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Piezoresistive effects of resonant tunneling structure for application in micro-sensors

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In this paper, piezoresistive properties of resonant tunneling structure made of undoped InGaAs/AlAs double-barrier quantum layers have been experimentally investigated, and the resonant tunneling structure was grown by molecular beam epitaxy (MBE) on semi-insulation (001)-oriented GaAs substrate. We found that the piezoresistivity of such quantum layers is about one order higher than that of the commonly used silicon structures. Micro accelerometers based on InGaAs/AlAs double-barrier resonant tunneling structures have also been designed and fabricated by control hole technique.

Keywords: Resonant tunneling, Piezoresistor, Double-barrier microstructure, Superlattice

IPC Code: B06B1/06; C30B

1 Introduction

The micro accelerometers based on piezoresistive effect have been extensively investigated because of their simple structures and well developed fabrication processes. Actually, there have been a lot of piezoresistive micro accelerometers on the market, such as 3058, 3022, 3031 and 3035 from IC Sensor, 2225M5A from ENDEVCO Co, 50B21 from PCB Co, 8042 and 8043A100 from Kistler Co, 5004 and 5009 from Columbia Research Laboratories. To further develop this kind of sensors and make them satisfy some special applications, the piezoresistivity of the sensing elements has to be largely improved.

The resonant tunneling diode (RTD) has been widely studied not only because of its applications in high speed/functionality circuits and devices, but also because of its application in the field of nano-electro-mechanical system[1,2] In this paper, we report on the effects of uniaxial pressure on 001-oriented AlAs/InGaAs double barrier resonant tunneling diodes RTDs. Pressure experiment on AlAs/InGaAs resonant tunneling diodes has been conducted, and the characteristics of piezoresistive effect are presented.

The negative differential resistance exhibited by resonant tunneling diodes (RTDs), the technological progress in epitaxial growth of heterostructures and the physics involved in the conduction mechanisms have stimulated a great deal of efforts on RTDs. Parallel to the progress made in the epitaxial growth, pressure experiments have been conducted at different temperatures on different RTDs structures with more or less pronounced resonance effects[3].

Pressure or stress plays a very important role for the transport properties in semiconductor materials. 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[4].

All these effects have been previously used in diverse integrated semiconductor pressure sensors with an improved degree of miniaturization[5-7]. Due to the aforementioned properties, the band structure and the line-up of the band discontinuities in heterostructure devices result in a defined pressure dependence of the transport properties. In this paper, the piezoresistive effects of the InGaAs/AlAs double-barrier resonant tunneling structures under pressure are presented, and the design and fabrication of micro-sensors based on RTDs are discussed.

2 Design and Fabrication Process

The double-barrier InGaAs/AlAs quantum layers were grown in a gas source molecular beam epitaxy (MBE) on semi-insulation (001)-oriented GaAs

substrate. A cross-sectional view of the RTD structure is shown in Fig.1. The GaAs/ $In_{0.1}Ga_{0.9}As$/GaAs quantum well serves to increase the peak–to-valley radio (PVCR) by increasing the separation between quasi-bound resonant states due to the lower effective mass of $In_{0.1}Ga_{0.9}As$ over GaAs, and by lowering the first resonant voltage. The barriers are formed by two symmetric AlAs layers. Because of the strain, the thickness of the AlAs barriers should be limited in the range 15-20Å. A GaAs/$In_{0.1}Ga_{0.9}As$/GaAs prewell between the emitter and the barrier, is employed to prevent impurity from diffusing into barrier as well as lower the peak voltage.

Fig. 2 shows the sketch map of the cross- section of the RTD, which has been formed by the process of surface micromachining and based on the GaAs bulk micromachining process, the cantilever and the proof mass were formed. First of all, double-barrier resonant tunneling microstructure was grown by MBE on the GaAs substrate. Then the first mesa is etched by reactive ion etching (RIE) to the collector layer. Afterwards an Au/Ge/Ni layer is deposited and etched to form emitter and collector ohmic contact. In addition, a second mesa is etched in the same way to the substrate, and 3000Å Si_3N_4 passivation layer is deposited by PECVD. Subsequently, down-lead holes are etched into the collector and emitter, and a sacrificial layer is deposited to fabricate air-bridge. A Cr/Au metal layer is vaporized and Au is electroplated.

