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The Simulation of Composite Resonant Tunneling Diodes for Multiple-Valued Logic Applications

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This paper presents a theoretical study on the composite resonant tunneling diodes (RTDs) for repetition of negative differential resistances (NDRs). A simple method has been proposed to simulate the I-V characteristics of the composite RTDs, and results of the theoretical analysis are reported. Based on a variety of one-peak RTDs, the current-voltage (I-V) characteristics of two or more vertically or horizontally integrated, serially, and in parallel connected RTDs are calculated and analyzed. The simulated results are in good agreement with the experimental data.

1. Introduction

The idea of using the quantized states in ultrathin heterostructures to obtain negative differential resistance (NDR) was first proposed by Esaki and Tsu[1]. Chang[2] observed the first NDR phenomenon at 77 K in a double barrier structure with a thin GaAs well sandwich between two AlGaAs barrier prepared by MBE. For the past decade, RTDs with multiple peaks in the I-V characteristics have attracted considerable interest for digital and analog circuit applications because it greatly reduces circuit complexity[1-4]. Among these applications, multilevel logic is the most potential one[3]. For this application, the RTD is required to have equally spaced and uniform peak current densities with the largest valley current less than the smallest peak current[5]. In general, it is very difficult to obtain satisfied multiple peaks I-V characteristics from individual RTDs. On the contrary, by using of vertically or horizontally integrated RTDs[1,4,6,7] or composite RTDs[3,8] can avoid such a difficulty. However, the dependence of the I-V characteristics of the composite diodes on the electrical properties of the individual RTDs and on the way of combinations has not yet been fully understood. In this study, a self-consistent scheme which solves the Schrödinger's and Poisson's equations with respect to the quantum structures of RTDs is implemented. This program is used to simulate the I-V characteristics of individual one-peak RTDs used for integrated or composite structures. In addition, a simple and efficient scheme based on current conservation and Kirchhoff's law is proposed for the simulation of the I-V characteristics of integrated and composite RTDs. Some interesting simulation results are discussed.

2. Numerical Simulation

In the present work, the self-consistent simulation of single RTD is conducted by solving the one-dimensional Schrödinger equation and the Poisson equation iteratively. However, for the simulation of integrated or composite RTDs, an alternative method is proposed. In general, the integration of a number of RTDs requires long heavily-doped spacer layers in the stacked structure, and thus the self-consistent simulation of I-V characteristics of such a device usually involve very lengthy CPU time and very large amount of memory. In this work, a very simple and efficient approach based on Kirchhoff's voltage law and current conservation, instead of using the self-consistent program, is developed for the simulation of integrated and composite RTDs. Here for illustration, the numerical details of the simulation method is devoted to the case of vertically integrated RTDs (see Fig. 1). For other composite RTDs, the same theory and algorithm can be equally applied. As shown in Fig. 1, based on the fact that the individual RTD in a composite device should operate independently, the vertically integrated RTD is essentially a series combination of a number of individual RTDs and resistors. Note that the resistor R is attributed to the heavily-doped spacer layer in the stacked structure which is required to break the coherence of the electron wavefunction of the two individual RTDs[6]. The numerical simulation for avertically integrated RTD begins with inputting an initial guess of V_1. Based on the given V_1, the value of I_1, V_R $(=I_1R)$, V_2 $(=V_a-V_1-V_R)$, and I_2 can be consecutively obtained. According to the circuit theory of Kirchhoff's law, constraint(s) for either diode currents (for the vertically integrated or serially connected cases) or diode voltage drops (for the horizontally integrated or connected in parallel cases) can then be determined. Based on the constraint (for the present case, I_1 is needed to equal to I_2), V_1 is updated by the following equation :

$$V_1^* = V_1 + \frac{G(V_1^*) - G(V_1)}{G'(V_1)},$$

where

$$G(V_1) = I_1 - I_2 = f_1(V_1) - f_2(V_2),$$

$$G'(V_1) = f_1'(V_1) + f_2'(V_2)*[1 + f_1'(V_1)*R]$$

Note that f_1 and f_2 represent the I-V function of RTD1 and RTD2, respectively. The original value of V1 is then replaced by V_1^* and the above iteration computation continues. The above iteration stops when it is satisfied with the predefined convergent criterion. Note that for the present case, the current difference between RTD1 and RTD2 less than a prespecified relative error is served as the convergent criterion.

