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Characterization of Improved AlGaAs/GaAs Resonant Tunneling Heterostructure Bipolar Transistors

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We report on the fabrication of AlGaAs/GaAs resonant tunneling heterostructure bipolar transistors (RTHBT's). The devices exhibit a current peak in the transfer characteristics, with peak-to-valley current ratios of 1.7 and 9 at 300 K and 77 K, respectively. The common-emitter small signal current gains at 300 K and 77 K reach 40 and 28, respectively. They are the best results to date for AlGaAs/GaAs resonant tunneling transistors. Because the double barriers are placed in the emitter and far from the emitter-base interface, and the heterostructure emitter suppresses the hole injection from the base to the emitter, the occurrence of the negative differential resistance (NDR) in the device characteristics is governed by the emitter current but not by the base current. The operation mechanism of the NDR behavior in the common-emitter output characteristics is discussed.

KEYWORDS: resonant tunneling, transfer characteristics, peak-to-valley current ratio, negative differential resistance, common-emitter small signal current gain

In recent years, resonant tunneling devices have attracted much attention because they exhibit negative differential resistances (NDR's) in device characteristics. In addition to the experimental opportunities they offer for the studies of quantum transport, they provide a variety of potential applications. Among these applications, resonant tunneling transistors are very promising because they can greatly reduce the circuit complexity for logic operations due to the NDR behavior in the transfer characteristics.[1-3] Several types of resonant tunneling transistors have been reported;[1,4-9] among them, resonant tunneling bipolar transistors have been shown to have better NDR performance in device characteristics and higher current gains than other types.[8,9] However, the device performance based on the AlGaAs/GaAs material system is still poor.[4]

In this letter, we report on the fabrication of improved AlGaAs/GaAs resonant tunneling heterostructure bipolar transistors (RTHBT's). In order to improve the NDR performance, the heterostructure emitter is used to suppress hole injection, and the double barriers are placed far from the emitter-base interface to eliminate hole diffusion to the double barriers. Simultaneously, the heterostructure emitter also improves the current gain. The operation principle of the NDR behavior in the common-emitter characteristics is discussed.

Figure 1 shows the schematic cross section of the finished RTHBT's. The devices were grown by molecular beam epitaxy on a (100)-oriented n^+-GaAs substrate at 600°C. The Al content of the AlGaAs emitter layer was 0.3. The double barriers were placed in the GaAs emitter layer and thus the emitter current governed the occurrence of the NDR behavior in device characteristics. The $Al_{0.4}Ga_{0.6}As$ barrier layers and the GaAs quantum well were undoped. The 200 Å undoped GaAs spacer layers surrounding the double barriers were used to prevent the Si dopants within the heavily doped electrodes from diffusing into the active region during growth. After growth, the emitter mesa area was formed and the base was also exposed using photolithography and wet etching. Next, AuGe and AuZn were applied to the emitter and base, respectively, and then alloyed for ohmic contacts. Finally, the base mesa area, and thus the individual device, was defined with mesa etching. The emitter-base junction area was 70 μm × 70 μm and the base-collector junction area was 250 μm × 170 μm. The collector ohmic contact was provided by In which was used for holding

