Journal of Electrical Engineering
The Institution of Engineers, Bangladesh
Vol. EE 31, No. I & II, December 2004

Base Transit Time of A Bipolar Transistor with Gaussian Base Doping Profile

Touhidur Rahman, Md. Ziaur Rahman Khan and M. M. Shahidul Hassan

Dedpartment of Electrical and Electronic Engineering, BUET, Dhaka, Bangladesh.
Email : shassan@ee.buet.ac.bd

ABSTRACT

In this work, an analytical expression for base transit time τ_b of a modern high-speed npn bipolar transistor with gaussian base profile is obtained. The doping dependence of mobility, bandgap narrowing effect and carrier velocity saturation at the base edge of the collector-base junction are incorporated in finding τ_b. The collector current density, J_n, and minority carrier stored charge per unit area, Q_{nB}, are separately expressed as a function of the injected electron density n(0) in the base in order to find τ_b. The modeling of J_n, Q_{nB} and τ_b is essential for the design of high-speed bipolar transistor. The base transit time calculated analytically is compared with numerical results in order to demonstrate the validity of the assumptions made in deriving the expression. The closed form expressions for collector current density and base transit time offer a physical insight into device operation and are a useful tool in device design and optimization.

1. INTRODUCTION

Modeling of charge storage effects in a high-speed bipolar junction transistor (BJT) is a topic of present interest and importance. Bipolar transistors have been used mainly due to their speed advantage and driving capability. Major applications today are RF front-end as well as fiber-optic circuits [1]. Numerous papers regarding emitter and base transit times of BJT have been published [2]-[5]. Van den Biesen [2] used a regional analysis to study transit times of BJT as a function of base-emitter bias. No closed form solution in [2] was obtained. Suzuki [3] has proposed J_n and τ_b models of uniformly doped base. Yuan [4] studied the effect of base doping on transit time. Later, Suzuki [5] obtained an expression for τ_b using a perturbation theory. But the equation form for τ_b is not concise and included several integrals. The transit time considering the velocity saturation at base-collector junction and the electrical field dependence of minority carrier mobility was determined in [6]. But the method was based on iterative techniques. So the equation forms for J_n and τ_b are not concise and they are inconvenient for us to understand device physics. An analytical model for base transit time for exponentially doped base has been developed in [7]-[8]. But the base doping usually follows gaussian profile.

In the present model, an analytical expression for base transit time for a gaussian-doped base is obtained considering bandgap narrowing effect, electrical field dependence of minority carrier mobility and velocity saturation at the base-collector junction. The results of the proposed model are compared with those obtained numerically.

2. ANALYSIS

The base transit time of an n^+pn^- bipolar junction transistor is given by the following relation

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

where, $n(x)$ is the electron concentration and $J_n(x)$ is the electron current density in the base, q is the charge of an electron and W_b is the width of the base.

The basic equations required for finding *n(x)* within the base region are [4]

$$-J_n = qD_n(x)\frac{dn(x)}{dx} + q\mu_n(x)E(x)n(x) \qquad (2)$$

and

$$E(x) = \frac{kT}{q}\left(\frac{1}{p(x)}\frac{dp(x)}{dx} - \frac{1}{n^2_{ie}}\frac{dn^2_{ie}}{dx}\right) \qquad (3)$$

where $D_n(x)$ is the electron diffusion coefficient, $\mu_n(x)$ is the electron mobility, n_{ie} is the effective intrinsic carrier concentration, *p(x)* is the hole concentration and *E(x)* is the electric field within the base. We define J_n in (2) so that it has a positive value. In obtaining (3) the carrier recombination in the base is neglected. In today's bipolar transistors carrier recombination in the base is negligible [9], which makes J_n constant.

Neglecting J_p and using (2) and (3) the total current density is given by

$$-J_n = qD_n(x)\frac{n^2_{ie}(x)}{n(x)+N_A(x)} \times \frac{d}{dx}\left(\frac{n(x)\left(n(x)+N_A(x)\right)}{n^2_{ie}}\right) \qquad (4)$$

The electron diffusion coefficient is given by [10]

$$D_n(x) = D_{no}\left(\frac{N_A(x)}{N_{ref}}\right)^{-\gamma_1} \qquad (5)$$

where, D_{no}=20.72 cm^2/s and N_{ref} =10^{17} cm^{-3} and γ_1=0.42.

