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Nonequilibrium Carrier Transport Observed in Pnp AlGaN/GaN HBTs

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1. Introduction

Wide bandgap semiconductors, such as GaN or AlN, are advantageous materials for high-power and/or high temperature electronics. Therefore, in principle, nitride-based heterojunction bipolar transistors (HBTs) have the ability to operate under high-temperature and/or high-power conditions with uniform threshold voltages and high current densities. Compared with Npn GaN-based HBTs, Pnp HBTs have certain advantages related to the n-type 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 that it allows us to fabricate an ultrathin base with heavy Si doping, which could lead to improved high-frequency characteristics. *Pnp* AlGaN/GaN HBTs also have a relatively high breakdown voltage (field) [1], high-power characteristics [2], and high-temperature operation up to 590 °C [3]. For the HBT with an ultrathin (less than 20 nm) base and a graded-base which contains the electric field inside the base, unique characteristics are expected in their carrier transport. Therefore, we fabricated the *Pnp* nitride-based HBTs with an ultrathin GaN base and a compositionally graded AlGaN base, to evaluate their direct current (DC) current-voltage (I-V) characteristics at room temperature.

2. Experimental

The device structure is shown in Fig. 1. The structure was grown on *c*-face sapphire substrate by low-pressure metalorganic vapor phase epitaxy (MOVPE). As a buffer layer for the GaN-based growth on the sapphire substrates, we used the Al_2O_3/AlN/graded-AlON/Al_2O_3 layer [4]. Source materials were trimethylgallium, trimethylaluminum, and ammonia. The *n*-type and *p*-type dopant sources were silane and bis-cyclopentadienylmagnesium, respectively. First, the Al_2O_3/AlN/graded-AlON/Al_2O_3 layer was formed by Ar-plasma electron cyclotron resonance (ECR) sputtering at room temperature. Next, the substrate was introduced into the MOVPE reactor and was heated to the growth temperature of 1000 °C. A 1.5-μm-thick undoped GaN layer was directly grown on this substrate. Then, a 1-μm-thick Mg-doped AlGaN/GaN superlattice subcollector, a 0.8-μm-thick undoped GaN collector, either a uniform GaN or a compositionally graded AlGaN base, and a 50-nm-thick Mg-doped AlGaN/AlGaN superlattice emitter were grown at 1000 °C. The thickness of the uniform base was varied from 18 to 150 nm. The thickness of the graded base was 85 nm. The superlattices consisted of the AlGaN barrier and (Al)GaN well in which the thicknesses (L) were kept equal. The Al mole fraction of the barrier layer in the subcollector was 0.1, and those of the barrier and well layer in the emitter were 0.3 and 0.15, respectively. The period thicknesses (2L) of the subcollector and emitter superlattices were 40 and 10 nm, respectively. From secondary ion mass spectroscopy, the Si doping concentration in the base layer and the Mg doping concentration in subcollector and emitter layers were estimated to be 4×10^{18} and 3×10^{19} cm^{-3}, respectively. The Mg doping concentration was the same for each Mg-doped layer. The typical dislocation density of the GaN layer grown on the sapphire substrate was around 6×10^{8} cm^{-2} using the buffer layer under a similar growth condition. The emitter and base mesas were defined by ECR plasma etching with Cl_2 at a microwave input power of 50 W. The emitter area of the HBT was 30 μm × 50 μm. Pd/Au metals were deposited by electron beam evaporation for the emitter and subcollector contacts, and Al/Au was used for the base contact.

3. Results and discussion

The I-V characteristics of the *Pnp* AlGaN/GaN HBTs were measured with a common-emitter configuration using a semiconductor characterization system (Keithley 4200-SCS) at room temperature.

We investigated the base width dependence of the current gain in *Pnp* AlGaN/GaN HBTs with a uniform GaN base. Figure 2 shows the maximum current gain as a function of the base width (W_B) for the HBTs. The maximum current gain has the dependence with $1/W_B^2$ for the base width above 30 nm, which corresponds to the carrier diffu-

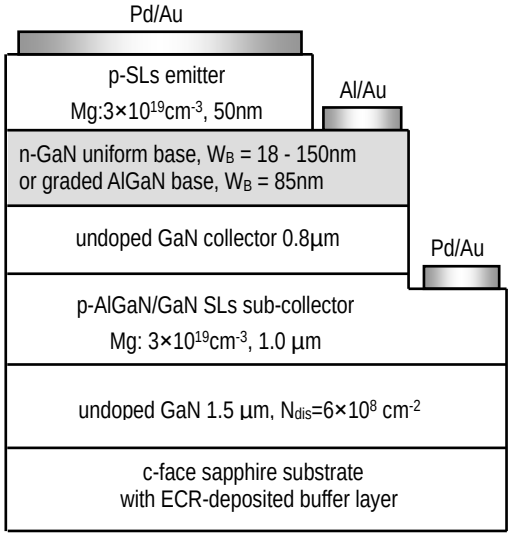

Fig. 1 Device structure of Pnp nitride-based HBT.

sion in the base layer [5]. On the other hand, we clearly observed different dependence for the base width below 30 nm. It has the dependence with $1/W_B$. Generally, a $1/W_B$ dependence observed in HBTs originated from high energy carrier injection from an emitter to a base [6]. Similar characteristics observed in our HBTs with an ultrathin (less than 20 nm) base might originate from the same physical phenomenon mentioned above.

