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Design and Analysis the fabrication steps of GaAs based HBT used in high Frequency Applications

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ABSTRACT: In this work, a GaAs based HBT device is modeled and simulated using different materials, in order to use in high frequency application. The doping level of each layer, choice of materials and dimensions, are taken from literature and optimized accordingly. The described method is suitable for next simple fabrication to a HBT used in real time high applications devices. In addition, a comparative study of performance parameters in between Silicon with HBT is also shown. Simulation is done on Silvaco.

KEYWORDS: Heterojunction, Wide bandgap materials, GaAs HBT, High frequency application, Dev Edit.

I. INTRODUCTION

The concept of the heterojunction bipolar transistor was evolved at increasing beta (amplification factor), due to which current gain will increase, therefore emitter defect become smaller. For small devices having larger perimeter area ratio, emitter periphery becomes dominant [1]. This effect is also named as “emitter size effect”. It will provide high power handling capability, high blocking voltage and high gain with very low on state resistance. With the use of Hetero structure, various properties of such devices can be achieved. There are significant advantages correspond to heterostructure (GaAs HBTs) design over the conventional homostructure (Si bipolar device) design. It includes higher switching frequency with reduction of geometrical dimensions. Such devices have more control of fundamental parameters in semiconductor crystal like effective mass of charge carriers, band gap ,mobilities effectively compare to conventional one. With varying electric field and bandgap , distinct force on electron and hole can be changed that improved device characteristics. Particularly the limitation of heterostructure is that the lattice constant of grown material must be matched in order to prevent quality degradation of quality of device. The Cross sectional view of HBT is shown in following fig 1. It is configured for Single HBT (SHBT), here lightly doped emitter with wide width and high concentration at base with thin width are used in HBTs.

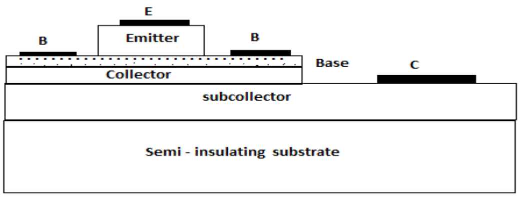

Fig 1: HBT cross section view

Due to this, base transit time become lowered and hot electron transport is possible through base layer .The collector layer is lightly doped and it is designed such that it provide high breakdown voltage. Emitter and base contact are made up of gold (Au). Here, GaAs substrate is taken, used for high frequency application, Substrate material can be altered according to required application. GaAs have high resistivity; therefore, it constitutes entire advantage of III-V group

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semiconductor by reducing the parasitic capacitance of device [2]. Due to high electron mobility and small base resistance, high frequency performance is obtained.

A. TECHNOLOGY PERFORMANCE:

BJT device does not have low base resistance and high gain simultaneously therefore performance of BJT will be limited. Heterojunction will improve the device performance by using different semiconductor material i.e. in base smaller band gap and in emitter larger band gap material is used. In addition, BJT have limitation in collector profile and material structure while in HBT collector transit time dominates over base and emitter transit time that helps to provide high frequency application. Unlike BJT, HBT have the capability to integrate digital function and microwave on a single chip and high current handling capability per unit chip area because current conduction will occur by complete emitter area.

B. WIDE BAND GAP MATERIAL:

These are the type of semiconductor material that permit devices to operate at much higher voltages, temperature and frequencies. It defines higher energy band gap , the difference between energy level is high where electrons switch between these levels. Mostly the wide band gap is of the order of 2-4 eV. Here AlGaAs is taken as wide bandgap material for emitter to attain higher base doping (like 10^{18} /cm^3) and lower emitter (like 10^{17} / cm^3). By altering the material composition for HBTs exclusive emitter/ base doping profile is obtained that make yield to reduce electron transit time and device parasitic. These materials also improve the injection efficiency and current gain where, emitter injection efficiency measures how efficiently emitter injects electron into the base. By altering the base doping (heavily doped) less base resistance will be obtained and collector to substrate capacitance to low level, HBT can be used for faster switching speed application. Injection efficiency can be increased by selecting appropriately the larger energy band gap semiconductor material for emitter compare to base material. Table 1 shows some wide band gap materials with their properties.

