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4H-SiC/Si Heterojunction Bipolar Transistors Fabricated by Surface Activated Bonding

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4H-SiC/Si heterojunction bipolar transistors with emitter-up (E-up) and collector-up (C-up) configurations were fabricated by surface activated bonding for the first time. Their electrical characteristics were measured at raised ambient temperatures. The common-base current gain α increased as the temperature was raised in the both E-up and C-up structures. In the E-up structure, α reached to ≈ 0.99 at 573 K. Improvements in both device structures and surface activated bonding conditions should provide further improvements in device performance.

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Wide gap semiconductor materials like SiC have been largely 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] Possibilities of SiC-based heterojunctions for devices have been intensively explored: Several authors reported on fabrication and characterization of SiC/Si heterojunctions by growing SiC films on Si substrates[3–8] or by directly bonding SiC and Si substrates to each other.[9–11] 3C-SiC were employed as wide gap emitters in SiC/Si heterojunctions bipolar transistors (HBTs).[3,4,6] 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) by ≈ 0.9 eV.

Heterojunctions of materials with difference in crystal structures, lattice constants, and thermal expansion coefficients have been realized by using surface activated bonding (SAB), in which the sample surfaces are activated by Ar fast atom beams in a high vacuum prior to bonding in low temperatures.[12,13] 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.[14] 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.[15] 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.

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, 1.2×10^{17} 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.

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 the 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,[16] 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 and ∼ 0.8 μm, respectively. The schematic cross sections of fabricated E-up and C-up devices are shown in Figures 1a and 1b, respectively.

We measured the 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 Figures 2a and 2b, respectively. As is seen from Figure 2a, 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 mA, which corresponded to a current density as low as ∼ 5×10^{-3} A/cm^2, for $V_{EB} = 1.2$ V. The values of parameters for the E-up and C-up HBT structures are summarized at Table I.

We observed that β increased as the device temperature was raised. As is shown in Figure 2b, β of 118 was obtained for $V_{EB} = 0.6$ V at 573 K, which corresponded to α ≈ 0.99. The result that β of the E-up structure exceeded 100 at 573 K suggests that SAB-based SiC/Si heterojunctions are promising as constituent of bipolar devices, although a lower R_B and a larger β must be achieved at room temperature from the practical viewpoints. The observed R_B, which should be attributable to the width of SiC emitter (5 mm), is likely to be decreased by narrowing it. The potential well in the *p*-Si base must be shallower so as to realize a larger β at room temperature. One essential approach is to optimize the conditions of the SAB process and the post-bonding annealing for reducing D_{it}. Practically base layers with larger concentrations of acceptors, which bring about thinner and shallower potential wells, should be additively useful. The dependence of α on the ambient temperature is shown in Figure 3a. Similar measurements were performed for the C-up structure. The dependence of α on the ambient temperature is shown in Figure 3b. The lower α in comparison with the result for the E-up structure is likely to be attributable to the thicker base layer of the C-up structure. The dependencies for both devices are approximately expressed as $\alpha \sim \exp(-E_a/kT)$ with the activation energy E_a of ≈ 0.05 and 0.18 eV for the E-up and C-up structures, respectively.

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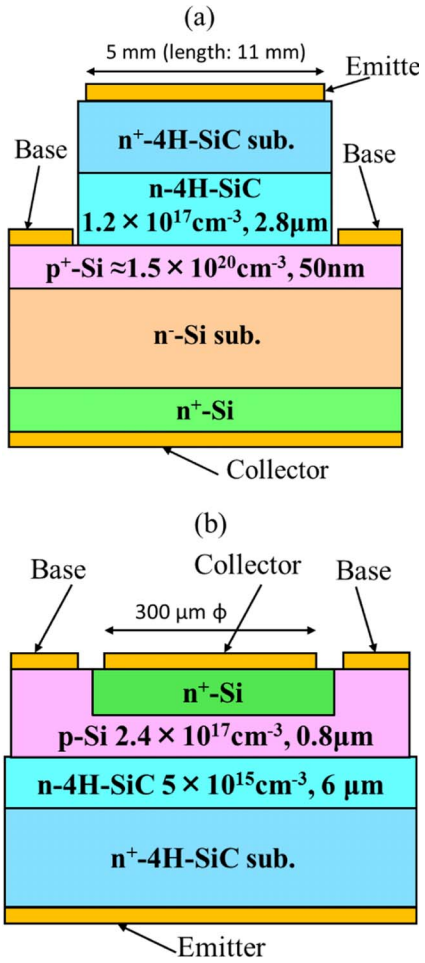

Figure 1. A schematic cross section of (a) E-up and (b) C-up structures of 4H-SiC/Si HBTs fabricated by the surface activated bonding.

