Temperature-dependent characteristics of an InP/InGaAs double heterojunction bipolar transistor with a step-graded InAlGaAs collector

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The dc and electron impact ionization characteristics of an InP/InGaAs double heterojunction bipolar transistor with a step-graded InAlGaAs collector structure are studied and reported. From the experiments, the studied device shows a better common-emitter breakdown voltage and lower output conductance at higher temperature operations. Due to the insertion of a step-graded InAlGaAs collector structure at the base-collector heterojunction, the usually observed switching and hysteresis phenomena in InP/InGaAs-based HBTs are not seen in the studied device. The temperature-dependent electron impact ionization characteristics are also investigated. Above all, the studied DHBT device provides the promise for millimeter-wave and power circuit applications. © 2008 American Institute of Physics. [DOI: 10.1063/1.2936964]

I. INTRODUCTION

Recently, InGaAs-based heterojunction bipolar transistors (HBTs) and high electron mobility transistors have attracted considerable attention because of their high-speed performance and high current handling capability.¹–³ For InP/InGaAs-based single HBTs with an InGaAs base-collector (B-C) homojunction, the low breakdown voltage arising from the high impact ionization rate in the narrow bandgap InGaAs collector becomes as a drawback for power application. Therefore, double HBTs (DHBTs) have been proposed and fabricated to improve the breakdown characteristics.⁴,⁵ However, the undesired current blocking effect and small current gain are usually observed in DHBTs.⁶,⁷ To overcome this problem, special collector designs such as p-n pair, composite collector structure, and a compositionally graded layer at the B-C junction to form the improved double heterojunction structures were used.⁸–¹¹ Previously, a chirped superlattice based InP/InGaAs/InP DHBTs with a continuous InAlGaAs grade layer was demonstrated by Neviani et al. to eliminate the current blocking effect.¹² In this work, an interesting InP/InGaAs DHBT with a step-graded InAlGaAs collector structure is studied and demonstrated. The basic structure of step-graded collector is to insert a quaternary InAlGaAs material between the base and collector layer. In addition, this quaternary alloy has a wide tunable bandgap varying between two ternary alloys of InP collector, the current blocking effect can be effectively reduced. In addition, a positive temperature dependence of the electron impact ionization coefficient (α) in InGaAs is found. It is unlike the phenomenon usually observed in most semiconductor materials.¹³ The positive temperature dependence of α may possibly initiate a positive feedback loop between power dissipation and ionization-induced increase of output conductance, so as to cause the catastrophic junction damage and breakdown.¹⁴ With the introduction of InP layer in InP/InGaAs-based DHBTs, a negative temperature-dependent α in the collector may be obtained. Thus, not only the breakdown voltage may be improved but also the stability of junction avalanche behavior can be expected. For power HBTs, the understanding of the temperature dependences of impact ionization is an important issue as the junction temperature is higher than room temperature during the device operation. In this work, the temperature dependences of electron impact ionization characteristics for the studied device are also investigated.

II. EXPERIMENT

The studied DHBT structure was grown by a low-pressure metal organic chemical vapor deposition system on an InP substrate. Silane (SiH₄) and dimethylzinc were used as the n- and p-type dopants, respectively. The epitaxial layers consisted of a 500 Å n⁺-In₀.₅₃Ga₀.₄₇As (n⁺ = 2 × 10¹⁹ cm⁻³) subcollector, a 3500 Å n⁻-InP (n⁻ = 3 × 10¹⁶ cm⁻³) collector, a step-graded structure, a 50 Å undoped In₀.₅₃Ga₀.₄₇As setback, a 750 Å p⁺-In₀.₅₃Ga₀.₄₇As (p⁺ = 3 × 10¹⁹ cm⁻³) base, a 500 Å n⁻-InP (n⁻ = 3 × 10¹⁷ cm⁻³) emitter, and a 2000 Å n⁺-In₀.₅₃Ga₀.₄₇As (n⁺ = 2 × 10¹⁹ cm⁻³) cap layers. The step-graded structure contained a 200 Å undoped In₀.₅₃Al₀.₁₉Ga₀.₃₈As (E₁₉ = 104 eV), a 150 Å undoped In₀.₅₃Al₀.₁₂Ga₀.₃₅As (E₁₂ = 0.94 eV), and a 100 Å undoped In₀.₅₃Al₀.₀₅Ga₀.₄₂As (E₅₆ = 0.83 eV) layer. After epitaxial growth, the conventional fabrication processes, including photolithography, vacuum evaporation, and chemical wet selective etching, were used to produce these DHBT devices. H₃PO₄:H₂O₂:H₂O=6:3:100 and HCl:H₂O=1:1 solutions were employed to etch the In(Al)(Ga)As and InP

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layers, respectively. AuGe/Au metal was used for the emitter and collector Ohmic contacts, and Pt/Au metal was evaporated to form the base Ohmic contact. The dc characteristics were measured by an HP4156A precision semiconductor parameter analyzer combined with a BD-8 probe station and an HT-200 hot chuck system.

