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Application of an AlGaAs/GaAs/InGaAs heterostructure emitter for a resonant-tunneling transistor

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An AlGaAs/GaAs/InGaAs resonant-tunneling heterostructure-emitter bipolar transistor with negative-differential-resistance (NDR) behavior has been fabricated and demonstrated. Typical device performances with current gain of 140 incorporating an N-shaped NDR with a peak-to-valley current ratio of 5.3 are obtained at room temperature. The NDR behavior is believed to mainly result from a double-barrier-like resonant-tunneling effect. In other words, the on and off electron resonant tunneling from a depleted GaAs emitter through an InGaAs quantum well and ultrathin base toward a collector layer yield the interesting NDR behavior. Consequently, the proposed device provides a good potential for applications in amplifiers, low-power consumption, and logic currents. © *1999 American Institute of Physics.* [S0003-6951(99)04943-8]

Over the past years, heterojunction bipolar transistors (HBTs) have attracted remarkable attention for microwave and digital circuit applications due to their high-speed and high-current capabilities.[1–3] However, one of inherent problems associated with HBTs is the large collector–emitter (CE) offset voltage ΔV_{CE} resulting from the difference in turn-on voltages between the base–collector (BC) homojunction and base–emitter (BE) heterojunction. This offset voltage generally causes the undesirable power consumption.[4] In order to overcome this problem, heterostructure-emitter bipolar transistors (HEBTs) have been proposed and successfully fabricated by Luo and co-workers.[5–7] In the HEBTs, both the ''effective'' BC and BE junctions can be considered as homojunctions. Thus, the nearly equal turn-on voltages between these two junctions and then an extremely small offset voltage may be obtained. Recently, HBTs with negative-differential-resistance (NDR) phenomena, that could be used to reduce circuit complexity, have been of considerable interest for a variety of potential applications.[8–13] Capasso and Kiehl proposed the N-shaped NDR behavior in a resonant-tunneling bipolar transistor (RTBT).[8] Also, Sen *et al.* reported a NDR resulting from a tunneling structure between the emitter and base region of a HBT at room temperature.[9] Furthermore, functional HEBTs with high-current gain, low-offset voltage, and N-shaped NDR phenomenon were studied by Liu and Lour.[11] Nevertheless, in view of HEBTs, the N-shaped NDR was found only in the superlattice–emitter structure.

In this letter, a resonant-tunneling heterostructure-emitter bipolar transistor (RTHEBT) with an AlGaAs/GaAs/InGaAs heterostructure emitter and an ultrathin base layer is proposed and fabricated. The transistor performances and an interesting N-shaped NDR phenomenon resulting from electrons tunneling through the base layer are demonstrated. Unlike other NDR-HBTs with double barriers (DBs) or multiple quantum wells (QWs) located at the emitter or base region, the studied RTHEBT has one barrier at the emitter and another at the base region. The device design also exhibits high-current gain and clear NDR performances.

The studied RTHEBT was grown on a (100)-oriented n^+-GaAs substrate by metal–organic chemical-vapor deposition (MOCVD). The used n- and p-type dopants were Si and C, respectively. The layer structure consisted of a 0.2 μm $n^+=3\times10^{18}$ cm^{-3} GaAs buffer layer, a 0.5 μm $n^-=5\times10^{16}$ cm^{-3} GaAs collector layer, a 100 Å $p^+=1\times10^{19}$ cm^{-3} GaAs base layer, a triple-layer heterostructure emitter, and a 0.3 μm $n^+=3\times10^{18}$ cm^{-3} GaAs cap layer, respectively. The triple-layer heterostructure emitter included a 100 Å $n^-=5\times10^{16}$ cm^{-3} $In_{0.2}Ga_{0.8}As$ QW, a 500 Å $n=5\times10^{17}$ cm^{-3} GaAs layer, and a 0.1 μm $n=5\times10^{17}$ cm^{-3} $Al_{0.45}Ga_{0.55}As$ confinement layer. After the epitaxial growth, traditional wet-etching and photolithographic processes were used to define the emitter and base regions. In particular, due to the ultrathin base layer, the patterned V grooves were implemented between p^+-GaAs base and n^--GaAs collector layers to support the base contact via the V grooves. Ohmic contacts were performed by alloying AuGe metal for the n-type emitter and collector. AuZn was deposited over the V grooves to facilitate the p-type base contact. The emitter and collector areas were 4.9×10^{-5} and 5×10^{-4} cm^{-2}, respectively.

