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Investigations on Electrical Characteristics of 1-kV *pnp* SiC BJTs Compared with *npn* SiC BJT

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Abstract

We investigate electrical characteristics in 1-kV *pnp* SiC BJTs compared with *npn* SiC BJT. The base resistance, current gain, and blocking capability are characterized. It is found that the base resistance is much lower in *pnp* SiC BJT than that in *npn* SiC BJT. However, the obtained current gains are low below unity in *pnp* SiC BJTs, whereas the *npn* SiC BJT exhibits a current gain of 14. The mechanism of the poor current gain of *pnp* SiC BJTs is discussed.

1. Introduction

Silicon carbide (SiC) has a superior material property for power devices. Through recent progress, 1-kV-class SiC metal-oxide-semiconductor field-effect transistors (MOSFETs) are now viable for mass production with low on-resistance and high switching frequency. SiC bipolar junction transistors (BJTs) are also candidates for power switching devices [1-3]. Owing to the superior material property, SiC BJTs are free from second breakdown phenomena [4], which was a critical issue for Si BJTs. SiC BJTs are also free from issues related to the gate oxide reliability and poor channel mobility in SiC MOSFETs, so that SiC BJTs exhibit very low on-resistance with high temperature stability[5].

In SiC BJTs, an n^+pn^- structure (n^+-emitter / p-base / n^--collector) has been employed because the injection efficiency between the emitter and base is estimated to be higher than that of p^+np^- structure, so that experimental investigations for *pnp* SiC BJTs are very limited. However, complimentary operation using push and pull transistors is important for power electronics as well as logic operation. Low-voltage *pnp* SiC BJT was first demonstrated by Lanni *et al.*[6], which employs a lateral p^+np^+ structure for logic operation. Reducing the doping concentration of the base layer to 10^{15}-10^{16} cm^{-3}, a current gain (β) of 37 was obtained with a blocking voltage of 35 V.

In this study, we demonstrate 1-kV-class *pnp* SiC BJTs and compare the device characteristics with *npn* SiC BJT. The base resistance, current gain, and blocking capability are characterized.

2. Experimental Procedures

The schematic structures of fabricated *pnp* and *npn* SiC BJTs are shown in Fig. 1. The emitter layer is 1.2 μm in thickness, the base layer is 0.35 μm in thickness with a doping concentration of 1×10^{18} cm^{-3}, and the collector layer is 10 μm in thickness with a doping concentration of 5×10^{15} cm^{-3}. The ideal blocking voltage estimated from the collector layer is 1.9 kV, although no junction termination is utilized in this study. For *pnp* SiC BJTs, the emitter doping concentration is varied from 2×10^{18} to 1×10^{20} cm^{-3}. The doping concentration of the base and emitter layers was confirmed by secondary ion mass spectrometry (SIMS). Both surface passivation for the emiter mesa and ion implantation for the ohmic contact of the base layer were not conducted.

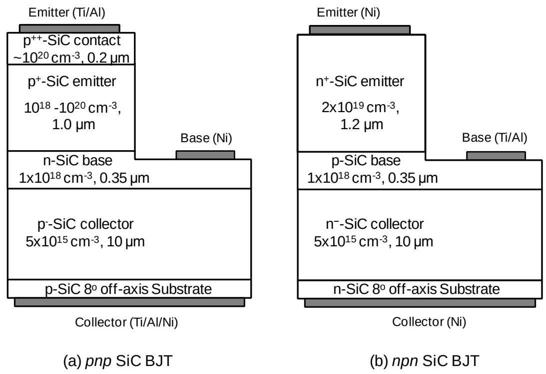


Fig. 1 Schematic cross sections of fabricated *pnp* and *npn* SiC BJTs.

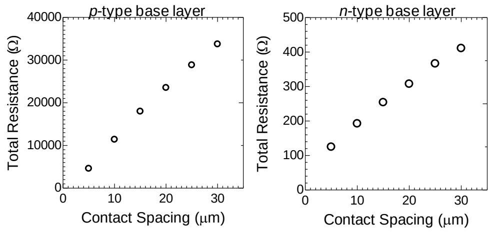
3. Results and Discussion

Base resistance

The current-voltage (*I-V*) characteristics of transmission line model (TLM) pattern for the base contact in *npn* and *pnp* SiC BJTs are shown in Fig. 2. The sheet resistance of the *p*-type base in *npn* SiC BJT was estimated to be 225 kΩ/□, whereas that of the *n*-type base in *pnp* SiC BJT was 2.29 kΩ/□. The base series resistance is very low in *pnp* SiC BJTs owing to the high electron mobility and high ionization ratio, which contributes to reducing driving losses and enhancing the switching characteristics in *pnp* SiC BJTs.

