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Hybrid (Confinement and Tunneling) Application of AlGaAs/GaAs Superlattice in a Double-NDR Transistor

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A new functional bipolar transistor employing an i–AlGaAs/n^+–GaAs superlattice as a confinement and a tunneling layer, simultaneously, has been demonstrated at low temperature. Electrons are injected from emitter to base by resonant–tunneling through the minibands in the superlattice. Whereas, most of holes injecting from base to emitter are reflected by the superlattice and few are tunneling through the superlattice due to their heavier effective mass. A high current gain of 65 and double N–shaped NDR phenomenon with peak–to–valley current ratios of 4:1 and 2.6:1, resulting from on and off resonance through minibands, were obtained in the common–emitter configuration.

1. INTRODUCTION

In recent years there has been increasing research activity in the area of functional bipolar transistors. The key characteristic of such devices is that they are particulary promising for the realization of a variety of digital and analog circuits with greatly reduced complexity. Following the first proposal of a resonant–tunneling (RT) transistor, many functional devices, employing double barriers structure have been demonstrated.[1–5] However, most of these devices exhibit one current peak and small current gain in the common–emitter configuration. More recently, multiple–state bipolar transistor with stacked AlInAs/GaInAs RT structure is reported.[6,7] On the other hand, the InP substrate, as compared with GaAs substrate, provides some drawbacks, e.g. high cost, more fragile and requirement of precise control of In content.

In this study, we report a new functional bipolar transistor which employs an i–AlGaAs/n^+–GaAs superlattice as a confinement and a tunneling barrier, simultaneously. For small input base current, the superlattice works as a minority carriers (holes) reflected basrrier and the device act as a conventional transistor. Increasing the base current to bring the emitter–base (E–B) junction to flat band condition, the double negative–differential–resistance (NDR) phenomenon occurs based on the sequential quenching of RT through the ground–band and the first–excited band in the superlattice. A high common–emitter current gain of 65 with two peak–to–valley current ratios of 4:1 and 2.6:1 was obtained. This is the best value ever reported using GaAs based materials till now.

2. EXPERIMENTS

The structure studied was grown by a MBE system on a (100)–oriented n^+–GaAs substrate. It consists of a 0.2–μm GaAs ($n^+=1\times10^{18}$ cm^{-3}) buffer layer, followed by a 0.5–μ GaAs ($n^-=5\times10^{16}$ cm^{-3}) collector, a 0.2–μm GaAs ($p^+=5\times10^{18}$ cm^{-3}) base, a 500–A GaAs ($n=5\times10^{17}$ cm^{-3}) emitter, 5–period AlGaAs/GaAs superlattice and a 0.3–μm GaAs ($n^+=1\times10^{18}$ cm^{-3}) cap layer. In the superlattice, the 50–A $Al_{0.5}Ga_{0.5}As$ barriers were undoped while the 50–A GaAs wells were heavily doped with Si to 1×10^{18} cm^{-3} to increase current density and to reduce the series resistance. After finishing the MBE growth, the device was implemented using conventional evaporation process and lift–off techniques. Au/Ge and Au/Zn were used as n–type and p–type contact materials, respectively. All the current–voltage (I–V) characteristics were measured by a Tektronix 577 curve tracer at 77 K.

3. RESULTS AND DISCUSSIONS

The physics of the device is well understood using the common–base configuration. As shown in Fig.1, the collector–base junction is kept at $V_{BC}=0$ V and the base–emitter voltage, V_{BE}, is increased successively. Figure 2 illustrates the corresponding current–voltage characteristics. For V_{BE} smaller the built–in voltage of GaAs p–n junction [Fig.1(a)], most of the bias voltage appears across this junction and this junction behaves as a regular diode that the conducting current increases with increasing V_{BE}. As V_{BE} further increasing to bring the E–B junction to flat–band condition, the junction strongly conducts and the additional bias voltage then start to fall across the superlattice. When the increase in V_{BE} causes the Fermi level E_{F1} elevate beyond the ground band E_1 of the superlattice [Fig.1(b)], the resonant–tunneling current through the ground band E_1 is abruptly reduced. This yields the first NDR phenomenon. Based on the same mechanism, the on and off resonance through the first–excited band E_2 will occur in sequence as V_{BE} bias is increased continuously. Similarly, the conducting current is increased, then is suddenly reduced and the second NDR behavior occurs. Experimentally, the first and the second NDR were observed and indicated at V_{BE}=2.5 and 3.0 V, respectively, in the Fig.2. The peak–to–valley current ratios for the two NDRs are 4:1 and 2.6:1. Furthermore, the two peak currents are nearly equal and much larger than the second valley current, which is difficult to meet in the conventional double–barrier structure.

