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SHORT COMMUNICATION

Silicon-germanium 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 analysed using a 2-D MEDICI device simulator. A conventional NPN *Si*/*SiGe*/*Si* double-heterojunction bipolar transistor (*SiGe* DHBT) having uniform 20 atomic per cent of germanium 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 15 atomic per cent of germanium 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 high collector current density in comparison with conventional *SiGe* DHBT, which makes it more promising for high speed, scaled down, field-specific applications.

Keywords: Single-heterojunction bipolar transistor, simulation, double-heterojunction bipolar transistor, *SiGe* SHBT, cutoff frequency *SiGe* technology, *SiGe* DHBT

NOMENCLATURE

n_c	Electron concentration in base-collector space charge layer
J_c	Collector current density
n_{dsat}	Saturation drift velocity
q	Electronic charge
J_k	Kirk current density
n_k	Electron concentration in base-collector space charge layer at the onset of Kirk phenomenon
V_{bctot}	Total voltage across base-collector junction
N_c	Collector impurity concentration
W_c	Metallurgical collector width
e	Silicon dielectric constant
E_0	Electric field at base-collector junction
V_{bp}	Retarding potential barrier for electrons
$n_{(Wb)}$	Electron density in base at base-collector junction
$KT/q=V_T$	Thermal voltage
n_{i0}	Intrinsic carrier concentration
$n_{(0)}$	Electron density in base at emitter-base junction
n_{ex}	Excess minority electron concentration inside base
ΔQ_b	Excess charge stored in the base
τ_{ebst}	Excess base charge storage time

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f_{tDHBT}	Cutoff frequency for *SiGe* DHBT
f_{tSiGe}	Cutoff frequency for *SiGe* DHBT without V_{bp}
W_{e1}	Surface emitter thickness
W_{e2}	Internal emitter thickness
W_b	Base thickness
V_{be}	Base-emitter applied bias voltage
V_{ce}	Collector-emitter applied bias voltage
ΔE_v	Valence band offset for the holes

1. INTRODUCTION

The application of silicon-germanium (*SiGe*) technology in mobile communication[1] and various defence-related fields[2] has lead to special interest in the *SiGe* microelectronics field in various defence organisations[3,4]. The better performance of an NPN *SiGe* double-heterojunction bipolar transistor (DHBT) structure is attributed to the valence band offset for holes at emitter-base and base-collector heterojunction. However, the conventional NPN *Si/SiGe/Si* DHBT structures exhibit sharp fall in cutoff frequency at high collector current densities, due to the formation of retarding potential barrier for minority electrons at base-collector heterojunction[5]. An alternate NPN *SiGe* HBT structure with linearly graded germanium atomic per cent (*at %*) has been proposed in collector to smooth-out this retarding potential barrier at base-collector hetrojunction for improving the current gain and cutoff frequencies at high collector current densities[6].

In the present study, an NPN *SiGe* single-heterojunction bipolar transistor (SHBT) structure with uniform 15 atomic per cent of germanium in base and collector is investigated to ensure the perfect base-collector homojunction and strained behaviour and stability of the *SiGe* layers[7]. A 2-D MEDICI device simulator[8] has been used to simulate the SHBT along with conventional NPN *SiGe* DHBT structure with uniform 20 atomic per cent of germanium in strained base to supplement and compare the earlier reported results on the formation of retarding potential barrier at base-collector heterojunction.

2. THEORY

In NPN silicon BJT, the expression relating electron concentration in base-collector space charge layer (n_c) with collector current density (J_c) for the ν_{dsat} condition[9] is given as

$$J_c = q\, \nu_{dsat}\, n_c \tag{1}$$

At the onset of Kirk phenomenon[9] (for J_c=J_k), n_c (= n_k) is related with the device parameters and total voltage (V_{bctot}) by the expression:

$$n_c = N_c + \left\{ \left((2\varepsilon) \frac{V_{bctot}}{q W_c^2} \right) \right\} \tag{2}$$

