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RESEARCH ARTICLE

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Piezoresistive properties of resonant tunneling diodes

Abstract A measurement system was designed and established to test the piezoresistive properties of resonant tunneling diodes (RTDs). The current-voltage characteristic shifts of RTD at different stress states were detected. The experimental results demonstrate that the piezoresistive sensitivity of RTD is larger than 1×10^{-8} Pa^{-1}. To accurately represent the piezoresistive properties of RTD, the current-voltage characteristic coherence of the same RTD was tested. According to the experimental results, the largest relative resistance shift of an RTD in the same measurement environment is less than 3%, of which 1% is caused by the testing apparatuses.

Keywords RTD, piezoresistive property, coherence, sensitivity, Raman

1 Introduction

Since the first observation of the negative differential resistance in the double barrier quantum well structure [1], the research on resonant tunneling diodes (RTDs) has been going on for two decades. RTDs, with features such as high speed, high frequency, and low voltage and power, have been extensively adopted in digital-logic circuits, analog circuits, signal processing, and digital-analog converter circuits as well as in microwave applications [2–5]. All these have taken advantage of the negative differential resistance effect of RTDs. In this paper, another important property of RTD, the piezoresistive property [6], is taken as a basis to study their mechanical-electrical converting capability.

The resonant tunneling effect-based RTD is a double-barrier-quantum-well structure, in which piezoresistive effect can be observed. In the aspect of quantum principal, this effect can be explained as follows. When a mechanical load is applied to RTD, a stress distribution will be generated in the quantum-well structure. Such a stress distribution will originate an inner electrical field in the quantum well and the existence of the inner electrical field will result in changes of the quantum energy level. Consequently, the change of the quantum energy level will finally cause a variation in resonant tunneling current. In short, the current-voltage characteristic of RTD will be changed when the applied mechanical load changes. At a certain biased resonant tunneling voltage, the relation between the mechanical load and the tunneling current can be equivalent to that between the mechanical load and the resistance variation [7,8]. According to some researches [9,10], the influence of temperature on the piezoresistive property of RTD is less than that on silicon-based piezoresistive property. What's more, the piezoresistive sensitivity of RTD is five to six times larger than that of silicon.

To quantitatively represent the piezoresistive property of RTD, a testing system used to test the piezoresistive property of GaAs-based RTD was established. Using this testing system, this paper measured the piezoresistive property of RTD, and analyzed its sensitivity. Moreover, to make the quantitative expression of RTD much more accurate, resistance coherence of the same RTD in the same testing environment was studied.

2 Sample preparation

By utilizing the molecular beam epitaxy (MBE) technique, RTD material structures were successfully generated on the GaAs substrate. The most important part of RTD is the AlAs/GaAs/In$_{0.1}$Ga$_{0.9}$As/GaAs/AlAs double barrier single quantum well structure.

Afterwards, an etching step was adopted to release the RTD structures. The structure and dimensions of the RTD material are shown in Fig. 1, from which we can see that two 5-nm undoped In$_{0.1}$Ga$_{0.9}$As layers were inserted into the insulating layers of the collector and emitter region. The purpose of doing so is to form a pre-well between the emitter region and the barrier region. In the pre-well there exist discrete energy levels, thus this structure transfers the resonant

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tunneling between the emitter region and the well to that between the pre-well and the well, which will result in a lower peak-voltage, a higher peak-to-valley current ratio (PVCR), a smaller area of emitter and a reduced latent capacitance. Furthermore, to reduce the parasitic capacitance and eliminate the marginal problem, a lift-off (double-air-bridging) technique was adopted to connect the electrodes with mesa located on the buffer layer. Figure 2 shows a scanning electron microscope (SEM) of the double-air-bridging structure in RTD. To eliminate the influence of the package on the piezoresistive properties of RTDs, all the testing samples used in this paper are naked chips.

N^+-GaAs	$3 \times 10^{18}\ \mathrm{cm}^{-3}$	500 nm
N^+-GaAs	$10^{17}\ \mathrm{cm}^{-3}$	10 nm
GaAs	Undoped (UD)	5 nm
$In_{0.1}Ga_{0.9}As$	UD	5 nm
GaAs	UD	0.5 nm
AlAs	UD	1.7 nm
GaAs	UD	0.5 nm
$In_{0.1}Ga_{0.9}As$	UD	4 nm
GaAs	UD	0.5 nm
AlAs	UD	1.7 nm
GaAs	UD	0.5 nm
$In_{0.1}Ga_{0.9}As$	UD	5 nm
GaAs	UD	5 nm
N^+-GaAs	$10^{17}\ \mathrm{cm}^{-3}$	10 nm
N^+-GaAs	$3 \times 10^{18}\ \mathrm{cm}^{-3}$	1 000 nm
Si-GaAs	substrate	

