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Device Simulation of Si-Ge HBT Using SILVACO TCAD

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***Abstract*--** In this paper, we have proposed a Si-Ge HBT Using Silvaco TCAD. In recent years, the band gap engineered devices have received considerable attention due to their inherent advantages such as high speed and high driving capability as compared to homo junction devices. The Si-Ge Hetero junction Bipolar Transistor (HBT) is the first band gap engineered device to be developed on Si. The recent advancement in material growth technology and device design has resulted in Si-Ge HBT's operating at more than 250GHz cutoff frequency. The present paper deals with the simulation of Si-Ge HBT structures using Silvaco TCAD. HBT structure has been generated through DevEdit and device simulation was carried out using Atlas. Base width and Ge profile are very important parameter for HBT. In view of this, the effect of variation of base width and Ge profile on the parameters like Collector Current (I_c), Current Gain (β), f_T and f_{max} has been studied.

***Keywords*—** HBT, Bipolar Junction Transistor, DEVEDIT 2D, Silvaco TCAD

I. INTRODUCTION

Homojunction bipolar transistor is the device made on Silicon because of its excellent current drive capability. In BJT base width is decreased to obtain high speed but due to this, base resistance is increased which causes slow device response. Low base resistance can also be achieved by high base doping but it degrades the current gain of device. Thus optimizing base doping and base width is unimaginable in BJT which is a need of high speed devices. To achieve low transit time without reduction in gain, hetero junction devices are used. Hetero junction is basically a junction formed between two dissimilar band energy materials [4]. Hetero junction devices introduced the concept of band gap engineering devices operating at microwave frequency range. Si-Ge HBT is the first band gap engineered device overcoming all the disadvantages of BJT. Si-Ge alloy practice band gap engineering in Si. Band gap engineering consists of the tailoring of an association of materials to custom design structure for the some desired properties unattainable in homo junction. The first prototype on Si is Si-Ge HBT.

Ge is introduced in Si material in order to make Si compatible to work on microwave frequency range and RF frequency, and thus Si-Ge alloy is formed. Si material has electron mobility 1600 m^2/Volt-sec whereas Ge has electron mobility of 3900 m^2/Volt-sec i.e. Ge mobility is about 2.5 times higher than Si. Introducing Ge in Si increases the mobility of Si-Ge material is the greatest advantages of Si-Ge alloy. Si-Ge band gap energy lies between band gap energy of Si (1.12eV) and Ge (0.66eV). Their lattice constants differ by roughly 4% and thus, Si-Ge alloy grown on Si substrate is compressively strained. This is referred as "pseudomorphic" growth of Si-Ge on Si with the Si-Ge film adopting the underlying Si lattice constant. Their stability can be improved by limiting the amount of Ge in the Si-Ge alloy.

Band gap shrinkage occurs on introducing Ge in Si and on every 1% addition of Ge, the shrinkage occurs is 7.5meV.The compressive strain in Si-Ge alloy lifts the valence band and conduction band at band extreme which increases mobility in the alloy. Thus, Si-Ge performance is increased and they are used for RF/microwave applications.

II. HOMOJUNCTION VS. HETEROJUNCTION BJT

The band gap engineered HBT structures on silicon have been introduced to overcome the demarcation of the homojunction BJT structure with relation to use in high frequency and gain devices. In BJT, base doping and base width cannot be optimized for high frequency and gain. Wider band gap material used for emitter region increases emitter injection efficiency and β in HBT. HBT allows higher doping concentration in base region to minimize the base resistance and to increase device speed in comparison to BJT. In present scenario HBT structure can operate up to 250 GHz. In this chapter, D.C. and microwave performance of homojunction BJT and HBT devices are compared. The results of optimized devices are shown in terms of I_C, β, f_T and f_{max}.

A 2-dimentional HBT structure has been shown using DEVEDIT 2D. The results have been simulated on ATLAS simulator. Both the HBT 2D and homojunction BJT structures as defined using DEVEDIT 2D are shown in figure-1and figure-2 respectively. Effective base width of both the structures has kept same. In a HBT structure, we have Si-Ge base whereas in BJT we have Si base.