The effective intrinsic concentration is [11]

$$n^2_{ie}(x) = n^2_{io}\left(\frac{N_A(x)}{N_{ref}}\right)^{\gamma_2} \qquad (6)$$

where n_{io} is the intrinsic carrier concentration without any bandgap narrowing, and the constant γ_2 is equal to 0.69.

The doping profile used in this analysis is given by [12]

$$N_A(x) = N_{A0}\exp\left(-x^2/2\sigma^2\right) \qquad (7)$$

where

$$\sigma = W_b \Big/ \left\{2\ln\left[N_{A0}/N_A(W_b)\right]\right\}^{\frac{1}{2}} \qquad (7a)$$

For low injection $n(x) << N_A(x)$ and the quasi-neutral condition becomes

$$N_A(x) = p(x) \qquad (8)$$

Eqn.(4) can be written as

$$-J_n = qD_n(x)\frac{n^2_{ie}(x)}{N_A(x)}\frac{d}{dx}\left(\frac{n(x)N_A(x)}{n^2_{ie}}\right) \qquad (9)$$

Using the equation for $D_n(x)$, $N_A(x)$ and $n_{ie}(x)$ in (9) gives

$$J_n = -q\,D_{no}\,n^2_{io}\,N_{ref}^{-(\gamma_2-\gamma_1)}\,N_{A0}^{-(1+\gamma_1-\gamma_2)} \times e^{(1+\gamma_1-\gamma_2)x^2/2\sigma^2}\frac{d}{dx}\left[\frac{n(x)N_A(x)}{n^2_{ie}(x)}\right] \qquad (10)$$

Upon integration of (10) from *x =0* to *x* gives

$$n(x) = \left(n(0) - J_n A\sqrt{\left(1-e^{-ax^2/\sigma^2}\right)}\right)e^{-(\gamma_2-1)x^2/2\sigma^2} \qquad (11)$$

where, $A = \dfrac{1}{q\,D_{no}}\left(\dfrac{N_{A0}}{N_{ref}}\right)^{\gamma_1}\sqrt{\dfrac{\pi}{2a}}\sigma$

and $a = 1+\gamma_1+\gamma_2$

At *x=0*, the electron concentration is given by [13]

$$n(0) = -0.5\,N_{A0} + 0.5\,N_{A0}\left[1+\frac{4n^2_{ie}(0)}{N^2_{A0}}e^{V_{be}/V_t}\right]^{1/2} \qquad (12)$$

Assuming that the electron velocity in the base-collector depletion region saturates at v_s, the electron current density J_n at $x=W_b$ is given by

$$n(W_b) = \frac{J_n}{q\,v_s} \qquad (13)$$

where $n(W_b)$ is the electron concentration at $x=W_b$.

Substituting this value of $n(W_b)$ in (11) and rearranging it, J_n can be expressed as

$$J_n = q\,v_s\,n(0)B \qquad (14)$$

where,

$$B = \frac{1}{\left(e^{(\gamma_2-1)W_b^2/2\sigma^2} + q\,v_s\,A\sqrt{\left(1-e^{-aW_b^2/\sigma^2}\right)}\right)}$$

The base stored charge per unit area is given by

$$Q_{nB} = q\int_0^{W_b} n(x)dx = q\,n(0)\sqrt{\frac{\pi}{2}\frac{\sigma^2}{(\gamma_2-1)}\left(1-e^{-(\gamma_2-1)W_b^2/\sigma^2}\right)} - K \qquad (15)$$

where

$$K = q\,J_n\,A\left(\sqrt{\frac{\sigma^2}{(1-\gamma_2)}\left(\frac{\pi}{4}\right)}\sqrt{e^{-(\gamma_2-1)w^2/\sigma^2}\left(1-e^{-aw^2/\sigma^2}\right)}\right)$$

$$-q\,J_n\,A\left[\sqrt{\frac{\sigma^2}{(1-\gamma_2)}\left(\frac{\pi}{4}\right)}\left\{2\sqrt{1-e^{-aw^2/\sigma^2}}+M\right\}\right]$$

where,

$$M=\sum_{s=1}^{\infty}(-1)^n\frac{m(m-1)(m-2)....(m-n+1)}{s!}P$$

where, $m=(\gamma_2-1)/(2a)$ and

$$P=\frac{\left(1-e^{-aw^2/\sigma^2}\right)^{s+\frac{1}{2}}}{s+\frac{1}{2}}$$

Using (14) and (15) in (1), the expression for transit time τ_b is given by

$$\tau_b=\frac{Q_{nB}}{J_n} \qquad (16)$$

Expression (15) is the main result of this analysis. Base transit time depends upon $n(0)$, σ, $N_A(0)$ and W_b. The electron concentration $n(0)$ at the base side of base-emitter junction can be determined if V_{be} is known.