Fig. 1 GaAs based AlAs /GaAs /InGaAs quantum well structure

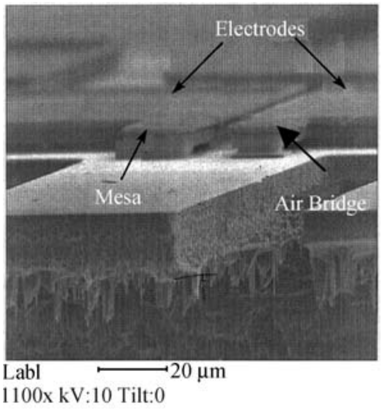

Fig. 2 SEM of a fabricated RTD structure

3 Experimental technique

As RTD is a film structure with double barrier single well, when the biased voltage of which is within a certain range, the resonant tunneling phenomenon will occur. What is more, with the variation of biased voltage, the resonant tunneling current will change. To illustrate the current-voltage characteristic curve of an RTD structure, a semiconductor parameter analyzer (Agilent 4156C) was employed. Meanwhile, to demonstrate the relation between the shift of the current-voltage characteristic and the applied pressure, the pressure should be precisely measured. In the testing system, a Raman spectrum analyzer (RENISHAW inVia) together with its fiber testing system was utilized to calibrate the stresses caused by the loaded pressures. The testing error of RENISHAW Raman spectrum analyzer is quite small, which will not affect the experimental results.

Figure 3 shows the schematic diagram of the testing system set up for the experiment. In the experiment, the testing sample is fixed at the center of the probe station, which would load on the structure a group of gradually increasing pressures with the function of its fixed probe tip and its height controlling button. After each pressure loading, the current-voltage characteristic of RTD was illustrated by the Agilent 4156C, and the value of the stress was calibrated by Raman spectrum analyzer. The whole testing procedure was inspected under a microscope.

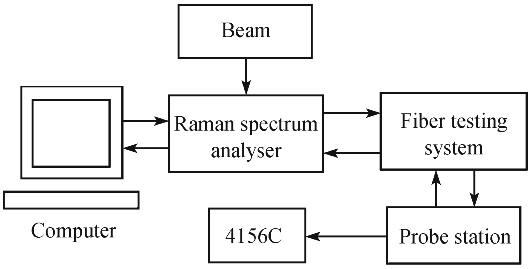

Fig. 3 Schematic diagram of the testing system

4 Experiment and analysis

4.1 Experiment description

To quantitatively express the piezoresistive property of RTD, a group of pressures were applied to the first RTD (RTD1) and the values of stresses were calibrated by the fiber testing system of the Raman spectrum analyzer. In the experiment, the probe tip (used for loading) was aimed at one of the electrodes of RTD, while the testing position of the Raman spectrum analyzer was at a place near the mesa of the RTD, as shown in Fig. 4.

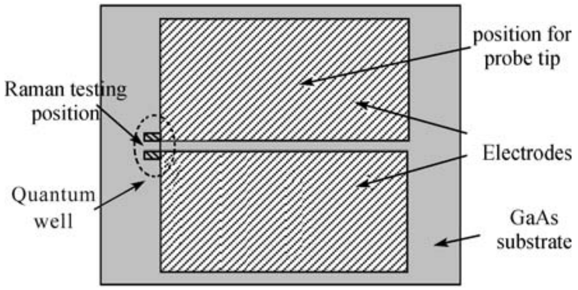

Fig. 4 Schematic diagram of RTD structure

Before calibrating the values of stresses, the residual stress σ_r (the inner stress resulting from the fabrication process, not influenced by the applied pressures) of the RTD structure at a free state (without any applied pressure) was calibrated as 1 277.366 MPa. Then the station was elevated by pushing the controlling button, therefore, a group of increasing pressures were applied to the structure. At the loading moments of the pressures, the stress σ of RTD was obtained by Raman spectroscopy. The value of the applied pressure P can be calculated as

$$P = \sigma - \sigma_r \tag{1}$$

Here, σ is the obtained value of stress on the surface, the unit of which is MPa. For a GaAs (100) crystal plane, the relationship between Raman shift and the stress is

$$\sigma = -576\Delta\omega \tag{2}$$

where $\Delta\omega$ is the Raman shift, the unit of which is cm^{-1}. The stress calibration results are shown in Fig. 5. According to Eq. (1) and Fig. 5, the values of the applied pressure are 0 MPa, 13.824 MPa, 25.344 MPa and 31.104 MPa, respectively.

