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RTD's Relaxation Oscillation Characteristics with Applied Pressure*

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Abstract: The relaxation oscillation characteristics of a resonant tunneling diode (RTD) with applied pressure are reported. The oscillation circuit is simulated and designed by Pspice 8.0, and the measured oscillation frequency is up to 200kHz. Using molecular beam epitaxy (MBE), AlAs/$In_xGa_{1-x}As$/GaAs double barrier resonant tunneling structures (DBRTS) are grown on (100) semi-insulated (SI) GaAs substrate, and the RTD is processed by Au/Ge/Ni/Au metallization and an air-bridge structure. Because of the piezoresistive effect of RTD, with Raman spectrum to measure the applied pressure, the relaxation oscillation characteristics have been studied, which show that the relaxation oscillation frequency has approximately a −17.9kHz/MPa change.

Key words: resonant tunneling diode; relaxation oscillation; Raman spectrum; piezoresistive effect
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1 Introduction

A resistor in a circuit containing a DC source, an inductor, and a capacitor will always undergo damped oscillations. A non-linear resistor with a region of negative differential conductance and set of suitable bias and circuit parameters will sustain repetitive oscillations. RTD is such a semiconductor heterostructure device with negative differential effect, and it has been widely used for high frequency operations and high speed applications. Oscillations of up to 712GHz have been reported[1] and several applications of RTDs for multivalued logic have been proposed[2].

However the RTD current-voltage (I-V) characteristics show special uniaxial stress dependence, mainly in the negative differential resistance (NDR) region[3]. This effect has been used in sensor design, such as pressure sensors and accelerometers[4].

In this work, an equivalent model of RTD and its oscillation circuit are simulated by Pspice 8.0, and its oscillation circuit is designed. Using MBE, the AlAs/$In_xGa_{1-x}As$/GaAs double barrier resonant tunneling structures are grown on semi-insulated (100) GaAs substrate, and RTD is fabricated with Au/Ge/Ni/Au metallization and an air-bridge structure. Finally, the relaxation oscillation characteristics with applied pressure have been studied, which display a frequency change of up to approximately −17.9kHz/MPa.

2 Oscillation circuit design

RTD is a semiconductor hetero structure device based on the quantum-mechanical effect; the principal effects involved are the quantization of electron energies in a quantum well structure and the tunneling of electrons through thin barrier materials.

2.1 RTD's equivalent model

According to Zhao[5], the equivalent model of RTD is shown in Fig. 1. It includes a conductance, a capacitance, and an inductance.

For small signals, the conductance and the capacitance are defined as

$$G = \frac{\partial J}{\partial V} = \frac{j_{i+1} - j_i}{\Delta V} \tag{1}$$

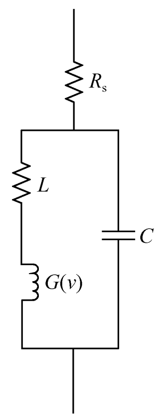

Fig.1　Equivalent model of RTD

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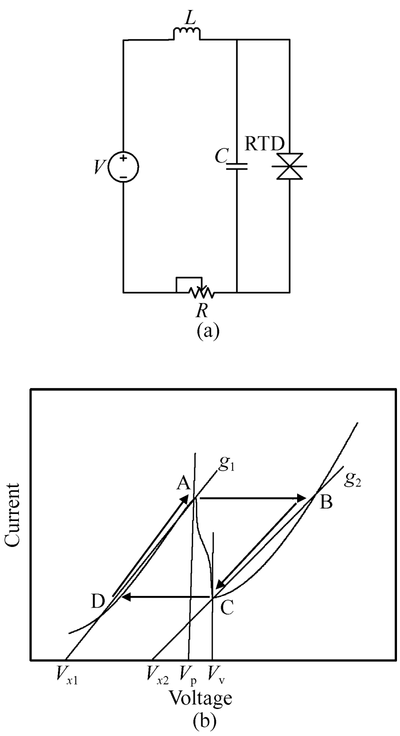

Fig.2 Working principal of oscillation circuit (a) Equivalent model;(b) Working mechanism

$$C = \frac{\Delta Q}{\Delta V} = \frac{Q_{\text{collecter}} - Q_{\text{emitter}}}{\Delta V} \quad (2)$$

where the charges Q_{colleter} and Q_{emitter} are obtained at each bias point by integrating the total charge density on the collector and emitter, respectively.

