image)

**Figure 11.** GaN Device.

- Silicon nitride passivation layer cleared to accept solder bumps
- Au pads exposed on GaN device
**Flip Chip Aligner**

- Placement and alignment
- Temporary tacking
- Solder reflow
- Testing
- Rework

**Figure 12.** Flip-Chip Substrate.

**Figure 13.** Device Assembly.
COTS Components

Chip coolers from Polycool, Inc.

Thermal Management Systems
- Air-cooled (composite fins, chip coolers)
- Water-cooled (micromechanical heat pump)

Thermal Interfaces
- Thermoelectric coolers
- Conformable, thermally conductive material
- Thermal adhesives and gels

Thermoelectric cooling system from Tellurex, Inc.

Figure 14. Power Electronic Packaging
Task 2. HBT Fabrication

Discrete GaN/AlGaN heterojunction bipolar transistors (HBTs) were fabricated on material grown by Molecular Beam Epitaxy. Dc current gains of ~10 were achieved in 90 µm emitter diameter devices measured at 300°C. Some of the key processing steps, such as ohmic contact annealing temperature and mesa fabrication by low damage dry etching, are described, together with Secondary Ion Mass Spectrometry measurements of the dopant and background impurity profiles.

Rf plasma-assisted Molecular Beam Epitaxy (MBE) at a rate of ~0.5 µm-hr\(^{-1}\) was used to grow the HBT structure on top of a 2 µm thick undoped GaN buffer that was grown on c-plane (0001) sapphire. An 8000 Å thick GaN subcollector (Si ~10^{18}\, cm\(^{-3}\)) was followed by a 5000 Å thick GaN collector (Si ~10^{17}\, cm\(^{-3}\)), a 1500 Å thick GaN base (Mg acceptor concentration ~10^{18}\, cm\(^{-3}\)), a 1000 Å thick Al\(_{0.15}\)Ga\(_{0.85}\)N emitter (Si ~5×10^{17}\, cm\(^{-3}\)), and a 500 Å grade to a 2000 Å thick GaN contact layer (Si ~8×10^{18}\, cm\(^{-3}\)), as shown in Figure 15.

The process flow for device fabrication is shown schematically in Figure 16. First the emitter metal (Ti/Al/Pt/Au) is patterned by lift-off and used as an etch mask for the fabrication of the emitter mesa. The dry etching was performed in a Plasma Therm 770 Inductively Coupled Plasma (ICP) system using Cl\(_2\)/Ar discharges. The process pressure was 5 mTorr, and the source was excited with 300 W of 2 MHz power. This power controlled the ion flux and neutral density, while the incident ion energy was controlled by application of 40 W of 13.56 MHz power to the sample chuck. Base metallization of Ni/Pt/Au was patterned by lift-off, and then the mesa formed by dry etching. The etch rate of GaN under our conditions was ~1100 Å-min\(^{-1}\), and was terminated at the sub-collector where Ti/Al/Pt/Au metallization was deposited. The contacts
were alloyed at 700-800 °C, as described in detail later. Figure 17 shows scanning electron micrographs of the completed devices – the emitter diameter is ~90 µm.

It has been firmly established that high specific contact resistivities are a limiting factor in GaN-based device performance, and in particular the p-ohmic contact. We examined the alloying temperature dependence of the current-voltage (I-V) characteristics for several different p-metal schemes. A typical set of results is shown in Figure 18 for Au/Ti/WSi$_x$/Ni and Au/Ti/WSi$_x$/Pd. Basically similar results were obtained for the Ni/Pt/Au, namely that the as-deposited contacts are rectifying. Annealing at progressively higher temperatures produced a significant improvement. But even for 800 °C anneals the contacts were not purely ohmic when measured at room temperature. This is consistent with past data, showing that p-metallization on GaN is often better described as a leaky Schottky contact.

