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Pressure effects in AlAs/$In_xGa_{1-x}As$/GaAs resonant tunnelling diodes for application in micromachined sensors*

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This paper reports the current–voltage characteristics of [001]-oriented AlAs/$In_xGa_{1-x}As$/GaAs resonant tunnelling diodes (RTDs) as a function of uniaxial external stress applied parallel to the [110] and the [1$\bar{1}$0] orientations, and the output characteristics of the GaAs pressure sensor based on the pressure effect on the RTDs. Under [110] stress, the resonance peak voltages of the RTDs shift to more positive voltages. For [1$\bar{1}$0] stress, the peaks shift toward more negative voltages. The resonance peak voltage is linearly dependent on the [110] and [1$\bar{1}$0] stresses and the linear sensitivities are up to 0.69 mV/MPa, −0.69 mV/MPa respectively. For the pressure sensor, the linear sensitivity is up to 0.37 mV/kPa.

Keywords: pressure effects, RTDs, micromachined sensors
PACC: 7360L, 7980

1. Introduction

In recent years, extensive research on resonant tunnelling diodes (RTDs) has been dominated by the needs of semiconductor heterostructure devices for high-frequency operation and high-speed applications.[1] Oscillations up to 712 GHz have been reported and several applications of RTDs for multivalued logic have been proposed.[2−4] However, the RTD current–voltage characteristics are very sensitive to pressure[5] and temperature[6] changes, mainly in the negative differential resistance region.

Pressure or stress plays a very important role in the investigation of the transport properties in semiconductor materials and offers a possibility of designing heterostructure devices with tailorable performances. The well-known effects are: the energy band-gap variation with hydrostatic pressure, the stress-induced piezoelectric field in III–V compound semiconductors, and the change of the band-edge curvature and the band-edge splitting with uniaxial pressure.[7]

Pressure or stress has been used to study the influence of different valleys involved in the conduction mechanism and to understand the underlying physics which determines both the coherent and the non-coherent current components for many semiconductor structures and devices. According to the obtained sensitivities, these pressure effects were possible to be used as a method to measure the pressure or stress, meeting the requirement of miniaturization and monolithic integration with conditioning electronic functions. This explains the growing interest of studying the effect of uniaxial pressure on semiconductor devices for sensing applications as well as the motivation of this work. Now a variety of pressure effects have been obviously used in diverse integrated semiconductor sensors with an improved degree of miniaturization.[8−10]

In this paper, we report a pressure dependence of the current–voltage characteristics of AlAs/$In_xGa_{1-x}As$/GaAs RTDs grown on [001] substrates. We attribute this pressure effect to the piezoelectric nature of the materials involved. And the GaAs pressure sensor based on the RTDs is designed and processed by control holes technology to study the application of pressure effect of RTDs in micromachined sensors.

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2. Fabrication of the RTDs

N^+-GaAs	$3\times10^{18}cm^{-3}$	500nm
N^+-GaAs	$10^{17}cm^{-3}$	10nm
GaAs	Undoped (UD)	5nm
$In_{0.1}Ga_{0.9}As$	UD	5nm
GaAs	UD	0.5nm
AlAs	UD	1.7nm
GaAs	UD	0.5nm
$In_{0.1}Ga_{0.9}As$	UD	4nm
GaAs	UD	0.5nm
AlAs	UD	1.7nm
GaAs	UD	0.5nm
$In_{0.1}Ga_{0.9}As$	UD	5nm
GaAs	UD	5nm
N^+-GaAs	$10^{17}cm^{-3}$	10nm
N^+-GaAs	$3\times10^{18}cm^{-3}$	500nm
GaAs	UD	1000nm
SI-GaAs	Substrate	

Fig.1. The dimensions of the resonant tunnelling structure.