In silicon BJT, at the onset of Kirk phenomenon, holes are injected into the collector from the base to compensate the electron charge in collector, resulting in the formation of the current-induced base. However, for *SiGe* DHBTs, there is a valence band discontinuity for holes at base-collector heterojunction, which suppresses the hole injection into the collector as n_c exceeds n_k. Eventually, there will be an accumulation of mobile electrons in collector and an accumulation of holes in base at base-collector heterojunction, which forms a dipole layer, and in turn, gives rise to E_0 at base-collector heterojunction. The rise in E_0 with J_c gives rise to V_{bp} at base-collector heterojunction in conduction band, which hinders the flow of electrons into the collector and an increased $n_{(Wb)}$ is now required to support the n_c and J_c. The electron concentration (n_c) in base-collector heterojunction space charge region corresponding to J_c, in *SiGe* DHBT, derived from the basic Poissons equation is:

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

The electron density $n_{(Wb)}$ required to maintain the n_c inside base-collector space charge region is simply given using current continuity and Boltzmann statistics across V_{bp}:

$$n_{(Wb)} = n_c exp(q\ V_{bp}/KT) \tag{4}$$

where retarding potential barrier (V_{bp}) for electrons can be expressed as

$$V_{bp} = \Delta E_v/q + KT/q[ln\{(J_c/qv_{dsat}N_b) - (N_c/N_b) - (2\varepsilon V_{bctot}/qN_bW_c^2)\}] \quad (5)$$

Solving Eqns (3), (4), and (5) for a uniformly-doped base gives the effect of bias-dependent V_{bp} and V_{be} on collector current density (J_c) as

$$J_c = (qD_n n_{io}^2/W_b N_b)[exp\{(qV_{be} + \Delta E_v - qV_{bp})KT\}/1 + \{D_n exp(qV_{bp}/KT)/W_b v_{dsat}\}] \quad (6)$$

Eqation (4) predicts that an increased $n_{(Wb)}$ in the base at base-collector space charge region is required to maintain the n_c in base-collector space charge region. A corresponding increase in electron density in base at the base-collector junction ($n_{(0)}$) is required to support electron diffusion across the base. The modified value of $n_{(0)}$ is:

$$n_{(0)} = [n_c(n_{dsat}W_b)/D_{nb}] + [n_c exp\ (qV_{bp}/KT)] \quad (7)$$

The term $[n_c\{\exp\ (qV_{bp}/KT)\}]$ on R.H.S. in Eqn (7) has been inducted to compensate for V_{bp}, to sustain the J_c. The excess minority electron concentration inside base, n_{ex} ($=n_{(Wb)}$) in base obtained from Eqns (4) and (7) is:

$$n_{ex} = n_c\{\exp(qV_{bp}/KT)\} \quad (8)$$

The excess charge stored in the base (ΔQ_b) can be expressed as

$$\Delta Q_b = \{(qW_b n_{ex})/2\} \quad (9)$$

The increased charge storage will be responsible for τ_{ebst}

$$\tau_{ebst} = d\Delta Q_b/dJ_c = \{W_b exp(qV_{bp}/KT)/2v_{dsat}\} \quad (10)$$

The cutoff frequency (f_{tDHBT}) for *SiGe* DHBT after taking into account ΔQ_b assumes the form:

$$f_{tDHBT} = [f_{tSiGe}^{-1} + 2\pi\tau_{ebst}]^{-1} = [f_{tSiGe}^{-1} + \pi\{W_b\ exp(qV_{bp}/KT)/v_{dsat}\}]^{-1} \quad (11)$$

where the additional term ($2\pi\ \tau_{ebst}$) shows the degradation in f_{tDHBT} as a consequence of τ_{ebst} described in Eqn (10). The analysis of *SiGe* DHBT illustrates the formation of V_{bp} at base-collector heterojunction 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_{bp} and associated τ_{ebst}. The proposed *SiGe* SHBT structure with 15 atomic per cent germanium profile in base and collector prohibits the formation of V_{bp} for electrons and promises higher cutoff frequency at high J_c in comparison with *SiGe* DHBT structure.

