

CURRENT-GAIN DEGRADATION IN NARROW BASE BIPOLAR TRANSISTORS DUE TO THE CARRIER VELOCITY LIMITATION

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SUMMARY

THE EFFECT OF CARRIER VELOCITY SATURATION in the base of bipolar transistors is studied. This effect limits the base transit time and also degrades the transistor current gain. It occurs in drift transistors and in uniform base transistors where there is no built in electrical field in the base. This effect significantly reduces transistor current gain in narrow base transistors and it can also be observed in transistors with a base of 1 μm or more in thickness.

1. INTRODUCTION

THE β DEGRADATION IN BIPOLAR TRANSISTORS due to phenomena in the emitter is discussed widely in the literature [1-9]. The following effects in the emitter are usually considered: band gap narrowing, emitter degeneration due to high doping level, carrier-

-carrier scattering, Auger recombination and others. These phenomena result in lowering β significantly (by as much as a few orders of magnitude). Therefore, similar effects in the base were not seriously considered.

In order to achieve a large value of β in an *npn* bipolar transistor, the current of injected holes into the emitter must be much smaller than the current of injected electrons into the base. With polysilicon emitters, high injection efficiency can be achieved since hole mobilities in polysilicon emitters are significantly lower due to the existence of grain boundaries. In heterojunction emitters, hole injection into the emitter is reduced by an energy gap difference. In modern bipolar transistors with either polysilicon emitters or heterojunction emitters, the effects in the emitter become less important and the effects in the base gain significance. In early transistors the carrier recombination in the base was considered, but as the base became thinner, this effect became negligible.

High-speed bipolar transistors today normally have metallurgical base thicknesses of about 0.1 μm to 0.2 μm . A quasi-neutral base-layer is even thinner. In these devices, the carrier velocity is saturated not only in the base-collector region (which is usually considered) but also in the neutral base region. Due to this velocity saturation, minority carriers can not be moved out of the vicinity of the emitter base junction fast enough, and this affects emitter injection efficiency. The purpose of this work is to analyse how this phenomenon affects the transistor current gain β .

2. CARRIER TRANSPORT THROUGH THE BASE WITH CARRIER VELOCITY LIMITATIONS IMPOSED

Neglecting recombination in the thin base layer and assuming a one-dimensional model with low injection levels, the steady-state electron current density in the base can be expressed with the well known drift-diffusion equation:

$$J_n = q D_n \frac{dn}{dx} + q \mu_n V_T \frac{n}{N_A} \frac{dN_A}{dx} \quad (1)$$

where: q – the electron charge, μ_n – an electron mobility, $n(x)$ – the electron concentration, $N_A(x)$ – impurity concentration in the base.

Using the Einstein relationship, $D_n = V_T \mu_n$, Eq. (1) can be also written in the form:

$$J_n = -q n(x) v(x) \quad (2)$$

where $v(x)$ is the electron velocity in base given by:

$$v(x) = -D_n \left(\frac{1}{n} \frac{dn}{dx} + \frac{1}{N_A} \frac{dN_A}{dx} \right) = -D_n \frac{d}{dx} \ln(n N_A). \quad (3)$$

When Eq. (3) is used to calculate the carrier velocity in a narrow base transistor, velocities in excess of the thermal velocity for silicon ($v_{th} \approx 10^7$ cm/s) in the base region are obtained. In real devices the average carrier velocity cannot be greater than the thermal velocity. This physical velocity limitation can be enforced by using the Mathiessen rule for combining two phenomena:

$$v_L(x) = \frac{1}{\frac{1}{v_s} + \frac{1}{v(x)}}. \quad (4)$$

There are a number of expressions to approximate the carrier velocity (mobility) limitation as a function of an electric field [10]. For this analysis the carrier velocity limitation given by [11] is used:

$$v_L = \frac{v}{\frac{1}{2} + \frac{1}{2} \sqrt{1 + \sqrt{2} \frac{v}{v_{sat}}} + 4 \left(\frac{v}{v_{sat}} \right)^2} \quad (5)$$

where $v_{sat} \approx 10^7$ cm/s is the saturation velocity in silicon and $v(x)$ is given by (3).