And the quantum inductance of RTD may be expressed in terms of the lifetime of the quasibound state in the well as

$$L = \frac{\tau}{G} \quad (3)$$

where τ is the lifetime of the charge in the well and G is the conductance.

2.2 Oscillation circuit and its working mechanism

Oscillators constituted by RTD consist of a voltage supply, a serial inductor, and a capacitor in parallel, as shown in Fig. 2 (a). When an RTD is biased in its NDR region, the principle of relaxation oscillation can be explained, as shown in Fig. 2 (b).

First, the current rises until it reaches the peak value (Point A).

The serial inductance, the parallel capacitor, and the NDR force the diode to switch from A to B. The inductance maintains the current while the capacitor takes up the current difference and therefore increases the RTD's voltage. Fast switching from A to B occurs.

The voltage reached is above the bias point and can not be maintained by the voltage source. Therefore, the voltage decreases with a time constant determined through the inductor and the nonlinear RTD's positive resistance.

If the valley voltage (Point C) is reached, a fast switch to point D takes place. The diode current increases while the inductor current remains constant. The current difference is supplied by the capacitor.

Through these four steps, when the bias voltage is in RTD's NDR, the relaxation oscillation will occur.

2.3 Simulation and design

The current flowing through RTD consists of two types of competing parts: tunneling current and excess current[6],

$$J = J_{\text{RT}} + J_{\text{EX}} \quad (4)$$

where J_{RT} is the resonant tunneling current, which induces the negative differential resistance directly; and J_{EX} is the excess current.

According to the equivalent model illustrated above, the circuit of RTD is established by Pspice 8.0. Besides R_s, L, and C, it uses two voltage-controlled current sources to substitute for J_{RT} and J_{EX}, respectively. The oscillator circuit has been conducted too, which employs a voltage source to supply the bias. The relaxation oscillation will occur when the bias voltage is in NDR, and the simulated oscillation frequency is up to 250kHz.

The measured *I-V* curves of RTD show their peak voltage and valley voltage are at 0.57 and 0.64V, respectively, with a peak valley ratio (PVR) about 1.7. Combined with the simulation model, the oscillator circuit has been built too. A change in the bias voltage of RTD and in the NDR, causes a relaxation oscillation to occur. The oscillation frequency was measured at 0.6V bias, which is nearly 200kHz.

The oscillation frequency is almost the same as the simulation results. If the bias voltage continues to increase, the oscillation will remain in NDR, but the oscillation frequency will change, and disappears when the NDR is exceeded.

3 Fabrication of RTD

The AlAs/In_xGa_{1-x}As/GaAs double barrier structures are fabricated on semi-insulated (100) GaAs substrate, grown by MBE.

Because of the influence of the resistance and the capacitor on the oscillation frequency, Au/Ge/Ni/Au metallization and air-bridge structures are introduced, and the RTD is processed. Detailed fabrication steps are shown in Fig. 3 (a), and the SEM of RTD is shown in Fig. 3 (b).