In Si-Ge HBT structure a Si substrate is doped with arsenic impurity which act as a collector followed by the growth of, Si-Ge layer on it to form base. It is doped with boron for p-type base, then again Si layer is grown to form emitter and it is doped with arsenic to form n-type emitter.

Homojunction BJT structure of 90nm base width is simulated for comparison with the HBT structure. This structure consists of an n-type collector with arsenic doping. The base width and structure parameters of both the structure have been kept same for comparison.

The optimized doping level for the both the structures have been selected in order to show comparison of optimized device performance.

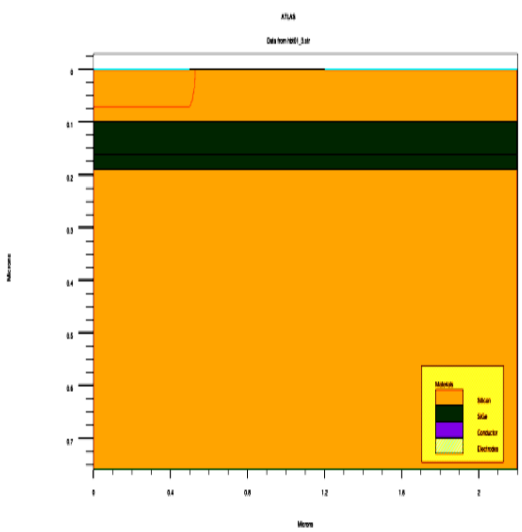

Figure-1 HBT structure for (base width = 90nm)

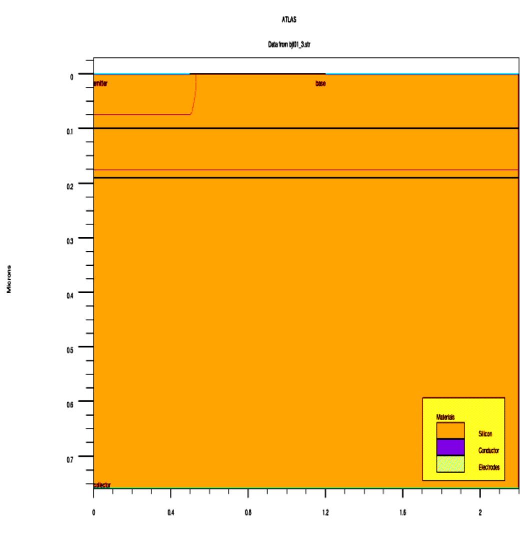

Figure-2 Homojunction BJT

The HBT and Conventional BJT device parameters as defined by our structure is given in Table-1

Parameters	HBT	Conventional BJT
Base width	90 nm	90 nm
Device height	760nm	760nm
Emitter Doping	$1 \times 10^{20}\ cm^{-3}$	$5 \times 10^{19}\ cm^{-3}$
Base Doping	$8 \times 10^{19}\ cm^{-3}$	$1 \times 10^{18}\ cm^{-3}$
Collector Doping	$8 \times 10^{19}\ cm^{-3}$	$5 \times 10^{19}\ cm^{-3}$
Ge Concentration in base region	20%	-

Table-1 Structural Parameters for HBT and Homojunction BJT

III. DEVICE STRUCTURE WITH DOPING PROFILE

The device structure with Doping Profile for 90 nm Base width HBT and Homojunction transistor is shown in figure 3 & figure 4.

