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Investigation of InGaP/GaAs MultipleNegative-Differential-Resistance (NDR) Device Prepared by MOCVD

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abstract

An interesting multiple S-shaped negative-differential-resistance (NDR) phenomenon is observed for an InGaP/GaAs heterostructure-emitter bipolar transistor (HEBT) under the inverted operation mode. This behavior is resulted from a sequential avalanche multiplication and two-stage barrier lowering effect. Under normal operation mode, a typical common-emitter current gain of 60 is obtained at collector current density of 400A/cm^2 for the studied HEBT without emitter-edge thinning structure.

Introduction

The HEBT can overcome the drawbacks of the conventional heterojunction bipolar transistor (HBT) such as the large collector-emitter offset voltage and the critical alignment of the compositional junction to the doping junction etc [1, 2]. Recently, there has been growing interest in the InGaP/GaAs material system for high-speed device fabrication due to its low DX center density, low surface recombination velocity, high valence-band-discontinuity (ΔEv) to conduction-band-discontinuity (ΔEc) ratio and high etching selectivity between InGaP and GaAs layers [3].

An interesting phenomenon of InGaP/GaAs HEBT's is the controlled negative-differential-resistance (NDR) properties. The interesting multiple switching properties is believed to be caused by a sequential avalanche multiplication and two-stage barrier lowering effect. This behavior may yield multiple stable states for multiple-valued logic applications [4].

Expperiments

The device structure studied was grown by metal organic chemical vapor deposition (MOCVD) on a (100) oriented n$^+$-GaAs substrate. The epitaxial layers consist of a 0.3-μm-thick n$^+$-GaAs buffer, a 0.5-μm-thick n$^-$-GaAs (n=2x10^{16}cm^{-3}) collector, a 0.1-μm-thick p$^+$-GaAs (p$^+$=1x10^{19}cm^{-3}) base, a 700-Å-thick n-GaAs (n=5x10^{17}cm^{-3}) emitter, a 0.1-μm-thick n-In$_{0.49}$Ga$_{0.51}$P (n=5x10^{17}cm^{-3}) confinement layer, and a 0.2-μm-thick n$^+$-GaAs cap layer. After the epitaxial growth, the HEBT device was fabricated with a mesa structure using conventional photolithographic and chemical wet selective etching techniques. The GaAs and InGaP layers were etched by the solution of 3 NH_4OH: 1 H_2O_2: 50 H_2O and 1 HCl: 1 H_2O, respectively. AuGe and

AuZn metals were used for n- and p-type layer ohmic contacts by vacuum evaporation, respectively.

Results and discussions

The experimental I-V characteristics of the studied device under inverted operation mode are shown in Fig.1. Significantly, the multiple S-shaped NDR phenomena are observed. The two-stage switching properties, as shown in Fig.2(a), provides the switching parameters as switching voltage V_{S1}= 7.51 V, V_{S2}= 6.63 V, holding voltage V_{H1}= 6.77 V, V_{H2}= 5.87 V, holding current I_{H1}= 4.37mA, I_{H2}= 8.13 mA, and control voltage efficiency $\eta_1(V_{S1}/ V_{H1})$= 1.109, $\eta_1(V_{S1}/ V_{H2})$ = 1.279, respectively. The corresponding energy band diagrams are illustrated in Fig.2. When the applied emitter-to-collector voltage V_{EC} is not so large (V_{EC}<7 V) , i. e., at the initial off-state, the conduction current is negligible as shown in Fig.1(a). If V_{EC} increases sufficiently, at some voltage V_{S1}, an avalanche multiplication will be observed near the reverse biased emitter-base (E-B) junction, as revealed in Fig.2(a). Holes, created by the avalanche multiplication, transport toward base region and charge the depletion region of base-collector (B-C) junction. This suppresses the potential barrier height for electrons injection. Therefore, more electrons are easier to transport over base toward emitter region. Furthermore, due to the large $\Delta Ev/\Delta Ec$ ratio, the magnitude of potential spike ΔEc at InGaP/GaAs heterointerface is much smaller than that of the potential height at GaAs E-B junction. Thus most of electrons injected from collector through base region can easily travel over ΔEc and reach the emitter electrode as shown in Fig.2(b). This barrier lowering effect and rapid increase of conduction current give the intermediate on-state of carrier transport characteristics, as shown in Fig.1(a) and 2(b). As the barrier height of base region is lowered, the confinement effect of ΔEc becomes relatively prominent. Hence, more electrons are confined at InGaP/GaAs interface when the conduction current is increased. At some current level, the sufficiently accumulated electrons will cause the second barrier lowering effect, as illustrated in Fig.2(c). This introduces the final on-state of carrier transport and rapid increase of conduction current as indicated by the dashed lines in Fig.2(c). This barrier lowering effect also exhibits the second S-shaped NDR in the I-V characteristics as shown in Fig.1(a). Consequently, the interesting multiple NDR phenomenon, i.e., the carrier transport from the initial off-state through intermediate on-state to the final on-state, is generated by the sequential avalanche multiplication and two-stage barrier lowering effect. The significant two-stage barrier lowering is caused by the successive accumulation of holes at base region and electrons at InGaP/GaAs heterointerface, respectively. The three-terminal-controlled I-V characteristics is shown in Fig.1(b). The controlled base current I_B is applied by 2 mA/step. Apparently, the multiple family NDR curves are observed. When the base current I_B is applied, under the inverted operation mode, the B-C junction is operated at more forward biased condition. This gives the magnitude of the V_{BC} voltage to be increased. Because the breakdown field of the reverse biased E-B junction is fixed about constantly, the required V_{EB} voltage to produce the avalanche multiplication is also maintained at a constant value. Therefore, the total V_{EC} voltage (V_{EB}+ V_{BC}), i. e., the V_{S1} value, needed to cause the avalanche multiplication is increased with increasing the base current I_B. So, the similar NDR curves shift toward right-hand side as the base current I_B is increased.