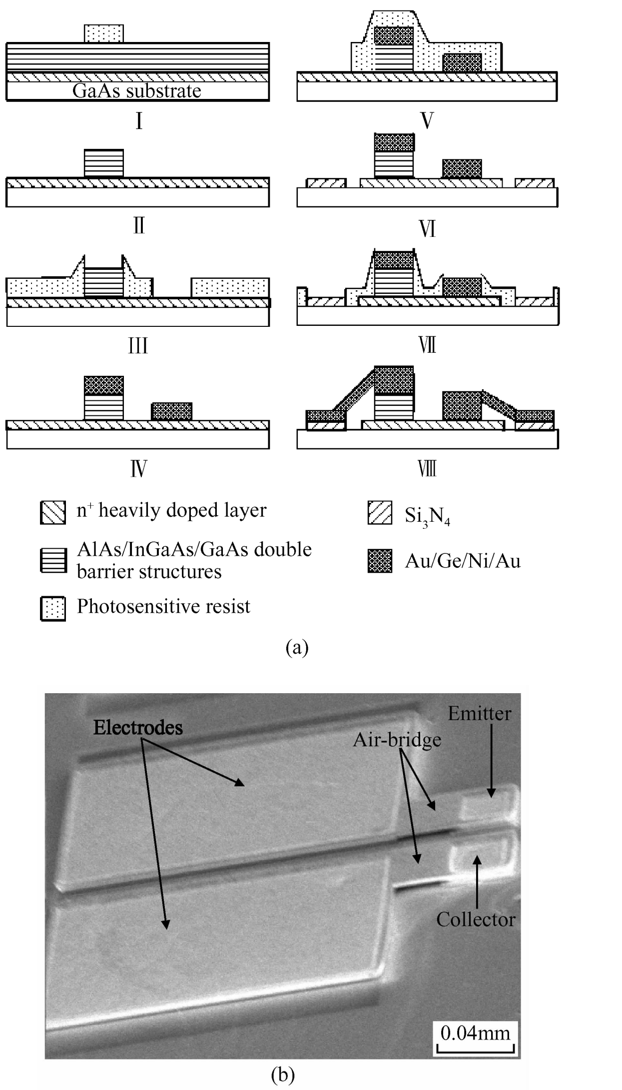

Fig.3　Fabrication and the SEM of RTD　(a) RTD's fabrication;(b) SEM photo of the RTD

4　Measurement and discussion

4.1　Oscillation characteristics with applied pressure

A Raman spectrum can measure the lattice vibrational energy of a material accurately. When stress exists in the microstructures, the lattice structure of the material changes, so using Raman spectrum can determine the stress of a material exactly[7].

We have introduced the Raman spectrum to measure the pressure changes applied on RTD, with a probe applying the stress to RTD and using Agilent4156C semiconductor analysis for current-voltage curve measurement. Figure 4 is the sketch map of the measurement system.

The inductance and the resistance in series are fixed at 22μH and 0.5Ω, respectively and the paralleled capacitance is 0.01μC. To deduce the influence of the environment and the electrical parameters, measurements were conducted at a stable temperature

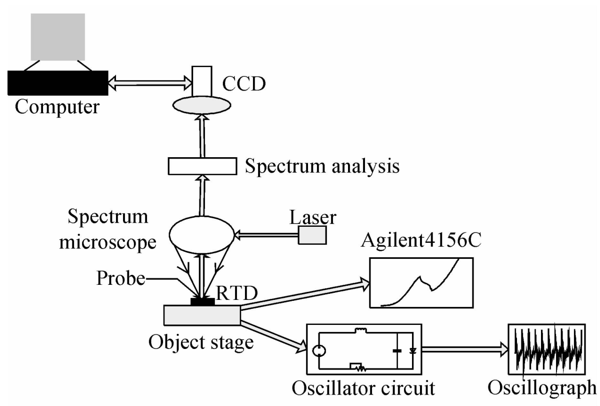

Fig.4　Sketch map of measurement system

(22℃ approximately) and at short intervals (30min in all). After the establishment of a measurement system, the conducting wires use twisted-pairs and were fixed to deduce the effect of the coupling inductance. The bias voltage was also nearly invariable, supplied by a MAX8526, which is a low-dropout linear regulator, and its output voltage accuracy is ±1.4% between 0 and 85℃.

Using an Agilent 4156C, the excursions of RTD's I-V curves were measured and an important phenomenon observed, as $\Delta R/R$ changed at different rates with applied stress. The change rate in NDR is much larger than other regions.

Setting the bias voltage of RTD in one point of its NDR, relaxation oscillation will occur and remain. Using the probe and Raman spectrum to apply and measure the stress, respectively, the oscillation frequency's variety with the applied pressure is shown in Fig. 5.

4.2　Discussion

For RTD, the change of the position of the energy states in the quantum well with applied external pressure can be attributed to two major effects: the pressure induces the change in the electrons effective mass and the generated piezoelectric fields inside the

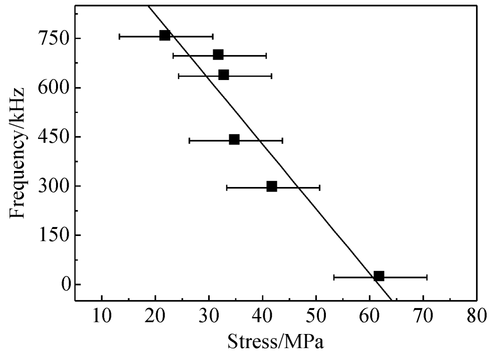

Fig.5　Measurement results

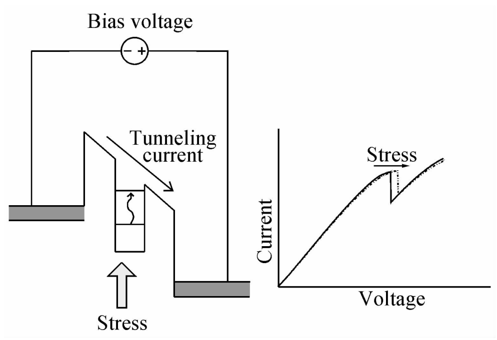

Fig.6 Piezoresistive effect of RTD

well and the barrier materials. Hydrostatic pressure induces a variation of carrier effective mass, which shifts the energy states in the well.