3. RESULTS

The equation for the base transit time of an n^+pn^- bipolar transistor with a gaussian doped base is obtained from J_n and Q_{nB}. Figure 1 gives the variation of the normalized minority carrier density $n(x)/n(o)$ within the base for different values of σ for a constant V_{be}. The normalized minority carrier concentration decreases with x and for increase of σ the value at any x increases.

Figure 2 compares the trajectories of J_n as a function of V_{be}, obtained analytically as well as numerically [6]. The analytical values are fairly close to those obtained from numerical calculation.

The dependence of base transit time on minority carrier injection ratio, $n(0)/N_{A0}$, is shown in Fig. 3 for three values of N_{A0}. Eqn. (7a) shows that for a given base width σ depends upon $N_A(W_b)$ and N_{A0}. For a given N_{A0}, $N_A(W_b)$ has been changed accordingly in order to have the same value of σ. Fig. 3 shows that the transit time depends upon N_{A0} and it increases with N_{A0} for a given value of σ. Therefore, for gaussian base profile the transit time depends on N_{A0} which is in contradictory to the base with uniform doping profile.

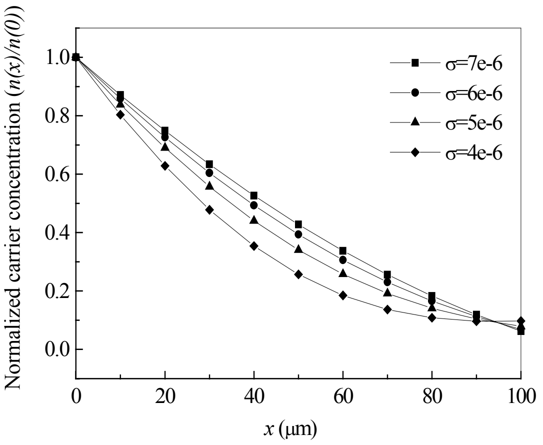

Fig. 1: Minority carrier concentration profile within the base for various values of σ with a constant V_{be}= 0.8 Volt.

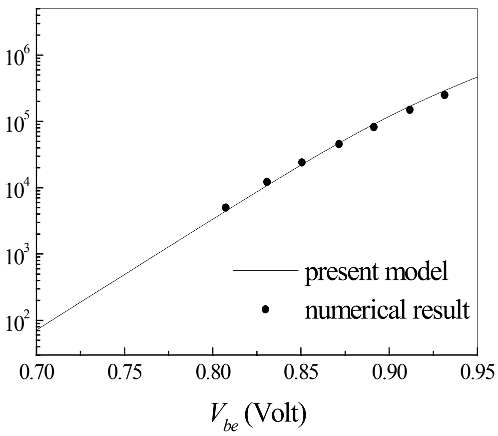

Fig. 2: Current density (J_n) Vs emitter-base (V_{be}) voltage.

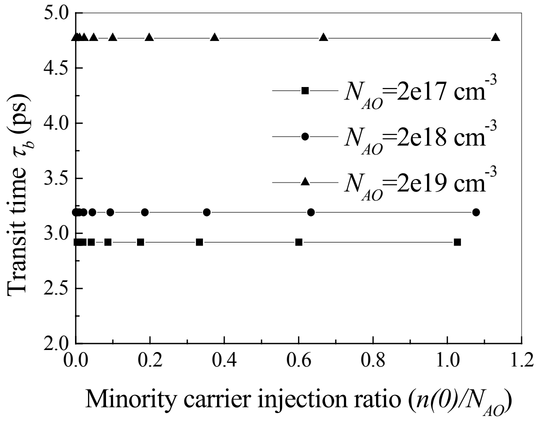

Fig. 3: Transit time as a function of minority carrier injection ratio for different values of N_{AO}.