The studied device also exhibits the bipolar transistor action when the normal operation mode is used. The typical common-emitter current gain of 60 is obtained at collector current density of 400 A/cm^2

without using the emitter-edge thinning technique. It is believed that the transistor performances may be improved significantly when the appropriate adjustments of device structure, such as the smaller n-GaAs emitter layer thickness and emitter edge thinning etc, are employed.

Conclusion

In summary, we have demonstrated the interesting multiple NDR phenomenon of InGaP/GaAs HEBT. This behavior is caused by a sequential avalanche multiplication and two-stage potential barrier lowering effect. The controlled switching and transistor performances provide a promise of the studied device to be a good candidate for circuit applications.

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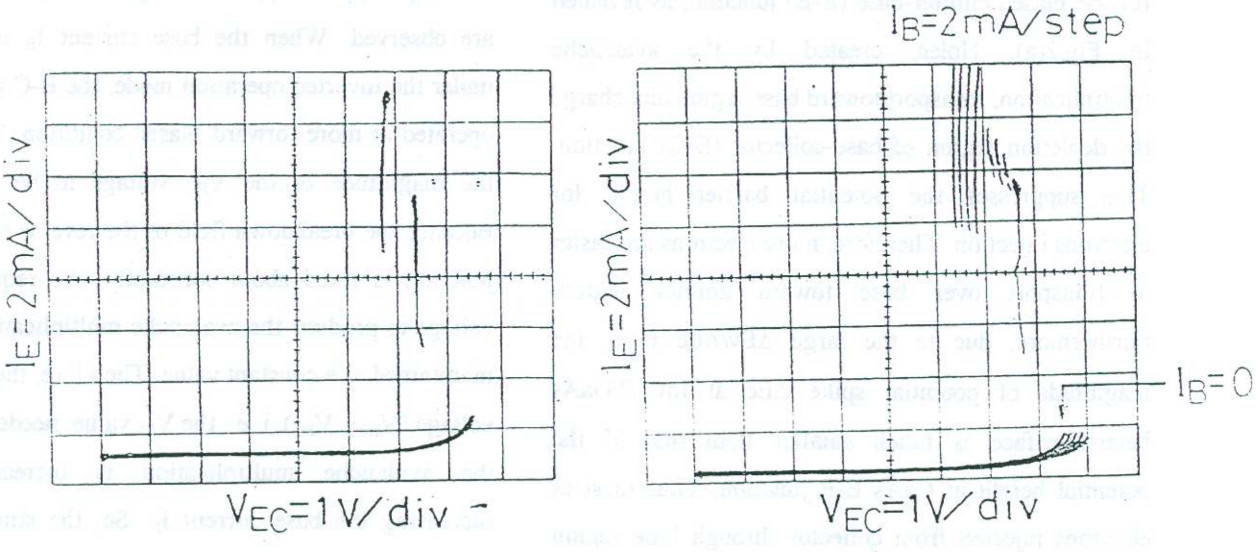

Fig.1 Current-voltage characteristics of the studied InGaP/GaAs HEBT (a) between emitter and collector, and (b) with the applied base current I_B (2 mA/step).

