Transferred-substrate HBTs with 254GHz \( f_t \)

D. Mensa, Q. Lee, J. Guthrie, S. Jaganathan and M.J.W. Rodwell

Transferred-substrate HBTs with record current gain cutoff frequency \( f_t \) of 254GHz are reported.

Introduction: Advances in device technology for heterojunction bipolar transistors (HBTs) are necessary to further improve the performance of associated high speed analogue and digital circuits. The most commonly quoted figures of merit for these devices are the current gain cutoff frequency \( f_t \) and power gain cutoff frequency \( f_{\text{max}} \). The transferred-substrate process has already yielded very high \( f_{\text{max}} \) [1] HBTs, but has not yet offered record \( f_t \). While applications such as reactive tuned amplifiers and distributed amplifiers immediately benefit from high \( f_{\text{max}} \), both \( f_t \) and \( f_{\text{max}} \) must be considered for digital systems as well as many analogue systems [2].

In this Letter we report the simultaneous achievement of record \( f_t \) and high \( f_{\text{max}} \) in one device. The device parasitics can then be examined, and inferences made about the relative value of various approaches toward further improvements in \( f_t \) and \( f_{\text{max}} \).

Table 1: MBE layer structure

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Doping</th>
<th>Thickness</th>
<th>%Ga</th>
<th>%Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cap</td>
<td>( n ) InGaAs</td>
<td>( 10^9 )</td>
<td>100</td>
<td>47/0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( n ) InGaAs</td>
<td>( 10^9 )</td>
<td>6.6</td>
<td>47/0 ( \rightarrow ) 0/48</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( n ) InAlAs</td>
<td>( 10^9 )</td>
<td>83.4</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>Emitter</td>
<td>( n ) InAlAs</td>
<td>( 8 \times 10^9 )</td>
<td>50</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( n ) InGaAs</td>
<td>( 5 \times 10^9 )</td>
<td>23.3</td>
<td>48 ( \rightarrow ) 0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( p ) InGaAs</td>
<td>( 2 \times 10^9 )</td>
<td>6.6</td>
<td>55/0</td>
<td></td>
</tr>
<tr>
<td>Base</td>
<td>( n ) InGaAs</td>
<td>( 5 \times 10^9 )</td>
<td>50</td>
<td>55/0 ( \rightarrow ) 47/0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( n ) InAlAs</td>
<td>( 10^9 )</td>
<td>25</td>
<td>47/0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( n ) InGaAs</td>
<td>( 5 \times 10^9 )</td>
<td>5</td>
<td>47/0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( n ) InGaAs</td>
<td>( 10^9 )</td>
<td>170</td>
<td>47/0</td>
<td></td>
</tr>
<tr>
<td>Buffer</td>
<td>( p ) InAlAs</td>
<td>UID</td>
<td>250</td>
<td>0/48</td>
<td></td>
</tr>
</tbody>
</table>

Processing and fabrication: The wafers were grown on a Varian Gen II MBE system on Fe-doped semi-insulating (100) InP substrates. The layer structures are as shown in Table 1. After completion of the collector growth sequence at 470°C, the wafer is cooled to 380°C to reduce beryllium outdiffusion during and after growth of the base [3]. A high As flux is also used to maximise beryllium as well as silicon incorporation. The compositional grading of the 400Å base is accomplished by eight 50Å 'stairsteps', referring to the downward steps seen by electrons in the conduction band as they traverse the base. After each 50Å step of base growth, the temperature of the gallium cell is increased to give a slightly wider bandgap InGaAsAs composition, followed by a 2min delay to allow stabilisation of the gallium flux. The change in the bandgap is calculated assuming a constant density of states and neglecting the effects of the tensile strain [4]. The base-emitter grade is an InGaAs/InAlAs superlattice [5], which the Table represents as an average effective composition. The composition of the InGaAs in the grade is the same as that at the base-emitter edge. The base-emitter grade is therefore strained. After growth of the InAlAs emitter and heavily doped InAlAs transition layer, there is a short superlattice to smooth out the conduction band discontinuity at the interface between the InAlAs and the InGaAs cap.