We found that the larger ideality factor (1.7) was obtained at the 4H-SiC/Si junction of E-up HBT, which suggests that the recombination or tunneling current dominates the electrical transport properties across the interfaces. The large number of interface states should be formed at the bonding interface according to our previous report,[15] which could act directly as trapping and recombination centers. β increased with increasing the devices temperature and the larger value was obtained at 573 K, while which is much smaller than those previously reported for 3C-SiC/Si[3] and a fluorine-doped SiC/Si[4] HBTs fabricated by the epitaxy growth and atmospheric pressure CVD reactor, respectively. The interface states formed at the 3C-SiC/Si heterojunction are ineffective as recombination centers and do not deteriorate the characteristics of the HBT. The dangling-bonds between SiC and Si were passivated by fluorine at the fluorine-doped SiC/Si HBTs. The interface sates degrade the current gain by combined effects of localized recombination and trapped charge that affect the band bending.[17] The current gain of HBT decreased as the interface states density increased.[18]

Table I. The common-base current gain (α), common-emitter current gain (β), base resistance (R_B), and collect current at V_{EB} = 0.6 V of Si/SiC heterojunction bipolar transistors.

	α	β	R_B (Ω)	I_C (V_{EB} = 0.6 V) (A)
E-up (299 K)	0.47	0.89	230	4.64×10^{-4}
E-up (573 K)	0.99	118	31	5.62×10^{-2}
C-up (299 K)	0.024	0.025	9828	5.94×10^{-7}
C-up (573 K)	0.35	0.54	152	3.19×10^{-3}

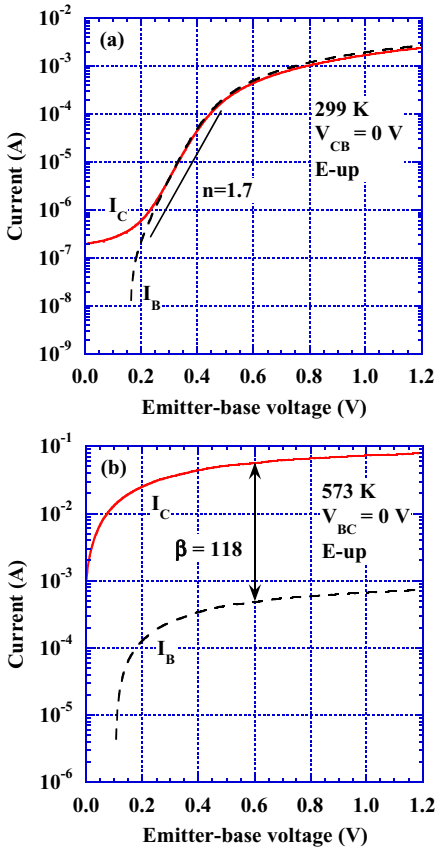

Figure 2. I_B-V_{EB} and I_C-V_{EB} characteristics with V_{CB} of 0 V for the SiC/Si HBT measured at (a) 299 and (b) 573 k, respectively.

The band profile of *n*-SiC/*p*-Si junctions was calculated by using the charge neutral level (CNL) model[19] for the SiC/Si interfaces. The interface states with energy lower (higher) than the energy of the

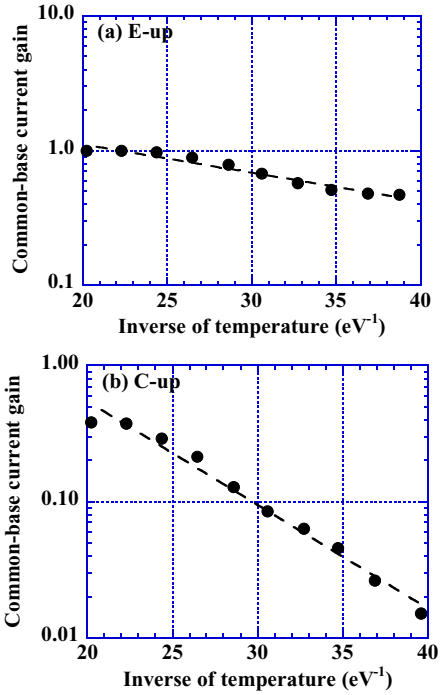

Figure 3. The dependencies of α on the ambient temperature for the (a) E-up and (b) C-up structures, respectively.

