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Common - Emitter Current - Voltage Characteristics of *Pnp* AlGaN/GaN Heterojunction Bipolar Transistors

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1. Introduction

Nitride-based heterojunction bipolar transistors (HBTs) have the potential to operate in high-temperature and/or high-power conditions with uniform threshold voltages and high current densities. Compared with *Npn* GaN-based HBTs [1], *Pnp* GaN-based HBTs [2] have some advantages related to the n-GaN base layer. One is a high base carrier concentration above 10^{18} cm^{-3}, which results in low base and contact resistances. The other is an ultra-thin base with heavy Si doping, which results in the improvement of device characteristics. Therefore, it is important to clarify the influence of n-type GaN base width on the device characteristics. In this conference, we will report the common - emitter current - voltage (*I-V*) characteristics of *Pnp* AlGaN/GaN HBTs with various base widths to investigate transport properties of minority carriers in the base.

2. Experimental procedure

The device structures were grown by low-pressure metalorganic vapor phase epitaxy as shown in Fig. 1. The source materials were trimethylgallium, trimethylaluminum, and ammonia. The doping gases for n-type and p-type were silane and biscyclopentadienyl-magnesium, respectively.

As a substrate, we used c-face sapphire with thin Al_2O_3/AlN/AlON/Al_2O_3 layer formed by electron cyclotron resonance (ECR) plasma deposition at room temperature [4]. After the substrates were heated to the growth temperature of 1000 °C, we directly grew a 1.5-µm-thick undoped GaN on this substrate. Then, we grew a 1-µm-thick Mg-doped AlGaN/GaN superlattice (SL) sub-collector, a 800-nm-thick undoped GaN collector, a Si-doped GaN base, and a 50-nm-thick Mg-doped AlGaN/GaN SL emitter. The dislocation density (N_{dis}) in GaN layer on this substrates grown under the same conditions was around 8×10^8 cm^{-2}. The AlGaN/GaN SL period thicknesses were 40 nm (20 nm / 20 nm) and 10 nm (5 nm / 5 nm) for the subcollector and the emitter, respectively. The total thicknesses of subcollector and emitter were 1 µm and 50 nm, respectively. The base width, W_B was varied from 30 to 150 nm. The Mg-doping and Si-doping concentrations were 3×10^{19} and 4×10^{18} cm^{-3}, respectively. The emitter and base mesas were defined by ECR plasma etching with Cl_2. The emitter size of the HBT was 90 µm × 150 µm. All samples were annealed at 700 °C in nitrogen ambience to activate the Mg acceptors. Pd/Au and Al/Au were used for the ohmic contacts of p-type and n-type layers, respectively. At the same time, we fabricated the transmission line model (TLM) patterns to evaluate the electrical properties of n-type GaN base. We confirmed that the good ohmic characteristics were obtained even in the ultra-thin base of 30 nm. *I-V* characteristics of *Pnp* AlGaN/GaN HBTs were measured with a semiconductor characterization system (Keithley 4200- SCS) in the common - emitter configuration.

3. Results and discussion

Here, we describe the electrical properties of a 80-nm-thick n-type GaN base. TLM measurements showed that the sheet resistivity and the specific contact resistivity to the base were 907 Ω/square for a 80 nm base and 2.6×10^{-5} Ω·cm^2, respectively. This sheet resistivity is two orders of magnitude smaller than the sheet resistivities of p-GaN in *Npn* nitride HBTs. These results are favorable for high-frequency operation of *Pnp* HBTs.

Figure 2 shows the typical common - emitter *I-V* characteristics of *Pnp* AlGaN/GaN HBTs at room-temperature. The base width was 80 nm. The base current, I_B was -0.5 mA/step. Good saturation properties were observed in common-emitter *I-V* characteristics in all devices. The breakdown voltage was more than 100 V. The maximum breakdown voltage reached 184 V with the 800-nm-thick GaN collector, which corresponds to the breakdown field of

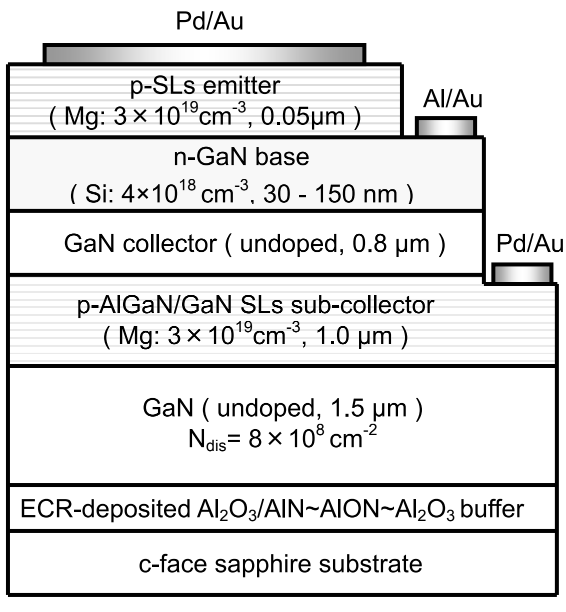

Fig. 1. Layer structure of *Pnp* AlGaN/GaN HBTs .