The measured common-emitter current–voltage (I–V) characteristic of the studied RTHEBT at room temperature is shown in Fig. 1. Three-terminal-controlled transistor performances with the N-shaped NDR behavior are obtained at $I_B \geqslant 1.2$ mA. Figure 2 depicts the relationship between the collector and base current. Clearly, the NDR with a peak-to-valley current ratio (PVCR) value up to 5.3 is observed. Due to the used thin base layer, the neutral base recombination current is reduced and then a large current gain is expected. The measured maximum current gains are 140 and 125 before and after the occurrence of NDR, respectively. It is also noticeable that the collector–emitter offset voltage is only of 100 mV even though the InGaAs/GaAs pseudomorphic structure is used. This implies that the potential spike at the BE junction is effectively lowered by the existence of the

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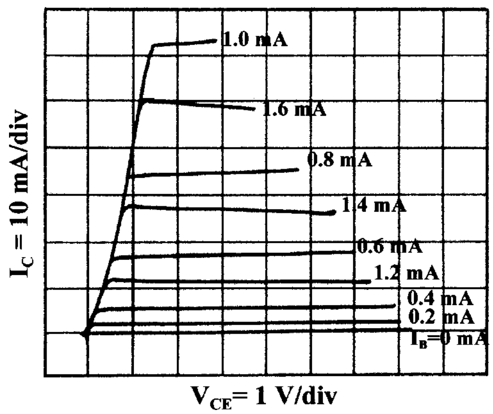

FIG. 1. Experimental current–voltage *(I–V)* characteristic of the AlGaAs/GaAs/InGaAs RTHEBT. The emitter area is 70×70 μm^2.

n-GaAs emitter. In other words, the RTHEBT really works as a traditional HEBT performance. Hence, it is very suitable for low-power consumption applications.

By solving Poisson's equations, the corresponding band diagram of the studied device is depicted in Fig. 3. Obviously, the potential spike at the BE junction is indeed eliminated. The device performances can be explained as follows. When the input base current (or V_{BE} voltage) is small ($I_B \leqslant 1.0$ mA), the RTHEBT behaves as a traditional transistor, as illustrated in Figs. 1 and 3(a). The AlGaAs emitter layer is employed as a minority-carrier (hole) confinement barrier and is physically separated from the BE junction. The 500 Å *n*-GaAs emitter controls electrons injecting from the emitter to the collector regime. As the applied V_{BE} bias is increased, the depletion layer of the *n*-GaAs emitter will be shrunken and the neutral *n*-GaAs emitter region is presented. In this condition, the band structure near the emitter side is effectively elevated and the resonant-tunneling mechanism can be formed by the successive connection of the *n*-GaAs depletion barrier, triangular InGaAs QW, and thin p^+-GaAs base layer, as depicted in Fig. 3(b). Physically, one barrier is formed in the emitter region and the other is one is found in the base region. The device performs as electrons tunnel through the effective double-barrier-like potential between the depleted emitter and collector regions. Within the regime, the current gains increase with increasing base current. As the on-resonance occurs, the maximum current gain of 140 is observed. Due to the presented low doping level and the absolute depletion in the thin InGaAs QW, the energy

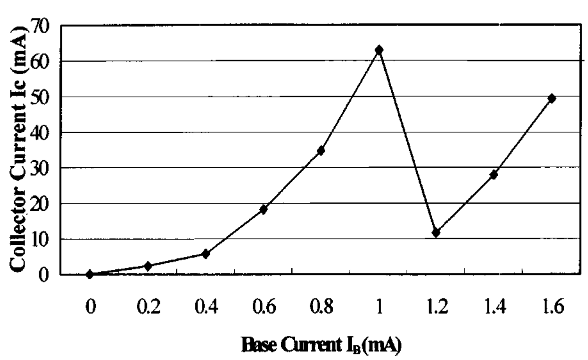

FIG. 2. Collector current vs base current of the studied RTHEBT. The PVCR value is 5.3.

