Room Temperature NDR Performance of GaInAs based SE-RTBT

M. H. Chowdhury, M. A. Mannan, and S. A. Mahmood

Abstract— Superlattice emitter resonant tunneling bipolar transistor (SE-RTBT) is facing problem due to thermal transfer of electrons over barrier which causes diminishing negative differential resistance (NDR) effect. Therefore resonant tunneling diode (RTD) with higher quasi-bound state energy causes transfer of electrons by RT effect instead of thermal process. The RT effect can be enhanced by controlling the barrier and well widths of RTD. It has been found that InP/GaInAs SE-RTBT shows better NDR characteristic at room temperature.

Index Term— Superlattice emitter resonant tunneling bipolar transistor (SE-RTBT), negative differential resistance (NDR), resonant tunneling diode (RTD), quasi-bound state, Multiple barriers RTD (MBRTD).

I. INTRODUCTION

The Resonant Tunnelling diode (RTD) is a nano-scale quantum diode. Diode is the simplest two terminal active electronic devices. Multiple barriers RTD (MBRTD) show the interesting characteristics of resonant tunnelling for certain quasi-bound energy states. The transmission probability of incident particles can be even one though barriers have a low transparency. Esaki et al. have done the pioneer work on the resonant tunneling phenomena [1] and later a large number of theoretical work have been carried out by many research groups [2-4]. The double barrier diode was the primary electronic device whose operating principle depends mainly on the quantum size effect.

The existence of negative differential resistance (NDR) at room temperature makes RTD as one of the most promising two terminal quantum effect device for applications such as in memory device, oscillator, amplifier in a wide range of frequencies [5, 6]. The tunneling action occurs so rapidly that the effect of transit time is negligible and thus smaller amount of signal distortion occurs [7, 8]. Therefore, high-frequency applications are feasible by using the tunnel diode. RTD shows good performance due to its high speed, large dynamic range of operation, low leakage current but it cannot be controlled like three terminal transistors. It has good application in oscillating circuits and digital switching due to its NDR characteristics. Therefore, RTD is incorporated with normal bipolar transistor (BJT) which is called Resonant Tunneling Bipolar Transistor (RTBT). The concept of RTBT was first proposed by Cappaso and Kiehl [9]. Both the gain and speed of RTBT are improved in comparison with conventional BJT. Resonant-tunneling bipolar transistors (RTBTs) have attracted considerable attention for applications, such as analog-to-digital converters, frequency multiple-valued logic circuits, parity bit generators, high speed switches, oscillators, signal amplifiers etc.

In this paper we will compare the performance of different RTBTs as well as the challenges to prepare RTBT for better desired performance. The effect of both barrier width and well width on the transmission of carriers (electron) through the RTBT has been investigated theoretically.

II. THEORY

In quantum mechanics wave functions can penetrate through potential barrier. For energies below the top of the barrier the wave is attenuated and it decays exponentially. It takes a significant distance for the decay to eliminate the wave completely. If the barrier is thinner than this critical distance the wave can excite a propagating wave in the region beyond the barrier i.e. tunneling occur.
Let us consider a flux particle of energy $E$ is incident on a potential barrier of height $V_0$ and width $b$ as shown in Fig. 1. In the three region of interest the solutions of Schrodinger equations are

$$\psi_1(x) = A_1 e^{j k x} + B_1 e^{-j k x}, \quad x < 0$$

$$\psi_2(x) = C_1 e^{j k x} + D_1 e^{-j k x}, \quad 0 < x < b$$

$$\psi_3(x) = E_1 e^{j k x} + F_1 e^{-j k x}, \quad x > b$$

where $k = \frac{2 \pi \sqrt{2mE}}{h}$, $\gamma = \frac{2 \pi \sqrt{(V_0 - E)}}{h}$ and $A_1, B_1, C_1, D_1, E_1, F_1$ are six plane wave co-efficient. By applying the boundary condition we get the transfer matrix of a single potential barrier as,

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = \begin{bmatrix} \mu_{11} & \mu_{12} \\ \mu_{21} & \mu_{22} \end{bmatrix} \begin{bmatrix} e^{j k b} & 0 \\ 0 & e^{-j k b} \end{bmatrix} \begin{bmatrix} E_1 \\ F_1 \end{bmatrix}$$

where

$$\mu_{11} = \cosh(\gamma b) - j \left( \frac{k^2 - \gamma^2}{2k \gamma} \right) \sinh( \gamma b)$$

$$\mu_{22} = -j \left( \frac{k^2 - \gamma^2}{2k \gamma} \right) \sinh(\gamma b)$$

$$\mu_{12} = \mu_{11}^*$$

Since we are interested in the tunneling of a particle from one side to other, we treat an incoming wave from one of the two sides. So putting $F_1 = 0$ we get $A_1 = \mu_{11} E_1$. The transmission probability is the ratio of the currents on the two sides of the barrier and is given by,

$$T = \frac{1}{|\mu_{11}|^2}$$

Let us now consider $n$ tunnel barrier width of each is $b$ and they are separated by quantum wells of width $w$ as shown in Fig. 2.

