Journal of Electron Devices, Vol. 10, 2011, pp. 511-514

© JED [ISSN: 1682 -3427]

Journal of Electron Devices
www.jeldev.org

EFFECT OF MAJORITY CARRIER CURRENT ON THE BASE TRANSIT TIME OF A BJT

[1]M M Shahidul Hassan, [2]Orchi Hassan and [3]Md. Iqbal Bahar Chowdhury

[1]Department of Electrical and Electronic Engineering, BUET, Dhaka 1000, Bangladesh. shassan@eee.buet.ac.bd
[2] Senior undergraduate student, Department of E.E.E., BUET, Dhaka 1000, Bangladesh.
[3]Department of Electrical and Electronic Engineering, UIU, Dhaka 1207, Bangladesh.

Received 2/09/2011, online 5/09/2011

Abstract

The main objective of this paper is to show that majority carrier current needs to be taken into account in determining base transit time τ_B of a bipolar junction transistor (BJT). In previous analytical works for τ_B, majority carrier current in the base was neglected. In this paper both drift and diffusion currents for electrons and holes are considered in obtaining minority carrier profile n(x) within the p-type base. In the model, it is assumed that the lateral injection of base current into the active base region is occurred from a source function, g. The energy-bandgap narrowing effects due to heavy doping, velocity saturation as well as doping dependent mobility are considered. The analytical expression for τ_B reduces to the well known form for uniformly doped base when g is zero.

***Keywords**:* Device modeling, bipolar junction transistor, base majority current, base minority current, transit time.

I. INTRODUCTION

BJTs have been used mainly due to their driving Capability and speed advantages [1]. Different delay times limit the speed of the device. The base transit time is often the single largest contribution to the total delay time and determines the transistor's high frequency performance. Therefore, it is very important to obtain an analytical expression for base transit time τ_B for high frequency bipolar junction transistor for efficient device design. Derivations for electron current density J_n and τ_B [2]−[6] were obtained by neglecting majority-carrier current J_p in the base of an npn BJT. Majority carrier current density J_p affects the minority carrier profile n(x) within the base and minority carrier current density J_n resulting in dependence of τ_B upon J_p. The base transit time (eqn. (1)) is the ratio of total minority carrier charge stored in the base Q_n and the minority current density J_n. Both Q_n and J_n depend upon J_p.

The majority carrier current density J_p needs to be included in obtaining τ_B. Recent work [7] has shown that the analysis for n(x) and J_n neglecting lateral base current density J_p for operation in saturation region is not valid and the authors have included majority carrier current density J_p in the analysis. In the present work, analysis is carried out for uniformly doped base for active mode of operation of BJT.

II. ANALYSIS

The following relation gives the base transit time of an npn bipolar junction transistor

$$\tau_B = q\int_0^{W_b} \frac{n(x)}{J_n(x)}dx \qquad (1)$$

where, x is the distance of a point in the base from the base side of the base emitter junction. q is the electronic charge and W_b is the base width.

The electron and hole current densities within the base are given

$$J_n = qn(x)\mu_n(x)E_n(x) + qD_n(x)\frac{dn(x)}{dx} \qquad (2)$$

$$J_p = qp(x)\mu_p(x)E_p(x) - qD_p(x)\frac{dp(x)}{dx} \qquad (3)$$

In order to develop a simple analytical model, some means must be found to incorporate the lateral injection of base current into the active base region.
This can be done by use of an approximate source function. An intuitively acceptable description is to assume that the lateral base current, hence the source function, is proportional to the majority carrier concentration at all places. In this way the physical

mechanism of majority carrier current flow can be incorporated in the model. For low level of injection ($n(x) << N_B$), the recombination within the base can safely be neglected. The divergence of majority (hole) current can be expressed as

$$\frac{dJ_p}{dx} = qgp(x) \quad (4)$$

where the coefficient g is the rate constant which describes the lateral injection of base current.

