InP/InGaAs Resonant Tunneling Diode with Six-Route Negative Differential Resistances

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Abstract — **Sequential tunneling behavior of p-n resonant tunneling diode with four-period InP/InGaAs superlattice is demonstrated. Theoretical calculation shows three split quantized energies in the four-period InP (50 Å)/InGaAs (25Å) superlattice structure. For the increase of more negative differential resistance (NDR) routes, high-field domain is formed in the superlattice under sufficiently large operation biases. Experimentally, an interesting six-route NDR characteristic, resulting from the form of split miniband structures and the extension of high-field domain in the InP/InGaAs superlattice, is observed at room temperature.**

I. INTRODUCTION

Over the past years, due to the rapid progress in exitaxial growth technologies, many novel negative differential resistance (NDR) devices exhibiting either N-shaped or S-shaped switching characteristics have been successfully fabricated and demonstrated [1-4]. Among the switching devices, resonant tunneling diodes (RTDs) have attracted considerable attention for practical circuit applications, such as oscillators, analog-to-digital converters, multiplexers, and logic circuits, attributed to the NDR and high-speed properties, [5-8]. However, some of the reported NDR devices generally only provide two-operation region, i.e., an initial off state and a final on state. Recently, in order to obtain multiple stable states for multiple-valued logic circuit applications, the resonant tunneling devices with multiple NDRs characteristics have attracted extensive interests because of their feature of circuit simplicity [9, 10]. Usually, the numbers of quantized minibands in resonant tunneling devices determines the route numbers of NDRs. The multiple NDRs could be achieved in double-barrier or superlattice structures with multiple minibands. Furthermore, though two or more NDR devices in series can create multiple-peak NDRs in the combined current-voltage (I-V) characteristics, it increases the complexity and element of circuits [9].

In general, as to the InP/InGaAs superlattice, only one-route N-shaped NDR is observed [3]. In this letter, we report a novel multiple NDR device based on a p-n RTD with four-period InP/InGaAs superlattice. For the requirement of more NDR routes, the widths of InGaAs wells are extremely thin in order to form split miniband structures and increase the numbers of minibands in the superlattice. In addition, high-field domain is formed in the InP/InGaAs superlattice under sufficiently large operation biases. Experimentally, interesting six-route NDRs is observed at room temperature for the identical device without the use of multiple RTDs in series.

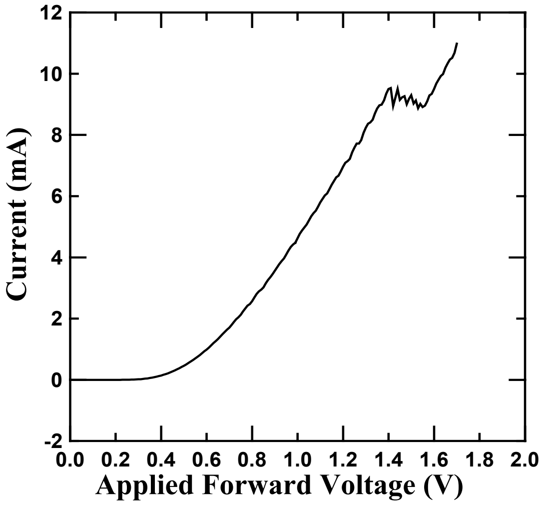
III. DECVICE STRUCTURE AND EXPERIMENTS

The studied InP/InGaAs RTD was grown an (100) oriented semi-insulating InP substrate by low-pressure MOCVD. The device structure includes a 0.5 μm $p^+ = 1 \times 10^{19}$ cm^{-3} $In_{0.53}Ga_{0.47}As$ layer, a 100 Å $n = 5 \times 10^{17}$ cm^{-3} $In_{0.53}Ga_{0.47}As$ layer, a four-period InP/$In_{0.53}Ga_{0.47}As$ (50Å /25Å) superlattice, and a 0.3 μm $n^+ = 1 \times 10^{19}$ cm^{-3} $In_{0.53}Ga_{0.47}As$ cap layer, respectively. In the superlattice, the InP barriers were undoped whereas the $In_{0.53}Ga_{0.47}As$ wells were doped to $n = 5 \times 10^{17}$ cm^{-3}. After the epitaxial growth, the conventional photolithograpgy, vacuum evaporation, and chemical wet etching process were used to fabricate the device. The InGaAs and InP layers were selectively etched by the solutions of 6 H_3PO_4: 3 H_2O_2: 100 H_2O and 1 HCl: 1 H_2O, respectively. Ohmic contacts were prepared by alloying evaporated AuGaNi and AuZn metals for n- and p-type layers, respectively.

