Transferred-substrate HBTs with 254GHz f_τ

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

Transferred-substrate HBTs with record current gain cutoff frequency f_τ 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 circuitry. The most commonly quoted figures of merit for these devices are the current gain cutoff frequency f_τ and power gain cutoff frequency f_{max}. The transferred-substrate process has already yielded very high f_{max} [1] HBTs, but has not yet offered record f_τ. While applications such as reactive tuned amplifiers and distributed amplifiers immediately benefit from high f_{max}, both f_τ and f_{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_τ and high f_{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_τ and f_{max}.

Table 1: MBE layer structure

Layer	Material	Doping	Thickness	InGaAlAs
		cm^{-3}	nm	%Ga/%Al
Cap	*n* InGaAs	10^{19}	100	47/0
	n InGaAs	10^{19}	6.6	47/0 → 0/48
	n InAlAs	10^{19}	83.4	0/48
Emitter	*n* InAlAs	8×10^{17}	50	0/48
	n InGaAlAs	5×10^{17}	23.3	0/48 →
	p InGaAlAs	2×10^{18}	6.6	→ 55/0
Base	*p* InGaAs	5×10^{19}	50	55/0 → 47/0
Collector	*n* InGaAs	10^{16}	25	47/0
	n InGaAs	5×10^{17}	5	47/0
	n InGaAs	10^{16}	170	47/0
Buffer	*i* InAlAs	UID	250	0/48

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_2 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 $In_xGa_{1-x}As$ 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_{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_{max}/f_τ ratio can be maintained.

Accurate determination of device parameters such as C_{je} 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 9.30fF, respectively.

Table 2: Comparison of terms in f_τ

$\tau_b + \tau_c$	$r_e C_{cb}$	$r_e C_{je}$	$R_{ex} C_{cb}$	Peak f_τ
0.41ps	0.045ps	0.084ps	0.092ps	254GHz

Device results and discussion: A simplified hybrid-pi model for the bipolar transistor is shown in Fig. 1. The parameters R_{bb} and the split between $C_{cb,intrinsic}$ and $C_{cb,extrinsic}$ are discussed elsewhere [1]. The terms in the expression for f_τ are compared and discussed. The device in this work comprised a 1 × 8μm emitter contact and a 2 × 12μm Schottky collector contact.

The values of these terms defining the f_τ are summarised in Table 2, and for the terms dependent on r_e, the emitter current was 10mA. C_{cb} has been extracted from the slope of the imaginary component of Y_{12} against frequency. R_{ex} was taken from the zero intercept of the plot of $1/\mathrm{Re}(Y_{21})$ against $1/I_e$. $\tau_b + \tau_c$ was determined from the zero intercept of $1/(2\pi f_\tau)$ against $1/I_e$ with $R_{ex}C_{cb}$ subtracted off, and C_{je} was determined from the slope of that plot with C_{cb} subtracted off. The data for extraction of forward transit time and C_{je} are plotted in Fig. 2.

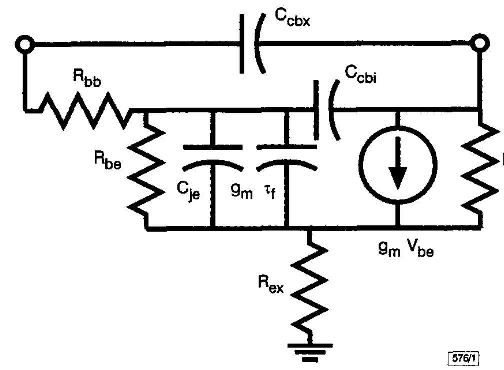

Fig. 1 *Hybrid-pi model of bipolar transistor*

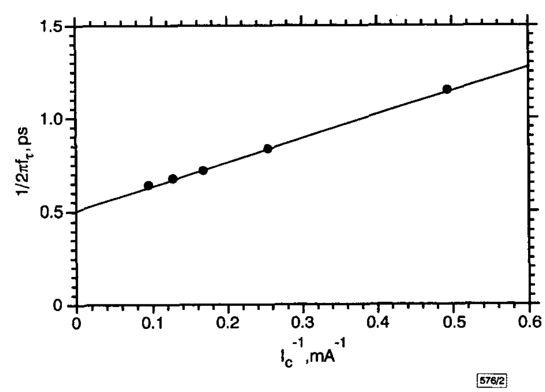

Fig. 2 *Forward delay against inverse emitter current*
Calculation of transit time and C_{je}

The RF results for the device are shown in Fig. 3. This data were obtained for the device biased at a V_{ce} of 1.0V and collector current I_c of 10mA.

F_τ is generally increased by thinning the semiconductor layers to reduce the transit time. In addition to the increase in R_{bb} expected with a thinner base layer, the base thickness cannot be arbitrarily reduced without incurring serious processing and yield penalties. Thinning the collector semiconductor from several thousand Angstroms to 1000Å presents little processing difficulty. However, the

f_{max} drops much faster as the collector is thinned than $C_{cb} = \epsilon A/d$ would predict. Additionally, as the collector semiconductor is thinned, increases in f_τ due to reduced τ_c are offset by an increasing $R_{ex}C_{cb}$ time constant.