The overall transfer matrix of $n$ number of tunnel can be expressed as

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = \begin{bmatrix} \mu_{11} & \mu_{12} \\ \mu_{21} & \mu_{22} \end{bmatrix} \begin{bmatrix} e^{-j k w} & 0 \\ 0 & e^{j k w} \end{bmatrix} \begin{bmatrix} A_2 \\ B_2 \end{bmatrix}$$

By multiplication the above equation can be expressed by a single matrix as

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = \begin{bmatrix} \mu_{n11} & \mu_{n12} \\ \mu_{n21} & \mu_{n22} \end{bmatrix} \begin{bmatrix} E_n \\ F_n \end{bmatrix}$$

As there is no incoming wave beyond $n^{th}$ barrier so putting $F_n = 0$, the overall transmission probability can be expressed as

$$T_n = \frac{1}{|\mu_{n11}|^2}$$

III. SE-RTBT

Superlattice is a structure composed of periodically alternating crystalline layers of several materials with different properties (e.g. band gap). In our case sandwich of two different materials with different band gap is used in an alternating periodic order to have the effect of resonant tunnelling (RT) in emitter region of BJT. Fig. 3 shows AlInAs/GaInAs superlattice as an example. Different techniques are used to grow superlattice, but the most common is molecular-beam epitaxy (MBE) and sputtering.
BJTs show good current capabilities over field effect transistor due to their three-dimensional capabilities but they suffer for gain, emitter efficiency and speed. The gain of BJT can be improved by high emitter doping and low base doping. BJT gain is defined by

$$\beta(BJT) = \frac{D_{nb}}{D_{pe}} \frac{N_{dfe}}{N_{atb}}$$

where, doping concentration in emitter, and

$$N_{dfe} = \int_{Emitter} N_d(x) dx$$

doping concentration in base,

$$N_{atb} = \int_{Base} N_a(x) dx$$

But heavy emitter doping cause emitter band gap shrinkage and low base doping increases the base spreading resistance which in-turn decrease the unity power gain frequency, $f_{max}$. To overcome this problem heterojunction concept has been introduced in base-emitter junction. Besides this using RTD in emitter region gives high speed and high gain. The main purpose of using superlattice in emitter region is basically as follows:

1) The superlattice (RTD) is used for hole confinement in base region (Fig. 4) which improves the emitter efficiency of BJT. For npn transistor the emitter efficiency is given by,

$$\gamma_e = \frac{I_{En}}{I_{En} + I_{Ep}}$$

where, $I_{En}$=Electron current from emitter to base and $I_{Ep}$=hole current from base to emitter. If hole is confined in base, $I_{Ep}$ is decreased and emitter efficiency is increased and this in-turn increases the current gain.

2) The superlattice creates resonant tunneling route for electrons from emitter to base as shown in Fig. 4. Electrons moves at a high speed from emitter to base and so base-emitter transit time decreases which improves the speed of the device and frequency response. Therefore, using RTD in emitter region improves the overall BJT performance. But it is very challenging to select appropriate RTD for emitter region. Both the barrier width and well width controls the transmission of carriers through the RTD. Fig. 5 shows the transmission coefficient versus energy for InP/In$_{0.53}$Ga$_{0.47}$As double barrier tunneling system. The barrier width of InP is 5nm and well width of In$_{0.53}$Ga$_{0.47}$As varies from 3nm to 10nm.

Here, we see that maximum transmission peak occurs for different energy for different quantum well thickness. Fig. 6 shows the transmission probability versus energy for fixed well width of 5nm. The barrier width varies from 5 nm to 10 nm. In this case we also found that maximum transmission peak occurs in different energy. Therefore, the number of superlattice with appropriate width is vital to get better performance from SE-RTBT.
bound energy is $E_1=0.123$ eV and $E_2=0.48$ eV and width of these energy bands are 0.004 eV and 0.06 eV respectively [12].