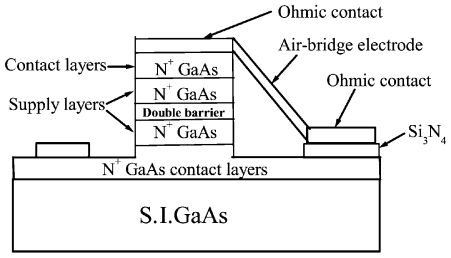


Fig.2. The cross section of the RTDs .

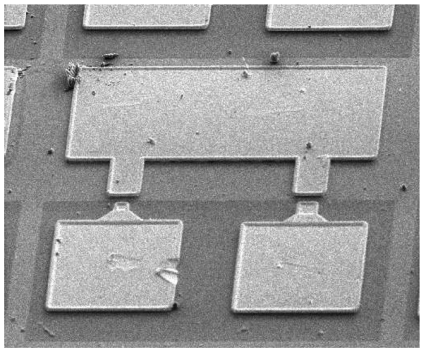


Fig.3. SEM image of the RTDs.

The resonant tunnelling structure is grown by molecular beam epitaxy (MBE) on a [001]-oriented undoped (semi-insulating) GaAs substrate. The detailed structure and dimensions are shown in Fig.1. Mesas are defined by photolithography on the epitaxial surface using reactive ion etching (RIE). And Si_3N_4 membrane is deposited and patterned to isolate the emitter and collector electrodes. A thick polyimide layer is used as sacrificial layer. The top of the structure is totally covered by polyimide except for the contact area on the diode mesa and the Si_3N_4 membrane. AuGeNi/Au ohmic contacts are used and alloyed at 380 °C. Then the air-bridge electrode is processed by eroding the polyimide layer (sacrificial layer). The specific process was shown in Ref.[11]. The cross-section of RTDs device structure is shown in Fig.2, and the SEM of the RTDs is shown in Fig.3.

3. Experimental tests and discussion

3.1. Experimental tests

A screw micrometer pressure setup was designed to apply the compressive stress along [110] and [$1\bar{1}0$] directions separately for the RTDs. And commercial laser Raman spectrum was used to quantitate the stress. The resolution of the Raman spectrum is $0.02\,cm^{-1}$, and the specific principle has been shown in Ref.[12]. Agilent 4156C semiconductor parameter analyser was used to measure the current–voltage characteristics of RTDs as a function of stress. And the schematic diagram of a specific experiment is shown in Fig.4.

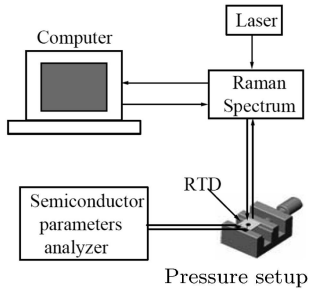


Fig.4. The schematic diagram of the pressure experiment.

All the measurements were performed at room temperature (300 K). The following parameters have been measured for the AlAs/$In_xGa_{1-x}As$/GaAs RTDs without applied pressure: a current peak-to-valley ratio (PVR) of 1.79, peak and valley voltages of 0.715 and 0.785 V, respectively, and the corresponding peak and valley currents of 80.8 and 44.9 mA.

When a compressive stress was applied with the screw micrometer pressure setup to the RTDs, in the I–V curves, the most obvious effect is the shift in the peak voltages. When the stress along the [110] direction was applied to the RTDs, we found that the peak voltages for positive bias shifted to more positive values, as shown in Fig.5. However, the peak voltages

for positive bias would shift to more negative values when the stress is applied along the $[1\bar{1}0]$ direction, as shown in Fig.6. The changes of stress dependence of the peak voltage are summarized in Fig.7. From the fit of the data in Fig.7, we found that the peak voltages increase linearly with increasing stress along [110] direction and the peak voltages decrease linearly with increasing stress along $[1\bar{1}0]$ direction. And the linear sensitivity is up to 0.69 mV/MPa and −0.69 mV/MPa respectively.

