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Short Communication

Analysis of quasi-saturation phenomena for SiGe double heterojunction bipolar transistors

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Abstract

In this paper, a high-voltage current-switching NPN SiGe double-heterojunction bipolar transistor (DHBT) has been analyzed and simulated using two-dimensional device simulator MEDICI. The analysis includes conductivity modulation, quasi-saturation phenomenon and effect of valence band offset for holes in a high-voltage SiGe DHBT and is compared with a conventional Si bipolar junction transistor (Si BJT). The valence band offset for holes is responsible for the presence of a retarding potential barrier at *collector-base* junction for electrons in SiGe DHBT. The retarding potential barrier formation along with reduced conductivity modulation in SiGe DHBT leads to a fall in its short-circuit current gain h_{FE} in comparison with Si BJT. As a consequence, the quasi-saturation current density limit J_{CQS} of SiGe DHBT degrades and leads to high-power dissipation, setting a severe limitation on its performance at high collector current density.

Keywords: SiGe DHBT, Si BJT, quasi-saturation, power dissipation, valence band offset.

1. Introduction

High-voltage current-switching Si bipolar junction transistors (Si BJTs) operating at high collector current density J_C and low-base-collector (*b–c*) bias voltage V_{BC} show pronounced transition between the ohmic saturation and the active regions in the output characteristic. The phenomenon, termed as quasi-saturation [1], shows a reduction in device current gain and limits the high current operation of device due to undue power dissipation. This quasi-saturation phenomenon in Si BJTs has already been studied and analyzed [2, 3]. Another important phenomenon at high J_C and high V_{CB}, termed as Kirk effect [4], is observed due to the base push-out and reversal of the gradient of the electric filed at the *b–c* junction. While studying the Kirk phenomenon for high J_C in the GaAs/GaAlAs NPN *double*-heterojunction bipolar transistor (DHBT), Tiwari [5] observed the formation of a retarding barrier potential V_{BP} for electrons of approx. 0.07 eV at emitter current density of 8×10^4 A/cm^2. This potential barrier has been identified as the prime source for an increase in charge storage in the base, and in the base current, and degradation in the device speed. Yu *et al.* [6] provided an analytical model for calculating V_{BP} and predicted an onset of

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high-level early injection in the base. This phenomenon in the SiGe base DHBTs is observed to rapidly decrease the cutoff frequency for J_C exceeding the Kirk effect limited current density J_K. However, the origin and consequence of the valence band offset for holes at *b–c* junction in quasi-saturation regime for a high-voltage current-switching SiGe DHBT are yet to be investigated and analyzed.

The present study was initiated to analyze the quasi-saturation performance of a high-voltage current-switching SiGe DHBT at high J_C and to study the effect of V_{BP} at *b–c* heterojunction. The parameter of quasi-saturation performance of the transistor is the maximum J_C permissible before the current gain starts to decrease. This maximum J_C limit is termed as quasi-saturation current density limit (J_{CQS}) which leads to undue power dissipation inside the device over this limit. It is known that J_{CQS} of high-voltage silicon bipolar junction transistor can be improved by increasing its base Gummel number (G_B) while maintaining the normal active region peak dc current gain h_{FE0} fixed. In the Si BJTs, this is obtained by using the deep-diffused emitter-base transistors [7]. The SiGe DHBT provides the flexibility of increasing G_B because it possesses higher emitter injection efficiency and a higher mobility for the strained SiGe base in comparison with a conventional Si BJT. Therefore, the superior emitter injection efficiency of these transistors, with a potential of providing higher G_B for achieving improved J_{CQS} for high-voltage transistors, needs to be explored.

In the present paper, we have traded off the higher emitter injection efficiency in the SiGe DHBT to increase its G_B. 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 and the corresponding high-doping and electric-field models have been included. However, the results show a highly degraded J_{CQS} in SiGe DHBT in comparison with Si BJT (having lower G_B). This contradicts the conventional theory given for the quasi-saturation phenomenon in Si BJTs [7]. The subsequent analysis by authors shows that the quasi-saturation study of DHBTs requires a simultaneous investigation of the effect of valence band offset for holes at *b–c* junction in NPN SiGe DHBT and leads to hole accumulation. It is responsible for the presence of V_{BP} at *b–c* heterojunction for electrons. Moreover, the accumulation of holes at the *b–c* junction prohibits the self-corrective phenomenon of conductivity modulation in SiGe DHBT. This leads to a constant collector resistance R_C, which, along with V_{BP}, leads to a severe fall in short-circuit current gain h_{FE} in SiGe DHBT in comparison with Si BJT. This effectively wipes out the advantage of higher G_B in SiGe DHBT for the improvement of J_{CQS}. The present work provides simulation results and offers an explanation for SiGe DHBT performance in quasi-saturation regime. The results are compared with a conventional Si BJT.