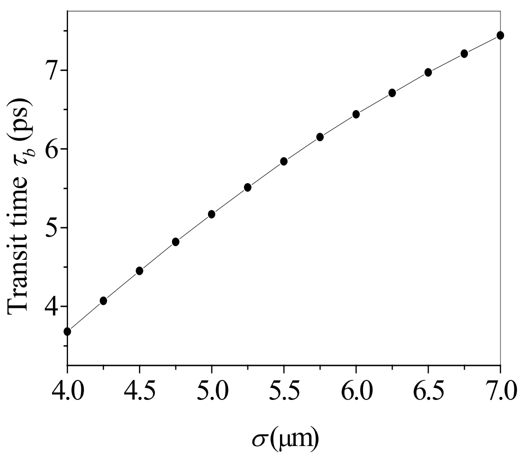

Fig. 4: Transit time with σ for V_{be} = 0.8 Volt.

Figure 4 shows τ_B as a function of σ for V_{be} = 0.8 Volt. The plot shows that the base transit time depends upon σ and it is an increasing function of σ. It is evident from (3) that the increase in σ reduces the aiding field in the base. Therefore, the base transit time increases with σ.

4. CONCLUSION

An equation for base transit time for the modern bipolar transistor with gaussian doping base is obtained considering bandgap narrowing effect, doping dependence of mobility and velocity saturation. For low level of injection the base transit time is found to be independent of base-emitter voltage. The base transit time depends on σ (slope of base doping). The analytical values have been observed to be in good agreement with the results of the numerical calculation available in literature.

REFERENCES

[1] H. M. Rein and M. Möller, “Design considerations for very-high-speed Si-bipolar IC’s operating up to 50 Gb/s,” *IEEE J. Solid-State Circuits*, vol. 31, pp.1076-1090, 1996.

[2] Van Den Baisen J.H., “A simple analysis of Transit times in bipolar transistors,” *Solid-State Electron.*, vol. 28, No. 11, pp. 1101-1103, 1985.

[3] K. Suzuki, “Analytical base transit time model for high-injection regions,” *Solid-State Electronics*, vol. 37, pp. 487-493, 1994.

[4] Yuan JS, “Effects of base profile on the base transit time of the bipolar transistor for all levels of injection”, IEEE Trans. Electron Devices, vol. 41. No. 2, pp 212-216, Feb 1994.

[5] K. Suzuki, “Optimum base doping profile for minimum base transit time considering velocity saturation at base-collector junction and dependance of mobility and bandgap narrowing on doping concentration,” *IEEE Trans. Electron Devices*, vol. 48, No. 9, pp. 2002-2207, 2001.

[6] P. Ma, L. Zhang, Y. Wang, “Analytical model of collector current density and base transit time based on iteration method,” *Solid-State Electronics,* vol. 39, No. 11, pp 1686-1686, 1996.

[7] M. M. L. Jahan and A. F. M. Anwar, “An analytical expression for base transit time in an exponentially doped base junction transistor,” *Solid-State Electronics*, vol. 39, pp. 133-136, 1996.

[8] M. M. Shahidul Hassan, Md. Ziaur Rahman Khan and Touhidur Rahman, “Empirical Expression for Base Transit Time in Bipolar Transistors,” Submitted to *IEEE Trans. Electron Devices* for review.

[9] K. Suzuki, “Optimum base doping profile for minimum base transit time,” *IEEE Trans. Electron Devices*, vol. 38, pp. 2128-2133, 1991.

[10] S. Szeto and R. Reif, “Reduction of f_t by nonuniform base bandgap narrowing,” *IEEE Electron Devices Lett.*, vol. 10, pp. 340-343, Aug. 1989.

[11] S. Selberherr, “Analysis and simulation of Semiconductor Devices,” Vienna, Austria: Springer-Verlag, 1984.

[12] Guoxin Li, Arnost Neugroschel, Chih-Tang Sah, Don Hemmenway, Tony Rivoli, Jay Maddux, “Analysis of bipolar junction transistors with Gaussian Base-Dopant Impurity-Concentration Profile,”IEEE Transaction on Electron Devices, vol. 48, No. 12, 2001.

[13] Muller RS, Kamins TI. Device electronics for intregrated circuits, 2nd ed. New York: wiley; 1986. p. 324.