InGaP/GaAsSb/InGaAsSb double heterojunction bipolar transistors with 703-GHz \( f_{\text{max}} \) and 5.4-V breakdown voltage

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Abstract: This letter presents the current-gain and high-frequency characteristics of double heterojunction bipolar transistors (DHBTs) consisting of an n-InGaP emitter, a p-GaAsSb/p-InGaAsSb base, and an n-InP collector. The impact of the thickness of the first base metal (Pt) on the base contact resistivity is investigated in a p-GaAsSb/p-InGaAsSb test structure for the purpose of improving \( f_{\text{max}} \). A low base contact resistivity (4.8 \( \Omega \mu \text{m}^2 \)) is obtained when the Pt layer is thinner than the p-GaAsSb layer. A fabricated InGaP/GaAsSb/InGaAsSb DHBT with a 0.25-\( \mu \)m emitter exhibits a high current gain of 33 even though the base sheet resistance is as low as 1025 \( \Omega /\text{sq} \). The DHBT also exhibits an \( f_{\text{max}} \) of 703 GHz and a breakdown voltage of 5.4 V. These results demonstrate that this DHBT technology is useful for fabricating high-speed integrated circuits with high output voltages.

Keywords: InP DHBT, InGaP emitter, graded InGaAsSb base, high current gain, maximum oscillation frequency, breakdown voltage

Classification: Electron devices, circuits and modules

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1 Introduction

InP/GaAsSb double heterojunction bipolar transistors (DHBTs) are alternatives to Type-I InP/InGaAs DHBTs [1]. There is no need to insert a band gap grading layer [2] between the GaAsSb base and the InP collector or chirped super-lattice collectors [3] because of the staggered base-collector band alignment. The band alignment offers advantages of high-speed and high-breakdown-voltage operation [1]. However, the electron mobility of GaAsSb is lower than that of InGaAs, which limits $f_T$ [1]. Recently, we proposed a compositionally graded InGaAsSb base in order to boost electron mobility, and demonstrated simultaneous $f_T$ and $f_{\text{MAX}}$ of over 500 GHz [4]. The quaternary graded-base DHBTs with $f_T/f_{\text{MAX}} = 547/784$ GHz have been also demonstrated [5] from a group of ETH-Zürich. Very recently, we demonstrated the $f_T$ of 695 GHz, which is the highest among the DHBTs with an InP collector, by boosting the collector current density of over 20 mA/$\mu$m$^2$ owing to the introduction of the substrate transfer technique [6]. According to the results, the use of a compositionally graded InGaAsSb base is a promising choice for improving high-frequency performance.

To improve $f_{\text{MAX}}$ further, the base resistance should be reduced along with the internal collector capacitance. In particular, low base contact resistivity is important
for lateral scaling of the device. A hybrid base structure consisting of heavily doped thin GaAsSb and compositionally graded InGaAsSb was reported as a way to reduce the base contact resistivity [7]. A high doping level ($\sim 9 \times 10^{19}$ cm$^{-3}$) can be obtained in GaAsSb relative to that of InGaAsSb [8]. In addition, insertion of a heavily doped thin GaAsSb contact layer does not cause much degradation of the current gain. Although the use of the hybrid base reduces the base contact resistivity by half, the value is still large (13 $\Omega \mu$m$^2$) [7]. In this letter, we investigate impact of first base metal thickness on base contact resistivity in a test structure for the purpose of improving $f_{max}$. Then, we discuss the current gain and high-frequency characteristics of an InGaP/GaAsSb/InGaAsSb DHBT with a 0.25-$\mu$m emitter fabricated on an InP substrate.

