ORIGINAL PAPER

TRANSIT TIME MODEL ANALYSIS THROUGH THE BASIS IN THE CASE OF DRIFT TRANSISTORS HBT

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Abstract. *The manufacturing technology for heterojunction bipolar transistor (HBT) is different from the one used for bipolar silicon junction transistor (BJT). The base in case of BJT is manufactured by using diffusion and the diffusion laws determine a Gaussian type of profile in the base. HBT devices are manufactured using molecular epitaxy which gives a contact doping profile. In case of HBT, producing an internal field by using uniform doping is no more possible. This is the reason why was used in the gradation of the molar composition. The Analysis using Octave soft was made for the transit time through the base of the drift HBT transistors type* $GaAs/Al_xGa_{1-x}As$.

Keywords: *HBT; the transit time; the molar concentration; the field factor from the base; octave.*

1. INTRODUCTION

There are two types of transistors: homojunction and heterojunction transistors. The homojunction transistors can improve their transit time through the base if the concentration is non-uniform.

Heterojunction bipolar transistors (HBT) offer a great number of advantages: electrical statistic gain and high cut-off frequency, high gain in power, fast speed of commutation. Adding to this, HBT transistors offer an additional advantage of the performances and functioning, improvement in conditions of very low temperatures, all these not being possible in case of conventional devices. In the case of HBT transistors we do not use diffusion, the base is constant, and in conditions of an internal field in the base results a compositional graded base.

The present paper studies the effects of the transit time through the HBT transistors base, using the Octave soft, for the following cases: constant internal electric field, medium value internal field, strong internal field, and a compositional graded base.

2. GENERAL ASPECTS

The general principles of heterojunction bipolar transistors (HBT) were established in 1957 [1]. This domain knows an intense development after 1983 [2]. Spectacular advancement in the electrical performances of the devices made, imposed revaluation of the old designing concepts and theoretical modelling of a new physical processes [3-17].

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Heterojunction is a junction made of two semiconductors having different forbidden energetic band. Usually, heterojunction devices are made of composed semiconductor materials, based on the elements of the periodic table, being found in the III and V groups [18-24]. This type of materials can be of ternary type, $A_xB_{1-x}C$ or quaternary, $A_xB_{1-x}C_yD_{1-y}$ and $(A_xB_{1-x})_yC_{1-y}D$. Semiconductor materials used in microelectronics are the ones based on GaAs and InP. In the first category we can find AlxGa1-xAs, and in the second one we have $In_xGa_{1-x}As_yP_{1-y}$ and $(Ga_xAl_{1-x})_yIn_{1-y}As$ [8].

To improve the frequency characteristics, BJT drift transistors use an accelerant electric field in the neutral region of the base. Using this particular field, the transit time of the minority carriers through the specific area significantly decreases. The internal electric field is obtained by non-uniform doping of the base [25]. Usage of a non-uniform doping profile is more difficult in case of HBT [7]. In this case is preferred the compositional gradation of the base region [6, 25].

As a definition, we can say that the transit time through the base represents the ratio between the total load of the minority carriers existing in excess in the base and the minority electric current that enter the collector, in the polarization condition VCB=0 [24-31]:

$$t_b = \left. \frac{-\int_0^{wB} q\hat{n}dx}{J_n(w_B)} \right|_{V_{CB}=0} \tag{1}$$

Usually, can be considered:

$$\left(\frac{\eta}{2}\right)^2 >> \left(\frac{w_B}{L_{nb}}\right)^2 \tag{2}$$

In this case, the constant values involved in the minority distribution become:

$$\lambda = \frac{\eta}{2w_B}, \quad \theta = \frac{\eta}{2w_B} \tag{3}$$

and:

$$\begin{cases} r1 = \lambda + \theta = \dfrac{\eta}{w_B} \\ r2 = \lambda - \theta = 0 \end{cases} \tag{4}$$