In order to find the carrier distribution $n(x)$ in the neutral base with the assumption that the classical drift-diffusion carrier velocity given by (3) is limited by formula (5) the following set of equations must be solved:

$$J_n = \frac{2q n(x) v(x)}{1 + \sqrt{1 + \sqrt{2} \frac{v(x)}{v_{sat}}} + 4 \left(\frac{v(x)}{v_{sat}} \right)^2} \quad (6)$$

where

$$v(x) = -D_n \left(\frac{1}{N_A} \frac{dN_A}{dx} + \frac{1}{n} \frac{dn}{dx} \right) = -D_n \frac{d}{dx} \ln(n N_A). \quad (7)$$

This solution has to be carried out together with Poisson's equation in the base-collector depletion layer:

$$E(x) = \frac{q}{\epsilon \epsilon_0} \int_{x_C}^x N_A(x) dx + E_b(x_C). \quad (8)$$

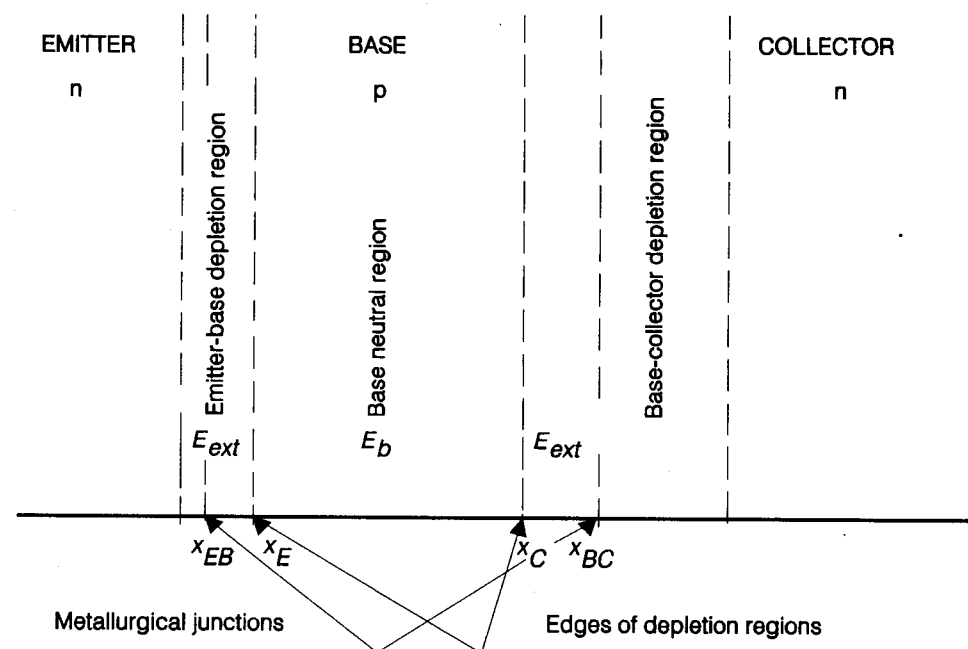


FIG. 1. Illustration of terms and symbols used for description of the transistor base

The same electrical field exists on both sides of x_C and the relation $E_b(x_C) = E_{ext}(x_C)$ should be used as a boundary condition (FIG. 1).

