ORIGINAL PAPER

TRANSIT TIME STUDY THROUGH THE BASE IN CASE OF DRIFT TRANSISTORS

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Abstract. *Within many years microelectronics developed based on p-n junctions made of germanium or silicon, namely on homojunctions (BJT). In this case the main technological difficulty was to control the level of doping concentrations. Semiconductor structures were obtained by the variation of type and concentration of the doping impurities. A new phase of the evolution of the semiconductor devices is the manufacturing and large scale using of heterojunctions. Heterojunction is the contact of two semiconductors, different according to the chemical composition, existing in a single crystal. Within this contact not only the energetic areas structure varies, but also the effective body of the carriers, their mobility and other parameters. The possibility of variation of these parameters allows the manufacture of unique devices that have record performance. Heterojunction bipolar transistors (HBT) have the following benefits: static gain in current, high cutting frequency, high speed of conversion, low temperature running. The aim of my study is transit time study through the base in case of drift transistors.*

Keywords: *BJT drift, HBT, transit time, Matlab.*

1. INTRODUCTION

1.1 DRIFT BJT TRANSISTORS

The semiconductor elements that are involved in the structure of heterojunctions can be found in the central part of the periodic table. Heterojunction is a junction made of two semiconductors which have different forbidden energy band.

The necessity of high frequency devices shows up in applications of microwaves with GHz, medical imaging systems with THz and also in the high-speed A/D convertors and in the 100 Gbit/s laser drivers [1-5].

Homojunction bipolar transistors (BJT composed of one material) present limitations which do not allow a high gain and a low base resistance (these are affecting the performance while functioning in high frequencies regime). Elimination of the inconvenience in the case of homojunction BJT was solved by Schokley and Kroemer. They used on purpose two different materials – a bigger band width in the emitter and a lower base width. This way the heterojunctions were designed, which have a better performance [6-8].

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The uniform doped base. The electric load of holes in excess is:

$$Q_p = qA\frac{\Delta p_B(0)\cdot w_B}{2} \tag{1}$$

The recombination current in the base I_r can be computed by using the controlled charge method [9-11]. If τ_B is the life time of the minorities in the base, then, in stable regime, at each τ_B seconds a current:

$$I_r = \frac{Q_B}{\tau_B} \tag{2}$$

should be permanently supplied to the base contact in order to re-establish the charge Q_B which vanishes by means of recombination. The result is the recombination current value in the neutral base volume region,

$$I_r = qA\frac{\Delta p_B(0)\cdot w_B}{2\tau_B} \tag{3}$$

Minority current which comes out of the base in the point $x=x_B$ will be a holes diffusion current, given by the relation (eq. 4):

$$I_p(x_B) = -qAD_B\frac{d(\Delta p_B)}{dx}\bigg|_{x=x_B} \tag{4}$$

where

$$I_p(x_B) = qAD_B\frac{\Delta p_B(0)}{w_B} \tag{5}$$

The supposition (hypothesis) „thin base" drives us to the linear approximation of the base minority distribution, leading us to the following:

$$I_p(0) \approx I_p(x_B) \tag{6}$$

This relation shows us that the recombination current in the base is little in comparison to the transported current value,

$$I_p(0) = I_p(x_B) + I_r \approx I_p(x_B) \tag{7}$$

The medium time in which the current $I_p(x_B)$ carries to the collector the charge Q_B is equal to:

$$t_B = \frac{Q_B}{I_p(x_B)} \tag{8}$$

and is named transit time of the minority carriers through the neutral base. If, we take into account the equations (1) and (3), we get:

$$t_B = \frac{w_B^2}{2D_B} \tag{9}$$

From equations (3) and (5) we get:

$$\frac{I_p(x_B)}{I_r} = \frac{\tau_B}{t_B} \tag{10}$$

Non-uniform doped base. The silicon bipolar transistor junctions are made by the thermic diffusion of some impurities, the doping profiles being from this moment non-uniform. The non-uniform doping in the base generates an internal electric field. Its existence is beneficial, contributing to the shortening of the transit time [12-15]. Apparently, another mathematical simulation is needed than the one used for the uniform base.

The first issue that should be solved is to define how the internal electric field E_0 is formed and to determine its value. We consider the neutral base of a bipolar transistor PNP which extends on the distance [0, w_B] and which is non-uniform doped (Fig. 1) with a concentration $N_B(x)$ of donor atoms, fully ionized at room temperature.

