Evaluation of the Influence of Technological Parameters on the cutoff frequency for the InP-based Single Heterojunction Bipolar Transistor

Jihane Ouchrif, Abdennaceur Baghdad, Aicha Sahel, Abdelmajid Badri, Abdelhakim Ballouk

Abstract— Communication and information systems have been developed, thanks to the use of Heterojunction Bipolar Transistors. These electronic devices are characterized by low noise and high speed.

The present paper contains information about a 2D physical and numerical modelling of the InP/InGaAs Single Heterojunction Bipolar Transistor SHBT that were carried out using the simulator TCAD-Silvaco (Technology Computer Aided Design). Due to many physical mechanisms occurring within this electronic device, we have integrated physical models in the simulation such as SRH/OPTR…..

Afterwards, we examined the impact of two technological parameters which are the emitter length L_e and the collector doping concentration N_C on the electrical performance of the InP/InGaAs SHBT, and in particular in terms of the cutoff frequency f_T. Finally, the obtained results led us understand how much these technological parameters can impact the cutoff frequency of the electronic device SHBT.

Index Terms— Cutoff frequency, Single Heterojunction Bipolar Transistor, TCAD-Silvaco, SRH, OPTR

1 INTRODUCTION

Today, semiconductor devices are used more and more in telecommunication systems. According to the state of the art, III-V semiconductor materials are characterised by their electronic transport properties, they demonstrate high electronic mobility and also a direct band gap. Because of their outstanding speed characteristics, electronic components based on III-V semiconductor materials can operate at very high frequencies [1].

Bipolar Heterojunction Transistors (HBTs) based on InP and InGaAs semiconductor materials have revealed excellent electrical characteristics. They are used in high frequency applications [2] [3].

In this present work, we evaluated the influence of two technological parameters related to the technology of InP/InGaAs SHBT on the electrical performance, in particular the cutoff frequency f_T. These parameters are: the collector doping concentration N_C, and the emitter length L_e.

The InP/InGaAs Single Heterojunction Bipolar Transistor is composed of semiconductor materials. There are two alloys, a binary alloy for InP (Indium Phosphide), and a ternary alloy for InGaAs (Indium Gallium Arsenide).

We find elsewhere [4] that the Molecular Jet Epitaxy was used for the growth of the epitaxial layers of the InP/InGaAs SHBT on an InP semi-insulating substrate.

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2 SHBT PHYSICAL AND NUMERICAL MODELING

2.1 InP/InGaAsSHBT Description

In this paper, we used the structure of the InP/InGaAs SHBT from research papers [3] [5] . It is an NpN Bipolar Transistor with a single heterojunction. For the emitter surface, it is equal to 5x5 μm^2.

From the top of this device, we find the following layers: the cap, the Emitter 1, the Emitter 2, the Spacer, the Base, the Collector, the Sub-collector, the buffer, and the substrate. Two semiconductor materials are used, InGaAs and InP.

The Table 1 below presents the specific characteristics of the epitaxial layers for the studied electronic device, respectively the material, the doping concentration, and the thickness. The studied device was created using the device structure and mesh editor DevEdit [6] which is an interactive tool of the TCAD-Silvaco.

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TABLE 1
LAYER STRUCTURE OF INP/INGAAS SHBT

Layer	Material	Doping (cm^{-3})	Thickness (nm)
Cap	$In_{0.47}Ga_{0.53}As$	n = $1x10^{19}$	135
Emitter 1	$In_{0.47}Ga_{0.53}As$	n = $1x10^{17}$	135
Emitter 2	InP	n = $1x10^{17}$	40
Spacer	$In_{0.47}Ga_{0.53}As$	-	5
Base	$In_{0.47}Ga_{0.53}As$	p =$1.5 x10^{19}$	65
Collector	$In_{0.47}Ga_{0.53}As$	n = $1 x 10^{16}$	630
Sub-collector	$In_{0.47}Ga_{0.53}As$	n = $1 x 10^{19}$	500
Buffer	$In_{0.47}Ga_{0.53}As$	-	10
Substrate	Semi-insulating InP		

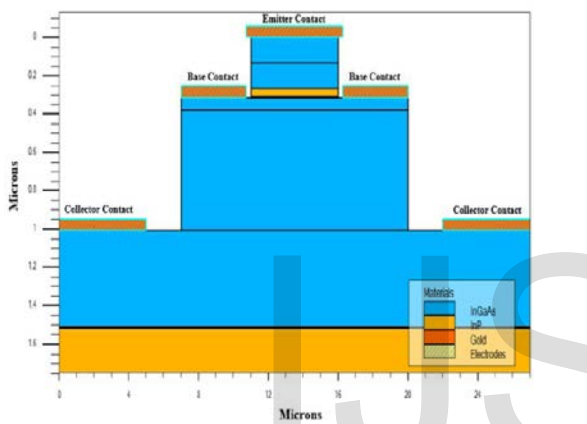

Fig. 1. Simulated Device Structure of the InP/InGaAs SHBT on InP Substrate [7]

The figure 1 presents the simulated device structure of the InP/InGaAs SHBT. It is the same figure obtained in the research paper [7].The layers in blue are made from the semiconductor material InGaAs, and those in yellow from the semiconductor material InP, the contacts are made from the material Gold.