As the measurement temperature is increased, the hole concentration in the p-GaN increases through higher ionization efficiency of the Mg acceptors. For example the hole concentration would increase from ~10% of the acceptor density at 25 °C to ~60% at 300 °C, based on Fermi-Dirac statistics. Figure 19 shows that the p-contact becomes truly ohmic at ≥300 °C. From transmission line measurements, we found $\rho_c \approx 2 \times 10^{-2} \Omega \text{cm}^2$ at this temperature. This indicates that the GaN/AlGaN HBT will perform better at elevated temperatures, where the base contact resistivity is lower. The contact barrier is of order 0.5 eV, whereas the Mg acceptor has an ionization level of 0.17 eV.
Figure 15. Schematic of MOCVD-grown GaN/AlGaN HBT.
Process Flow For GaN/AlGaN HBT

Emitter Ohmic Metallization

Emitter Mesa Dry Etching

Base Mesa Etching

Collector Metal Contact

Base Metallization

Device Isolation

Substrate

Figure 16. Schematic of process sequence for GaN/AlGaN HBT.
Figure 17. SEM micrographs of complete HBT.
Figure 18. Annealing temperature dependence of I-V characteristics for Au/Ti/WSi/Ni and Au/Ti/WSi/Pd contacts on p-GaN.

Figure 19. Measurement temperature dependence of I-V characteristics for Au/Ti/WSi/Ni contact on p-GaN.
Task 3. **HBT Electrical Characterization and Analysis**

We obtained a common-emitter current gain of $\leq 3$ at 25 $^\circ$C, increasing to ~10 at 300 $^\circ$C. A Gummel plot from the MBE device is shown in Figure 20. The performance was still limited by the base resistance and methods to increase the base doping and lower the extrinsic resistance in this region will be critical for future efforts in this area. The common base current gain, $\alpha$, was in the range 0.75 (25$^\circ$C) to 0.9 (300$^\circ$C), indicating that the base transport factor is close to unity and that $I_B$ is dominated by re-injection to the emitter.

Another important aspect of the realization of GaN/AlGaN HBTs is confinement of the Mg doping to the base. If the p-type spills over into the relatively lightly doped emitter, then the junction is displaced and the advantage of the heterostructure is lost. Figure 21 shows SIMS profiles of Mg in working devices from MBE material. The base layer is well-defined, with some incorporation of Mg into the overlying layers in this particular sample. Both the emitter and emitter-contact layers remain n-type even with the incorporation of the Mg, because the electron concentration exceeds the hole concentration contributed by this Mg.
Figure 20. Gummel plot measured at 300 °C for GaN/AlGaN HBT.

Figure 21. SIMS profiles of Mg in MOCVD (left) and MBE (right) GaN/AlGaN HBT structures.
Future Development

(a) Improved p-ohmic contacts

A serious drawback of p-n junction GaN electronic and photonic devices is the high contact resistance between p-type GaN and its contact metal, which increases turn-on voltages and produces heating of the device. Many different metal schemes have been examined, and generally it is found that contact metals with large work functions can reduce turn-on voltages. Ni/Au remains the standard metallization employed for most light-emitting diodes and laser diodes. The problem is even more acute for electronic devices such as heterojunction bipolar transistors, where a specific contact resistance in the $10^7 \ \Omega \ \text{cm}^2$ range is desirable, far smaller than the desired values ($10^5 \ \Omega \ \text{cm}^2$) for photonic devices and well below the typical values obtained experimentally with Ni/Au ($10^2 – 10^3 \ \Omega \ \text{cm}^2$).

One possible approach to reducing the contact resistance is growth of an overlayer of a smaller gap semiconductor. A well-known example of this is use of In$_x$Ga$_{1-x}$As contact layers on n-GaAs. Due to the heterojunction band discontinuity at the interface of InAs/GaAs, which creates a barrier for transport of electrons, it is generally necessary to grade the interface from GaAs to InAs using In$_x$Ga$_{1-x}$As. In the case of growth of GaAs on GaN, there is a large valence band offset, generally reported to be between 1.8 and 2.0eV. It would therefore be desirable to incorporate graded layers of GaAsN, but it is only possible to achieve N in GaAs or As in GaN concentrations of a few per cent. However, since it is possible to achieve extremely high hole concentrations ($>10^{20} \ \text{cm}^{-3}$) in carbon-doped GaAs, it seems like a valuable exercise to measure the contact resistance of GaAs(C)/GaN(Mg) structures. In this section we report that while good specific contact resistances can be obtained to the individual GaAs(C) and GaN(Mg) layers, there is still relatively poor hole transport across the interface between the two materials.
The starting material was ~1µm of p+ GaN(Mg) grown on sapphire by rf plasma activated Molecular Beam Epitaxy. The room temperature hole concentration was $\sim 10^{17}$ cm$^{-3}$. Layers of GaAs(C) with thicknesses of 1200-2000Å were grown either by Metal Organic Chemical Vapor Deposition (MOCVD) or Metal Organic Molecular Beam Epitaxy (MOMBE) at 650°C or 525°C, respectively. The source chemicals were trimethylgallium and arsine in both cases. Hall measurements showed hole concentrations in the GaAs of $1 \cdot 1 \times 10^{20}$ cm$^{-3}$ for the MOCVD sample and $1 \cdot 3 \times 10^{19}$ cm$^{-3}$ for the MOMBE sample.

