Compositionaly Graded-Base InP/InGaAsSb
Double Heterojunction Bipolar Transistors with 500-GHz \(f_T\) and \(BV_{CEO} > 5V\)

Norihide Kashio\(^1\), Takuya Hoshi\(^2\), Kenji Kurishima\(^2\), Minoru Ida\(^2\), and Hideaki Matsuzaki\(^2\)

\(^1\) NTT Device Innovation Center, NTT Corporation, 3-1 Morinosato Wakamiya, Atsugi, Kanagawa, 243-0198 Japan
Phone: +81-46-240-2240 E-mail: kashio.norihide@lab.ntt.co.jp
\(^2\) NTT Device Technology Labs, NTT Corporation, 3-1 Morinosato Wakamiya, Atsugi, Kanagawa, 243-0198 Japan

Abstract
This paper describes an epitaxial growth method, device fabrication, and characterization for InP/InGaAsSb double heterojunction bipolar transistors (DHBTs). A compositionally graded InGaAsSb base with large variation of the conduction band (126 meV) can be formed simply by modulating the CBr4 flow in metalorganic chemical vapor deposition. A fabricated InGaAsSb-base DHBT exhibits \(f_T = 501\) GHz, \(f_{max} = 503\) GHz, and breakdown voltage of 5.3 V. From the high-frequency characteristics, average electron velocity is estimated to be 4.0 \times 10^7 \text{ cm/s}. These results indicate that the compositionally graded InGaAsSb base is useful for increasing the average electron velocity and boosting \(f_T\).

1. Introduction
As alternatives to conventional type-I InP/InGaAs double heterojunction bipolar transistors (DHBTs), InP/InGaAsSb DHBTs with a compositionally graded base have recently been developed [1]-[3]. They have demonstrated both high-speed performance (\(f_T > 500\) GHz) and a relatively high breakdown voltage (\(BV_{CEO}\)) of over 5 V owing to their simple collector structure consisting only of InP. Their superior performance makes them promising candidates for use in ICs operating in the sub-THz range. In this paper, we present a simple epitaxial growth method for forming a compositionally graded InGaAsSb base in metalorganic chemical vapor deposition (MOCVD). We also discuss device fabrication and characterization of DHBTs with the compositionally graded InGaAsSb base.

2. CBr4-flow-modulation method for forming compositionally graded InGaAsSb

Fig. 1 shows a schematic band diagram of an InP/InGaAsSb DHBT. The DHBT structure was grown on a 3-inch InP substrate by MOCVD. It consists of an n-InGaAs cap, 20-nm-thick n-InP emitter, 30-nm-thick compositionally graded InGaAsSb base, and 100-nm-thick n-InP collector. The InGaAsSb base was formed by increasing the CBr4 supply ratio from the collector side to the emitter side at a constant group-III and group-V precursor supply ratio as shown in Fig. 2. Note that the solid In and Sb contents automatically decrease with increasing the CBr4 flow [1]. In Fig.1, the solid In and Sb contents decrease from \(x = 0.18\) and \(y = 0.43\) on the collector side to \(x = 0.10\) and \(y = 0.35\) on the emitter side. The bandgap variation is calculated to be 85 meV. The value is slightly smaller than in our previous report [1]. This is because we take into account strained effects on the conduction band. The doping level is also graded from 2.9 \times 10^{19} \text{ cm}^{-3} on the collector side to 5.7 \times 10^{19} \text{ cm}^{-3} on the emitter side. Thus, the variation of the conduction band is estimated to be 126 meV, which corresponds to an average quasi-electric field of 42 kV/cm. These results indicate that the CBr4-flow-modulation method is an effective way to form a compositionally graded InGaAsSb with a large variation of the conduction band.

3. Device fabrication and characterization

Fig. 3 shows a cross-sectional view of a DHBT with an emitter width of 0.2-0.25 \mu m. The DHBT epitaxial structure is the same as that in Fig. 1. The base metal is self-aligned to the emitter mesa. The external base surface is covered with the InP emitter (InP ledge). The emitter-base spacing is ~0.05 \mu m. Fig. 4 shows \(I-V\) curves for the DHBT. We obtained a high current gain of over 50. The inset shows the collector leakage current as a function of collector-emitter voltage \((V_{CE})\). It should be noted that the \(BV_{CEO}\) for the InGaAsSb-base DHBT \((5.3\) V) at collector current density \((J_c)\) of 0.01 mA/\mu m^2 is higher by 1.5 V than that for the type-I InP/InGaAs DHBT \((3.8\) V). This is because the collector for the InGaAsSb-base DHBT consists of pure InP.
The S-parameters of the DHBT were measured from 0.5 to 50 GHz with an HP8510C network analyzer. Fig. 5 shows the current gain ($|h_{21}|^2$) and Mason’s unilateral power gain ($U_g$) as a function of frequency. The DHBT exhibits $f_t = 501$ GHz and $f_{max} = 503$ GHz. Next, we extracted base-collector electron transit time ($\tau$) from Z-parameters [2]. The inset of Fig. 5 shows the sum of $r_c C_pe$ and $\tau$ as a function of the inverse of collector current. Here, $r_c$ and $C_pe$ are emitter dynamic resistance and emitter-base capacitance, respectively. We obtained a $\tau_0$ of 0.20 ps, which corresponds to average electron velocity of $4.0 \times 10^7$ cm/s. This value compares well with that for type-I InP/InGaAs DHBTs [4]. These results suggest that the large quasi-electric field in the graded InGaAsSb base enhances the forward momentum of electrons in the base, which results in high $f_t$.

For further improvement in $f_{max}$ we have proposed a hybrid base structure consisting of a 3-nm-thick highly doped GaAs$_{0.68}$As$_{0.32}$ contact ($p = 8.9 \times 10^{19}$ cm$^{-3}$) and a 17-nm-thick graded InGaAsSb base [3]. The collector is 100-nm-thick InP. Fig. 6 shows $|h_{21}|^2$ and $U_g$ as a function of frequency. The InGaAsSb-base DHBTs with the GaAsSb contact exhibit $f_t = 513$ GHz and $f_{max} = 637$ GHz. The GaAsSb contact markedly boosts $f_{max}$ by as much as 134 GHz. From the extraction of the device parameters, we concluded that the reduction in base resistance is the main factor causing the improvement in $f_{max}$ [3]. We have also obtained a high $BV_{CEO}$ of 5.2 V for DHBTs with the GaAsSb contact. Therefore, the use of a GaAsSb contact effectively improves $f_{max}$ while maintaining a high $BV_{CEO}$ of more than 5 V.

4. Conclusions

A CBr$_2$-flow-modulation method for forming a compositionally graded InGaAsSb-base DHBT has been presented. A fabricated InGaAsSb-base DHBT exhibits simultaneous $f_t$ and $f_{max}$ of over 500 GHz and a $BV_{CEO}$ of 5.3 V. From the high-frequency characteristics, high average electron velocity ($4.0 \times 10^7$ cm/s) is estimated, which is attributed to the large quasi-electric field (42 kV/cm) in the graded InGaAsSb base. The use of a highly doped GaAsSb contact boosts $f_{max}$ up to 637 GHz while maintaining a $BV_{CEO}$ of over 5 V in InGaAsSb-base DHBTs. These results demonstrate that InGaAsSb-base DHBT technology is useful for obtaining both high-speed performance and high $BV_{CEO}$.

References