3. NUMERICAL ALGORITHM

With the entire metallurgical base is divided into 1000 sections, the numerical algorithm proceeds as follows:

- 1) The built-in electric field in the base is calculated for each section using:

$$E_b(x) = V_T \frac{1}{N_A(x)} \frac{dN_A(x)}{dx} . \quad (9)$$

- 2) Using Poisson's equation (8), the size of the base-collector depletion region and the electric field $E_{ext}(x)$ are calculated (FIG. 1). Note that at the interface $x = x_C$ the electric field $E_b(x_C)$ is obtained from using (9) and is used as a boundary condition in the solution of the Poisson's equation. The charge of moving carriers $qn(x)$ is also considered

but in the first iteration $n(x) = 0$ is assumed. Note that after steps 1) and 2) the electrical field in the entire metallurgical base is known.

3) For the given value of the current J_{nt} through the base the initial electron concentration at the base-collector metallurgical junction $n(x_{BC})$ (FIG. 1) is calculated from:

$$n(x) = \frac{J_n}{q v_L(x)} = \text{const} \quad (10)$$

where the electron velocity v_L is calculated from Eq. (5) with the assumption that at x_{BC} the drift is the dominant mechanism and the carrier velocity $v = \mu E_{ext}(x_{BC})$.

4) Since the recombination phenomena in a narrow base can be neglected, the current through each of the 1000 sections is the same:

$$J_n = \frac{q v_i (n_i + n_{i+1})}{1 + \sqrt{1} + \sqrt{2} \frac{v_i}{v_{sat}} + 4 \left(\frac{v_i}{v_{sat}} \right)^2} \quad (11)$$

where: n_i, n_{i+1} – electron concentrations at nodes i and $i + 1$, v_i – the unlimited carrier velocity computed using the incremental formula derived from (3):

$$v_i = D_n \frac{2}{n_i + n_{i+1}} \frac{n_{i+1} - n_i}{\Delta x} + \mu_n E_i \quad (12)$$

where E_b is the electric field in section i computed earlier in steps 1) and 2).

Using the initial value $n(x_{BC})$ obtained in step 3) assumed to be n_{i+1} (1001 node) the adjacent value of electron concentrations n_i are computed using the Newton-Raphson method applied to the set of nonlinear Eqs. (11) and (12). The successive values of electron concentrations are computed starting at the edge of the collector, moving toward the edge of the emitter using an increment of Δx .

5) The electron distribution obtained in step 4) can now be used to improve solution of Poisson's equation. Steps 2) through 5) are repeated until convergence is reached. This usually requires 10 + 20 iterations in order to obtain the accuracy of computer resolution.

6) Once the minority carrier distribution is obtained, the carrier velocities are calculated from the carrier distribution in the base using Eq. (10).

Computations can be performed for cases with and without imposing the carrier velocity limitation. For the case without the velocity limitation, the denominator in Eq. (11) is equal to 2. It should be emphasized that the procedure just described allows

for computation of both the quasi-neutral base layer and the base-collector depletion layer and produces a smooth transition between those layers. In fact, in many cases it is difficult to clearly distinguish the boundary between those layers.

In narrow base transistors, impurity concentrations are relatively high, and a high electric field usually exists in the base-collector depletion region. When carriers with relatively low kinetic energy in the quasi-neutral base region reach the depletion region where a much higher electric field exists, they may move with significantly higher velocities than are predicted in a classical approach (higher than saturation velocity) until they gain higher kinetic energy [12, 13]. This occurs because the carrier scattering is a function of kinetic energy, not electric field. In narrow base transistors the minority carriers in the base have relative high energy (velocity close to saturation velocity) therefore the velocity overshoot phenomenon will not occur on the base-collector interface.

