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Transport characteristics of minority carriers in 4H-SiC/Si heterojunction bipolar transistor structures fabricated by surface activated bonding

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Abstract

4H-SiC/Si heterojunction bipolar transistor structures with emitter-up (E-up) and collector-up (C-up) configurations were fabricated by surface activated bonding. Their electrical characteristics were measured at raised ambient temperatures. The common-based current gain α increased as the temperature was raised. The activation energy of α was found to be 0.05 and 0.18 eV for the E-up and C-up structures, respectively. In the E-up structures, α reached to 0.99 at 573 K.

1. Introduction

SiC have been widely applied to electron devices with high electric power capabilities due to their tolerance against high electric fields and high ambient temperature [1]. SiC-based power MOSFETs and Schottky diodes that exceed Si-based devices in performances have been utilized in a variety of power-electronics (sub) systems [2]. Several groups reported on fabrication and characterization of SiC/Si heterojunctions by growing SiC films on Si substrates or by directly bonding SiC and Si substrates to each other [3-6]. 3C-SiC were employed as wide gap emitters in SiC/Si heterojunctions bipolar transistors (HBTs) [3, 4]. 4H-SiC is assumed to be more promising as emitters in HBTs since the band gap of 4H-SiC (3.23 eV) is larger than that of 3C-SiC (2.36 eV).

We previously fabricated and characterized III-V semiconductors/Si heterojunctions [7, 8], which were successfully utilized as tunneling junctions in hybrid tandem solar cells [9, 10]. As for SiC-based heterojunctions, we observed that the reverse leakage currents of n-4H-SiC/p-Si junctions were decreased and their ideality factors were improved by annealing them at higher temperatures [11]. Furthermore the conduction band offset and the density of interface states were estimated by analyzing the capacitance-voltage characteristics of n-SiC/p-Si and n-SiC/n-Si junctions [12]. In this work we discuss the transport properties of electrically injected minority electrons in 4H-SiC/Si HBT structures with emitter-up (E-up) and collector-up (C-up) configurations fabricated by SAB

2. Experimental procedure and results

For fabricating the E-up HBT structures, we started with preparation of a 5-mm by 11-mm n-type 4H-SiC epi wafer, which was composed of a 2.8-µm, 1.2×1017− cm−3 epi layer grown on a heavily n-type-doped (~ 1×10^{19} cm^{-3}) SiC substrate. An ohmic contact (emitter contact of HBTs) had been fabricated on the back side of the 4H-SiC epi wafer by evaporating Al/Ni/Au and annealing at 1000 ◦C.

We also made a p-on-n base/collector structure by respective implantations of B and P ions to the surface and back side of a high-resistive n-type (a donor concentration of ~ 1×10^{15} cm^{-3}) Si substrate and a subsequent annealing (900 ◦C for 1 min.). The implantation energy was 10 keV. The height and position of peak in distribution of B atoms were estimated to be ≈ 1.5×10^{20} cm^{-3} and ≈ 50 nm, respectively, after the annealing. Note that these characteristics of B atom distribution gives a measure of the impurity concentration and thickness of the base of HBT structures.

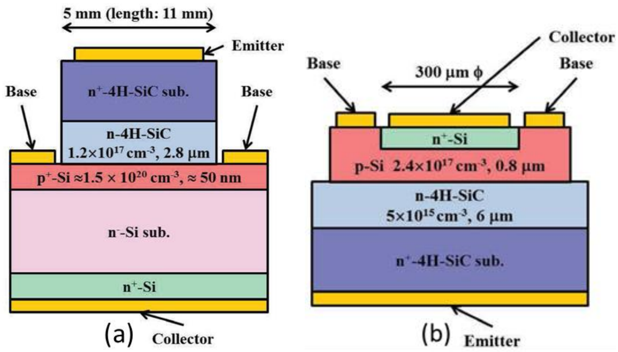

Fig. 1. A schematic cross section of 4H-SiC/Si HBT structures fabricated by the surface activated bonding.

