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First demonstration of an AlGaN/GaN heterojunction bipolar transistor

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Abstract.
We have demonstrated the first AlGaN/GaN heterojunction bipolar transistor. The layer structures were grown by MOCVD on c-plane sapphire. The magnesium doped GaN base was nominally 2000 Å thick. Selective base regrowth was used to repair damage to the base and provide a lower extrinsic base sheet resistance. These initial devices show current gain as high as 3, and breakdown voltages greater than 40V. The low gain is believed to be caused by short minority carrier diffusion lengths in the base.

1. Introduction

Recent progress in GaN electronics has produced record figures for high frequency, high power FETs[1, 2]. With its large bandgap and electron velocities as high as 2×10^7 cm·s^{-1}[3], GaN shows great promise for implementing bipolar transistors. Bipolar transistors have several intrinsic advantages over FETs. HBTs generally have more uniform threshold voltages, higher linearity, and higher power densities than FETs. Difficulties with p-type material, however, remain an obstacle for bipolar technologies in GaN.

To achieve high output conductance and reduce base access resistance, high base doping is required. High Mg concentrations, however, may contribute to higher recombination rates in the base. The RIE etch used to contact the buried base layer is physically driven, damaging the base surface and making it difficult to contact. Additionally, because high-speed devices will eventually require sub-micron emitter mesas and a thin base layer, a thick extrinsic base is needed for reducing sheet resistance under the contact.

For these reasons, a GaN based bipolar transistor requires a heterojunction emitter, regrown extrinsic base and self aligned emitter-base lithography. Selective area regrowth was used in an attempt to repair the damaged base surface and provide additional extrinsic base thickness. To avoid re-alignment, the emitter contact was used as an etch mask for the GaN emitter mesa.

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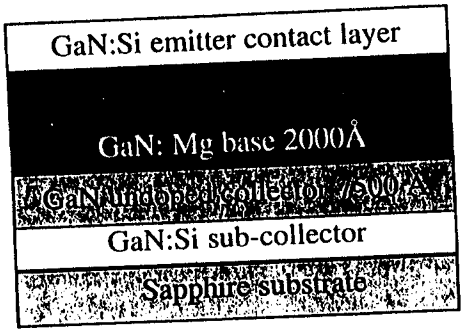

Figure 1. Layer structure as grown by MOCVD

2. Materials

The AlGaN/GaN heterostructure for these devices was grown on c-plane sapphire by MOCVD. The emitter-up scheme included an n^+ GaN (Si) subcollector, an unintentionally doped (UID) $N_D \sim 5\times10^{16}$cm^{-3} collector, a p-type, $N_A \sim 1\times10^{19}$ cm^{-3}GaN (Mg) base, and an n^+ $N_D \sim 5\times10^{18}$ cm^{-3} emitter. The collector, base, and emitter were 7500 Å, 2000 Å, and 5000 Å thick respectively (See figure 1).

The UID collector was followed by a 2000 Å base layer, with a Mg concentration on the order of 1×10^{19} cm^{-3}. The Mg is a deep acceptor in GaN, however, resulting in incomplete ionization of the dopants[4]. Our measurements show the Mg level to be 160 meV from the GaN valence band edge, and we expect a hole concentration on the order of 5×10^{17}cm^{-3} at room temperature. The Si doped emitter consisted of an AlGaN barrier layer which was graded out to GaN in the bulk of the emitter. The layer structures mentioned here have not been tested for crystal quality or carrier concentrations, but material grown under similar conditions supports the numbers quoted above. Although the material grown was high quality single crystal GaN, several materials issues remain and were central considerations for the design of the transistors.

Hydrogen, resident during the growth of the crystal, passivates the Mg acceptors, and a high temperature anneal is required to activate these acceptors [4]. Also, because Mg is a deep acceptor, high dopant concentrations are required to achieve sufficient carriers. The high Mg levels ($N_A \sim 1\times10^{19}$ cm^{-3}), however, reduce carrier mobility, resulting in a base resistance on the order of 1.6 Ω·cm for these devices. High acceptor concentrations in the base may also shorten minority carrier diffusion lengths, reducing the base transport factor. Although the projected base emitter injection efficiency is near unity, a low current gain may result from high recombination rates in the base-emitter junction and the thick neutral base.