E-beam deposited TiPtAu was used as a contact metallization for the GaAs and NiAu for the GaN. Both were patterned by lift-off to produce a transmission line method (TLM) grid. The pad spacings were 2, 4, 8, 16 and 32µm, with the pads being 100x150µm$^2$. Mesas were formed in the GaAs by NH$_4$OH:H$_2$O$_2$ wet etching to prevent current spreading. A scanning electron micrograph (SEM) of the complete structure is shown in Figure 22. Pieces of the samples were also annealed at 450-800°C for 15 secs under a N$_2$ ambient in a Heatpulse 610T system.

Figure 23 shows a schematic of the band diagram for the p-GaAs(C)/p-GaN(Mg) structure. Most of the bandgap difference is taken up by the valence band offset. We assume there will also be a high density of interface states because of the lattice and bonding mismatches. With this band alignment, the use of GaAs overlayers on GaN should provide excellent n-type contacts, but provide a high barrier to hole transport. However a recent report by Horita et.al. found that GaAs interlayers modified the band alignment at a metal/n-GaN interface. In their case they only grew about 4 monolayers of GaAs, which was found to grown epitaxially in a (111) orientation on the (0001) p-GaN. Such thin layers are probably not robust
enough for practical devices that must undergo thermal processes. This is why we chose to grow thicker GaAs layers.

To examine the chemical and structural characteristics we performed Secondary Ion Mass Spectrometry (SIMS) and Transmission Electron Microscopy (TEM) analysis. Figure 24 shows SIMS profile of the MOMBE-grown structure. The GaAs/GaN interface is quite sharp and the carbon concentration is $\sim 2 \times 10^{19}$ cm$^{-3}$. In correlating the carbon and hole concentrations we can see that the active fraction is high, indicating that the electrical properties of the GaN are not much degraded by the growth on a lattice-mismatched substrate. Figure 25 shows a cross-sectional TEM micrograph of the MOCVD-grown structure. There is a high concentration of threading dislocations ($\sim 5 \times 10^{10}$ cm$^{-2}$) due to the lattice mismatch between the Al$_2$O$_3$ substrate and the p-GaN. These dislocations continue into the overgrown GaAs layer.

A summary of the electrical results is shown in Table II. For unannealed contacts on GaAs(C) we obtained values of specific contact resistance between $9-14 \times 10^{-6}$ ohm.cm$^2$, with the lower values obtained for the higher doped MOCVD material. After the 800$^\circ$C anneal, these values were reduced by factors of 2-3. Clearly the contact resistance to the GaAs is quite low. Similarly for the GaN(Mg), values typical of state-of-the-art Ni/Au contacts were obtained, i.e. in the $10^{-2} - 10^{-3}$ ohm-cm$^2$ range. The contact resistance of the GaAs/GaN structure is better than that of GaN alone, but was still in the $10^{-3}$ Ωcm$^2$ range. Clearly the abrupt GaAs/GaN interface has too large a valence band offset even for tunnelling from a GaAs layer doped to metallic levels to overcome. Much better hole transport would be obtained if the composition of the carbon-doped layer could be graded from GaN to GaAs, but this is not possible given the large miscibility gap of this system. Approaches involving piezo-induced accumulation of holes are difficult to envision for vertical current transport structures, while various types of superlattices
are not attractive for the reason one still needs a small gap material that can be heavily doped p-type and remain thermally stable. There has also been little success achieving p-type doping of high-In content InGaN alloys. At this stage, reduced acceptor compensation in the GaN and use of reacted contact metallizations might be the most promising approaches.

