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Induced base transit time of an epitaxial $n^+pn^-n^+$ bipolar transistor in saturation

M.M. Shahidul Hassan [a,*], A.H.M.A. Rahim [b]

[a] Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh
[b] Department of Electrical Engineering, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

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Abstract

Minority carrier recombination, drift and diffusion currents are considered in determining induced base transit time of an epitaxial $n^+pn^-n^+$ bipolar transistor operated in quasi-saturation and hard-saturation. The dependence of transit time upon the characteristics of the epitaxial–substrate interface is also studied for the transistor driven into hard saturation. The study shows that transit time in the induced base is significant when the transistor is driven into hard saturation and the interface is highly reflecting. The induced base transit time calculated analytically is compared with numerically obtained results in order to demonstrate the validity of the assumptions made in deriving analytical expressions. The closed form expressions for collector current density and transit time offer a physical insight into device operations at various bias conditions and are a useful tool in device design and optimization.

1. Introduction

Injection of minority carriers in the lightly doped collector is a key factor limiting the performance of epitaxial $n^+pn^-n^+$ bipolar junction transistors (BJTs). In quasi-saturation mode of operation [1], the collector–base junction is internally forward biased resulting in injection of minority carriers in an injection region formed near the junction. As a result, the injection region is electrically equivalent to a portion of the base region and this region is called induced base. The time required by carriers to travel the induced base is called induced base transit time τ_C in this paper. Due to an increase of charge storage in the induced base, collector current density J_C will be reduced [2] and the induced base transit time, which is often the dominant factor for the total delay time of BJTs, is enlarged. As a result of increase of the induced base transit time the different performance parameters like the maximum frequency of operation and cut-off frequency of a bipolar transistor will decrease. Note that the well-known Kirk effect [3] also limits the performance of a BJT. But the physical mechanism for quasi-saturation is different from Kirk phenomenon. The Kirk effect is a phenomenon which occurs when the collector current density J_C is high and the bipolar transistor is reverse-biased at high collector–base voltage V_{CB}. The collector space charge region moves towards the low–high (n^-n^+) interface with J_C. In the present paper, quasi-saturation and hard-saturation are studied. In hard saturation mode of operation, the whole collector region is occupied by minority carriers. Some work has been reported on base transit time of a BJT operated in saturation. Van den Biesen [4] used a regional analysis to study transit times of BJTs as a function of base–emitter bias. No closed form solution in [4] was obtained. Recently Dai and Yuan [5] have obtained an analytical equation of base transit time taking high-current quasi-saturation into account. But recombination and drift currents in epitaxial collector were neglected The minority carrier reflecting nature of low–high (n^-n^+) junction at the collector contact was also not considered in their work. Transit time can be obtained if the minority carrier distribution within

* Corresponding author. Fax: +880-2-9611594.
E-mail address: shassan@eee.buet.ac.bd (M.M. Shahidul Hassan).

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the induced base is known. In order to find more accurate expression for minority carrier profile, the analysis should include recombination, diffusion and drift currents within the induced base. As the collector minority carrier lifetime [6] is finite, minority carrier recombination within the injection region cannot be neglected at high injection.

In the present analysis minority carrier recombination, drift and diffusion currents are considered for finding minority carrier profile and hole current density in the collector both for quasi- and hard-saturation modes of operation of the transistor. The work shows that the collector transit time of a BJT operated in hard saturation depends upon the characteristics of the epitaxial–substrate interface and can become significant when the interface is highly reflecting. The proposed analytical induced base transit time model is applicable for all levels of injection in the collector. The validity of the assumptions made in obtaining analytical expressions has been verified through a numerical solution of the exact equations of the device.

2. Analysis

The induced base transit time τ_C of a BJT operated in quasi-saturation is given by the following relation

$$\tau_c = -q\int_0^{x_1} \frac{n(x)}{J_{nc}(x)}\,dx \tag{1}$$

where, $n(x)$ is the electron concentration and $J_{nc}(x)$ is the electron current density in the collector, q is the electronic charge and x_1 is the width of the injection region.