### 2 Base contact resistivity

We used metal-organic chemical vapor deposition (MOCVD) to grow a 3-nm-thick p-GaAsSb/17-nm-thick compositionally graded p-InGaAsSb on 3-inch (001) InP substrates as a test structure. The GaAsSb and InGaAsSb layers were doped with carbon. The average doping levels in the GaAsSb and InGaAsSb were $\sim 9 \times 10^{19}$ cm$^{-3}$ and $\sim 7 \times 10^{19}$ cm$^{-3}$, respectively. Here, an undoped InP collector and a n-type doped subcollectors are grown on a InP substrate prior to the GaAsSb/InGaAsSb layers growth. Transmission-line-model measurements were performed to estimate base contact resistivity and sheet resistance. We used conventional $e$-beam evaporation for deposition of metal electrodes. The base metal consisted of Pt/Ti/Mo/Au. The thicknesses of the metal layers were controlled by standard quartz crystal film thickness meter. Optimization of the Pt thickness is important for obtaining low contact resistivity [9]. Fig. 1 plots the base contact resistivity and sheet resistance as a function of Pt thickness. The base sheet resistance remains constant regardless of Pt thickness. On the other hand, base contact resistivity falls to 4.8 $\Omega \mu$m$^2$ with thinning of the Pt layer to 2 nm. When the Pt layer is thicker than the GaAsSb layer (>3 nm), Pt possibly penetrates the GaAsSb layer and diffuses into the InGaAsSb layer, which might result in an increase in the contact resistivity. From these results, we conclude that the Pt layer should be thinner than the GaAsSb layer to obtain low contact resistivity.
3 Device structure and fabrication

We used a MOCVD-grown DHBT structure consisting of an n-InGaAs emitter cap, a 15-nm-thick n-In$_{0.86}$Ga$_{0.14}$P emitter, a 3-nm-thick p-GaAsSb/17-nm-thick compositionally graded p-InGaAsSb base, a 100-nm-thick n-InP collector, and an n-InGaAs/n-InP subcollector on semi-insulating (001) InP substrate. A cross-sectional view of the DHBT is shown in Fig. 2. The fabrication sequence was almost the same as in [2]. Base metal (Pt/Ti/Mo/Au) was self-aligned to the emitter mesa. To obtain low base contact resistivity, 2-nm-thick Pt was used as a first base metal layer. The base sheet resistance and contact resistivity were 1025 $\Omega/$sq. and 1.6 $\Omega\cdot\mu$m$^2$, respectively. The base contact resistivity was much lower than that expected from the TLM-based investigation, possibly due to the high doping level of the p-GaAsSb contact layer ($>9 \times 10^{19}$ cm$^{-3}$). The emitter width was 0.25 $\mu$m, and the emitter-base (EB) spacing was $\sim$0.05 $\mu$m. The In$_{0.86}$Ga$_{0.14}$P emitter on the extrinsic base layer acted as a passivation ledge to suppress the surface recombination current of the base.

It is reported that a composite InP/InGaP emitter improves the current gain of InP/GaAsSb DHBTs by reducing the Type-II band discontinuity at the emitter-base junction [10]. Here, we used a simple emitter consisting only of In$_x$Ga$_{1-x}$P to improve current gain. Previously we investigated the dependence of the solid In content of In$_x$Ga$_{1-x}$P emitter ($x$) on the current gain of large-emitter-area DHBTs [11]. As expected, DC current gain increases with decreasing $x$ owing to the decrease of conduction band offset at the emitter-base interface. The large-area device with 15-nm-thick In$_{0.77}$Ga$_{0.23}$P emitter exhibits DC current gain of 20, which is higher than that with InP emitter. With considering the balance of this knowledge and lattice matching to the InP substrate, we employed the In$_{0.86}$Ga$_{0.14}$P emitter with $x = 0.86$.