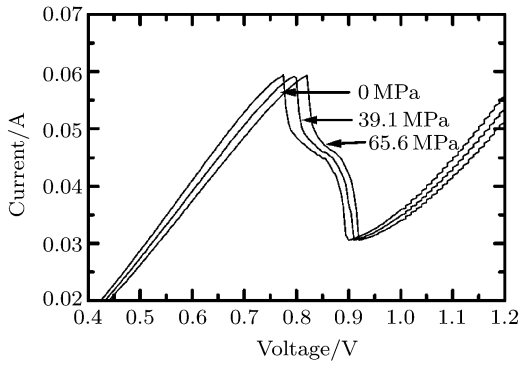


Fig.5. The *I-V* curves of the RTDs under stress along [110] direction.

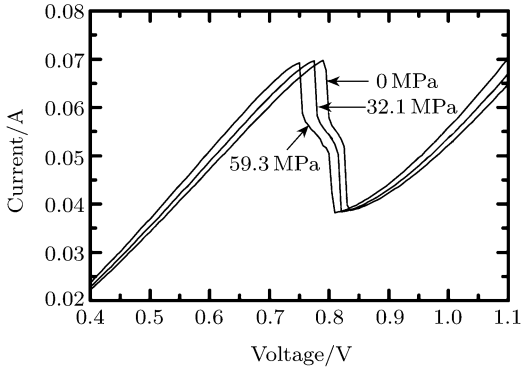


Fig.6. The *I-V* curves of the RTDs under stress along $[1\bar{1}0]$ direction.

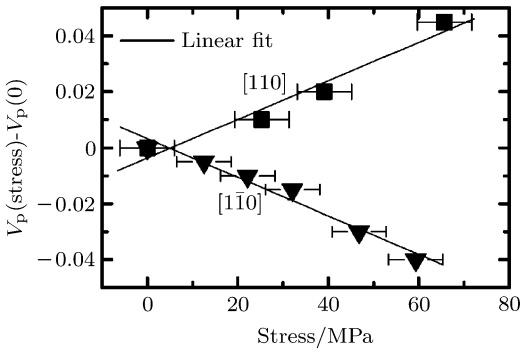


Fig.7. Shift of the peak voltage with stress along the [110] and $[1\bar{1}0]$ directions.

The ±0.69 mV/MPa pressure sensitivity of the peak voltage and the deduced K-factor, which is about 103, can directly be used when monitoring the peak voltage shift in pressure measurements. The K-factor is here defined as:

$$K = \frac{\Delta V_{\text{peak}}}{\zeta V_{\text{peak}}}, \tag{1}$$

where ζ is the strain. The values reported here is about two times larger than that of the GaAs piezoresistance effect.[9] The higher sensitivity and the linearity of pressure effect in RTDs show that it is very suitable for the application in micromachined sensor.

3.2. Discussion

The electrical conductivity in III–V compounds under applied uniaxial pressure can be described generally by the relation between electric-field E_i and current i_j:[13]

$$\mathrm{d}E_i = \rho_{ij}\mathrm{d}i_j + \mathrm{d}_{ikl}\sigma_{kl} + \pi_{ijkl}\sigma_{kl} + fl, \tag{2}$$

where ρ_{ij} is the resistivity, $\mathrm{d}_{ikl} = \partial E_i/\partial\sigma_{kl}$ are the piezoelectric coefficients, σ_{kl} is the uniaxial pressure or stress, and $\pi_{ijkl} = \partial^2 E_i/\partial i_j \partial_{kl}$ are the piezoresistance coefficients. The remaining terms in Eq.(2), which include the change of resistivity with current as well as the change of piezoelectric coefficients with stress can be neglected. Piezoresistance is static and has a magnitude, which depends on both the doping type and level. The piezoresistance could also be neglected according to Ref.[14].