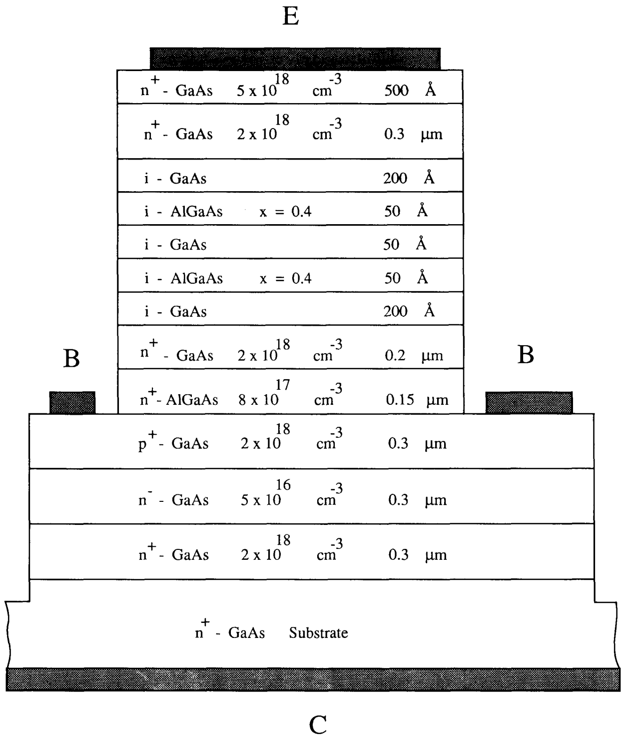


Fig. 1. Schematic cross section of the AlGaAs/GaAs RTHBT.

the substrate during growth.

Figure 2 shows the common-emitter transfer characteristics (the collector current, I_C, as a function of the base-emitter voltage, V_{BE}, with a constant collector-emitter voltage, V_{CE}, of 1.5 V) and the corresponding base current, I_B, at 300 K. A prominent current peak is obtained in the collector current. The peak-to-valley current ratio (PVCR) is 1.7. At 77 K, the PVCR increases to 9. These results are the best to date for AlGaAs/GaAs resonant tunneling transistors. The operation mechanism of the NDR behavior in the transfer characteristics of the present devices is essentially similar to that in refs. 8 and 9.

Figure 3 shows the common-emitter small signal current gains as functions of the base-emitter voltage with constant collector-emitter voltages of 1.7 V and 2.2 V at 300 K and 77 K, respectively. They reach 40 and 28 at 300 K and 77 K, respectively. The improvement of the current gains in the RTHBT's is due to the heterostructure emitter that effectively suppresses the hole injection from the base to the emitter. The current gain reveals a hysteresis at the base-emitter voltage range corresponding to the NDR region shown in Fig. 2.

The common-emitter output characteristics of the RTHBT at 300 K and 77 K are shown in Figs. 4(a) and 4(b), respectively. Although they appear similar to those presented in refs. 8 and 9, the parameter that dominates the occurrence of the NDR feature in our devices is the emitter current, not the base current. For the device characteristics shown in refs. 8 and 9, the base current dominates the occurrence of the NDR behavior. As shown in Fig. 5(a), the collector current peaks for the base currents of 2.4 mA and 2.145 mA occur in the linear region and the saturation region, repectively. We can note that the collector current peak for $I_B = 2.145$ mA is slightly larger than that for $I_B = 2.4$ mA. The collector peak and valley currents and the corresponding emitter currents as functions of the base current at 300 K are shown in Fig. 5(b). The emitter current peak and valley remain constant for different base currents, indicating that the occurrence of the NDR in the device characteristics is governed by the emitter current. This is because the double barriers in the present structure are far from the base-

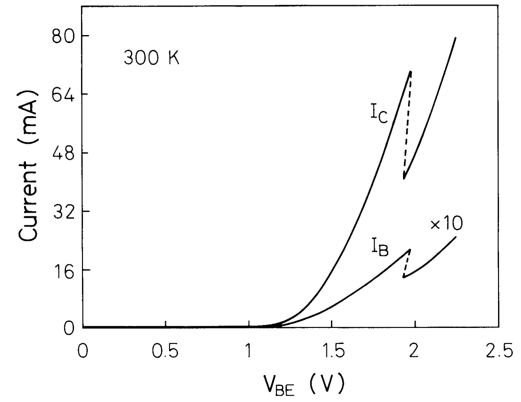


Fig. 2. Collector and base currents as functions of the base-emitter voltage, V_{BE}, with a constant collector-emitter voltage of 1.5 V at 300 K.

