Ultra high-speed InP/InGaAs DHBTs with f_t of 203 GHz

Su Yongbo(苏永波)[1], Jin Zhi(金智)[1,†], Cheng Wei(程伟)[1], Liu Xinyu(刘新宇)[1],
Xu Anhuai(徐安怀)[2], and Qi Ming(齐鸣)[2]

(1 Institute of Microelectronics, Chinese Academy of Sciences, Beijing 100029, China)
(2 Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China)

Abstract: InP/InGaAs/InP double heterojunction bipolar transistors (DHBTs) were designed for wide band digital and analog circuits, and fabricated using a conventional mesa structure with benzocyclobutene (BCB) passivation and planarization process techniques. Our devices exhibit a maximum f_t of 203 GHz, which is the highest f_t for DHBTs in mainland China. The emitter size is $1.0 \times 20\ \mu m^2$. The DC current gain β is 166, and $BV_{CEO} = 4.34$ V. The devices reported here employ a 40 nm highly doped InGaAs base region and a 203 nm InGaAsP composite structure. They are suitable for high speed and intermediate power applications.

Key words: InP; DHBT; BCB; passivation
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1. Introduction

InP HBTs have inherent material advantages such as high electron saturation velocity and high electron mobility, making them suitable for ultra high speed mixed signal circuits and optoelectronic communication ICs[1]. InP-based double heterojunction bipolar transistors (DHBTs) have been aggressively pursued because of their superior material transport properties over other semiconductor materials. InP/InGaAs-based single heterojunction bipolar transistors (SHBTs) have demonstrated good microwave characteristics, but their high cutoff frequencies are achieved at the expense of breakdown voltage because of the narrow gap of the InGaAs collector. Wide-bandgap InP collector layers in DHBTs can improve the breakdown voltage, while it is difficult to design the collector structure because of current blocking that results from the positive conduction band discontinuity between the InGaAs and InP. For an InP collector, a blocking barrier of about 0.26 eV must be overcome between the base and the collector. In order to remedy this problem, several B-C heterojunction designs have been investigated, including a tunneling InP collector and InGaAs/InP or InGaAs/InAlAs chirped superlattice linear-graded B-C designs[2]. And we use an InGaAsP composite collector structure, which can effectively eliminate the energy spike at the B-C junction and avoid the current blocking effect. The theoretical analysis of this structure was in Ref.[3].

In this paper, an InP-based DHBT with a simple epitaxy layer structure using benzocyclobutene (BCB) passivation and planarization process techniques is reported. The devices have been scaled vertically to reduce electron collector transit time and aggressively scaled laterally to minimize the base-collector capacitance. The device shows excellent DC and RF characteristics which is suitable for high speed and intermediate power optoelectronic applications such as ultrahigh speed mixed signal circuits and optoelectronic communication ICs[4].

2. Design and fabrication

The epitaxial layer of the HBTs was grown by molecular beam epitaxy on a Fe-doped semi-insulating (100) InP substrate. The layer structure is listed in Table 1.

Compared with the epitaxial layer structure in Ref.[5], the total thickness of the emitter is reduced from 320 to 200 nm. Because the wet etching process is used, a thinner emitter will result in smaller undercut that leads to smaller emitter and base resistances[6]. Besides, the thickness of the base is reduced from 50 to 40 nm because a thinner base results in a shorter base transit time, which leads to higher current gain cutoff frequency. Furthermore, a composite collector structure containing InGaAsP was designed, which can effectively eliminate the energy spike at the B-C junction and avoid the current blocking effect[3]. The thickness of the collector is also reduced from 303 to 203 nm, resulting in a higher cutoff frequency.

The fabrication process was as follows. First, the device was fabricated using a standard three-mesa process. The emitter metal Ti/Pt/Au was formed by e-beam evaporation and lifted off. The InGaAs emitter contact layer and the InP emitter layer were etched by $H_2O_2/H_3PO_4/H_2O$ and HCl: H_3PO_4 solutions, respectively. Ti/Pt/Au layers were used for the base Ohmic contact metals, and the InGaAsP layer was etched by inductively coupled plasma (ICP) etching with Cl_2. The collector contact metal Ti/Au was evaporated on the surface of the InGaAs subcollector. Then, two Ti/Au posts were evaporated on both the base metal and the collector metal. The posts moved the height of the base metal and the collector metal to

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[†] Corresponding author. Email: jinzhi@ime.ac.cn

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Table 1. Layer structure for the InP/InGaAs DHBT.

