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Journal
IEEE Electron Device Letters, 24(3)

ISSN
0741-3106

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Publication Date
2003-03-01

Very High Voltage Operation (>330 V) With High Current Gain of AlGaN/GaN HBTs

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***Abstract*—N-p-n $Al_{0.05}$GaN/GaN heterojunction bipolar transistors with a common emitter operation voltage higher than 330 V have been demonstrated using selectively regrown emitters. Devices were grown by metalorganic chemical vapor deposition on sapphire substrates. The n-type emitter was grown selectively on a 100-nm-thick p-base with an 8 μm n-collector structure using a dielectric mask. The shallow etch down to the collector mitigates damages induced in the dry etch, resulting a low leakage and a high breakdown. The graded AlGaN emitter results in a common emitter current gain of $\sim$ 18 at an average collector current density of up to 1 kA/cm^2 at room temperature.**

***Index Terms*—AlGaN, breakdown voltage, common emitter, current gain, GaN, Gummel plot, HBTs, regrown emitters.**

I. INTRODUCTION

THE III-nitrides based electronic devices have gained increased interest in high temperature and high power application due to their wide bandgap, higher critical electric field strength, higher electron saturation drift velocity, and strong polarization effects compared to other semiconductors. Impressive high voltage operation of AlGaN/GaN field effect transistors (FETs) and GaN-based rectifiers continue to be reported [1]–[3]. However, no GaN-based heterojunction bipolar transistors (HBTs) with operation voltage higher than 100 V have been presented. In contrast to FETs, HBTs are normally off devices, and employ vertical current transport. HBTs potentially offer more uniform threshold voltages, higher linearity, and higher current densities.

Due to the difficulty associated with p-type doping in GaN and lack of low-damage etch methods, there have been limited number of reports on nitride-based bipolar transistors. Several groups [4], [5] have demonstrated common emitter operation of AlGaN/GaN HBTs at room temperature (RT), though the current gain and the current density have been low (approximately $\leq$ 10 and $\leq$ 10 A/cm^2 respectively). We have previously achieved GaN homojunction bipolar transistors using the selective emitter regrowth technique [6], exhibiting a common emitter current gain of $\sim$ 6–10 with an average output current density of $\sim$ 1 kA/cm^2 at RT. The transistors had a collector thickness of 0.7 μm with an unintentional doping (UID) concentration of n $\sim 5 \times 10^{16}$ cm^{-3}, and operated up to > 70 V in a common emitter configuration. The current gain was in part limited by the emitter injection efficiency. An AlGaN/GaN HBT is preferred.

To realize a high breakdown voltage GaN HBT, it is necessary to lower the background doping in the collector and eliminate leakage paths due to threading dislocations [7] and etch-induced damage. When growing thicker GaN on sapphire substrate by metalorganic chemical vapor deposition (MOCVD), threading dislocations increasingly annihilate, and the background doping in GaN decreases as well, which leads to a better material for collector. Therefore, we processed AlGaN/GaN HBTs on a thick collector of 8 μm with a thin base of 0.1 μm utilizing selective emitter regrowth. Both significant increases in current gain and breakdown voltage were obtained. To our knowledge, these are the highest values reported for AlGaN/GaN HBTs.

II. EXPERIMENTS

The devices were grown by MOCVD on c-plane (0001) sapphire substrates, and the growth conditions for the base–collector structure were similar to what we have reported elsewhere [6]. Using a patterned dielectric mask Al_xN_y *[8]*, the graded AlGaN emitter was selectively regrown at 1100 °C at a pressure of 300 Torr.

A 2-μm n-type subcollector ($\sim 1 \times 10^{18}$ cm^{-3} Si doped) was first grown followed by an 8-μm UID GaN collector (n $\sim 5 \times 10^{15}$ cm^{-3}) and a 100-nm thick p-type GaN base ($\sim 2 \times 10^{19}$ cm^{-3} Mg doped). The regrown emitter consists of first an 8-nm UID GaN spacer, followed by 8 nm of UID GaN graded to $Al_{0.05}$GaN, and an 105 nm Si-doped $Al_{0.05}$GaN ($\sim 1 \times 10^{18}$ cm^{-3}). A 4-nm Si-doped $Al_{0.05}$GaN graded to GaN along with a GaN:Si contact layer ($\sim 1 \times 10^{18}$ cm^{-3}) completed the regrowth.

After emitter regrowth, the regrowth mask was etched away and acceptor activation was performed. Next, Pd/Au base contacts were deposited, and a shallow base mesa with $\sim$ 300 nm etched into the collector was defined by Cl_2 reactive-ion etch (RIE). As the last step, Al/Au contacts were deposited on both emitter and collector. The schematic cross section of a completed device is shown in Fig. 1. Since the Al/Au collector contact is not on the subcollector, the effective collector thickness is determined by the lateral separation between the collector contact and base contact, which is about 2–3 μm due to our current mask design.