GaAs overlayers with high p-type doping levels were grown on p-GaN. While good specific contact resistances were obtained for the GaAs and GaN layers individually, hole transport through the GaAs/GaN interface was still relatively poor due to the large valence band offset.

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

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho_c$(ohm·cm$^2$) - unannealed</th>
<th>$\rho_c$(ohm·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>
Figure 22. SEM micrograph of TLM pattern on GaAs/GaN structure.

Figure 23. Schematic of band diagram for GaAs/GaN structure.
Figure 24. SIMS profiles for GaAs/GaN structure grown by MOMBE.

Figure 25. TEM cross-section of GaAs/GaN structure grown by MOCVD.
We will optimize the growth of the GaAs(C)/GaN(Mg) structures on more heavily doped GaN(Mg). The barrier to hole transport should decrease as the hole concentration increases.

In addition, some preliminary results show that the presence of native oxides, even 10-20Å thick, on p-GaN can dramatically increase the specific contact resistance for subsequent metallization. We will focus on pre metal deposition cleaning processes that inhibit oxide formation on GaN. Initial results show that boiling in (NH$_4$)$_2$S solutions is a promising approach, and this solution does not affect the photoresist mask.

(b) Methods for Removing Dry Etch Damage in p-GaN

We have preliminary data on the electrical effects of plasma damage in p-GaN, using Schottky contacts.

The layer structure consisted of 1µm of undoped GaN (n~5x10$^{16}$ cm$^{-3}$) grown on a c-plane Al$_2$O$_3$ substrate, followed by 0.3 µm of Mg doped (p~10$^{17}$ cm$^{-3}$) GaN. The samples were grown by rf plasma-assisted Molecular Beam Epitaxy. Ohmic contacts were formed with Ni/Au deposited by e-beam evaporation, followed by lift-off and annealing at 750°C. The GaN surface was then exposed for 1 min to ICP H$_2$ or Ar plasmas in a Plasma-Therm 790 System. The 2MHz ICP source power was varied from 300-1400 W, while the 13.56 MHz rf chuck power was varied from 20-250 W. The former parameter controls ion flux incident on the sample, while the latter controls the average ion energy. Prior to deposition of 250µm diameter Ti/Pt/Au contacts through a stencil mask, the plasma exposed surfaces were either annealed under N$_2$ in a rapid thermal annealing system, or immersed in boiling NaOH solutions to remove part of the surface. As reported previously it is possible to etch damaged GaN in a self-limiting fashion in hot alkali or acid solutions. The current-voltage (I-V) characteristics of the diodes were recorded on an HP
A parameter analyzer. A schematic of the final test structures is shown in Figure 26. The unetched control diodes have reverse breakdown voltages of ~2.5-4 V depending on the wafer – these values were uniform (±12%) across a particular wafer.

Figure 27 shows the I-V characteristics from samples exposed to either H$_2$ (top) or Ar (bottom) ICP discharges (150 W rf chuck, 2 mTorr) as a function of source power. In both cases there is an increase in both the reverse breakdown voltage and the forward turn-on voltage, with these parameters increasing monotonically with the source power during plasma exposure.

Figure 28 shows this increase in breakdown voltage as a function of source power, and also the variation of the chuck dc self-bias. As the source power increases, the ion density also increases and the higher plasma conductivity suppresses the developed dc bias. Note that the breakdown voltage of the diodes continues to increase even as this bias (and hence ion energy, which is the sum of this bias and the plasma potential) decreases. These results show that ion flux plays an important role in the change of diode electrical properties. The other key result is that Ar leads to consistently more of an increase in breakdown voltage, indicating that ion mass is important rather than any chemical effect related to removal of N$_2$ or NH$_3$ in the H$_2$ discharges.