Table 1: Wide band gap materials [3,4,5]

Material	Bandgap	Properties
AlGaAs	1.42 – 2.16 eV	High injection efficiency.
GaN	3.4 eV	High power devices
SiC	2.0 – 7.0 eV	High temperature and voltages devices
SiO_2	8.9 eV	Masking material for diffusion
AlN	6.42	RF filter

According to applied various material in HBT, it can be used to fulfill various applications. With change in base doping concentration at higher level, lower forward transit time, lower base resistance and improvement of maximum frequency of oscillation is obtained. Grading high efficiency will be obtained for HBT due to ability of device to turn off itself completely with less base voltage change and very small turn on voltage variation between devices. Table 2 represents some applications of HBT with various materials.

Table 2: Various applications of HBT using different materials

Material	Applications	Remark
GaAs	High frequency applicationin optoelectronics	high mobility for electron (5000 cm2-V/Sec)
AlGaAs	Broad band power amplifier	smaller input
InGaAs	Higher speed potential	High electron velocity(2×10^7 cm/sec)

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It is clear from the table , that, by changing the materials for HBT various application will be acquired , since every materials have its unique properties that make it suitable for intended applications.

II. MODELING OF HBT: LITERATURE REVIEW

The work presented by V. Palankovski used two dimensional device-simulator MINIMOS-NT to show the simulation of power HBT on GaAs and showed better device performance [6]. The work presented by A.J. Garcia-Loureiro T.F. Pena , [2002], used finite element method to show the HBT for microwave application [7]. The work presented by Chung-Yen Hsu , [2010], used ANSYS, thermal modeling tool for HBTs design for high speed application. It also analyzes the maximum temperature region and temperature distribution of GaAs based HBT Devices. The work presented by Yang-Hua Chang, [2013], used finite element analysis software to study self-heating effect in HBT, also provided more accurate results under high power application [8]. The work presented by Bo-Rong Lin , [2014], used 2-D TCAD numerical simulation tool to implement self-heating and impact ionization that allow to study the failure mechanism of the devices. The work presented by Manas Ranjan Jena, used silvaco tool and given result for higher frequency application [9]. The work presented by Elissaveta Gadjeva, [2015], used Cadence PSpice simulator and the graphical analyzer for parameter extraction of small-signal HBT[10]. The work presented by UpomaSaha, [2015], used silvaco/atlas tool, incorporated various effects that exist in real life scenarios and corresponding effect for different parameters like response for electron concentration, electron current density and transit time are studied[11].

The proposed work focus on modeling of fabrication Process Flow of HBT in high Frequency Application by using Dev Edit tool. This tool provide flexibility at certain extent, at same time device applications can be altered by changing the materials. It is Easy to handle compare to Athena simulator. Various application can be implemented with the change in concentration of semiconductor material for emitter, base and collector. Fig 2 shows Layered architecture of HBT ,which contains several layer like base, emitter and collector etc. Every layer have its own significance that will be discussed further.

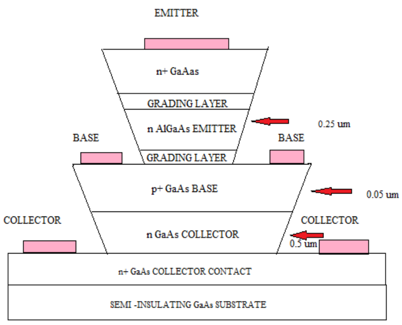

Fig.2 Layered Architecture of HBT

HBT Layout design is shown in Fig.3, where two type of layout design is defined and both have different specifications and properties.

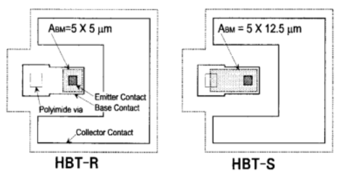

Fig.3 Layout Design of HBT

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HBT -R and HBT-S both have same emitter area and base contact area but different base-collector mesa area. Base resistance are different for both HBT-R and HBT-S. HBT-R shows transit frequency increased by 35 % compare to HBT-S and reduction of collector to base capacitance by 56 % , that is used for high speed operation [12].

