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Current Gain Simulation at High Collector Current Densities for Metal-Oxide Heterostructure Transistors

Ahmed S. Falah, Khalid R. Jasim

Department of Electrical Engineering, College of Engineering, Al-Mustansiriya University, Baghdad, IRAQ

Abstract

An NPN Si/SiGe/SiGe Graded Heterojunction Bipolar Transistor (SiGe GHBT) has been compared with contemporary NPN Si/SiGe/Si Double Heterojunction Bipolar Transistor (SiGe DHBT) for current gain performance at high collector current densities, using a 2-dimensional MEDICI device simulator. The analysis predicts that the base-collector homojunction of the SiGe GHBT structure is responsible for improved current gain at high collector current density in comparison with the conventional SiGe DHBT and provides the option of operation at higher collector current densities.

Keywords: SiGe GHBT; Current gain; Retarding potential barrier; Linear tapering

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1. Introduction

It has been already reported that the NPN Si/SiGe/Si DHBT structures exhibit rapid fall in the current gain at high collector current densities [1]. This rapid fall in the current gain leads to the fall in transistor efficiency and make it impractical for use at high collector current densities. The degraded current gain at high collector current densities in DHBT structures is attributed to the formation of retarding potential barrier for electrons at base-collector junction [2]. The velocity saturation of electrons in collector and the valence band offset for holes at base-collector junction leads to the formation of retarding potential barrier.

In the present work, the conventional NPN SiGe DHBT structure with uniform 20 *at%* of Ge in base is simulated to supplement the earlier reported results on the formation of retarding potential barrier. These results are used as the basis for comparing the structures evolved to improve the current gain at high current densities. The objective has been to transform the base-collector heterojunction with the closest approximation to homojunction. Therefore, in the present work the GHBT structure with a uniform Ge *at%* in base region and a linearly graded germanium *at%* in collector has been chosen with a perfect homojunction at base-collector metallurgical junction [3]. The base-collector homojunction completely inhibits the formation of retarding potential barrier due to valence band offset and the grading of germanium ensures the strained behavior and stability of the SiGe layers [4]. A further advantage of choosing the NPN GHBT structure lies in the fact that the process of growing a box-type uniform SiGe base layer over a linearly graded SiGe collector region is more practical to achieve dislocation free strained base and collector SiGe layers [6].

A two-dimensional MEDICI device simulator, known for its authenticated results at the device level for SiGe HBT structures [4], has been used in the present analysis and the high doping and electric field models have been included. The performance of both the HBT structures for current gain is compared and authenticated by investigating the conduction band electron energy, net carrier concentration profiles, metallurgical junction, and dependence of collector current density on base-emitter bias voltage. A theoretical formulation has been provided to supplement the improved performance obtained in the proposed Si/SiGe/SiGe heterostructure in comparison with SiGe DHBT structure.

In NPN silicon BJT the finite electron concentration n_c in collector-base space charge layer is necessary to sustain the flow of collector current in the transistor. An expression relating the electron density n_c with the collector current density J_c for the constant drift velocity v_{dsat} condition is given as [5]:

$$J_c = qv_{dsat}n_c \quad (1)$$

At sufficiently high collector current density the high electron concentration in the space charge region of collector lowers the potential barrier at base-collector junction. This leads to the onset of Kirk phenomenon [6] where the base-collector junction shifts into the collector space-charge region resulting in the vertical widening of the effective neutral base region width. The total voltage across base-collector junction (V_{bctot}) is the sum of built in potential barrier at base-collector junction (V_{bi}) and the terminal base-collector voltage (V_{bct}). At the onset of Kirk phenomenon, (at Kirk current density J_k), the electron density in base-collector space charge region, n_c (= n_k, electron density at start of Kirk effect), is related with the device parameters and V_{bctot} by the expression:

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

where N_c is the collector-doping concentration, ε is the dielectric constant for Si, q is the electronic charge and W_c is the collector width as now whole collector width corresponds to space charge region.

In Si 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 having a sizable alloy mole fraction, there is a valence band discontinuity for holes at base-collector junction. 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 base due to valence band offset at base-collector 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. A further increase in the collector current density will consequently increase the dipole strength and increases the electric field E_0. The presence of the electric field E_0 at base-collector heterojunction gives rise to a retarding potential barrier (V_{bp}) in conduction band, which would oppose the electrons flowing from emitter to collector through base. An increased electron density in the base at base-collector junction $n_{(Wb)}$ is now required to support and maintain the electron density n_c and collector current density J_c. The electron density n_c in base-collector space charge region for collector density J_c, in SiGe DHBT derived from the basic Poisson's equation is:

$$n_c = N_c + \left\{\left((2\varepsilon)\frac{V_{bctot} + E_0W_c}{qW_c^2}\right)\right\} \quad (3)$$

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

$$n_{(Wb)} = n_c \exp\left(\frac{qV_{bp}}{KT}\right) \quad (4)$$

where $KT/q = V_T$ is the thermal voltage

The retarding potential barrier V_{bp} for electrons can be expressed as:

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

where ΔE_v is the valence band discontinuity for holes and N_b is the neutral base width.