From the previous equations, the minority concentration expression becomes:

$$\hat{n}(x) = A_1 \exp\left(\frac{\eta}{w_B} x\right) + A_2 \tag{5}$$

and the minority current will be expressed by the relation (6):

$$Jn = qD_n\left(\frac{dn}{dx} - \frac{\eta}{w_B} n\right) = -qD_n A_2 \frac{\eta}{w_B} \tag{6}$$

The total load of minorities in excess existing in the base is:

$$Q_b = -q\int_0^{w_B} n dx = -qA_1 \frac{w_B}{\eta}\left[\exp(\eta) - 1\right] - qA_2 w_B \qquad (7)$$

Knowing all these relations, transit time through the base can be computed, using the following relation:

$$t_b = \frac{w_B^2}{D_n \cdot \eta^2}\left\{\frac{A_1}{A_2}\left[\exp(\eta) - 1\right] + \eta\right\} \qquad (8)$$

But, for V_{CB}=0 and relation (3) we get:

$$\frac{A_1}{A_2} == -\exp\left(-2\theta \cdot w_B\right) = -\exp(-\eta) \qquad (9)$$

From relations (8) and (9), it can be obtained the general expression of transit time through the base of a transistor having a constant internal electric field, as it shows:

$$t_b = \frac{w_B^2}{D_n} \cdot \frac{\eta - 1 + \exp(\eta)}{\eta^2} \qquad (10)$$

where:

w_B – the base width;

D_n – the diffusion constant of the electrons in the base:

$$D_n = \frac{kT}{q} \cdot \mu_n \qquad (11)$$

η – the electric field factor for the base:

$$\eta = \frac{\Delta E_{gB}}{kT} \qquad (12)$$

The energy difference between the band gap of the emitter and of the base, it is:

$$\Delta E_g = \Delta E_{gE} - \Delta E_{gB} = E_g(GaAs) - E_g(Al_x Ga_{1-x} As) \qquad (13)$$

where x represents the Al molar fraction from the Ga.

3. COMPUTER MODELLING

The Analysis using Octave soft was made for the transit time through the base of the drift HBT transistors type $GaAs/Al_xGa_{1-x}As$ [32]. Using the equation (10), transit time for bases that have an internal electric field of medium value, can be determined using the relation:

$$t_b = \frac{w_B^2}{D_n} \cdot \frac{\eta - 1}{\eta^2} \qquad (14)$$

In case of transistors that have a strong internal field, then the transit time through the base can be written as it follows:

$$t_b = \frac{w_B^2}{\eta^2 \cdot D_n} \tag{15}$$

Using the equation (12), the transit time for a compositional graded base can be determined as it follows:

$$t_b = \frac{w_B^2}{2 \cdot D_n} \cdot \frac{2kT}{\Delta Eg} \tag{16}$$

As a result of the analysis of equation (10), referring to the transit time through the base depending on the molar concentration of Al, we got the following outputs (Figs. 1-3 and Table 1):

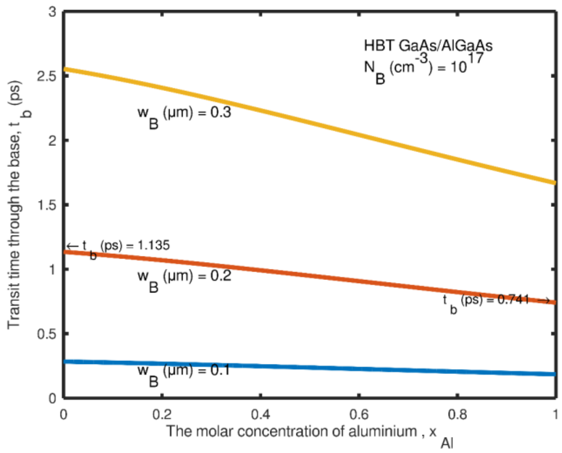

Figure 1. Transit time variation through the base for the HBT transistors GaAs/Al$_x$Ga$_{1-x}$As depending on the molar concentration of aluminium for the case N$_B$=10^{17} cm^{-3}.