Layer	Thickness (nm)	Dopant	Doping (cm^{-3})
In$_{0.53}$Ga$_{0.47}$As	40	Si	3×10^{19}
InP	90	Si	3×10^{19}
InP	10	Si	1×10^{18}
InP	60	Si	3×10^{17}
In$_{0.53}$Ga$_{0.47}$As	5	UID	UID
In$_{0.53}$Ga$_{0.47}$As	40	Be	3×10^{19}
In$_{0.53}$Ga$_{0.47}$As	20	Si	2×10^{16}
In$_{0.73}$Ga$_{0.27}$As$_{0.58}$P$_{0.42}$ （E_g=0.95 eV）	10	Si	2×10^{16}
In$_{0.88}$Ga$_{0.12}$As$_{0.27}$P$_{0.73}$ (E_g=1.15 eV)	10	Si	2×10^{16}
InP	3	Si	3×10^{18}
InP	160	Si	2×10^{16}
InP	50	Si	1.5×10^{19}
In$_{0.53}$Ga$_{0.47}$As	25	Si	3×10^{19}
InP	300	Si	3×10^{19}
InP substrate			

the same level as the emitter metal. Next, BCB was coated, and then etched by oxygen RIE until the emitter metal and two posts were exposed. Finally, Ti/Au was evaporated to form the bridge and the pad[5,7].

The devices are passivated with and the wafer was planarized in BCB to minimize device leakage current associated with semiconductor surface charge effects. The dielectric constant of BCB is ε_r = 2.7. This can reduce spurious resonances from the RF measurements through substrate mode coupling[8].

3. Device measurement results and discussion

3.1. DC characteristics

The DC characteristics of the HBT were measured with HP4155A parameter analyzer. DC common-emitter characteristics of the DHBT with 1.0 × 20 μm^2 emitter are depicted in Fig.1. The collector-emitter offset voltage is approximately 0.23 V, and the knee voltage is 0.7 V at I_c = 9.2 mA. The small signal current gain at DC (β) is 166. From Fig.1, we can calculate the common emitter breakdown voltage (BV$_{CEO}$) to be 4.34 V at a reverse current of 100 μA. The breakdown voltage is not increased greatly mainly because we decreased the thickness of the collector layer. This will increase the Kirk current and f_t, but will decrease the breakdown voltage. Standard transmission line measurements (TLM) shows the measured base sheet resistance is 1902 Ω/□, and the specific contact resistivity is 7.42 × 10^{-6} Ω·cm^2.

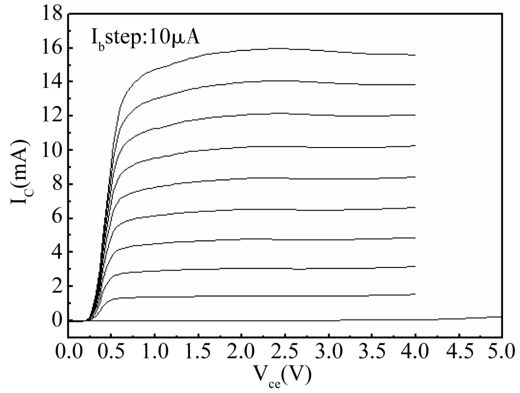

Fig.1. Common emitter V_{ce}–I_c characteristics of the HBT with the 1.0 × 20 μm^2 emitter.

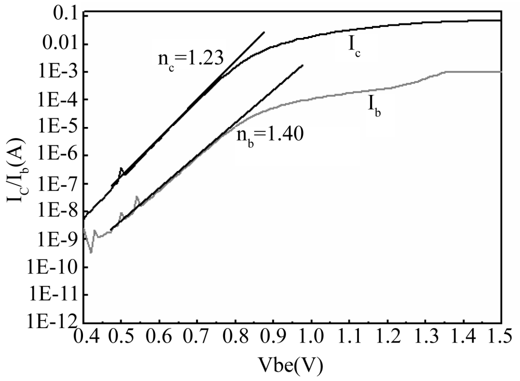

Fig.2. Gummel plot of InP/InGaAs DHBT with the 1.0 × 20 μm^2 emitter.

Calculated from the Gummel plot of the InP/InGaAs DHBT with 1.0 × 20 μm^2 emitter area (Fig.2), the ideality factors for the base and collector current are n_b = 1.40, n_c = 1.23, respectively. The ideality factor reflects the surface recombination of the base. The recombination on the surface of extrinsic base is relative to the surface recombination velocity and availability of minority carriers in the extrinsic base[9,10]. Figure 2 reveals that this DHBT exhibited good base current ideality factor n_b, indicating that the self-aligned process and the BCB passivation and planarization process techniques used in this study result in little surface recombination current. But the collector current ideality factor was a little larger than theoretical value, mainly because the terminal currents of InP DHBTs are limited by the carrier transport across the base layer. And the collector current is limited by the band discontinuity of the base-emitter junction[11].