Manuscript received October 2, 2002; revised February 19, 2003. This work was supported by the Office of Naval Research Compact Power Supplies MURI program under the supervision of Dr. J. Zolper and Dr. H. Dietrich. The review of this letter was arranged by Editor D. Ueda.

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Digital Object Identifier 10.1109/LED.2003.811400

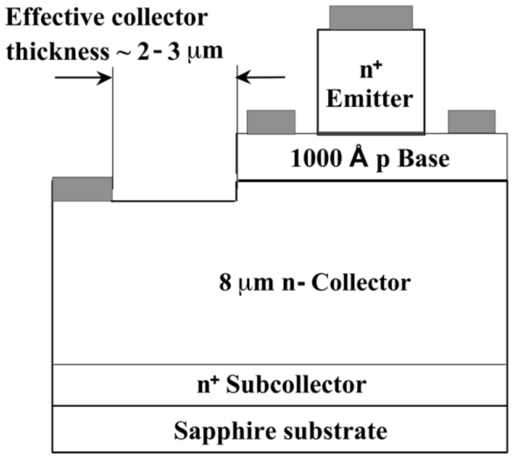

Fig. 1. Schematic cross section of a completed HBT device with a shallow base mesa etched into the collector, and the effective collector thickness is limited by the lateral separation between base and collector contacts.

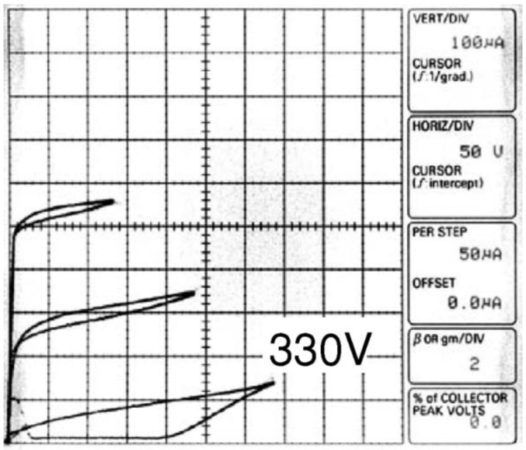

Fig. 2. Common emitter operation of $Al_{0.05}GaN/GaN$ HBTs (emitter size 20×50 μm^2) with a breakdown voltage higher than 330 V.

III. Results and Discussions

On wafer $Al_{0.05}GaN/GaN$ HBTs with an emitter size of 20×50 μm^2 were characterized at RT. The common emitter high voltage performance of the devices was measured on a curve tracer. As shown in Fig. 2, the emitter–collector breakdown voltage exceeded 330 V.

The high breakdown voltage is attributed to the low background doping level in the collector and the suppression of leakage in the lateral base–collector junction with the reduced RIE etch damage in the shallow base mesa etch, which is in turn a direct result of a shorter-time etch. Capacitance–voltage (C–V) measurements showed that the UID donor concentration in the 8-μm collector is $\sim 5 \times 10^{15}$ cm^{-3}. Assuming the effective collector thickness to be 2 μm, the peak electric field at the base–collector junction is calculated to be $\sim$ 1.8×10^6 V/cm, using a breakdown voltage of 340 V and a base doping concentration of 2×10^{19} cm^{-3}. Considering that surface effects and the presence of electric field crowding at the mesa edge have been neglected, the calculated field is in reasonable agreement with the theoretical predicted breakdown field [9].