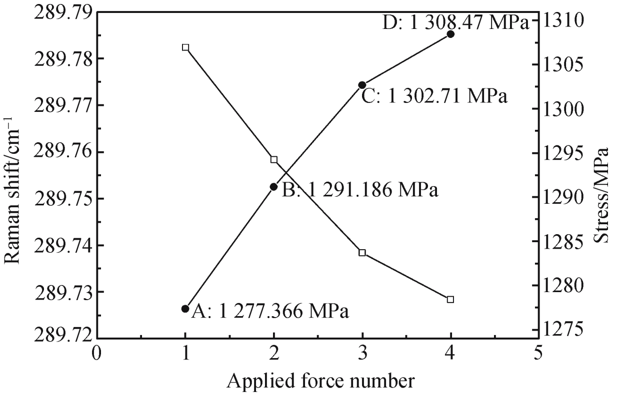

Fig. 5 Raman shifts and different stresses

To demonstrate the current-voltage characteristics of RTD at different stress states, the semiconductor parameter analyzer was connected with the emitter and collector electrodes, and the voltage of the analyzer was set to a certain range. Subsequently, after each pressure loading, the current-voltage characteristic of the quantum well structure was obtained. The position of the quantum well in the RTD structure is shown in Fig. 4.

To eliminate the influence of laser on the property of RTD, at every loading moment, the current-voltage characteristic of RTD was measured before the stress calibration. There were several minutes interval between the stress calibration and the next current-voltage characteristic measurement. The purpose of doing so was to ensure that the former stress calibration would not affect the ensuing current-voltage characteristic measurement. Figure 6 illustrates the current-voltage characteristics consistent with the pressures given in Fig. 5.

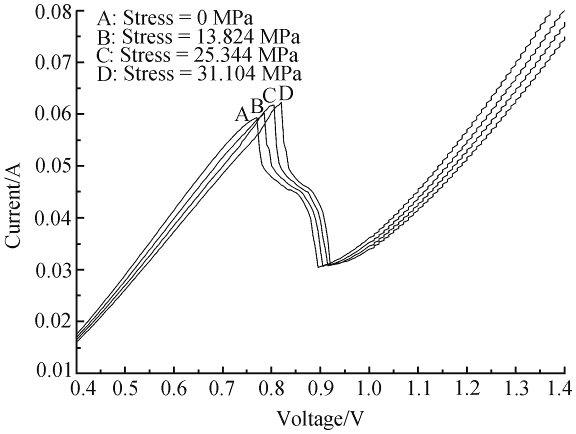

Fig. 6 Current-voltage characteristics of RTD at different pressure loading states

To make the quantitative express of piezoresistive properties of RTDs much more accurate, we analyzed the current-voltage characteristic shift resulting from the instability of the structure itself. In this paper, the current-voltage characteristic coherence of RTD under the same testing condition was studied. In room temperature (strictly controlled to be 300 K) and vacuum conditions, the current-voltage characteristics of the same RTD structure (RTD2) were measured for five times. The biased voltage range was set from −2 to 2 V, in which there were 400 testing points, as shown in Fig. 7. In the figure, five lines of different shapes were used to illustrate the above five characteristic curves. To make it easier for observation and analysis, the curves within the voltage range of 0.7 to 1.5 V are shown in Fig. 7.

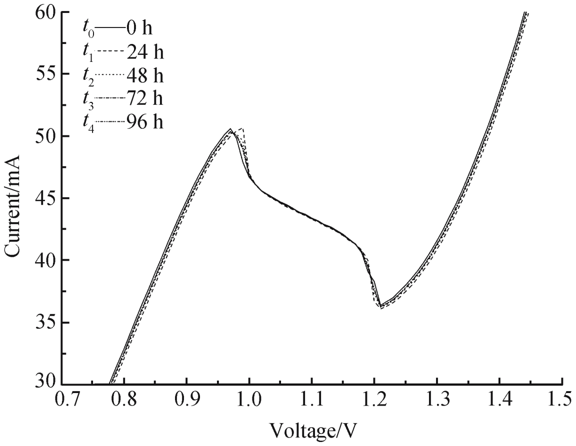

Fig. 7 Current-voltage characteristics of RTD at different time

4.2 Sensitivity analysis

Suppose that the resistance is R_0 when the applied pressure is 0 MPa, while at other pressure loading states, the resistance is $R_i\,(i=1,2,\ldots,3)$, thus the piezoresistive sensitivity is

$$s = \frac{R_i - R_0}{R_0 P} \tag{3}$$

where P is the four applied pressures.

