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 ($\beta$) 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$_x$Ga$_{1-x}$N) as a wide bandgap emitter [7]. We succeeded in fabricating quasi-Al$_x$Ga$_{1-x}$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$_x$Ga$_{1-x}$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 $\mu$m, $N_d = 1 \times 10^{18}$ 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 $\mu$m, $N_d \sim 1 \times 10^{19}$ cm$^{-3}$) and a Si-doped n$^-$-GaN contact layer grown at 600 $^\circ$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$_x$Ga$_{1-x}$N/SiC heterojunction and the common-emitter current gain at $I_B = 1$ mA.

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...
the current transport characteristics at least in the low current range. That is because the doping concentration of the quasi-Al$_{0.33}$Ga$_{0.67}$N emitter epilayer ($N_d \sim 1 \times 10^{19}$ cm$^{-3}$) is about ten times larger than that of the SiC base epilayer ($N_p = 1 \times 10^{15}$ 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$_{0.33}$Ga$_{0.67}$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.

References