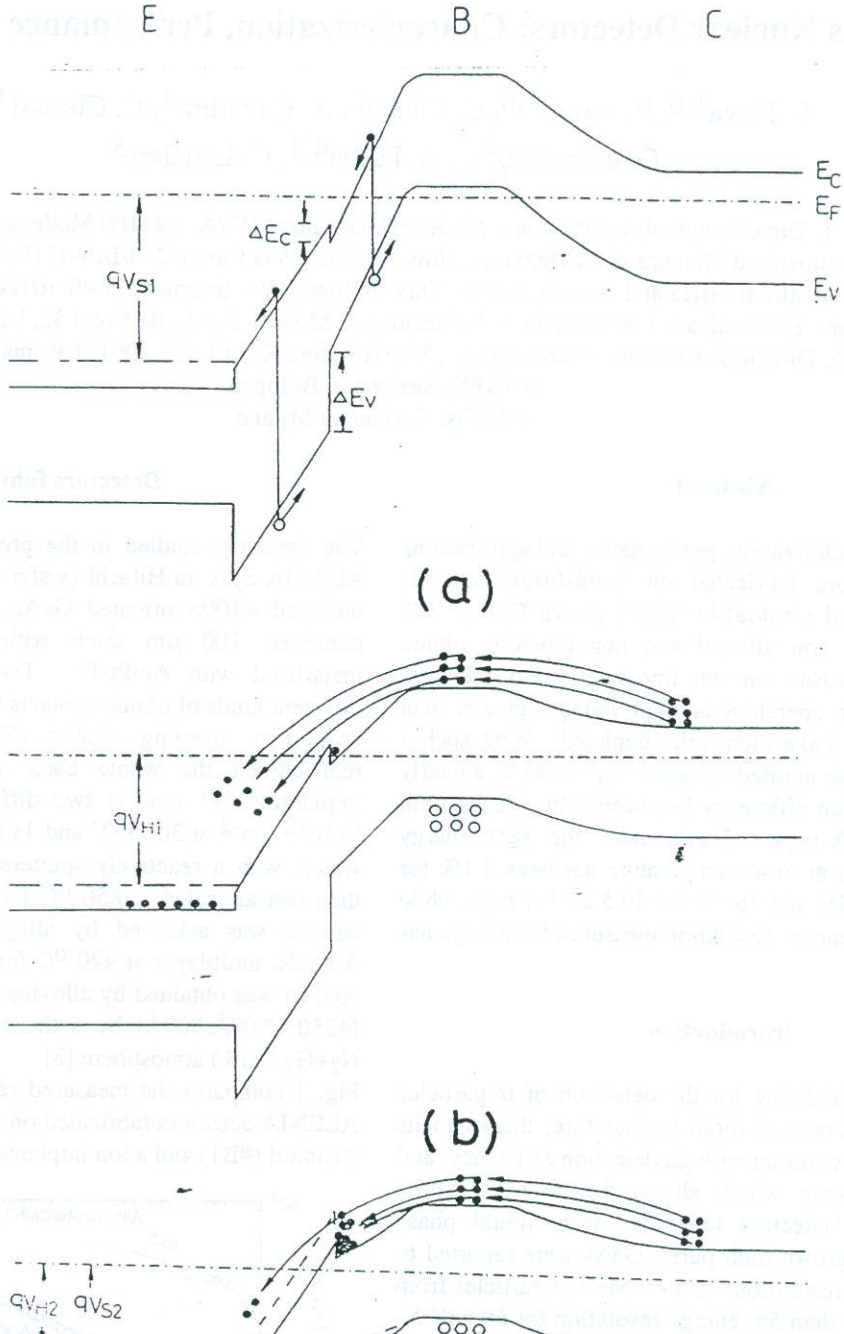

Fig.2 Schematic energy band diagrams of the studied InGaP/GaAs HEBT under the inverted operation mode at (a) onset of the first switching process, (b) intermediate on-state, and (c) onset of the second switching process.