Design and Analysis of GaAs based HBT for High Frequency Applications

Manas Ranjan Jena
Department of EIE, ITER
Sikha 'O' Anusandhan
University
Bhubaneswar, Odisha, India

Mihir Narayan Mohanty
Department of ECE, ITER
Sikha 'O' Anusandhan
University
Bhubaneswar, Odisha, India

ABSTRACT

GaAs based Hetero-junction Bipolar Transistors (HBTs) have recently emerged as an important device technology for high speed and high frequency applications. The advantages of the HBTs fabricated on the new material systems are subjects of great interest and also studied by some of the researchers. The GaAs/AlGaAs device technology is ideally suited for such applications. In this work we are designing a device based on HBT technology, in order to investigate its characteristics and performance for high frequency applications. It proves that, the technology can be widely used and can replace CMOS Technology. Since HBT gives more advantage in terms of higher power gain and better thermal capabilities, i.e. for the same power, CMOS will dissipate more heat which increases the costs of the cooling systems. The emergence of GaAs HBT technology is destined to challenge silicon bipolar domination at the high end.

Keywords

GaAs HBT, High Speed and High Frequency applications.

1. INTRODUCTION

The main motivation for studying and developing HBTs is to capitalize on the advantage to device performance that can result from having an emitter material of a wider band gap than that of Base [1-3]. This advantage applies to both dc- and high frequency performance. Another advantageous feature of HBTs is that the use of alloys compositional grading in the various regions of the device, so providing an opportunity to create "alloy fields" to aid the transport of carriers through the device. This allows for increasing base resistance for improving frequency of operations.

2. HBT Technology

HBT (Hetero junction Bipolar Transistor) have more advantages in terms of high transconductance (g_m) ,we will study in this chapter the HBT technology. We will start by virtually fabricating an AlGaAs/GaAs HBT by SILVACO TOOL. In this case emitter is a $AL_xGa_{1-x}As$ based materials where x is the mole fraction. In this case the emitter width is chosen in such a way the grading distance which is calculated based on graded in emitter side. The base region is heavily doped as per reduction in base resistance. For high frequency application as we know cutoff frequency is inversely related to base resistance.(R_B) , for that reason base is heavily doped.

In a single-heterojunction device, the base, collector, and sub collector will all be of the same material, such as GaAs, while, in the AlGaAs system, for example, a small mole fraction of aluminum is added to the emitter to increase the bandgap. The energy band diagram [6, 7] for this system is shown in Fig2.

Due to the wide bandgap emitter, for a given bias, the energy barrier seen by holes injected into the emitter is higher than that for electrons injected into the base. The most significant result of the base/emitter heterojunction is that the potential barrier seen by base holes in the valence band is higher than that seen by emitter electrons in the conduction band. Thus, for a given base/emitter bias, the ratio of electrons injected to holes injected (the emitter injection efficiency) will be higher, and thus the gain will be higher [7, 8].

In silicon devices, the cutoff frequency is dominated by the base transit time. As V_{CE} increases, the collector depletion region pushes into the base, reducing its width, and thus f_T will go up. However, these measurements show that the III-V HBT is behaving in an opposite manner. In these devices, the complex relationship of drift velocity to electric field in the collector depletion region can reduce f_T at higher biases. These effects, and others, can make it difficult to simulate a III-V device using models based on silicon physics.

2.1 Design Steps for Fabrication

The main idea behind to fabricate a HBT is that looking to the real characteristics of a transistor which specifies that to be more frequency operated a HBT the main condition is that the base is to be heavily doped. As base is doped heavily that gives less base resistance which satisfied the mathematically analysis for HBT to be in high frequency application not a si type BJT. The relation is given below [7-8].

$$f_{\max} = \sqrt{\frac{f_t}{8\Pi C_{bc} R_b}} \tag{1}$$

Step1: For Band Gap

$$E_g(Al_x Ga_{1-x} As) = \begin{matrix} 1.424 + 1.247x & 0 \le x \le 0.45 \\ 1.990 + 0.125 + 0.143x^2 & x > 0.45 \end{matrix} \tag{2}$$

The above relation specifies that in the emitter side as Al concentration is graded the band gap is varies as the above formulas.