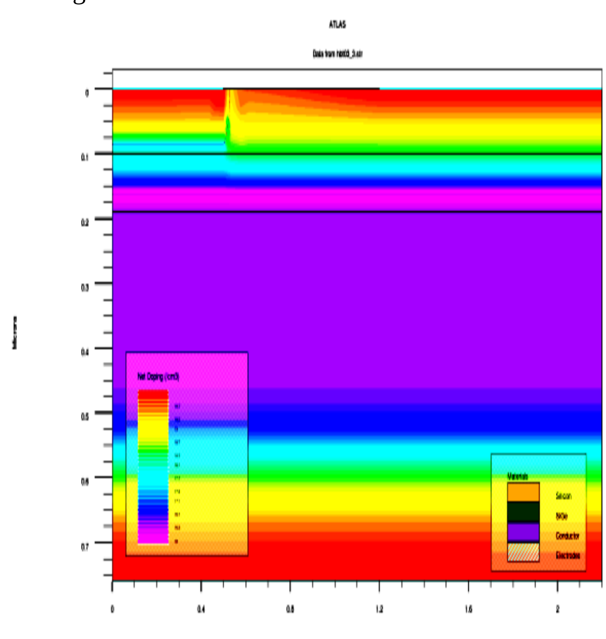

Figure-3 HBT Doping Profile

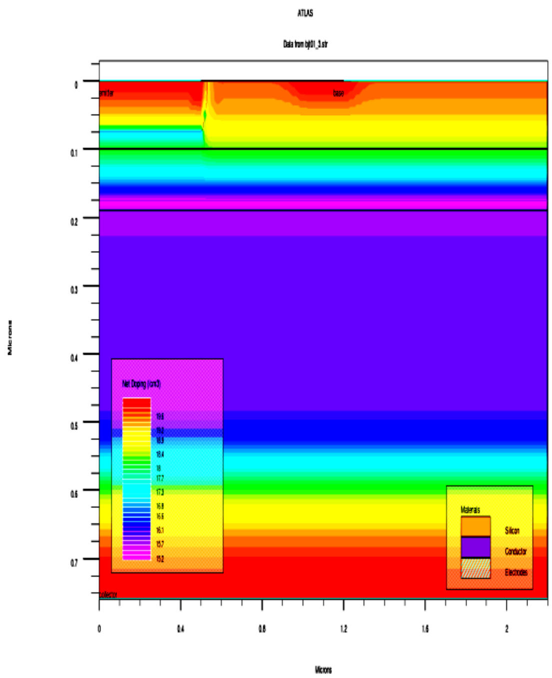

Figure-4 Homojunction BJT Doping Profile

IV. EXTRACTION OF PARAMETERS

A-Current Gain

The β has been calculated from I_C vs V_{CE} curve at V_{BE} = 0.9V and given by

$$\beta = \frac{I_C}{I_B} \quad \ldots\ldots\ldots\ldots\ldots\ldots .. (1)$$

In case for BJT the electrons and hole experience same amount of energy barrier. In both the cases when electrons are injected in base and holes back injected in emitter whereas in case of HBT they don't experience same value of energy. The β equation is

$$\frac{I_C}{I_B} = \frac{D_{nB} W_E N_E}{D_{pE} W_E N_B} e^{\frac{\Delta E_v}{T k_B}} \quad \ldots\ldots\ldots\ldots\ldots (2)$$

Where

ΔE_v is Valance Band discontinuity at Si/Si-Ge Heterojunction. The equation clearly shows that irrespective of base doping current gain depends upon the valence band discontinuity.

B-Cutoff Frequency

Cutoff frequency is the frequency at which current gain drops to unity. At low frequency current gain is independent of frequency but at high frequency it decreases due to capacitances.

f_T is given by equation.

$$f_T = \frac{1}{2\pi\tau_{ec}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where,

τ_{ec} is transit time

C-Maximum Oscillation Frequency (f_{MAX})

Maximum oscillation frequency is the frequency at which power gain drops to unity [4]. At low frequency power gain is independent of frequency but at high frequency it decreases due to capacitances.

f_{max} is given by equation.

$$f_{max} = \sqrt{\frac{f_T}{8\pi C_{jc} R_b}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where,

C_{jc} = Collector Base Capacitance,

R_b = Base Resistance

V. RESULT

Simulation results for both homojunction BJT and HBT structures are being compared below.

A-Characteristics curve

Figure-5 & Figure-6 show I_C Vs V_{CE} plot of Si-Ge HBT and homojunction BJT respectively β and I_C has been calculated. This characteristic curve has been plotted for constant I_B it is varied 0 µA to 5 µA for both graphs.