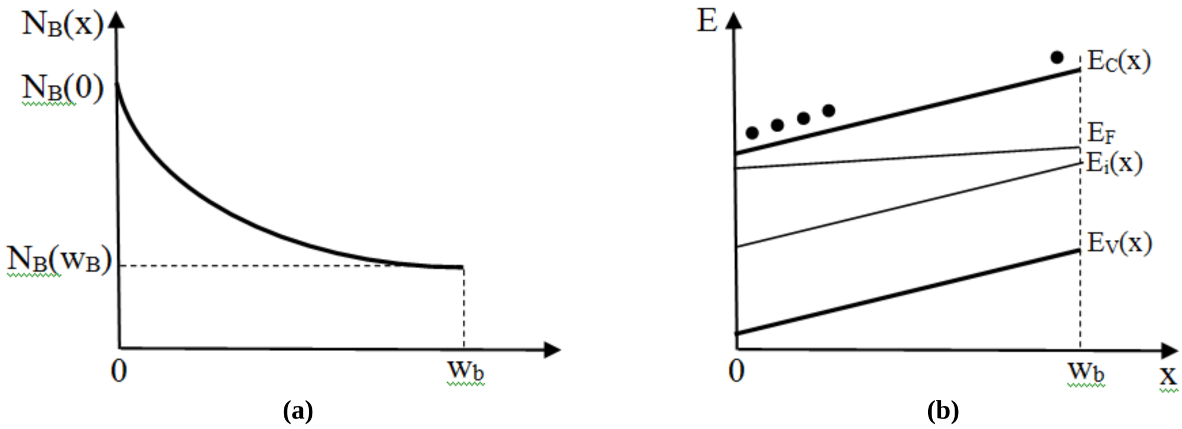

Figure 1. Base of a drift transistor: (a) non-uniform doping profile; (b) diagram of energetic bands in balance.

The concentration of free electrons in a point x of the base:

$$N_B(x) = n(x) = N_C \cdot exp\left[-\frac{E_C(x) - E_F}{kT}\right] \tag{11}$$

In conditions of balance, the Fermi level is constant and from equation (11) we gather that the conduction band edge $E_C(x)$ should be an increasing function if $N_B(x)$ decreases with the distance. Implicitly, the intrinsic level $E_i(x)$, which is parallel to $E_C(x)$, increases with the distance. The gradient of $E_i(x)$ is proportional to the electric field, $qE_0 = \frac{dE_i}{dx}$. That determines the following situation that in the non-uniform base is generated an internal electric field directed from the high concentration region to the low concentration region. The value of the internal field E_0 is deducted from the condition that at thermodynamic balance, the electronic current in the base should be null,

$$n(x) = N_B(x) \tag{12}$$

$$J_n = qn\mu_n E_0 + qD_n \frac{dn}{dx} = 0 \tag{13}$$

Using Einstein equation, we get:

$$E_0 = -\frac{kT}{q}\frac{1}{N_B(x)}\frac{dN_B(x)}{dx} = 0 \tag{14}$$

A special attention should be given to the exponential doping base:

$$N_B(x) = N_B(0) \cdot exp\left[-\eta \frac{x}{w_B}\right] \tag{15}$$

where

$$\eta = ln \frac{N_B(0)}{N_B(w_B)} > 1 \tag{16}$$

is named field factor. For such a profile we have:

$$\frac{dN_B(x)}{dx} = -\frac{\eta}{w_B} N_B(x) \tag{17}$$

and the internal field looks like:

$$E_0 = -\frac{\frac{kT}{q}}{w_B}\eta \tag{18}$$

Therefore, the exponential doping base has a constant internal electric field. Such a situation is very well lent to an analytical mathematic simulation, and, in many cases the real diffusion profile of the base is approximated to an exponential one.

Transit time through the base in the case of BJT transistors with exponential doping

The transit time, t_B, is defined as the ratio between the total minority in the base Q_B and the current J_p which carries the charge,

$$t_B = \frac{Q_B}{J_p} = \frac{q\int_0^{w_B} p(x)dx}{J_p} \tag{19}$$

The transit time through the base of a drift transistor is given by the relation:

$$t_B = \frac{1}{D_B}\int_0^{w_B}\left[\frac{1}{N_B} \cdot \int_x^{w_B} N_B(x')\,dx'\right]dx \tag{20}$$

For an exponential doping type, equation (15), the general relation has an analytical form as follows:

$$t_B = \frac{w_B^2}{D_B} \cdot \frac{e^{-\eta} + \eta - 1}{\eta^2} \tag{21}$$

For a transistor with a uniform doped base the transit time t_{B0} is given by the eq. 9.

The reduction of the transit time in case of the drift transistors comparing to the ones that are uniform doped is given by the ratio:

$$\frac{t_B}{t_{B0}} = \frac{2(e^{-\eta} + \eta - 1)}{\eta^2} \tag{22}$$

1.2 DRIFT HBT TRANSISTORS

Molar graded base

Usage of a non-uniform doping profile is more difficult in case of the HBT transistors [9, 11]. In this case it is preferable the compositional grading of the base region. For a linear compositional grading (Fig. 2) the forbidden energetic band of the base varies according to a relation as follows:

$$E_g(x) = E_g(0) - \frac{\Delta E_g}{w_B} x \tag{23}$$

where

$$\Delta E_g = E_g(0) - E_g(w_B) \tag{24}$$

Such a variation type generates an internal electrical field in base,

$$E = -\frac{1}{q}\frac{\Delta E_g}{w_B} \tag{25}$$

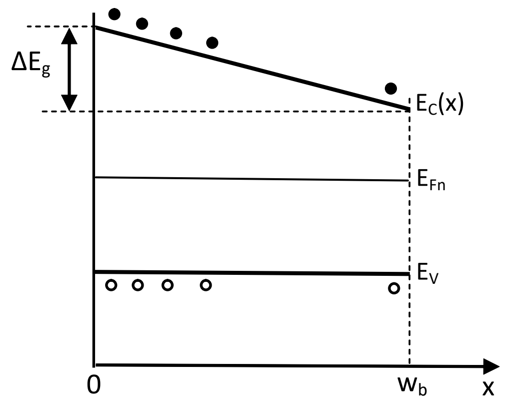

Figure 2. Relative diagram of the energetic bands from the neutral region of the molar graded base.

As in the BJT drift transistor, it can be presented in the following relation:

$$E = -\frac{kT}{q}\frac{\eta}{w_B} \tag{26}$$

the field factor η being in this case given by the equation:

$$\eta = \frac{\Delta E_g}{kT} \tag{27}$$

Transit time at molar graded transistors HBT

Spatial variation of the molar composition of the base in case of HBT transistors generates a spatial variation of the forbidden energetic band, and, implicitly, the one of the intrinsic concentration of carriers [9, 11].

Considering a uniform doped base, p(x) = N_A and linear molar graded (equation 23), the transit time through the base of such a transistor is as follows:

$$t_B = \frac{w_B^2}{D_B} \cdot \frac{e^{-\eta} + \eta - 1}{\eta^2} \tag{28}$$

2. TRANSIT TIME ANALYSIS THROUGH THE BASE USING MATLAB

2.1 DETERMINATION OF THE TRANSIT TIME THROUGH THE BASE FOR A UNIFORM DOPED TRANSISTOR BJT

The analysis of the transit time through the base for a uniform doped transistor BJT (t_{B0}) was made using Matlab [16]. In Fig. 3 we presented the transit time through the base depending on the doping concentration of the base (N_B) using various values of the band width (w_B = 0.5, 2, 6 µm).

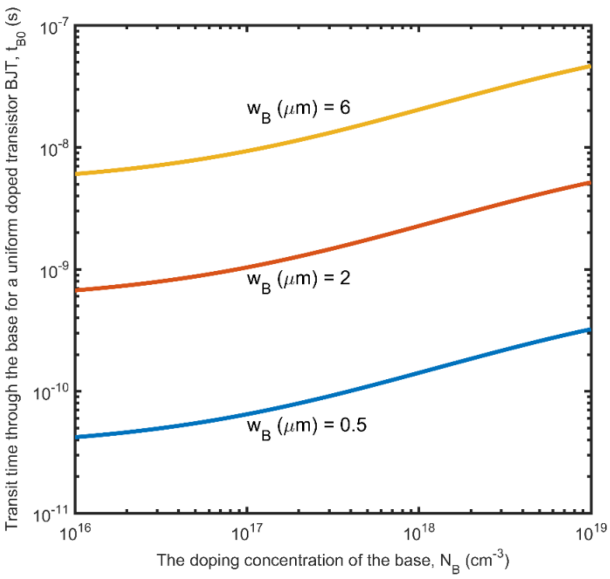

Figure 3. Transit time through the base for a uniform doped transistor BJT depending on the doping concentration of the base.

Fig. 3 presents the fact that the transit time through the base for a uniform doped transistor BJT decreases while the base concentration reduces and is in direct ratio with the base thickness.

The ratio between the transit time through the base of a drift transistor t_B and the transit time through the base of an uniform doped transistor t_{B0} depending on the doping concentrations from the ends of the neutral base $N_B(0)$ and $N_B(w_B)$ was presented in Fig. 4.