2. Simulation results and discussion

The device parameters and biasing for the simulated device structures are chosen such that the device output characteristics are defined by quasi-saturation phenomenon rather than Kirk effect. For this purpose, we have kept the J_{CQS} much lower purposely than J_K by applying a low V_{BC}. The quasi-saturation performance of the NPN Si/SiGe/Si DHBT and the NPN Si BJT is compared for identical device dimensions and bias conditions, except for a higher base doping (N_B) in the DHBT. The SiGe DHBT is chosen to have higher N_B of 1.7×10^{18} cm^{-3} (with uniform 20% mole fraction of Ge in base) in comparison with the N_B of 3.6×10^{17} cm^{-3} in Si BJT for the same base thickness (W_B) of 0.1 *m*m. The emitter in both transistor structures is chosen to have a two-step doping configuration, as is done in conventional SiGe DHBT. The surface emitter doping of 5×10^{19} cm^{-3} and its thickness (W_{E1}) of 0.2 *m*m are chosen to provide an ohmic contact and the internal emitter doping of 8×10^{18} cm^{-3} and its thickness (W_{E2}) of 0.1 *m*m are selected to obtain lower base-emitter (*b–e*) capacitance. The collector doping of 1×10^{15} cm^{-3} and its thickness (W_C) of 20 *m*m is chosen to achieve a reach through epitaxial collector. We have chosen the shallow emitter and the base for device simulation and comparison such that the SiGe DHBT base remains strained and no dislocation formation occurs inside SiGe DHBT base.

The higher N_B in the SiGe DHBT structure provides relatively higher G_B of 17×10^{12} cm^{-2} in comparison with 3.6×10^{12} cm^{-2} in the Si BJT. The simulation for both the transistors is carried out for the peak current gain h_{FE0} of 100 and forced gain of 5. Here, we have traded off the higher current gain of SiGe DHBTs to provide higher G_B for achieving higher J_{CQS}. The Kirk current density J_K of 1614 A/cm^2 is calculated for the Si BJT, for a terminal *b–c* voltage V_{BC} of 2V and the punch-through voltage of 304 V [9].

The expression relating J_K to J_{CQS} can be stated as [9]:

$$J_{CQS} = J_K \left[\frac{(V_{BC} + 0.5)}{W_C E_C} \right]. \tag{1}$$

A value of 201 A/cm^2 is obtained for J_{CQS} using eqn (1) for the critical electric filed E_C of 10^4 V/cm. The computed value of J_{CQS} and J_K predicts that the SiGe DHBT can operate in quasi-saturation regime for the collector current density in the range of 201–1614 A/cm^2. An NPN bipolar transistor in quasi-saturation regime is shown in Fig. 1(a), where the total dc voltage drop $V_{CE(sat)}$ across the collector–emitter terminals of a metal contacted n^+–*p*–*n* Si BJT operating in the quasi-saturation region is expressed as [7]:

$$V_{CE(sat)} = V_{CER} + V_{MOD} - V_{BC} + V_{BE} + I_C R_{sat}, \tag{2}$$

where V_{CER} is the voltage drop across the nonconductivity modulated collector region, V_{MOD}, the voltage drop in the conductivity modulated collector region and V_{CC} and V_{EE} are the collector and emitter supply voltages, respectively. $I_C R_{sat}$ ($I_C R_{sat1} + I_C R_{sat2}$) is the drop in the ohmic contacts of the *n*-type collector and n^+-emitter.

