ORIGINAL PAPER

COMPARATIVE ANALYSIS OF BIPOLAR JUNCTION TRANSISTORS AND HETEROJUNCTION BIPOLAR TRANSISTORS USING MATLAB

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Abstract. *The study presents a comparative analysis between the classic bipolar silicon junction transistor (BJT) and AlGaAs/GaAs heterojunction bipolar transistor (HBT), pointing out the benefits of the latter. The mathematical simulation of the specific physical processes in the two devices is accompanied by a numerical analysis using Matlab application. The computer analysis highlights the benefits of using HBT transistors, namely: static amplification factor with values of 1000-2000 and a transition frequency of 400-500 GHz.*

Keywords: *BJT, HBT, matlab.*

1. INTRODUCTION

While IC technology progressed by reduction of transistors' geometry and high embedment densities, very soon came into focus the fact that the structure of basic transistors has some serious limitations. One of the major problems came from the necessity that base doping should be less than emitter's doping for a greater current gain. This produces a greater resistance for the intrinsic base region, which, combined with the emitter-base capacity, will finely limit the transistor's commutation speed.

In 1957, Herbert Kroemer suggested to be used as emitter a semiconductor with forbidden energy band greater than base's one [1]. In such heterostructure energy, band diagram shows that potential barrier for holes is higher ($V_p>V_n$), thus limiting the hole injection from base to emitter. Therefore, a greater base concentration than emitter's can be used, and intrinsic base resistance of the transistor goes down. Implicitly, the gain in power and limited work frequency can be substantially improved.

Also the idea of an emitter with wide forbidden energy band was suggested by Shockley and patented as being original [2], but Kroemer was the one who presented for the first time the analysis of heterojunction bipolar transistors (HBT).

In 1963 the idea of a laser double heterojunction (DH) was independently suggested by Kroemer, Alferov and Kazarinov [3]. Heterojunctions limited electrons and holes close to junction.

There were needed six more years to practically demonstrate this concept, when in 1969 Alferov and his team members developed the first AlGaAs/GaAs heterojunction using a process named epitaxy from liquid phase [4].

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AlGaAs, a semiconductor consisting of three elements, has electro-chemical features close to those of GaAs composite semiconductor. And what is more important, the network constants of the materials are close, allowing the production of high quality metallurgic junction.

Today HBT occupies the first place on the high frequency market, such as satellite communication, mobile phone communication and other wireless applications [5], [6].

2. COMPARATIVE ANALYSIS OF AlGaAs/GaAs EMITTER-BASE HETEROJUNCTIONS AND OF Si EMITTER – BASE JUNCTIONS

2.1. SEMICONDUCTOR JUNCTIONS AND HETEROJUNCTIONS

Semiconductor junction. A junction made of two semiconductors of the same type is named homojunction. If two extrinsic semiconductors, one of type – p, with a concentration N_A (cm^{-3}), the other one of type – p, with a concentration N_D (cm^{-3}), are put in close contact, a junction PN is obtained [7].

Semiconductor heterojunctions. A junction made of two different semiconductor materials is named heterojunction. Usually, heterojunction devices are made of composite semiconductor materials, based on the elements from group III and V of periodic table [8-13].

2.2. GENERAL ASPECTS OF COMPUTER ASSISTED DESIGN FOR INHERENT TENSION CALCULATION

PN junction with silicon. Internal tension is a constant tension and does not produce a net current by junction. It only maintains the thermodynamic equilibrium of the junction [7].

$$V_b = \frac{kT}{q} \cdot ln\left(\frac{N_A \cdot N_D}{n_i^2}\right) \qquad (1)$$

where

$\frac{kT}{q}$ – thermal potential;

N_A – doping concentration of the base;

N_D – doping concentration of the emitter;

n_i – intrinsic concentration of carriers.

For Matlab simulation we considered $N_D=10^{15}…10^{17}$ cm^{-3} and analysed internal tension V_b for $N_A=10^{16}$ cm^{-3}, $N_A=10^{17}$ cm^{-3} and $N_A=10^{18}$ cm^{-3} (Fig. 1).

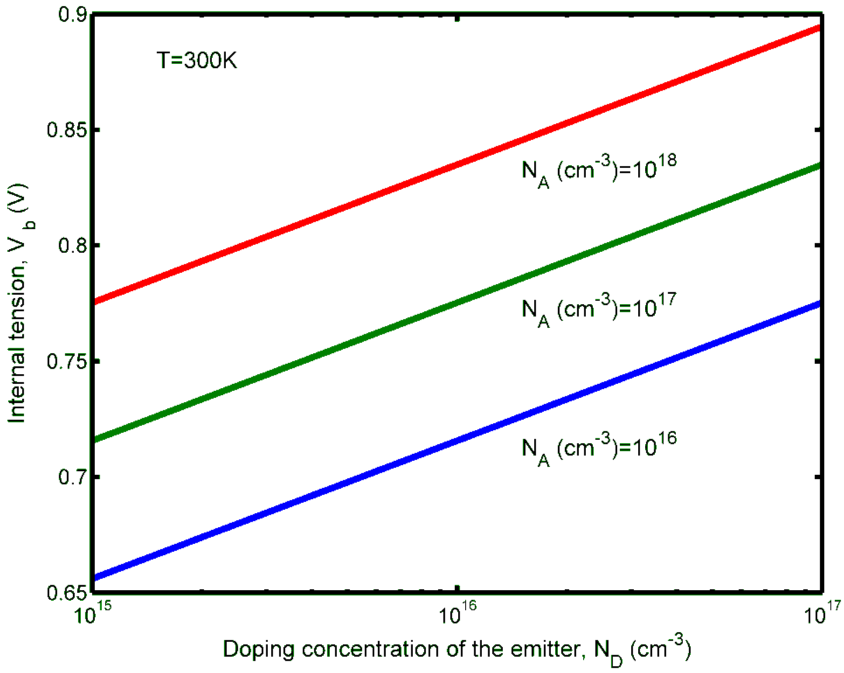

Figure 1. Internal tension variation of PN junction with Si depending on the emitter's doping concentration for various base's doping concentration.