3.2. RF characteristics

The small signal S parameters of the InP/InGaAs DHBT were measured on-wafer with an HP8510C net work analyzer. Short-open-load-through calibration was performed with off-wafer calibration standards. On-wafer open and short structures were then used to deembed the pad parasitic. The characteristics of the current gain h_{21} and maximum available gain (MAG) of the device are shown in Fig.3. The current gain cutoff frequency f_t and the maximum oscillation frequency f_{max} was extrapolated by extending the curves at the −20 dB/decade line. From Fig.3, the f_t and f_{max} of the InP/InGaAs DHBT with a 1.0 × 20 μm^2 emitter area were 203 and 80 GHz, respectively, at V_{ce} = 1.7 V and I_c =43.2 mA.

The current-gain cutoff frequency is

$$\frac{1}{2\pi f_t} = \tau_b + \tau_c + \frac{kT}{qI_c}(C_{je} + C_{cb}) + (R_{ex} + R_c)C_{cb}\,, \qquad (1)$$

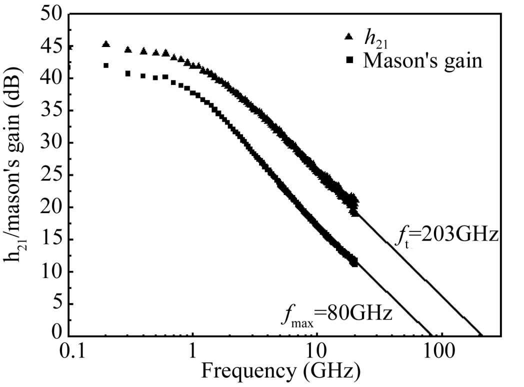

Fig.3. High-frequency performance of the $1.0 \times 20\ \mu\text{m}^2$ InP/In GaAs DHBT.

where τ_b and τ_c are the electron base transit time and collector transit time respectively, R_{ex} and R_c are the parasitic emitter and collector resistances, C_{cb} is the collector junction capacitance, and I_c is the collector current. $\tau_b \approx T_b^2/2D_{nb}$ is proportional to the square of the base thickness T_b. τ_c is the mean delay of the collector displacement current, $\tau_c = T_c/2V_{eff}$, where T_c is the collector thickness and V_{eff} is the electron effective velocity under a voltage bias[11]. We can see that thinning the base and collector layers will reduce both τ_b and τ_c components of $1/2\pi f_t$ and therefore increase f_t. Compared with the epitaxial layer structure in Ref.[5], the thickness of the base is reduced from 50 to 40 nm, and the thickness of the collector is also reduced from 330 to 203 nm. So we obtained a higher f_t.

The value of the maximum oscillation frequency f_{max} is

$$f_{max} = \sqrt{f_t/8\pi R_{bb}C_{cb}}. \qquad (2)$$

According to Eq.(2), this base resistance is the most important reason why the f_t of the device is very high but the f_{max} remains very low. Minimizing the base resistance R_{bb} or base-collector junction capacitance C_{cb} can improve the high frequency performance[12]. The base sheet resistance and base specific contact resistivity in Ref.[13] are 600 Ω/□ and 2.3×10^{-7} Ω·cm^2, respectively, while our measured parameters are 1902 Ω/□ and 7.42×10^{-6} Ω·cm^2. The base sheet resistance and the base specific contact resistivity are too high, leading to very high base resistance. The current gain (β) at DC of our device is larger, so we can deduce that the doping density of the base does not reach our expectations, which is why the base sheep resistance and the base specific contact resistivity are so high. This high base resistance is the most important reason why the f_t of the device is very high but the f_{max} remains lower.

4. Conclusion

We have developed a high speed InP/InGaAs DHBTs with a composite collector structure containing InGaAsP and a BCB passivation and planarization process. The InP/InGaAs DHBT device with a $1.0 \times 20\ \mu\text{m}^2$ emitter area shows good DC characteristics of $V_{offset} \approx 0.23$ V, $V_{knee} \approx 0.7$ V, and $BV_{ceo} \approx 4.34$ V. A high f_t of 203 GHz were attained at $V_{ce} = 1.7$ V and $I_c = 43.2$ mA. This is the highest frequency ever reported for InP-based DHBTs in mainland China.

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