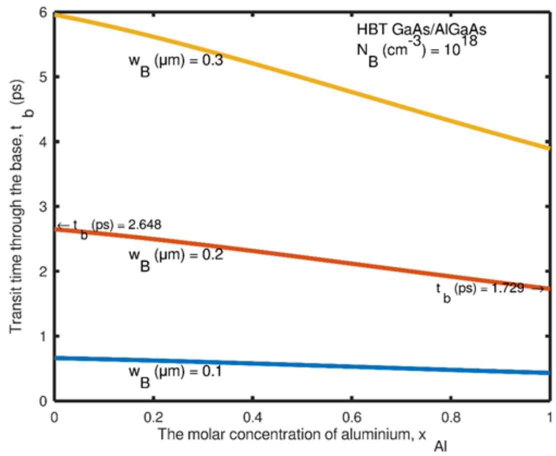

Figure 2. Transit time variation through the base for the HBT transistors GaAs/Al$_x$Ga$_{1-x}$As depending on the molar concentration of aluminium for the case N$_B$=10^{18} cm^{-3}.

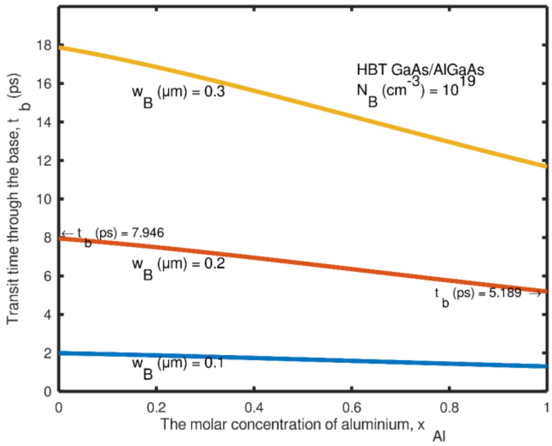

Figure 3. Transit time variation through the base for the HBT transistors GaAs/AlxGa1-xAs depending on the molar concentration of aluminium for the case NB=1019 cm^{-3}.

In the Figs. 1-3 and Table 1 it can be noticed that alongside with the decreasing of the doping concentration of the base (N$_B$), of the base width (w$_B$) and the increasing of the molar fraction of Al, transit time through the base decreases reaching a minimal value of 0.185 ps for the case $N_B = 10^{17}$ (cm^{-3}) and w_B = 0.1 μm. The average value of the transit time is 3,77ps, corresponding to a base concentration $N_B = 10^{18}$ (cm^{-3}) and a base width w_B = 0.3 μm.

Table 1. Transit time through the base depending on various doping concentrations of the base and various values of base width

		t_b (ps) maxim	t_b (ps) minim
$N_B = 10^{17}$ (cm^{-3})	w_B = 0.3 μm	2.554	1.668
	w_B = 0.2 μm	1.135	0.741
	w_B = 0.1 μm	0.283	0.185
$N_B = 10^{18}$ (cm^{-3})	w_B = 0.3 μm	5.959	3.891
	w_B = 0.2 μm	2.648	1.729
	w_B = 0.1 μm	0.6621	0.4324
$N_B = 10^{19}$ (cm^{-3})	w_B = 0.3 μm	17.879	11.676
	w_B = 0.2 μm	7.946	5.189
	w_B = 0.1 μm	1.986	1.297

Following an analysis of the equation (10) of the transit time through the base depending on the field factor in the base, we got the following outputs (Figs. 4-6 and Table 1):

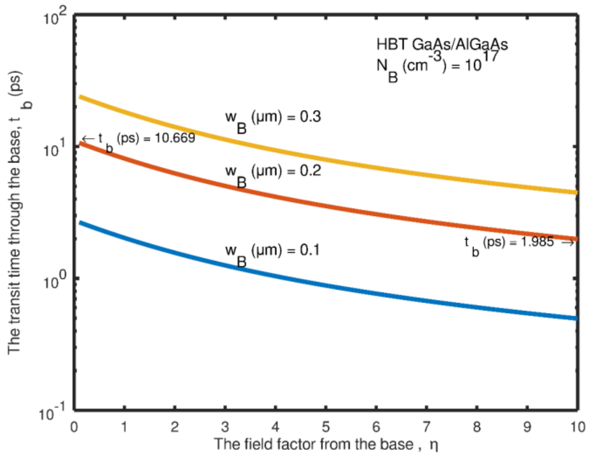

Figure 4. Variation of the transit time through the base for the HBT GaAs/Al_xGa_{1-x}As depending on the field factor from the base for the case $N_B=10^{17}$ cm^{-3}.