N^+-GaAs	$3\times10^{18}cm^{-3}$	500nm
N^+-GaAs	$2\times10^{17}cm^{-3}$	10nm
GaAs	Undouped	5nm
$In_{0.1}Ga_{0.9}As$	Undouped	5nm
GaAs	Undouped	0.5nm
AlAs	Undouped	1.7nm
GaAs	Undouped	0.5nm
$In_{0.1}Ga_{0.9}As$	Undouped	4nm
GaAs	Undouped	0.5nm
AlAs	Undouped	1.7nm
GaAs	Undouped	0.5nm
$In_{0.1}Ga_{0.9}As$	Undouped	5nm
GaAs	Undouped	5nm
N^+-GaAs	$2\times10^{17}cm^{-3}$	10nm
N^+-GaAs	$3\times10^{18}cm^{-3}$	1000nm
SI-GaAs substrate		

Fig. 1 — Double-barrier structure as grown by MBE

Finally, the sacrifice layer is removed and the RTD structure is formed. The quad-beam and the proof mass of the accelerometer were fabricated by GaAs controlling hole etch technology.

Fig. 3 shows the GaAs accelerometer structure being formed via control hole technique. In this case, holes have been etched from the front side as deep as the required beam thickness. The backside etching has to be stopped when the front side holes are visible. The front side and backside etching has been done both using ICP (Inductively Coupled Plasma) etching with argon and Cl_2 as etching gases.

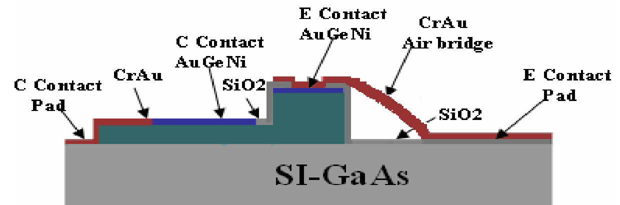

Fig. 2 — Sketch map of the cross-section of the RTD

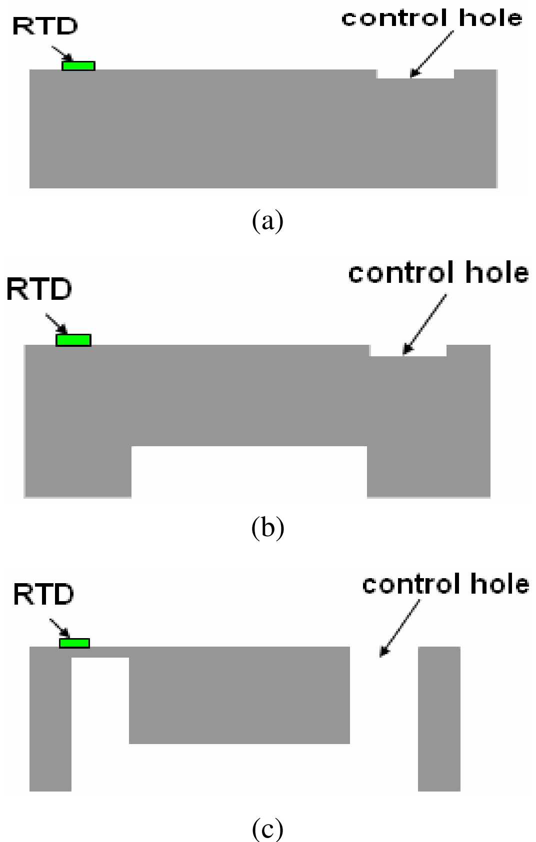

Fig. 3 — Controlling the thickness of beam via several control holes on the front side

To study the piezoresistive properties of the fabricated resonant tunneling structure, an RTD based micro accelerometer with a cantilever-mass structure has been used, Fig.4 shows the SEM picture of the RTD based accelerometer that we have fabricated. Since the acceleration applied to the sensor will be the same as that of applied pressure to the mass at its center, the base of the cantilevers will sense the largest stresses. Thus, when RTDs are located at the base of each cantilever, they will under the largest strains so that providing the largest sensitivities.