III. RESULTS AND DISCUSSION

The schematic energy band diagram of the studied DHBT at thermal equilibrium is depicted in Fig. 1. The enlarged diagram near the B-C junction is also shown.

In this work, a step-graded InAlGaAs structure is introduced and added in the B-C junction. The distribution of the base-collector barrier in the depleted collector region provides the electrons with sufficient kinetic energy to transport through the conduction band spikes even at zero bias. The presence of the InGaAs setback layer near the base can further suppress the current blocking effect. This layer elevates the first conduction band spike into the base-collector space charge region, which can substantially block electrons transiting into the collector. Moreover, inserting the step-graded InAlGaAs layers would break the high and wide spike at the B-C interface into several low and narrow spikes. Therefore, the improvement of collection efficiency of electrons injecting into the base is expected.

Figure 2 shows the common-emitter current-voltage ($I-V$) characteristics of the studied device measured at different temperatures. The controlled base current ($I_B$) is applied as $I_B=20$ μA/step. Under $I_B=100$ μA, the dc current gain ($\beta_i$) is increased from 49.3 to 56.4 as the temperature is increased from 300 to 450 K. When the temperature is increased, carriers within the collector region are provided with more thermal energy, so as to increase the probability of impact ionization. Therefore, the contribution of thermal generation apparently plays a key role in the increase of collector current ($I_C$).

The common-emitter breakdown voltage ($BV_{CEO}$), defined here as the $I_C$ reaches 100 μA with $I_B=0$, is 8.05 V. This value is remarkably superior to those of the previous reports InP/InGaAs HBTs with InAlGaAs (Ref. 14) ($BV_{CEO}=5.3$ V) and step-graded InGaAsP (Ref. 15) collectors ($BV_{CEO}=5$ V). Moreover, the studied device exhibits the low offset and saturation voltages of 98.4 mV and 0.33 V, respectively. It certainly leads to a larger voltage operation range. The significant improvements are attributed to the use of the step-graded structure to have an effective energy gap in the band structure and to increase the breakdown electric field. Furthermore, the studied device shows good transistor performance even in the temperature of up to 450 K. These superior characteristics again demonstrate the great potential of the studied device in practical circuit applications.

Figure 3 shows the temperature dependences of $\beta_F$ at $I_C=1$ and 1 μA, respectively. It can be seen that the decrease of $\beta_F$ in the low collector current region ($I_C=1$ μA) is pronounced. At $I_C=1$ μA, the $\beta_F$ is decreased from 25 to 15.4 as the temperature is elevated from 300 to 450 K. Moreover, the larger $\beta_F$ at higher temperature is found at $I_C=1$ mA.
\[ = 1 \text{ mA}. \] It is mainly attributed to the higher thermal collector leakage current with increasing temperature. This gives a remarkable contribution to the collector current \( I_C \) and results in higher dc current gains.\(^{14} \)

The ideality factors of the collector current \( n_C \) and base current \( n_B \) as a function of the temperature are shown in the of Fig. 3(b). The \( n_C \) (\( n_B \)) are decreased from 1.15 (1.27) to 1.05 (1.19) as the temperature is increased from 300 to 450 K. The 1-kT-like \( I_C \) indicates that the transport of conducting carriers is primarily dominated by the thermoionic emission and diffusion mechanisms.\(^{17} \) The deviation of \( n_C \) value from unity is due to the contribution of tunneling current through the B-E (B-C) heterojunction.\(^{16} \) In addition, the decreasing tendency of \( n_C \) with elevating temperature also suggests the substantial contribution of thermionic emission at higher temperature. The near unity value of \( n_B \) reveals that the bulk recombination current component dominates the whole base current. With increasing temperature, the contributions of other base current components, such as the reverse hole injection from the base into emitter, are increased and cause the reduction of \( n_B \).\(^{17} \) Clearly, this good performance of ideality factors is directly related to the use of the step-graded collector heterostructure.

Figure 4 shows B-C reverse saturation current \( I_{CB0} \) as a function of the collector-base voltage \( V_{CB} \) under different temperatures. The B-C leakage current \( I_{CB0} \) is essentially related to the intrinsic leakage of the B-C layer rather than the extrinsic leakage induced by the process fabricated. The enlarged view under higher \( V_{CB} \) region (\( V_{CB} > 6 \) V) is shown in the inset of Fig. 4. Clearly, a positive temperature dependence of \( I_{CB0} \) is found. Furthermore, over a lower field region (\( V_{CB} < 6 \) V), the \( I_{CB0} \) values, dominated by the thermal generation, are much less than those observed in InP/InGaAs HBTs with an InGaAs (Ref. 18) or an InAlGaAs collector (Ref. 17) by at least one or two orders in magnitude at room temperature. As \( V_{CB} \) is greater than 6 V, the field dependence of the avalanche effect of thermal generation causes the rapid increase of \( I_{CB0} \).\(^{17} \) In particular, due to the enhanced impact ionization at high temperature, the raised thermal generation component gives rise to substantial avalanche multiplication, which certainly causes the decrease of the breakdown voltage.