III. WORKING PRINCIPLE

The working principle of HBT and BJT are similar, in both, base-emitter junction, collector-base junction is forward biased and reversed biased respectively, due to which equilibrium condition get disturbed. Electrons are injected from emitter-base junction through base and collector depletion region, and reach to collector contact with less recombination to holes in base. Collector current I_C can be represented as follows [13]:

$$I_C = \left[\frac{\alpha_n M}{1-\alpha_n M}\right] I_B + \left[\frac{M}{1-\alpha_n M}\right] I_{CBO}$$

Where,
α_n = base transport factor
M = Carrier avalanche multiplication factor
I_{CBO} = collector leakage current
I_B = Base current

Unlike BJTs, injection of holes from base to emitter is minimized here. Therefore, current produced due to holes will also be reduced. For fulfillment of this, wide band-gap semiconductor material in emitter of HBT is used. Due to this, hole experiences large barrier for conduction as compare to electrons, and constitutes less current [14].Output characteristics of HBT is shown in following graph[14], where input current is keep constant.

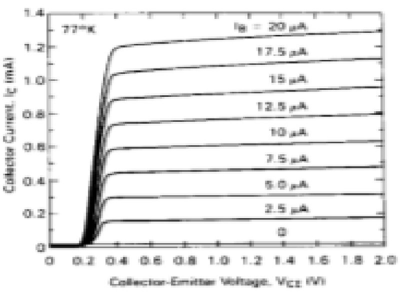

Fig.4 I_C vs V_{CE} characteristics [14]

The above characteristics of I_c vs V_{CE} shows the dependency of the collector current (I_C) on collector emitter voltage (V_{CE}) when the base current (I_B) has a constant value (V_{BE} is held constant). It is clear that at low temperature, effective base hole concentration is lowered due to effect of carrier freeze-out. It also allows base-width modulation effect [14]. Table 3 shows some fundamental comparison in basic properties of HBT with BJT.

Table-3: Comparison between HBT and BJT

S.No.	Parameter	HBT	BJT
1	Material	AlGaAs/GaAs	Si
2	Application	Power amplifier in laser devices and mobile telephones	Amplifier switches, television
3	Base Resistance	70 W	200 W
4	Performance	Better Performance	Less
5	Collector substrate capacitance	O F	15 fF
6	Forward Transit Time	4 ps	12 ps
7	Cost	Low	High

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From the above table, it is clear that HBT have low base resistance and forward transit time due to that cutoff frequency will be increased [15]. Therefore it is much useful for high frequency application comparatively BJT. Unlike BJT, Breakdown voltage is also improved in HBT due to use of wide band gap materials (AlGaAs). AlGaAs/GaAs HBT also attained better position into digital, analog and power applications.

IV. PROCESS MODELING OF HBT

The material of substrate is semi-insulating GaAs on which fabrication of HBT is done, grown.

1. A heavily doped n+ GaAs with the concentration on the order of $4 \times 10^{18} cm^{-3}$ is grown for collector contact. A lightly doped n type GaAs layer is grown for collector.
2. A heavily doped p+ GaAs layer is grown for base. Generally, carbon and beryllium (Be) is used as base dopant.
3. A wide band gap AlGaAs layer is grown for emitter. To reduce the base and base contact resistance heavily doped p+ GaAs layer is used. An n+ InGaAs-alloy contact layer can be grown for Emitter contact to provide stability and low resistance. For device isolation multiple boron damage implant is used.
4. A heavily doped n+ GaAs layer is grown for the fabrication of low resistance ohmic contacts.

Table 4: Choices of Materials for HBT [15]

Region	Material	Thickness (um)	Concentration(/ cm^3)
Substrate	GaAs	50 um	
Collector	n GaAs	0.5 um	3×10^{16}
Base	P+ GaAs	0.05 um	5×10^{18}
Emitter	n AlGaAs	0.25 um	5×10^{17}

From the table 4, it is clear that, base and collector materials are same but emitter material is different, since here we are implementing SHBT. Base doping concentration is taken much higher compare to emitter and collector so that base resistance is low and device can have high cut off frequency to be used in high frequencyapplication.