The basic equations required for finding $n(x)$ and $J_{nc}(x)$ within the injection region are

$$J_{nc}(x) = q\mu_n n(x)E(x) + qD_n\frac{dn}{dx} \tag{2}$$

$$J_{pc}(x) = q\mu_p p(x)E(x) - qD_p\frac{dp}{dx} \tag{3}$$

$$\frac{1}{q}\frac{dJ_{nc}}{dx} = U_n \tag{4}$$

$$\frac{1}{q}\frac{dJ_{pc}}{dx} = -U_p \tag{5}$$

and the Poisson's equation

$$\frac{dE}{dx} = \frac{q}{\varepsilon_s}(p(x) - n(x) + N_C) \tag{6}$$

The symbols used are standard ones as given in the literature.

Exact solution of these nonlinear differential equations will be extremely difficult, if not impossible. In the following analysis, analytical expressions for the transit time for different regions of operation of a BJT have been derived considering some assumptions and approximations. Validity of the assumptions have been tested by comparing the results with the numerical solution of the exact equations. The analysis was carried out considering the device to be in (i) quasi-saturation, and in (ii) hard saturation.

2.1. Quasi-saturation

The quasi-neutrality condition is assumed to prevail in the injection region. The quasi-neutrality condition requires that

$$p(x) - n(x) + N_C \approx 0 \quad 0 \leqslant x \leqslant x_1 \tag{7}$$

The electron current density $J_{nc}(x)$ can be obtained from the hole current density $J_{pc}(x)$ using the following relation

$$J_C = J_{nc}(x) + J_{pc}(x) \tag{8}$$

where, the collector current density J_C is independent of x and is constant.

Substituting Eqs. (7) and (8) in Eq. (1), the expression for τ_C can be of the following form

$$\tau_C = -q\int_0^{x_1} \frac{p(x) + N_C}{J_C - J_{pc}(x)}\,dx \tag{9}$$

$p(x)$ and $J_{pc}(x)$ are obtained considering that the collector is lightly doped n-type Si semiconductor of constant doping N_C. It is bounded by heavily doped n^+ region at a distance W_C from the base–collector junction. For high level of injection, an appreciable number of holes are injected into the injection region. For high injection, $p(x) \approx n(x)$ and recombination is considered. At low level of injection, $n(x) \approx p(x) + N_C$ and carrier recombination within the induced base can be neglected.

2.1.1. High injection

When differentiating Eqs. (2) and (3) with respect to x and using Eqs. (4) and (5) and applying the condition that $dn/dx = dp/dx$ and $p(x) \approx n(x)$, it can be shown that

$$\frac{p(x)(1+m)}{\mu_{pi}\tau_p} = 2V_T\frac{d^2p}{dx^2} \tag{10}$$

where, $V_T = kT/q$, $m = \mu_{pi}/\mu_{ni}$ and μ_{ni} (μ_{pi}) is the electron (hole) mobility in the injection region. In obtaining Eq. (10) slow variation of electric field, dE/dx, within the conductivity modulated injection region is disregarded and the recombination process is given by $U = p(x)/\tau_p$. Here τ_p is the hole life time.

The solution of Eq. (10) is of the form

$$p(x) = p_0 \cosh\frac{x}{L_a} + B \sinh\frac{x}{L_a} \tag{11}$$

where, p_0 is the hole minority carrier density at the base–collector metallurgical junction, $x = 0$ and B is an arbitrary constant. The ambipolar diffusion length is given by

$$L_a = \left(\frac{2V_T \tau_p \mu_{pi}}{1+m}\right)^{1/2} \tag{12}$$

The neutrality condition (7) does not hold all along the collector because the hole concentration will reduce to zero before the electron concentration becomes equal to N_C [7]. There is no analytical solution for $n(x)$ in the region adjacent to the injection region [7]. The numerical analysis [7] shows that the width of this region is very thin. In the present analytical work, this region is not considered.

