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# Study of Cutoff Frequency of High Collector Current Density in SiGe Single-Heterojunction Bipolar Transistor

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**Abstract:** The cutoff frequency performance of an NPN Si/SiGe/SiGe Single-heterojunction bipolar transistor (SiGe SHBT) at high collector current densities has been analyzed using a 2-dimensional MEDICI device simulator. A conventional NPN Si/SiGe/Si Double-heterojunction bipolar transistor (SiGe DHBT) having uniform 14%Ge in the base region has been investigated for comparison. The analysis shows the formation of a retarding potential barrier for minority carrier electrons at the base collector heterojunction of the DHBT structure. Whereas, the base-collector homojunction of the SiGe SHBT structure, having a uniform 14%Ge profile in its base and collector, inhibits the formation of such a retarding potential barrier. The SHBT structure with a base-collector homojunction shows an improved cutoff frequency at a high collector current density in comparison with conventional SiGe DHBT, which makes it more promising for high speed, scaled down, field-specific applications.

**Key words:** Band Gap Narrowing, Drift Velocity, Mobile Communication, Valence Band Offset

## INTRODUCTION

The use of silicon-germanium (SiGe) technology in the field of mobile communications[1] and various other high –frequency devices[2] has led to a special interest in the SiGe microelectronics. The better performance of an NPN SiGe double-heterojunction transistor (DHBT) structure is attributed to the valence band offset for holes in emitter-base (e-b) and base collector (b-c) junction. However, the NPN Si/SiGe/Si DHBT structures exhibit sharp fall in cutoff frequency *ftDHBT* at high collector current densities, due to the formation of retarding potential barrier ($V_{RB}$) for minority electrons at b-c heterojunction[3, 4]. We have already investigated and proposed an alternate NPN SiGe HBT structure with linearly graded Ge% in collector to smooth out $V_{RB}$ at b-c junction for improving the current gain and cutoff frequencies at high collector current densities[5]. However, the present work investigates an NPN SiGe Singleheterojunction Bipolar Transistor (SHBT) structure with perfect b-c homojunction and uniform 14% of germanium in base and collector while ensuring the strained behavior and stability of the SiGe layers[6, 7]. We have also simulated a conventional NPN SiGe DHBT structure with uniform 14% of Ge in strained base to supplement the earlier reported results in the formation of $V_{RB}$ at a b-c junction. A two-dimensional MEDICI device simulator known for its authenticated results at the device level for SiGe HBT structures[8] has been used in the present analysis.

In an NPN silicon BJT, the expression relating electron concentration in b-c space charge layer ($n_c$) with a collector current density ($J_c$) for the saturated drift velocity ($n_{dsat}$) condition is given as [9]:

$$J_c = q\, v_{dsat} n_c \qquad (1)$$

where, q is the electronic charge.

At the onset of Kirk phenomenon, (for $J_c$=$J_k$, *Kirk current density*), $n_c$ (= $n_k$, electron density in collector space charge layer in Kirk regime) is related to the device parameters and total voltage across b-c junction $V_{bctot}$ by the expression:

$$n_c = N_c + \left\{ \left( (2\varepsilon) \frac{V_{bctot}}{qW_c^{\,2}} \right) \right\} \qquad (2)$$

where, $N_c$ is the collector doping, $W_c$ is the collector width and ε is silicon dielectric constant. In Si BJT, at the onset of Kirk phenomenon, holes are injected into the collector from the base to compensate the electron charge in the collector, resulting in the formation of the current induced bias. However, for SiGe DHBTs, there is a valence band discontinuity four holes at the b-c *heterojunction*. This valence band discontinuity suppresses the hole injection into the collector as $n_c$ exceeds $n_k$. Eventually, there will be an accumulation of mobile electrons in collector due to velocity saturation and an accumulation of holes in the base due to valence band offset at a b-c junction. The combination of these mobile electrons together with localized holes form a dipole layer and in turn give rise to an electric field ($E_0$) at b-c junction. The rise in $E_0$ with $J_c$ gives rise to $V_{RB}$ at a b-c junction in the conduction band, which would oppose the electrons flowing from emitter to collector

through the base. An increased electron concentration at base edge of the b-c junction space charge region $n_{(Wb)}$ is now required to support the $n_c$ and $J_c$. The electron density $n_c$ in b-c space charge regions corresponding to $J_c$, in SiGe DHBT, derived from the basic Poisson's equation is:

$$n_c = N_c + [\{2\varepsilon(V_{bctot} + E_0 W_c)\}/(q\, W_c^2)] \tag{3}$$

The increased electron density $n_{(Wb)}$ required to maintain the $n_c$ inside a b-c space charge region is simply given by using current continuity and Boltzmann statistics across $V_{RB}$:

$$n_{(Wb)} = n_c \exp(qV_{RB} / KT) \tag{4}$$

where, $V_{RB}$ for electrons can be expressed as:

$$V_{RB} = \Delta E_v + KT \ln$$

$$\left[\frac{J_c}{qv_{dsat} N_b} - \frac{N_c}{N_b} - \frac{2\varepsilon(V_{bctot})}{qN_b W_c^2}\right] \tag{5}$$