Table 1. Internal tension of PN junction with silicon.

N_D [cm^{-3}]	N_A [cm^{-3}]	V_b [V]
10^{15}	10^{16}	0.6560
	10^{17}	0.7156
	10^{18}	0.7753
10^{17}	10^{16}	0.7753
	10^{17}	0.8349
	10^{18}	0.8946

In case of silicon junction, internal tension has values between 0.6560 and 0.8946 V, in the range of the used doping concentrations (Fig. 1). As the product of N_A and N_D increases, the internal tension of PN junction with silicon increases, too, reaching a maximum value of 0.8946 V for $N_A=10^{18}$ cm^{-3} and $N_D=10^{17}$ cm^{-3} (Table 1).

NP heterojunction type AlGaAs/GaAs. The calculation formula for internal tension in case of NP heterojunction type AlGaAs-GaAs is [9, 14]:

$$qV_b = \Delta E_C + E_{gB} + kT \cdot ln\left(\frac{N_A \cdot N_D}{N_{CE} \cdot N_{VB}}\right) \tag{2}$$

where:
q – electron charge;
ΔE_c – discontinuity of valence band;
E_{gB} – energy of base's forbidden band;
kT – thermal energy;
N_{CE} – actual density of energetic states in emitter's conduction band;
N_{VB} – actual density of energetic states in base's valence band.

Matlab analysis was realised for $N_D=10^{15}\ldots10^{17}$ cm^{-3} and the internal tension V_b for $N_A= 10^{16}$ cm^{-3}, $N_A=10^{17}$ cm^{-3} and $N_A=10^{18}$ cm^{-3} was tested (Fig. 2).

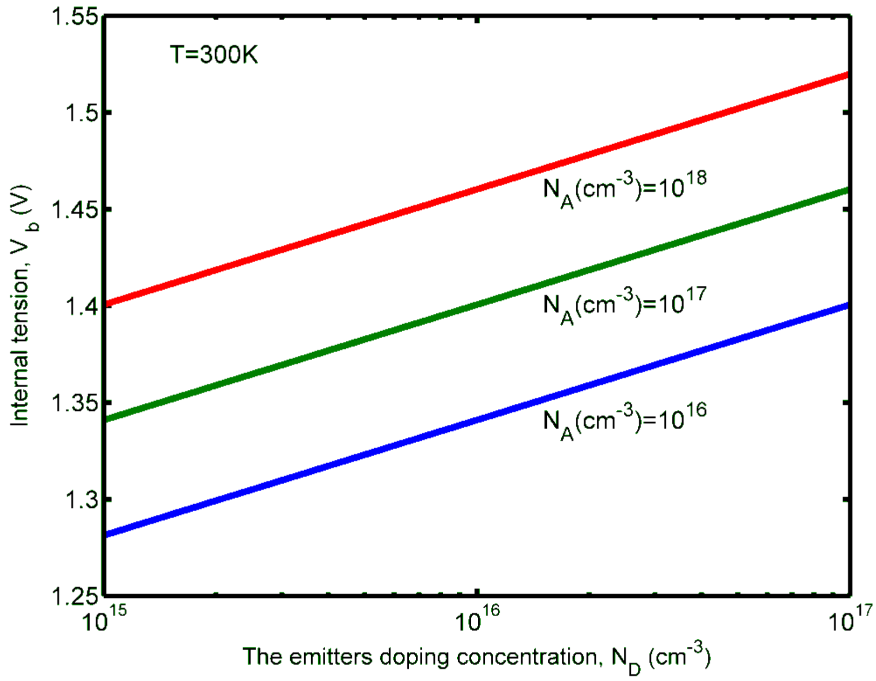

Figure 2. Internal tension variation of NP AlGaAs/GaAs heterojunction depending on the emitter's doping concentration for various base's doping concentration.

Table 2. Internal tension of NP heterojunction with AlGaAs/GaAs

N_D [cm^{-3}]	N_A [cm^{-3}]	V_b [V]
10^{15}	10^{16}	1.2814
	10^{17}	1.3411
	10^{18}	1.4007
10^{17}	10^{16}	1.4007
	10^{17}	1.4603
	10^{18}	1.5200

For AlGaAs/GaAs (Fig. 2) system, internal tension has values in the range 1.2814-1.5200 V (Table 2). The difference in comparison with internal tension of PN junction with silicon has its origin in the potential barrier which appears in the interface between the two semiconductors with different forbidden energy bands.

2.3. GENERAL ASPECTS OF THE COMPUTER ASSISTED DESIGN OF THE ELECTRIC FIELD CALCULATION

PN junction with silicon. The expression for electric field in the case of PN junction with silicon is [7]:

$$E(x) = \begin{cases} -\dfrac{qN_A}{\varepsilon}\cdot(x+x_p), & x\epsilon[-x_p,0] \\ +\dfrac{qN_D}{\varepsilon}\cdot(x-x_n), & x\epsilon[0,x_n] \end{cases} \quad (3)$$

where:

ε – silicon inductive capacity;
[-x_p, 0] – distance of transition region in p region;
[0, x_n] – distance of transition region in n region.

