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Improved current gain at high collector current densities for SiGe heterostructure transistors

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Abstract

A two-dimensional simulation study is presented to analyze the current gain performance of an NPNSi/SiGe/SiGe graded heterojunction bipolar transistor (SiGe GHBT) having a uniform 20 atomic per cent (*at%*) Ge profile in its base and a linear tapering of Ge *at%* in collector with *zero at%* Ge at collector ohmic contact. A contemporary NPN Si/SiGe/Si *double* heterojunction bipolar transistor (SiGe DHBT) having a uniform 20 *at%* Ge profile in the base region and *zero* Ge *at%* in collector is also simulated for comparison. The analysis predicts that a valence band offset for holes at base-collector junction gives rise to the formation of dynamic retarding potential barrier for minority carrier electrons at the base-collector heterojunction of the DHBT structure, which increases with the collector current density. However, the formation of such a potential barrier is smoothed out in an SiGe GHBT structure with base-collector homojunction. The GHBT structure shows an improved current gain and a better current-gain fall-off at high collector current density in comparison with the conventional SiGe DHBT, thus providing the option of operation at higher current densities.

Keywords: SiGe DHBT, SiGe GHBT, current gain, retarding potential barrier, linear tapering.

1. Introduction

Silicon-germanium (SiGe) technology is compatible with the present-day Si process technology and provides the option of bandgap engineering; hence the attraction of integrating the SiGe technology for the advancement of the present-day device field. Extremely high cut-off frequency of 30 GHz and maximum frequency of oscillation of 50 GHz in the Si/SiGe/Si NPN double heterojunction bipolar transistors (DHBTs) has already been reported [1]. The SiGe technology thus is a prime candidate for application in the high-frequency communication field. This improvement in the DHBT structure is attributed to the valence band offset for holes at emitter-base and base-collector junction [2]. One important aspect of the operation of SiGe devices is their requirement of operation at high current densities to achieve high cut-off frequency performance. Moreover, the scaling down of the present-day electronic devices forces their operation at very high collector current densities ($> 10^5$ Amp/cm^2). Therefore, the operation and performance of SiGe heterostructure transistors at high collector current densities is of prime concern for the microelectronics researchers and process engineers.

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It has already been reported that the NPN Si/SiGe/Si DHBT structures exhibit rapid fall in the current gain at high collector current densities [3]. This fall in the current gain leads to a fall in transistor efficiency and makes 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. 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. The analysis of NPN Si/SiGe/Si DHBT structure by Yu *et al.* [3] shows the drop in the collector current density curve as the forward base-emitter bias exceeds approx. 0.77 volts, predicting a sharp fall-off in the current gain of the transistor above 0.77 volts. An increase in collector doping is suggested by Tiwari [4] to prevent the formation of such retarding potential barrier in the GaAs/GaAlAs DHBTs. However, increasing the collector doping has an adverse effect on the breakdown voltage of bipolar transistors. Therefore, some alternative HBT structures without valence band offset for holes at base-collector junction need to be evolved for improving the transistor current gain and efficiency at high collector currents. 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 an approximately perfect homojunction at base-collector metallurgical junction and a graded germanium profile in collector has been chosen. The base-collector homojunction inhibits completely 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 [5]. 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.

A two-dimensional MEDICI device simulator, known for its authenticated results at the device level for SiGe HBT structures [6, 7], has been used in the present analysis and high doping and electric field models have been included. The performance of both the HBT structures for current gain and frequency response has been 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.

2. Theory

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. The high electric field in this space charge layer leads to saturation of electron velocity, which maintains constant drift velocity n_{dsat} conditions. An expression relating the electron density n_c with the collector current density J_c for the constant drift velocity condition is given as [8]:

$$J_c = qv_{dsat}n_c\,. \tag{1}$$

At sufficiently high collector current density the electron concentration in the base-collector space charge region increases above the collector doping concentration. This 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 where the base-collector junction shifts to 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 the start of the Kirk effect) is related to the device parameters and V_{bctot} by the expression:

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

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

In Si BJT, at the onset of the 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 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:

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

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}:

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

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

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

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

where ΔE_v is the valence band discontinuity for holes and N_b, the neutral base width. Equation (5) predicts that an increase in collector current density augments the retarding potential barrier until a value equivalent to valence band offset for holes at base-collector junction is achieved.