The details of the transferred-substrate process have been enumerated in previous publications [1]. The motivation for the transferred substrate process is the freedom to process both sides of the epitaxial film, allowing lithographic definition of the emitter and the collector. This yields rapid improvement in \( f_{\text{max}} \), as the emitter and collector dimensions are scaled. This lateral scaling can be accompanied by an appropriate vertical scaling, thinning of the semiconductor layers to reduce the transit time. In this way, a reasonable \( f_{\text{max}}/f_t \) ratio can be maintained.

Accurate determination of device parameters such as \( C_{\text{v}} \) requires knowledge of the parasitics introduced by the GSG probe pads. Measurement of similar open pad test structures allows determination of this pad capacitance. This capacitance is then subtracted from the measured S-parameters allowing the calculation of device parameters. The input and output pads on this device had capacitances of 10.95 and 9.30pF, respectively.

Table 2: Comparison of terms in \( f_t \)

<table>
<thead>
<tr>
<th>( \tau_c + \tau_t )</th>
<th>( r_c C_{\text{v}} )</th>
<th>( r_c C_{\text{vt}} )</th>
<th>( R_c C_{\text{v}} )</th>
<th>Peak ( f_t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.41ps</td>
<td>0.045ps</td>
<td>0.084ps</td>
<td>0.092ps</td>
<td>254GHz</td>
</tr>
</tbody>
</table>

Device results and discussion: A simplified hybrid-pi model for the bipolar transistor is shown in Fig. 1. The parameters \( R_c \) and the split between \( C_{\text{v}} \) and \( C_{\text{vt}} \) are discussed elsewhere [1]. The terms in the expression for \( f_t \) are compared and discussed. The device in this work comprised a 1 x 8µm emitter contact and a 2 x 12µm Schottky collector contact.

The values of these terms defining the \( f_t \) are summarised in Table 2, and for the terms dependent on \( r_c \), the emitter current was 10mA. \( C_{\text{v}} \) has been extracted from the slope of the imaginary component of \( Y_{\text{v}} \) against frequency. \( R_c \) was taken from the zero intercept of the plot of 1/4π(\( Y_{\text{v}} \)) against 1/\( Y_{\text{v}} \). \( \tau_c + \tau_t \) was determined from the zero intercept of 1/(2\pi\( Y_{\text{v}} \)) against 1/\( Y_{\text{v}} \), with \( R_c C_{\text{v}} \) subtracted off, and \( C_{\text{v}} \) was determined from the slope of that plot with \( C_{\text{vt}} \) subtracted off. The data for extraction of forward transit time and \( C_{\text{v}} \) are plotted in Fig. 2.

![Fig. 1 Hybrid-pi model of bipolar transistor](image1)

![Fig. 2 Forward delay against inverse emitter current](image2)
Fig. 3 Current gain, maximum stable gain, and Mason unilateral gain for device from wafer A

\[ V_{ce} = 1.0 \text{V}, \; I_e = 10 \text{mA} \]

The transferred-substrate process allows for narrowing of the collector finger to reduce \( C_C \). Proportionally reducing the widths of the collector and emitter stripes reduces \( R_C C_L \), allowing high \( f_m \), to be obtained in device layer structures that have the thin collectors necessary for high \( f_c \). Decreasing the ratio of collector to emitter stripe widths reduces \( R_C C_L \), as well as further increasing \( f_m \). But decreasing this ratio will reduce the Kirk effect threshold; this will lead to a compromise in which sufficient Kirk threshold must be maintained to support high current density with a narrow enough collector to provide high \( f_m \).