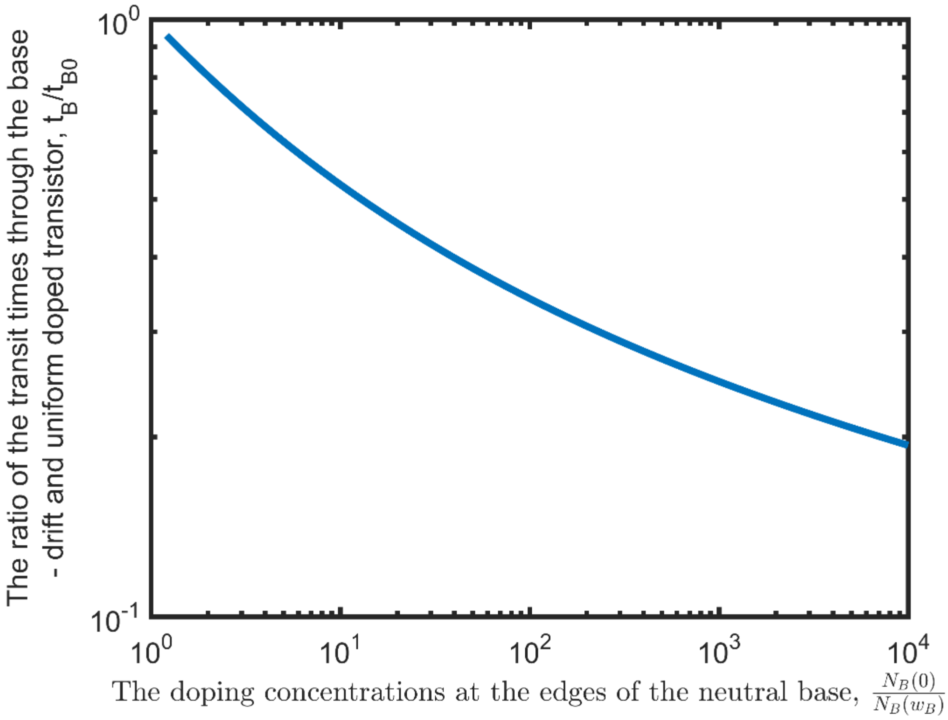

Figure 4. The ratio of the transit times through the base of a drift transistor and of an uniform doped transistor depending on the doping concentrations at the edges of the neutral base.

In Fig. 4 we can notice that the ratio of the transit times through the base tB/tB0 increases while the ratio of the doping concentrations at the edges of the neutral base decreases.

For a ratio $\frac{N_B(0)}{N_B(w_B)} = 10$, the value of the field factor is η=2,3, that determines $\frac{t_B}{t_{B0}} = 0{,}43$. If the time t_B is the one that determines the value of the transition frequency f_r the drift transistor provides a frequency f_r which is approximatively twice bigger than the uniform base transistor.

Apparently, the frequency performances of the silicon bipolar transistor can be improved by the accomplishment of an internal field as big as possible. In practice an important limitation occurs due to the variation of the mobility in function of the doping concentration, which decreases at high concentration values. For this reason, actually exists an optimum value for factor η for which the transit time value is minimum, η≈5.

In Fig. 5 we presented the internal electric field according to the field factor.

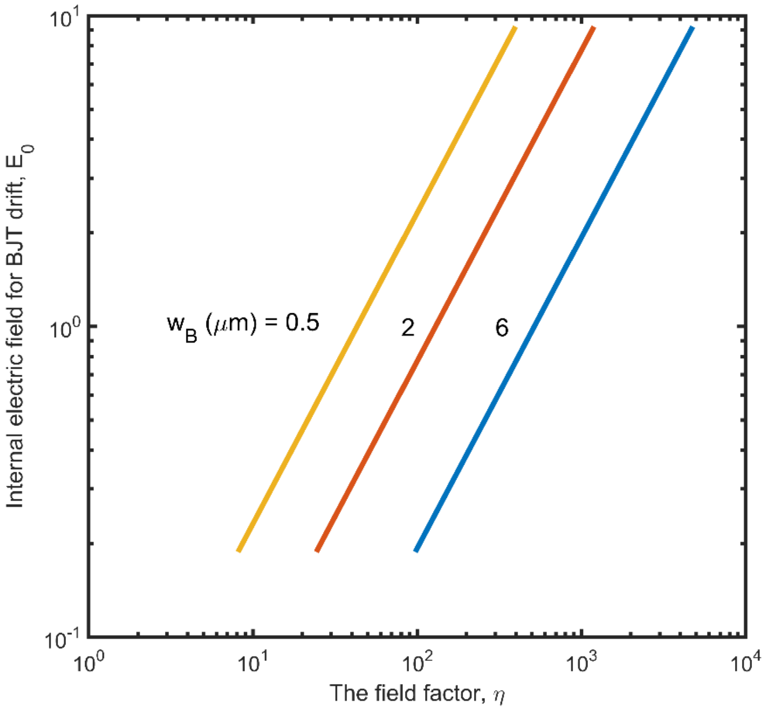

Figure 5. Internal electric field E0 according to the field factor η

2.2. TRANSIT TIME CALCULUS THROUGH THE BASE FOR DRIFT TRANSISTORS HBT Si/SiGe WITH MOLAR GRADED BASE $Si_{1-x}Ge_x$

For a drift transistor, the transit time through the base is given by the equation (28) where: w_B – base thickness, $D_B = D_n$ – diffusion parameter of the electrons through the base,

$$D_n = \frac{kT}{q} \cdot \mu_n \tag{29}$$

η - field factor in the base, given by the equation (27) where $\Delta E_g = \Delta E_{gb}$ and can be computed using the following relations,

$$\Delta E_{gb} = E_{gb}\big|_{y=0} - E_{gb}\big|_{y=w_B} = E_g(Si) - E_g(Si_{1-x}Ge_x) \tag{30}$$

$$\Delta E_{gb} = 0{,}96x - 0{,}43x^2 + 0{,}17x^3 \tag{31}$$

and x is the molar concentration value x_{Ge} in the point $y=w_B$ (namely at the right edge of the base).