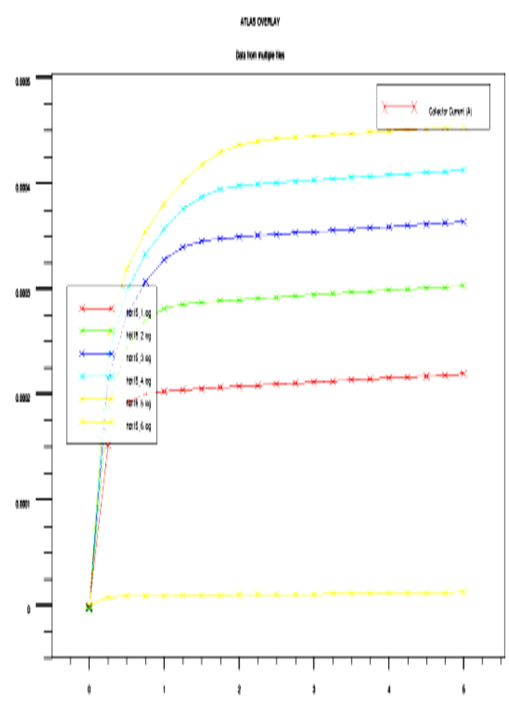

Figure-5 Collector Current vs Collector Voltage plot for 90nm HBT structure

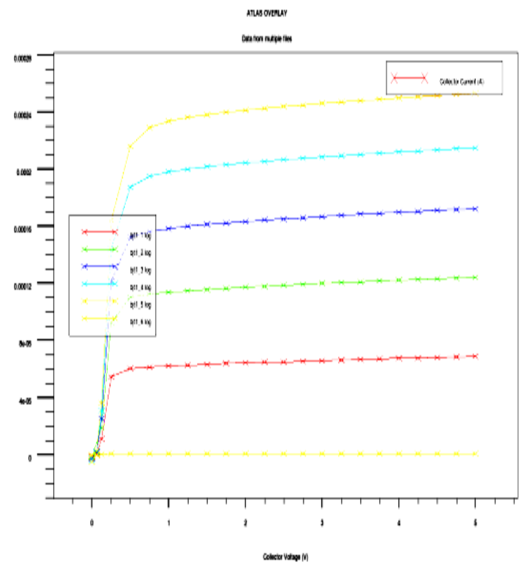

Figure-6 Collector Current Vs Collector Voltage plot for Homojunction BJT

B-Collector current

The characteristic curve drawn above can be compared by the Tony Plot overlay. Thus, figure-7 gives the comparison of I_C Vs V_{CE} plot of HBT and Homojunction BJT respectively at 2 µA. It is clear from the figure-7 that at same I_B i.e. 2 µA there is substantial amount of increase in I_C, in HBT as compared to BJT. Figure-7 gives the comparison of I_C Vs V_{BE} plot of HBT and Homojunction BJT respectively. It is so because introducing Ge in the base region leads to decrease in conduction band or the injection efficiency increases as compared to BJT. This allows more electrons to cross the base region, thus the I_C is increased in HBT.

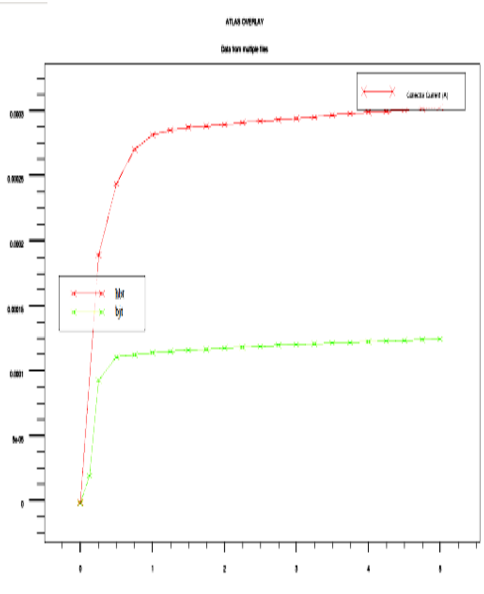

Figure-7 Collector Current Vs Base Voltage Plot for Conventional BJT and HBT

B-Current Gain vs. Frequency Plot

Figure-8 shows the comparison between BJT and HBT current gain vs. frequency plot. From the figure-8 we can calculate value of HBT and BJT cutoff frequency. It is the frequency at which the current gain drops to unity. So the figure-8 shows that cutoff frequency for HBT is higher as compared to BJT. This is so because decrement in transit time due to higher mobility of strained Si-Ge layer results in higher cutoff frequency. Since the injection efficiency increases the current gain so it is higher for HBT as compared to BJT.