Current Gain

The common-emitter *I-V* characteristics of the fabricated *pnp* SiC BJT are shown in Fig. 3. The doping concentration of the *p*-type emitter layer is 3×10^{19} cm^{-3}. Transistor opera



(a) *npn* SiC BJT (b) *pnp* SiC BJT

Fig. 2 *I-V* characteristics of TLM patterns for the base layer in (a) *npn* SiC BJT and (b) *pnp* SiC BJT. The contact width was 200 μm.

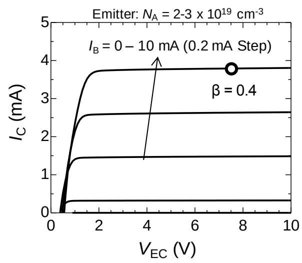


Fig. 3 Common-emitter *I-V* characteristics of fabricated *pnp* SiC BJT. The doping concentration of the *p*-type emitter is N_A = 2-3 $\times 10^{19}$ cm^{-3}.

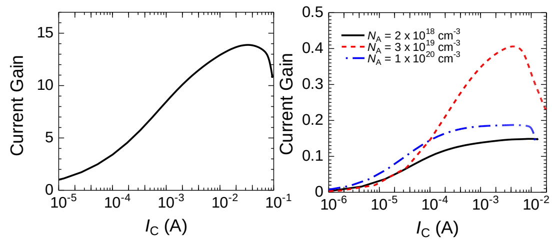
tion was obtained, but the maximum current gain was limited at β_{pnp} = 0.4. On the other hand, the maximum current gain of the fabricated *npn* SiC BJT was β_{npn} = 14. The current gain in the *pnp* SiC BJT is much lower than that in *npn* SiC BJT.

The current gains ($\beta = I_C/I_B$) of the *npn* and *pnp* SiC BJTs plotted against the collector current are shown in Fig. 4. The emitter doping concentration of *pnp* SiC BJT was varied from $N_A = 2 \times 10^{18}$ to 1×10^{20} cm^{-3}. The current gain in the *npn* SiC BJT decreased at low current range, which may be caused by surface recombination at the emitter mesa [3]. The maximum current gain of 14 will be improved by surface passivation.

For the *pnp* SiC BJTs, we propose the following limiting factors of the current gain. In the case of $N_A = 2 \times 10^{18}$ cm^{-3}, the ratio of the carrier concentration in the emitter to the base layer is almost unity by taking into account of incomplete ionization in the *p*-type emitter. The hole diffusion coefficient is lower than that of the electron, decreasing the injection efficiency of the base-emitter junction. In the case of $N_A = 3 \times 10^{19}$ cm^{-3}, the increased hole concentration improves the injection efficiency, but carrier recombination such as surface recombination may limit the current gain. In the case of $N_A = 1 \times 10^{20}$ cm^{-3}, the hole concentration drastically increases owing to reduced Al ionization energy [7]. However, bandgap narrowing effect in the heavily-doped emitter may severely degrade the injection efficiency [8], so that the current gain was limited. From above, a *p*-type emitter with a doping concentration of ~3×10^{19} cm^{-3} with surface passivation will be favorable to *pnp* SiC BJTs.

Blocking Characteristics

The open-base blocking characteristics are shown in Fig. 5. The blocking voltage of the *pnp* SiC BJT was 1030 V in spite of no junction termination for the base-collector junction. The blocking voltage of the *npn* SiC BJT was 980 V. The blocking capability of the *pnp* SiC BJT is expected to be similar to that of *npn* SiC BJT.



(a) *npn* SiC BJT (b) *pnp* SiC BJT

Fig. 4 Current gains plotted against the collector current measured in fabricated (a) *npn* SiC BJT and (b) *pnp* SiC BJTs with various emitter doping concentration.

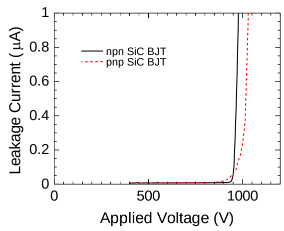


Fig. 5 Open-base blocking characteristics of fabricated *npn* and *pnp* SiC BJT.

4. Conclusions

We investigated 1-kV-class *pnp* SiC BJTs. The current gain was poor below unity, while the current gain was 14 in the *npn* SiC BJT with the same structure. *pnp* SiC BJTs suffered from poor injection efficiency of the base-emitter junction. In the final paper, temperature dependence of the current gain will be presented.

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