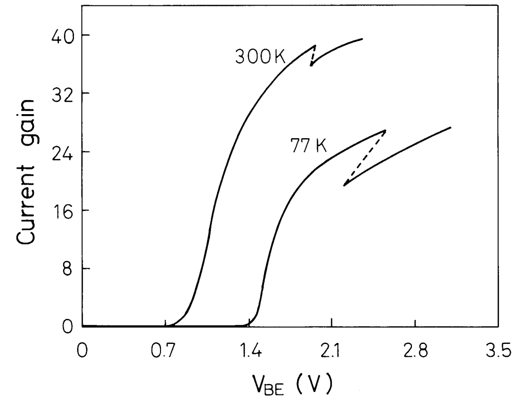
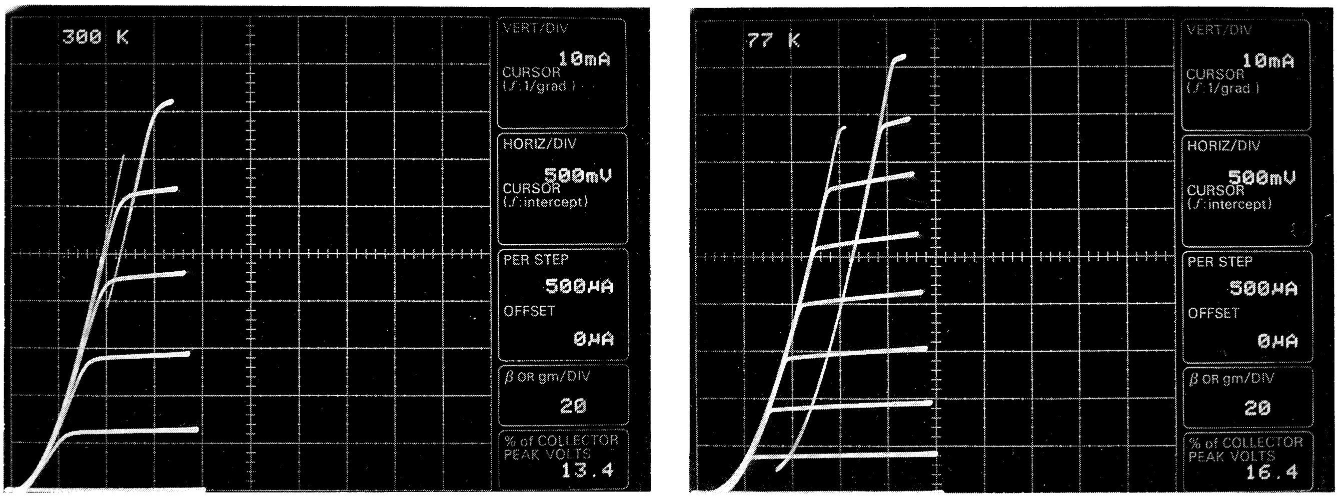


Fig. 3. Common-emitter small signal current gains as functions of the base-emitter voltage. The constant collector-emitter voltages at 300 K and 77 K are 1.7 V and 2.2 V, respectively.



VERT/DIV 10mA
CURSOR (ƒ:1/grad)
HORIZ/DIV 500mV
CURSOR (ƒ:intercept)
PER STEP 500μA
OFFSET 0μA
β OR gm/DIV 20
% of COLLECTOR PEAK VOLTS 13.4

VERT/DIV 10mA
CURSOR (ƒ:1/grad)
HORIZ/DIV 500mV
CURSOR (ƒ:intercept)
PER STEP 500μA
OFFSET 0μA
β OR gm/DIV 20
% of COLLECTOR PEAK VOLTS 16.4