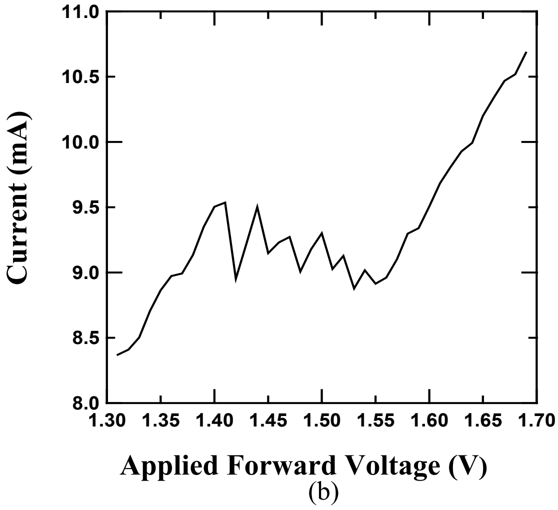
III. RESULTS AND DISCUSSION

The experimental forward I-V characteristic, measured by an HP4155B semiconductor parameter analyzer, of the studied InP/InGaAs RTD at room temperature is illustrated in Fig. 1. The turn-on voltage is about 0.38 V at the current level of 0.1 mA. Clearly, an interesting six-route NDR characteristic is observed. The insert depicts the enlarged view of the I-V characteristics of the multiple NDRs. The peaks of the NDRs are observed at V = 1.41, 1.44, 1.47, 1.50, 1.52, 1.54 V. The peak-to-valley current ratios (PVCRs) of the NDRs are 1.065, 1.039, 1.029, 1.03, 1.028 and 1.012, respectively.

In order to investigate the miniband structures, InP/InGaAs superlattice with variable well widths are analyzed and compared. By the calculation of transfer matrix, the dependence of transmission coefficient on the longitudinal incidence electron energy for the InP/InGaAs superlattices under ideal flat-band condition is depicted in Fig. 2. Here, the thickness of InP barrier is fixed at 50 Å. As seen from the figure, only one miniband, i.e., the ground band E_0, is obtained for the four-period superlattice with 50 Å-InGaAs wells. Though three quantized energies that the transmission coefficients are close to unity are expectable, they are nearly near each other and generally established as the same miniband at room temperature. Then, only one-route NDR is observed as to the previous report [3]. However, as the widths of InGaAs wells are reduced to 25 Å, the miniband structures trend to split. The second and third minibands, i.e., the first excited band E_1 and the second excited band E_2, substantially appears. That is to say, the quantized energies separate each other and the numbers of "effectively" minibands increase, as the widths of InGaAs wells are decreased in the four-period superlattice. In the experimental device, the energy difference (~ 22 meV) between two minibands is nearly identical. On the other hand, further increasing the periods of the InP/InGaAs superlattice, though the numbers of minibands are increased, they strongly couple (wide energy range of E_0) each other and can be also established as one miniband. Thus, the short-period InP/InGaAs superlattice with the relatively thin InGaAs wells could achieve the split miniband structures.



(a)



(b)

Fig.1. (a) Experimental current-voltage characteristic of the InP/InGaAs RTD at room temperature. (b) Enlarged view of the multiple NDRs.

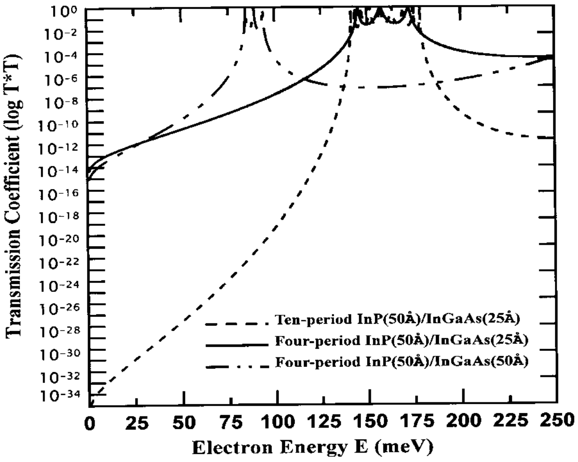


Fig.2. The dependence of transmission coefficient on longitudinal incidence electron energy under ideal flat-band condition for the InP/InGaAs RTD with variable well widths. Here, the thickness of InP barrier is fixed at 50 Å.

Figure 3 shows the corresponding conduction band diagram of the studied RTD. Because the inserted n-InGaAs layer between superlattice and base layer is not too thick, the superlattice is depleted completely and the depletion region extends into n^+-InGaAs cap layer at equilibrium. At low voltage level, the applied voltage is essentially across the p-n junction and the device acts as traditional diodes. Once the applied voltage is enough large, the InP/InGaAs superlattice will go into flat-band condition, as illustrated in Fig. 3(a). However, six-route N-shaped NDRs are observed though only three split minibands are indicated in the superlattice, as clearly seen in Fig. 1. Furthermore, the applied voltage of the studied device must be enough large to enable the superlattice to attain the flat-band condition. Thus, we suggest that the tunneling mechanism of the MNDR behavior should be dominated by high-effect domain [11]. It is worthy to note that the high-field region may initially occur on the left side of the superlattice because the doping concentration of the inserted n-InGaAs layer is lower when compared to the n^+-InGaAs cap layer.