Solving eqns (3)–(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:

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

where n_{io} is the intrinsic carrier concentration.

Equation (6) predicts that the collector current density decreases with increase in retarding potential barrier at base-collector junction for electrons. Moreover, eqn (5) predicts that any increase in collector current density by increasing base-emitter forward-biasing increases the retarding potential barrier, which in turn will impede the increase in the collector current density. As a consequence, the effect of increased base-emitter forward-biasing on collector current density is countered by a simultaneous increase in the retarding potential barrier, which would be reflected as a fall in the current gain at high collector current densities in SiGe DHBT structure.

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

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

where $[n_c(n_{dsat}W_b)/D_{nb}]$ 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 eqn (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 effective valence band offset dE_v (= $\Delta E_v - qV_{bp}$) at emitter-base junction provides higher emitter injection efficiency of SiGe HBTs. It can be considered as the effective valence band offset accounting for high current barrier effects, in terms of valence band dis-

continuity ΔE_v, and conduction band retarding potential barrier V_{bp}. The relation of the effective band offset dE_v with electron density in the base at base-emitter junction $n_{(0)}$ and applied base emitter bias V_{be} (for a specific J_c) is expressed as:

$$V_{be} = \left[V_t \ln\left\{ \left(\frac{n_{(0)}^2}{n_{i0}^2} \right) + \left(\frac{n_{(0)} N_b}{n_{i0}^2} \right) \right\} - \frac{d(E_v)}{q} \right]. \tag{8}$$

Equations (7) and (8) show the effect of retarding potential barrier V_{bp} on electron density in the base at emitter-base junction $n_{(0)}$ and applied base-emitter voltage V_{be} to sustain the collector current density J_c. The substitution of the expression for $n_{(0)}$ from eqn (7) in eqn (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 eqn (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.

3. 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 physical parameters and doping profiles in the different regions of these structures are shown in Fig. 1. The surface emitter doping of 5×10^{19} cm^{-3} and its thickness W_{e1} of 0.2 *m*m is chosen to provide ohmic contact. The emitter doping of 1×10^{19} cm^{-3} and its thickness W_{e2} of 0.1 *m*m is selected to lower the emitter-base junction capacitance. This two-step emitter profile is typical of heterostructure devices, provided the heterostructure device has an inherent high current gain which could be traded-off to achieve lower internal emitter doping. The base thickness W_b of 0.05 *m*m 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 *m*m 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 2. 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.

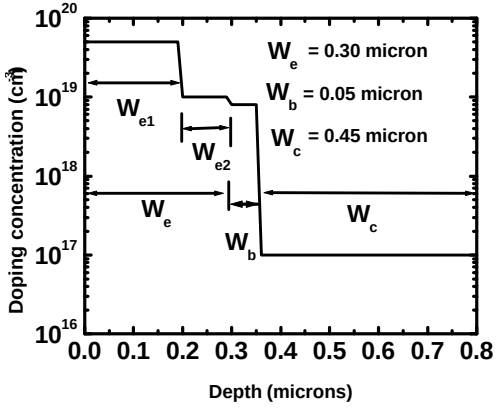

FIG. 1. Doping profile in the emitter, base and collector region of the NPN SiGe DHBT and GHBT structures. W_e, W_b, and W_c are, respectively, the total emitter, base, and collector width in the HBTs. W_{e1} and W_{e2} are the two-step emitter widths.