Here, K is Boltzmann's constant, T is the absolute temperature and $N_b$ is the base doping. Solving Eq. (3), (4) and (5) for a uniformly doped base gives the effect of bias dependent $V_{RB}$ and base-emitter bias ($V_{be}$) on $J_c$ as:

$$J_C = \left[\left(\frac{qD_n n_{io}^2}{W_b N_b}\right)\left(\frac{e^{\left((qv_{be} + \Delta E_v - v_{RB})/KT\right)}}{1 + \frac{D_n e^{(v_{RB}/KT)}}{W_b v_{dsat}}}\right)\right] \tag{6}$$

where, $W_b$ is the base width, $D_n$ is the electron diffusion coefficient in base, $n_{i0}$ is the intrinsic carrier concentration.

Equation (4) predicts that an increased $n_{(Wb)}$ in the base of a b-c space charge region is required to maintain the $n_c$ in a b-c space charge region. A corresponding increase in the minority electron concentration at the e-b junction would be required to maintain the increased $n_{(Wb)}$. Therefore, excess charge stored in the base can be expressed as:

$$DQb = \{(q\, Wb\, n(Wb)) / 2\} \tag{7}$$

This increased charge storage will be responsible for an extra base charge storage time. The storage time $\tau_{ebst}$ obtained using Eq. (6) and (7) is:

$$t_{ebst} = dDQ_b / dJ_c = \{W_b \exp(q\, V_{RB} / KT) / 2n_{dsat}\} \tag{8}$$

The cutoff frequency $f_{tDHBT}$ for SiGe DHBT after taking into account the excess electronic charge stored in the base assumes the form:

$$f_{tDHBT} = [f_{tSiGe}^{-1} + 2pt_{ebst}]^{-1} = \big[f_{tSiGe}^{-1} + p\{W_b \exp(qV_{RB} / KT) / V_{dsat}\}\big]^{-1} \tag{9}$$

where the additional term ($2\ \pi\ \tau_{ebst}$) shows the degradation in the SiGe DHBT cutoff frequency $f_{tDHBT}$ as a consequence of $\tau_{ebst}$ described in Eq. (8).

The analysis of SiGe DHBT illustrates the formation of $V_{RB}$ at b-c junction due to valence band offset for holes. The theory also predicts a fall in cutoff frequency at high $J_c$ as a consequence of $V_{RB}$ and associated $\tau_{ebst}$. Whereas, the proposed SiGe SHBT structure with 14% Ge in base and collector prohibits the formation of $V_{RB}$ for electrons and promises higher cutoff frequency at high $J_c$ in comparison with the SiGe DHBT structure.

## RESULTS AND DISCUSSION

The physical parameters and doping profiles in the different regions of NPN Si/SiGe/Si DHBT and Si/SiGe/SiGe SHBT is chosen such that both the structures have identical device dimension and doping densities. The impurity concentration profile in the base and collector of both structures is shown in Fig. 1. The surface emitter doping of $1\times10^{20}$ $cm^{-3}$ and $W_{e1}$ of 0.12 μm is chosen to provide ohmic contact. The internal emitter doping of $8 \times 10^{18}$ $cm^{-3}$ and $W_{e2}$ of 0.1 μm is selected to lower the e-b capacitance. The base thickness $W_b$ of 0.07 μm with a uniform base doping of $3\times10^{18}$ $cm^{-3}$ is chosen in both the structures. The collector doping of $3\times10^{16}$ $cm^{-3}$ and $W_c$ of 0.8 μm is chosen in both structures. A uniform 14% Ge is chosen in the base of conventional Si/SiGe/Si DHBT structure. The proposed Si/SiGe/SiGe SHBT structure has a uniform 14% Ge in the base and collector.

The variation in the electron energy for the simulated structures at $V_{be}$ of 1.1 Volts and collector-emitter voltage ($V_{ce}$) of 2.0 Volts is shown in Fig. 2. We have analyzed the effect of band gap narrowing (due to high doping in the base of HBTs) and the result presented in Fig. 2 includes its effect along with valence band offset for holes at *a b-c junction*. The SiGe DHBT structure operating at $J_c$ of $5 \times 10^5$ A-$cm^{-2}$ predict a $V_{RB}$ of approx. 0.09 eV at the b-c heterojunction for conduction band electrons. After canceling out the effect of heavy base doping induced band-gap narrowing effect in the $V_{RB}$ of DHBT and SHBT (≈ 0.03 eV for a base doping of $3 \times 10^{18}$ $cm^{-3}$), the resultant $V_{RB}$ of approx. 0.06 eV is observed in SiGe DHBT. The simulation result is in excellent agreement with the value of $V_{RB}$ of approx. 0.058 eV obtained from the solution of Eq. (5).