Electrons and holes diffusion leads to the occurence of an internal field, and the field opposes to diffusion. The process develops until the equilibrium is reached, Fermi level being the same everywhere.

In equilibrium the net electrons current is zero, the net holes current is zero, and charges of the two regions p and n form a dipole. Electrostatically, the PN junction presents in equilibrium three distinct regions: two neutral regions and a transition one.

Matlab simulation was realized for two cases: $N_A=10^{17}$ cm^{-3}, $N_D=10^{17}$ cm^{-3}, respectively $N_A=10^{18}$ cm^{-3}, $N_D=10^{17}$ cm^{-3} (Fig. 3).

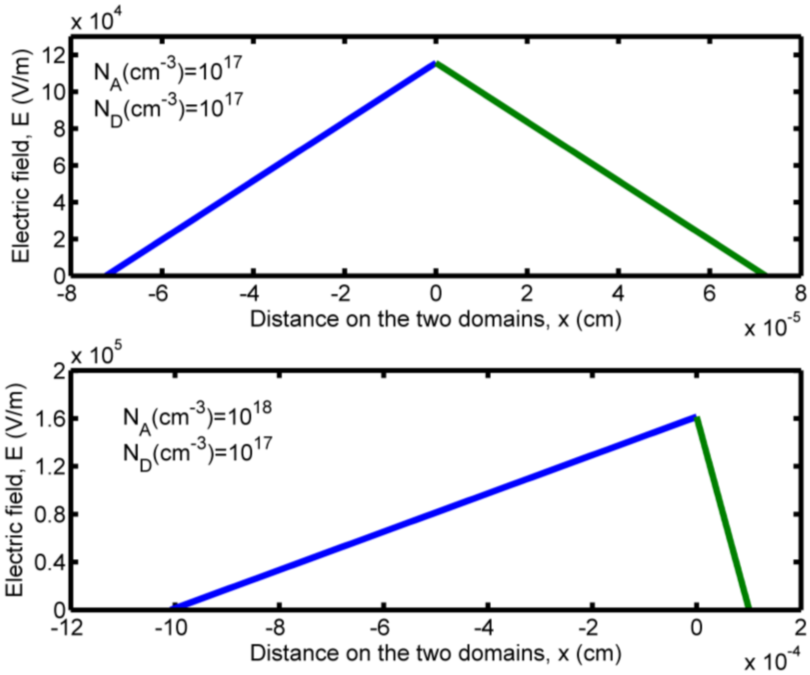

Figure 3. Electric field variation in the transition region for a PN junction with Si dependent on distance (on the two domains) for various base's doping concentrations and equal emitter's doping concentrations.

For the case $N_A=10^{17}$ cm^{-3} and $N_D=10^{17}$ cm^{-3} it can be noticed that $x_n=x_p=0.72237$ μm, and the electric field has an uniform distribution in the two regions (Fig. 3).

For the case $N_A=10^{18}$ cm^{-3} and $N_D=10^{17}$ cm^{-3} it can be noticed that $x_n=1.0082$ μm and $x_p=10.082$ μm, and the electric field is more extended in p region (Fig. 3).

In w region exists a non-zero electric field oriented from region – n, with a higher potential, to region – p, with lower potential. At the ends of the depletion region the field becomes null because we enter in neutral regions where the electric field is zero. For PN junction, the electric field is negative because is oriented contrariwise to ox positive axis. The maximum absolute value of the field is placed at the metallurgic junction (x=0), because all the electric flux lines generated by dipole flow through that point (Fig. 3).

NP heterojunction AlGaAs/GaAs type. The expression of the electric field in case of NP heterojunction AlGaAs-GaAs type is [9, 14]:

$$E_E = \frac{qN_D}{\varepsilon_E}(x + x_n), E_B = -\frac{qN_A}{\varepsilon_B}(x - x_p) \quad (4)$$

where:
ε_E – permittivity of AlGaAs region;
ε_B – permittivity of GaAs region.

In order to determine the electric field in Matlab we considered two cases: $N_D=10^{17}$ cm^{-3}, $N_A=10^{17}$ cm^{-3}, respectively $N_D=10^{17}$ cm^{-3}, $N_A=10^{18}$ cm^{-3} (Fig. 4).