The conduction and valence band electron energy in SiGe DHBT for *b–c* terminal voltage V_{CB} = 2.0 volts and *b–e* terminal voltage V_{BE} = 0.7 volts are shown in Fig. 1(b). The results show the presence of a retarding potential barrier for electrons at the *b–c* junction. This retarding potential barrier for the electron in SiGe DHBT determines its quasi-saturation performance at high J_C. Figure 2 shows the dependence of J_C on V_{BE} for Si BJT and Si DHBT structures at V_{CE} of 2.7 volts. The SiGe DHBT shows higher values of J_C for the identical V_{BE} in comparison with Si BJT for J_C as a consequence of heterojunction at the *b–e* junction. However, the results show a decrease in slope in the J_C curve for higher J_C (> 1000 A/cm^2) in SiGe DHBT. This degradation in the slope is not observed in the Si BJT

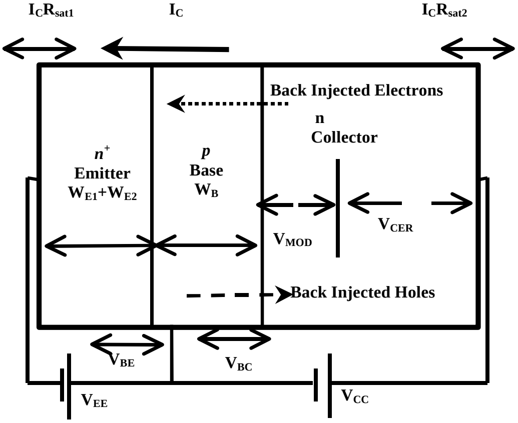

FIG. 1(a). An NPN bipolar transistor in quasi-saturation. V_{CER} is the voltage drop across the nonconductivity-modulated collector region, V_{MOD}, the voltage drop in the conductivity modulated collector region, V_{BC}, the *b–c* junction voltage, V_{BE}, *b–e* junction voltage and V_{CC} and V_{EE} are the collector and emitter supply voltages, respectively. $I_cR_{sat1} + I_cR_{sat2}$ is the voltage drop at the ohmic contacts of the *n*-type collector and n^+-emitter. W_{E1} and W_{E2} are the two-step emitter widths and W_B is the base width.

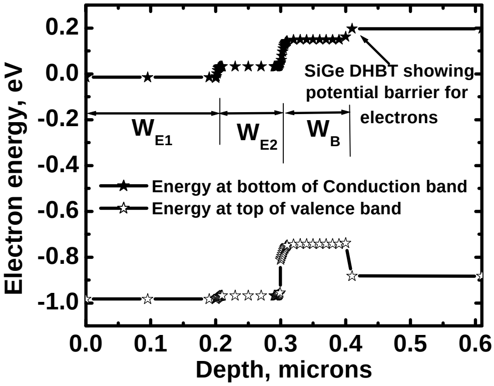

FIG. 1(b). Electron energy in NPN SiGe DHBT structure versus vertical depth at V_{BE} of 0.7 volts and V_{CE} of 2.7 V. The retarding potential barrier for conduction electrons is visible at the *b–c* heterojunction. W_{E1} and W_{E2} are the two-step emitter widths and W_B is the base width.

structure and is a direct consequence of the formation of V_{BP} at *b–c* junction in SiGe DHBT [6]. The compensation of this degradation in the J_C requires an increased V_{BE} to sustain the same J_C. This implies that the presence of V_{BP} at *b–c* junction in the SiGe DHBT will lead to a dawdling increase in J_C with applied V_{BE}. This sluggish increase in J_C with V_{BE} in the input characteristic will be reflected in the output characteristic of the SiGe DHBT as a decrease in the device current gain. This effectively predicts an early quasi-saturation region in the output characteristic and a reduced J_{CQS} for SiGe DHBT in comparison with Si BJT.

The results obtained from MEDICI simulator in the quasi-saturation regime of the output characteristics for Si BJT and SiGe DHBT are shown in Fig. 3. The simulated results show a highly degraded J_{CQS} for SiGe DHBT in comparison with the conventional high-voltage Si BJT. This result contrasts with the phenomena conceived on the basis of increasing G_B for improved J_{CQS} [7]. Therefore, the quasi-saturation analysis of a high-voltage NPN SiGe DHBT must include the effect of valence band offset for holes at *b–c* junction and V_{BP} in order to explain the output characteristics where J_{CQS} is smaller than J_K.