The 4H-SiC epi wafer was attached to the Si substrate by using SAB. So that an n-SiC/p-Si/n-Si stack was obtained. The samples were not heated during the bonding process. The properties of SiC/Si interfaces were improved by a post-bonding annealing at 700 ◦C for 1 h in a nitrogen ambient. Then base and collector contacts were formed by metal evaporation and annealing so that the HBT structures were fabricated. The C-up HBT structures were fabricated by bonding a p-type Si substrate to an n-type 4H-SiC epi wafer, thinning the Si substrate into the base layer by the ion cut process, defining circular collector regions by the implantation of P ions and annealing, making Si mesa for isolation, and forming base and collector contacts by metal evaporation and annealing. The concentrations of impurities in the p-type Si substrate and n-type SiC epi layer were ≈ 2.4×10^{17} and ~ 5×10^{15} cm^{-3}, respectively. The diameter of collector region and the thickness of the base were 300 µm and ≈ 0.8 µm, respectively. The schematic cross sections of fabricated E-up and C-up devices are shown in Figs. 1(a) and 1(b), respectively.

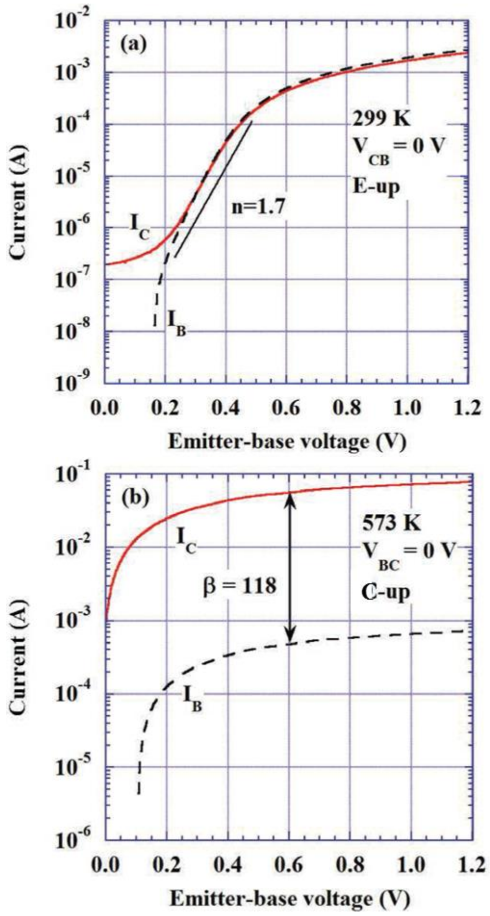

Fig. 2. I_B-V_{EB} and I_C-V_{EB} characteristics with V_{CB} of 0 V measured for the SiC/Si HBT at 299 (a) and 573 K (b), respectively. The dependencies of α on the ambient temperature for the E-up (a) and C-up (b) structures, respectively.

We measured characteristics of E-up structure at various ambient temperatures between 299 and 573 K. Dependencies of the base and collector currents (I_B and I_C) on the emitter-base voltage V_{EB} with the base-collector voltage V_{CB} fixed to 0 V at 299 and 573 K are shown in Figs. 2(a) and (b), respectively. As is seen from Fig. 2(a), I_C was slightly smaller than I_B for V_{EB} > 0.3 V at room temperature. The common-emitter current gain β was 0.89 at V_{EB} = 0.6 V. The corresponding common-base current gain α was 0.47. The ideality factors of I_B and I_C were found to be ≈ 1.7 for V_{EB} between 0.3 and 0.4 V. The base resistance R_B was estimated to be 230 Ω from the dependence of I_C for a larger V_{EB}. Such a large base resistance was likely to explain I_C remaining ~ 2 - 3 mA, which corresponded to a current density as low as ~ 5×10^{-3} A/cm^2, for V_{EB} = 1.2 V. We observed that β increased as the device temperature was raised. As is shown in Fig. 2 (b), β of 118 was obtained for V_{EB} = 0.6 V at 573 K, which corresponded to α ≈ 0.99.

3. Conclusions

4H-SiC/Si HBT structures were fabricated by using the surface activated bonding of 4H-SiC and Si wafers withouyt heating. Their characteristics were improved by raising the ambient temperatures. The common-emitter current gain β of > 100 was demonstrated at 573 K.

Acknowledgements

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