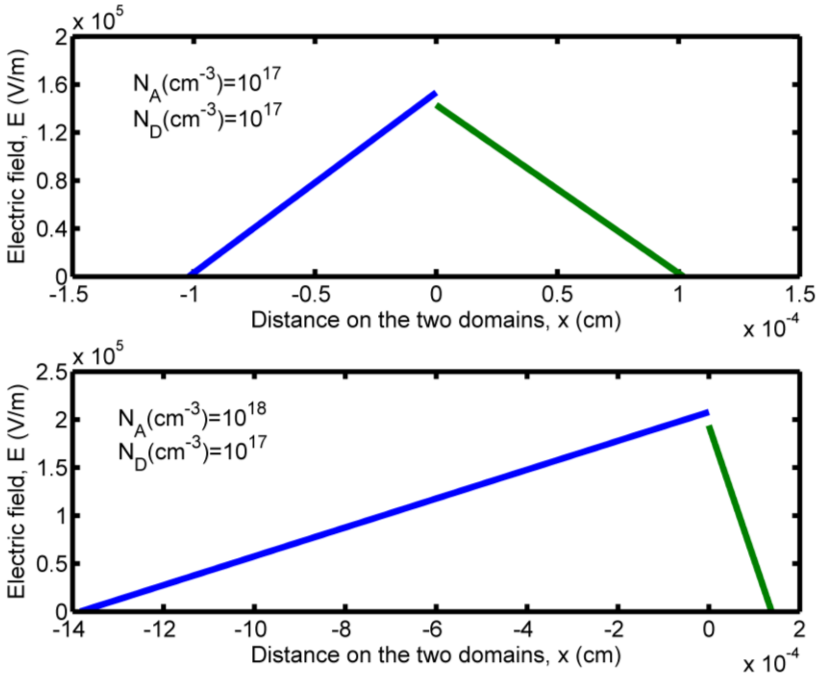

Figure 4. Electric field variation in the two regions of spatial charge for a NP heterojunction AlGaAs/GaAs type, dependent on distance (on the two domains) for various base's doping concentrations and equal emitter's doping concentrations.

For case $N_A=10^{17}$ cm^{-3} and $N_D=10^{17}$ cm^{-3} it can be noticed that $x_n=x_p=1.02$ μm, and the electric field has an uniform distribution in both regions.

For case $N_A=10^{18}$ cm^{-3} and $N_D=10^{17}$ cm^{-3} it can be noticed that $x_n=1.3826$ μm and $x_p=13.826$ μm, and the electric field extends more in the region type AlGaAs.

Comparing to the silicon junction (Fig. 3), the electric field in the semiconductor heterojunction (Fig. 4) is discontinuous in the point x=0 because of the different value of the dielectric constant for the two semiconductor materials:

$$\varepsilon_E=106,4655\cdot 10^{-14}\ [\text{F/cm}]$$

$$\varepsilon_B=114,165\cdot 10^{-14}\ [\text{F/cm}]$$

2.4. GENERAL ASPECTS OF THE COMPUTER ASSISTED DESIGN OF THE THICKNESS CALCULATION FOR THE TRANSITION REGION

PN junction with silicon. The transition region provides the transit from the neutral region – p to the neutral region – n. It is extended around the metallurgical junction to a distance x_n in the region – n and x_p in the region – p. The region w is depleted of the mobile carriers, $n_0 \approx 0$ and $p_0 \approx 0$, this being the reason why the transition region is also called the depletion region.

The expression for the computation of the transition region thickness in case of a PN junction with silicon is [7]:

$$w = \left(\frac{2\varepsilon}{q} \cdot \frac{N_A + N_D}{N_A \cdot N_D} \cdot V_b\right)^{\frac{1}{2}} \quad (5)$$

In order to determine the transition region thickness using Matlab we analysed three cases: $N_A=10^{16}$ cm^{-3}, $N_A=10^{17}$ cm^{-3} and $N_A=10^{18}$ cm^{-3} for $N_D=10^{15}\ldots10^{17}$ cm^{-3} (Fig. 5).

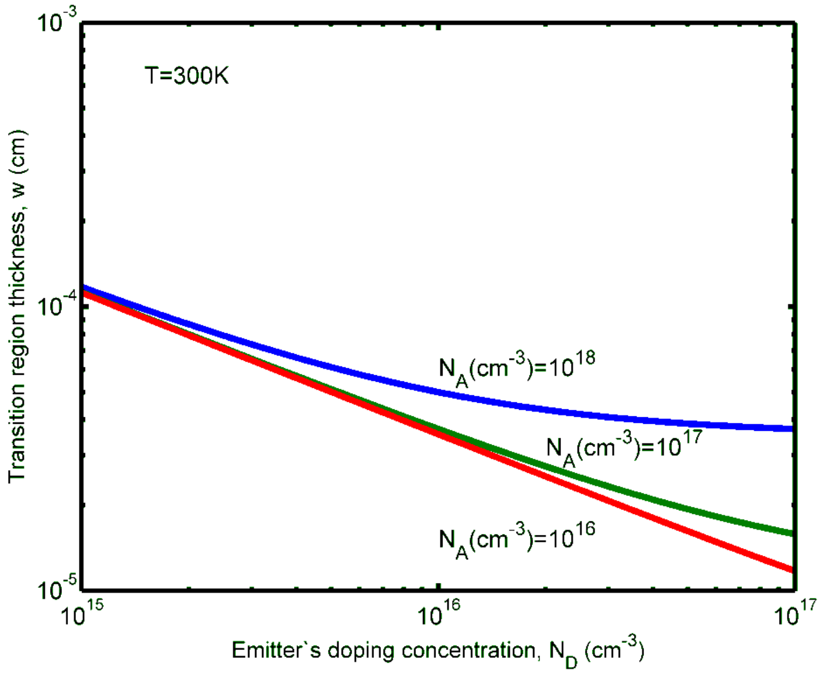

Figure 5. Transition region thickness variation for a PN junction with Si dependent on emitter's doping concentration for various doping concentrations of the base.

Table 3. Transition region thickness for PN junction with Si

N_D [cm^{-3}]	N_A [cm^{-3}]	V_b [V]	w_b [cm]
10^{15}	10^{16}	0.6560	1.1726e-4
	10^{17}	0.7156	1.1236e-4
	10^{18}	0.7753	1.1186e-4
10^{17}	10^{16}	0.7753	3.7081e-5
	10^{17}	0.8349	1.5811e-5
	10^{18}	0.8946	1.1720e-5

In case of direct polarization, the neutral region potential – p is positive, having as a result the contraction of the potential barrier. The external electric field will be oriented opposite to the internal field, thus contracting the total field, and the transition region thickness w decreases with the applied direct tension (Table 3).