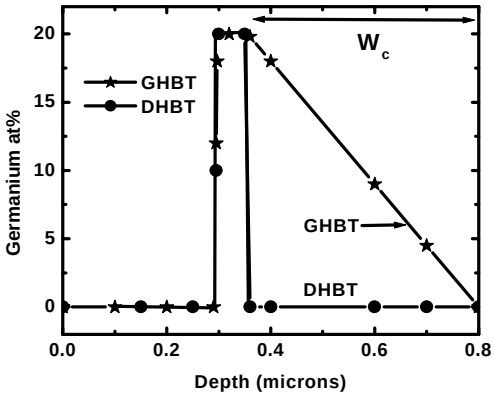

FIG. 2. Ge profile in the emitter, base and collector for the SiGe DHBT and GHBT. W_c is the collector width in the HBTs.

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 profiles shown in Fig. 3 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.

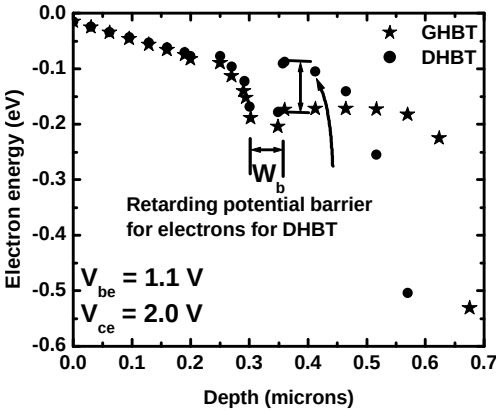

FIG. 3. Conduction band electron energy E_C for SiGe DHBT and GHBT including the effect of valence band offset and band gap narrowing. W_b is the base width. The DHBT curve, at a collector current density of 9.22×10^5 A-cm^{-2}, shows a total retarding potential barrier qV_{bp} of 0.09 eV at base-collector junction for electrons.

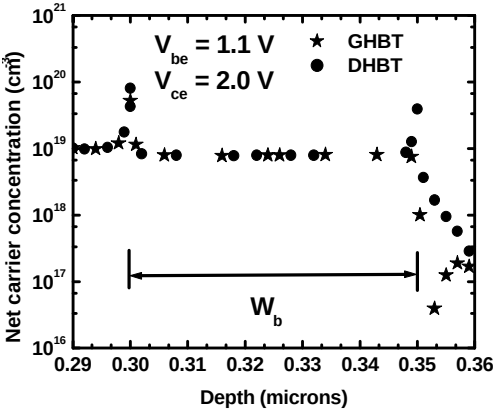

FIG. 4. Net carrier concentration in SiGe DHBT and GHBT at collector-emitter voltage V_{ce} of 2 Volts and base-emitter voltage V_{be} of 1.1 Volts. W_b is the base width. The curves show the higher concentration of carriers in the base at emitter-base and base-collector junction in DHBT in comparison with GHBT.

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 bandgap narrowing in the base. The simulated result is consistent with the retarding potential barrier of approx. 0.058 eV obtained by solving eqn (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. 3 for the collector current density of 1.6×10^6 A-cm^{-2} in the GHBT structure exhibit 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 the 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. 4. A net carrier concentration of 8.11×10^{19} and 3.93×10^{19} cm^{-3} is obtained, respectively, in the base of DHBT structure at emitter-base and base-collector junctions. 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 even for a higher collector current density of 1.6×10^6 A-cm^{-2} in GHBT, a lower net carrier concentration of 6.34×10^{18} cm^{-3} corresponding to a lowered electron concentration of 1.86×10^{19} cm^{-3} at base side of base-collector junction is obtained. Subsequently, the simulation results predict a correspondingly lowered electron concentration of 3.07×10^{19} cm^{-3} at the emitter-base junction in GHBT structure in comparison with DHBT structure. This is qualitatively consistent with the net electron concentration computed at the base-emitter junction of DHBT and GHBT, respectively, using the theoretical formulation derived in eqn (7). Therefore, even for a higher collector current density, the GHBT structure requires lower electron concentration (and holes, due to charge neutrality condition) at the emitter-base and base-collector junctions, in comparison with DHBT structure. This increase in electron concentration at both the metallurgical junctions in the base of DHBT will force an associated increase in base-emitter biasing voltage V_{be}, which would eventually lead to reduced current gain for DHBT structure at high current densities.