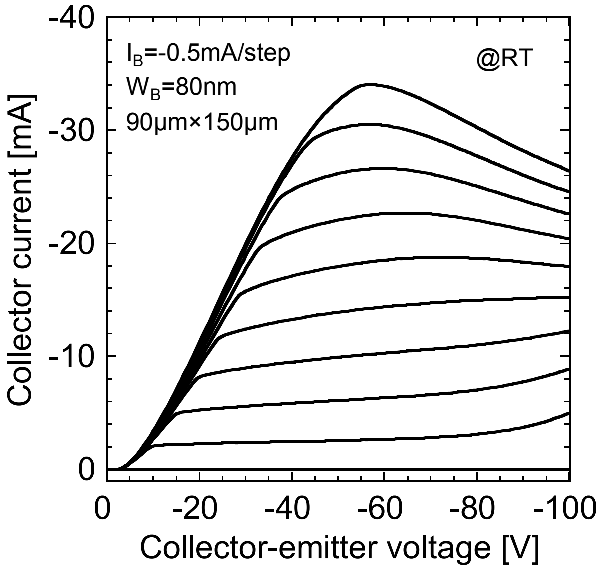

Fig. 2. Common - emitter I-V characteristics of *Pnp* AlGaN/GaN HBTs at room-temperature. The base width and the emitter size were 80 nm and 90 × 150 μm^2, respectively.

2.3 MV/cm. This large value was achieved because of the relatively low dislocation density layer grown on the sapphire with the Al_2O_3/AlN/AlON/Al_2O_3 layer, and is one of the advantages of the GaN-based HBTs. Gummel plots with V_{CB} = -50 V were also taken and are shown in Fig. 3. The obtained maximum β was around 7 at the collector current of 25 mA. The results are consistent with the common - emitter *I-V* characteristics.

In high power operation above the collector current of 20 mA and the collector bias of 60 V, the collector current decreased with increasing the collector bias as shown in Fig. 2. This was ascribed to the heat generation at the p-n junction because we used the sapphire substrates, which have the relatively low thermal conduction.

Figure 4 shows the maximum β as a function of the W_B. The maximum β of 15 was obtained in the HBT with the W_B of 30nm. The broken line was the calculated result of β = $2L_h^2/W_B^2$, assuming the minority hole diffusion length (L_h) is 130 nm. The base width dependence of the β qualitatively coincides with the calculated result taking account of the minority carrier diffusion. Therefore, the current gsin was dominated by the diffusion of the minority holes in the base layer. Electron beam induced current (EBIC) measurements revealed that the minority hole diffusion length in n-type GaN was around 170 nm for the N_{dis} of 8 × 10^8 cm^{-2} and the Si doping concentration of 4 × 10^{18} cm^{-3} [3]. Thus, the minority hole diffusion length obtained from the HBT characteristics agreed well with the results of the EBIC measurements.

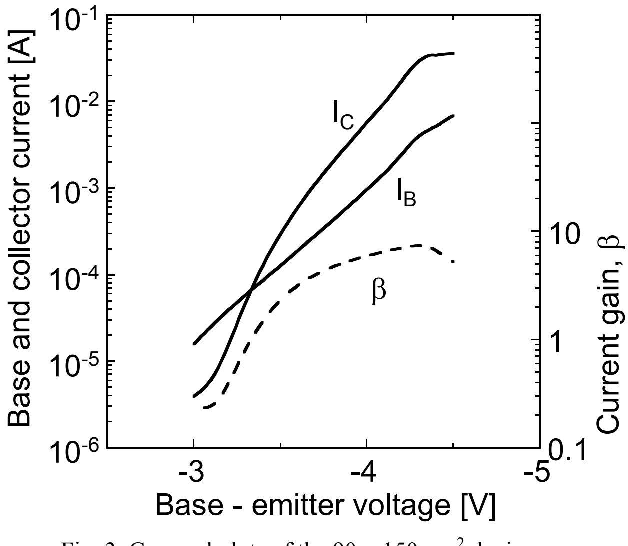

Fig. 3. Gummel plots of the 90 × 150 μm^2 device.

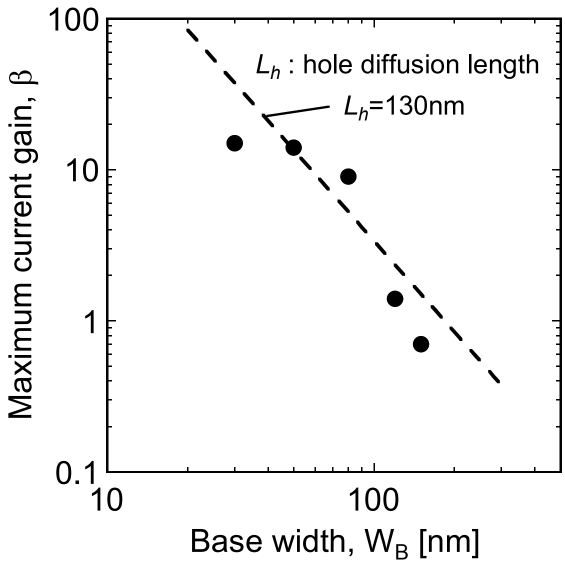

Fig. 4. Common - emitter current gain as a function of the base width. The broken line was the calculated result by β = $2L_h^2/W_b^2$, assuming the L_h = 130 nm.

4. Conclusions

We fabricated the *Pnp* AlGaN/GaN HBTs with the various base widths and evaluated their common - emitter *I-V* characteristics at room-temperature. The breakdown voltage was more than 100 V in all devices. The maximum current gain was 15 in the HBT with the base width of 30 nm. The current gain was dominated by the diffusion of the minority holes in the base layer.

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