At the boundary x_1 of the injection region, $p(x_1)$ is always somewhat arbitrary. In this work, $p(x_1)$ is considered to be equal to N_C. Using this boundary condition and $J_p = 0$ at $x = x_1$, minority carrier profile can be obtained from Eqs. (2) and (3) and can be written as

$$p(x) = N_C \cosh\left(\frac{x_1 - x}{L_a}\right) - \frac{J_C L_a}{2qD_{ni}} \sinh\left(\frac{x_1 - x}{L_a}\right) \tag{13}$$

Eliminating electric field $E(x)$ from the expressions for current densities in Eqs. (2) and (3), and substituting the derivative of $p(x)$ obtained from Eq. (13), and using Eq. (12), $J_{pc}(x)$ can be expressed as

$$J_{pc}(x) = -\frac{2mJ_C}{1+m} \sinh^2\left(\frac{x_1 - x}{2L_a}\right) + \frac{qL_a N_C}{\tau_p} \times \sinh\left(\frac{x_1 - x}{L_a}\right) \tag{14}$$

Substituting Eqs. (13) and (14) in Eq. (9), the integration gives an analytical expression for transit time as,

$$\tau_{ch} = \tau_p \ell n\left[1 + \frac{m}{1+m} \sinh^2\frac{x_1}{L_a} \operatorname{sech}\frac{x_1}{L_a} - \frac{2qD_{pi}N_C}{(1+m)J_C L_a} \sinh\frac{x_1}{L_a}\right] \tag{15}$$

where τ_{ch} is the induced base transit time for high injection.

The hole current density J_{pco} entering the collector through the base at $x = 0$ can be obtained from (14). If J_{pco} is known for a given J_C, x_1 can be obtained from Eq. (14) and τ_{ch} can then be determined from Eq. (15).

The voltage drop across injection region under high level of injection can be evaluated by integrating electric field obtained from Eqs. (5) and (6) and substituting $p(x)$ from Eq. (13). Electric field $E(x)$ and V_{inj} are found to be,

$$E(x) = \frac{J_C}{q\mu_{ni}(1+m)p(x)} + \frac{(1-m)V_T}{(1+m)L_a p(x)} \times \left(N_C \sinh\frac{x_1 - x}{L_a} - \frac{J_C L_a}{2qD_{ni}} \operatorname{sech}\frac{x_1}{L_a} \cosh\frac{x_1 - x}{L_a}\right) \tag{16}$$

and

$$V_{inj} = -\frac{J_C L_a}{q\mu_{ni}(1+m)\sqrt{f^2 - p_0^2}} \times \ln\left[\frac{1 + p_0 \tanh(x_1/2L_a)\Big/\left(f - \sqrt{f^2 - p_0^2}\right)}{1 + p_0 \tanh(x_1/2L_a)\Big/\left(f + \sqrt{f^2 - p_0^2}\right)}\right] - \frac{V_T(1-m)}{1+m} \ln\frac{p_0}{N_C} \tag{17}$$

where,

$$f = \frac{J_C L_a}{2qD_{ni}} \operatorname{sech}\frac{x_1}{L_a} - p_0 \tanh\frac{x_1}{L_a}$$

2.1.2. Low injection

Under low injection, recombination within the injection region can be neglected. The hole current density J_{pco} is small in comparison with the electron current density J_{nc} ($x = 0$). The limit of collector current density J_C for which hole current J_{pco} can be neglected has been given in [8]

$$\left(1 + \frac{N_C}{p_0}\right) \ll \frac{\mu_{pi}}{\mu_{ni}} \frac{J_C}{J_{pco}} \tag{18}$$

The minority carrier hole profile $p(x)$ within the induced base region, as reported in the literature [7,9], is

$$p(x) - p_0 - 0.5N_C \ln\frac{p_0}{p(x)} = \frac{J_C}{2qD_{ni}} x \tag{19}$$

Using $p(x_1) = n_i$ [7], expressions for low-injection width and induced base transit time can be obtained as

$$x_1 = -\frac{2qD_{ni}}{J_C}\left[(p_0 - n_i) + 0.5N_C \ln\frac{p_0}{n_i}\right] \tag{20}$$

$$\tau_{cl} = -\frac{qN_C}{J_C} x_1 + \frac{q^2 D_{ni}}{J_C^2}[(p_0 - n_i)(p_0 + N_C + n_i)] \tag{21}$$

where, n_i is the intrinsic carrier concentration.