Figure 5 shows the common-base \( I-V \) characteristics of the studied device at different temperatures. The significantly abrupt turn-on feature is obtained. This is different from the slower and graded turn-on behaviors usually seen in InP/InGaAs HBTs with InP collector.\(^{16} \) Moreover, the switching or hysteresis phenomenon\(^{19,20} \) in the InP/InGaAs HBT is not seen in our device. The switching or hysteresis phenomenon mainly results from the competition between tunneling effect and thermionic emission over the collector heterobarrier.\(^{21} \) In the common-base \( I-V \) characteristics, the emitter acts as a current source and injects electrons into the base. Electrons diffuse across the base and contribute the collector current. However, if the current blocking is presented, the actual collector current is determined primarily by the C-B bias. The absence of switching phenomenon in our studied device suggests that the tunneling effect in the C-B junction is negligible. The common-base breakdown voltage \( B V_{CB0} \), defined here as \( I_C \) reaches 100 \( \mu \)A with \( I_E = 0 \), is 11.3 V (9.9 V) at 300 K (450 K). Obviously, the common-base breakdown characteristics, mainly caused by the impact ionization in the collector region, are improved by the use of step-graded InAlGaAs collector structure. This is due to a wider effective bandgap.

The electron ionization coefficient \( \alpha \) at different temperatures versus the inverse electric field \( 1/E \) is shown in Fig. 6. The electron impact ionization coefficient \( \alpha \) is found as a function of the average electric field \( E_T \) in the collector as\(^{22} \)

\[
\alpha = \frac{M - 1}{W_c},
\]

and
pressed as than unity. Here, we neglect the contributions from holes, modulation of the local electric field, and ionization of the carrier.  

\[ E_v = \frac{V_{NB} + V_{CB}}{W_C}, \]  

where \( W_C \) and \( V_{NB} \) are the width of collector depletion region and built in voltage in the B-C junction, respectively. Equations (1) and (2) are held under the following assumptions: (i) the multiplication is initiated by electrons, (ii) \( \alpha \) is a function of the local electric field, and (iii) M-1 is much smaller than unity. Here, we neglect the contributions from holes, secondary electron ionization effects, and the base width modulation (Early effect). In Fig. 6, the studied device shows higher \( \alpha \) values at higher temperature. This is caused by the increase of electron ionization coefficients in InGaAs with increasing temperature. Besides, most impact ionizations are initiated by electrons with energy close to the bandgap at low field. As the temperature is elevated, the decrease of bandgap increases the probability of impact ionization, which leads to the positive temperature dependence of \( \alpha \). Moreover, at high fields, most of the impact ionizations are initiated by high-energy electrons. The transport of carriers is mainly determined by different scattering mechanisms, such as optical phonon scattering, ionized impurity scattering, and alloy scattering. Among these scattering mechanisms, the optical phonon scattering is inelastic and could be the key source of energy loss at a higher temperature.

To further investigate the impact ionization in the collector region that is activated by the primary electron current \( \alpha_i I_E \), \( \alpha \) values are measured at different temperatures with a constant electric field of \( E_v=200 \text{ kV/cm}. \) It can be expressed as

\[ \Delta I_B(V_{CB}) = I_{BO}(V_{CB} = 0) - I_B(V_{CB}) = M I_{BO} + (M - 1) \alpha_i I_E, \]  

where \( \alpha_i \) is the common-base current gain and \( I_E \) is the emitter current. The calculated results are revealed in Fig. 7. The emitter current \( I_E \) values are 1, 2, 3, and 4 mA. When the temperature is increased from 300 to 450 K, the \( \alpha \) values are increased from 76.5, 60, 51, and 41.5 to 361, 187, 136, and 115.5 cm\(^{-1}\) for emitter currents of \( I_E=1, 2, 3, \) and 4 mA, respectively. As the primary electron current is increased, the measured \( \alpha \) of a fixed electric field \( E_v \) is decreased gradually. This is because that the injected electrons start to modulate the effective doping and electric field in the collector space charge region and subsequently cause the decrease of \( \alpha \). Furthermore, the temperature-induced phonon scattering, which reduces the population of the high-energy tail of the electron distribution, would have only little effect on the ionization rate.

\[ E_v = \frac{(V_{NB} + V_{CB})}{W_C}, \]  

where \( W_C \) and \( V_{NB} \) are the width of collector depletion region and built in voltage in the B-C junction, respectively.

**IV. CONCLUSION**

The dc and electron impact ionization characteristics of an InP/InGaAs DHBT with a step-graded InAlGaAs collector structure are studied and demonstrated in this paper. From the experimental results, the studied device shows a better common-emitter breakdown voltage and lower output conductance over higher temperature operations. With the use of the step-graded InAlGaAs collector structure at the B-C heterojunction, the switching and hysteresis phenomena usually found in InP/InGaAs-based HBTs are not observed in our studied device. The temperature dependences of electron impact ionization are also investigated. Above all, the studied device provides the promise for millimeter-wave, power, and high-temperature circuit applications.

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