The AlGaN/GaN material system, however, also offers several advantages for HBT applications. Theoretically, a change in aluminum composition of as little as 10% can lead to a conduction band energy drop of ~10kT. Quasi-electric fields as high as 1.3×10^4 V·cm^{-1} introduced by a 10% Al compositional grade over a 2000Å base could significantly reduce base transit times, overcoming high recombination rates. Quasi fields in the base,

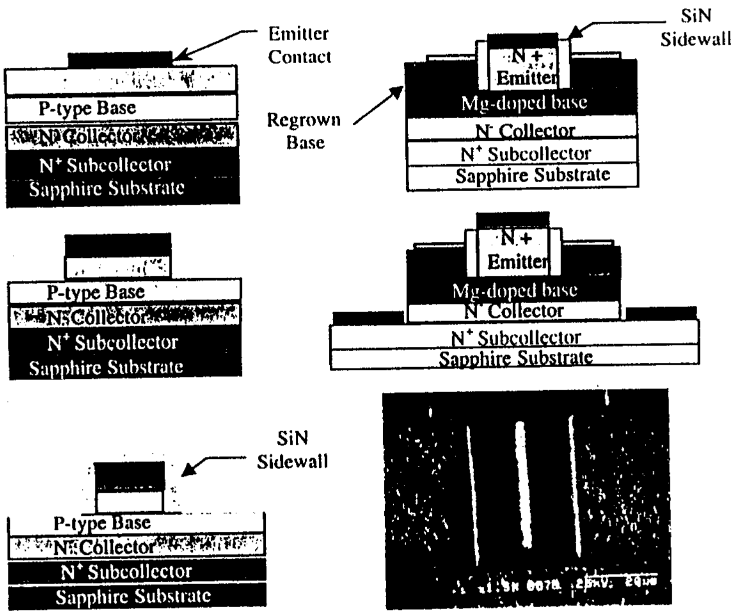

Figure 2. Process flow diagram for the AlGaN/GaN HBT, and an SEM image of a finished device. The collector contact is not visible due to the high conductivity of the subcollector.

coupled with high breakdown fields and electron velocities on the order of 2×10^7 cm·s^{-1} in the collector could lead to short transit times with high power capabilities.

3. Fabrication

After a standard solvent clean and lift-off lithography, W was sputtered onto the AlGaN/GaN film. The W emitter contact was then used as an etch mask during the Cl_2 RIE emitter mesa etch(See figure 2). Uncertainty of the exact thickness of the emitter made etch control difficult, and electrical measurements were used to determine when the base layer had been accessed. When the etching was complete, the emitter was protected by a SiN capping layer. The SiN acted as a mask for selective growth, preventing GaN from depositing on the emitter's sidewalls or top metal contact. The SiN may also reduce surface recombination in exposed base material.

Thick base contact pads were regrown by MOCVD to repair etch damage caused by the Cl_2 RIE and reduce base sheet resistance under the contacts. After regrowth, the Mg acceptors in the base were activated with a high temperature anneal in an N_2 ambient. Base contacts were then applied to the regrown pads and the base mesa was etched by Cl_2 RIE. Lastly, subcollector contacts were defined and electrical characterization performed.

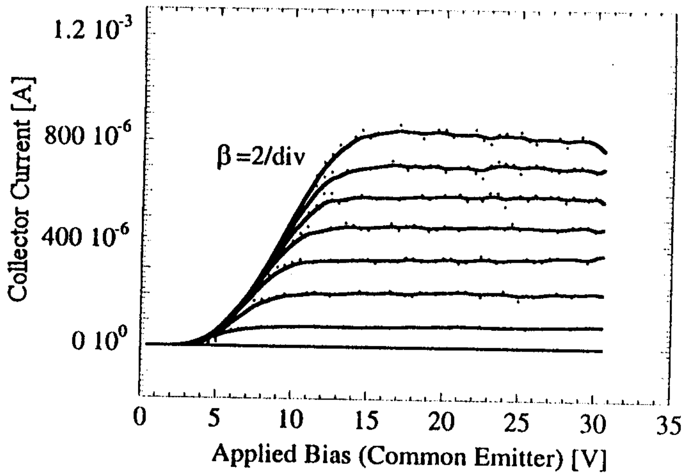

Figure 3. Common emitter characteristics for an HBT with a 1 μm×20 μm emitter finger. The base current step size is 50 μA