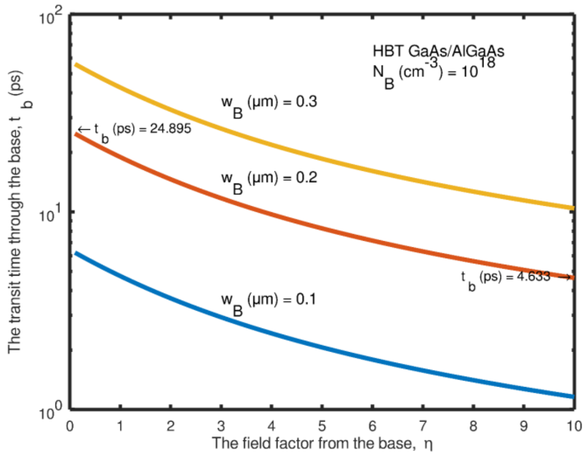

Figure 5. Variation of the transit time through the base for the HBT GaAs/Al_xGa_{1-x}As depending on the field factor from the base for the case $N_B=10^{18}$ cm^{-3}.

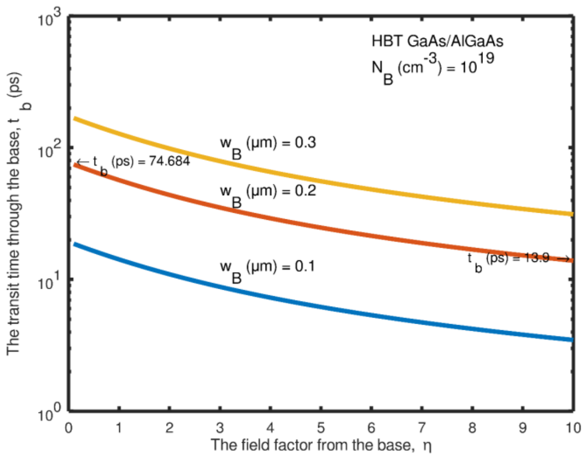

Figure 6. Variation of the transit time through the base for the HBT GaAs/Al_xGa_{1-x}As depending on the field factor from the base for the case $N_B=10^{19}$ cm^{-3}.

Table 2. Transit time through the base depending on various doping concentrations of the base and various values of the base width.

		t_b (ps) maxim	t_b (ps) minim
$N_B = 10^{17}$ (cm^{-3})	$w_B = 0.3$ µm	24.006	4.467
	$w_B = 0.2$ µm	10.699	1.985
	$w_B = 0.1$ µm	2.6673	0.496
$N_B = 10^{18}$ (cm^{-3})	$w_B = 0.3$ µm	56.013	10.425
	$w_B = 0.2$ µm	24.895	4.633
	$w_B = 0.1$ µm	6.223	1.158
$N_B = 10^{19}$ (cm^{-3})	$w_B = 0.3$ µm	168.04	31.2
	$w_B = 0.2$ µm	74.684	13.9
	$w_B = 0.1$ µm	18.621	3.474

From Figures 4-6 and Table 2 can be observed that alongside with the decreasing of the doping concentration of the base (N_B) and of the base width (w_B), transit time through the base slowly decreases reaching a minimal value of 0.496 ps, while the field factor in the base increases (η) for case $N_B = 10^{17}$ (cm^{-3}) and $w_B = 0.1$ µm. Average value of the transit time is 25,43 ps, this value corresponding to base concentrations $N_B = 10^{18}$ (cm^{-3}), $N_B = 10^{19}$ (cm^{-3}) and values of the field width $w_B = 0.3$ µm, $w_B = 0.2$ µm. Following the analysis of the equation (11), of the transit time through the base according to the field factor in the base, we gained the following results (Figs. 7-9 and Table 3):