Simulation of Process flow of HBT:

1. In Silvaco tool click on dev edit icon, Dev edit window appears as given follow

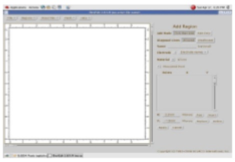

Fig 5 : Dev Edit Window

2. Select the work region parameter from work region menu, as given below:

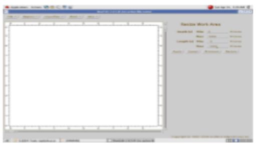

Fig 6: Work Area window

3. From right side window select GaAs substrate from material tab on which device is fabricated, corresponding structure is represented below:

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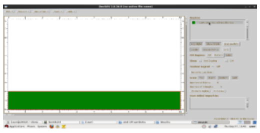

Fig 7: Semi insulating GaAs substrate

4. For Growth of n+ GaAs, from region menu select add region, followed by selecting GaAs from material tab and high doping from concentration tab to form collector contact.

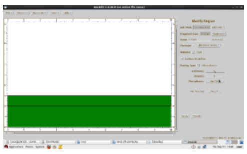

Fig 8: Growth of n+ GaAs

5. Collector window will be formed over n+ GaAs collector contact.

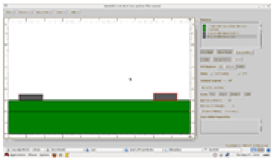

Fig9: Formation of collector window

6. Select the GaAs material from material tab with moderate doping from concentration field and grow on n+ GaAs to form n type GaAs Collector.

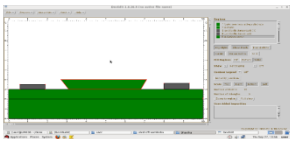

Fig 10: n type GaAs collector formation

7. Select the GaAs substrate from material tab with p+ higher concentration from concentration field to form Base over collector.

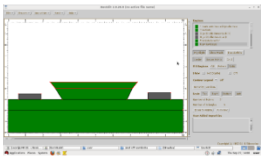

Fig 11: Formation of p+ GaAs Base

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8. Base window will be formed over p+ GaAs base.

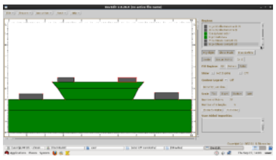

Fig 12: Formation of Base window

9. Grading layer will be deposited over p+ GaAs base.

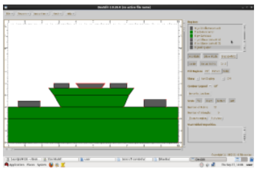

Fig 13: Grading layer Formation

10. Select the AlGaAs material from material tab and moderate concentration from the concentration field with n type impurity to from Emitter.

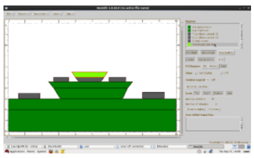

Fig 14: n AlGaAs Emitter formation

11. Again, Grading layer will be formed over emitter.

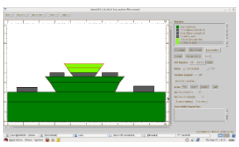

Fig 15: Grading layer formation

12. Select the GaAs as a material with high concentration and n+ type impurity GaAs to form contact over grading layer.

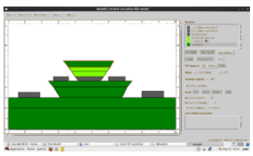

Fig16: Formation of n+ GaAs Contact

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13. For emitter contact select InGaAs alloy and final structure will be obtained.

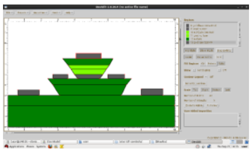

Fig 17: Emitter contact formation

V.CONCLUSIONS

The paper presented a simulation process of AlGaAs HBT on Silvaco tool, where the basic modeling steps and fabrication design parameters used in high frequency applications, taken into consideration. In contrast to the BJT, this study showed that HBT has higher gain and better electrical properties. Such type of device modeling helps, in further, implementation of real time device used in high frequency application.

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