Extended Abstracts of the 2006 International Conference on Solid State Devices and Materials, Yokohama, 2006, pp. 978-979

E-10-5

Pnp AlGaN/InGaN/GaN Double Heterojunction Bipolar Transistors with Low-Base-Resistance (< 100 Ω/sq)

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1. Introduction

Nitride-based heterojunction bipolar transistors (HBTs) are promising devices for high-power applications. One of the most serious obstacles to developing practical nitride-based HBTs is the relatively high base resistance. Fabricating a low resistance base is easier for *Pnp* HBTs than it is for *npn* nitride-based HBTs. We have reported the performance of a *Pnp* AlGaN/GaN HBT with a low-resistance base [1]. The sheet base resistance was 650 Ω/sq for a 120-nm base. For high-speed operation, it is important to decrease the base width and the base resistance. In this work, we fabricated *Pnp* AlGaN/InGaN/GaN double heterojunction bipolar transistors (DHBTs) with low base resistance and investigated their current-voltage (*I-V*) characteristics.

2. Experimental procedure

We used sapphire substrates for epitaxial growth of HBT structures. First, we deposited an Al_2O_3/graded-AlON/AlN/Al_2O_3 buffer layer by electron cyclotron resonance (ECR) plasma sputtering at room-temperature (RT) [2]. The device structures were directly grown on the substrates with the buffer layer by low-pressure metalorganic vapor phase epitaxy. Group III sources were trimethylaluminum, trimethylgallium, triethylgallium, and trimethylindium. The group V source was ammonia. The dopant sources were silane and cyclopentadienylmagnesium for n-type and p-type layers, respectively.

Table I summarizes the epitaxial layer parameters of a fabricated DHBT. First, we grew a 2-μm-thick undoped GaN buffer layer. Then, we grew a 1.6-μm-thick Mg-doped AlGaN/GaN superlattice subcollector, a 800-nm-thick unintentionally-doped (uid) GaN collector, a 50-nm-thick Si-doped $In_{0.06}Ga_{0.94}N$ base, a 10-nm-thick Mg-doped $Al_{0.6}Ga_{0.4}N$ emitter, and a 40-nm-thick Mg-doped AlGaN/GaN superlattice. The growth temperatures for the buffer, subcollector, and collector layers was 1000 °C, and that for for base and emitter layers were 790 °C. The Si-doping concentration in the base layer was as high as 2×10^{20} cm^{-3}. The emitter and base mesas were defined using conventional photolithographics technique and ECR plasma etching with Cl_2. The emitter size was 30 μm × 50 μm. *Al/Au* and *Pd/Au* were used for the ohmic contacts of the *n*-type and *p*-type layers, respectively.

3. Results and Discussion

Transmission line model (TLM) measurements were carried out to investigate the characteristics of the ohmic contacts to the n^+-InGaN base layer exposed by the emitter mesa etching. The pad area was 80 μm × 50 μm, and the spacings between the pads ranged from 4 to 20 μm. Figure 1 shows the total resistance as a function of the spacing between two TLM pads. The sheet resistance of the etched n^+-InGaN base was determined to be 96 Ω/sq with a resistivity of 2.9×10^{-4} Ω-cm for the original layer thickness of 50 nm. The specific contact resistivity was determined to be 1.1×10^{-3} Ω-cm^2. This is the first time a sheet resistance of less than 100 Ω/sq has been reported for nitride-based HBTs. Separate room-temperature Hall-effect measurements revealed an electron concentration of 2×10^{20} cm^{-3} and a mobility of 78 cm^2/V-s for the base layer, which means the resistivity is 4×10^{-4} Ω-cm. The results of TLM measurements are consistent with those obtained from Hall-effect measurements.

TABLE I Epitaxial Layer Parameters of a Fabricated DHBT

	Layer	Thickness (nm)	Doping (cm^{-3})	AlN or InN fraction (%)
Emitter	*p*-InGaN	2	3×10^{19}	0.03
	p-AlGaN/GaN SLs	(5/5)×4	3×10^{19}	(0.6/0)
	p-AlGaN	10	3×10^{19}	0.6
Base	n^+-InGaN	50	2×10^{20}	0.06
Collector	*uid*-GaN	500		0
Subcollector	*p*-AlGaN/GaN SLs	(20/20)×40	3×10^{19}	(0.15/0)
Buffer	*uid*-GaN	2000		0
Sapphire substrates with Al_2O_3/AlON/ALN/ Al_2O_3 buffer				