The resonant current peak voltage shifts are attributed to the polarization charges due to the piezoelectric constant difference between AlAs and GaAs layers.[15] Under [110] stress, the electric field ε in each layer is induced by the polarization charges at the interfaces as shown in Fig.8(a). Because the piezoelectric constant of the AlAs layers is larger than that of the GaAs layers, the direction of the electric field is antiparallel to that of the applied electric field E_a for positive bias, therefore higher applied voltage is needed to reach the resonant tunnelling condition (see Fig.9(a)). However, for $[1\bar{1}0]$ stress, the polarization charges have the opposite sign at each heterointerface compared with the [110] case as shown in Fig.8(b). Hence, more negatively applied voltages are needed to obtain resonant tunnelling (see Fig.9 (b)).[15]

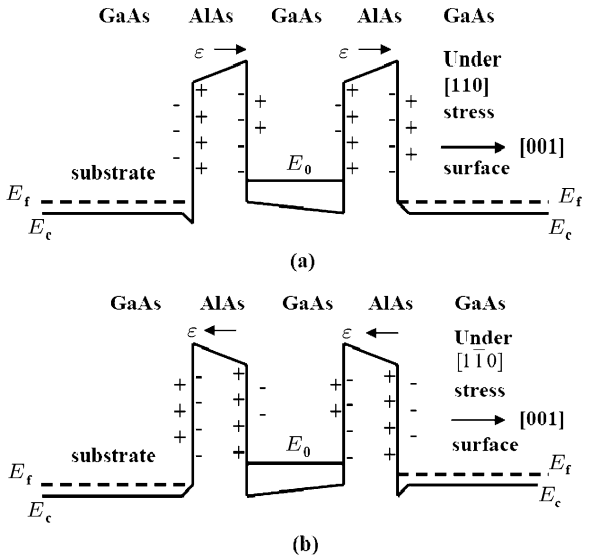


Fig.8. Schematic band diagram and polarization charge distribution for [001] oriented RTDs under stress: (a) along [110] direction. (b) along [1$\bar{1}$0] direction.

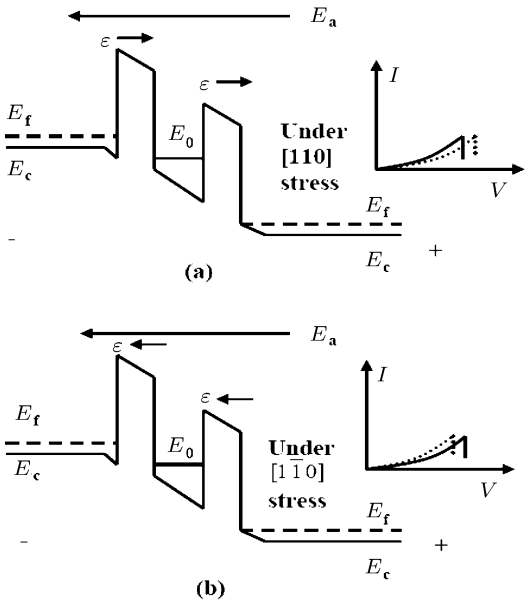


Fig.9. Schematic band diagram and I-V curves for positive bias for [001]-oriented RTDs under stress: (a) along [110] direction. (b) along [1$\bar{1}$0] direction. The solid I–V curve represents the current without applied stress and the dotted curve represents the current with applied stress.

4. Pressure sensor based on the pressure effect of RTDs

In order to study in detail the application of the pressure effect in micromachined sensors, the GaAs membrane pressure sensor based on RTDs has been designed and processed by the control holes technology (the radius and thickness of the membrane is 370 and 7 μm respectively). And in order to obtain higher sensitivity, the supply layers (N^+-GaAs:10^{17} cm^{-3}) of RTDs are increased to 20 nm, and double air-bridge RTDs are designed and processed to make the negative differential resistance region more abrupt. The process of RTDs has been illustrated in Section 2. After the RTDs are processed, the circular membrane is constructed using control holes that have been etched initially from the front side, being as deep as the required membrane thickness. The back-side etching of the membrane is stopped when the front-side holes become visible.[16] The process integration of RTD and GaAs micromachined technology is implemented. And the SEM image of the structure is shown in Fig.10.