The common–emitter characteristics of the device can be easily realized by means of the picture developed above. At low base currents I_B (and hence low base–emitter voltage), the device behaves as a conventional bipolar transistor. Among this region, the superlattice is used as confinement layer to minority carriers (holes) only. Holes injecting from base to emitter are mostly reflected by the barrier due to their heavier effective mass. However, electrons controlled by the GaAs p–n junction can pass the base and then reach the collector easily. Thus high emitter injection efficiency as well as high current gain are maintained as in a single heterojunction bipolar transistors. As shown in Fig.3(a), a common–emitter current gain as high as 65 was obtained when the transistor operated before the flat–band condition. With increasing I_B (V_{BE}) beyond the flat–band condition, the excess applied voltage V_{BE} start appearing across the superlattice which now acts as a tunneling barrier for electrons. When resonant–tunneling through the ground band E_1 and the first–excited band E_2 in the superlattice quenching sequentially at some threshold base currents I_{th1} and I_{th2}, the input electron current across the GaAs p–n junction reduces abruptly. This results in sudden quenching of the current gain and abrupt reduction of collector current at these two threshold base currents and gives rise to two NDR regions. It is found, from Fig.3(b), that the two NDR regions with peak–to–valley current ratios of 4:1 and 2.6:1 were observed as I_{th1} and I_{th2} indicated at 1.2 mA and 1.6 mA, respecively. Note also that the current gain of the transistor in the second (1.2 mA$<I_B<$1.6) and the third (1.6 mA$<I_B$) operation regimes is reduced to 38 and 35, respectively. This is expected due to the larger hole current tunneling through the superlattice under larger forward bias.

Instead the transistor is controlled by the input base current, Fig.4 shows the common–emitter I–V characteristics of the device when controlled by the input base–emitter voltage V_{BE} with 0.5 V/step. It is found that bi–stable output collector current, as indicated in figure by arrow, occurs when V_{BE}=2.5 and 3 V, i.e. the value that result in the quenching of RT. These bi–stable output currents are resulted from two different input emitter currents, as we can see in Fig.2 at V_{BE}=2.5 and 3 V. However, the active region for the higher output collector is not shown in Fig.5 due to the NDR effect.

4. CONCLUSIONS

A new functional transistor which employs an i–AlGaAs/n^+–GaAs superlattice as a confinement and a tunneling layer has been demonstrated. A high common–emitter current gain of 65 and two NDR regions with peak–to–valley current ratios of 4:1 and 2.6:1 were obtained when the transistor is controlled by input base currents. On the other hand, the I–V characteristics when controlled by V_{BE} are also demonstrated to assess the device operation mechanism. Based on these excellent performances, the device will be attractive in the design of multipli–valued logic circuits and frquency multipliers.

5. REFERENCES

1) F. Capasso and R.A. Kiehl: J. Appl. Phys. 58 (1985) 1366.
2) N. Yokoyama, K. Imamura, S. Muto, S. Hiyamizu and H. Nishi: Jpn. J. Appl. Phys. 24 (1985) L853.
3) F. Capasso, S. Sen, A.C. Gossard, A.L. Hutchinson and J.H. English: IEEE Electron Device Lett. 7 (1986) 573.
4) T. Futatsugi, Y. Yamaguchi, K. Imamura, S. Muto, N. Yokoyama and A. Shibatomi: Jpn. J. Appl. Phys. 26 (1987) L131.
5) T. Futatsugi, Y. Yamaguchi, S. Muto, N. Yokoyama, A. Shibatomi: 1987 IEDM, p.877.
6) S. Sen, F. Capasso, A.Y. Cho and D.L. Sivco: IEEE Electron Device Lett. 9 (1988) 533.
7) F. Capasso, S. Sen, A.Y. Cho and D.L. Sivco: Appl. Phys. Lett. 53 (1988) 1056.