2.2 METHODOLOGY

2.2.1 Physical Modeling

In the simulation program, we have considered the influence of doping concentration on electron and hole mobilities for the electronic device InP/InGaAs SHBT. In every region, the effective mobility of electrons and holes is defined by the equation of Caughey - Thomas [3] [8] and written by the following:

$$\mu = \mu_{min}\left(\frac{T_L}{300}\right)^{\beta} + \frac{\mu_{max}\left(\frac{T_L}{300}\right)^{\delta} - \mu_{min}\left(\frac{T_L}{300}\right)^{\beta}}{1+\left(\frac{T_L}{300}\right)^{\gamma}\left(\frac{N}{N_C}\right)^{\alpha}} \quad (1)$$

Where,
β, δ and γ are the temperature dependent coefficients, T_L = 300 K.

Different physical phenomena are happening inside the studied electronic device InP/InGaAs SHBT, and in order to consider them, we added some physical models [9] contained in the simulator TCAD-Silvaco.

Among them, we cite the recombination model SRH (Shockley read Hall), the carrier statistic model BGN (Bandgap Narrowing), the Selberherr's model of the ionization impact (IMPACT SELB), the optical model OPTR and the Tunnel effect model BBT.STD (Band-to-Band)….

2.2.2 Numerical Modeling

In the simulation, the core tool ATLAS allowed us to solve numerically a serie of semiconductor equations [10] related to the continuity of the carriers and to the electric fields in each of the InP/InGaAs SHBT layers. Among these equations, we cite the Poisson's equation, the carrier continuity equations for electrons and holes.
The Newton method was chosen in the numerical simulation to solve these equations.

- The Poisson's equation is expressed by the following:

$$\text{div}\,(\varepsilon\nabla\psi) = \rho \quad (2)$$

Ɛ : the dielectric constant of the material.
Ψ : the local voltage potential
And ρ : is the local charge density

- The electric field:

$$\vec{E} = -\nabla\psi \quad (3)$$

- The carrier continuity equation for electrons is:

$$\frac{\partial n}{\partial t} = \frac{1}{q}\,\text{div}\,\vec{J_n} + G_n - R_n \quad (4)$$

$\vec{J_n}$ is the electron current.
The generation and recombination rates for the electrons are, respectively, G_n and R_n.

- The carrier continuity equation for holes is:

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\,\text{div}\,\vec{J_p} + G_p - R_p \quad (5)$$

$\vec{J_p}$ is the hole current.
The generation and recombination rates for the holes are, respectively, G_p and R_p.

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3 RESULTS AND DISCUSSIONS

We have carried out a 2D physical and numerical Modelling of the InP/InGaAs SHBT. Figures below show the simulation results for AC parameters in terms of the cutoff frequency f_T. In other previous work [7], we investigated the impact of technological parameters on the static current gain β, and in this present paper we evaluated the influence of two technological parameters: the collector doping concentration and the emitter length on the cutoff frequency f_T.

The cutoff frequency f_T is defined as the frequency for which the dynamic current gain h_{21} of the transistor in common emitter configuration is equal to unity. It is calculated by the following equation:

$$f_T = \frac{1}{2\pi\tau_{EC}} \quad \text{(X)}$$

Where,
τ_{EC} : the emitter-to-collector delay time.

In the research paper [11], we simulated the dynamic current gain h_{21} (dB) as a function of the frequency. We found that the cutoff frequency f_T for the studied electronic device is equal to 7 GHz. The current gain β_0 is around 35.956 dB.

We then evaluated the impact of two technological parameters: the collector doping concentration N_C and the emitter length L_e on the cutoff frequency f_T.

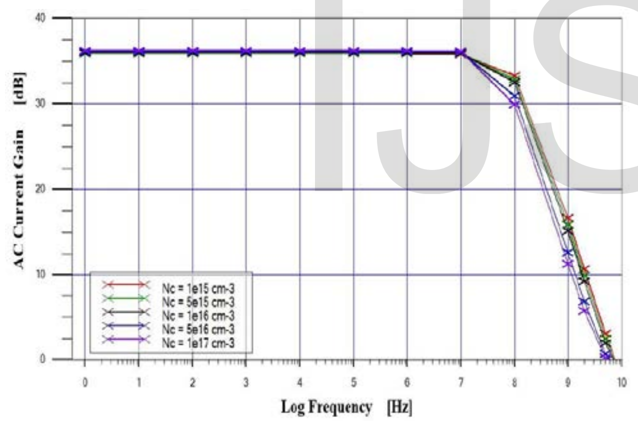

Fig.2. AC Current gain (dB) h_{21} versus frequency for different collector doping concentrations at T=300K