The dependence of collector current density J_c on the base-emitter bias voltage V_{be}, for the DHBT and GHBT structures, is shown in Fig. 5. The results predict the requirement of base-emitter bias voltage of 1.1 volts for the DHBT and 0.97 volts for the GHBT structure to sustain the collector current density of 9.22×10^5 A-cm^{-2}. The base-emitter bias voltage for the GHBT structure is observed to increase linearly with the collector current density, whereas the collector current density for the DHBT structure approximately saturates above the base-emitter bias voltage of 0.98 volt. Therefore, at higher collector current densities the DHBT structure needs higher base-emitter bias voltage in comparison with GHBT structure for sustaining the same collector current density. The requirement of higher base-emitter bias voltage will adversely influence the current gain of DHBT in comparison with GHBT structure.

The dependence of current gain on the collector current density for the DHBT and the GHBT structure is shown in Fig. 6. The monotonically decaying behavior of current gain in

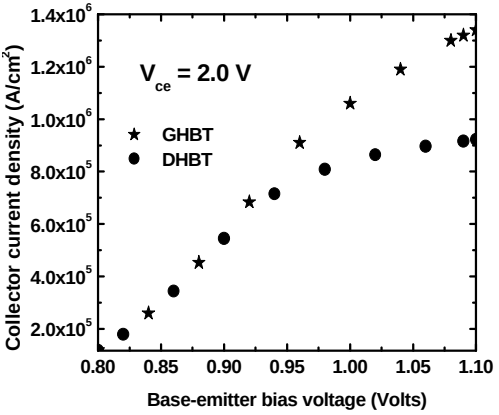

FIG. 5. Dependence of collector current density J_c on base-emitter bias voltage V_{be}. The GHBT structure shows the higher slope of collector current density curve in comparison with SiGe DHBT at high collector current density.

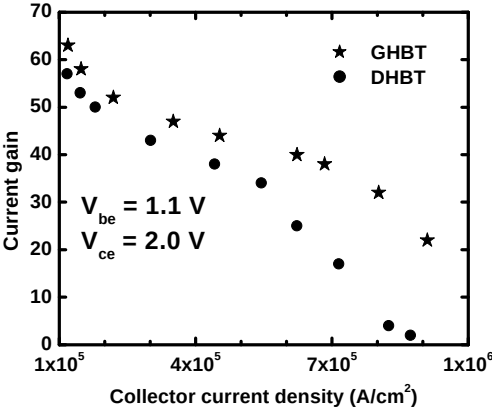

FIG. 6. Current gain vs collector current density plot for NPN SiGe DHBT and GHBT.

both the structures for the collector current densities less than 4.0×10^5 A/cm^2 is attributed to the Kirk effect [7] and high-level injection of minority carriers in the base. At higher collector current densities ($> 4.0 \times 10^5$ A/cm^2), the current gain in the GHBT structure falls to 72% of its initial value for two-fold change in the current density, whereas in the DHBT structure it falls to 10% for two-fold change in the collector current density. Therefore, the DHBT shows a sharp fall-off in the current gain in comparison with GHBT structure as the collector current density increases. The results are consistent with fall in the current gain in DHBT structure, predicted by eqn (6), due to the formation of retarding potential barrier at base-collector junction in the DHBT structure. The basic merit of the GHBT structure is the utilization of base-collector homojunction to prohibit the formation of such retarding potential barrier. The results establish superior current gain performance of the GHBT structure in comparison with the DHBT device. Although the results presented in the present work are for the pre-selected doping profiles and physical parameters of the device, the phenomena of better performance of the GHBT structure over comparable DHBT structures will be consistent with other device configurations and doping profiles.

4. 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 the 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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