The analyzed cases are presented in Table 1.

Table 1. Transit time analysis through the base

w_B = 0,5 μm	μ_n [$cm^2/V\cdot s$]	D_n [cm^2/s]	$\frac{w_B^2}{D_B}$ [ps]	η	t_b [ps]
$N_B=10^{16}$ cm^{-3}	1500	38.9	64.35	1	23.551
				10	5.804
$N_B=4\cdot10^{17}$ cm^{-3}	400	10.4	241.31	1	88.31
				10	21.77
$N_B=10^{19}$ cm^{-3}	100	2.59	965.25	1	353.26
				10	87.062

Transit time analysis through the base according to the field factor was made within the value range: η=1÷10, that is $\Delta E_{gb} = kT \div 10kT$ or $\Delta E_{gb} = 26mV \div 260mV$. The results are presented in Figs. 6-8.

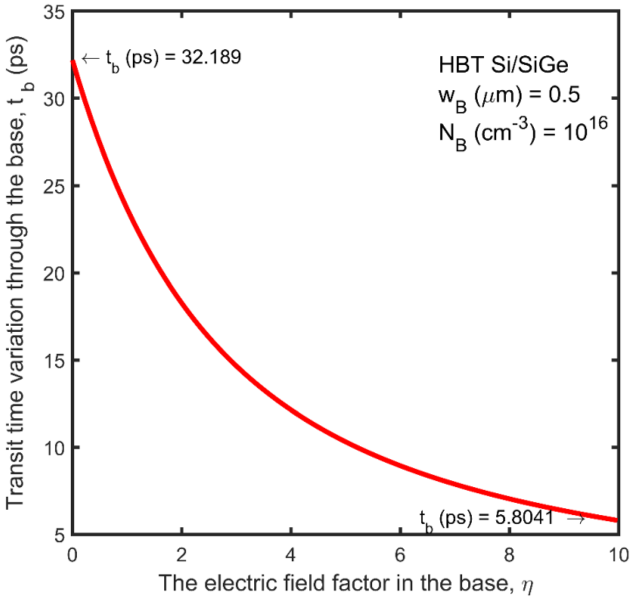

Figure 6. Transit time variation through the base for a drift transistor HBT Si/SiGe according to the electric field factor in the base for a base concentration value of $N_B=10^{16}$ cm^{-3}.

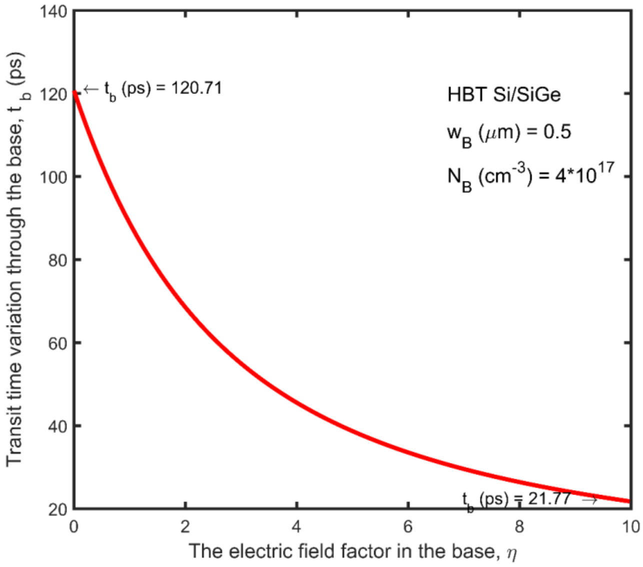

Figure 7. Transit time variation through the base for a drift transistor HBT Si/SiGe according to the electric field factor in the base for a base concentration value of $N_B=4\cdot10^{17}$ cm^{-3}.

