A New InGaP/GaAs Tunneling Heterostructure–Emitter Bipolar Transistor (T-HEBT)

© Jung-Hui Tsai[¶], Ching-Sung Lee[*], Wen-Shiung Lour[+], Yung-Chun Ma, Sheng-Shiun Ye

Department of Electronic Engineering, National Kaohsiung Normal University,
802 Kaohsiung, Taiwan
[*] Department of Electronic Engineering, Feng Chia University,
100 Taichung, Taiwan
[+] Department of Electrical Engineering, National Taiwan Ocean University,
Keelung, Taiwan

(Получена 25 октября 2010 г. Принята к печати 29 октября 2010 г.)

Excellent characteristics of an InGaP/GaAs tunneling heterostructure-emitter bipolar transistor (T-HEBT) are first demonstrated. The insertion of a thin *n*-GaAs emitter layer between tynneling confinement and base layers effectivelty eliminates the potential spike at base-emitter junction and reduces the collector-emitter offset voltage, while the thin InGaP tunneling confinement layer is employed to reduce the transporting time across emitter region for electrons and maintain the good confinement effect for holes. Experimentally, the studied T-HEBN exhibits a maximum current gain of 285, a relatively low offset voltage of 40 mW, and a current-gain cutoff frequency of 26.4 GHz.

1. Intruduction

Heterojunction bipolar transistors (HBTs) have attracted significant interest in high-speed digital and microwave circuit applications due to their superior performance [1–3]. However, the conventional HBTs suffered from a large collector-emitter (C-E) offset voltage (ΔV_{CE}) resulting from a considerable potential spike at base-emitter (B-E) junction, which causes the unnecessary power consumption in circuit applications [4].

In order to decrease the potential spike and offset voltage, some improved HBTs, e.g., setback-layer HBTs [5], heterostructure-emitter bipolar transistors (HEBTs) [6–8], and tunneling-emitter bipolar transistors (TEBTs) [9,10], have been well addressed. As to the setback-layer HBTs, an undoped spacer layer inserted at B-E junction is entirely depleted at equilibrium and it helps to lower the energy band at the emitter side. Nevertheless, the potential spike might be not completely eliminated unless the undoped spacer layer is enough thick. Then, it will cause large spacer recombination current and degrade the current gain [5]. With respect to the HEBTs, a small energy-gap *n*-type emitter layer is added between confinement and base layers to reduce the potential spike. However, the transistor will perform with inferior confinement effect for holes if the small energy-gap emitter layer is too thick. Then, the charge storage in neutral-emitter region will enhance the base recombination current and give rise to the total base current to increase. In other words, though a relatively low C-E offset voltage can be achieved, the current gain might be decreased particularly under large forward B-E bias [7]. Nevertheless, when the small energy-gap emitter layer is too thin, the transistor will act as conventional HBTs and the undesirable offset voltage is still considerably large. On the other hand, for the TEBTs with the considerable difference of transmission coefficients between electrons and holes, the tunneling injection could reduce the angular spread of a thermal distribution and nonradiatice recombination cross section, which helps increase the current gain [9,10].

In this article, we first experimentally investigate the device characteristics of an InGaP/GaAs tunneling HEBT (T-HEBT). Part of the injecting electrons could tunnel through the thin InGaP tunneling layer and easily transport over the small energy-gap emitter layer, which could substantially decrease the neutral-emitter recombination current, enhance the current gain, and maintain a low C-E offset voltage, simultaneously.

2. Device structures

The studied InGaP/GaAs T-HEBT was grown on an (100) oriented semi-insulating GaAs substrate by low-pressure metal-organic chemical-vapor deposition system (LP-MOCVD). The epitaxial layers of the device consisted of a $0.5\,\mu$m $p^+ = 10^{19}\,\mathrm{cm}^{-3}$ GaAs subcollector layer, a $0.5\,\mu$m $n^- = 2\times10^{16}\,\mathrm{cm}^{-3}$ GaAs collector layer, a $0.1\,\mu$m $p^+ = 10^{19}\,\mathrm{cm}^{-3}$ GaAs base layer, a 300 Å $n = 5\times10^{17}\,\mathrm{cm}^{-3}$ small energy-gap emitter layer, a 50 Å $n = 5\times10^{17}\,\mathrm{cm}^{-3}$ $In_{0.49}Ga_{0.51}P$ tynneling confinement layer, and a $0.3\,\mu$m $n^+ = 10^{19}\,\mathrm{cm}^{-3}$GaAs cap layer. After the epitaxial growth, the conventional photolithography, vacuum evaporation and wet selective etching processes were used to fabricate the device. Here, the GaAs and InGaP layer were selectively etched by the solution of $NH_4OH:H_2O_2:H_2O = 6:3:100$ and $H_3PO_4:HCl = 1:100$, respectively. AuGeNi and AuZn metals were employed as *n*-type and *p*-type ohmic contacts, respectively. The schematic cross section of the experimental device is shown in Fig. 1. The emitter area is $50\times100\,\mu\mathrm{m}^2$.