4. RESULTS OF NUMERICAL SIMULATIONS

In real transistors, impurity distributions in the base are nonuniform and the built-in electric field affects carrier transport. The carrier velocities are higher and carrier velocity limitations can have even more significant effects on transistor performance. Impurity distributions in bases of such transistors result from ion implantation, annealing and diffusion processes. The impurity profile is given approximately by the Gaussian distribution:

$$N(x) = N_T \exp \left[- \left(\frac{x(1-d)}{L_g} \right)^2 \right]. \quad (13)$$

Six different Gaussian distributions for $d = (0.0, 0.1, 0.2, 0.3, 0.4, 0.5)$ were chosen for the numerical simulations shown in FIG. 2. A transistor with $0.12 \mu\text{m}$ base thickness (metallurgical base-collector junction) was analysed first. Minority carrier distributions and carrier velocity distributions with and without carrier velocity limitations are shown in FIGS. 3–6. The transistor current was chosen to ensure that for both cases the electron concentration at the emitter-base edge was the same. This corresponds to the same voltage applied to the emitter-base junction. About 40% lower transistor current was observed when the effect of carrier velocity limitation was considered.

Similar computations were performed for transistors with base thicknesses ranging from $0.02 \mu\text{m}$ to $5 \mu\text{m}$ with impurity profiles shown in FIG. 2. FIGURE 7 illustrates the degradation effect due to the carrier velocity limitation for Gaussian-type profiles.

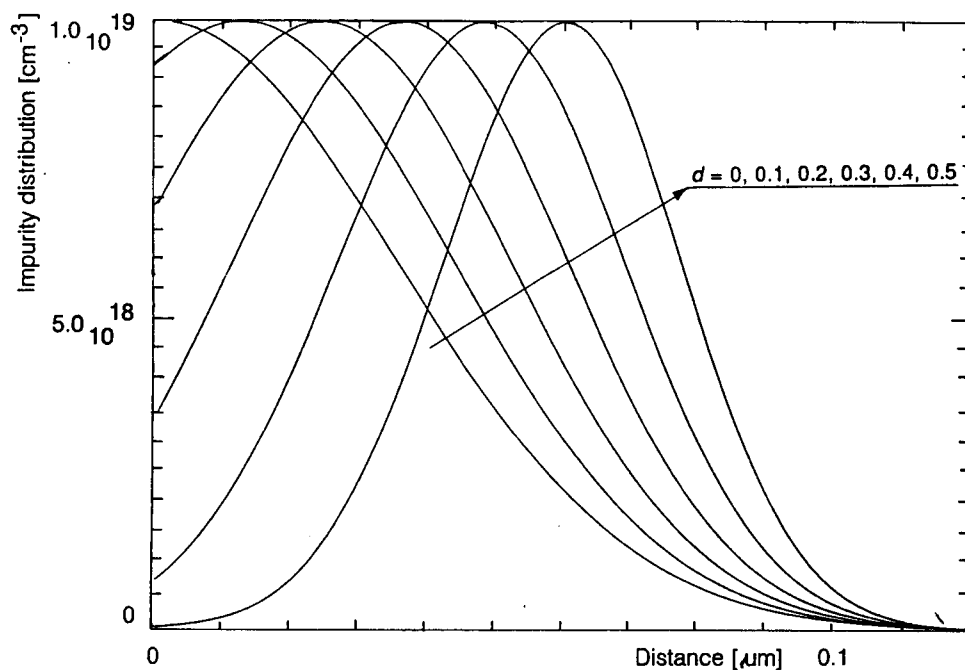


FIG. 2. Gaussian impurity distributions for $N_T = 10 \text{ cm}^{-3}$, $N_{BC} = 3 \cdot 10^{16} \text{ cm}^{-3}$, $d = 0.0, 0.1, 0.2, 0.3, 0.4, 0.5$ of Eq. (13)