3. Results and Discussions

Figure 2 shows the simulated results of a double barrier AlInAs/InGaAs RTD[8]. The simulated curve is in close fit to the experimental data except for the NDR region. The relatively larger discrepancy of curves in the NDR region is thought to be due to the existing of an average ac signal, which results from the occurrence of oscillation in the measurement circuit, has been superimposed on the static I-V curve.With two identical RTDs as shown in Fig. 1 connected in series, simulated results of such a composite RTD is plotted in Fig. 3. Very good agreement between the simulated and experimental curves[8] is shown. In the present case, a resistor of 0.01Ω is used. The insert of Fig. 3 shows the potential drop at each RTD. Note that the present simulation can be employed to clarify the operation of the individual RTDs in composite RTDs. It is found that the series resistor plays an important role on the I-V curve of the composite RTDs. In general, a larger resistor results in a smaller peak current density, a larger valley current density, and a larger shift of the NDR region on the voltage scale. If the two RTDs are not identical in the I-V characteristics, very different results may appear. Figure 4 shows one of the special case. With one RTD has a higher peak current, lower valley current, and a larger operation range of voltage in the NDR region than those of the other, three peaks in the I-V curves may be obtained which is in good agreement with the experimental results reported by Wu *et al*[9]. Figure 5 shows the calculation results of a composite RTD in which two identical one-peak RTDs are connected in parallel. Note R_1 and R_2 are used to model the practical resistance that may arise from different contact condition and/or the cap layer structure. A different parallel-connection of RTDs proposed by Capasso *et al*[3] has also been analyzed. Figure 6 shows the results which is also in good agreement the experiments.

4. Conclusions

In conclusion, we have developed an efficient method to simulate the I-V characteristics of combined RTDs with multiple NDRs. Very good agreement with experimental results has been obtained. The present numerical scheme could provide a clear picture about the details of the operation of individual RTD in an integrated or a composite RTD system. In addition, a criteria for obtaining uniform peaks and valleys, equally spaced NDR regions, and a specified number of NDR regions has proposed which is of important for the optimal composite RTD design.

5. References

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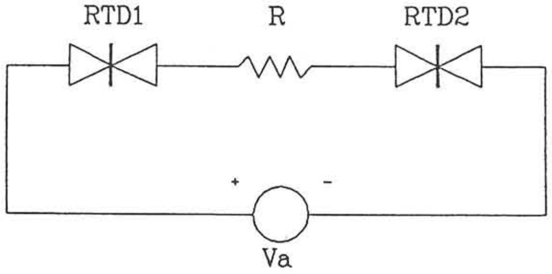

Fig. 1 An equivalent circuit for a vertically integrated RTDs.

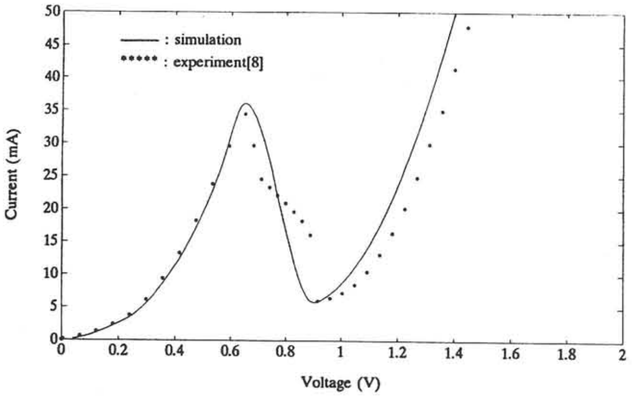

Fig.2 Comparison between the simulated and experimental results of a InAlAs/InGsAs RTD.