Integration of eqn. (4) gives

$$J_p(x) = J_o + qgN_b x \quad (5)$$

where, J_o is the hole current density entering the emitter from base at x = 0. J_o for an emitter width $X_E << L_E$ can be written as [8]

$$J_o = -\frac{qD_{pe}n_{ie}^2}{X_E N_E}\left(e^{\frac{qV_{be}}{kT}} - 1\right) \quad (6)$$

where, D_{pe} is the diffusion constant for holes in the emitter, n_{ie} is the effective intrinsic carrier concentration in the emitter, X_E is the width of the emitter and L_E is the diffusion length for holes in the emitter.

For operation of a BJT in active mode, it can be assumed that $J_p(W_b) = 0$. From (5), it can be shown that

$$g = -\frac{J_o}{qN_B W_b} \quad (7)$$

where, N_B is the constant base doping density.

If quasi- neutrality in the vase is assumed,

$$p(x) = n(x) + N_B \text{ and } \frac{dp(x)}{dx} = \frac{dn(x)}{dx} \quad (8)$$

For low level of injection, eqn. (8) reduces to $p(x) \approx N_B$. Substituting electric field E obtained from eqn. (3) into eqn. (2) and using eqns. (7) and (8), it can be shown that

$$\frac{dn(x)}{dx} = \frac{J_n}{qD_{nb}} - \frac{g}{D_{pb}} n(x)x \quad (9)$$

For a practical transistor, $J_o << J_n$. This condition is applied in obtaining eqn. (9).

The solution of eqn. (9) gives

$$n(x) = n_o\left(1 - \frac{b}{2}x^2\right) - ax\left(1 - \frac{b}{3}x^2\right) \quad (10)$$

where,

$$a = \frac{J_n}{qD_{bn}} \text{ and } b = \frac{g}{D_{bp}}$$

Considering the velocity saturation of minority carrier electrons at the reversed biased base-collector junction, the electron current density J_n can be expressed as

$$J_n = -qv_s(w_b) \quad (11)$$

Electron concentration n_w at $x = W_b$ can be obtained from eqn. (10) by replacing x by W_b. From eqns. (10) and (11),

$$J_n = \frac{qv_s n_o\left(1 - \frac{b}{2}W_b^2\right)}{1 - \frac{v_s W_b}{D_{bn}}\left(1 - \frac{b}{3}W_b^2\right)} \quad (12)$$

Upon integration of eqn. (10) from x = 0 to x = W_b and using eqn. (1), base transit time τ_B can be expressed as

$$\tau_B = -\frac{qn_o W_b}{J_n}\left(1 - \frac{g}{D_{bp}}\right) - \frac{W_b^2}{2D_{bn}}\left(1 - \frac{g}{D_{bp}}\right) \quad (13)$$

Eqn. (13) for τ_B contains the rate constant g. This is the first time an expression for τ_B incorporating J_p is obtained.

Electron current will flow towards the emitter and becomes negative in eqn. (2). As it is a positive quantity, J_n is replaced by $-J_n$ in eqn. (13). With $-J_n$ eqn. (13) becomes

$$\tau_B = \frac{qn_o W_b}{J_n}\left(1 - \frac{g}{D_{bp}}\right) - \frac{W_b^2}{2D_{bn}}\left(1 - \frac{g}{D_{bp}}\right) \quad (14)$$

In previous works majority carrier current was neglected. With $J_p = 0$, rate constant will also be zero. With g = 0, eqn. (13) reduces to

$$\tau_B = \frac{qn_o W_b}{J_n} - \frac{W_b^2}{2D_{bn}} \quad (15)$$

Now, from eqns. (9) and (11) for g = 0 and at x = W_b

$$\frac{qn_oW_b}{J_n} = \frac{qW_b}{qv_sn_w}\left(n_w + \frac{qv_sn_wW_b^{\ 2}}{qD_{bn}}\right) = \frac{W_b}{v_s} + \frac{W_b^{\ 2}}{D_{bn}} \quad (16)$$

From eqns. (15) and (16),

$$\tau_B = \frac{qn_oW_b}{J_n} + \frac{W_b^{\ 2}}{2D_{bn}} \quad (17)$$

Eqn. (17) is a well known form for base transit time [4] of an uniformly doped base.