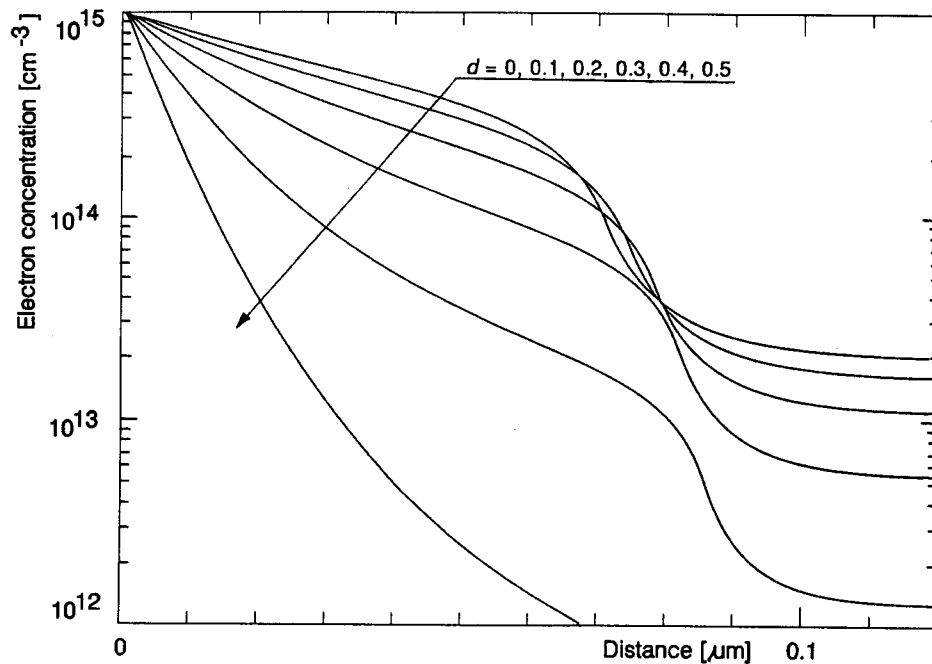


FIG. 3. Electron concentration in base without carrier velocity limitation for the uniform base transistor with $1.2 \mu\text{m}$ metallurgical base thickness and different Gaussian impurity profiles

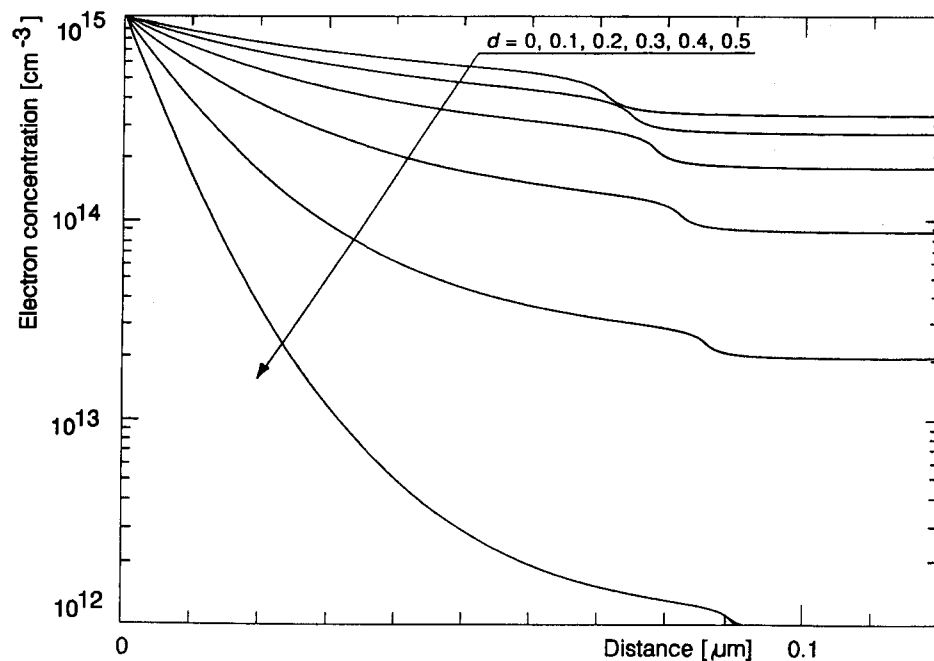


FIG. 4. Electron concentration in base with carrier velocity limitation for the uniform base transistor with 1.2 μm metallurgical base thickness and different Gaussian impurity profiles

