High-Performance In_{0.49}Ga_{0.51}P/GaAs Tunneling Emitter Bipolar Transistors

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(Received September 7, 1992; accepted for publication November 21, 1992)

Two techniques were used in the fabrication of InGaP/GaAs TEBTs and experimental results by the two fabrication techniques were compared. It is found that the TEBT fabricated by base diffused ohmic contact technique with base surface passivated by an InGaP layer shows a differential current gain as high as 306. To our knowledge, the current gain obtained was the highest value reported to date in InGaP/GaAs hetero-structure bipolar transistors with similar base doping ($1 \times 10^{19} \text{ cm}^{-3}$) and thickness (100 nm).

KEYWORDS: InGaP/GaAs, tunneling emitter bipolar transistor, gas source molecular beam epitaxy, base diffused ohmic contact, surface recombination current, emitter edge-thinning design

1. Introduction

Recently the InGaP/GaAs material system has attracted much attention because of its larger valence-band discontinuity and smaller conduction-band discontinuity.^{1–4} Combining this material system with the concept of tunneling emitter bipolar transistor (TEBT),⁵ we can improve the emitter injection efficiency dramatically.^{2,4} Only a 100-Å thick InGaP layer is necessary to suppress the hole injection.⁶ Moreover, the InGaP layer not only can serve as an etch-stop layer during device processing but also provides the formation of emitter edge-thinning layer (or guard ring structure) to passivate the extrinsic base surface.³ It has been shown⁴ that no junction grading is necessary for InGaP/GaAs TEBTs to achieve small offset voltage and high current gain. The advantages of easy growth (no grading) and easy processing (selective etch) make the InGaP/GaAs TEBTs suitable for digital, analog, and power integrated-circuit applications.

In this paper, the performance of self-aligned In_{0.49}Ga_{0.51}P/GaAs TEBT grown by gas source molecular beam epitaxy (GSMBE) and fabricated both by base diffused ohmic contact and conventional techniques is presented. It is found the devices fabricated by base diffused ohmic contact technique show better performance than those by conventional technique. A very high current gain of 306 and a very small offset voltage of 40 mV were achieved without the need of compositional grading of the e-b junction. The current gain was comparable to that of conventional carbon doped base, graded e-b junction AlGaAs/GaAs HBT⁷ with similar base doping and thickness.

2. Experiments

The In_{0.49}Ga_{0.51}P/GaAs TEBT structure was grown by gas source molecular beam epitaxy (GSMBE) on a semi-insulating (001)-oriented GaAs substrate. The material parameters of the TEBT structure used in our study and the cross-section of a fabricated device are shown in Fig. 1. The barrier layer thickness is 10 nm and the p⁺ base layer is 100 nm. The doping concentrations of the emitter, base, collector, and subcollector were 4×10^{17} , 1×10^{19} , 5×10^{16} , and $2 \times 10^{18} \text{ cm}^{-3}$, respectively. The cap layer consisted of two layers (150 and 100 nm) with doping concentrations of 1×10^{18} and

$5 \times 10^{18} \text{ cm}^{-3}$, respectively. Traditional e-b self-aligned processing was used with standard photolithographic and wet chemical etching techniques. The collector cap layer was exposed by a wet chemical etching followed by the deposition of the collector and emitter AuGeNi ohmic contact metal and lift-off. Then, the photoresist was patterned to expose the base layer by one or two-step etching; the same photoresist was used for AuBe evaporation to form the base ohmic contact. The InGaP layer was exposed by 1H₂SO₄:1H₂O₂:24H₂O, which selectively etches GaAs. After the selective etch, two different structures were fabricated: One (type 1) was that the AuBe was evaporated on the InGaP layer and annealed at 350°C for 10 s to insure a good ohmic contact; in this case, the surface recombination current was reduced because the extrinsic base surface was protected by the undoped InGaP layer which has a lower intrinsic surface recombination velocity compared with GaAs; the other structure (type 2) was that the InGaP was removed selectively by HCl to expose the GaAs base for the AuBe evaporation; in this case, there was no InGaP layer to passivate the GaAs base surface. The spacing between the emitter edge and the base contact was $\approx 0.3 \mu\text{m}$ according to the self-aligned technique used. Finally, isolation etching

Fig. 1. The cross-section of the fabricated TEBT. Type 1: the AuBe diffuses through the shaded area. Type 2: the shaded area is etched away and the AuBe is evaporated directly on top of the p⁺ GaAs base.

was done to isolate one device from the other. Except for the InGaP layer of type 1 TEBT, no other surface passivation was used. Rectangular emitters with different areas of 4964, 2256, and 1200 μm^2 were studied.

3. Results and Discussions

Figure 2 shows the transferred current I_C and base current I_B versus b-e bias V_{BE} of type 2 TEBT (emitter area 4964 μm^2) with b-c short-circuited. Note that the ideality factor of the I_C is 1.0 for $V_{BE} < 1.1$ V. This suggests that the potential spike ΔE of the e-b junction is negligibly small such that the diffusion process instead of the thermionic emission process is the rate-limiting step for the emitter injection current. This is confirmed by the small ΔE_C of InGaP/GaAs system. Moreover, the device shows significant current gain for $V_{BE} > 0.9$ V (or $I_C > 100$ nA). However, for a GaAs homojunction diode, the surface recombination current level is much larger than the injection current level.⁸⁾ This means that the thin 10-nm InGaP layer somehow suppresses the surface recombination current and thus a good current gain is obtained. The current gain versus emitter perimeter-to-area (L/S) ratio at constant collector current density (J_C) is shown in Fig. 3. The data of AlGaAs/GaAs HBT with uniform base and graded base have also been taken from refs. 9 and 10 for comparison. As can be seen, the current gain of type 2 TEBT shows a small dependence on the L/S ratio. Note that there was no surface passivation in type 2 TEBT. The schematic band diagram of the TEBT under active bias is shown in Fig. 4. The surface recombination can occur either at the emitter side or the base side. For the emitter side, the holes must either tunnel through or emit thermionically over the valence-band potential spike. On the other hand, for the base side, the electrons have to either tunnel through or emit thermionically over the conduction-band potential spike. Because the $\Delta E_C \ll \Delta E_V$, we neglect the surface recombination process at the emitter side. According to Tiwari's simulation,¹¹⁾ the electrons are injected