3 Experimental Details and Discussion

Pressure experiments have been conducted on the accelerometer structure to study the piezoresistive effects of resonant tunneling structure, piezoresistive effect is defined as a change in electrical resistance of solids when subjected to stress fields. Fig.5 shows the schematic of the pressure-dependent measurement system, pressure is applied to the proof mass of the accelerometer structure by the probing station, the *I-V* characteristic of the RTD was tested by using Agilent 4156C semiconductor parameters analyzer and the stress *S* is quantitated by Raman spectroscopy, the resolution of the Raman spectrum is 0.02cm^{-1}, and the specific principle was shown in Ref. (8). In terms of the experiment, it is found that AlAs/InGaAs double-quantum-well nano-thin film has remarkable negative differential resistance (NDR) and more sensitive piezoresistor effect.

All the measurements were performed at room temperature (300K). The following parameters have been measured for the AlAs/InxGa1-xAs/GaAs RTDs without applied pressure: a current peak-to-valley ratio (PVR) of 1.8, peak and valley voltages of 0.79 and 0.835 V, respectively, and the corresponding peak and valley currents of 69.7 and 38.7mA, When pressure was applied with probe for the RTDs, testing the *I-V* curves, the most obvious effect is the shift in the peak voltages, and the measured *I-V* curves and piezo-resistive effects in different bias voltage are presented in Fig. 6. It shows that the negative differential resistance region is most sensitive to the pressure.

In order to analyze the piezoresistive effect, the piezoresistive sensitivity and linear correlation have been taken into accounted, and the piezoresistive sensitivity *K* has been defined as the change rate of the resistance under unit stress[9]. Under a given bias, the resistance can be denoted:

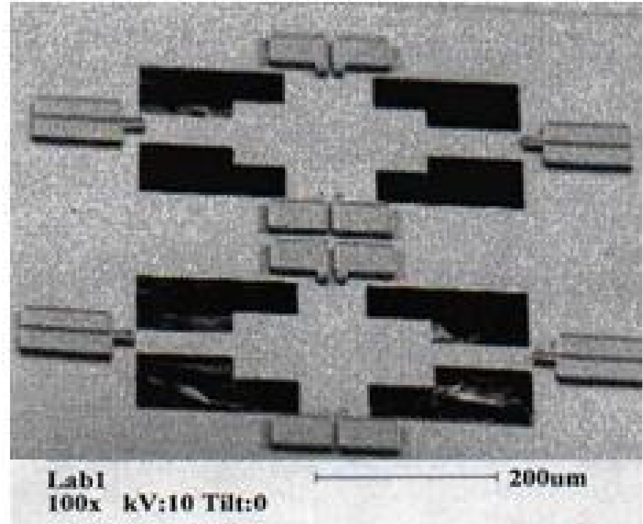

Fig. 4 — Structure of RTD based accelerometer

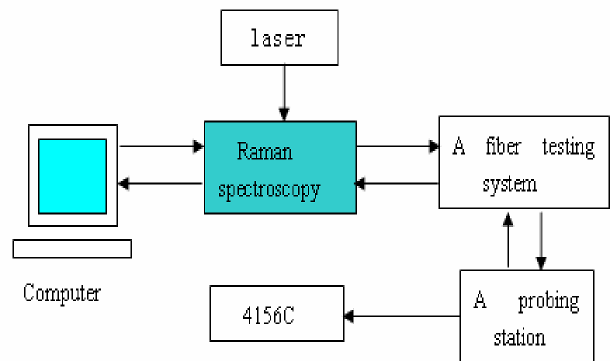

Fig. 5 — Piezoresistor effect measurement system for resonant tunneling structure