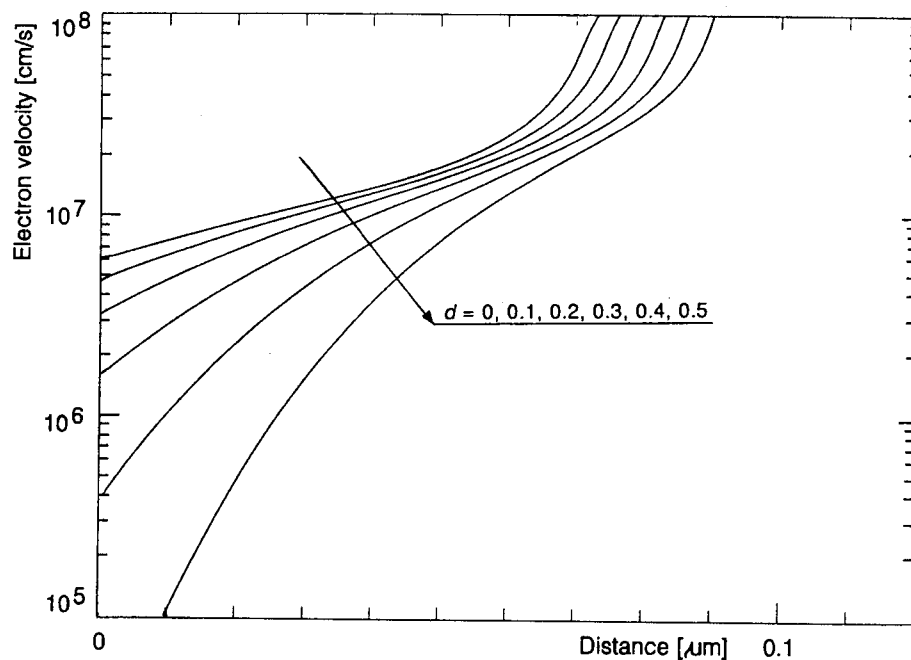


FIG. 5. Electron velocity distribution in base without carrier velocity limitation for the uniform base transistor with 1.2 μm metallurgical base thickness and different Gaussian impurity profiles