3. PERFORMANCE OF *SiGe* DHBT & SHBT STRUCTURES

The physical parameters and doping profiles in the different regions of NPN *Si/SiGe/Si* DHBT and *Si/SiGe/SiGe* SHBT are chosen such that both the structures have identical device dimensions and doping densities. The surface emitter doping of 5×10^{19} cm^{-3} and thickness of 0.2 μm is chosen to provide ohmic contact. The internal emitter doping of 1×10^{19} cm^{-3} and thickness of 0.1 μm is selected to lower the emitter-base capacitance. The base thickness (W_b) of 0.05 μm with a uniform base doping of 8×10^{18} cm^{-3} is chosen in both the structures. The collector doping of 1×10^{17} cm^{-3} and thickness of 0.45 μm is chosen in both the structures. A uniform 20 atomic per cent germanium is chosen in the base of conventional *Si/SiGe/Si* DHBT structure. The proposed *Si/SiGe/SiGe* SHBT structure has a uniform 15 atomic per cent germanium in the base and collector.

The variation in the electron energy for the simulated structures at V_{be} of 1.1 V and V_{ce} of 2.0 V is shown in Fig. 1. The *SiGe* DHBT structure operating at J_c of 9.22×10^5 Åcm^{-2} predicts a V_{bp} of approx. 0.09 eV at the base-collector heterojunction for conduction band electrons. The formation of V_{bp} (due to valence band offset for holes) is prohibited by the base-collector homojunction in the SHBT structure, and the simulation results shown in Fig. 1, for J_c of 1.6×10^6 Åcm^{-2} in the SHBT structure, exhibits only a small V_{bp} of 0.03 eV, which is solely attributed to the high doping in the base. The higher V_{bp} of 0.09 eV in the DHBT structure leads to large accumulation of mobile electrons at base-collector heterojunction.

The variation of net carrier concentration with the vertical depth of the *SiGe* DHBT and *SiGe* SHBT structures for the chosen bias conditions is

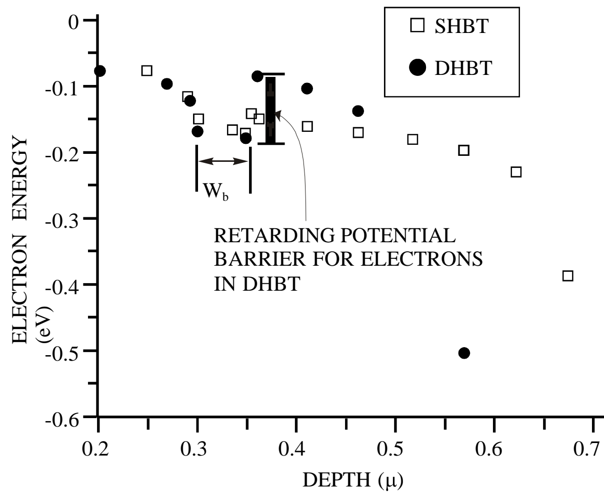

Figure 1. Conduction band electron energy for *SiGe* DHBT and SHBT including the effect of valence band offset and band-gap narrowing at collector-emitter voltage of 2 V and base-emitter voltage of 1.1 V. W_b is the base thickness. The DHBT curve, at a collector current density of 9.22 x 10^5 Å/cm², shows a total retarding potential barrier of 0.09 eV at base-collector junction for electrons.

shown in Fig. 2. A net carrier concentration of 8.11 × 10^{19} and 3.93 × 10^{19} cm^{-3} is obtained in the base of DHBT structure at emitter-base and base-collector junctions, respectively. This corresponds to an electron concentration of 4.36 × 10^{19} cm^{-3} and 2.92 × 10^{19} cm^{-3} in the base of DHBT structure at the corresponding metallurgical junctions.

A lower net carrier concentration of 6.02 ξ 10^{18} cm^{-3}, which corresponds to an electron concentration of 1.04 × 10^{19} cm^{-3}, is obtained, for relatively higher J_c of 1.6 × 10^6 $Åcm^{-2}$ at base-collector heterojunction in the base of SHBT structure in comparison with DHBT devices. The simulation results predict an electron concentration of 2.42 × 10^{19} cm^{-3} at the emitter-base junction in SHBT structure. The results demonstrate that the formation of V_{bp} at base-collector heterojunction in *SiGe* DHBT forces the requirement of higher electron concentration at base-emitter and base-collector heterojunction, for achieving J_c comparable with the *SiGe* SHBT.