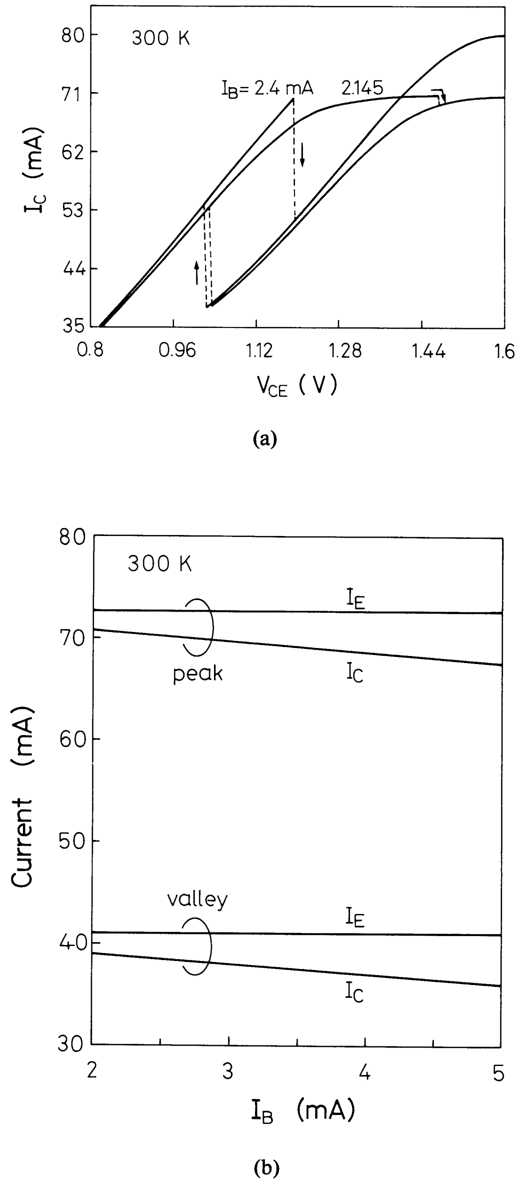
(a) (b)

Fig. 4. Common-emitter output characteristics (collector current versus the collector-emitter voltage for different base currents) at (a) 300 K and (b) 77 K.

emitter interface, and thus only electrons in the emitter are involved in the current transport through the double barriers. Due to $I_E = I_C + I_B$, the collector current peak and valley linearly decrease with the base current. Therefore, for a smaller base current, which leads to a smaller collector current, a larger collector-emitter voltage is needed to achieve the sufficient collector current for the occurrence of the NDR behavior.

Finally, the operation principle of the NDR feature in the common-emitter output characteristics shown in Figs. 4(a) and 4(b) is discussed. Figure 6 shows the base-emitter voltage as a function of the collector-emitter voltage for two different base currents at 300 K. The V_{BE} increases continuously with V_{CE} until the collector current reaches such a value where the emitter current peak is reached. At that moment, the base current also enters the NDR region. In order to maintain the base current, V_{BE} must increase abruptly, resulting in the abrupt decrease of the collector-base voltage, V_{CB}. As a result, the collector current decreases abruptly. Similarly, as V_{CE} decreases and the emitter (collector) current valley is reached, the necessary abrupt decrease of V_{BE} causes an abrupt increase of V_{CB}, resulting in the abrupt increase of the collector current. Therefore, the collector current exhibits a peak and a valley as V_{CE} is increased and decreased, respectively.

In conclusion, AlGaAs/GaAs resonant tunneling heterostructure bipolar transistors have been fabricated. The PVCR's in the transfer characteristics at 300 K and 77 K are 1.7 and 9, respectively. The common-emitter small signal current gains at 300 K and 77 K reach 40 and 28, respectively. They are the best results for AlGaAs/GaAs resonant tunneling transistors to date. Because the double barriers are placed in the emitter and only electrons are involved in the current transport through the double barriers, the NDR behavior in device characteristics is governed by the emitter current but not by the base current. The operation principle of the NDR behavior in the common-emitter output characteristics has been discussed.



(a)

(b)

Fig. 5. (a) Expanded common-emitter output characteristics for two different base currents at 300 K. (b) Collector current peak and valley, and the corresponding emitter currents as functions of the base current at 300 K.

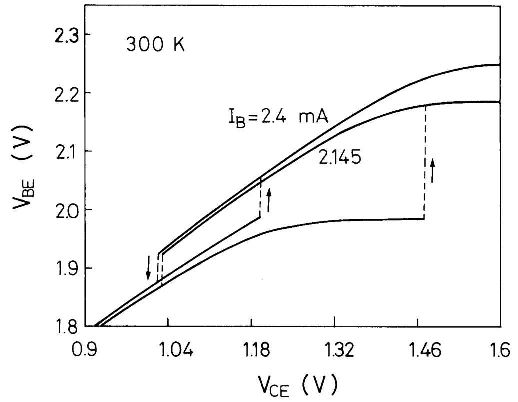


Fig. 6. Base-emitter voltage as a function of the collector-emitter voltage for two different base currents at 300 K.

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