In the case that an electric field exists inside the base, a carrier transport in the base would change to the drift –related transport. To clarify the effect of an electric field inside the base, we fabricated a HBT with a compositionally graded $Al_xGa_{1-x}N$ base. The composition x was 0 at the base/collector junction and continuously graded to x of 0.08 at the emitter/base junction. The base width was 85 nm.

Figure 3 shows the Gummel plots of the HBTs with a uniform base and a compositionally graded base, respectively. Base-collector bias was 50 V. Compared with the graded base HBT, it is clear that higher base currents were needed to get the same collector current for the uniform base HBT. This means that the injected carrier from an emitter to a base was effectively accelerated into the base and reached to the collector due to the electric field in the base. The ratio (α_{exp}) of the current gain between graded base and uniform base was 1.84 in our experiments.

The electric field into the base was estimated to the 12 kV/cm from the base width and the bandgap difference (ΔE_g = 0.10 eV) between GaN and $Al_{0.08}Ga_{0.92}N$ [7]. Using the value of the electric field, we can calculate the base field factor (κ) to be 3.85. According to the theory [8], the ratio (α_{calc}) of the current gain between graded base and uniform base can be calculated using following equations:

$$f(\kappa) = \frac{2}{\kappa}\left(1 - \frac{1}{\kappa} + \frac{1}{\kappa}\exp(-\kappa)\right) \qquad (1)$$

$$\alpha = \frac{1}{f(\kappa)} \qquad (2)$$

We obtained α_{cal} to be 2.58 in our HBTs. The calculated value was almost consistent with the experimental one. Therefore, the enhancement of the current gain observed in the HBT with the graded base was ascribed to the carrier drift in the base due to the electric field inside the base.

4. Conclusions

We fabricated the *Pnp* nitride-based HBTs with an ultrathin GaN base and a compositionally graded AlGaN base to investigate their carrier transport at room temperature. We found nonequilibrium carrier transports in the nitride-based HBTs. They were ascribed to the high energy carrier injection into the base for the HBTs with an ultrathin base, and to the carrier drift motion induced by the electric field inside the base for the HBT with the graded base.

Acknowledgements

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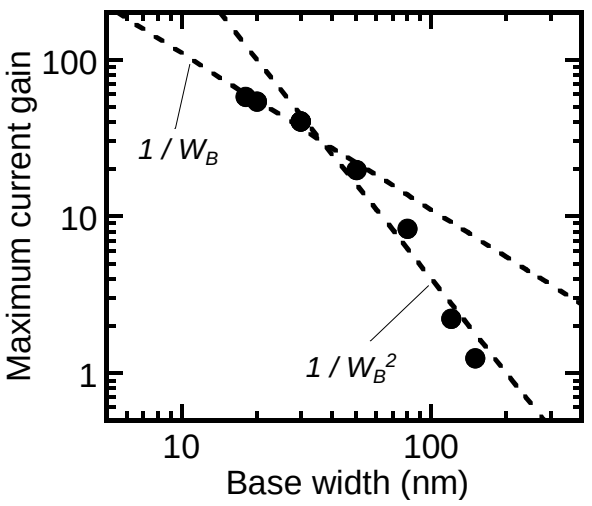

Fig. 2 Maximum current gain as a function of the base width of the HBTs with a uniform base.

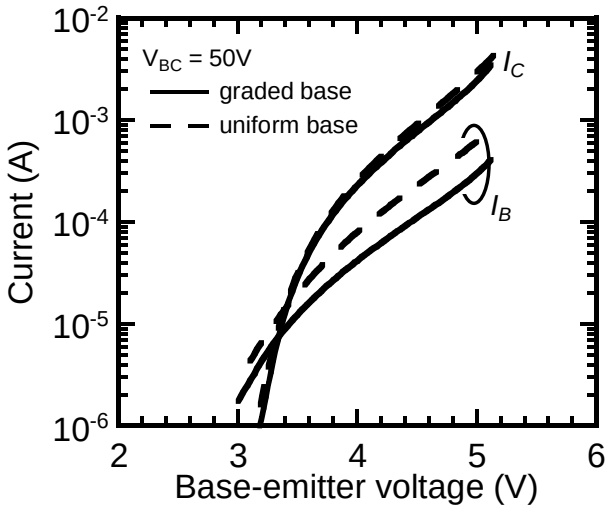

Fig. 3 Collector and base currents as a function of base-emitter voltage for the HBTs with a uniform base and a graded base, respectively.