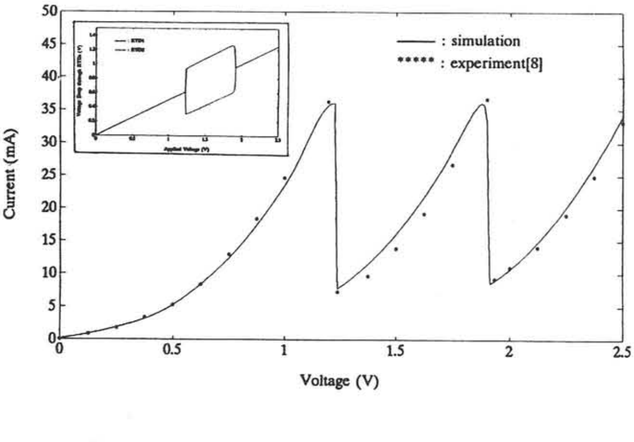

Fig. 3 Comparison between the simulated and experimental results for a composite RTD which is built with the series connection of two identical RTDs as shown in Fig. 1. The inset shows the potential drop at each individual RTD in the composite device.

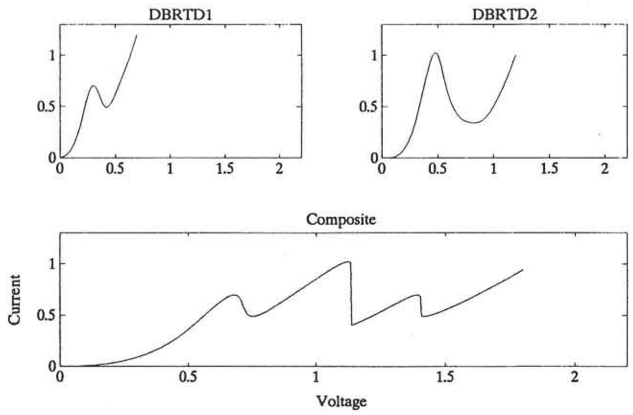

Fig. 4 The simulation result of a composite RTDs which is built with the series connection of two different RTDs. The composite RTD exhibits three peaks in the I-V curve.

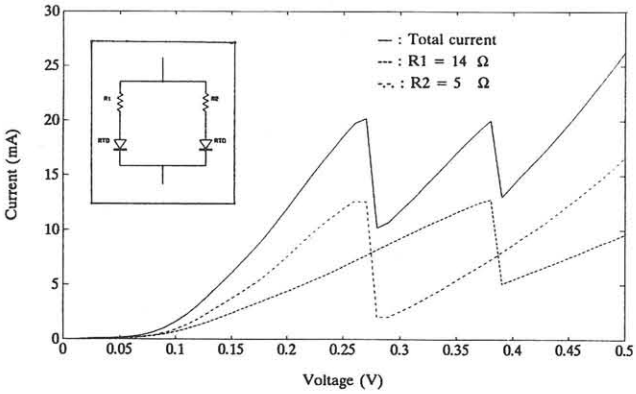

Fig. 5 The simulation result of a composite RTD built with two identical RTDs connected in parallel. The insert shows the circuit configuration.

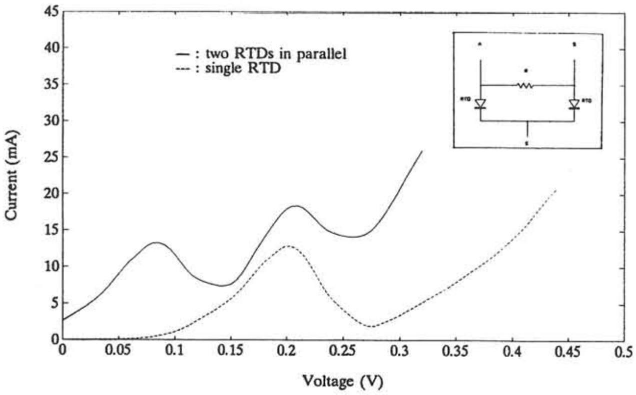

Fig. 6 The simulation result of a different composite RTD built with two identical RTDs connected in parallel. The insert shows the circuit configuration.