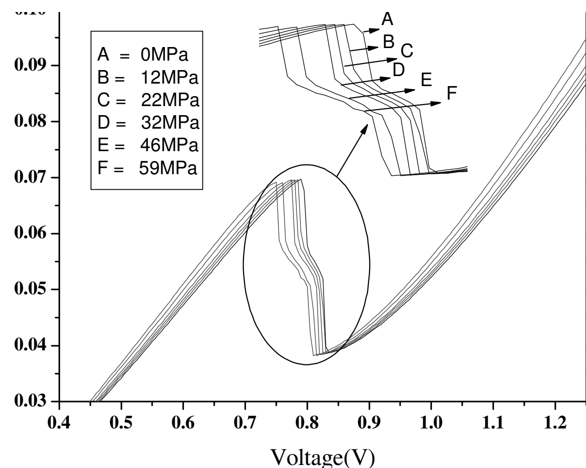

Fig. 6 — Shifts of *I-V* curve under the applied stress

$$R(stress) = R(0) * (1 + K * S) \quad \ldots(1)$$

Where R (stress) is the resistance under stress, $R(0)$ the resistance without stress, and S is stress. Through the processing of the experimental data, the resistance (R) and the relative stress (S) could be obtained, so the piezoresistive sensitivity K can be calculated as:

$$K = \Delta R / R * S = \frac{R(stress) - R(0)}{R(0) * S} \quad \ldots(2)$$

Fig. 7 shows the piezoresistive sensitivity of the piezoresistance under different biases. It can be seen that the largest piezoresistive sensitivity occurred at the region of negative differential resistance and that the sensitivity can be adjusted by the bias. Therefore, one needs to choose a reasonable bias to obtain a better sensitivity as well as good linear correlation.

The linear correlation coefficient is defined as:

$$r = \frac{\sum(\Delta Si \times \Delta Ri)}{\sqrt{\sum \Delta Si^2} \times \sqrt{\sum \Delta Ri^2}} \quad \ldots(3)$$

where $\Delta Si = Stress(i) - \overline{Stress}$, $\Delta Ri = R(i) - \overline{R}$ (i = 0,1,2...6). To acquire a linear correlation, one needs to keep r approach to ±1. Fig. 8 shows the linear correlation coefficient with different bias.

From the above analyses, the reasonable bias, 0.8 V, can be obtained, which results in a piezoresistive sensitivity $K = 2.54 \times 10^{-9}$, a value of about one order higher than that of silicon piezoresistors[10], and $r = 0.998$, a much better linear correlation. The resistance–stress curve with bias = 0.8V has been showed in Fig. 9.

The physical theory comes from the Meso-piezoresistance effect[11]. In principle, the strain generates piezoelectric fields in AlAs/InGaAs quantum well structures and the resulting fields will change the quantum states (discrete energy levels in quantum well) of RTD; because resonant tunnel current of RTD depends on the quantum states directly. In the end, the resonant tunnel current will be influenced by stress fields. Totally, it looks like a change in electrical resistance of RTD when subjected to stress fields.

When subjected to stress fields, the pressure induces piezoelectric fields in the barriers and the well of the RTD. All III–V compounds are piezoelectric due to the polar character of the bonds between different atoms[12,13]. A general description of the electrical conductivity in III–V compounds under applied