Solving Eq. (3), (4) and (5) for a uniformly doped base gives the effect of bias dependent retarding potential barrier V_{bp} and base-emitter biasing V_{be} on the collector current density J_c as:

$$J_c = \left[\left(\frac{qD_nn_{io}^2}{W_bN_b}\right)\left(\frac{e^{\left(qV_{be}+\Delta E_v-V_{bp}\right)/KT}}{1+\frac{D_ne^{V_{bp}/KT}}{W_bv_{dsat}}}\right)\right] \quad (6)$$

where, n_{i0} is the intrinsic carrier concentration. The modified value of electron density in base at emitter-base junction $n_{(0)}$ in term of V_{bp} is expressed as:

$$n_{(0)} = \left[\left(n_c\left(v_{dsat}W_b\right)\right) + \left(n_c\exp\left(\frac{qV_{bp}}{KT}\right)\right)\right] \quad (7)$$

where $[n_c\ (v_{dsat}\ W_b)\ /\ D_{nb}]$ is the electron density in the base at the base-emitter junction corresponding to the electron density in base-collector space-charge region n_c

The second term in Eq. (7), $[n_c\{exp\ (qV_{bp}/KT)\}]$ is the electron density in base at the base-emitter junction as a result of increased electron concentration in base at base-collector junction because of the retarding potential barrier at base-collector junction.

The relation of the effective band offset δE_v and valence band discontinuity ΔE_v with $n_{(0)}$ and V_{be} (for a specific J_c) is expressed as:

$$V_{be} = \left[\begin{array}{l} V_t \ln\left\{ \left(\frac{n_{(0)}^2}{n_{i0}^2} \right) + \left(\frac{n_{(0)} N_b}{n_{i0}^2} \right) \right\} \\ - \frac{\delta(E_v)}{q} \end{array} \right] \quad (8)$$

The substitution of the expression for $n_{(0)}$ from the Eq. (7) in Eq. (8) predicts the necessity for an increase in V_{be} to account for the increase in $n_{(0)}$ required to sustain the collector current density J_c. This requirement of increase in V_{be} for a given collector current density J_c will be reflected as a fall in the current gain of the DHBT structure. This prediction is consistent with the discussion of Eq. (6) where an increase in retarding potential barrier V_{bp} at high collector current density predicts a fall in the DHBT collector current density J_c and current gain.

The analysis of SiGe DHBT illustrates the formation of retarding potential barrier at base-collector junction due to valence band offset for holes. The theory also predicts a fall in the current gain at high collector current density as a consequence of this retarding potential V_{bp}. Whereas, the proposed GHBT structure with uniform Ge profile in base and grading of Ge *at%* in collector avoids the retarding potential barrier for electrons at base collector homojunction. Consequently, this structure promises an improved current gain at high collector current density in comparison with SiGe DHBT structure.

2. Simulation Results for SiGe DHBT and GHBT Structures

The current gain performance of the NPN Si/SiGe/Si DHBT and proposed NPN Si/SiGe/SiGe heterostructure is compared for identical device dimensions, doping densities and bias conditions. The surface emitter doping of 5×10^{19} cm^{-3} and its thickness W_{e1} of 0.2 μm is chosen to provide ohmic contact. The emitter doping of 1×10^{19} cm^{-3} and its thickness W_{e2} of 0.1 μm is selected to lower the emitter-base. 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 W_c of 0.45 μm have been chosen in both the structures.

The germanium profile in different regions of Si/SiGe/Si DHBT and Si/SiGe/SiGe HBT structures is shown in Fig 1. An optimized mole fraction of germanium has been chosen to retain the strained behavior and stability of SiGe regions [5]. A uniform 20 *at%* Ge has been chosen in the base of conventional Si/SiGe/Si *Double* HBT (DHBT) structure, whereas its collector does not contain any germanium mole fraction. The base-collector homojunction, in the proposed Si/SiGe/SiGe *Graded* HBT (GHBT) structure has been ensured by choosing a uniform 20 *at%* Ge in base and tapering it linearly to zero *at%* Ge at the collector ohmic contact.

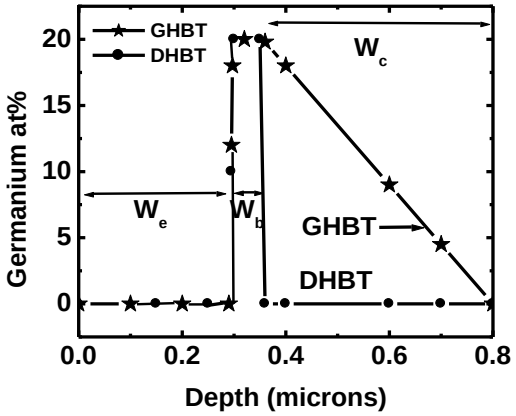

Fig. (1) Ge profile in the emitter, base and collector for the SiGe DHBT and GHBT. W_e, W_b, and W_c are the total emitter, base, and collector width, respectively in the HBTs.