Fig. 2. The transferred current I_C and base current I_B versus b-e bias V_{BE} of type 2 TEBT (area 4964 μm^2) with b-c short-circuited.

Fig. 3. The current gain versus emitter perimeter-to-area ratio (L/S) at constant collector current density J_C for type 2 InGaP/GaAs TEBT, AlGaAs/GaAs uniform and graded base HBT.

Fig. 4. The schematic band diagram of the TEBT under active bias.

through a surface channel near the e-b junction to reach the base surface. As shown in Fig. 4, the potential barrier at the e-b junction under forward bias inhibits the electron injection to the base surface, suppressing the surface recombination current. At high bias condition (say $V_{BE} > 1.1$ V), the ΔE_C may probably protrude the conduction band minimum of the quasi-neutral base. In this case, part of the emitter injection current is due to tunneling. The tunneling injection can reduce the angular spreading of a thermal distribution and the nonradiative recombination cross section,¹²⁾ which help reduce the lateral diffusion to reach the base surface. In this case, the surface recombination can also be suppressed.

To further reduce the surface recombination cur-

rent, type 1 TEBT was also fabricated, in which the base surface was passivated by the InGaP material. The differential current gains (h_{fe} 's) versus collector current density (J_C) of type 1 and 2 are shown in Figs. 5(a) and 5(b), respectively. Because the anneal condition of the base contact in type 1 device was not optimized, the yield was low and the curves shown in Fig. 5(a) were abstracted from the highest current gain devices. The reliability and reproducibility of the curve with emitter area $2256 \mu\text{m}^2$ may be questioned from the characteristics in Fig. 5(a), which is due to the poorer annealing condition and equipment. However, since we only concerned with the highest current gain that can be achieved by type 1 and type 2 devices, this issue is not important for later discussion. Note that the highest current gains of type 1 devices are all higher

Fig. 5. The differential current gains (h_{fe} 's) versus collector current density (J_C) of types (a) 1 and (b) 2 TEBTs.

than that of type 2 devices with the same emitter area. At low J_C , h_{fe} vs J_C curves of type 1 and 2 TEBTs show similar behavior. Nevertheless, the improvement of h_{fe} of type 1 compared with type 2 becomes significant at high J_C for the three different emitter areas investigated. It can be seen that the highest h_{fe} (306) of type 1 is higher than that (214) of type 2 with emitter area of $1200 \mu\text{m}^2$. The current gain (306) obtained, to our knowledge, was the best value reported with similar base doping and thickness in InGaP/GaAs TEBT or HBT. The current gain achieved was comparable to those of carbon doped base, graded e-b junction AlGaAs/GaAs HBTs.⁷⁾ The common-emitter current-voltage (I - V) characteristics of type 1 TEBT (emitter area $1200 \mu\text{m}^2$) is shown in Fig. 6. As can be seen, a very high gain and a small offset voltage (65 mV) were achieved. The type 2 TEBT showed similar I - V characteristics but the offset voltage was only 40 mV. The small offset voltage is attributed to the small ΔE_C in InGaP/GaAs heterojunction. Note that as shown in Fig. 6, the device has a wide saturation region, which is due to the large series resistance in the device.

Comparing the h_{fe} 's of type 1 and 2 TEBTs in Figs. 5(a) and 5(b), at low J_C , the h_{fe} 's of type 1 were slightly lower than those of type 2. This may be due to the anneal induced recombination center beneath the AuBe base contact and thus the current gains were reduced. However, the h_{fe} 's of type 1 were actually higher than those of type 2, which was attributed to the suppression of surface recombination current at the extrinsic base surface. Therefore, the anneal condition of AuBe on InGaP needs to be further optimized. We can also use the rapid diffusion of zinc from films of tungsten doped with zinc to obtain better diffused ohmic contact¹³⁾ on InGaP layer, which is now being investigated. We didn't measure and compare the base contact resistivities of the devices, because the base contact resistance did not affect the dc current gain of type 1 and type 2 devices.

Fig. 6. The common-emitter current-voltage characteristics of type 1 TEBT (emitter area $1200 \mu\text{m}^2$).

4. Conclusion

In summary, we have fabricated self-aligned $\text{In}_{0.49}\text{Ga}_{0.51}\text{P}/\text{GaAs}$ TEBT's with two different structures. A high current gain of 306 and a small offset voltage of 40 mV were obtained without the use of junction grading. The high-performance InGaP/GaAs TEBT's can be obtained with easy growth (no grading) and easy fabrication (wet selective etch).

Acknowledgements

The authors are grateful to Dr. F. Williamson and Prof. M. I. Nathan at the University of Minnesota, U.S.A., and to Profs. S. C. Lee and H. H. Lin, at National Taiwan University, R.O.C., for their various help throughout this work. This work was supported by the National Science Council of the Republic of China under contract No. NSC 82-0404-E-002-283.

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