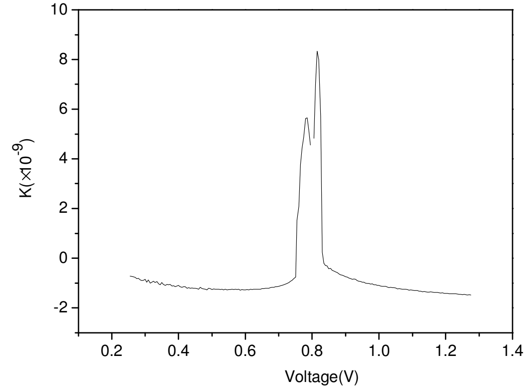

Fig. 7 — Piezoresistive sensitivity of the piezoresistance with biased

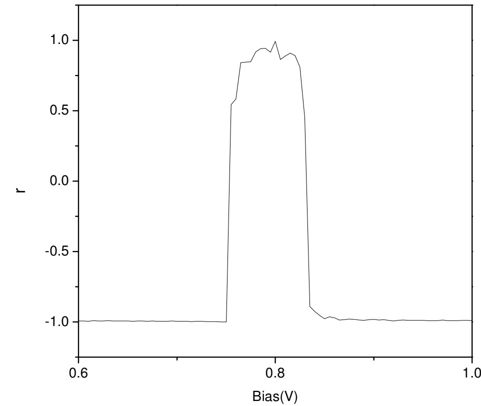

Fig. 8 — Linear correlation coefficient with bias

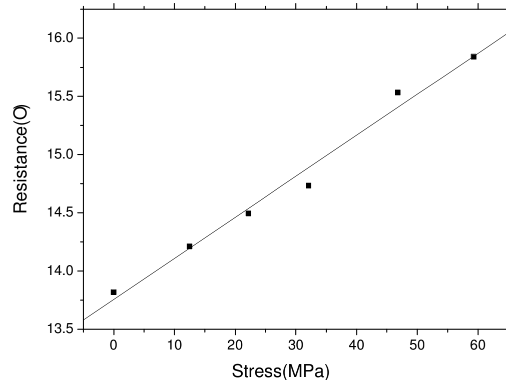

Fig. 9 — Resistance–stress curve with bias=0.8V

uniaxial pressure can be described by the relation between piezoelectric[14] fields Ei and stress σ_{ij}.

$$dE_i = \rho_{ij} di_j + d_{ikl}\sigma_{kl} + \pi_{ijkl} i_j \sigma_{kl} + fl \quad \ldots(4)$$

where ρ_{ij} is resistivity, i_j the current, σ_{kl} the uniaxial pressure or stress, $d_{ikl} = \partial E_i / \partial \sigma_{kl}$ are the piezoelectric coefficients, and $\pi_{ijkl} = \partial^2 E_i / \partial i_j \partial \sigma_w$ are the piezoresistance coefficients.

Piezoelectric fields will change the quantum states in the light of quantum electronics, which makes the quantum well incline (Fig.10), and consequently, the value of (E_0-E_C) will change. Since the peak-voltage Vp is dependent on this value directly, it will change correspondingly. From the *I-V* characteristics, it is easy to note that the curve will shift to the left or right with the positive or negative fields as stress is applied. Totally in the negative differential resistance region, when the bias voltage is defined, it appears that the electrical resistance of RTD changes sensitively when subjected to stress fields.

4 Application

Clearly, AlAs/InGaAs double-quantum-well nano-thin film has more sensitive piezoresistor effect than that of silicon structures, so that they can be used and integrated into M/NEMS. Applications of such quantum structures include micro-sensors and actuators, such as pressure sensor, acoustics sensor, acceleration sensor and so on. Study of micro-sensor based on resonant tunneling structure is still continued.

5 Conclusion

This paper reported the fabrication of resonant tunneling piezoresistor sensors. The sensitive piezoresistor effect of RTD has been confirmed by pressure experiments, thereby demonstrating the feasibility of integrating them into some kinds of advanced microsystems with low power consumption, high sensitive and high degree of miniaturization. The sensing capabilities can also be easily integrated together with components such as HEMTs, or HBTs to perform signal conditioning functions. Furthermore, the principle can be extended to other III-V material systems.

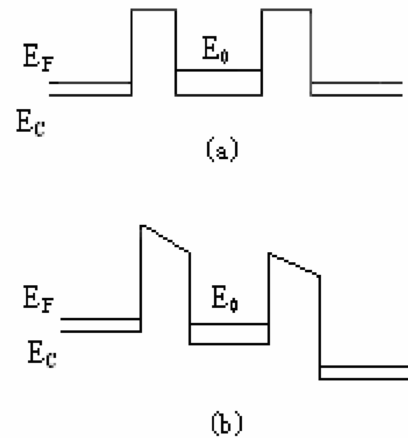

Fig. 10 — RTD band diagrams: (a) without applied pressure, (b) under applied pressure

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