V_{inj} for low injection can be obtained by integrating Eq. (3) between limits 0 to x_1 and substituting $p(0) = p_0$ and $p(x_1) = n_i$ as,

$$V_{inj} = V_T \ln(p_0/n_i) \tag{22}$$

In the above derivation, J_{pc} is considered to be zero.

2.1.3. Voltage outside the injection region

The collector can be divided into three different regions, namely (a) injection region, (b) an intermediate region and (c) an end region [7]. The injection region is terminated at $x = x_1$, where, both the hole current density and excess hole concentration are neglected. But electron density decreases and space-charge neutrality does not exist in (b). The numerical work [7] shows that the width of this region is very thin. In this work, this region is neglected. In the end region, electron current density determines both the field and the electron distributions within this region.

The voltage across this region was derived in [7] and was found to be

For $|J_C| < J_0$,

$$V_1 = -\frac{v_s(W_C - x_1)}{\mu_{nc}(-(J_0/J_C) - 1)} \tag{23a}$$

For $|J_C| > J_0$

$$V_1 = E_s(W_C - x_1) - \frac{qN_C}{2\varepsilon_s}\left(1 + \frac{J_C}{J_0}\right)(W_C - x_1)^2 \tag{23b}$$

where, μ_{nc} is the electron mobility in the end region, E_s is the electric field for which the electron velocity takes its scattering limited value v_s [9,10] and $J_0 = qv_sN_C$.

The transistor enters active mode from quasi-saturation when base–collector junction becomes reverse-biased. The limit of quasi-saturation mode is reached when $x_1 = 0$. When the terminal voltage V_{CE} exceeds the voltage given in Eq. (24), the device enters the active mode. V_{CE} can be written as [8,11],

$$V_{CE} = V_{BE} + I_BR_B - \left(\frac{1}{1 + J_C/J_0}\right)\rho W_C J_C - I_CR_{sat} \quad \text{for } |J_C| < J_0 \tag{24a}$$

and

$$V_{CE} = V_{BE} + I_BR_B + E_sW_C - \frac{qN_C}{2\varepsilon}\left(1 + \frac{J_C}{J_0}\right)W_C^2 - I_CR_{sat} \quad \text{for } |J_C > J_0| \tag{24b}$$

where, ρ is the resistivity of the collector, V_{CE} is the externally applied voltage between collector and emitter, V_{BE} is the base–emitter junction voltage, R_B is the extrinsic base resistance, R_{sat} is the external series resistance.

The dc collector to emitter voltage under quasi-saturation is given by

$$V_{CE} = V_{BE} + V_{CB} + I_BR_B + V_{inj} + V_1 - I_CR_{sat} \tag{25}$$

where, V_{CB} is the collector–base junction voltage. The emitter–base junction voltage V_{BE} can be obtained from J_{BE} [5]. The hole current density J_{BE} in the emitter due to the injection of holes from forward biased emitter–base junction is given by $J_{BE} = J_B - J_{pco}$. As the emitter is heavily doped the band gap narrowing effect [12] has to be considered in calculation of V_{BE}.

2.2. Hard saturation

When the transistor is driven into hard saturation, minority carrier occupies the whole collector region, and the width of the injection region will become equal to the collector width W_C. The hole concentration p_w at $x = W_C$ is determined by hole current density J_{pw} at the interface. The hole current density flowing through it is [13]

$$J_{pc}(W_C) = qS_{eff}p_w \tag{26}$$

where, S_{eff} is the effective surface recombination velocity [13]. Considering p_w in Eq. (26) as the boundary value for $p(x)$, an expression for $p(x)$ within the collector can be obtained from Eq. (13) and is written as,

$$p(x) = \left[p_0\left(\cosh\frac{W_C - x}{L_a} + \frac{L_a(1+m)S_{eff}}{2D_{pi}}\sinh\frac{W_C - x}{L_a}\right) + \frac{J_CL_a}{2qD_{ni}}\sinh\frac{x}{La}\right] \Big/ \left[\cosh\frac{W_C}{L_a} + \frac{L_a(1+m)S_{eff}}{2D_{pi}}\sinh\frac{W_C}{L_a}\right] \tag{27}$$