Results and conclusions: The transferred-substrate process has yielded devices with simultaneously high \( f_c \) and \( f_m \). The next step to further improve both \( f_c \) and \( f_m \) is to reduce the ratio of the width of the collector finger to the width of the emitter finger. A further reduction in \( C_C \) is under investigation. The acquisition of a stepper alignment tool will allow for a reduction in the base mesa size and all alignment tolerances. With this lithographic capability the frequency performance of transferred-substrate HBTs should increase dramatically.

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References


Improvement to modified Routh approximation method

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The modified Routh approximation method yields a stable reduced model which maintains the first few time-moments and Markov parameters of an original model. An improvement is made so that the impulse energy of the original model is also preserved in the reduced model.

Introduction: In the last three decades, considerable efforts have been made in the area of order reduction of complex linear time-invariant systems, and numerous techniques have been reported. Among them, the Routh approximation (RA) method [1] has attracted continuous attention, mainly due to its computational simplicity and stability preserving properties. However it has been found that this method may fail to produce good reduced models.

Several attempts have been made to improve or modify the RA method [2 – 7]. In [2 – 4], focus was placed on the initial time-moments or steady state response, and no attention was given to the transient response. On the other hand, in [5 – 7], both the steady state and transient responses were considered by matching Markov parameters as well as time moments.

The aim of this Letter is to improve the modified RA (MRA) method presented in [7]. The MRA method yields a stable \( k \)-th order reduced model \( G_{k}(s) \) where the first \( \{k + 1\}/2 \) time moments and \( k/2 \) Markov parameters of \( G_{k}(s) \) coincide with those of an original model. The method is further modified so that the impulse energy of the original model is also preserved in the reduced model.

Improved MRA method: Consider a linear time-invariant system represented by the transfer function

\[ G(s) = \frac{b_0 + b_1 s + b_2 s^2 + \cdots + b_{n-1} s^{n-1}}{a_0 + a_1 s + a_2 s^2 + \cdots + a_n s^n} = \frac{s^{n-1}}{M_1 + M_2 s + M_3 s^2} \]

where \( a_0 \neq 0 \). The \( T_{2k} \) and \( M_{2k} \) are, respectively, the time moments and Markov parameters of \( G(s) \). Let \( k \) be an integer such that \( k < n \) and \( n - k = \text{even} \), and suppose that the parameters \( \gamma_i, \beta_i, \alpha_i, \beta_i, i = 1, 2, ..., [n + 1]/2 \) have been computed as in [7]. Then the MRA method generates the \( k \)-th order reduced model \( G_k(s) = B_k(s)/A_k(s) \) by the following recursive equations [7]: for \( m = even \)

\[ A_m(s) = s^2 A_{m-2}(s) + \left( \gamma_{m+1} + \alpha_{m+1} \frac{s^2}{s^2 + m^2} \right) A_{m-2}(s) \]

\[ B_m(s) = \beta_{m+1} \frac{s^{m+1}}{s^{m+2}} + \delta_{m+1} \frac{s^{m+2}}{s^{m+2}} + s^2 B_{m-4}(s) + \left( \gamma_{m+1} + \alpha_{m+1} \frac{s^2}{s^2 + m^2} \right) B_{m-2}(s) \]

with \( B_2(s) = B_0(s) = 0, \; A_2(s) = 1/s \) and \( A_4(s) = 1 \). For \( m = odd \), set \( \alpha_i = 0 \) when \( i = 0 \) in eqns. 2 and 3.

As observed in [7], the first \( \{k + 1\}/2 \) time moments and \( k/2 \) Markov parameters of \( G_k(s) \) are retained in \( G_k(s) \), i.e. if \( G_k(s) = \frac{s^{n-1}}{M_1 + M_2 s + M_3 s^2} \)

\[ G_k(s) = s^2 + s + \frac{s^2}{m_1 + m_2 s + m_3 s^2} \]

then \( \xi = T_{2k} = 0, i = 0, 1, ..., \{k - 1\}/2 \) and \( m_i = M_i, i = 1, 2, ..., [k/2]. \)