STEP 2: Band Gap Discontinuity (ΔE_v & ΔE_c)

In this case it is the NPN HBT. So ΔE_v should be higher than ΔE_c, which indicates less number of hole will be recombined. Hence the gain(DC gain) enhanced.

$$\Delta E_c(x) = 0.55x$$

$$E_g(Al_xGa_{1-x}As) = \begin{array}{ll} 1.247 + 0.55x & 0 \le x \le 0.45 \\ 0.476 + (0.125 - 0.55) + 0.143x^2 & x > 0.45 \end{array} \quad (3)$$

STEP 3: Doping Conc. V_s μ_n and μ_p

In this step the main discussion is that in AlGaAs (emitter part) when doped with ‘N’ type impurities then The majority carrier mobility that is electron mobility in N type semiconductor in AlGaAs is determined by the following formula

$$\mu_n = \frac{7200}{\left[1 + (5.51 * 10^{-17}) N_d\right]^{0.233}} \quad (4)$$

Similarly the majority hole mobility in p type material is determined by the following formulas

$$\mu_p = \frac{380}{\left[1 + (3.71 * 10^{-17}) N_a\right]^{0.266}} \quad (5)$$

In the above cases it is observed that we are going for N type HBT as the mobility for electron in N type material is higher than in P type materials. For that reason N type HBT is more preferable compare to P type HBT.

STEP 4: Doping Conc. Vs Minority Electron Mobility

In this step we are determining how the electron is behaving in base region when it is coming from the emitter region. Basically the minority electron mobility is a function of doping concentration which is given bellow.

$$\mu_{n(MinorityElectronMobility)} = 8300\left[1 + \frac{N_a}{3.98 * 10^{15} + \frac{N_a}{641}}\right]^{-1/3} \quad (6)$$

STEP 5: Calculation for DC β gain:

The gain which is expressed as

$$\beta = \frac{I_c}{I_b} = \frac{\tau_n}{\tau_b} \quad (7)$$

where ζ_n is the minority recombination life time. And ζ_b is the total transit time through base layer.

ζ_b which is expressed as

$$\tau_b = \frac{X_B{}^2}{2D_{nB}} \quad (8)$$

And

$$D_{nB} = \mu_n * 0.0258 cm^2 / s \quad (9)$$

Where The minority recombination life time which is defined as follows

$$\tau_n = \left[\frac{N_a}{1 * 10^{10}} + \frac{N_a}{1.6 * 10^{20}}{}^2\right]^{-1} \quad (10)$$

This indicates the minority recombination life time fully depends on base doping concentration.

And finally the gain which to be defined as

$$\beta = \frac{\tau_n}{\tau_b} = \frac{6.2 * 10^{-19} s}{1.2 * 10^{-12} s} \quad (11)$$

In this simulation work we have been simulated the AlGaAs/GaAs HBT which have given a cut of frequency of around 50 GHz. And also in this mode of operation the device intrinsic as well as extrinsic behavior has also represented by parameter extraction technique by the help of MATLAB tool. By changing the base width as well as emitter width the variation in gain also reflecting.

3. Result and Discussion

The simulated result is shown below for understanding the performance of the technology and how mobility is varying with respect to doping concentrations. In this case the HBT structure is simulated in Silvaco tool and it is observed in Fig 4 which is current gain vs Frequency that the cut off frequency can be reached around 50 GHz. This is achieved by the process of emitter grading where we used the mathematically equations for calculating the mole fraction of X, which is around 0.35 µm.

Fig 1 and Fig 2 represents the general structure of HBT and its band diagram. Fig 3 is the design based on silvaco tool. Here it is the AlGaAs/GaAs HBT where we used the exact mathematically equations (eq. 2 to eq. 11) for designing approach. And its simulation output is shown in fig 3. Then after the current gain vs frequency is extracted and is shown in fig 4, which concluding its operating frequency is around 50 GHz.