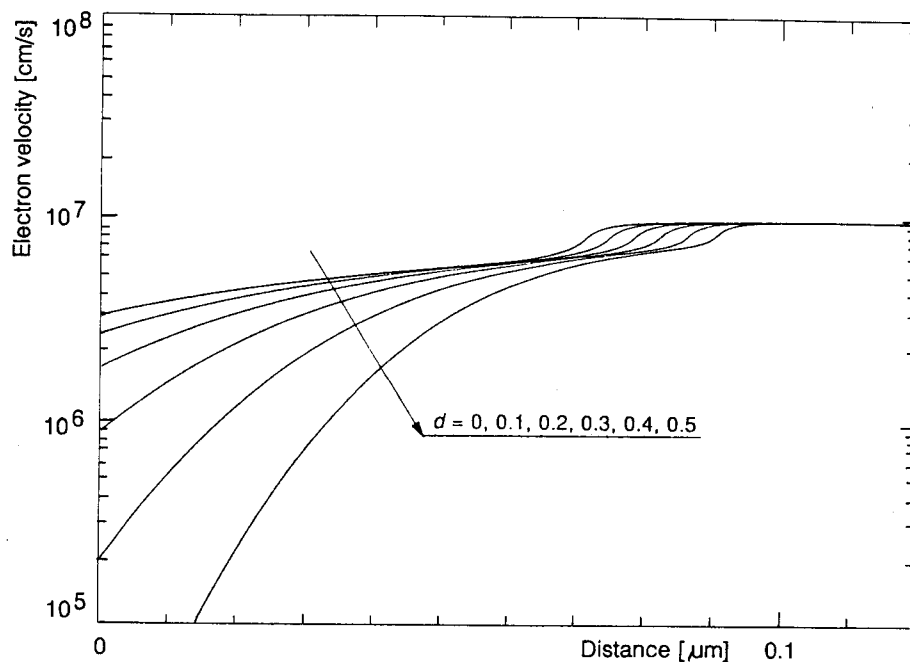


FIG. 6. Electron velocity distribution in base with carrier velocity limitation for the uniform base transistor with $1.2 \mu\text{m}$ metallurgical base thickness and different Gaussian impurity profiles

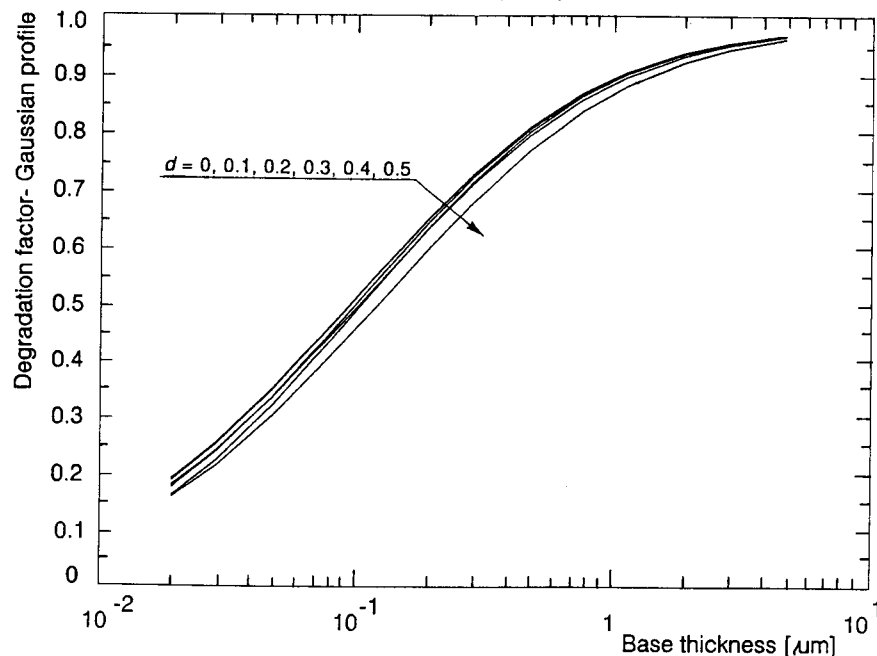


FIG. 7. Current gain degradation due to the effect of carrier velocity limitation for different Gaussian profiles as a function of base width. Calculated as the ratio of the transistor currents with and without carrier velocity limitations obtained for the same minority carrier concentration on the emitter edge of base