III. RESULTS

The following relations for diffusion coeficients and effective carrier concentration [6] are used for simulation,

For electrons

$$D_n = D_{no}\left(\frac{N_i}{N_r}\right)^{-\gamma_1}$$

where, D_{no} = 20.72 cm^2/v.s, N_r = $1x10^{17}$ cm^{-3} and γ_1=0.42 and N_i is the doping density.

For holes

$$D_p = D_{po}\left(\frac{N_i}{N_r}\right)^{-\gamma_2}$$

where, D_{po} = 12.5227 cm^2/v.s and γ_2=0.38. For effective intrinsic concentration

$$n_i^{\ 2} = n_{io}^{\ 2}\left(\frac{N_i}{N_r}\right)^{-\gamma_3}$$

where, γ_3 = 0.69 and n_{io} =$1.4x10^{10}$ cm^{-3}.

The electron concentration at x = 0 consider Webster effect [9,10]

$$n_o = \frac{\frac{n_{ib}^{\ 2}}{N_B} - 0.5N_B + 0.5N_B\left(1 + \frac{4n_{ib}^{\ 2}}{N_B^{\ 2}}e\frac{V_{BE}}{V_T}\right)^{0.5}}{f_w}$$

where, n_{ib} is the effective intrinsic carrier cncentration in the base and V_T (= kT/q) is the thermal volatge. The factor f_w can be expressed as

$$f_w = \frac{1}{2} + \sqrt{\frac{1}{4} + \frac{n_{ib}^{\ 2}}{N_B^{\ 2}}e^{V_{BE}/V_T}}$$

Fig. 1 shows τ_B as a function of base-emitter junction voltage V_{be} of an npn bipolar junction transistor, obtained analytically with J_p. For low level of injection, τ_B depends upon V_{be} for $g \neq 0$. It increases with V_{be}. On the other hand τ_B is independent of V_{be} (eqn. (17)) for g = 0 and it is found to be equal to 12.817 ps.

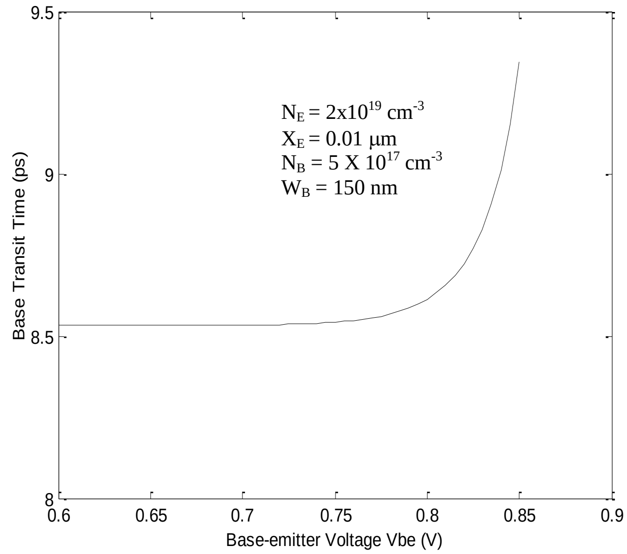

Fig. 1. Base transit time τ_B as a function of V_{be}.

Fig. 2 gives the variation of g as a function of V_{be} for given N_E , $X_{E,}$, N_B and W_b. The rate constant also depends upon V_{be}.

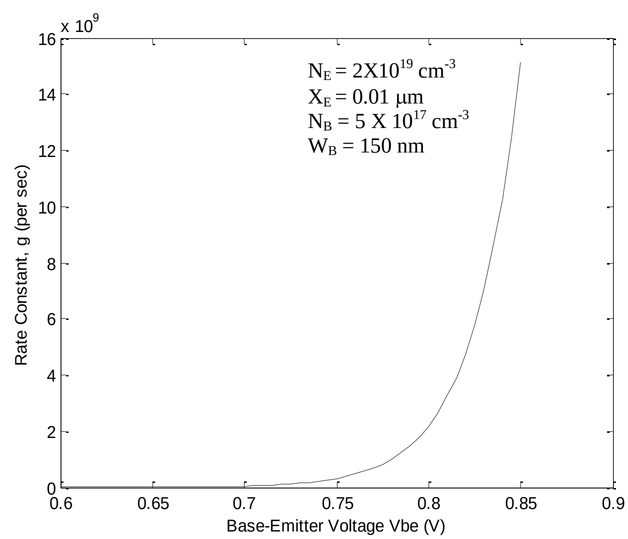

Fig. 2. Variation of rate constant g as a function of V_{be}.