The hole current density $J_{pc}(x)$ can be obtained by taking the derivative of Eq. (27) and substituting it in Eqs. (2) and (3)

$$J_{pc}(x) = \frac{mJ_C}{1+m} + \frac{2qD_{pi}}{(1+m)TL_a}\left[p_0\left(\sinh\frac{W_C - x}{L_a} + \frac{(1+m)L_aS_{eff}}{2D_{pi}}\sinh\frac{W_C - x}{L_a}\right) - \frac{J_CL_a}{2qD_{ni}}\cosh\frac{x}{L_a}\right] \tag{28}$$

where,

$$T = \cosh\frac{W_C}{L_a} + \frac{(1+m)S_{eff}L_a}{2D_{pi}}\sinh\frac{W_C}{L_a}$$

The induced base transit time can be obtained from Eqs. (9), (27) and (28) and can be expressed as

$$\tau_{cs} = \tau_p\left[\ell n\left(\left[J_C - \frac{2qD_{pi}}{TL_a}\left(\frac{p_0L_a(1+m)S_{eff}}{2D_{pi}}\cosh\frac{W_C}{L_a} - \frac{J_CL_a}{2qD_{ni}} + p_0\sinh\frac{W_C}{L_a}\right)\right] \Big/ \left[J_C - \frac{2qD_{pi}}{TL_a}\left(\frac{p_0L_a(1+m)S_{eff}}{2D_{pi}} - \frac{J_CL_a}{2qD_{ni}}\cosh\frac{W_C}{L_a}\right)\right]\right)\right] \tag{29}$$

The voltage across the collector is given by

$$V_{inj} = -\frac{J_C L_a T}{q\mu_{ni}(1+m)\sqrt{B^2 - A^2}} \times \ln\left(\frac{1 + A\tanh(W_C/2L_a)/(B - \sqrt{B^2 - A^2})}{1 + A\tanh(W_C/2L_a)/(B + \sqrt{B^2 - A^2})}\right) - V_T\left(\frac{1-m}{1+m}\right)\ln\frac{p_0}{p_w} \tag{30}$$

where,

$$p_w = \left[p_0 + \frac{J_C L_a}{2qD_{ni}}\sinh\frac{W_C}{L_a}\right] \Big/ \left[\cosh\frac{W_C}{L_a} + \frac{(1+m)S_{eff}L_a}{2D_{pi}}\sinh\frac{W_C}{L_a}\right]$$

$$A = p_0 + \frac{J_C L_a}{2qD_{ni}}\sinh\frac{W_C}{L_a}$$

$$B = \frac{p_0(1+m)L_a S_{eff}}{2D_{pi}} - \frac{J_C L_a}{2qD_{ni}}\cosh\frac{W_C}{L_a}$$

2.3. Total base transit time

The total base transit time is given by [5]

$$\tau_B = \frac{q}{-J_n}\int_{-W_B}^{0} n(x)\,dx + \tau_C$$

where, J_n is electron current density in the base, W_B is the base width and τ_C is the induced base transit time. Neglecting recombination within the thin base, τ_B is given by [5]

$$\tau_B = \frac{qW_B}{2J_n}(n(0) + n(-W_B)) + \tau_C \tag{31}$$

where, $n(0)$ and $n(-W_B)$ can be calculated from Eqs. (7) and (9) of [5].

3. Results and discussion

The induced base transit time τ_C of an epitaxial $n^+pn^-n^+$ bipolar transistor has been calculated in high injection quasi-saturation, low injection quasi-saturation, and also in hard saturation conditions through Eqs. (15), (21) and (29), respectively. The dependence of τ_C on collector current density J_C, collector width W_C, emitter–collector voltage V_{CE}, and effective surface recombination velocity S_{eff} have been incorporated in the derivations. Voltage across the emitter–base junction V_{BE} and base–collector junction V_{BC} for a given J_B and voltage across different regions in the collector also appear in the computation. The analytical expressions for $p(x)$ and $J_{pc}(x)$ are obtained assuming a number of approximations. To evaluate the analytical values, the exact system Eqs. (2)–(6) were solved numerically. Nonlinear differential equations (2)–(6) were normalized and solved by ODE routines in the Matlab. In this computational work, the collector doping density $N_C = 1 \times 10^{15}$ cm^{-3} is considered. Electron and hole mobilities are obtained from the relations given in [14].