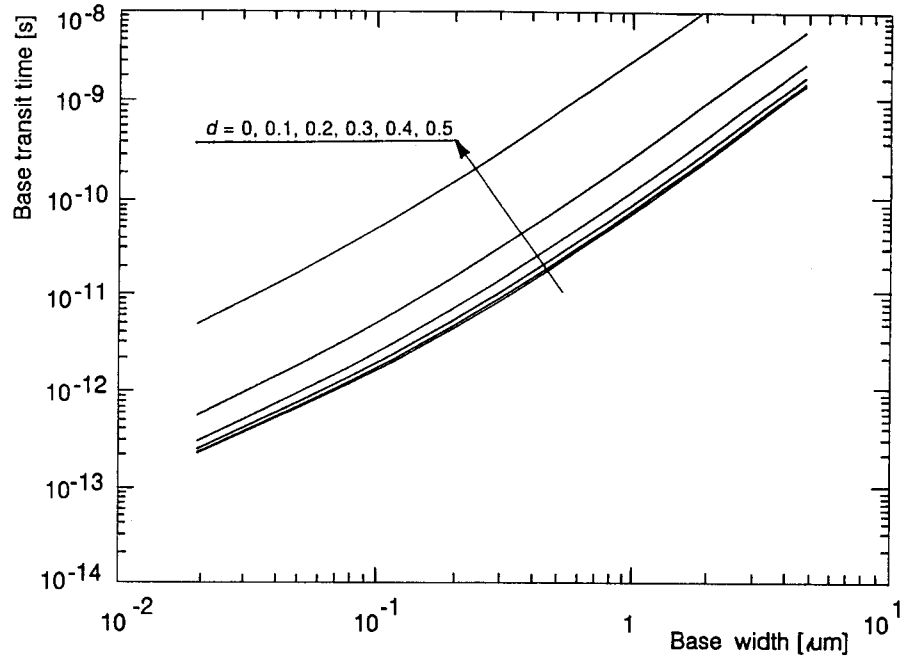


FIG. 8. Transient time degradation due to the effect of carrier velocity limitation for different Gaussian profiles as a function of base thickness. Calculated as the ratio of the base transit times current with and without carrier velocity limitation

Having the minority carrier velocity $v(x)$ distribution in the base, the carrier transit time t_t through base can be computed using equation:

$$t_t = \int_{x_E}^{x_C} \frac{dx}{v(x)}. \quad (14)$$

The transient time was computed for cases with and without the carrier velocity limitations. FIGURE 8 shows the effect of transient time degradation for the Gaussian-type impurity profile as a function of base thickness, computed as a ratio between base transit times with and without carrier velocity limitations.

5. CONCLUSIONS

To isolate the effect of carrier saturation velocity in this analysis, many important effects such as mobility dependence on impurity concentrations, recombination, and high current effects were intentionally neglected. Inclusion of such effects into the numerical analysis is straightforward. However, the effect of the carrier velocity limitation would be obscured.

The assumption that $n(x_C) = 0$ leads to a serious error in a thin-base transistor even in the case without carrier velocity limitation. This error is more significant if the electric field in base-collector region is low (impurity doping level is low). To eliminate the current-induced base widening, the impurity doping in this region should be relatively high to secure a large electric field. Such a field may also improve the device performance by exploiting velocity overshoot near the low-high electric field boundary. However, the effect of velocity overshoot should not be overestimated in a narrow base transistor because the mean carrier velocity (and kinetic energy) in the quasi-neutral base are already high and a large gradient of mean kinetic energy is unlikely.

The assumption that $n(x_C) = J_n/qv_s$ also leads to an error for a narrow base transistor. Further, the effect of a limited carrier velocity must be taken into consideration for narrow base transistors even if diffusion is the dominant transport mechanism in the base and drift is inconsequential.

The current gain degradation shown in FIG. 7 computed for various Gaussian distributions, displays approximately an universal relation because various Gaussian profiles possible have a minor effect on the current gain. FIGURE 7 shows that the peak locations of Gaussian distributions (FIG. 2) have little effect on current degradation. Even for a relatively thick base of $1\text{ }\mu\text{m}$ with a Gaussian impurity distribution, β is degraded by about 10 percent. The carrier velocity limitation has a more significant effect on the base transit time, as expected.

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MALENIE WSPÓŁCZYNNIKA WZMOCNIENIA PRĄDOWEGO W TRANZYSTORACH BIPOLARNYCH SPOWODOWANE NASYCENIEM PRĘDKOŚCI NOŚNIKÓW

STRESZCZENIE

W pracy jest analizowany wpływ nasycenia prędkości nośników ładunku w bazie tranzystora bipolarnego na jego wzmocnienie prądowe, które w wyniku efektu nasycenia prędkości nośników ładunku silnie maleje. Efekt ten jest znaczny w tranzystorze z bardzo cienkiej bazy, ale także widoczny z bazy o grubości 1 μm , a nawet więcej.