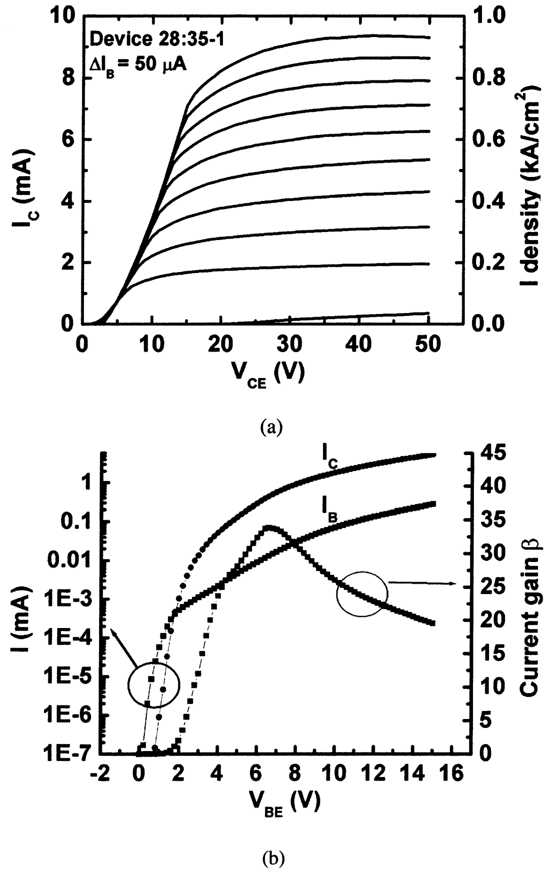

Fig. 3. (a) Common emitter I_C–V_{CE} curves of $Al_{0.05}GaN/GaN$ HBTs (emitter size 20×50 μm^2) with base current $I_B = 0$–450 μA in a step of 50 μA. (b) Gummel plots with $V_{BC} = 0$ V.

The common emitter current–voltage (I-V) characteristics and Gummel plot measurements were taken on HP 4145B semiconductor parameter analyzer. A typical device I–V performance is shown in Fig. 3. Fig. 3(a) illustrates the well-behaved family curves of I_c versus V_{CE}, with I_B ranging from 0 to 450 μA in 50-μA steps. The device was able to operate at an average output current density as high as 1 kA/cm^2 with a high current gain of $\sim$ 18, which is to date the highest value reported from common emitter operation at this high current level of an AlGaN/GaN HBT. The selective area emitter regrowth offers three advantages. First, the offset voltage of $<$ 2 V at a low base current was observed. This reduction compared with the traditional triple mesa AlGaN/GaN HBTs is due to the improved base contacts afforded by this procedure, as the RIE etch damage to the base in conventional topologies was avoided. The second advantage is precise placement of the junction. Our secondary ion mass spectrometry (SIMS) study shows that a sharp Mg decay profile ($\sim$ 35 nm/decade) is indeed obtained in a regrown emitter structure with a proper acid etch before the regrowth [10]. The adoption of a thin UID GaN spacer and a graded AlGaN structure in the regrown emitter structure ensured the appropriate placement of the heterojunction, which was effective to increase the emitter injection coefficient. The third crucial advantage of this technique is the ability to aggressively scale base thickness to smaller dimensions, which is not feasible in conventional triple mesa fabrication without an etch stop at the base. In our devices, a base thickness of 100 nm was chosen to reduce the recombination in the base as well as to obtain a reasonable base conductivity.

The Gummel plot with $V_{\rm BC} = 0$ [Fig. 3(b)] shows that the current gain increased rapidly with $V_{\rm BE}$ and reached a peak value of 35 at a collector current of $\sim$ 0.5 mA, and then dropped gradually when the current increased. We have carried out a study on the measured device characteristics influenced by the presence of leakage currents and poor ohmic contacts. This study reveals that current gain peaks at low current levels are not the gain of the intrinsic device, but an artifact resulting from effect of base–collector leakage coupled with poor ohmic base contacts [11]. The intrinsic current gain of $\sim$ 18 is then determined at a higher current level of $\sim$ 9 mA (the corresponding average current density is 900 $\mathrm{A/cm^2}$), where the leakage currents were measured to be negligible. The current gain of $\sim$ 18 corresponds to a current transfer ratio (α) of $\sim$ 0.9474. Since there is no experimentally directly measured minority carrier lifetime in p-GaN reported in the literature, the minority carrier diffusion length L_{nB} is instead estimated from the device performance. Assuming an emitter injection coefficient of unity in the AlGaN/GaN heterojunction, L_{nB} is calculated to be $\sim$ 0.3 μm in the p-base, using $\mu_{nB} = 100$ and $\mu_{\rm pE} = 10$ $\mathrm{cm^2V^{-1}S^{-1}}$, $W_B = 100$ nm with depletion regions into the base neglected, and a hole concentration of 3.4×10^{17} $\mathrm{cm^{-3}}$. This result is close to the reported value of $L_{nB} \sim 0.5$ μm [12].

IV. CONCLUSIONS

We have demonstrated the highest voltage operation (> 330 V) along with the highest current gain ($\sim$ 18) at a high average output current density (up to 1 $\mathrm{kA/cm^2}$) of $\mathrm{Al_{0.05}GaN/GaN}$ HBTs in the common emitter configuration. Devices employed graded AlGaN:Si emitters selectively regrown by MOCVD and lateral base–collector diodes defined by a shallow RIE base mesa etch, which increased the emitter injection efficiency thus the current gain and reduced the leakage thus the breakdown voltage.

ACKNOWLEDGMENT

The authors are thankful to D. Jena and D. Green for helpful discussions.

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