[¶] E-mail: jhtsai@nknucc.nknu.edu.tw

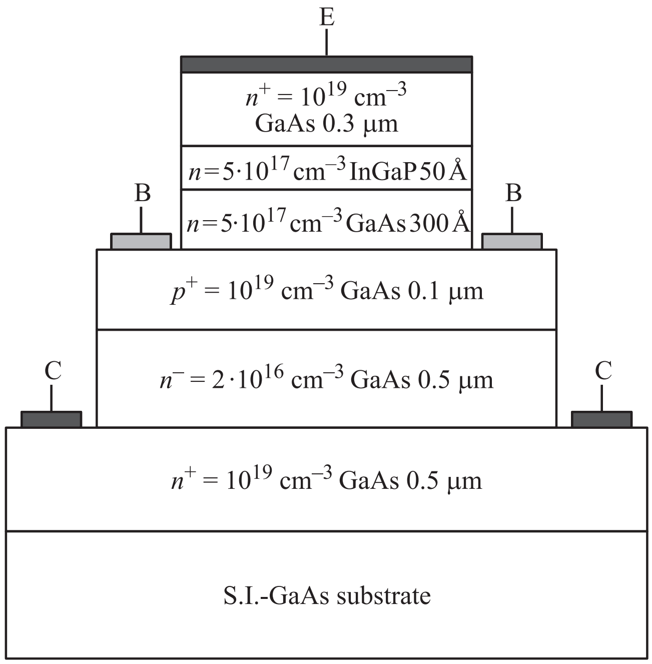

Fig. 1. Schematic cross section of the experimental InGaP/GaAs tunneling heterostructure-emitter bipolar transistors (T-HEBT).

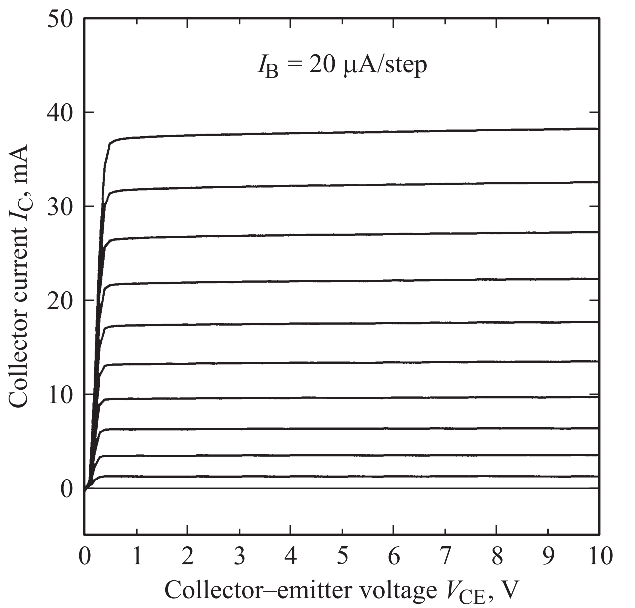

Fig. 2. Typical common-emitter current-voltage characteristics of the studied device at room temperature.

3. Results and discussion

The typical common-emitter current-voltage characteristics of the studied T-HEBT at room temperature, measured by an HP4155C semiconductor parameter analyzer, are shown in Fig. 2. The control base current I_B is $20\,\mu$A/step. A maximum collector current is about 37 mA and a relatively low C-E offset voltage of only 40 mV at $I_B = 20\,\mu$A is observed. Fig. 3 shows the Gummel plots of the devices at $V_{BC} = 0$. The current gain reaches unity at $V_{BE} = 0.96$ V and the device exhibits a maximum current gain of 285. These characteristics are excellent than the previous InGaP/GaAs HEBT [8]. In addition, when compared with the previous InGaP/GaAs TEBT with a maximum current gain of 236 and a low offset voltage of 40 mV, the studied T-HEBT shows a larger current gain and maintains the relatively low offset voltage [10]. The ideality factor n_c for collector current is nearly equal to unity at low current level for the studied T-HEBT. This denotes that the diffusion and tunneling mechanisms dominate the electron transportation across the B-E junction. Another, the ideality factor n_b of 1.69 for base curren at low current level is observed, which means that the employments of a thin n-InGaP tunneling confinement layer and a small