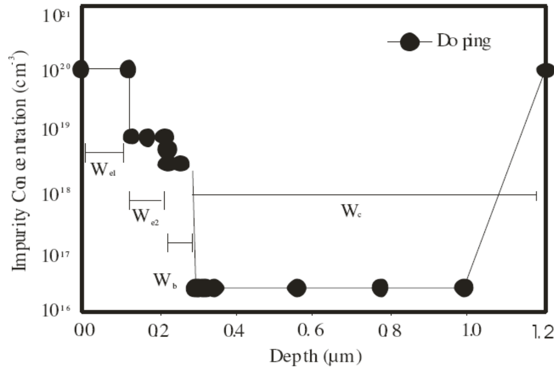


Fig. 1: Impurity Doping Profile in the Emitter, Base and Collector for the SiGe DHBT and SHBT, $W_b$ is the Base Width and $W_{e1}$ and $W_{e2}$ are the Two-step Emitter Widths

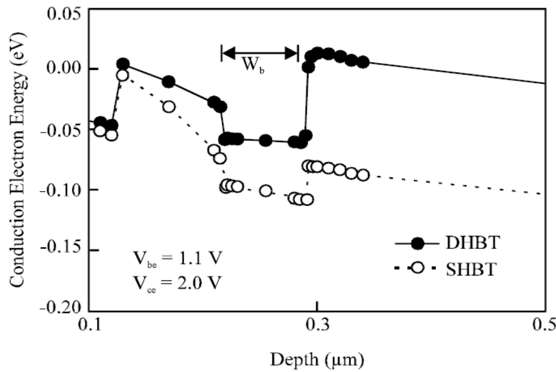


Fig. 2: Conduction Band Electron Energy for SiGe DHBT and SHBT Including the Effect of Valence Band Offset and Band Gap Narrowing at Collector-emitter Voltage $V_{ce}$ of 2 Volts and Base-emitter Voltage $V_{be}$ of 1.1 Volts. $W_b$ is the Base Width

This $V_{RB}$ is a consequence of the valence band offset four holes at the b-c junction and a function of $J_c$ as described in theory part. This $V_{RB}$ leads to accumulation of mobile electrons at b-c junction until the emitter electrons passing through base acquire enough energy to overcome it. On the other hand, the formation of $V_{RB}$ (due to valence band offset for holes) is prohibited by the b-c homojunction in the SHBT structure. Therefore, even for a higher $J_c$ of $1.43 \times 10^6$ A/cm$^2$, the simulation results shown in Fig. 2 for the SHBT structure exhibits only a small $V_{RB}$ of 0.03 eV, which is solely attributed to the high doping in the base. The higher $V_{BR}$ of 0.09 EV in the DHBT structure leads to large accumulation of mobile holes and electrons at the b-c heterojunction.

The variables of hole and electron concentrations in the vertical depth of the SiGe DHBT and SiGe SHBT structures for the chosen bias conditions are shown in Fig. 3 and 4, respectively. A net hole concentration of $9\times10^{19}$ and $4\times10^{19}$ cm$^{-3}$ is obtained on the base of DHBT structure at e-b and b-c junctions, respectively.

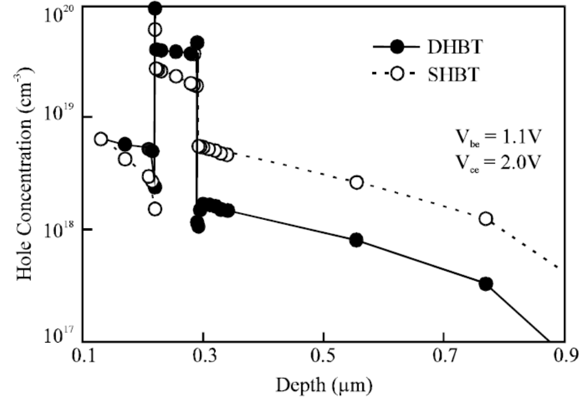


Fig. 3: Hole Concentration in SiGe DHBT and SHBT at Collector-emitter Voltage $V_{ce}$ of 2 Volts and Base-emitter Voltage $V_{be}$ of 1.1 Volts