According to Eq. (3), we obtained the relation between sensitivity and its corresponding pressure at different loading states, as shown in Fig. 8. As shown in the figure, whatever the applied pressure would be, the largest sensitivity always appears at a biased voltage of 0.895 V, which is the 'valley' position. In other words, at the valley position, the piezoresistive property of RTD is the most obvious. According to quantum theory, with the function of different biased voltages, there will be a shift of E_o, which is the energy level of the first quantum well in the resonant tunneling film. When $E_\mathrm{o}=E_\mathrm{c}$ (where, E_c is the energy level at the bottom of the conductive band in emitter electrode), the tunneling current reaches the largest value, namely the peak. When E_o is reduced to the lowest value, the tunneling current passing through the double barrier reaches its lowest value, namely the valley. The shift of E_o within the quantum well leads to the largest variation of current at its peak and valley positions, which results in the largest variation of resistance. According to Eq. (3), the largest piezoresistive sensitivity appears at the position of peak or valley, and the position will not change as the applied pressure changes. Among the different testing samples, there are some differences in the fabrication process and the inner parameters. For a certain RTD, the largest sensitivity may appear at its peak or valley position. As to the RTD structure studied in this paper, it appears at the valley position due to its parameters and its fabrication processes.

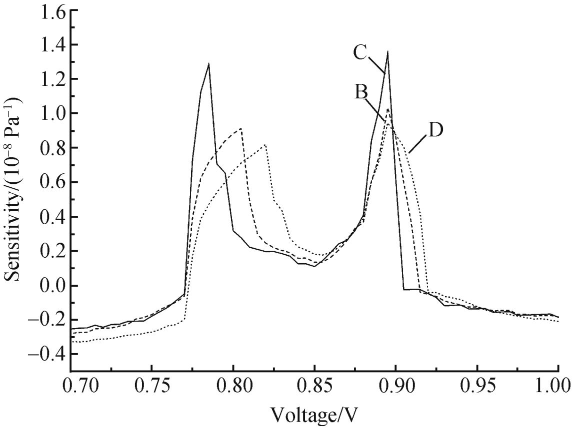

Fig. 8 Relationship between the voltage and sensitivity of a RTD

According to Fig. 8, the largest piezoresistive sensitivity of the RTD structure is larger than 1×10^{-8} Pa^{-1}. When compared with the piezoresistive sensitivity of silicon, the largest sensitivity of RTD is larger than that of silicon by almost ten times (the largest sensitivity of silicon is 1.381×10^{-8} Pa^{-1} [11]).

4.3 Coherence analysis

From Fig. 7 it can be known that under the condition of the same temperature and pressure, the current-voltage characteristics of the same RTD structure are different at different times; the largest relative resistance shift of the RTD is $\left|\frac{R_i - R'_0}{R'_0}\right|$ ($i=0,1,\ldots,4$), which is smaller than 3% (where R_i is the resistance tested at different time, R'_0 is the average resistance of R_i). Figure 9 shows the relation between the relative resistance shift of different times and the biased voltage.

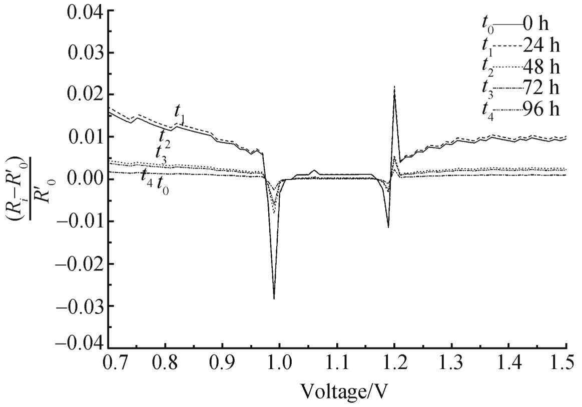

Fig. 9 Relation between the voltage and relative resistance shift

With a strict control of the temperature and pressure in the measurement environment, the main cause leading to the shift was the measurement error of the testing apparatuses as well as the instability of the sample structure resulting from the fabrication processes. Using the same testing system, a resistor with fixed resistance (theoretically to be 15 Ω) was detected to be 14.935 686 ± 0.000 000 2 Ω, the largest relative resistance shift was analyzed to be 1%. Therefore, we consider that 1/3 of the 3% relative resistance shift of RTD was caused by the testing apparatuses.

Subsequently, according to Fig. 6, when the RTD structure was at the four pressure loading states, the largest relative resistance shift increased as the pressure increased, and the values of which were 14.3%, 25.9%, and 29.2%, respectively. Compared with 3%, it can be known that the measurement error of piezoresistive property caused by instability of RTD is quite low.

5 Conclusion

The AlAs/GaAs/InGaAs quantum well structure was designed and the film structure was successfully generated using the MBE technique. With an etching process and a lift-off (double-air-bridging) technique, the RTD structure was formed. A piezoresistive property measurement system was established with a semiconductor parameter analyzer, a Raman spectrum analyzer, and a probe station. The current-voltage characteristics of RTD in the same environmental condition and at different pressure loading states were measured. From the experimental results, the largest resistance shift of RTD in the same environmental condition is smaller than 3%, the piezoresistive sensitivity of RTD is larger than 1×10^{-8} Pa^{-1}.

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