Fig. 1 compares the trajectories of J_{pc} as a function of x, obtained analytically as well as numerically. Fig. 2 shows the comparison of hole density p. Fig. 3 compares the values of τ_C against V_{BC}. Employing Eq. (1), each value of τ_C is computed through a trapezoidal integration of the profiles generated in Figs. 1 and 2. It can be seen that the analytical values are fairly close to those obtained numerically. The boundary values required for solutions of the ODEs were obtained as follows: for given V_{BE} and V_{BC}, n_0 and p_0 are obtained by the procedure given in [15]; J_{no} is obtained by the procedure given in [2]; J_{pco} and E_0 are obtained by substituting $x = 0$ in expressions (14) and (16), respectively.

Fig. 4 gives the variation of τ_C as a function of S_{eff}. Hole density p_w and total charge storage under the profile $p(x)$ within the collector in hard saturation decrease with increasing S_{eff}. This decrease of total charge reduces induced transit time τ_C with S_{eff}. At low values of S_{eff}, the interface effectively blocks the minority carriers to enter the n^+ region and the stored charge increases resulting in an increase of τ_C. Fig. 5 shows J_{pco} and J_{pw} as a function of collector current J_C for a given J_B. The plot shows that at low collector current density J_C, a significant fraction of the total base current J_B will enter the collector and J_{pco} cannot be neglected. The

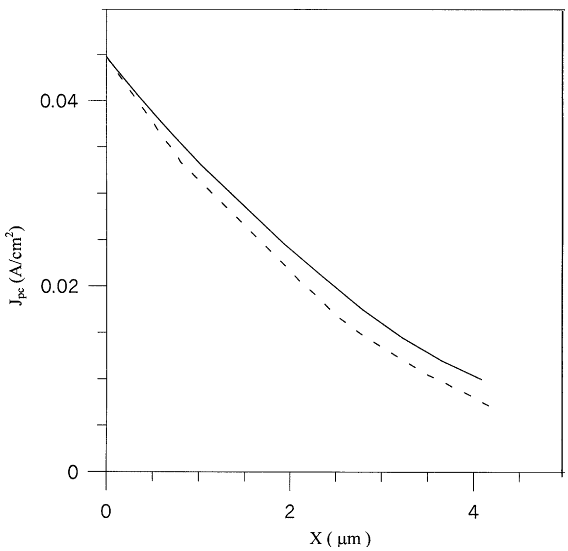

Fig. 1. Comparison of analytically obtained profile of collector minority carrier hole current density J_{pc} with numerically obtained profile of J_{pc} (—, numerical; - - -, analytical).

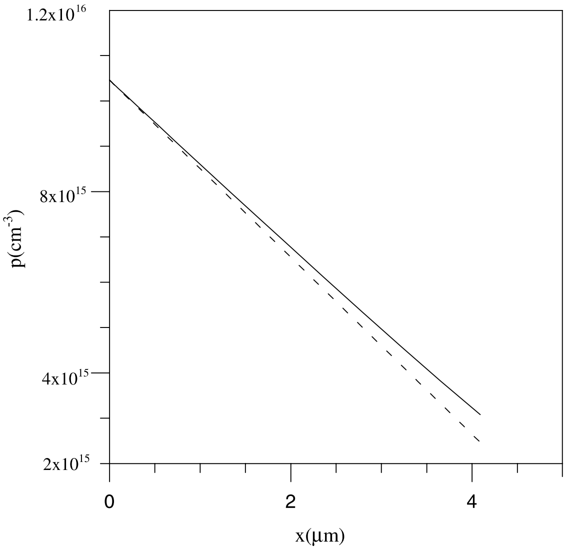

Fig. 2. Minority carrier hole distribution $p(x)$ within the collector when base–collector junction is forward biased (—, numerical; - - -, analytical).