In case of inverse polarization, the internal potential barrier of the junction increases. In w region operates an internal field, oriented from region – n to region – p, which is overlapped by an external field. To a greater field corresponds a greater electric charge, hence it results that x_n and x_p increase and, implicitly, w increases, too. In conclusion, the transition region thickness w increases with the applied inverse tension.

NP heterojunction type AlGaAs/GaAs. Heterojunction is a junction made of two semiconductors which have different forbidden energetic band. The main difference from homojunction is the different value of electric permittivity in the two semiconductor materials.

The expression for calculation of transition region thickness in case of NP heterojunction type AlGaAs/GaAs is [9]:

$$w^2 = \frac{\left(N_D + N_A\right)^2}{\varepsilon_E \cdot N_D + \varepsilon_B \cdot N_A} \cdot \frac{2\varepsilon_E \cdot \varepsilon_B \left(V_b + V_a\right)}{q \cdot N_D \cdot N_A} \quad (6)$$

The Matlab analysis was made, as in case of PN silicon junction, for cases: $N_A=10^{16}$ cm^{-3}, $N_A=10^{17}$ cm^{-3} and $N_A=10^{18}$ cm^{-3} for $N_D=10^{15}\ldots10^{17}$ cm^{-3}, considering the inverse tension V_a=0 (Fig. 6).

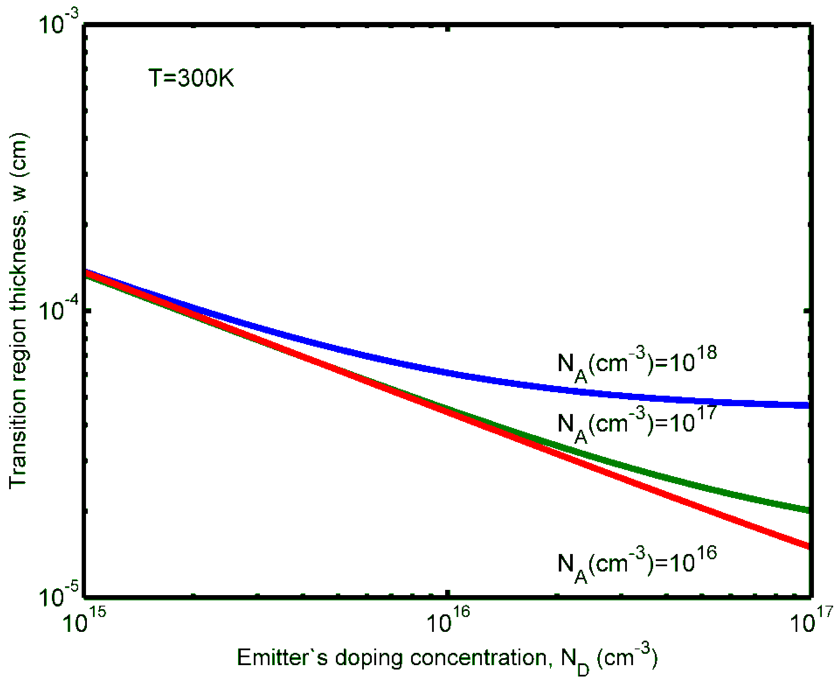

Figure 6. Thickness variation of the spatial charge region for a NP heterojunction type AlGaAs/GaAs, dependent on emitter's doping concentration for various doping concentrations of the base.

Table 4. Transition region thickness for NP heterojunction type AlGaAs/GaAs

N_D [cm^{-3}]	N_A [cm^{-3}]	V_b [V]	w_b [cm]
10^{15}	10^{16}	1.2814	1.3738e-4
	10^{17}	1.3411	1.3430e-4
	10^{18}	1.4007	1.3660e-4
10^{17}	10^{16}	1.4007	4.6738e-5
	10^{17}	1.4603	2.0056e-5
	10^{18}	1.5200	1.4963e-5

The difference, compared to the transition region thickness of PN silicon junction, is due to the potential which appears at the interface between the two semiconductors with different forbidden energetic bands (Figs. 5 and 6, Tables 3 and 4).

2.5. GENERAL ASPECTS OF THE COMPUTER ASSISTED DESIGN OF THE CALCULATION OF THE DIRECT CURRENT OF EMITTER-BASE JUNCTION

PN silicon junction. Through the transition region of PN junction flow four different current components, two of diffusion and two of drift, one for each carrier type.

The diffusion currents are positive. In the case of direct polarization, the electrons diffusion current increases depending on the equilibrium state. In case of inverse polarization, the diffusion current decreases comparing to the equilibrium state. In relation to the region from which flows, the diffusion current is a majority carrier current.

The drift currents are negative. In relation to the region from which flows, the drift current is a minority carrier current generated in the neutral region on a distance equal to a diffusion length in relation to the margin of the transition region.

Junction's current (total current) is given by the amount of the diffusion and drift components. In case of direct polarization, the total current is a diffusion current and is named direct current. The total current increases with the applied direct tension. In case of inverse polarization, the total current is a drift current and is named inverse current. The total current does not vary with the inverse tension.

