Georgia Institute of Technology
School of Electrical and Computer Engineering

Next Generation High Power HBT

A Proposal Presented to the Academic Faculty
in Partial Fulfillment of Institute Requirements for the
Undergraduate Thesis Option

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1. Introduction

A Heterojunction Bipolar Transistor is a transistor where the emitter/collector and base are made of two different materials, with the emitter/collector designed to have a larger bandgap than the base. The added potential barrier prevents the injection of holes (in an n-p-n device) into the base, and enables it to overcome the limitations on gain and associated tradeoffs inherent to a traditional Bipolar Junction Transistor (BJT) [1]. HBT transistors designed for high-voltage applications are being used in many industries, including telecommunications, optoelectronics, and automobile control modules. Their superior material properties have made nitride based compounds, GaN and InGaN in particular, an attractive alternative to Si based HBT’s [2].

1.1 Wide Bandgap Device Applications

The fact that extremely efficient light emission can be achieved in heteroepitaxial layers of wide bandgap materials, in conjunction with the commercialization of blue, green, and white GaN-based Light Emitting Diodes (LED) has created tremendous interest in the optoelectronic device applications of such compounds. GaN/AlGaN bipolar transistors are also an attractive option for various satellite, radar, and communications applications in the 1-5GHz frequency range, at temperatures >400C and powers >100W. There is a strong focus on developing high current, high voltage switches in the AlGaN materials system for applications in the transmission and distribution of electric power in the sub-systems of emerging vehicle, ship, and aircraft technology [2]. To reduce on-resistance, power consumption, and unit cost, nitride power electronics may find a place in control modules for Hybrid Electric Vehicles (HEV) [3].
1.2 GaN Material Properties

GaN, compared to Si, has a wide bandgap, high electron saturation velocity, high thermal conductivity, and wide temperature operation range capability. This allows GaN based devices to sustain high temperature operations up to 300°C (the best Si based devices cannot operate at temperatures >100°C) [4]. Their higher current densities, better linearity, and more uniform threshold voltages find ample use in power microwave applications [2]. Table 1 shows a comparison of the properties of viable semiconductor material systems, and the inherent advantages offered by GaN.

<table>
<thead>
<tr>
<th>Material</th>
<th>Si</th>
<th>GaAs</th>
<th>InP</th>
<th>GaN</th>
<th>AlN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice Constant</td>
<td>5.43</td>
<td>5.65</td>
<td>5.87</td>
<td>3.19</td>
<td>3.11</td>
</tr>
<tr>
<td>Bandgap (eV)</td>
<td>1.12</td>
<td>1.42</td>
<td>1.35</td>
<td>3.39</td>
<td>n.a.</td>
</tr>
<tr>
<td>Breakdown Field (x10^6 V/cm)</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>&gt;2.5</td>
<td>n.a.</td>
</tr>
<tr>
<td>Saturation Velocity (x10^7 cm/s)</td>
<td>0.9</td>
<td>0.6</td>
<td>0.9</td>
<td>2.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Electron Mobility (cm^2/V/s)</td>
<td>1450</td>
<td>8500</td>
<td>4600</td>
<td>1000</td>
<td>135</td>
</tr>
<tr>
<td>Thermal Conductivity (W/cmK)</td>
<td>1.3</td>
<td>0.3</td>
<td>0.68</td>
<td>1.3</td>
<td>2.85</td>
</tr>
</tbody>
</table>

Table 1. Properties of dominant semiconductor materials [4].

2. History and Current Findings

InGaN/GaN HBT’s have met with considerable success recently. Devices have been reported with high current gain [5], and high voltage operation [6]. Initial work on nitride based HBT’s focused on the AlGaN/GaN material system [7], but the high ionization energy of the Mg acceptor in GaN [8] limits the effective hole density in the base layer, severely restricting device performance. InGaN alloys, however, have been shown to possess lower ionization energies for the Mg acceptor [9], providing a pathway for higher base carrier densities and a reduction in base sheet resistance.
A recent publication not only shows high current gain, but low offset and knee voltages with reliable operation up to 300C. Figure 1 shows these results at 25C. The breakdown voltage ($BV_{CEO}$) of the device under consideration was greater than 40V. It shows a maximum incremental current gain ($h_{fe}$) of 37, low offset and knee voltages of approximately 2–3 and 5–6 V, respectively, and low output conductance. The low offset and knee voltages represent very good values for a nitride based HBT, where typical offset voltages are $>5$ V and knee voltages $>10$ V. The offset voltage is limited in a typical nitride HBT by two factors: high sheet resistance of the base layer, and imperfect ohmic contact to the base layer. The use of InGaN in the base layer contributes to the low offset voltage observed, inasmuch as the higher base carrier density reduces the lateral sheet resistance and hence minimizes the voltage drop between the base contacts and the intrinsic device [10].

![Figure 1. Common-emitter I-V characteristics for InGaN/GaN HBT [10].](image)

A graded emitter-base design is said to show better results than conventional designs. It provides a larger hetero-barrier for holes, and thus higher emitter injection efficiency along with potentially higher current gain. Another benefit of the graded emitter-
base design is a better accommodation of the strain produced by the lattice mismatch between GaN and InGaN, making the formation of defects at the emitter-base junction less likely [11].

Extrinsic base re-growth of the base p-InGaN layer is also said to improve device performance. Etching damage in the HBT fabrication process often results in the degradation of base ohmic characteristics. This is due to the fact that etching of p-type nitride semiconductors decreases the effective acceptor concentration (the difference between the real acceptor concentration and the n-type defect concentration) near the surface. This makes it very difficult to form good ohmic contacts, which is one of the reasons for degradation of nitride HBTs [12].