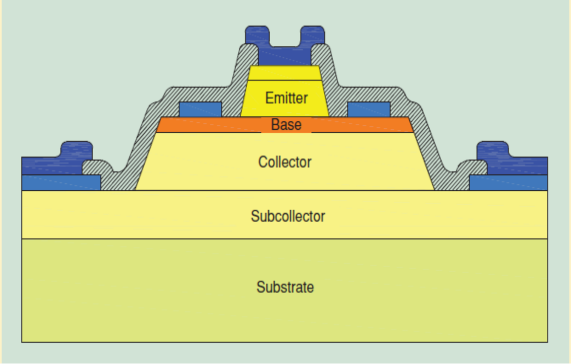

Fig 1: Cross section of III-V HBT

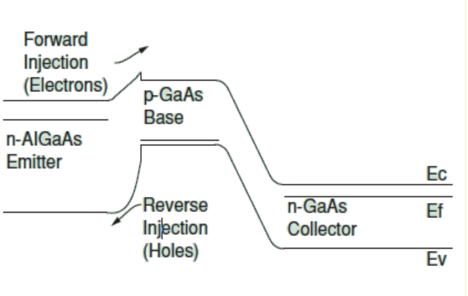

Fig 2: Energy band diagram of an AlGaAs/GaAs HBT.

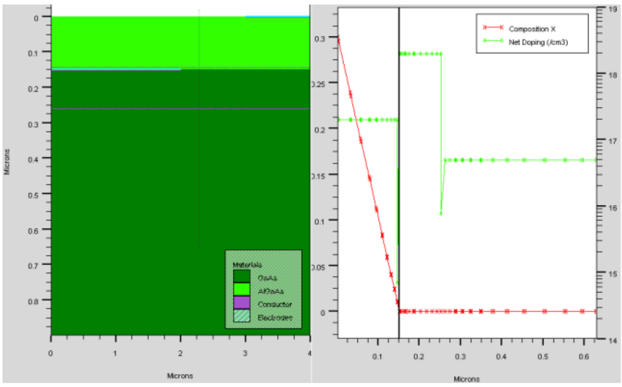

Figure 3: Simulation Result for HBT

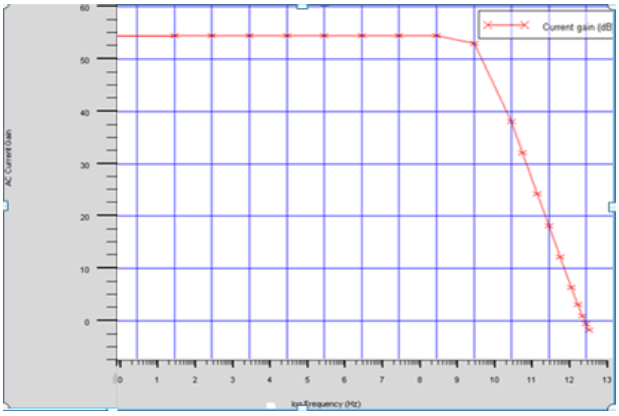

Fig 4: Current Gain V$_s$ Frequency (Simulation Result)

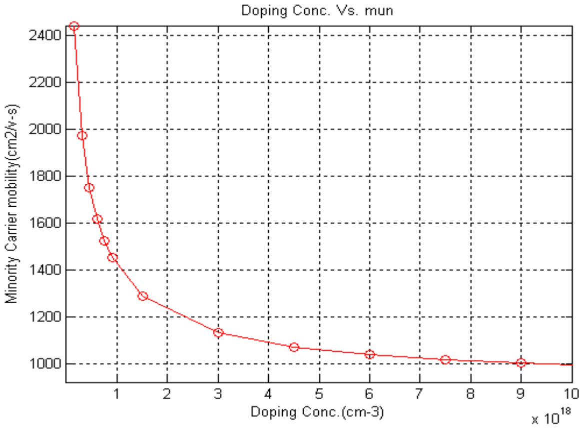

Fig 5: Doping V$_s$ μ$_n$ (Minority Carrier Mobility)

Fig 3 and Fig 4 is the simulation in silvaco tool and fig 4 represents the device frequency operation. Fig 5 is representing the variation in mobility with respect to doping which shows how the mobility of electron is vary in base region.

4. CONCLUSION

This is a simulation process of AlGaAs/GaAs HBT on Silvaco Tool where we observed that by taking a consider amount of Al mole fraction in emitter side the corresponding cut off frequency is reached towards 50 GHz range of operations. In this work we haven’t shown how it is used in circuit design but because of its high frequency of operation also gives good gain at this range which helps the circuit design in high frequency applications.

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