![Fig. 7. Energy Band Diagram of AlInAs/GaInAs SE-RTBT.](image)

The NDR phenomena are observed in the output characteristics of this device at 77K temperature as shown in Fig. 8. Here, the first NDR regions are dominant then the second one. From Fig. 7 it shows that second quasi-bound state is nearer to the top of the barrier so many electrons travel directly over the superlattice rather than tunnel through the $E_2$ band and so the second NDR is relatively insignificant compare to the first one. On the other hand at higher temperature say in room temperature so many electrons gain enough thermal energy to overcome the barrier directly than tunnel through it and so RT action and NDR phenomenon are not observed in the output characteristics. The disadvantages of this device are: (i) low temperature (77k) NDR phenomena is observed but at high temperature (even at room temperature) it is vanished, (ii) the current gain is very low (~13), (iii) number of superlattice period is high (20).

![Fig. 8. Common-emitter output characteristics ($I_e=0.1$ mA/step) of AlInAs/GaInAs SE-RTBT at 77K. Data are taken from reference, [12].](image)

### B. InP/GaInAs SE-RTBT

InP device has good application in optoelectronic integrated circuits (OEICs) due to its compatibility with long wavelength
(1.3μm and 1.5 μm) and this device also has good thermal conductivity (0.68 w cm⁻¹°C⁻¹) with low turn-on voltage [10]. Again the electron mobility of InP is high. Therefore, it is very suitable for high speed operation. In this SE-RTBT both the InP and Ga₀.₄₅In₀.₅₅As is lattice matched so the growth of this superlattice is strain free and easy to grow. Here InP work as barrier (Eg=1.34 eV) and Ga₀.₄₅In₀.₅₅As as quantum well [10]. The properties of this superlattice are shown in Table-II.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>InP/GaInAs Superlattice Properties [13]</th>
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<tbody>
<tr>
<td>Properties</td>
<td>InP/GaInAs</td>
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<tr>
<td>Band discontinuity</td>
<td>ΔEₜₐₜ = 0.35 eV</td>
</tr>
<tr>
<td>Turn-on voltage</td>
<td>0.34V</td>
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Here, the valence band discontinuity (ΔEₜₐₜ) is smaller than the previous structure but it shows good hole confinement in the base region. This device shows smaller conduction band discontinuity then the previous one which results smaller collector-emitter offset voltage of 60mV [13]. Therefore the power loss is less in this device. Tsai et al. used this device structure for their SE-RTBT. For their device 5 periods InP (5nm)/ Ga₀.₄₅In₀.₅₅As (8nm) is used instead of 20 periods. Here, emitter size is decreased to 100μm [13]. In the previous device emitter size was five times higher than this. If the emitter thickness is high the transistor has inferior hole confinement. This causes charge storage in neutral-emitter region which enhances base recombination current as well as total base current. The hole diffusion length of the GaInAs is very low which causes huge decrease in current gain under large base emitter voltage (Vₑₑ) [13]. By decreasing the emitter length this problem has been removed. This SE-RTBT shows high current gain of 670 [13].

In InP/GaInAs Superlattice three quasi-bound states has been observed at Eₜₐₜ=0.73 eV, Eₜₐₜ=0.95eV and Eₜₐₜ=1.18eV [13]. Here the first quasi-bound state energy is almost double than second quasi-bound state energy (0.48 eV) of AllnAs/GaInAs SE-RTBT. Therefore this device shows good RT characteristics at high temperature. The NDR phenomena are observed in the output characteristics of this device at room temperature as shown in Fig. 9. Three NDR regions occur even at room temperature which was missing in the previous SE-RTBT. Here, the voltage differences between two NDR regions are identical (ΔVₑₑ ~ 0.22 V) that is the difference of high field voltage is identical. Therefore, if the superlattice quasi-bound state energy is high with high barrier height, NDR effect can be observed at room temperature.

![Fig. 9. Forward base-emitter I-V characteristic at room temperature. Data are taken from reference [14].](image)

V. CONCLUSION

SE-RTBT shows the controlled NDR characteristic, which is absent in RTD. The NDR effect in SE-RTBT is temperature dependent. At high temperature better thermal transfer of electrons over barrier results in AlInAs/GaInAs SE-RTBT as its quasi-bound state energy is small. This causes diminishing RT phenomena. InP/GaInAs SE-RTBT shows better NDR performance even at room temperature. The higher quasi-bound state energy of InP/GaInAs SE-RTBT prevents thermal transfer of electrons over barrier. Thus nano-scale resonant tunnelling diode with conventional BJTs shows the controlled NDR region and improves the current gain of BJTs.

REFERENCES