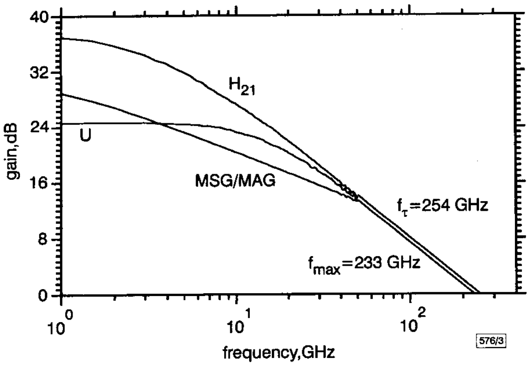

Fig. 3 *Current gain, maximum stable gain, and Mason unilateral gain for device from wafer A*

$V_{ce} = 1.0\text{V}$, $I_c = 10\text{mA}$

The transferred-substrate process allows for narrowing of the collector finger to reduce C_{cb}. Proportionally reducing the widths of the collector and emitter stripes reduces $R_{bb}C_{cb}$, allowing high f_{max} to be obtained in device layer structures that have the thin collectors necessary for high f_τ. Decreasing the ratio of collector to emitter stripe widths reduces $R_{ex}C_{cb}$, as well as further increasing f_{max}. 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_{max}.

Results and conclusions: The transferred-substrate process has yielded devices with simultaneously high f_τ and f_{max}. The next step to further improve both f_τ and f_{max} is to reduce the ratio of the width of the collector finger to the width of the emitter finger. A further reduction in C_{je} 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.

Acknowledgments: These results would not have been possible but for the guidance of B. Agarwal, now at Rockwell Semiconductor Systems in Newport Beach, and R. Pullela, now at Lucent Technologies. This work was supported by the ONR under grant N00014-98-1-0068.

22 February 1999

Electronics Letters Online No: 19990398

DOI: 10.1049/el:19990398

D. Mensa, Q. Lee, J. Guthrie, S. Jaganathan and M.J.W. Rodwell (*Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106, USA*)

References

1 LEE, Q., AGARWAL, B., MENSA, D., PULLELA, R., GUTHRIE, J., SAMOSKA, L., and RODWELL, M.J.W.: 'A > 400GHz f_{max} transferred-substrate heterojunction bipolar transistor IC technology', *IEEE Electron Device Lett.*, 1998, **19**, pp. 77–79

2 SANO, E., YONEYAMA, M., YAMAHATA, S., and MATSUOKA, Y.: 'InP/InGaAs double-heterojunction bipolar transistors for high-speed optical receivers', *IEEE Trans.*, 1996, **ED-43**, (11), pp. 1826–1832

3 HAFIZI, M., METZGER, R., and STANCHINA, W.: 'Dependence of DC current gain and f_{max} of AlInAs/GaInAs HBTs on base sheet resistance', *IEEE Electron Device. Lett.*, 1993, **14**, (7), pp. 323–325

4 KURISHIMA, K., NAKAJIMA, H., YAMAHATA, S., KOBAYASHI, T., and MATSUOKA, Y.: 'Effects of a compositionally graded $In_xGa_{1-x}As$ base in abrupt-emitter InP/InGaAs heterojunction bipolar transistors', *Jpn. J. Appl. Phys.*, 1995, **34**, pp. 1221–1227

5 HAFIZI, M., CROWELL, C., PAWLOWICZ, L., and KIM, M.: 'Improved current gain and f_τ through doping profile selection in linearly graded heterojunction bipolar transistors', *IEEE Trans.*, 1998, **ED-43**, (11), pp. 1826–1832

6 MENSA, D., LEE, Q., GUTHRIE, J., JAGANATHAN, S., and RODWELL, M.J.W.: 'Transferred-substrate HBTs with 250GHz current-gain cutoff frequency'. Tech. Dig. Int. Electron Device Meeting, 1998, pp. 657–660

Improvement to modified Routh approximation method

Younseok Choo

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 ahve 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 kth-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

$$\begin{aligned} G(s) &= \frac{b_0 + b_1 s + b_2 s^2 + \cdots + b_{n-1} s^{n-1}}{a_0 + a_1 s + a_2 s^2 + \cdots + a_n s^n} \\ &= T_0 + T_1 s + T_2 s^2 + \cdots \\ &= \frac{s}{M_1} + \frac{s^2}{M_2} + \frac{s^3}{M_3} + \cdots \end{aligned} \quad (1)$$

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

$$A_m(s) = s^2 A_{m-4}(s) + \left(\gamma_{[\frac{(m+1)}{2}]} + \alpha_{[\frac{(m+1)}{2}]} s^2\right) A_{m-2}(s) \quad (2)$$

$$\begin{aligned} B_m(s) = \beta_{[\frac{(m+1)}{2}]} s^{[\frac{(m+1)}{2}]} + \delta_{[\frac{(m+1)}{2}]} s^{[\frac{(m-1)}{2}]} + s^2 B_{m-4}(s) \\ + \left(\gamma_{[\frac{(m+1)}{2}]} + \alpha_{[\frac{(m+1)}{2}]} s^2\right) B_{m-2}(s) \end{aligned} \quad (3)$$

with $B_{-2}(s) = B_0(s) = 0$, $A_{-2}(s) = 1/s$ and $A_0(s) = 1$. For m = odd, set $\alpha_1 = \beta_1 = 0$ in eqns. 2 and 3.

As observed in [7], the first $[(k + 1)/2]$ time moments and $[k/2]$ Markov parameters of $G(s)$ are retained in $G_k(s)$, i.e. if

$$\begin{aligned} G_k(s) &= t_0 + t_1 s + t_2 s^2 + \cdots \\ &= \frac{s}{m_1} + \frac{s^2}{m_2} + \frac{s^3}{m_3} + \cdots \end{aligned} \quad (4)$$

then $t_i = T_i$, $i = 0, 1, ..., [(k - 1)/2]$ and $m_i = M_i$, $i = 1, 2, \cdots, [k/2]$.