The Effect of Emitter Size Scaling on $f_{\text{max}}$ 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 $f_r$ can be readily obtained in these HBTs because of superior electron transport of InP-related materials, $f_{\text{max}}$ depends rather on processing technique as well as device size and is thus less predictable compared to $f_r$. For instance, while several reports have shown that $f_{\text{max}}$ improves with decreasing emitter width [1], it has also been reported that $f_r$, which is one of the important factors determining $f_{\text{max}}$, deteriorates when emitter size is down scaled beyond certain limit [2]. Thus in order to achieve high $f_{\text{max}}$, it is crucial to understand the device scaling of $f_{\text{max}}$ in correlation with the behavior of $f_r$.

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

Table I  Epitaxial layer structures of SHBTs and DHB Ts

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Doping</th>
<th>Thickness(nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emitter</td>
<td>$n^+$-InGaAs</td>
<td>Si:3e19</td>
<td>100 —</td>
</tr>
<tr>
<td></td>
<td>$n^+$-InP</td>
<td>Si:2e19</td>
<td>20 —</td>
</tr>
<tr>
<td></td>
<td>n-InP</td>
<td>Si:3e17</td>
<td>80 —</td>
</tr>
<tr>
<td>Base</td>
<td>$p^+$-InGaAs</td>
<td>C:3e19</td>
<td>50 —</td>
</tr>
<tr>
<td>Collector</td>
<td>n-InGaAs</td>
<td>Si:1e16</td>
<td>300 100</td>
</tr>
<tr>
<td></td>
<td>n-InP</td>
<td>Si:1e18</td>
<td>—  20</td>
</tr>
<tr>
<td></td>
<td>i-InP</td>
<td>Si:1e16</td>
<td>—  180</td>
</tr>
<tr>
<td>Sub-collector</td>
<td>$n^+$-InGaAs</td>
<td>Si:1e19</td>
<td>400 —</td>
</tr>
</tbody>
</table>

2. Device fabrication

The epitaxial layers of HBTs studied in this work were grown by MOCVD. Table 1 shows epitaxial layer structures of SHBT as well as DHB T with ballistic launcher structure in the collector region [3]. The former type of HBT has typical $f_r$ of 160 GHz, whereas in the latter case $f_r$ exceeds 200 GHz. To reduce base resistance, the base layer was heavily dopped to $4 \times 10^{19}$ 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 fix 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. $f_{\text{max}}$ 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 $f_r$ and $f_{\text{max}}$ of SHBTs and DHB Ts as a function of $W_e$. The emitter length was fix at 2.1 μm. As shown in Fig.3, both type of HBTs show similar $W_e$ dependence of $f_{\text{max}}$. As long as $W_e$ is greater than 1 μm, $f_{\text{max}}$ is inversely proportional to square root of $W_e$. This $W_e$ dependence of $f_{\text{max}}$ indicates ideal scaling relationship for small scale HBTs. However, as $W_e$ is decreased to below 1 μm, the variation of $f_{\text{max}}$ with $W_e$ deviates from ideal
scaling and turns to decreasing trend. Qualitatively, this behavior of $f_{\text{max}}$ can be understood by degradation of $f_r$, also shown in Fig. 3.

Regarding maximum $f_{\text{max}}$, while the $f_{\text{max}}$ of SHBT peaked at 265 GHz, in DHBT peak $f_{\text{max}}$ of 313 GHz was obtained (Fig. 2). Note that the optimum $W_E$ is far below the size at which $f_r$ starts to drop. This indicates that in order to optimize device size for high $f_{\text{max}}$ 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 $f_{\text{max}}$ behavior, $f_r$ was plotted as a function of $R_\text{BC}$ as shown in Fig. 4. The time constant $R_\text{BC}C_{\text{BC}}$ was estimated from $f_r$ and $f_{\text{max}}$ using the common relationship between $f_r$ and $f_{\text{max}}$:

$$f_{\text{max}} = \sqrt{\frac{f_r}{8\pi R_\text{BC}C_{\text{BC}}}}. \quad (1)$$

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

$$f_{\text{max}} = \frac{f_r}{(8\pi f_{\text{max}}^2)R_\text{BC}C_{\text{BC}}}. \quad (2)$$

Note that $R_\text{BC}C_{\text{BC}}$ continues to decrease even after $f_{\text{max}}$ starts to decrease. Therefore, when $W_E$ is excessively decreased, it is $f_r$ rather than $R_\text{BC}C_{\text{BC}}$ that is limiting $f_{\text{max}}$.

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

$$f_{\text{max}}^\text{opt} = \frac{1}{4\pi R_\text{BC}C_{\text{BC}}} \left( \frac{f_r + 2\rho_c^E C_0}{1 + \left( \frac{f_r}{\rho_c^E C_0} \right)^2} \right)^{1/2} \quad (3)$$

$$W_E^\text{opt} = W_F \left( \frac{\rho_c^E C_0}{f_r + \rho_c^E C_0} \right) \quad (4)$$

From (3) and (4), it can be clearly understood that the optimum $f_{\text{max}}$ is determined by ratio $\frac{f_r}{\rho_c^E C_0}$. If the emitter contact is good ($f_r >> \rho_c^E C_0$), $f_{\text{max}}$ is insensitive to $f_r$ and the dominant factor that determines $f_{\text{max}}^\text{opt}$. In this case, significant increase in $f_{\text{max}}$ can be expected by improving $f_r$ and by further pushing the down scaling of $W_E$. On the other hand, with poor contact ($f_r \ll \rho_c^E C_0$), decreasing $W_E$ below $W_E$ proves to be useless and $f_{\text{max}}^\text{opt}$ is insensitive to $f_r$ (and thus to $f_E$). The ratio $\frac{f_r}{\rho_c^E C_0}$ in our HBTs is about 3. Thus, for further improvement of $f_{\text{max}}$, improving not only $f_r$ but also emitter contact is effective.

5. Conclusions

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

Reference