The increase in breakdown voltage on the p-GaN is due to a decrease in hole concentration in the near-surface region through the creation of shallow donor states. The key question is whether there is actually conversion to an n-type surface under any of the plasma conditions. Figure 29 shows the forward turn-on characteristics of the p-GaN diodes exposed to different source power Ar discharge at low source power (300 W), the turn-on remains close to that of the unexposed control sample. However there is a clear increase in the turn-on voltage at higher source powers, and in fact at ≥750 W the characteristics are those of an n-p junction. Under these conditions the concentration of plasma-induced shallow donors exceeds the hole
concentration and there is surface conversion. In other words the metal-p GaN diode has become a metal-n GaN-p GaN junction. We always find that plasma exposed GaN surfaces are N₂-deficient relative to their unexposed state, and therefore the obvious conclusion is nitrogen vacancies create shallow donor levels. This is consistent with thermal annealing experiments in which N₂ loss from the surface produced increased n-type conduction.

The influence of rf chuck power on the diode I-V characteristics is shown in Figure 30 for both H₂ and Ar discharges at fixed source power (500 W). A similar trend is observed as for the source power experiments, namely the reverse breakdown voltage increases, consistent with a reduction in p-doping level near the GaN surface.

Figure 31 plots breakdown voltage and dc chuck self-bias as a function of the applied rf chuck power. The breakdown voltage initially increases rapidly with ion energy (the self bias plus ~25 V plasma potential) and saturates above ~100 W probably due to the fact that sputtering yield increases and some of the damaged region is removed. Note that these are very large changes in breakdown voltage even for low ion energies, emphasizing the need to carefully control both flux and energy. We should also point out that our experiments represent worse-case scenarios because with real etching plasma chemistries such as Cl₂/Ar, the damaged region would be much shallower due to the much higher etch rate. As an example, the sputter rate of GaN in a 300 W source power, 40 W rf chuck power Ar ICP discharge in ~40Å·min⁻¹, while the etch rate in a Cl₂/Ar discharge under the same conditions is ~1100Å·min⁻¹.

An important question is the depth of the plasma-induced damage. We found we were able to etch p-GaN very slowly in boiling NaOH solutions, at rates that depended on the solution molarity (Figure 32) even without any plasma exposure of the material. This enabled us to directly measure the damage depth in plasma exposed samples in two different ways.
The first method involved measuring the etch rate as a function of depth from the surface. Defective GaN resulting from plasma, thermal or implant damage can be wet chemically etched at rates much faster than undamaged material because the acid or base solutions are able to attack the broken or strained bonds present. Figure 33 shows the GaN etch rate as a function of depth in samples exposed to a 750 W source power, 150 W rf chuck power Ar discharge. The etch rate is a strong function of the depth from the surface and saturates between \(-425\) to \(-550\)Å. Within this depth range the etch rate is returned to the “bulk” value characteristic of undamaged p-GaN.

The second method to establish damage depth of course is simply to measure the I-V characteristics after removing different amounts of material by wet etching prior to deposition of the rectifying contact. Figure 34(top) shows the I-V characteristics from samples exposed to 750 W source power, 150 W rf chuck power (-160 V dc chuck bias) Ar discharges and subsequently wet etched to different depths using 0.1 M NaOH solutions before deposition of the Ti/Pt/Au contact. Figure 24 (bottom) shows the effect of the amount of material removed on the diode breakdown voltage. Within the experimental error of \(\pm 12\)%, the initial breakdown voltage is re-established in the range 400-450Å. This is consistent with the depth obtained from the etch rate experiments described above. These values are also consistent with the damage depths we established in n-GaN diodes exposed to similar plasma conditions.