The expression for the direct current of a silicon PN junction (Shockley equation) is [7]:

$$J_{direct} = J_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right] \tag{7}$$

where
J_0 – saturation current of PN junction;

$$J_0 = q\cdot\frac{D_p}{L_p}\cdot\frac{n_i^2}{N_D} + q\cdot\frac{D_n}{L_n}\cdot\frac{n_i^2}{N_A} \tag{8}$$

D_n – diffusion factor of the electrons;

$$D_n = \frac{kT}{q}\cdot\mu_n \tag{9}$$

L_n – diffusion length of electrons (minority carriers) in neutral region - p;

$$L_n = \sqrt{D_n\cdot\tau_n} \tag{10}$$

D_p – diffusion factor of the holes;

$$D_p = \frac{kT}{q}\cdot\mu_p \tag{11}$$

L_p – diffusion length of the holes (minority carriers) in neutral region - n;

$$L_p = \sqrt{D_p\cdot\tau_p} \tag{12}$$

Direct current variation of emitter-base junction was determined using Matlab for cases: $N_A=10^{16}$ cm^{-3}, $N_A=10^{17}$ cm^{-3} and $N_A=10^{18}$ cm^{-3}, considering $N_D=10^{17}$ cm^{-3} (Fig. 7).

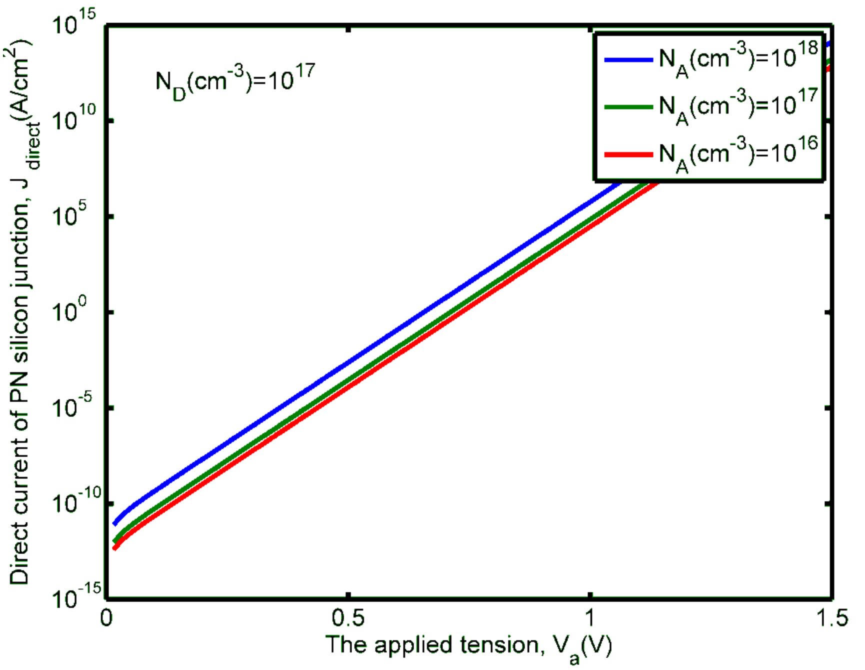

Figure 7. Direct current variation of PN silicon junction dependent on the applied tension for various doping concentrations of the base.

Table 5. Direct current of PN silicon junction.

N_D [cm^{-3}]	N_A [cm^{-3}]	V_a [V]	J_{direct} [A/cm^2]
10^{17}	10^{16}	1.5	$6.9649 \cdot 10^{12}$
	10^{17}		$1.6671 \cdot 10^{13}$
	10^{18}		$1.3814 \cdot 10^{14}$

Direct current of homojunction is a diffusion - recombination current. The diffusion produces the minority carriers transport (electrons and holes) over the potential barrier of the junction, and the recombination of the minority carriers in semiconductor's neutral regions provides stable flow of the current (Fig. 7). If we want to double the direct current of a PN junction, we do not double the concentration of strong doped region, but we reduce two times the concentration of the low doped region (Table 5). We do this because the direct current flowing through the junction is a minority carriers current, not a majority carriers current. The majority carriers junction has only one role – to supply the minority carriers recombination around the metallurgical junction.

NP heterojunction type AlGaAs/GaAs. The direct current of a heterojunction is transformed in diffusion current. The essential distinction between heterojunction and homojunction is that the densities of minority carriers from the margins of transition region, existing in these expressions, cannot be computed using the quasi-equilibrium relations.

The expression for the direct current of a NP heterojunction type AlGaAs/GaAs is [9], [14]:

$$J_{n,em} = A^* T^2 \exp\left(-\frac{q\varphi_0}{kT}\right)\left[\exp\left(\frac{qV_a}{mkT}\right) - 1\right] \quad (13)$$

where

A^* – Richardson's constant;

m – ideality factor of the current of electrons injected by emitter-base heterojunction directly polaryzed;

$$m = 1 + \frac{\varepsilon_E N_D}{\varepsilon_B N_A} \quad (14)$$

The direct current variation of NP heterojunction type AlGaAs/GaAs, using Matlab, is given in Fig. 8, where we considered N_D<< N_A and $N_A=10^{18}$ cm^{-3}, $N_A=10^{19}$ cm^{-3} and $N_A=10^{20}$ cm^{-3}.

