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Current Transport Characteristics of Quasi-$Al_xGa_{1-x}N$/SiC Heterojunction Bipolar Transistors with Various Band Discontinuities

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1. Introduction

SiC bipolar junction transistors (BJTs) are promising for power switching devices because of low on-resistance and high breakdown voltage [1]. Since BJTs are current-controlled devices, high common-emitter current gain (β) over 100 is required to use simple drive circuits. A number of studies have been devoted to improve the current gain [2-4], and a high current gain of 257 was achieved recently [5]. In SiC BJTs, however, current-gain reduction with elevating the temperature is inevitable because injection efficiency decrease by increasing hole density in the base region [6].

Heterojunction bipolar transistors (HBTs) are theoretically expected to have a high current gain even at elevated temperature because a wide bandgap emitter can suppress the injection of holes from the base to the emitter. We previously proposed AlGaN/SiC HBTs employing AlN/GaN short-period superlattices (quasi-$Al_xGa_{1-x}N$) as a wide bandgap emitter [7]. We succeeded in fabricating quasi-$Al_xGa_{1-x}N$/SiC HBTs with various average Al compositions by changing the ratio of AlN and GaN layer thicknesses, and controlling the band offset between quasi-$Al_xGa_{1-x}N$ and SiC. However, an ideal performance expected from the HBT structure has not been obtained. It is important to investigate current transport mechanism for better understanding of the HBT operation.

In this paper, we investigated the current transport characteristics of HBTs with various Al compositions (various band discontinuities) by means of Gummel plot that shows the base and collector current characteristics plotted against the emitter-base voltage.

2. Device Fabrication

The fabricated HBT structure is shown in Fig. 1. We used n^+-SiC substrates with an n^--SiC collector layer and a p-SiC base layer (0.5 µm, $N_a = 1 \times 10^{18}$ cm^{-3}). An n^--SiC spacer layer was grown by chemical vapor deposition followed by a Si-doped AlN/GaN short-period superlattice (0.1 µm, $N_d \sim 1 \times 10^{19}$ cm^{-3}) and a Si-doped n^+-GaN contact layer grown at 600 °C by molecular beam epitaxy. HBTs with various Al compositions were fabricated by changing the ratio of AlN and GaN layer thicknesses. Growth was started with AlN that has smaller lattice mismatch and better wetting (smaller interface energy) with SiC than GaN.

Table I shows the conduction band discontinuities at the quasi-$Al_xGa_{1-x}N$/SiC heterojunction measured by Capacitance-voltage (C-V) measurements and the common-emitter current gain (β) at I_B = 1 mA. The HBTs with Al compositions over 0.5 have a Type I heterojunction and a current gain larger than 1 due to the elimination of potential barriers to electron injection. Fig. 2 shows common-emitter I-V characteristics of $Al_{0.5}Ga_{0.5}N$/SiC HBT. A common-emitter-mode operation (β = 2.2 at I_B = 1 mA) was successfully obtained.

Table I. The conduction band discontinuity at the quasi-$Al_xGa_{1-x}N$/SiC heterojunction and the common-emitter current gain at I_B = 1 mA.

Al composition	ΔE_C	Gain (β)
0.33	- 0.56 (Type II)	0.22
0.4	- 0.39 (Type II)	0.53
0.5	+ 0.21 (Type I)	2.2
0.6	+ 1.10 (Type I)	2.4

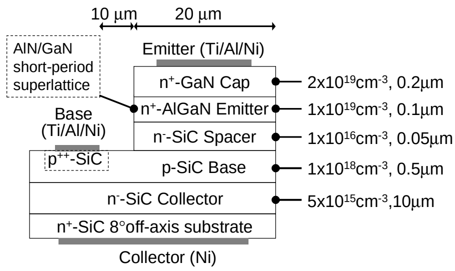

Fig. 1. Schematic cross section of fabricated AlGaN/SiC HBTs.

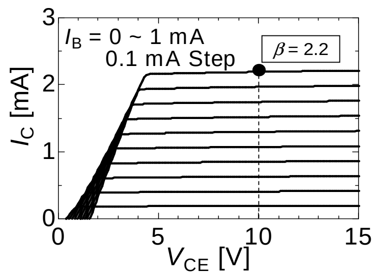

Fig. 2. Common-emitter I-V characteristics of $Al_{0.5}Ga_{0.5}N$/SiC HBTs.