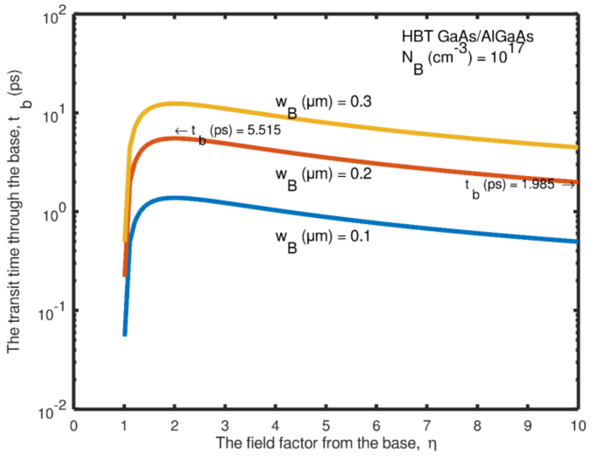

Figure 7. Variation of the transit time through the base for HBT transistors GaAs/$Al_xGa_{1-x}As$ depending on the field factor in the base for the case $N_B=10^{17}$ cm^{-3}.

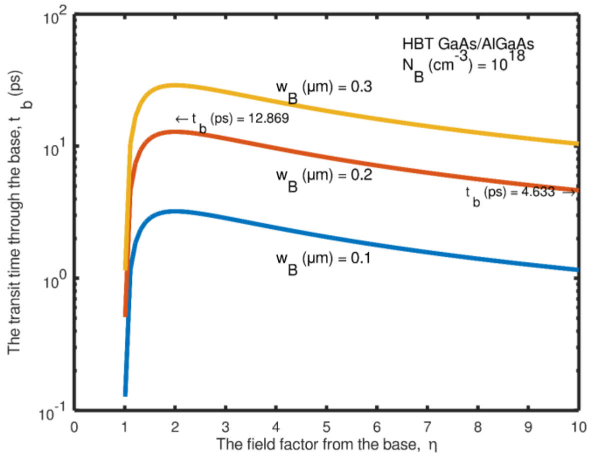

Figure 8. Variation of the transit time through the base for HBT transistors GaAs/$Al_xGa_{1-x}As$ depending on the field factor in the base for the case $N_B=10^{18}$ cm^{-3}.

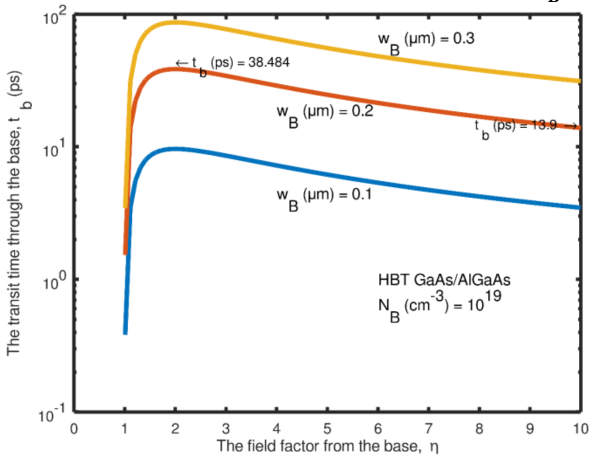

Figure 9. Variation of the transit time through the base for HBT transistors GaAs/$Al_xGa_{1-x}As$ depending on the field factor in the base for the case $N_B=10^{19}$ cm^{-3}.