In the case of uniaxial and biaxial pressures, the piezoelectric field induced contribution to the energy shift is stronger than the one related to the effective mass change. The well-known effects are: the energy band gap variation with hydrostatic pressure, the stress induced piezoelectric field in Ⅲ-Ⅴ compound semiconductors, the change of the band edge curvature, and the band edge splitting with uniaxial pressure. Then, the *I-V* characteristics of RTD will change. The observed effects are principally a shift of the peak and the valley voltages, and a shift of the peak and the valley currents[8], shown in Fig. 6.

For the oscillation circuit in Fig. 2 (a), because the corresponding switching time from A to B and C to D is very short compared with the time from B to C and D to A, the capacitor can be neglected. Therefore, we only need to calculate the time for the D to A and B to C transitions. The following equation can be obtained:

$$V_o = Ri_d + L\frac{d_{i_d}}{d_t} + V_d \tag{5}$$

where V_d and i_d are the bias voltage and the current flow in RTD, respectively.

The next simplification will be to approximate the *I-V* curve between D to A and B to C through linear functions, so that g is constant in the two positive resistance regions. The equation can then be easily solved by using the following assumption:

$$i_d = gV_d - gV_x \tag{6}$$

Thus, Equation (5) can been written as

$$V_o = (Rg+1)V_d - RgV_x + gL\frac{d_{V_d}}{d_t} \tag{7}$$

For solving the differential equation, a boundary condition is necessary. If the transition from point D to A (B to C) is set to begin at $t=0$ and the corresponding voltage at point D (B) is $V_D(V_B)$, the solution for the entire oscillation period, under the assumption that gR is much less than 1, is:

$$t = g_1 L\left[\ln\left(\frac{V_D - Rg_1V_{x1} - V_o}{V_p - Rg_1V_{x1} - V_o}\right)\right] + g_2 L\left[\ln\left(\frac{V_B - Rg_2V_{x2} - V_o}{V_v - Rg_2V_{x2} - V_o}\right)\right] \tag{8}$$

Looking at Eq. (8), the oscillation frequency is decided by L, R, V_p, and V_v, *et al*. Because of the piezoresistive effect of RTD, which will vary its *I-V* curves as illustrated above, the oscillation frequency will change as pressure is applied, and due to the different change rate of $\Delta R/R$ in NDR, the changed value of frequency can be adjusted by the bias voltage.

The change of the oscillation frequency can be calculated as follows:

$$S = \frac{\partial f}{\partial s} = \frac{\sum_{i=1}^{n}(f_i - f_0)}{\sum_{i=1}^{n}(s_i - s_0)} \tag{9}$$

For these types of RTDs and the circuit parameters, the change is -17.9kHz/MPa approximately, here the negative sign indicates the frequency decreases as pressure is applied.

4.3 Error analysis

As simulation and measurement results show, the resistance in series with RTD can affect its *I-V* characteristics greatly. Figure 7 (a) is the measured RTD's *I-V* characteristics with the resistance in series. As the resistance increases, the gap between the peak and valley voltage shrinks, which makes the RTD's NDR much narrower. At the same time, the peak current is nearly unchanged, but the valley current is larger, and the PVR decreases.

Another cause of the measured oscillation frequency error is the influence of environment, such as temperature. Some papers have proposed that as temperature increases, the peak current will decrease and the valley current will increase, which results in the fall of the PVR as a whole; the opposite is just the reverse[9], and Figure 7 (b) is the measured *I-V* characteristics at various temperatures.