3. Results and Discussion

In BJTs, the collector current, which reflects the electron current injected from the emitter to reach the collector, is dominated by the diffusion process in the base region, and the ideality factor n is typically 1.0. However, in the AlGaN/SiC HBTs, the conduction band discontinuities or

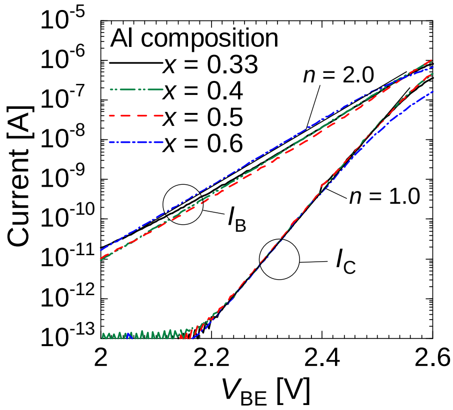

Fig. 3. Gummel plots of HBTs with Al compositions of 0.33, 0.4, 0.5, and 0.6 with a shorted collector-base junction.

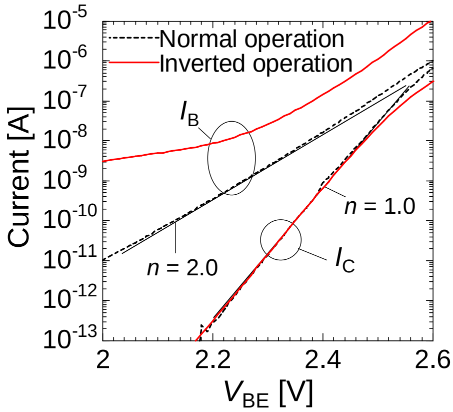

Fig. 4. A Gummel plot and a reverse Gummel plot of $Al_{0.5}Ga_{0.5}N$/SiC HBT with a shorted collector-base junction.

the severe interface states may affect the current transport characteristics and result in additional voltage drops for electron injection from the emitter to the base.

We investigated current transport characteristics of the HBTs with various Al compositions (various band discontinuities) by means of Gummel Plots. Gummel plots cannot be simply compared at the base-emitter voltages over 2.7 V because the base currents are limited by the series resistance of the base region in that range and the series resistances are different among the HBTs. In this paper, Gummel plots were compared in the 2.0 V to 2.6 V range, although the current gain is rather small because the recombination current is still dominant in the voltage range.

Fig. 3 compares Gummel plots of the HBTs with Al compositions of 0.33, 0.4, 0.5, and 0.6 in the 2.0 V to 2.6 V range. The ideality factors n of the collector current characteristics were 1.0. This result indicates that the collector current is, in spite of the various band discontinuities, dominated by the diffusion process in the base region in the low current range. In addition, the collector currents of the HBTs with various Al compositions were almost the same in the low current range from 10^{-13} A to 10^{-9} A. This result indicates that electrons are injected without any additional voltage drops from the emitter to the base region. Even if there are some potential spikes caused by the conduction band discontinuities, they may be low enough not to affect the current transport characteristics at least in the low current range. That is because the doping concentration of the quasi-$Al_xGa_{1-x}N$ emitter epilayer ($N_d \sim 1 \times 10^{19}$ cm^{-3}) is about ten times larger than that of the SiC base epilayer ($N_a = 1 \times 10^{18}$ cm^{-3}) and therefore the depletion layer of the emitter is very thin (< 1 nm) at the forward bias. The differences of base currents among the HBTs were small, and the ideality factors n of the base current characteristics were 2.0, indicating that the recombination current at the emitter-base junction is dominant. The base currents of the HBTs are mainly determined by the interface states at the AlGaN/SiC heterojunction, rather than the band discontinuities at the AlGaN/SiC heterojunction in the low current range.

By comparing a Gummel plot in the normal mode with the same plot with the emitter and collector reversed (inverted operation), we can investigate the differences of the electron injection between from n-AlGaN to p-SiC and from n-SiC to p-SiC. Fig. 4 compares the Gummel plot with the reverse Gummel plot of the $Al_{0.5}Ga_{0.5}N$/SiC HBT. The collector currents for the Gummel plot and the reverse one were almost the same in the low current range. In other HBTs, the collector currents for the Gummel plot and the reverse one were also almost the same (not shown). This result indicates that the band discontinuities and the severe interface states at the AlGaN/SiC heterojunction do not affect the electron injection in the low current range. The base current in the reverse Gummel plot was much larger than that in the Gummel plot. This is because the collector-base junction area, which includes parasitic diode under the base contact, is much larger than the emitter-base junction area.

4. Conclusion

The HBTs with various band discontinuities at the $Al_xGa_{1-x}N$/SiC heterojunction were investigated. It revealed that the band discontinuities and the severe interface states at the heterojunction did not affect the current transport characteristics at least in the low current range. The current transport characteristics of collector currents are dominated by the diffusion process in the base region.

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