TABLE 2
Influence of collector doping concentration on the cutoff frequency

Collector doping concentration N_C (cm^{-3})	Current gain β_0(dB)	f_T(GHz)
1 $x10^{17}$	36.259	5.5
5 $x10^{16}$	36.139	6.0
1$x10^{16}$	35.956	7.0
5 $x10^{15}$	35.92	7.4

According to the figure 2 and the table 2, we noticed that when the collector doping concentration is decreased, the cutoff frequency increases slightly. Among the investigated values of collector doping concentration, it is N_c equal to 1 $x10^{15} cm^{-3}$ which gives the highest cutoff frequency equal to 7.55 GHz.

The improvement in comparison to the reference device is around 7.28%. This improvement is slight, and it is not important. The collector doping profile does not have an important influence on the cutoff frequency of this electronic device.

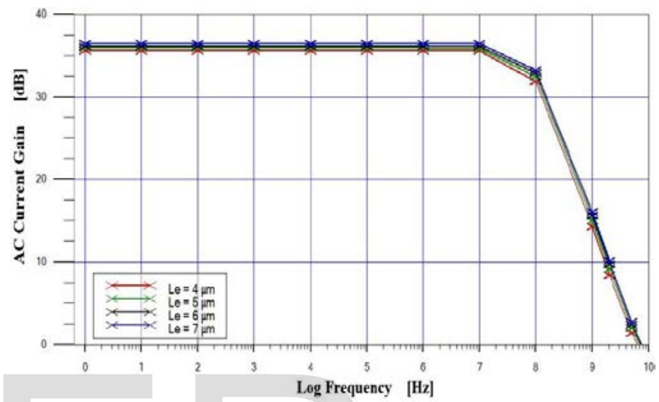

Fig.3. AC Current gain (dB) h_{21} versus frequency for different emitter lengths at T= 300 K

TABLE 3
Influence of emitter length on the cutoff frequency

Emitter length L_e (µm)	Current gain β_0(dB)	f_T(GHz)
4	35.659	6.5
5	35.956	7
6	36.619	7.2
7	36.51	7.5

As shown in the figure 3 and the table 3, we observed for the investigated values that when the emitter length is increased, the cutoff frequency increases slightly. Therefore, for L_e equal to 7 µm we found that f_T is around 7.5 GHz. The improvement in comparison to the studied device is around 6.67%.

Indeed, the emitter length as an investigated technological parameter does not have a crucial influence on the cutoff frequency, because the estimated improvement is small.

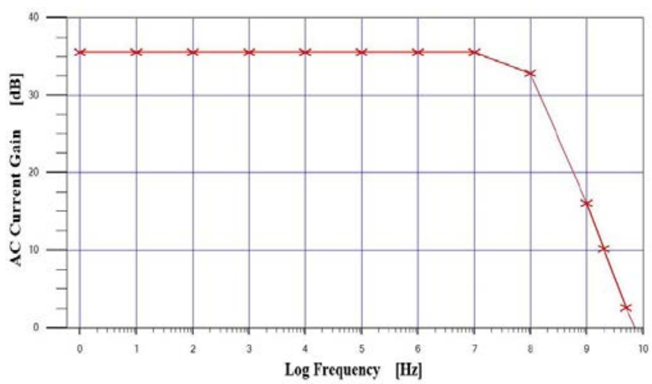

Fig.4. AC Current gain (dB) $\boldsymbol{h_{21}}$ versus frequency for optimal values of technological parameters at T=300K

The figure 4 presents the AC Current gain h_{21} as a function of the frequency for optimal values of technological parameters at T=300K. In particular for a collector doping concentration equal to 1 x10^{15}cm^{-3} and an emitter length of the order of 7 µm , we found that the cutoff frequency f_T is equal to 7.5 GHz. The current gain β_0 is around 35.559 dB. The improvement in comparison to the reference device is around 6.67% for the cutoff frequency. This improvement is slight.

4 Conclusion

We used the simulator TCAD-Silvaco to model the electronic device InP/InGaAs Single Heterojunction Bipolar Transistor. We have added the physical models included in the simulator such as SRH, OPTR, and BBT.STD…. to take into consideration the various physical mechanisms occurring inside this electronic device. We then simulated the AC current gain (dB) as a function of the frequency. We examined the impact of technological parameters on the cutoff frequency f_T, in particular the influence of the collector doping concentration N_C and the emitter length L_e. Taking the optimal values of the investigated parameters, we found that the cutoff frequency f_T is equal to 7.5 GHz. Therefore, we improved slightly the reference electronic device. The improvement in comparison to the reference device is around 6.67 % for the cutoff frequency f_T , and it is insufficient. We suggest to evaluate the influence of other technological parameters related to the other layers of the device structure, and especially the parameters of the base layer.

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