The other method of removing plasma-induced damage is annealing. In these experiments we exposed the samples to the same type of plasma (Ar, 750 W source power, 150 W rf chuck power) and then annealed under \(\text{N}_2\) at different temperatures. Figure 35 (top) shows the I-V characteristics of these different samples, while Figure 35 (bottom) shows the resulting breakdown voltages as a function of annealing temperature. On this wafer, plasma exposure caused an increase in breakdown voltage from \(~2.5\) to \(~18\) V. Subsequent annealing at \(400^\circ\text{C}\)
initially decreased the breakdown voltage, but higher temperature produced a large increase. At temperatures above 700°C, the diodes characteristics returned toward their initial values and were back to the control values by 900°C. This behavior is similar to that observed in implant-isolated compound semiconductors where ion damage compensates the initial doping in the material, producing higher sheet resistances. In many instances the damage site density is larger than that needed to trap all of the free carriers, and trapped electrons or holes may move by hopping conduction. Annealing at higher temperatures removes some of the damage sites, but there are still enough to trap all the conduction electrons/holes. Under these conditions the hopping conduction is reduced and the sample sheet resistance actually increases. At still higher annealing temperatures, the trap density falls below the conduction electron or hole concentration and the latter are returned to their respective bands. Under these conditions the sample sheet resistance returns to its pre-implanted value. The difference in the plasma exposed samples is that the incident ion energy is a few hundred eV compared to a few hundred keV in implant-isolated material. In the former case the main electrically active defects produced are nitrogen vacancies near the surface, whereas in the latter case there will be vacancy and interstitial complexes produced in far greater numbers to far greater depths. In our previous work on plasma damage in n-GaN we found that annealing at ~750°C almost returned the electrical properties to their initial values. If the same defects are present in both n- and p-type material after plasma exposure, this difference in annealing temperature may be a result of a Fermi level dependence to the annealing mechanism.

The main conclusions of this study may be summarized as follows:

1. The effect of either H$_2$ or Ar plasma exposure on p-GaN surfaces is to decrease
the net acceptor concentration through creation of shallow donor levels, most likely NV. At high ion fluxes or ion energies there can be type conversion of the initially p-type surface. The change in electrical properties is more pronounced with Ar than with H₂ plasmas under the same conditions.

2. Two different techniques for measuring the damage depth find it to be in the range 400-550Å under our conditions. After removing this amount of GaN, both the breakdown voltage and wet chemical etch rates are returned to their initial values.

3. Post-etch annealing in N₂ at 900°C restores the initial breakdown voltage on plasma exposed p-GaN. Annealing at higher temperatures degraded the electrical properties, again most likely due to N₂ loss from the surface.

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**Figure 26.** Schematic of p-GaN Schottky diode structures
Figure 27. I-V characteristics from samples exposed to either H$_2$ (top) or Ar (bottom) ICP discharges (150W rf chuck power) as a function of ICP source power prior to deposition of the Ti/Pt/Au contact.
Figure 28. Variation of diode breakdown voltage in samples exposed to H₂ or Ar ICP discharges (150 W rf chuck power) at different ICP source powers prior to deposition of the Ti/Pt/Au contact. The dc chuck self-bias during plasma exposure is also shown.

Figure 29. Forward turn-on characteristics of diodes exposed to ICP Ar discharges (150 W rf chuck power) at different ICP source powers prior to deposition of the Ti/Pt/Au contact.
**Figure 30.** I-V characteristics from samples exposed to either H$_2$ (top) or Ar (bottom) ICP discharges (500W source power) as a function of rf chuck power prior to deposition of the Ti/Pt/Au contact.
Figure 31. Variation of diode breakdown voltage in samples exposed to H₂ or Ar ICP discharges (500 W source power) at different rf chuck powers prior to deposition of the Ti/Pt/Au contact. The dc chuck self-bias during plasma exposure is also shown.

Figure 32. Wet etching rate of p-GaN in boiling NaOH solutions as a function of solution molarity.
Figure 33. Wet etching rate of Ar plasma exposed (750 W source power, 150 W rf chuck power) GaN as a function of depth into the sample.
Figure 34. I-V characteristics from samples exposed to ICP Ar discharges (750 W source power, 150 W rf chuck power) and subsequently wet etched to different depths prior to deposition of the Ti/Pt/Au contact (top) and breakdown voltage as a function of depth removed (bottom).
Figure 35. I-V characteristics from samples exposed to ICP Ar discharges (750 W source power, 150 W rf chuck power) and subsequently annealed at different temperatures prior to deposition of the Ti/Pt/Au contact (top) and breakdown voltage as a function of annealing temperature (bottom).
We will integrate these processes into the HBT fabrication scheme, and this should dramatically improve the p-contact resistance. Issues involve the type of masks to be used and the compatibility of the thermal and chemical processes with these masks.

**Key issues for Phase II**

- include piezo-electric effects in model
- performance of packaged devices
- decrease p-contact resistance
- dry etch damage removal
- optimize layer structure and buffer
- mask design for optimized e-b contact separation
- device isolation (implant versus mesa)