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E-1-3

The Effect of Emitter Size Scaling on f_{max} in InP/InGaAs HBTs

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1. Introduction

InP-based HBTs are promising candidates for such applications as high speed ICs for 40Gbps optical communication systems. While high f_T can be readily obtained in these HBTs because of superior electron transport of InP-related materials, f_{max} depends rather on processing technique as well as device size and is thus less predictable compared to f_T. For instance, while several reports have shown that f_{max} improves with decreasing emitter width [1], it has also been reported that f_T, which is one of the important factors determining f_{max}, deteriorates when emitter size is down scaled beyond certain limit [2]. Thus in order to achieve high f_{max}, it is crucial to understand the device scaling of f_{max} in correlation with the behavior f_T.

In this paper, we investigate the emitter size dependence of f_{max} of single and double heterojunction HBTs (SHBTs and DHBTs) with different f_T. With optimum device design, a state-of-the-art f_{max} of 313 GHz was obtained. Critical design consideration in improving the f_{max} of InP-based HBT will be discussed.

Table I Epitaxial layer structures of SHBTs and DHBTs

Layer	Material	Doping	Thickness(nm)	
			SHBT	DHBT
Emitter	n^+-InGaAs	Si:3e19	100	←
	n^+-InP	Si:2e19	20	←
	n-InP	Si:3e17	80	←
Base	p^+-InGaAs	C:4e19	50	←
Collector	i-InGaAs	Si:1e16	300	100
	n^+-InP	Si:1e18	-	20
	i-InP	Si:1e16	-	180
Sub-collector	n^+-InGaAs	Si:1e19	400	←

2. Device fabrication

The epitaxial layers of HBTs studied in this work were grown by MOCVD. Table I shows epitaxial layer structures of SHBT as well as DHBT with ballistic launcher structure in the collector region [3]. The former type of HBT has typical f_T of 160 GHz, whereas in the latter case f_T exceeds 200 GHz. To reduce base resistance, the base layer was heavily doped to 4×10^{19} cm^{-3}. Prior to formation of base contact, the wafers were annealed at 500 C to remove hydrogen out from the carbon-doped base layers [4]. As shown in Fig.1, the HBTs were fabricated using self-aligned process. The emitter width, W_E, ranged from 0.2 μm to 2.6 μm, whereas the width of each base finger, $W_B/2$, was fixed at 0.5 μm.

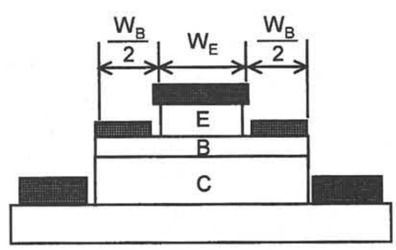

Fig. 1. Schematic cross section of fabricated HBT

3. Experimental Results

The RF performance of the HBTs was characterized by on-wafer measurement of S-parameters from 0.1 to 40 GHz. f_{max} was obtained by extrapolating Mason's unilateral gain (MUG) with –6 dB/Oct. slope as shown in Fig. 2.

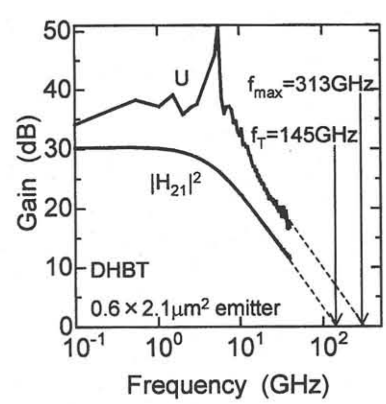

Fig.2. Frequency dependence of $|H_{21}|$ and MUG

Fig.3 plots f_T and f_{max} of SHBTs and DHBTs as a function of W_E. The emitter length was fixed at 2.1 μm. As shown in Fig.3, both type of HBTs show similar W_E dependence of f_{max}. As long as W_E is greater than 1 μm, f_{max} is inversely proportional to square root of W_E. This W_E dependence of f_{max} indicates ideal scaling relationship for small scale HBTs. However, as W_E is decreased to below 1 μm, the variation of f_{max} with W_E deviates from ideal scaling and turns to decreasing trend. Qualitatively, this behavior of f_{max} can be understood by degradation of f_T, also shown in Fig.3.