3. Preliminary Research

Preliminary research in this project has so far focused on developing ohmic contacts and a brief etching study. A good etch process is crucial to reducing the offset voltage since etch damage typically results in an increase in base sheet resistance, and also degrades base contact properties [10]. Reliable ohmic contacts are important to ensure that the device is stable over time and temperature, and their parasitic resistance could place an upper limit on performance [13]. The Transmission Line Method (TLM) was used to conduct measurements.

3.1 Ohmic Contact

The purpose of an ohmic contact is to allow electrical current to flow into or out of the semiconductor. The contact should have a linear I-V characteristic, be stable over time and temperature, and contribute as little resistance as possible. Placing a metal in intimate contact with a III-V semiconductor such as GaN under thermal equilibrium causes band-
bending and the buildup of a potential barrier. The principal strategy employed to achieve an ohmic contact is to dope the surface of the semiconductor sufficiently high to ensure that the dominant conduction mechanism across this barrier is field emission or quantum tunneling. The major procedure adopted to realize this is to employ metals that, upon alloy with the semiconductor material, can very highly dope the surface layer. A common approach is to apply an appropriate metallization to the wafer, and then alloy the metal into GaN. During the alloy, a component of the metal enters GaN and highly dopes the surface. It is crucial to choose the right metal layers, and determine the right time and temperature for the process. Variations are caused by differences in the heating furnace and thermocouple equipment used [13].

The experiments conducted focused on developing a data set that could be used for future applications as well. While Ti/Al/Pd/Au/Ni have all proved to be good candidates, the group chose to focus on the Au/Ni metallization. Samples were coated with Au/Ni, each layer 20Å thick. Temperatures from 500°C to 600°C, and time periods from 0 to 10 minutes were investigated. A large amount of raw data was collected with the aim of obtaining a linear I-V characteristic, and low resistance. Results showed that there was a small but noticeable difference between the results obtained after various surface treatments. Surface treatment for 30 minutes using Buffered Oxide Etch (BOE) solution with simultaneous ultrasound treatment showed marginally better results than simply rinsing in BOE solution for 10 minutes. Figure 2 shows the graph of a sample heated for 2 minutes at 550°C. Characteristics move towards ohmic as larger spacing between contact patterns is used. The lowest specific contact resistance recorded was $4.38 \times 10^{-2}$ ohm-cm$^2$. 
An ideal result would show linear behavior regardless of contact spacing. As those ideal characteristics have not been achieved, the group may try to experiment with different metal combinations.

![Graph showing voltage vs. current](image)

**Figure 2.** GaN on Sapphire with Au/Ni heated for 2min. at 550C.

### 3.2 Measurement Technique

The TLM or ladder network technique was used for measuring the specific contact resistance. It is known to be a reliable method within measurement limits, i.e. when the width of the potential contacts is much less than the transfer length involved. A current source is connected to two large-area ohmic contacts, through which it drives a known current. Two probes connected to a high impedance voltmeter are connected between one of the current pads and each of a series of evenly spaced narrow ohmic contacts formed at right angles to the direction of current flow. This allows a graph of potential against
position to be drawn, and extrapolation followed by simple calculations yields the desired contact resistance. This method assumes that the resistance is constant for any particular contact, independent of current density [14].

3.3 Etching Study

A preliminary etching study is currently being worked upon. Photo-enhanced wet etching is the technique proposed. Since the idea is to try electrode-less etching, an oxidizing agent is necessary in its place. H$_2$O$_2$ (Hydrogen Peroxide – 30% solution) and K$_2$S$_2$O$_8$ (Potassium Persulfate – Solid) will be the reagents involved. KOH (Potassium Hydroxide – Solid) shall be the etching medium. The process shall take place in the presence of ultraviolet light used to illuminate the wafer. The concentrations of chemicals involved and reaction time period are the independent variables in this study. Etching rates and the profile of the resulting wafer form the measured parameters. The study seeks to create a data bank used for every etching procedure in future.

4. Proposed Research

The objective of the proposed research is to fabricate an InGaN/GaN HBT with a high current gain, breakdown voltage ($V_{BR}$) and current density ($J$), while ensuring reliable device operation at temperatures up to 300°C. This would involve experimenting with various layer structures (doping concentrations, layer thicknesses), device topologies (geometry and stacking layout) and design schemes (e.g. base re-growth). To achieve these objectives, material quality needs to be carefully controlled, and device processes optimized. The ultimate goal is to target reliable manufacturability of the device developed.
5. Facilities Needed

Growth, fabrication and testing facilities are needed for this project. These include a Metal Organic Chemical Vapor Deposition (MOCVD) reactor, Rapid Thermal Annealing system (RTA), Scanning Electron Microscope (SEM), Electron beam metal evaporator, spinning and photolithography equipment, probe station, and semiconductor parameter analyzer.

6. Conclusion

Nitride based devices offer an attractive alternative to existing Silicon based technology because of their superior material properties. These devices are used in various segments of industry, and have attracted the attention of a number of companies and research institutions. A large amount of research has been reported recently, with impressive current and voltage gains described for GaN based HBTs. Different design schemes, layout patterns, and material compositions are suggested.

This project has started with work focused on developing ohmic contacts and collecting etching related data. The TLM method of measurement has been used throughout the ohmic contact development. We hope to better existing performance levels reported for InGaN/GaN HBT’s, while ensuring process reliability and targeting manufacturability of the technologies developed.
Bibliography