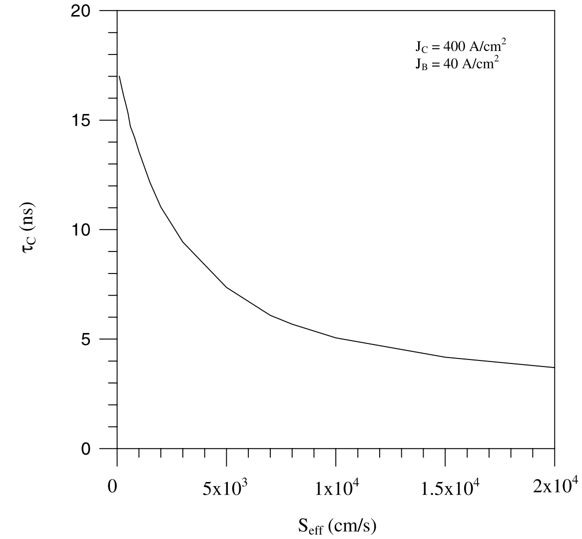

Fig. 4. Analytically calculated induced base transit time versus effective surface recombination velocity for given collector and base current densities for collector width of 5 μm and $N_C = 1 \times 10^{15}$ cm^{-3}.

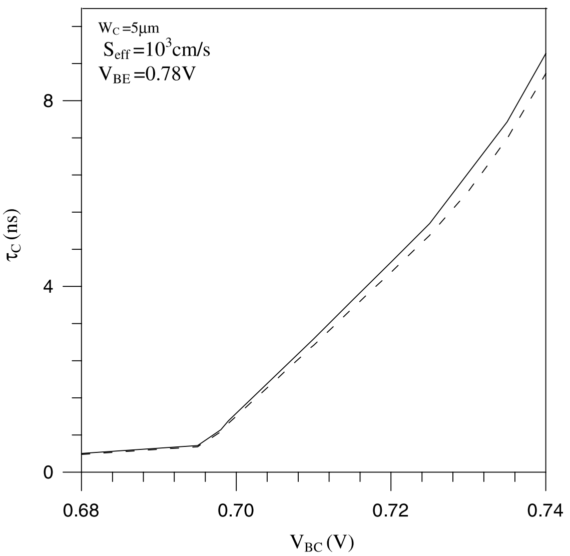

Fig. 3. Comparison of numerically calculated induced base transit time with analytical transit time versus base–collector junction voltage for a given base–emitter voltage (—, numerical; - - -, analytical).

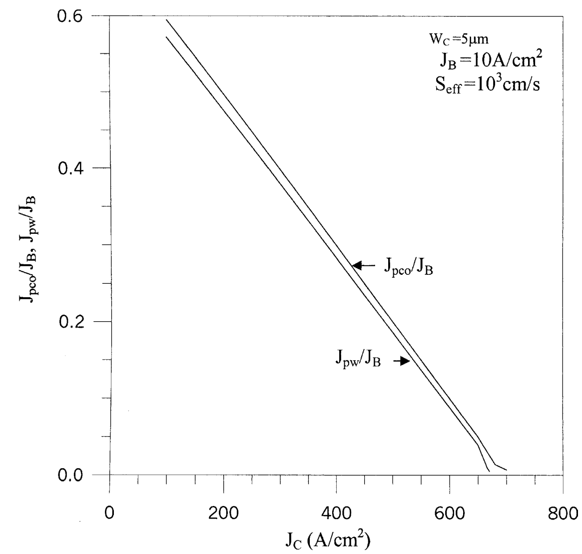

Fig. 5. Collector hole current density J_{pco} and J_{pw} as a function of collector current density J_C for a given base current density J_B.

transistor drives into saturation at low collector current density J_C, and the collector–base junction is strongly forward biased for a given J_B. The junction injects carriers into the induced base and recombination of the stored charge within the collector and also at the interface increases J_{pco} and J_{pw} with decrease of J_C. Fig. 6 shows τ_C as a function of W_C for given J_C and J_B. It is seen that induced base transit time increases with W_C. Increasing W_C increases voltage drops across the collector and makes quasi-saturation more prominent. Larger amounts of charge are required to drive BJT in hard saturation resulting in longer transit time. The induced base transit time and total base transit time as a