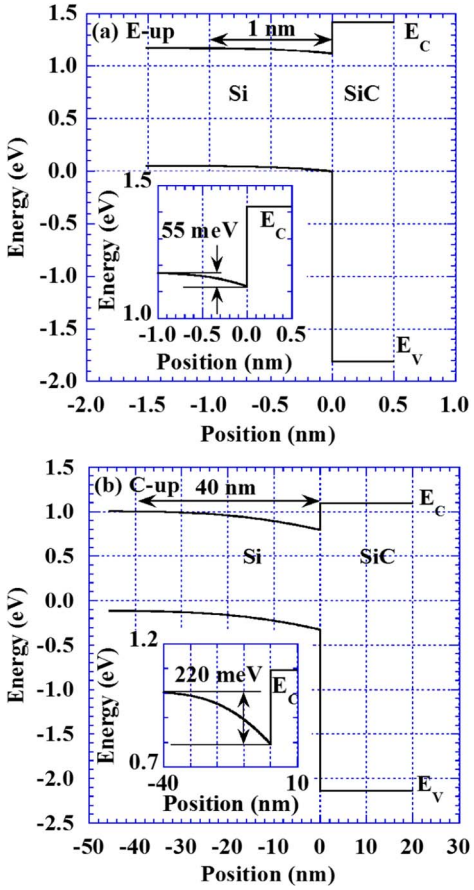

Figure 4. The band profiles of *n-SiC/p-Si* junctions for the (a) E-up and (b) C-up structures in a case that the band in the SiC layers is flat at room temperature.

CNL E_{CNL} are assumed to have donor-like (acceptor-like) features. We assumed that carriers at the interface states are in equilibrium with those in the valence band of Si layers even when bias voltages are applied across the junctions. This assumption might be justified if the concentration of acceptors in Si layers is much higher than the concentration of donors in SiC layer. We also assumed that the density of interface states is independent of its position in the mid-gap. The density of interface states D_{it} and conduction-band offset ΔE_C were preset as 2.3×10^{13} cm^{-2}eV^{-1} and 0.3 eV, respectively.[15] The energy of CNL E_{CNL} was assumed to be 0.36 eV above the valence band edge of Si.[19]

The band profiles obtained for junctions in the E-up and C-up structures in a case that the band in the *n*-SiC layer is flat at room temperature are shown in Figures 4a and 4b, respectively. The origin of energy corresponds to Fermi level in Si layers. As is typically seen for the E-up structure (Figure 4a), positive charges with a density of $\approx 8 \times 10^{12}$ cm^{-2} are built at the interface due to Fermi level lower than the CNL by $\approx$ 0.36 eV. Negative charges with the same density due to ionized acceptors are, consequently, induced in the p^+-Si layer, which makes a potential well with a depth of 0.055 eV and a width of 1 nm in its conduction band. In the C-up structure, the depth and width of the well are 0.22 eV and 40 nm, respectively. The difference in shapes of the potential wells is attributable to the higher (lower) concentration of acceptors in the base of E-up (C-up) structure. The short width of the potential well in the E-up structure suggests that carriers easily tunnel between the valence band of *p*-Si layer and the interface states. The assumption that carriers between the two parts are in the thermal equilibrium is, consequently, likely to be justified in the E-up structure. In the C-up structure, in contrast, the potential well might be too wide for the assumption to be justified. Furthermore it is notable that E_a of α ($\approx$ 0.05 and 0.18 eV for the E-up and C-up structures, respectively) agrees with the depth of the potential well.

Due to the large band gap difference between 4H-SiC and Si, the measured α should almost agree with the base transport factor ($\alpha \equiv I_C/I_E \approx I_{Cn}/I_{En}$). Thus the result that E_a agreed with the depth of the potential well in the E-up structure provides us with a view that electrons injected from the SiC emitter into the Si base are once trapped in the potential well. A part of the trapped electrons are thermally excited and escape from the well into the base, when the 4H-SiC/Si HBTs temperature was raised to 573 K. We find that the thermal activation energy is about 0.05 eV (at 573 K), which is consistent with the potential well. At room temperature the interface states act recombination centers, which degrade the current gain. We find a slight discrepancy between E_a and the depth of the potential well for the C-up structure, which might be explained by assuming that carriers in the interface states are not in thermal equilibrium with those in the base layer.

In conclusion 4H-SiC/Si HBTs were realized for the first time, in which the lattice-mismatched Si-4H-SiC heterojunction was achieved by using the surface activated bonding without heating. Their characteristics were improved by raising the ambient temperatures. The common-emitter current gain β of > 100 was demonstrated at 573 K. The initial characterization of the bonded 4H-SiC/Si HBT provides important insights that suggest improvements in future devices. It should improve HBT parameters such as the current gain to optimize the condition of SAB process, post-banding annealing, and device structure. We believe that these experiments will ultimately provide much insight into the applicability of SAB for lattice-mismatched hetero-devices, especially involving 4H-SiC.

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