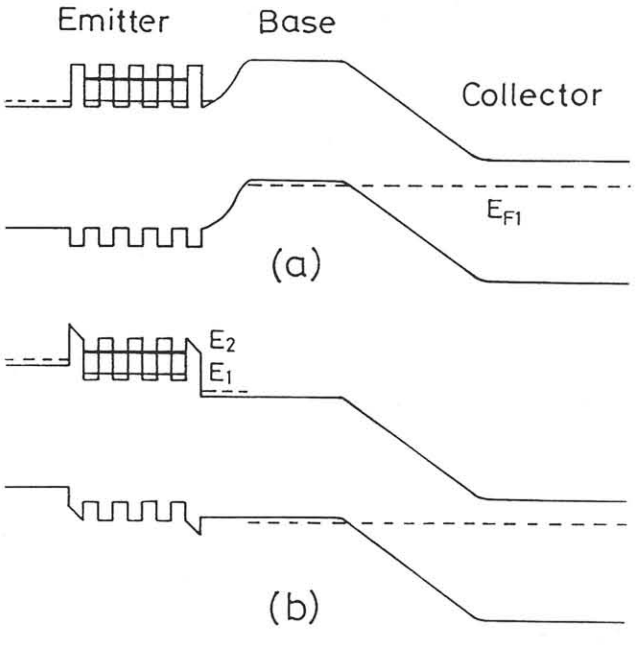

Fig.1 The corresponding energy band diagram of the studied device using common–base configuration (a) before and (b) after flat band condition. The collector–base junction is kept at V_{BC}=0 V.

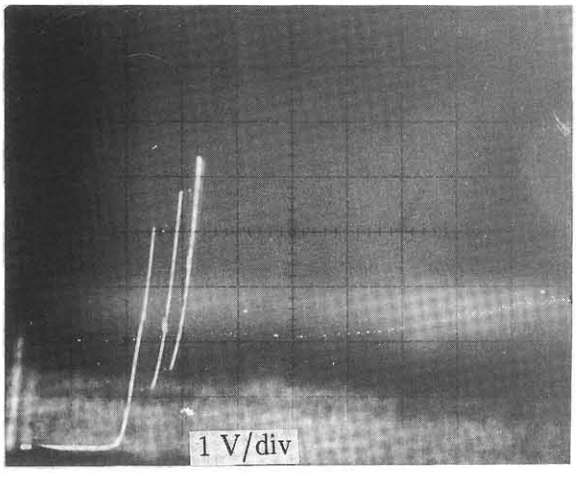

Fig.2 Current–voltage characteristics for the emitter–base junction. Obviously, there are two NDR regions existing in the output characteristics.

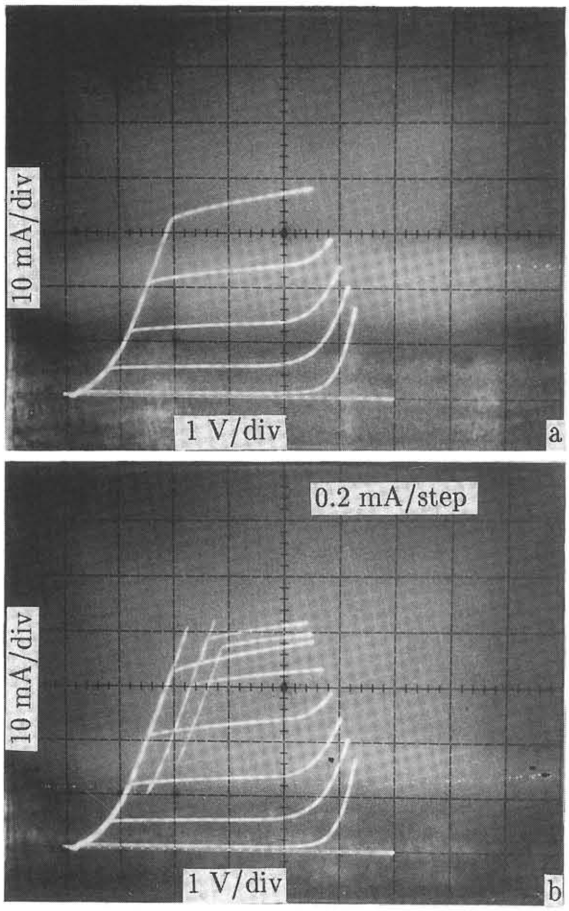

Fig.3 The common–emitter characteristics of the studied device controlled by input base current at (a) low base currents and (b) higher threshold base current.

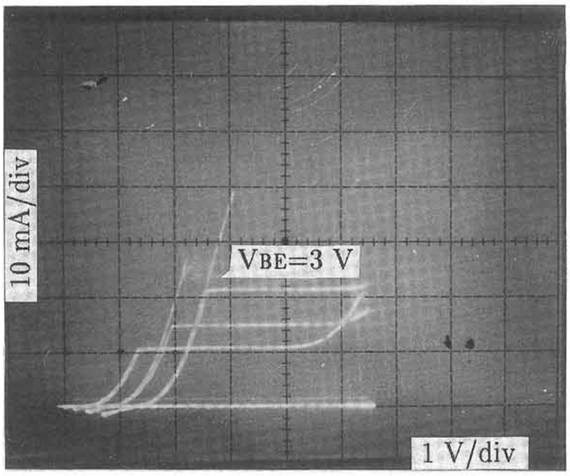

Fig.4 The common–emitter characteristics of the studied device controlled by the base–emitter voltage.