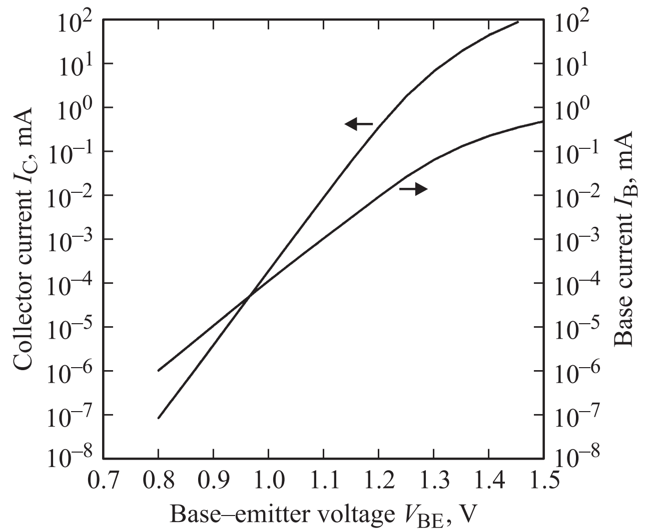

Fig. 3. Measured Gummel plots at $V_{BC} = 0$.

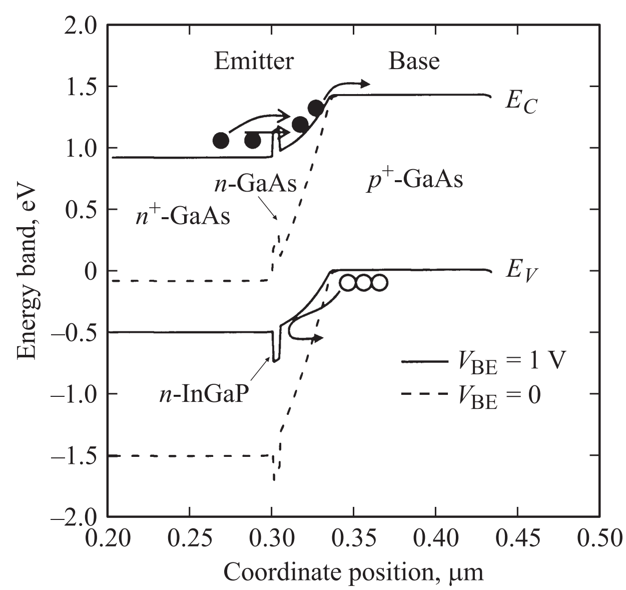

Fig. 4. Corresponding energy-band diagrams near emitter junction at equilibrium (dashed line) and $V_{BE} = 1.0$ V (solid line).

