

**EFFECT OF MAJORITY CARRIER CURRENT ON THE BASE TRANSIT TIME OF A BJT**<sup>1</sup>M M Shahidul Hassan, <sup>2</sup>Orchi Hassan and <sup>3</sup>Md. Iqbal Bahar Chowdhury<sup>1</sup>Department of Electrical and Electronic Engineering, BUET, Dhaka 1000, Bangladesh. [shassan@eee.buet.ac.bd](mailto:shassan@eee.buet.ac.bd)<sup>2</sup>Senior undergraduate student, Department of E.E.E., BUET, Dhaka 1000, Bangladesh.<sup>3</sup>Department of Electrical and Electronic Engineering, UIU, Dhaka 1207, Bangladesh.

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**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  $\tau_B$  of a bipolar junction transistor (BJT). In previous analytical works for  $\tau_B$ , 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  $\tau_B$  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  $\tau_B$  for high frequency bipolar junction transistor for efficient device design. Derivations for electron current density  $J_n$  and  $\tau_B$  [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  $\tau_B$  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  $\tau_B$ . 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

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

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

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

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

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 ( $n(x) \ll N_B$ ), 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  $X_E \ll L_E$  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,

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

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,  $J_o \ll J_n$ . 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,

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

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  $\tau_B$  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  $\tau_B$  contains the rate constant  $g$ . This is the first time an expression for  $\tau_B$  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  $x = W_b$

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

From eqns. (15) and (16),

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

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

### III. RESULTS

The following relations for diffusion coefficients 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,  $D_{no} = 20.72 \text{ cm}^2/\text{v.s}$ ,  $N_r = 1 \times 10^{17} \text{ cm}^{-3}$  and  $\gamma_1 = 0.42$  and  $N_i$  is the doping density.

For holes

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

where,  $D_{po} = 12.5227 \text{ cm}^2/\text{v.s}$  and  $\gamma_2 = 0.38$ . For effective intrinsic concentration

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

where,  $\gamma_3 = 0.69$  and  $n_{io} = 1.4 \times 10^{10} \text{ cm}^{-3}$ .

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 concentration 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  $\tau_B$  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,  $\tau_B$  depends upon  $V_{be}$  for  $g \neq 0$ . It increases with  $V_{be}$ . On the other hand  $\tau_B$  is independent of  $V_{be}$  (eqn. (17)) for  $g = 0$  and it is found to be equal to 12.817 ps.

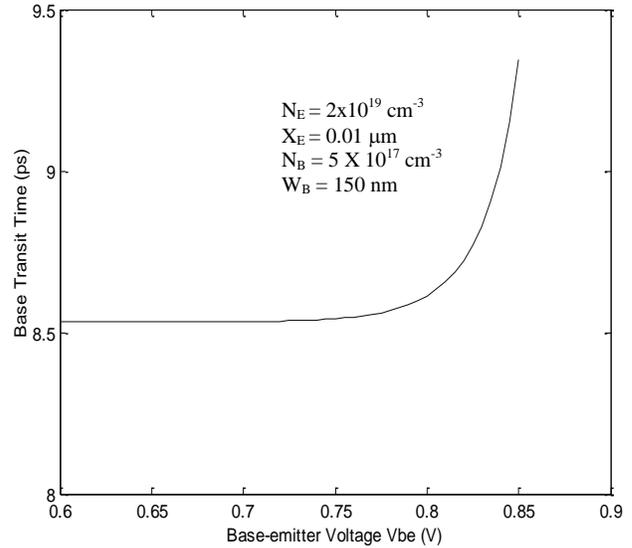


Fig. 1. Base transit time  $\tau_B$  as a function of  $V_{be}$ .

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  $V_{be}$ .

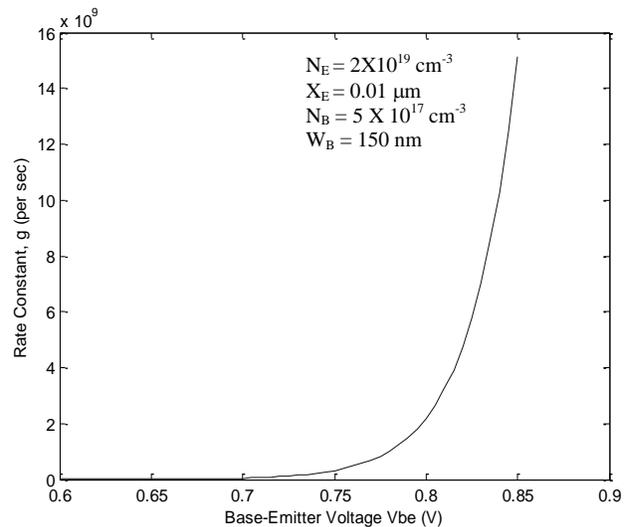


Fig. 2. Variation of rate constant  $g$  as a function of  $V_{be}$ .

Fig. 3 plots  $\tau_B$  as a function of base width  $W_b$  for  $g \neq 0$  and also for  $g = 0$ . For  $g \neq 0$ , the value of  $\tau_B$  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

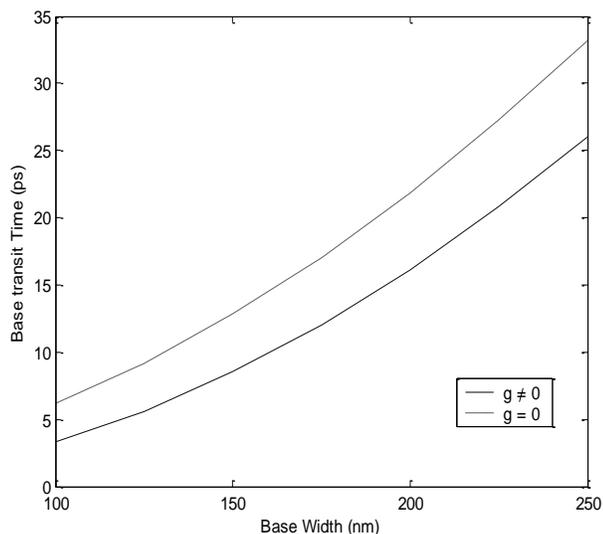


Fig 3. Comparison of base transit time  $\tau_B$  for  $g = 0$  and  $g \neq 0$ .

#### 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  $\tau_B$ . 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  $\tau_B$  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", 2<sup>nd</sup> Edition, John Wiley and Sons (1986).  
 [9] 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).