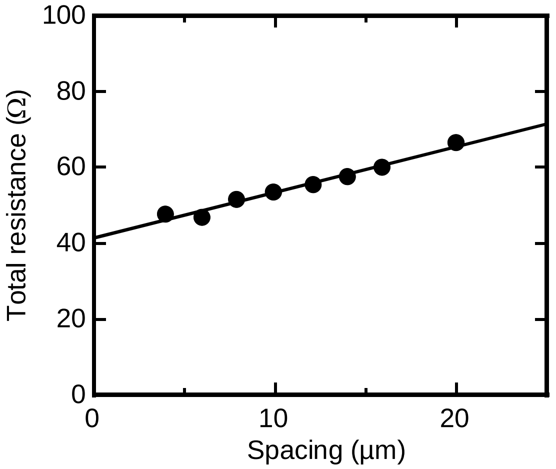

Fig. 1. Total resistances as a function of the spacing between two TLM pads.

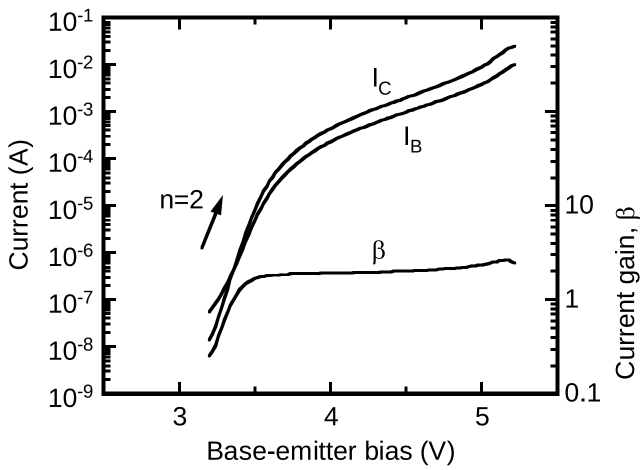

Fig. 3. Gummel plot of the *Pnp* AlGaN/InGaN/GaN DHBT with V_{BC} = 20V.

Figure 2 shows the common-emitter *I-V* characteristics of a *Pnp* AlGaN/InGaN/GaN DHBT at RT. Base current ranged from 0 to -1.8 mA in -0.2 mA steps. Good saturation properties were observed at emitter-collector bias up to -50 V in common-emitter *I-V* characteristics. The large Early voltage is ascribed to the heavily Si-doped InGaN base layer. Leakage current was as low as 10 µA at the emitter-collector bias of -50 V, indicating that the reverse leakage current of the n^+-InGaN/uid-AlGaN/*p*-AlGaN/GaN SLs diode was relatively small.

Figure 3 shows the Gummel plot obtained at a collector-base bias of 20 V at RT. The maximum current gain was 2.7 at the collector current of 23 mA.

The base current ideality factor was around 2 at collector current below 10^{-5} A. In relatively large (30 µm × 50 µm) abrupt AlGaAs/GaAs HBT, the important base current components are the space-charge recombination and the base bulk recombination currents. The ideality factor of around 2 indicates that the space-charge recombination current is larger than the base bulk recombination current [3]. The current gain nearly saturated at collector current above 10^{-5} A. Such gain behavior has also been observed in AlGaAs/GaAs HBTs with an abrupt emitter-base junction [3].

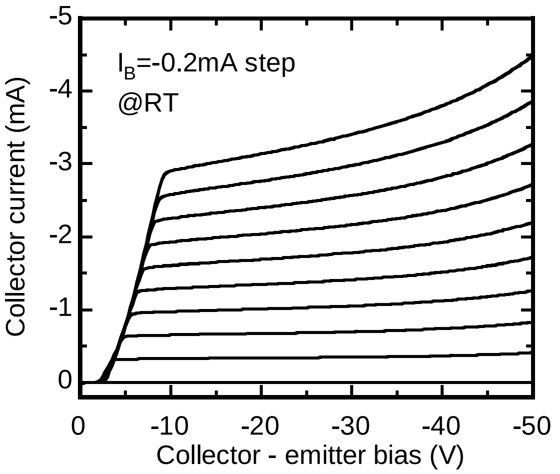

Fig. 2. Common-emitter *I-V* characteristics of a *Pnp* AlGaN/InGaN/GaN DHBT at RT.

4. Conclusions

We have fabricated the *Pnp* AlGaN/InGaN/GaN DHBTs with low base resistance and investigated the *I-V* characteristics. The sheet base resistance is lower than 100 Ω/sq. The common-emitter *I-V* characteristics showed good saturation properties because of the heavily Si-doped InGaN base layer. Current gain nearly saturated, which is similar to the properties of abrupt AlGaAs/GaAs HBTs.

Acknowledgements

We are grateful to Dr. K. Torimitsu, Dr. H. Takayanagi, and Dr. J. Yumoto for their encouragement throughout this work.

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