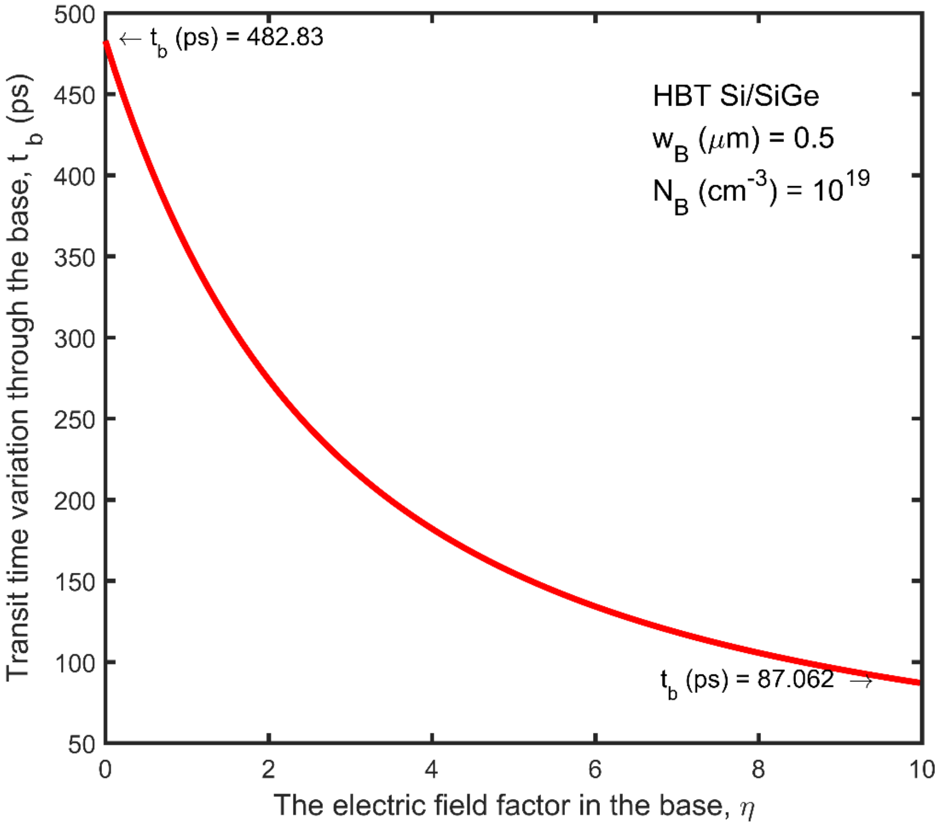

Figure 8. Transit time variation through the base for a drift transistor HBT Si/SiGe according to the electric field factor in the base for a base concentration value of $N_B=10^{19}$ cm^{-3}.

In the Figs. 6-8 and Table1 we can notice that if the field factor value increases, the transit time through the base decreases. While $\eta = \frac{\Delta E_{gb}}{kT}$, and kT has a constant value, η is in direct proportion to the value ΔE_{gb}. Therefore, as much as the value ΔE_{gb}increases, also increases the value of field factor, and implicitly results a lower transit time value.

The transit time through the base depends on the field factor by the equation (28). The field factor depends on the variation of the forbidden band between the two edges of the base according to the equation (27). In its turn, this depends on the molar fraction of germanium, according to the equation (31).

In Fig. 9 we presented the internal electric field depending on the field factor, where can be noticed that while the field factor decreases, the electrical field decreases in direct proprotion to it.

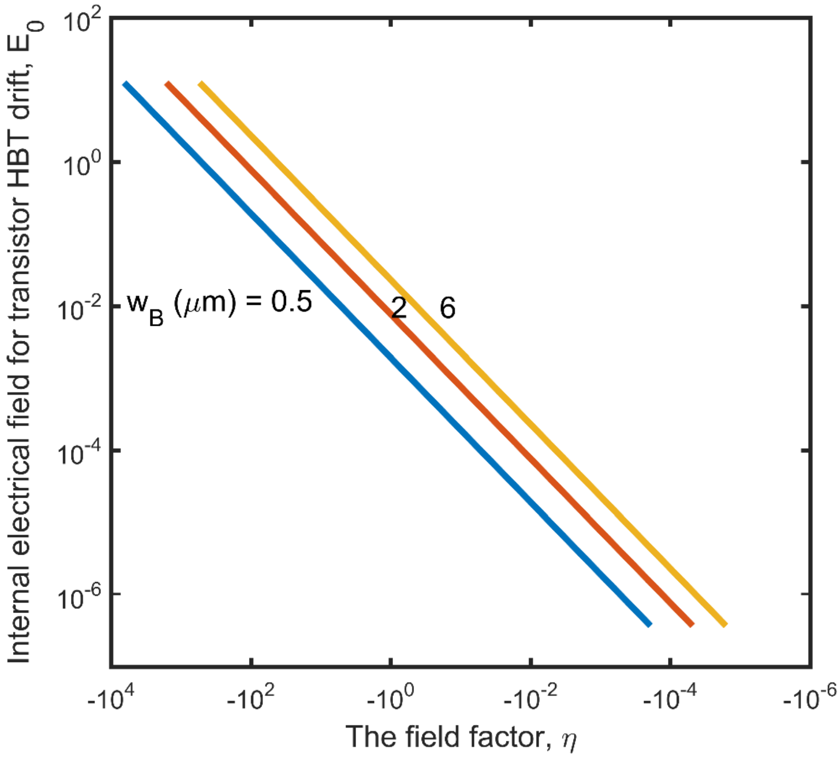

Figure 9. Internal electric field for a transistor HBT drift according to the field factor

Using the three equations (27), (28) and (31), we can directly get the link between the transit time through base and the percentage concentration of germanium at the edge of the base-collector junction; we considered that this value is null for the base-emitter junction. The results of the analysis are given in the Figs. 10-12.