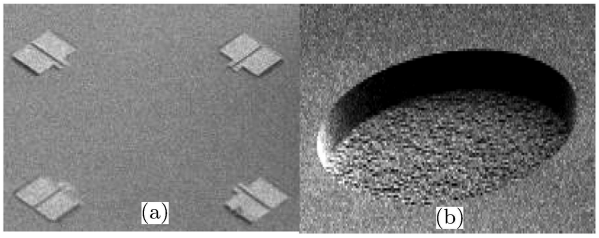


Fig.10. SEM image of pressure sensor structure. (a) Top view of the membrane; (b) Back cavity.

After the pressure sensor is processed, it is packaged hermetically. The experimental tests are conducted by putting the pressure sensor in the pressure vessel, applying pressure in air to the sensor and then measuring the current–voltage characteristics of the RTDs as a function of pressure. The test results are shown in Fig.11, and the pressure dependence of the peak voltage is shown in Fig.12. From the fit of the data in Fig.12, the peak voltages are found to increase linearly with increasing pressure, and the linear sensitivity of the pressure sensor is up to 0.37mV/kPa.

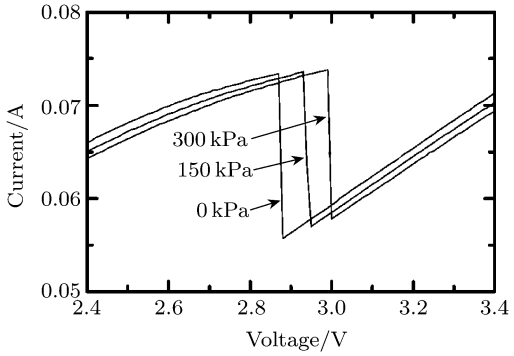


Fig.11. Pressure-dependent current–voltage characteristics of the pressure sensor.

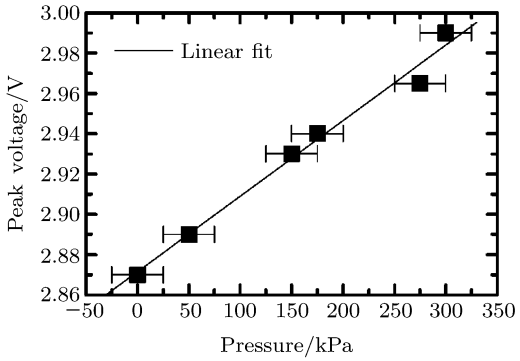


Fig.12. The pressure-dependent peak voltage.

5. Conclusion

The current–voltage characteristics of [001]-oriented AlAs/$In_xGa_{1-x}As$/GaAs RTDs as a function of uniaxial external stress applied parallel to the [110] and the [1$\bar{1}$0] orientations have been experimentally studied. The experimental results show that the pressure effect of RTD is very suitable for the application in micromachined sensor due to its linearity and the higher sensitivity. And we have shown that the variation of the current–voltage characteristics of RTDs under the influence of pressure is the change of the polarization charges due to the piezoelectric constant difference between AlAs and GaAs layers. The GaAs pressure sensor based on the RTDs have been designed and processed by control holes technology to illustrate the pressure effect of the RTDs for the application in micromachined sensor. And the experimental results show that the peak voltages increase linearly with increasing pressure, and the linear sensitivity of the pressure sensor is up to 0.37 mV/kPa. The sensing capabilities can be easily integrated together with components such as high electron mobility transistor (HEMT) or heterojunction bipolar transistor (HBT) to perform signal conditioning functions. Furthermore, the principle can be extended to other III–V material systems. However, the design of the diode has to be optimized. In our case, the peak current through the diodes is very high. Therefore, the heat dissipation in the thin membrane will become so high that the contacts and junctions will degrade very rapidly. The best diodes to use are those with low peak current and high peak-to-valley current ratio. Further research will have to be done on:

1. The temperature dependence of the RTDs.
2. The structure with more optimized RTDs to determine the linearity and sensitivity of the sensor.

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