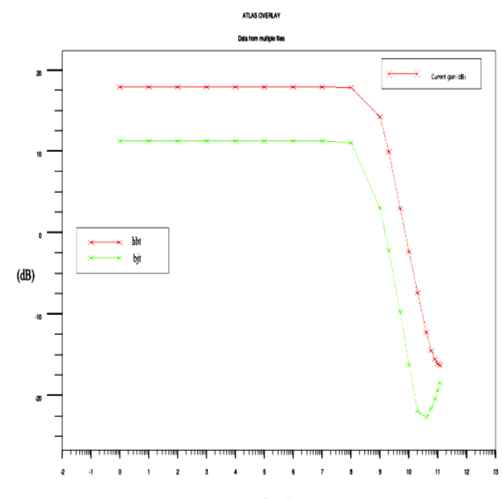

Figure-8 Comparison between HBT and BJT Current Gain Vs Cutoff Frequency

C-Power Gain vs. Frequency Plot

Figure-9 shows Power gain vs. f_{max} for Si-Ge HBT and BJT and from the graph we can calculate the value of HBT and BJT f_{max}. It is the frequency at which the power gain drops to unity. So it is clear from the figure that f_{max} for HBT is much higher as compared to BJT.

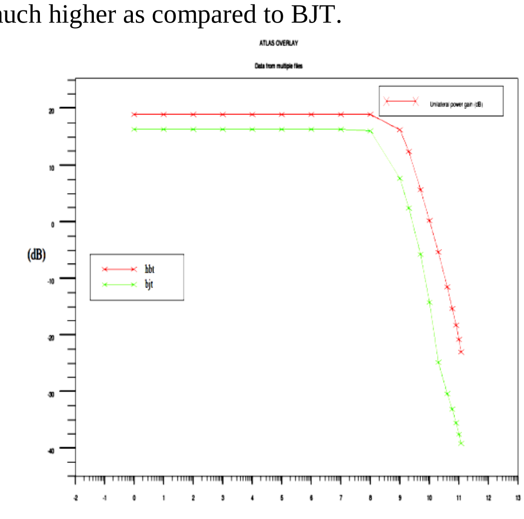

Figure-9 Comparison between HBT and BJT Power Gain Vs Maximum Oscillation Frequency

The comparison between 90nm HBT and Conventional BJT parameters is given by Table-2.

Parameters	Homojunction BJT	HBT(Base Width 90 nm)
Cutoff frequency (G Hz)	17.7	36.6
Maximum oscillation frequency (G Hz)	20.0	40.0
Current gain	87	554
Collector current (m A)	0.30	0.60
Transit time (n sec)	0.02	0.0043

Table-2 Comparison Between the different parameters of Homojunction BJT and Si-Ge HBT

VI. CONCLUSION & FUTURE SCOPE

In this paper simulated results show that Si-Ge HBT has very low transit time as compared to BJT. Because, Ge introduction in base results in strained Si-Ge layer grown on Si substrate, leading to higher mobility and lower transit time. Transit time is inversely proportional to the f_T so less transit time results in increased cutoff frequency as compared to BJT. Moreover from the structure parameters it is clear that though base is heavily doped in HBT in comparison to BJT, its β and I_C are high. This is because; its current gain exponentially depends upon the band gap energy rather than the base region doping. So a small change in band energy leads to large change in current gain.

HBT products in future will find application in light wave systems, communication systems and mixed analog-digital systems. Further improvements in materials and device structure can be brought for even higher performance systems.

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