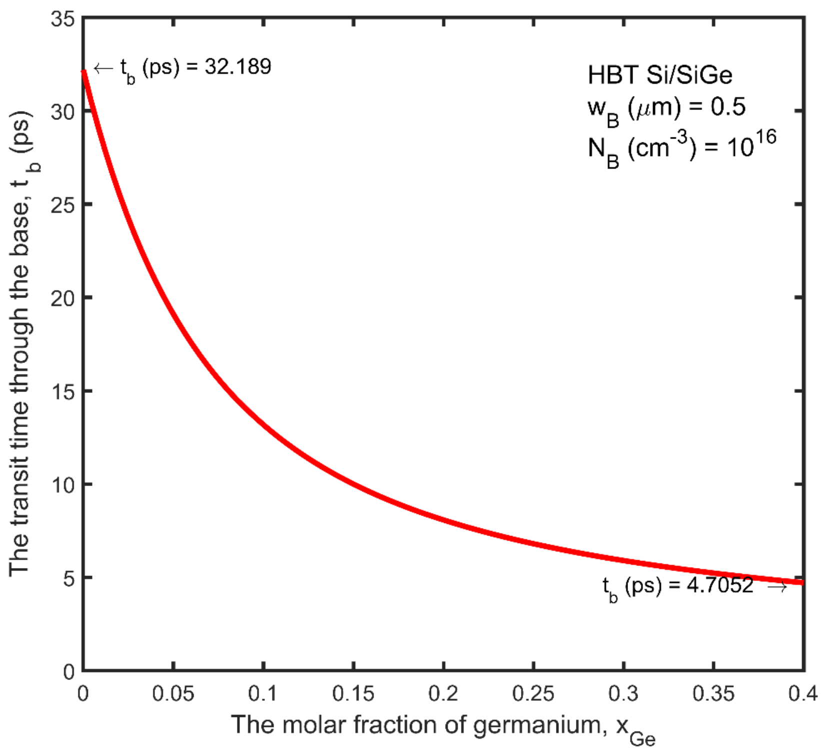

Figure 10. Variation of the transit time through the base for a transistor HBT Si/SiGe, with a molar graded base, dependent on the value of the molar fraction of germanium from the interface of the collector-base junction for a base concentration $N_B=10^{16}$ cm^{-3}.

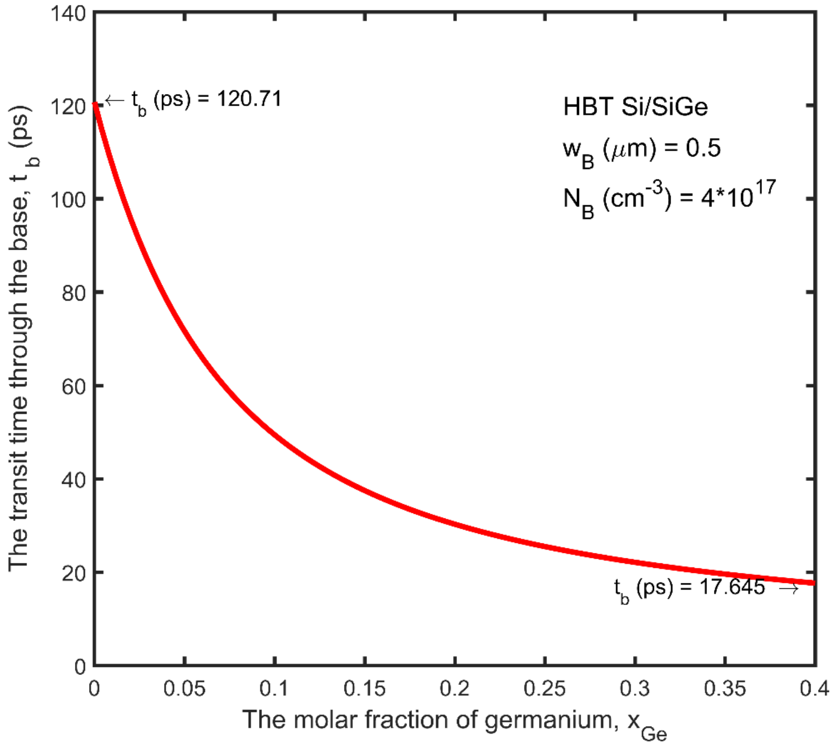

Figure 11. Variation of the transit time through the base for a transistor HBT Si/SiGe, with a molar graded base, dependent on the value of the molar fraction of germanium from the interface of the collector-base junction for a base concentration $N_B=4\cdot10^{17}$ cm^{-3}.