Table 3. Transit time through the base according to various doping concentrations of the base and various values of the base width

		t_b (ps) maxim	t_b (ps) minim
$N_B = 10^{17}$ (cm^{-3})	$w_B = 0.3$ μm	12.409	4.467
	$w_B = 0.2$ μm	5.515	1.985
	$w_B = 0.1$ μm	1.378	0.496
$N_B = 10^{18}$ (cm^{-3})	$w_B = 0.3$ μm	28.955	10.425
	$w_B = 0.2$ μm	12.869	4.633
	$w_B = 0.1$ μm	3.217	1.158
$N_B = 10^{19}$ (cm^{-3})	$w_B = 0.3$ μm	86.864	31.274
	$w_B = 0.2$ μm	38.484	13.9
	$w_B = 0.1$ μm	9.651	3.474

From Figs. 7-9 and Table 3 can be observed that in case of transistors with a strong internal electric field, the transit time through the base grows fast for a field factor in the base having value 2, afterwards this one slowly decreases alongside with the doping concentration of the base (N_B) and the base width (w_B), reaching a minimal value of 0.496 ps for the case $N_B = 10^{17}$ (cm^{-3}) and $w_B = 0.1$ μm. The average value of the transit time is 3.99 ns, this value corresponding to base concentrations $N_B = 10^{17}$ (cm^{-3}), $N_B = 10^{18}$ (cm^{-3}), $N_B = 10^{19}$ (cm^{-3}) and values of the field width $w_B = 0.2$ μm, $w_B = 0.1$ μm, $w_B = 0.3$ μm. Following the analysis of the equation (12), of the transit time through the base according to the field factor in the base, we gained the following results (Figs. 10-12 and Table 4):

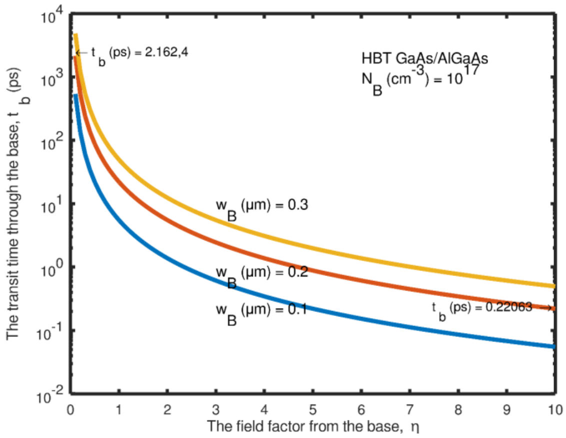

Figure 10. Variation of the transit time through the base for HBT transistors GaAs/Al_xGa_{1-x}As depending on the field factor in the base for the case $N_B=10^{17}$ cm^{-3}.

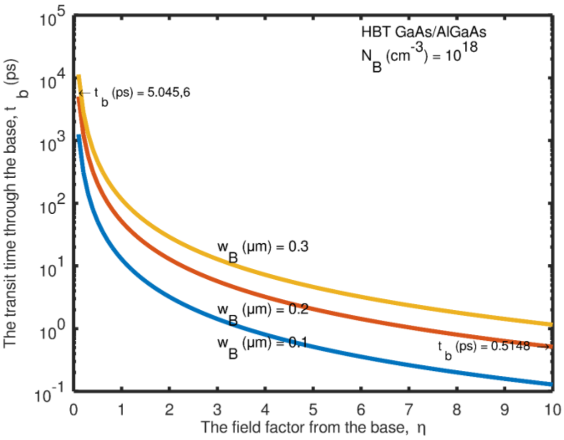

Figure 11. Variation of the transit time through the base for HBT transistors GaAs/Al_xGa_{1-x}As depending on the field factor in the base for the case $N_B=10^{18}$ cm^{-3}.

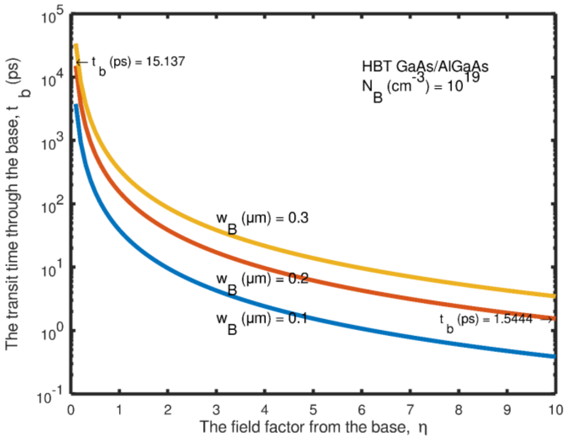

Figure 12. Variation of the transit time through the base for HBT transistors GaAs/Al_xGa_{1-x}As depending on the field factor in the base for the case $N_B=10^{19}$ cm^{-3}.