5 Conclusion

This paper reports the equivalent model and oscillator circuit of RTD established and simulated by Pspice 8.0. Using a simple circuit with a DC voltage source, a capacitance, and an inductance, the relaxation oscillation circuit of RTD has been designed, and the measurement results are nearly identical to the simulation results. Because of the piezoresistive effect of AlAs/$In_xGa_{1-x}As$/GaAs double barrier RTDs, the relaxation oscillation characteristics with applied

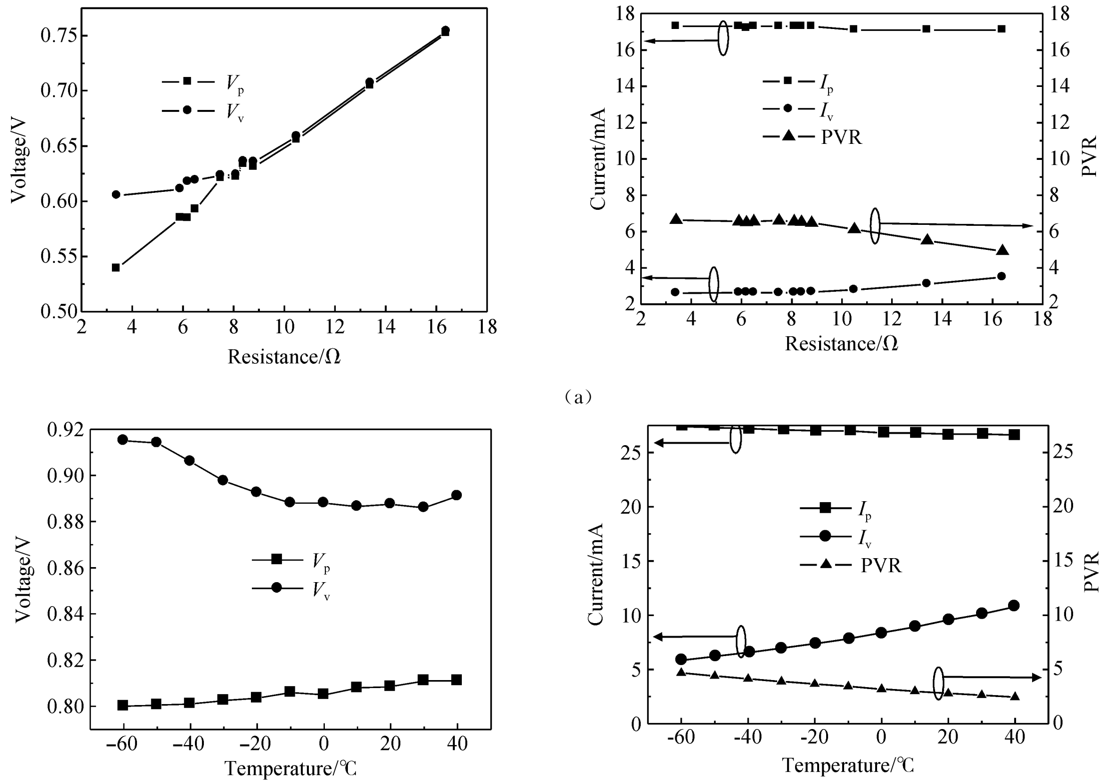

Fig. 7　RTD's *I-V* characteristics with resistance in series and temperature variety　(a) With the resistance in series; (b) At different temperatures

pressure have also been conducted, the observed frequency change is approximately −17.9kHz/MPa.

The piezoresistive effect of AlAs/$In_xGa_{1-x}As$/GaAs double barrier structures based on RTD's relaxation oscillation implies that it can be used to design some novel sensors with frequency output, and compared with the piezoresistive effect of silicon, these types of devices have many excellent features, such as sensitivity, which can be adjusted by the bias voltage, half-digital outputs, and so on.

Measurement error is mainly attributed to the resistance and coupling inductance of the conducting wires, and the environment influence, such as temperature. Future work will include:

(1) RTDs with much lower current, higher PVR, and wider NDR;

(2) Optimized circuit parameters for precise pressure measurement.

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RTD 在压力下的弛豫振荡特性*

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摘要： 报道了共振隧穿二极管(RTD)在压力下的弛豫振荡特性.采用 Pspice 8.0 软件仿真并设计了振荡电路，测得其振荡频率达 200kHz.在(100)半绝缘(SI)GaAs 衬底上利用分子束外延(MBE)技术生长了 AlAs/In_xGa_{1-x}As/GaAs 双势垒共振隧穿结构(DBRTS)，并采用 Au/Ge/Ni/Au 金属化和空气桥结构成功加工出了 RTD.由于 RTD 的压阻效应，采用显微喇曼光谱仪标定所加应力大小，对 RTD 在加压条件下的振荡特性进行了研究，结果表明其弛豫振荡频率大致有 −17.9kHz/MPa 的改变量.

关键词： 共振隧穿二极管；弛豫振荡；喇曼光谱仪；压阻效应

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