When the applied voltages are greater than the flat-band voltage, i.e., after the high-field domain is formed, the first resonant tunneling behavior will occur as the Fermi level E_F of n^+-InGaAs cap layer aligns to the E_0 within the superlattice, as seen in Fig. 3(b). Similarly, if the E_F aligns to the E_1 and E_2, the second and third resonant tunneling behaviors will occur, as shown in Figs. 3(c) and 3(d), respectively. After the above process, further increasing the bias will make the high-field region extend to the adjacent superlattice period and cause another quantum well to break off from the above resonant tunneling. Another resonant tunneling will occur through the high-field region in the first and second periods of the superlattice and the low-field region in the other periods of the superlattice, as seen in Fig. 3(e). Then, the fourth-route NDR phenomenon will appear. Identically, as the high-field region extends to the third and fourth periods of the superlattice, the fifth and sixth oscillatory behaviors may occur, as illustrated in Figs. 3(f) and 3(g), respectively. This exhibits the interesting multiple NDR characteristic of the studied InP/InGaAs RTD.

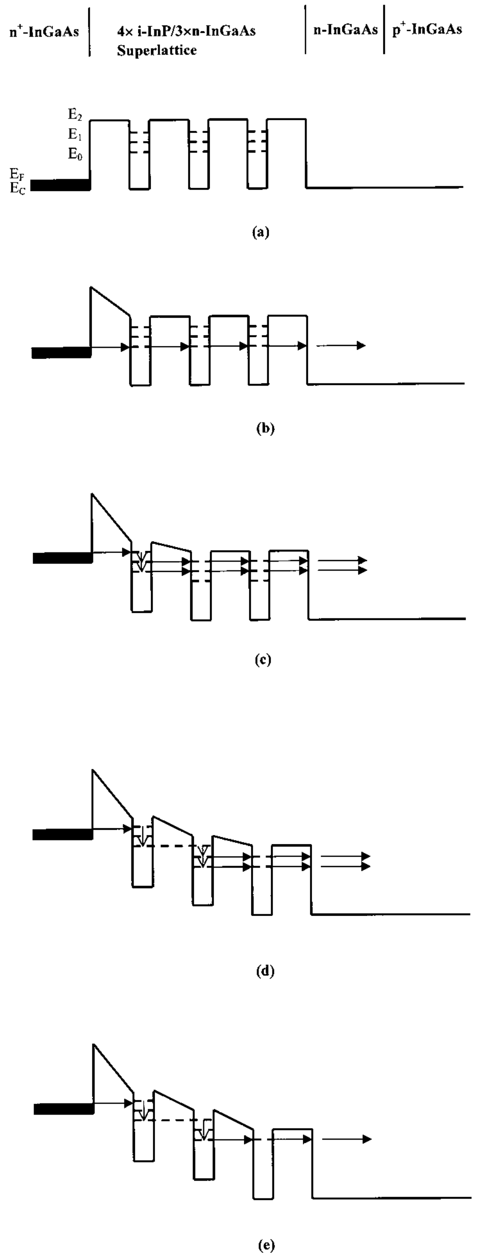


Fig.3. The corresponding conduction band diagram of the InP/InGaAs RTD (a) under flat-band condition, (b) at the onset of E_F aligning to E_0, (c) at the onset of high-field region extending to the second period of the superlattice, (d) at the onset of high-field region extending to the third period of the superlattice, (e) at the onset of the high-field region extending to the fourth period of the superlattice.

Significantly, the experimental I-V characteristic demonstrates that the voltage difference of 30 mV between two NDRs for the first- to third-route NDRs is nearly identical, which means that the energy differences of E_1-E_0 and E_2-E_1 are nearly equal. Also, the voltage difference is of 20 mV is identical for the fourth- to sixth-route NDRs, which indicates that the strength difference of high-field voltage is also the same. Thus, the interesting MNDR characteristic is achieved attributed to the sequential tunneling behaviors.

VI. CONCLUSION

In summary, a novel InP/InGaAs RTD with short-period superlattice has been successfully fabricated and demonstrated. The relatively thin InGaAs wells are employed to form split minibands. The interesting six-route NDRs are achieved attributed from the split miniband structures and the extension of high-field domination in the superlattice. Consequently, the studied device shows good potential for circuit applications.

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