4 Device characteristics

Fig. 3(a) plots the base and collector currents as a function of base-emitter voltage for the fabricated DHBT with the In$_{0.86}$Ga$_{0.14}$P emitter. The ideality factors for base and collector currents are 1.46 and 1.02, respectively. The current gain is 33 at a collector current density ($J_c$) of 13 mA/$\mu$m$^2$. The value is higher by 27% than that of an InP emitter with a similar base sheet resistance of $\sim$1000 $\Omega/$sq. (current gain:
26 at $J_c = 13 \text{mA}/\mu \text{m}^2$). Fig. 3(b) shows the $I$-$V$ curves of the DHBT. The base current step is 75 $\mu$A. The DHBT provides a high current density of over 15 $\text{mA}/\mu \text{m}^2$. The breakdown voltage ($BV_{CEO}$) is 5.4 V at $J_c = 0.01 \text{mA}/\mu \text{m}^2$, while the base-collector breakdown voltage ($BV_{CBO}$) is about 5 V at $J_C = 0.01 \text{mA}/\mu \text{m}^2$. These results indicate that the In$_x$Ga$_{1-x}$/P emitter is useful for improving the current gain and providing high-current-density operation at the same time.

The high-frequency characteristics were investigated by measuring the $S$-parameters with a Keysight N5227A PNA. The measurement frequency range was from 500 MHz to 50 GHz. Fig. 4(a) shows the $J_C$ dependence of $f_T$ and $f_{\text{max}}$ at $V_{CE} = 1.4 \text{ V}$. Both $f_T$ and $f_{\text{max}}$ become highest at around $J_c \sim 10 \text{ mA}/\mu \text{m}^2$. Fig. 4(b) shows the frequency response of the current gain ($|h_{21}|^2$) and Mason’s unilateral power gain ($UG$) at $J_c = 10 \text{ mA}/\mu \text{m}^2$ and $V_{CE} = 1.4 \text{ V}$. $f_T$ is 501 GHz and $f_{\text{max}}$ is 703 GHz. While the obtained peak $f_T$ is comparable to that of the previously reported DHBTs [7], the obtained $f_{\text{max}}$ is higher by 66 GHz.

To clarify the reason for the improvement, we extracted DHBT parameters by utilizing the hybrid-$\pi$ model small-signal equivalent circuit [7]. Fig. 5 shows the small-signal equivalent circuit and Table I summarizes the base resistance ($R_{\text{bb}}$), internal collector capacitance ($C_{bc,\text{in}}$), and $f_{\text{max}}$. Clearly, the significant reduction in
Rbb improves fmax. The reduction in Rbb mainly results from the low base contact resistivity. These results suggest that the proposed base metal structure is effective in reducing Rbb and boosting fmax.

For further improvement in fmax, Cbc,in should be significantly reduced by scaling down the emitter dimension. However, our minimum emitter dimension was 0.25 µm because the fabrication technology was based on i-line lithography. As reported in [12] for InP/InGaAs DHBTs with ft/fmax of 521-GHz/1.15-THz, electron-beam lithography is useful for scaling down the emitter dimension to 130 nm or less. Thus, a combination of electron-beam lithography and the base metal structure of this study would enable a significant reduction in both Rbb and Cbc,in, which would in turn improve fmax.

5 Conclusion

To improve fmax, the base contact resistivity was investigated in a p-GaAsSb/p-InGaAsSb test structure. It was found that the first base metal layer (Pt layer) should be thinner than the GaAsSb base contact layer to obtain low contact resistivity. A 0.25-µm-emitter InGaP/GaAsSb/InGaAsSb DHBT was fabricated, and its measured base contact resistivity was as low as 1.6 Ωµm². The fabricated DHBT exhibited an fmax of 703 GHz and a BVCEO of 5.4 V simultaneously. The device parameters extracted from the equivalent circuit model revealed that a significant reduction in Rbb improved fmax. Scaling down of the emitter dimension to 130 nm or less would significantly reduce Cbc,in, and leads to a further improvement in fmax.

Table 1. Base resistance (Rbb), internal collector capacitance (Cbc,in), and fmax

|            | Rbb (Ω) | Cbc,in (fF) | fmax (GHz) |
|------------|---------|-------------|------------|
| This work  | 16.8    | 2.5         | 703        |
| Ref. [3]   | 24      | 2.0         | 637        |

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