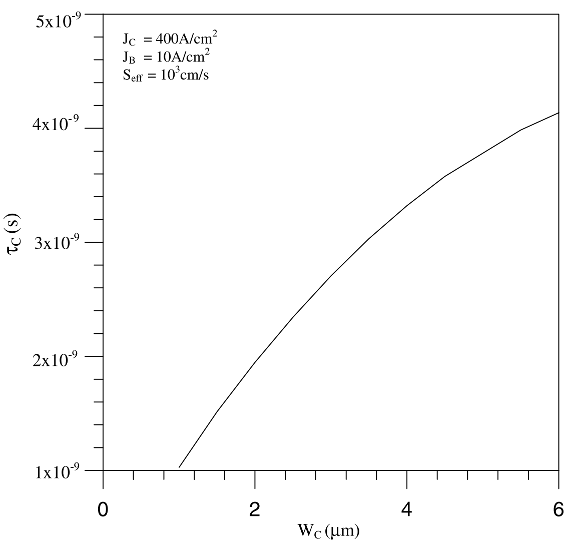

Fig. 6. Induced base transit time versus collector width for given collector and base current densities.

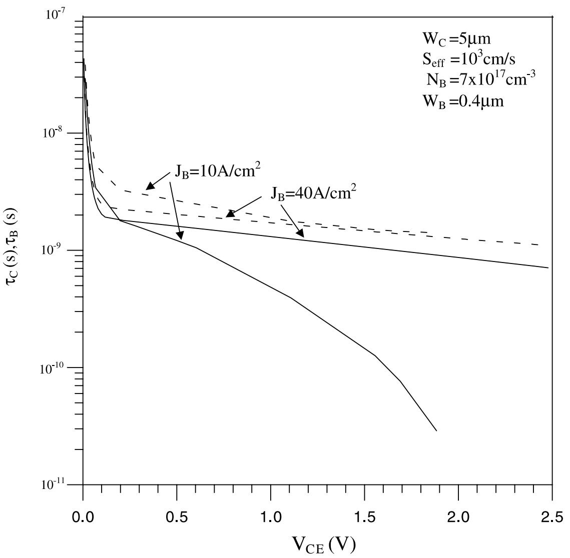

Fig. 7. Total base transit time and induced base transit time as a function of collector-emitter voltage V_{CE} for two base current densities (—, τ_C; - - -, τ_B).

function of V_{CE} are plotted in Fig. 7 for two values of J_B. At low V_{CE}, BJT operates in hard saturation and τ_C becomes large due to large storage of charge. The transistor enters active mode regime from quasi-saturation at high V_{CE}. In the active mode of operation, injection region disappears and the first term in Eq. (31) contributes to the total transit time. When BJT is in quasi-saturation, τ_C decreases with V_{CE} as the injection width decreases. The quasi-saturation occurs in a wider bias range if J_B is increased. This is because a larger J_B requires a larger V_{BE} and a larger V_{BE} results in a larger collector current and thus a larger voltage drop in the end region, keeping the internal base–collector junction forward biased long after the external base–collector terminal is reverse biased. For the BJT with large J_B, the increase of base transit time occurs at a large collector-emitter voltage because of this enhanced quasi-saturation effect.

4. Conclusion

Analytical derivations for base transit time for the modern bipolar transistor in quasi-saturation and also in hard saturation have been presented considering recombination, drift and diffusion currents within the collector. The induced base transit time is found to be dependent upon injection level of minority carriers. At low injection, the width of the induced base is small resulting in low transit time. When the collector is invaded by minority carriers, the transit time has been studied incorporating the minority carrier blocking property of the low–high junction. When the interface is highly reflecting, i.e. has a low value of S_{eff}, the interface prevents injected holes from freely reaching the collector contact and large holes are accumulated in the collector and transit time will increase with injection of minority carriers. The analytical values of transit times have been evaluated through numerical solution of exact system dynamic relations. The analytic values have been observed to be in good agreement with the numerical results.

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