Table 4. Transit time through the base according to various doping concentrations of the base and various values of the base width

		t_b (ps) maxim	t_b (ps) minim
$N_B = 10^{17}$ (cm^{-3})	w_B = 0.3 μm	4865.4	0.4964
	w_B = 0.2 μm	2162.4	0.2206
	w_B = 0.1 μm	540.60	0.0551
$N_B = 10^{18}$ (cm^{-3})	w_B = 0.3 μm	11353.0	1.1583
	w_B = 0.2 μm	5045.6	0.5148
	w_B = 0.1 μm	1261.4	0.1287
$N_B = 10^{19}$ (cm^{-3})	w_B = 0.3 μm	34058.0	3.4749
	w_B = 0.2 μm	15137.0	1.5444
	w_B = 0.1 μm	3784.2	0.3861

From Figs. 10-12 and Table 4 can be observed that alongside with the decreasing of the doping concentration of the base (N_B) and of the base width (w_B), the transit time through the base quickly decreases (for η=0...2), reaching a minimal value 0.0551 ps alongside with the growing of the field factor in the base (η) in the case when $N_B = 10^{17}$ (cm^{-3}) and w_B = 0.1 μm. The average value of the transit time is 4.43 ns corresponding to values of base concentration $N_B = 10^{17}$ (cm^{-3}), $N_B = 10^{18}$ (cm^{-3}), $N_B = 10^{19}$ (cm^{-3}) and of base width w_B = 0.2 μm, w_B = 0.3 μm, w_B = 0.1 μm, w_B = 0.2 μm, w_B = 0.3 μm. Following the analysis of the equation (13), of the transit time through the base according to the field factor in the base, we gained the following results (Figs.13-15 and Table 5):

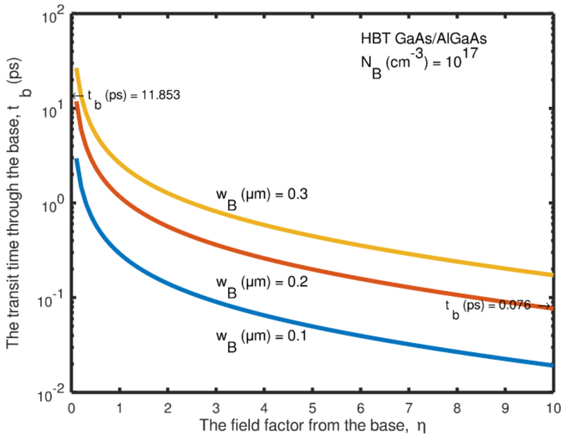

Figure 13. Variation of the transit time through the base for HBT transistors GaAs/Al$_x$Ga$_{1-x}$As depending on the field factor in the base for the case $N_B=10^{17}$ cm^{-3}.

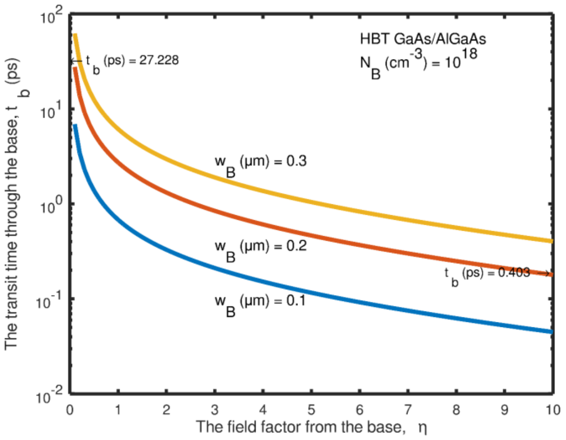

Figure 14. Variation of the transit time through the base for HBT transistors GaAs/Al$_x$Ga$_{1-x}$As depending on the field factor in the base for the case $N_B=10^{18}$ cm^{-3}.