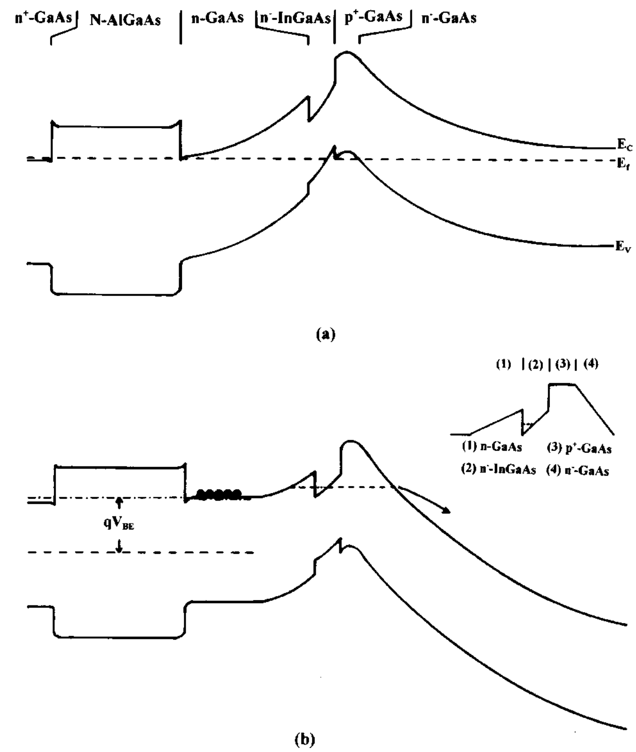

FIG. 3. Corresponding energy-band diagrams for the studied device (a) at equilibrium and (b) under normal operation mode. The inset shows the linear and triangular approximation for calculating the transmission coefficient.

band can be considered to be nearly linear in this region. Therefore, a triangular approximation can be used to calculate the transmission coefficient as shown in the inset of Fig. 3(b). By employing the Airy's functions and transfer-matrix method, the dependence of the transmission coefficient on the longitudinal incidence electron energy (E_z) in the InGaAs QW is obtained, as illustrated in Fig. 4, which takes the bottom of the n^--InGaAs triangular QW as a reference. The calculated results show that there are three subbands,

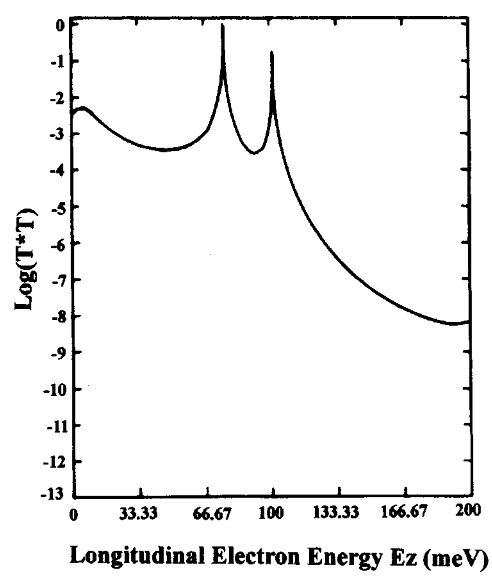

FIG. 4. Relationship between the transmission coefficient and longitudinal incidence electron energy (E_z) in the InGaAs QW. Note that the neutral GaAs emitter conduction band aims the bottom of the n^--InGaAs triangular QW.

i.e., the ground band E_1 (6 meV), first-excited band E_2 (76.5 meV), and the second-excited band E_3 (101.5 meV), in the InGaAs triangular well. The ground band E_1 has a small transmission and is very close to the conduction-band edge. Therefore, the on- and off-resonance through E_1 is negligible. The NDR behavior is not observed, as the input current (I_B) is small. The collector currents and, hence, current gain are increased until $I_B \geqslant 1.2$ mA. On the contrary, the first-excited band E_2 clearly exhibits the unit transmission coefficient and is well located in the InGaAs triangular well. Further increase of the base current (or V_{BE}) can cause the Fermi level of the neutral *n*-GaAs emitter to align with and elevate the first-excited band E_2. Hence, the on- and off-resonance are substantially observed. This causes a peak current and then the current is quenched. An interesting N-shaped NDR phenomenon is then obtained. The corresponding energy-band diagram is shown in Fig. 3(b). After the NDR performance, most electrons directly tunnel through or inject over the thin base region. This is similar to conventional DB devices. In fact, we also observe an insignificant NDR with a negligible PVCR value. However, it is very sensitive to applied voltage and the off-resonance voltage is very small. This might be attributed to the slightly weak transmission coefficient and thermal effect at room temperature. No other NDR in the common-emitter I–V curve is observed. Again, the collector current and current gain increase with the base current. Another transistor operation regime with the available current gain of 125 is observed.

In summary, an AlGaAs/GaAs/InGaAs RTHEBT with an N-shaped NDR phenomenon has been demonstrated at room temperature. Due to the used thin base layer and the insertion of an InGaAs QW, resonant tunneling is formed and excellent transistor performances incorporating an N-shaped NDR are observed. Consequently, the presented transistor and switching characteristics show the studied device to be a good candidate for circuit applications.

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