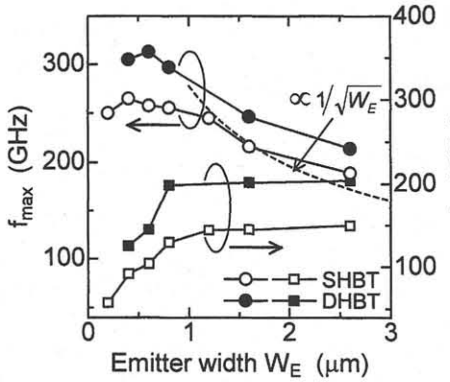

Fig.3. Emitter width dependence of f_{max}

Regarding maximum f_{max}, while the f_{max} of SHBT peaked at 265 GHz, in DHBT peak f_{max} of 313 GHz was obtained(Fig. 2). Note that the optimum W_E is far below the size at which f_T starts to drop. This indicates that in order to optimize device size for high f_{max} a specific design guideline taking all relevant parameters into account is needed.

4. Discussion

In order to gain insight into the factors responsible for the f_{max} behavior, f_T was plotted as a function of R_BC_{BC} as shown in Fig.4. The time constant R_BC_{BC} was estimated from f_T and f_{max} using the common relationship between f_T and f_{max}:

$$f_{\max} = \sqrt{\frac{f_T}{8\pi \, R_B C_{BC}}} . \qquad (1)$$

This plot allows us to determine which of the two parameters, f_T or R_BC_{BC}, is dominating the f_{max}. Figure 4 indicates that when W_E is greater than 1.0 μm f_{max} is mainly determined by R_BC_{BC}. As a result, f_{max} increases with decreasing W_E. The maximum f_{max} can be obtained by drawing a line tangent to the plotted curve, then evaluating f_{max} from the line slope using the following relationship which is equivalent to eq. (2).

$$f_T = (8\pi f_{\max}^2) R_B C_{BC} \qquad (2)$$

Note that R_BC_{BC} continues to decrease even after f_{max} starts to decrease. Therefore, when W_E is excessively decreased, it is f_T rather than R_BC_{BC} that is limiting f_{max}.

To obtain more specific design guidelines for high f_{max} HBT, we performed a simple analysis. Taking the emitter size dependence of f_T and R_BC_{BC} into account, it can be shown that the optimum f_{max} as well as the emitter width that determines the optimum point are expressed as follows:

$$f_{\max}^{\ opt} \cong \frac{1}{4\pi\sqrt{R_B^{ext} C_{BC}^{\ ext}}} \left(\tau_F + 2\rho_c^{\ E} c_0 \left(1 + \sqrt{1 + \frac{\tau_F}{\rho_C^{\ E} c_0}} \right) \right)^{-1/2} \qquad (3)$$

$$W_E^{\ opt} \cong W_B \sqrt{\frac{\rho_c^{\ E} c_0}{\tau_F + \rho_c^{\ E} c_0}} \qquad (4)$$

R_B^{ext}	:	External base resistance
C_{BC}^{ext}	:	External collector capacitance
τ_F	:	Total carrier transit time delay
ρ_c	:	Specific contact resistivity of emitter contact
c_0	:	Collector capacitance per unit area

From (3) and (4), it can be clearly understood that the optimum f_{max} is determined by ratio $\tau_F/\rho_c^E c_0$. If the emitter contact is good ($\tau_F >> \rho_c^E c_0$), τ_F is the dominant factor that determines f_{max}^{opt}. In this case, significant increase in f_{max} can be expected by improving f_T and by further pushing the down scaling of W_E. On the other hand, with poor contact ($\tau_F << \rho_c^E c_0$), decreasing W_E below W_B proves to be useless and f_{max}^{opt} is insensitive to τ_F (and thus to f_T). The ratio $\tau_F/\rho_c^E c_0$ in our HBTs is about 3. Thus, for further improvement of f_{max}, improving not only τ_F but also emitter contact is effective.

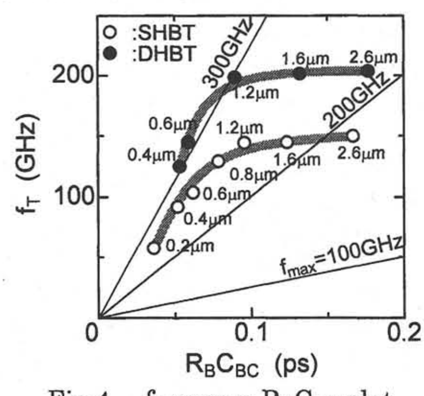

Fig.4. f_T versus R_BC_{BC} plot

5. Conclusions

Emitter size scaling in InP-based HBTs for high f_{max} was investigated. Using simple analysis, we clarified the essential key factors in improving f_{max}. While an excellent f_{max} of 313 GHz was obtained with our HBT, the analysis suggests that further improvement is possible by improving the emitter contact.

Reference

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