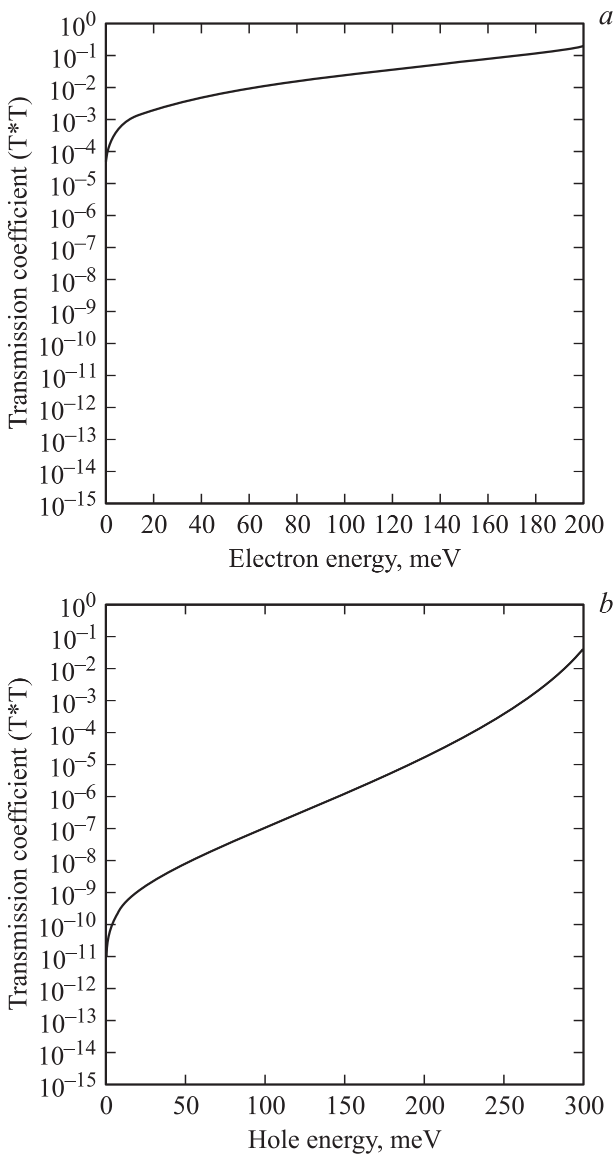

Fig. 5. Transmission coefficients under ideal flat-band condition for (*a*) electron energy and (*b*) hole energy.

energy-gap *n*-GaAs emitter layer do not promote the base recombination current. Also, the device shows a large current-gain cutoff frequency f_t of 26.4 GHz under the bias condition of $V_{CE} = 3$ V and $I_C = 30$ mA. The transporting time τ_E across the emitter regime is reduced by the tunneling behavior, even though the addition of an *n*-type GaAs layer at B-E junction.

In order to investigate the device mechanism, the carrier transporting behaviors are explained as follows. By the two-dimensional semiconductor simulation package SILVACO, the corresponding energy-band diagrams near B-E junction at equilibrium and under forward bias are illustrated in Fig. 4. Due to the employment of a thin as well as small energy-gap *n*-GaAs emitter layer between the tunneling confinement and base layers, the low C-E offset voltage is achieved because of the elimination of potential spike at B-E junction even under forward bias of +1.0 V.

Furthermore, the transmission coefficients versus energy under ideal flat-band condition for electrons and holes are calculated in Figs 5, *a* and 5, *b*, respectively. The transmission coefficient of electrons reaches 2×10^{-1} at electron energy of 200 meV, while it is only 3×10^{-2} at hole energy of 300 meV. Therefore, part of the electrons injecting from n^+-GaAs cap layer could travel through the thin InGaP confinement layer by tunneling behavior and easily transport over the small energy-gap *n*-GaAs emitter toward the base region for decreasing the neutral-emitter recombination current, as seen in Fig. 4. The large valence band discontinuity ($\Delta E_V \approx 0.3$ eV) at InGaP/GaAs heterojunction provides good confinement effect for holes to promote the emitter injection efficiency. Also, though the InGaP tunneling confinement layer is thin enough, the hole tunneling current can be substantially neglected due to the relatively small transmission coefficient for holes.

4. Conclusion

In summary, a new high-performance InGaP/GaAs T-HEBT has been experimentally investigated. The studied device shows low collector-emitter offset voltage, high current gain, and excellent high-frequency characteristic by the addition of a thin *n*-GaAs emitter layer at B-E junction and the employment of a thin InGaP tunneling confinement layer in emitter region, simultaneously. Consequently, the T-HEBT could provide good potential for signal amplifier and circuit applications.

This work is supported by the National Science Council of the Republic of Chine under Contract No. NSC 99-2221-E-017-018.

References

[1] K. Runge, R.L. Pierson, P.J. Zampardi, P.B. Thomas, J. Yu, K.C. Wang. Electron. Lett., **33**, 765 (1997).
[2] Y.S. Noh, C.S. Park. Electron. Lett., **37**, 1523 (2001).
[3] J.H. Tsai. Jpn. J. Appl. Phys., **40**, 5865 (2001).
[4] Y.S. Lin, J.J. Jiang. IEEE Trans. Electron. Dev., **56**, 2945 (2009).
[5] J.J. Liou, C.S. Ho, L.L. Liou, C.I. Huang. Sol. St. Electron., **36**, 819 (1993).
[6] H.R. Chen, C.Y. Chang, C.P. Lee, C.H. Huang, J.S. Tsang, K.L. Tsai. IEEE Electron. Dev. Lett., **15**, 336 (1994).
[7] J.H. Tsai, S.Y. Cheng, W.S. Lour, W.C. Liu, H.H. Lin. Semicond. Sci. Technol., **12**, 1135 (1997).
[8] S.I. Fu, S.Y. Cheng, P.H. Lai, Y.Y. Tsai, C.W. Hugn, W.C. Liu. Jpn. J. Appl. Phys., **46**, L74 (2007).
[9] A.F.J. Levi, R.N. Nottenburg, Y.K. Chen, J.E. Cunningham. Appl. Phys. Lett., **54**, 2250 (1989).
[10] S.S. Lu, C.C. Wu. IEEE Electron. Dev. Lett., **13**, 458 (1992).

Редактор Т.А. Полянская