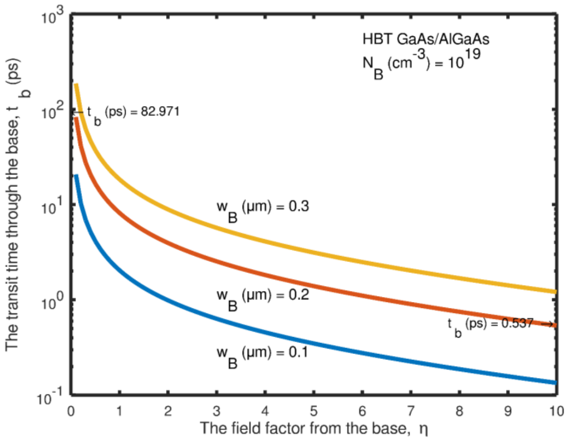

Figure 15. Variation of the transit time through the base for HBT transistors GaAs/Al$_x$Ga$_{1-x}$As depending on the field factor in the base for the case $N_B=10^{19}$ cm^{-3}.

Table 5. Transit time through the base according to various doping concentrations of the base and various values of the base width

		t_b (ps) maxim	t_b (ps) minim
$N_B = 10^{17}$ (cm^{-3})	w_B = 0.3 μm	26.669	0.172
	w_B = 0.2 μm	11.853	0.076
	w_B = 0.1 μm	2.963	0.019
$N_B = 10^{18}$ (cm^{-3})	w_B = 0.3 μm	62.228	0.403
	w_B = 0.2 μm	27.657	0.179
	w_B = 0.1 μm	6.914	0.044
$N_B = 10^{19}$ (cm^{-3})	w_B = 0.3 μm	186.68	1.209
	w_B = 0.2 μm	82.971	0.537
	w_B = 0.1 μm	20.743	0.134

From Figs. 13-15 and Table5 one can observe that alongside with the decreasing of the doping concentration of the base (N_B) and of the base width (w_B), the transit time through the base quickly decreases, too, reaching a minimal value of 0.019 ps while the field factor in the base increases for the case $N_B = 10^{17}$ (cm^{-3}) and w_B = 0.1 μm. The average value of the transit time is 23.59 ps, corresponding to values of the base concentration $N_B = 10^{17}$ (cm^{-3}), $N_B = 10^{19}$ (cm^{-3}) and of base width w_B = 0.2 μm, w_B = 0.1 μm, w_B = 0.3 μm.

4. CONCLUSIONS

The manufacturing technology of HBT is different from the one used for BJT. The base in case of BJT is manufactured by using diffusion and the diffusion laws determine a Gaussian type of profile in the base. HBT devices are manufactured using molecular epitaxy which gives a contact doping profile. In case of HBT, producing an internal field by using uniform doping is no more possible. This is the reason why was used in the gradation of the molar composition. In the case of an imposed experiment, compositional gradation of the heterojunction’s passing region allows the attenuation of the discontinuity in the conduction and valence of the bands. The energetic band of the base is variable with the distance and the equation generates an electric field.

The average transit time through the base for a transistor with a constant internal field is 25,4ps, obtained for great values of doping concentration and for little values of the base width. In the case of an average internal field, the doping concentrations of the base and the base width do not matter anymore, the average transit time through the base being 3,99ns. In the case of HBT transistors with a strong internal field, the average transit time through the base is 4.43 ns obtained in the conditions of a maximal value of the doping concentration, no matter what the base width is. The average transit time in the case of a compositional graded base is 23.59ps, obtained for low values of the base doping concentrations (10^{17} cm^{-3}) and for average values of the base width (0,2 μm), or for high values of base doping concentrations (10^{19} cm^{-3}).

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