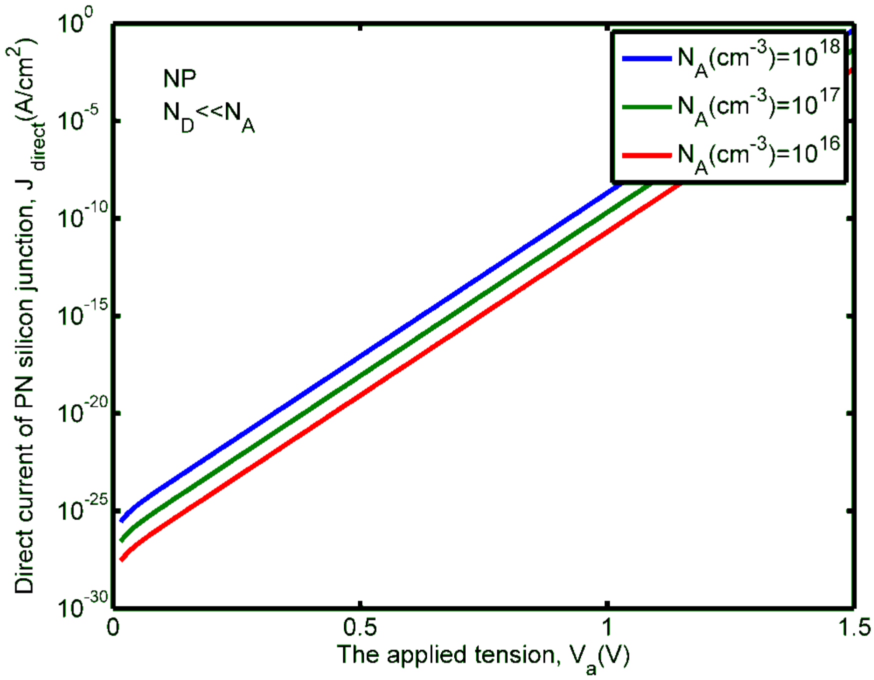

Figure 8. Direct current variation of NP heterojunction type AlGaAs/GaAs dependent on the applied tension for various doping concentrations of the base in condition N_D<<N_A.

Table 6. Direct current of PN silicon junction

N_A [cm^{-3}]	V_a [V]	J_{direct} [A/cm^2]
10^{16}	1.5	0.4855
10^{17}		0.0486
10^{18}		0.0049

In case of heterojunction type AlGaAs/GaAs (Fig. 8), the diffusion of electrons is replaced by a thermoelectronic injection mechanism through the energetic barrier of conduction band, and the diffusion of the holes is, practically, blocked by the energetic barrier of valence band (Table 6).

3. BIPOLAR TRANSISTORS WITH JUNCTION AND HETEROJUNCTION

Bipolar junction transistor is formed of two junctions (for example PN) placed back to back. P region of the first junction emits carriers in N base, and is named emitter, and the other P region collects them, and is named collector [7].

If the base is thick, the carriers injected by the emitter disappear by recombination before reaching the collector. There are only two diodes which do not collaborate.

If the base is thin, very few careers recombine while they are passing through it, the current injected by emitter reaching almost entirely the collector. Therefore, the two junctions are electrically coupled, forming together a transistor. The device is named bipolar because both electrons and holes take part in its functioning. In terms of doping, transistors can be PNP or NPN. They can be made with homojunctions (BJT) or with heterojunctions (HBT).

Bipolar heterojunction transistor presents multiple advantages: static gain in current, high cut frequency, high gain in power, high speed of commutation. Furthermore, HBT transistors present the additional advantage of improving performance and functioning in very low temperature conditions [8, 15].

3.1 GENERAL ASPECTS OF COMPUTER ASSISTED DESIGN OF THE CALCULATION OF CURRENT AMPLIFICATION STATIC FACTOR

BJT transistor. The approximate relation which gives the value of static gain in current for BJT transistor is [7, 8]:

$$\frac{1}{\beta}=\frac{D_{pe}}{D_{nb}}\cdot\frac{w_B}{w_E}\cdot\frac{N_A}{N_D}+\frac{1}{2}\cdot\left(\frac{w_B}{L_{nb}}\right)^2 \qquad (15)$$

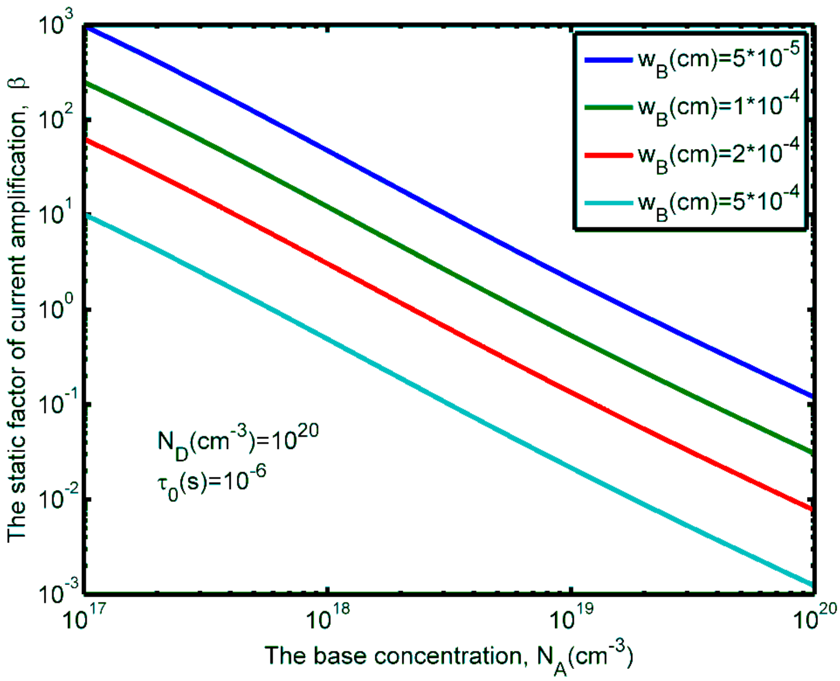

Figure 9. Variation of static factor of current amplification, dependent on the base concentration for various thicknesses of the base in case of BJT transistor.

