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Multiple negative-differential-resistance switches based on an InGaP/GaAs/InGaAs step-compositional-emitter bipolar transistor for multiple-valued logic application

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Abstract

A novel functional InGaP/GaAs/InGaAs step-compositional-emitter heterojunction bipolar transistor (HBT) is fabricated and demonstrated. Due to the avalanche multiplication and discontinuous confinement effects for electrons in the InGaAs quantum well and at InGaP/GaAs heterojunction, respectively, an interesting triple-route S-shaped negative-differential-resistance switch is observed under inverted operation mode at room temperature. In addition, the excellent transistor performances including a high current gain of 220 and a low offset voltage of 60 mV are achieved under normal operation mode. Consequently, the device could be used for signal amplifier under normal operation mode and multiple-valued logic circuit application under inverted operation mode.
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1. Introduction

Heterojunction bipolar transistors (HBTs) have shown a very high speed and a high current gain because of its widegap emitter that allows the base to more heavily doped than the emitter, maintaining high emitter injection efficiency [1,2]. However, the conventional HBTs are usually only used as signal amplifiers, and they suffer from large collector–emitter (C–E) offset voltage (ΔV_{CE}) increasing the undesirable power consumption in digital circuit applications [3]. Some attracted devices, such as double heterojunction bipolar transistors (DHBTs) [4], graded-emitter HBTs [5] and heterostructure-emitter bipolar transistors (HEBTs) [6,7], have been proposed and fabricated to overcome the above disadvantage and still maintain large current gain.

Recently, a variety of semiconductor devices exhibiting either S-shaped or N-shaped negative-differential-resistance (NDR) properties have been widely employed for switches, memory cell, and logic circuit applications [6–11]. As to the S-shaped switching devices, attributed to the avalanche multiplication in reverse-biased region and the confinement effect for carriers, the potential barrier is lowered and then the NDR phenomenon is substantially observed [6–8].

In particular, for the requirement of additional circuit applications functional HBTs have been achieved to reduce greatly the number of elements as well as process steps [6,7,9–11]. Over the past years, the interesting NDR phenomena of the varied functional AlGaAs/GaAs and InGaP/GaAs heterostructure-emitter bipolar

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transistors (HEBTs) under inverted operation mode have been presented [6,7]. For the AlGaAs/GaAs HEBT, only a single S-shaped NDR is obtained because the hole and electron accumulation may occur simultaneously [6]. As to the InGaP/GaAs HEBT, the interesting two-route NDR behaviors are observed due to the distinct two-stage barrier lowering mechanisms. The avalanche multiplication and confinement effects for electrons at InGaP/GaAs heterojunction mainly cause the multiple NDR [7].

In this paper, a new functional InGaP/GaAs/InGaAs HBT with step-compositional-emitter structures is proposed and successfully fabricated. It can be operated under bi-directional operation modes to increase the device function. The device performances including a high current gain and a low offset voltage under forward operation mode as well as an interesting triple-state S-shaped NDR under inverted operation mode are demonstrated.

2. Experiments

The studied device was grown on an (1 0 0) oriented semi-insulating GaAs substrate by metal-organic chemical-vapor deposition (MOCVD). The device structure includes a 0.5 μm $n^+ = 1\times10^{19}\ cm^{-3}$ GaAs subcollector layer, a 0.5 μm $n^- = 5\times10^{16}\ cm^{-3}$ GaAs collector layer, a 0.1 μm $p^+ = 1\times10^{19}\ cm^{-3}$ GaAs base layer, a $n = 5\times10^{17}\ cm^{-3}$ step-compositional emitter, and a 0.3 μm $n^+ = 1\times10^{19}\ cm^{-3}$ GaAs cap layer. The step-compositional emitter contains a 100 Å $In_{0.2}Ga_{0.8}As$ quantum well (QW), a 300 Å GaAs layer, and a 0.1 μm $In_{0.49}Ga_{0.51}P$ layer, respectively. After the epitaxial growth, the device was processed by conventional photolithographic and vacuum evaporation techniques. Ohmic contacts were prepared by alloying evaporated AuGaNi and AuZn metals for n-type emitter, collector and p-type base, respectively. Fig. 1 shows the cross section of the studied InGaP/GaAs/InGaAs step-compositional-emitter HBT. The emitter area is $5\times10^{-5}\ cm^2$.