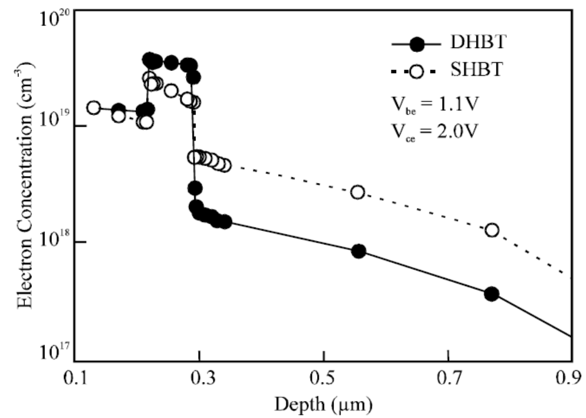


Fig. 4: Electron Concentration in SiGe DHBT and SHBT at Collector-emitter Voltage $V_{ce}$ of 2 Volts and Base-emitter Voltage $V_{be}$ of 1.1 Volts

This corresponds to an electron concentration of $3.6\times10^{19}$ cm$^{-3}$ and $2.67\times10^{19}$ cm$^{-3}$ at the base of DHBT structure at the corresponding metallurgical junctions. On the other hand, at a b-c junction in SHBT structure, a lower hole concentration of $2\times10^{19}$ cm$^{-3}$ corresponding to an electron concentration of $1.62\times10^{19}$ cm$^{-3}$, is obtained for relatively higher $J_c$ of $1.43\times10^6$ A/cm$^2$. The simulation results predict an electron concentration of $2.32\times10^{19}$ cm$^{-3}$ at the e-b junction in SHBT structure. The results demonstrate that the formation of $V_{RB}$ at a b-c junction in SiGe DHBT forces the requirement of higher electron concentrations at e-b and b-c junction, for achieving $J_c$ comparable with the SiGe SHBT.

The higher net electron concentration $n_{(Wb)}$ leads to minority charge storage in the base region of DHBT structure. The increase in the base transit time due to charge storage in the base of the DHBT structure is derived in Eq. (8) and the corresponding fall in the cutoff frequency is predicted by Eq. (9). On the other hand, the proposed SiGe SHBT is having very small $V_{RB}$ (only due to heavy base doping) and a smaller charge accumulation at a b-c junction in comparison with DHBT structure.

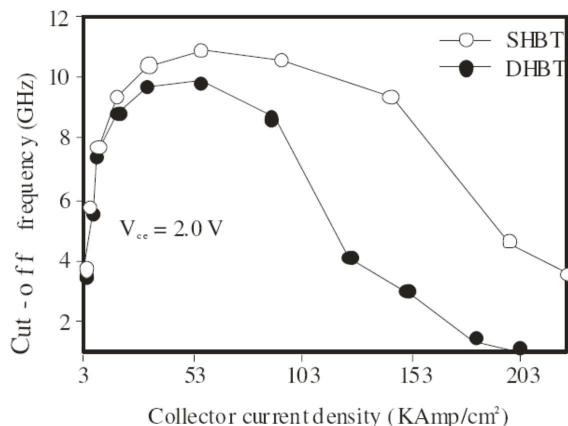


Fig. 5: Cutoff Frequency Vs. Collector Current Density Plot for SiGe DHBT and SHBT at Collector Emitter Voltage V of 2 volts

Therefore, a higher cutoff frequency is expected in SiGe SHBT, which is confirmed by the simulation results shown in Fig. 5, showing the dependence of cutoff frequency on the $J_c$ for DHBT and SHBT. The simulation results show a fall of 70% in the peak cutoff frequency value (from 10 GHz to 3 GHz) for DHBT structure for a 3--fold increase in $J_c$ value from $5\times10^4$ Amp/cm$^2$ to $15\times10^4$ Amp/cm$^2$. Whereas, the SHBT structure shows only a 18% drop in peak cutoff frequency (from 11 GHz to 9 GHz) for the same increase in $J_c$. This proves the improvement in cutoff frequency roll-off in the SHBT structure in comparison with SiGe DHBTs as the $J_c$ increases and promises to be a leading candidate for application in prospective scaled-down devices.

## CONCLUSION

We have proposed a new NPN SiGe SHBT structure with uniform 14% Ge in base and collector with a b-c homojunction to improve the cutoff frequency performance at high $J_c$. The SHBT promises a superior cutoff frequency performance in comparison with the conventional SiGe DHBT structure due to the absence of $V_{RB}$ of electrons at b-c junction, which has been found to be the prime source of degradation of cutoff frequency in DHBT at high $J_c$. A comparison of conduction band electron energy and net hole and electron concentration profile at high current density for the simulated SiGe DHBT and SHBT structures supplement the theoretical formulation for the higher cutoff frequency performance of the SHBT structure.

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