In case of silicon bipolar transistors (BJT), the injection of carriers from emitter to base is made by diffusion. A good static amplification factor is given if the base doping is considerably less than emitter's. Hence, the base resistance is great and the transistor's gain in power reduces (Fig. 9). Being realized by means of diffusion, the base is thick and transition frequency cannot be greater than 5 GHz.

The amplification factor of BJT transistor (for a base of 0.5 microns thickness) reaches the value of 100 if the emitter is doped with a concentration $N_D=10^{20}$ cm^{-3}, and the base with a concentration $N_A=10^{17}$ cm^{-3}, namely a proportion $N_D/N_A=1000$ (Fig. 9).

HBT transistor. The approximate relation which gives the value of static gain in current for HBT transistor is [6]:

$$\frac{1}{\beta}=\frac{D_{pe}}{\bar{v}_n w_E}\cdot\frac{N_A}{N_D}\cdot\exp\left(-\frac{\Delta E_V}{kT}\right)+\frac{1}{2}\cdot\left(\frac{w_B}{L_{nb}}\right)^2 \quad (16)$$

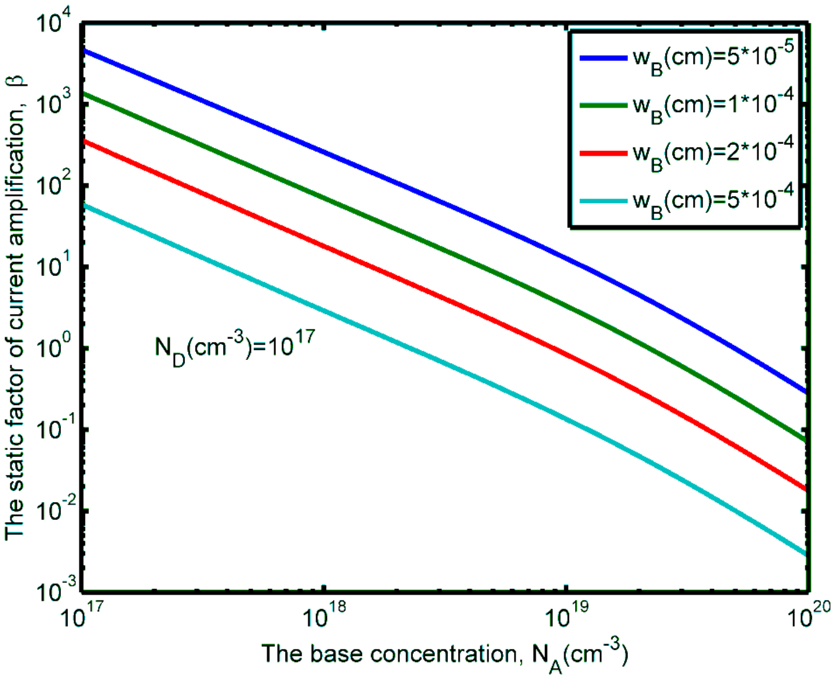

Figure 10. Variation of static factor of current amplification dependent on base concentration for various thicknesses of the base for a HBT transistor.

If instead of emitter - base silicon homojunction is used a heterojunction type AlGaAs/GaAs, the emitter has a forbidden band greater than the one of the base, and at the interface between the two regions appears an energy barrier which functions as an 'electron launcher'. The injection is of thermoelectronic type, thus allowing to work with a base concentration which is greater than emitter's concentration [13, 16].

A value of 100 of the amplification factor in case of HBT transistor, for a base thickness comparatively similar is obtained if $N_D/N_A=0.1$ (Fig. 10). The base can be much more doped than the emitter. Therefore, the transistor does not reach anymore the high injection state and the gain linearity is provided for a much larger range of current. Furthermore, the significant reduction of base resistance forbids the degradation of β linearity, by transistor's entry in self-agglomeration state.

4. CONCLUSIONS

The comparative study between the electrical features of HBT – AlGaAs/GaAs and BJT-Si transistors was centred on the analysis of emitter-base junction (spatial charge region, electric field, direct current) and of static factor of current amplification.

Mathematical simulation of the specific physical processes in the two devices was computer assisted, using Matlab programs [17].

Computer analysis took into account the variation of lifetime and electrical mobility dependent on doping concentration.

In case of BJT transistor, the injection of carriers from emitter to base is made by means of diffusion. A good static factor of amplification is obtained if the base doping (N_A) is considerably lesser than emitter's one (N_D).

Comparing to BJT transistor, the use of an abrupt heterojunction for HBT transistor improves the maximum gain in current with $\exp(\Delta E_V/kT)$ factor. The injection is of thermoelectronic type, thus allowing to use greater base concentrations (N_A) than the ones used for the emitter (N_D). This is the main advantage of HBT transistor.

The results of the study highlight the considerably superior performances of HBT transistors (Table 7).

Table 7. Comparative analysis of the performances of BJT and HBT transistors

	V_b [V]	E [kV/m]	w [cm]	J_{direct} [A/cm^2]	β
BJT	0.65÷0.89	0÷120	10^{-4}÷10^{-5}	10^{-15}÷10^{15}	10^{-3}÷10^{3}
HBT	1.28÷1.52	1600÷2000	10^{-4}÷10^{-5}	10^{-30}÷1	10^{-3}÷10^{4}

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