The higher net carrier concentration $n_{(Wb)}$ and $n_{(0)}$ lead to minority charge storage in the base region of DHBT structure. On the other hand, the proposed *SiGe* SHBT is having very small V_{bp} (only due to heavy doping) and a smaller charge accumulation at base-collector heterojunction in comparison with DHBT structure Therefore, a higher cutoff frequency is expected in *SiGe* SHBT, which is confirmed by the simulation results (Fig. 3), showing the dependence of cutoff frequency on the J_c for DHBT and SHBT structures under consideration.

The simulation results show a fall of 77 per cent in the cutoff frequency value for DHBT structure for a two-fold increase in J_c value from 3.5 x 10^5 A/cm², whereas the SHBT structure shows only a 10 per

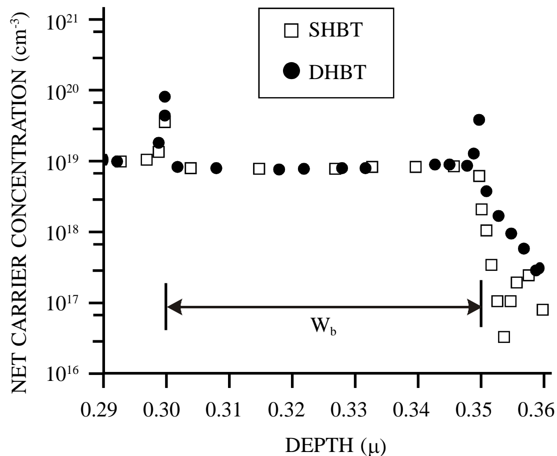

Figure 2. Net carrier concentration in *SiGe* DHBT and SHBT at collector-emitter voltage of 2 V and base-emitter voltage of 1.1 V. W_b is the base thickness. The curves show the higher concentration of carriers in the base at emitter-base and base-collector junctions in DHBT in comparison with SHBT.

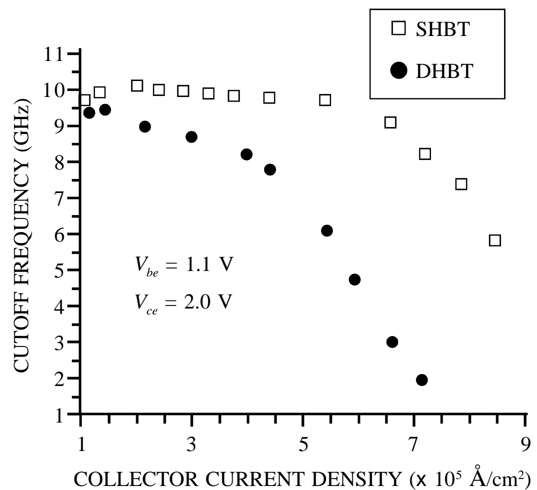

Figure 3. Cutoff frequency versus collector current density plot for *SiGe* DHBT and SHBT.

cent drop in cutoff frequency for the same increase in J_c. This proves the improvement of cutoff frequency in SHBT structure in comparison with *SiGe* DHBTs as the J_c increases and promises to be a prime candidate for application in prospective scaled down, high cutoff frequency devices.

4. CONCLUSION

A new NPN *SiGe* SHBT structure with uniform 15 atomic per cent germanium in base and collector with a base-collector homojunction has been proposed to improve the cutoff frequency performance at high J_c. The SHBT promises a superior cutoff frequency performance in comparison with conventional *SiGe* DHBT structure due to the absence of V_{bp} for electrons at base-collector heterojunction, which is the prime source of degradation of cutoff frequency in *SiGe* DHBT at high J_c. A comparison of conduction band electron energy and net carrier 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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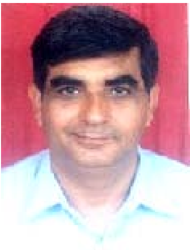

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