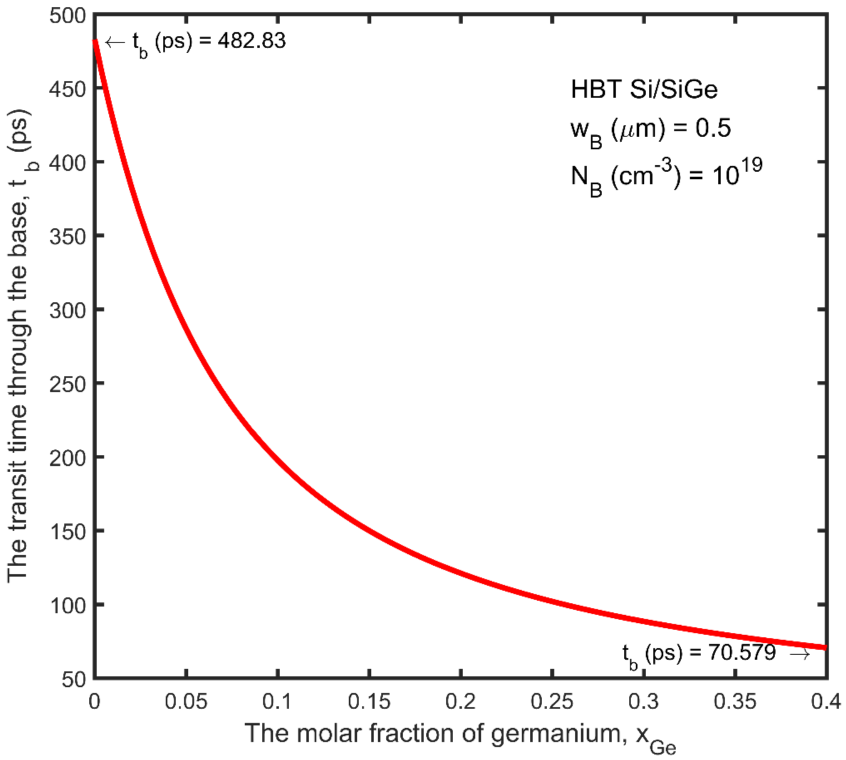

Figure 12. Variation of the transit time through the base for a transistor HBT Si/SiGe, with a molar graded base, dependent on the value of the molar fraction of germanium from the interface of the collector-base junction for a base concentration $N_B=10^{19}$ cm^{-3}.

In the Figures 10-12 we observe that the transit time decreases while the molar fraction increases and the transit time through the base increases while the base concentration increases.

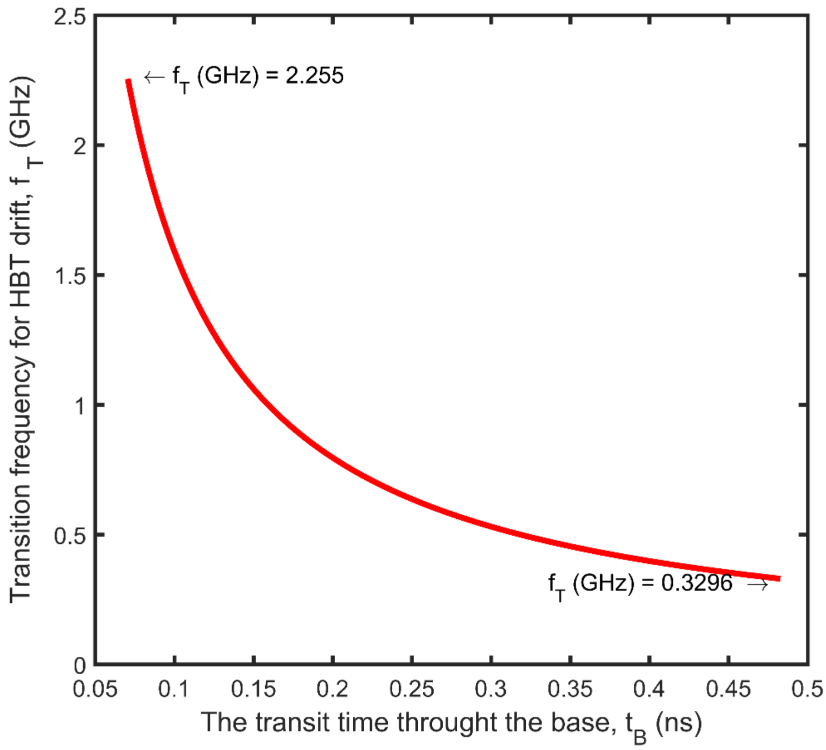

Figure 13. Transition frequency for HBT drift according to the transit time through the base.

According to the results and to the Figure 13 we observe that the transition frequency for HBT drift increases while the transit time through the base decreases.

3. CONCLUSIONS

While the speed of the electrons drifting through the base increases, the transit time through the base decreases. The internal electric field (E) generated in the region of the base due to the variation of the forbidden band (produced by the variation alongside the base of the molar fraction x_{Ge}) and generated by the gradation with germanium in the base accelerates the move of the electrons from the emitter to the collector. A short time of transit determines a high transition frequency, which determines a better performance of the transistor.

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