A supplementary result observed from Fig. 3 is that the J_{CQS} obtained for Si BJT from simulation results is quite higher than that obtained from eqn (1). The current density J_{CQS} for Si BJT using MEDICI simulator and eqn (1), for the saturation voltage of 0.5 volt, is ≈ 1100 and 201 A/cm^2, respectively. This shows that the theoretical basis of predicting J_{CQS} by eqn (1) is not consistent with the simulated results, since the formulation of this equation assumes a constant value of epitaxial collector resistance R_C [9]. Therefore, an obvious omission in this equation is the dependence of J_{CQS} on the conductivity modulation of

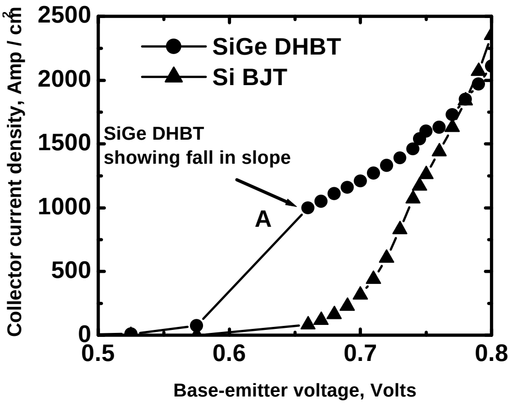

FIG. 2. Collector current density J_C versus *b–e* bias voltage V_{BE} for Si BJT and SiGe DHBT at the collector–emitter bias V_{CE} of 2.7 V. A reduced slope in J_C near point 'A' for SiGe DHBT is a consequence of the formation of retarding potential barrier for electrons at *b–c* junction as the collector current density increases.

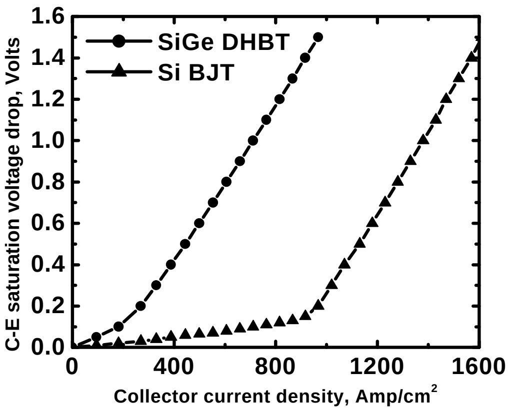

FIG. 3. Collector–emitter saturation voltage drop $V_{CE(sat)}$ versus collector current density J_C for Si BJT and SiGe DHBT for a forced gain of 5.

the epitaxial collector by minority holes. The conductivity modulation in the Si BJT lowers R_C. Since the higher value of R_C is primarily responsible for the degradation of gain in the quasi-saturation region, lowering the value of R_C increases J_{CQS}. This is why quasi-saturation effect in Si BJT is not as deleterious and has a self-corrective measure in the form of conductivity modulation. Therefore, for a given V_{CB}, the simulated results for Si BJT show a higher J_{CQS} in comparison with the value predicted by eqn (1), where a constant value of R_C is chosen. The output characteristic curve for Si BJT in Fig. 3 extends well (slope) to the left for saturation voltage of 0.5 volts (J_c = 1110 A/cm^2) of what is otherwise expected (J_C = 200 A/cm^2). However, eqn (1) correctly predicts J_C, which would initiate the process of forward biasing of the *b–c* junction. This equation predicts the J_{CQS} of ≈ 163 A/cm^2 for the saturation voltage of 0.02 volt, which is in close agreement with the current density of ≈ 170 A/cm^2 predicted by the MEDICI simulator. Unfortunately, due to the valence band offset for holes at *b–c* junction, the conductivity modulation effect (reduced R_C) in the case of NPN SiGe DHBT will be abridged. This would further aggravate the J_{CQS} in SiGe DHBT in comparison with Si BJT. To overcome the problem of valence band offset at *b–c* junction and remove the absence of conductivity modulation in SiGe HBTs, the authors have proposed a novel SiGe Single-HBT structure [10].

3. Conclusions

The studies in the present work were initiated to improve the quasi-saturation phenomena in bipolar transistors by exploiting the higher current gain of SiGe DHBTs. For this purpose, we have traded off its higher current gain for increasing the base Gummel number in the SiGe DHBTs. However, the results show highly degraded quasi-saturation performance for SiGe DHBTs. This has been identified as a consequence of a retarding potential barrier formation for minority electrons at the *b–c* heterojunction, which is not observed in the Si

BJTs. The combined effect of back-injected electrons and valence band offset for holes at *b–c* junction in conjunction with the absence of conductivity modulation of collector explains this highly degraded J_{CQS} in a high-voltage SiGe DHBT.

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