The chosen operating conditions of SiGe DHBT and GHBT structure ensures the performance evaluation in the high collector current density region (>10^5 Amp/cm^2). The simulation results on conduction band electron energy for both the structures include the influence of valence band offset for holes and bandgap narrowing due to the heavily doped base. The electron energy profile shown in Fig. 2, for the collector current density of 9.22×10^5 A-cm^{-2}, predict the total retarding potential barrier V_{bp} of approx. 0.09 eV for the conduction band electrons at the base-collector heterojunction in the SiGe DHBT structure. The valence band offset for holes at base-collector heterojunction is observed to contribute 0.06 eV in the total retarding potential barrier in the DHBT structure. This is obtained by excluding the influence of heavy doping effect on band gap narrowing in the base. The simulated result is consistent with the retarding potential barrier of approx. 0.058 eV obtained by solving Eq. (5) for SiGe DHBT accounting only for the valence band offset for holes. Whereas, the formation of such a retarding potential barrier (due to valence band offset for holes) is prohibited by the base-collector homojunction in the GHBT structure. Therefore the simulation results shown in Fig. 2, for the collector current density of 1.6×10^6 A-cm^{-2} in the GHBT structure, exhibits a small potential barrier of 0.03 eV, which is solely attributed to the high doping in the base. The retarding potential barrier of 0.06 eV in the DHBT structure leads to accumulation of mobile electrons at base-collector heterojunction.

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

shown in Fig. 3. 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. Whereas, a lower net carrier concentration of 6.34 × 10^{18} cm^{-3}, which corresponds to an electron concentration of 1.86 × 10^{19} cm^{-3}, is obtained, for a higher collector current density of 1.6 × 10^{6} A-cm^{-2} at base-collector junction in the base of GHBT structure. The simulation results predict an electron concentration of 3.07 × 10^{19} cm^{-3} at the emitter-base junction in GHBT structure.

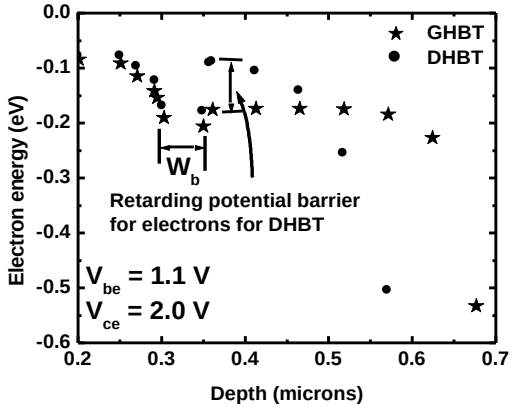

Fig. (2) Conduction band electron energy E_C for SiGe DHBT and GHBT including the effect of valence band offset and band gap narrowing. W_b is the base width

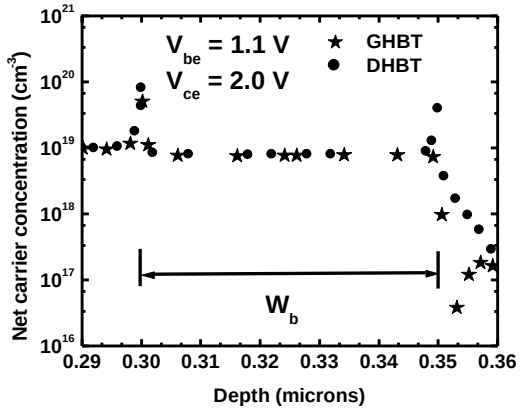

Fig. (3) Net carrier concentration in SiGe DHBT and GHBT at collector-emitter voltage V_{ce} of 2 Volts and base-emitter voltage V_{be} of 1.1 Volts. W_b is the base width

This increase in electron concentration at both the metallurgical junctions in the base of DHBT forces the requirement of an associated increase in base-emitter biasing voltage V_{be}.

3. Conclusions

An NPN SiGe GHBT structure with uniform 20 *at%* germanium in the base and tapering it linearly to zero *at%* Ge at the collector ohmic contact is proposed to improve the current gain performance of the SiGe HBTs at high collector current densities. The base-collector homojunction inhibits the formation of retarding potential barrier due to absence of valence band offset for holes at base-collector metallurgical junction and 20 *at%* of germanium and its tapering ensures the strained behavior and stability of the SiGe layers. The absence of retarding potential barrier in SiGe GHBT is observed to provide better current gain performance at high collector current densities in comparison with DHBT structure. A theoretical model for SiGe DHBT has been developed to supplement the simulation results for current gain dependence on the physical parameters and device structure. A comparison of conduction band electron energy, net carrier concentration profile and dependence of collector current density on the base emitter voltage has been provided for the SiGe HBT structures. The theoretical formulation and the simulated results on the current gain performance establish the superiority of the GHBT structure in comparison with the DHBT device configuration at high collector current densities.

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