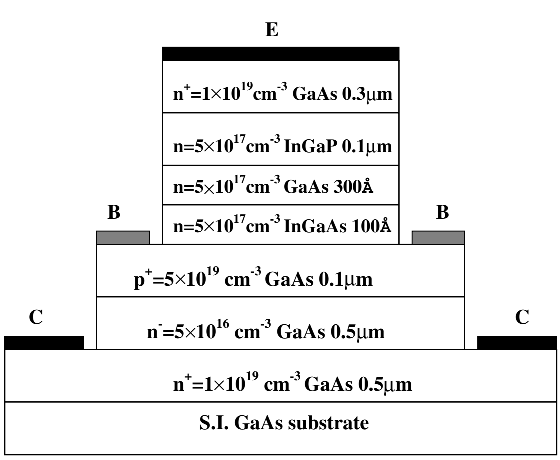

Fig. 1. Schematic cross section of the studied InGaP/GaAs/InGaAs step-compositional-emitter HBT.

3. Experiment results and discussion

As the base terminal is open, the experimental two-terminal current–voltage (*I–V*) characteristic under inverted operation mode at room temperature, measured by a Tektronix 370 curve tracer, is shown in Fig. 2(a). Clearly, an interesting triple-route S-shaped NDR phenomenon is observed. The corresponding switching parameters such as switching voltages $V_{S1} = 6.7$ V, $V_{S2} = 5.05$ V, and $V_{S3} = 4.1$ V, holding voltages $V_{H1} = 5.75$ V, $V_{H2} = 4.4$ V, and $V_{H3} = 3.2$ V, holding currents $I_{H1} = 2$ mA, $I_{H2} = 6.4$ mA, and $I_{H3} = 9.2$ mA, and the control voltage efficiencies $\mu_1(V_{S1}/V_{H1}) = 1.17$, $\mu_2(V_{S1}/V_{H2}) = 1.52$, and $\mu_3(V_{S1}/V_{H3}) = 2.1$ are found. Fig. 2(b) depicts the proposed circuit application of the studied

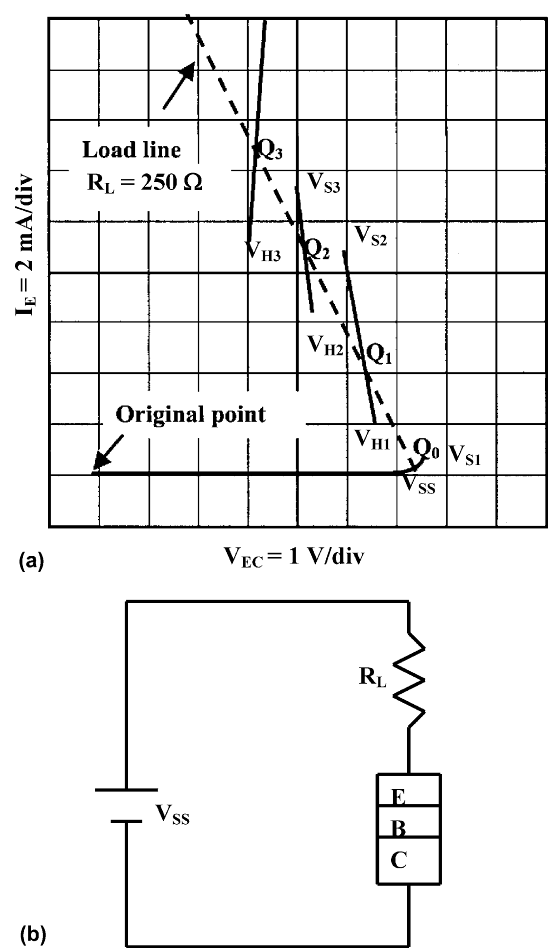

Fig. 2. (a) Two-terminal current–voltage characteristic of the studied InGaP/GaAs/InGaAs step-compositional-emitter HBT under inverted operation mode at room temperature. The dashed line represents the load line as $V_{SS} = 6.5$ V, $R_L = 250\ \Omega$, are applied. Note that the original point represents $V_{EC} = 0$ V, $I_E = 0$, and $V_{SS} = 0$ V, simultaneously. (b) The proposed circuit application of the studied device.

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