Fig. 3 plots τ_B as a function of base width W_b for $g \neq 0$ and also for g = 0. For $g \neq 0$, the value of τ_B for a given W_b is found lower than that for g = 0. An aided electric field will be created by the majority carrier current density J_p as is evident from eqn. (3). This field allows the injected electrons in leaving the base faster

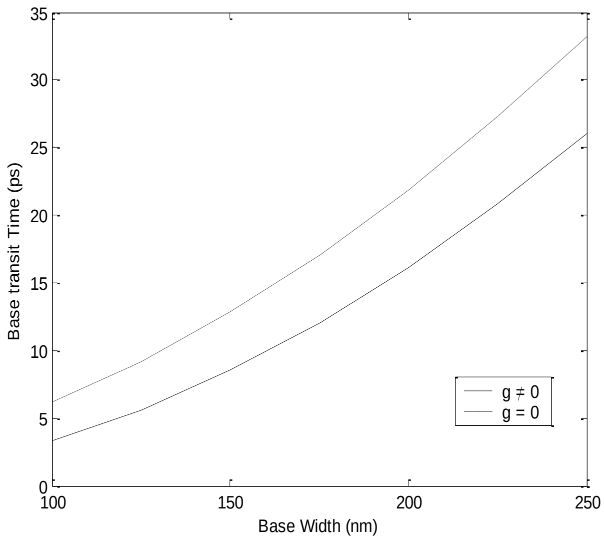

Fig 3. Comparison of base transit time τ_B for g = 0 and $g \neq 0$.

IV. CONCLUSION

An analytical model incorporating majority carrier current J_p has been developed for uniformly doped base in order to show that J_p can not be neglected in obtaining base transit time τ_B. The lateral injection of base current into the active base region is incorporated in the model by using an approximate source function, g. It is assumed that the source function g is proportional to the majority carrier at all places. The values of base transit time with $g \neq 0$ are found different from the values of τ_B with g = 0.

References

[1] H. M. Rein and M. Moller, "Design consideration for very high-speed Si-bipolar IC's operating to 50Gb/s", IEE J Solid-State Circuit, **31**, 1076, (1998).

[2] J. J. H. van der Beisen, "A simple regional analysis of transit times in bipolar transistors", Solid State Electron., **29**, 529, (1986).

[3] M. Pingxi, L. Zhang and Y. Wang, "Analytical model of collector current density and base transit time based on iteration method", Solid State Electronics, **39**, 221, (1996).

[4] K. Suzuki, "Analytical base transit time model of uniformly- doped base bipolar transistors for high-injection regions", Solid-State Electronics, **36**, 109, (1993).

[5] M. M. Shahidul Hassan and M.W. K. Nomani, "Base-transit-time model considering field dependent mobility for BJTs operating at high-level injection", IEEE Trans. Electron Devices, **53**, 2532, (2006).

[6] K. Suzuki,"Optimum base-doping profile for minimum base transit time considering velocity saturation at base-collector junction and dependence of mobility and bandgap narrowing on doping concentration", IEEE Trans. Electron Devices, **48**, 2102, (2001).

[7] G. T. Wright and P. P. Frangos, "A Simple, Analytical, One-Dimensional Model for Saturation Operation of the Bipolar Transistor", Electronic and Electrical Engineering Department, University of Birmingham, England.

[8] R. S. Muller and T. I. Kamins," Device Electronics for Integrated Circuits", 2nd Edition, John Wiley and Sons (1986).

[98] Y. Yue, J. J. liou, A. Ortiz-Conde and F. G. Sanchez, "Effects of High-level, Free-carrier Injection on the Base Transit Time of Bipolar Junction Transistors" , Solid-State Electronics, **39**, 27, (1996).

[10] W. M. Webster, "On the Variation Junction-transistor Current-amplifier factor with Emitter Current", IRE, **42**, 914, (1954).