4. Experimental results

Among the devices tested, the best devices exhibited a current gain ($\beta = I_C/I_B$) of 3. The devices were tested to 30 volts V_{CE} bias . The breakdown for the devices was over 40 V in the common emitter configuration. For the small 1μm×20 μm device shown in figure 3, the base current step was 50 μA, with beta between 2 and 3 over the current range tested. The early voltage for these devices was too high to measure accurately.

Because of current crowding effects, owing to the high lateral resistance in the base, the active areas of the devices are not known, and current densities were not inferred. The base contacts on these devices were not ohmic, and the contact barrier had to be reverse biased in order to forward bias the base emitter junction.

A V_{CE} offset of approximately 5 volts was observed in the common emitter I-V curves. Although some offset is expected in HBTs due to differing built in voltages of the base-emitter and base-collector junctions, the offset observed is greater than predicted, and cannot be explained by this mechanism. We believe that the offset is due to a parasitic forward biased base-collector diode, and is primarily a result of the non-ohmic contacts to the base. We believe that when the contact problems to the base are solved, the offset will be substantially reduced.

A Gummel plot taken on a larger device, 20μm×20 μm square, also shows current gains between 2 and 3 (See figure 4). The Gummel plot was taken with zero collector-base bias ($V_{CB} = 0$). The transistor begins providing gain when the base current reaches approximately 10 μA and beta levels off at 3 when the base current reaches approximately 100 μA.

The low current gains observed are thought to be related to short minority carrier diffusion lengths in the base and a high recombination rate in the base-emitter depletion

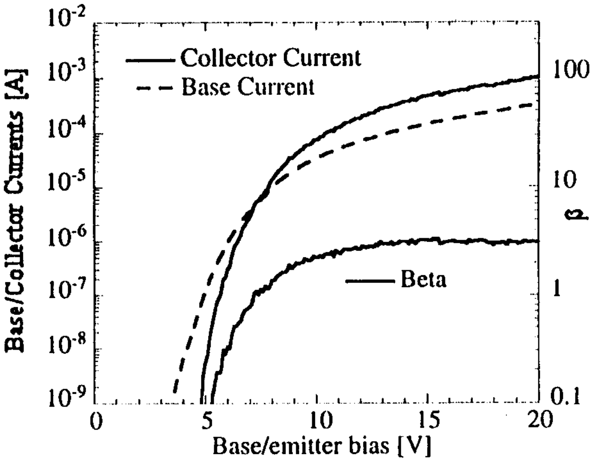

Figure 4. Gummel plot of a 20μm×20μm HBT. The base and collector currents are measured over a range of base-emitter bias. The base-collector voltage is held at zero. The left axis measures current, while the right axis indicates current gain, β

region. Due to the processing limitations mentioned earlier, the base layer was grown relatively thick, > 2000 Å. Due to a correlation between base thickness variation across the wafer and the gain of the devices, we believe that recombination in the neutral base is limiting the gain of the transistor. Furthermore, we believe that because the base-collector junction covers a far greater area than the forward active emitter-base junction, collector leakage may also reduce the current gain.

Future devices will have improved base contacts, and a thinner, graded base to enhance electron transport across the neutral region. Finally, smaller base contacts must be used to reduce collector/base leakage parasitics as well as capacitance. The most notable trade-off associated with these measures is the increase in the base resistance that will follow from a thinner base. In addition to degrading AC performance, a higher base resistance also reduces the active area of the device due to current crowding effects. This necessitates sub-micron emitters for a useful HBT technology.

5. Conclusion

The demonstration of an AlGaN/GaN heterojunction bipolar transistor represents a milestone in the development of this material system. The initial development of the GaN bipolar serves to advance the state-of-the-art in GaN material and fabrication technologies and supply a new tool to the scientific study of the (Al)GaN material system.

Ultimately, the mature AlGaN/GaN HBT may find its way into a variety of emerging applications ranging from communications and radar to switching power supplies.

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