Pressure effect study on the I–V property of the GaAs-based resonant tunnelling structure by photoluminescence measurement*

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This paper discusses the I–V property of the GaAs-based resonant tunnelling structure (RTS) under external uniaxial pressure by photoluminescence studies. Compressive pressure parallel to the [110] direction, whose value is determined by Hooke's law, is imposed on the sample by a helix micrometer. With the increase of the applied external uniaxial compressive pressure, the blue shift and splitting of the luminescence peaks were observed, which have some influence on the I–V curve of RTS from the point of view of the energy gap, and the splitting became more apparent with applied pressure. Full width at half maximum broadening could also be observed.

Keywords: resonant tunnelling structure, I–V curve, photoluminescence measurement, peak shift, peak split, full width at half maximum broadening

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1. Introduction

Over the past few decades, silicon-based micro electro mechanical system (MEMS) accelerometers have been widely used in various applications from biomedical, aerospace, to automotive,[1] based mainly on the existing processing techniques associated with silicon technology. However, gallium arsenide (GaAs) presents particular material properties and technological advantages over Si.[2,3] The most important feature of GaAs is the possibility of forming compatible ternary and quaternary compounds by alloying. Using GaAs as a substrate, many novel sensors based on GaAs have been developed, such as thermoconvertors[4], infrared detectors,[5] optical sensors[6] and accelerometers,[7] etc.

In recent years, extensive research has been done on the applications of GaAs-based resonant tunnelling diodes (RTD) by the needs of semiconductor heterostructure devices for high frequency operation and high speed applications. These devices exhibit a negative differential resistance region in the current–voltage characteristics. Many researchers have investigated the I–V property of RTD. For example, A. Wacker discussed how the complex stationary current–voltage characteristic exhibiting domain branches is generated continuously as the doping increases.[8]

Our research group designed a micro accelerometer with a four-beam-mass structure including GaAs/AlAs/InGaAs double barrier RTDs as its sensitive element, according to the negative differential resistance effect. The sensitivity of the RTD based micro accelerometer is adjustable within a range of 3 orders when the bias voltage of the sensor changes, and the largest sensitivity of 560.2 mV/g is about 10 times larger than that of the silicon-based micro piezoresistive accelerometer.[7] Jian Wang *et al.* discussed the pressure effects on AlAs/InGaAs/GaAs RTDs, in Ref. [9], they contributed the shift of current–voltage characteristics of [001]-oriented AlAs/InGaAs/GaAs RTDs to uniaxial external pressure applied parallel to the [110] orientations.

Many other researchers have made further studies on the influence of stress on GaAs or its ternary and quaternary compound materials in order to make a conclusion on how those materials can be used for micro sensors. For example, F. Smaoui discussed the influence of the strain induced by the lattice mis-

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match on two ultra-short type II GaAs/AlAs superlattices (SLs) deposed, respectively, on GaAs and $Ga_{1-x}In_xAs$ substrates through photoluminescence (PL) studies.[10] M. E. Constantino *et al.* reported the observation of stress effects on GaAs at the interface of molecular beam epitaxy (MBE) grown ZnSe/GaAs.[11]

In this work, the I–V property of the GaAs-based resonant tunnelling structure (RTS) under external uniaxial pressure parallel to the [110] direction is presented by PL studies. First, we analysed the cause of the final results of PL measurement. Second, the I–V property of GaAs-based RTS is explained, related to the shift of the internal energy gap.

The PL measurement is a contactless, nondestructive method for researching the electronic structures of materials. Light is directed onto a sample, where it is absorbed, and imparts excess energy into the material in a process called photo-excitation. Photo-excitation causes electrons within the material to transit into higher excited states. When these electrons return to their equilibrium states, the emission of light will include several different processes. Mainly, several possible processes for radiative and non-radiative recombination are illustrated. The PL is related to the energy separation between the excited state and the equilibrium state, whose intensity depends on the radiative process.

2. Experiment

The testing sample called RTS used in PL measurement is shown in Fig. 1. All samples, cut along the [110] direction, were MBE grown on the semi-insulated GaAs substrates, whose dimension is 10 mm×4 mm×400 μm.

GaAs undoped(UD) 50 nm
GaAs (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} cm^{-3} 10 nm
N^+–GaAs 3×10^{18} cm^{-3} 500 nm
GaAs UD 1000 nm
SI-GaAs substrate

Fig. 1. Structure and dimensions of the testing sample.

From Ref. [9], we found that the I–V curve shifts to a more positive value under a certain outer bias voltage, when a pressure less than 100 MPa is applied parallel to the [110] direction, as shown in Fig. 2. So in this experiment, we focus on the influence of the internal energy bands on the outer I–V curve under external pressure parallel to the [110] direction.

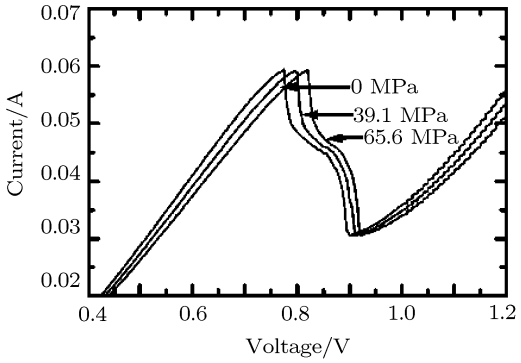


Fig. 2. I–V curve under external pressure parallel to the [110] direction.[9]

In the experiment, the pressure-loading device with the testing sample in its centre was fixed on the position controlling platform of a Raman spectrum analyser, which applied shear pressures of higher values ranging from 0 MPa to 1300 MPa along the [110] direction of the sample in order to display the change of internal energy bands, as shown in Fig. 3. Suppose the deformation of the sample is elastic; at the time of each loading, the stress in the sample was calculated by the step length such that the helix micrometer moved according to Hooke's law.

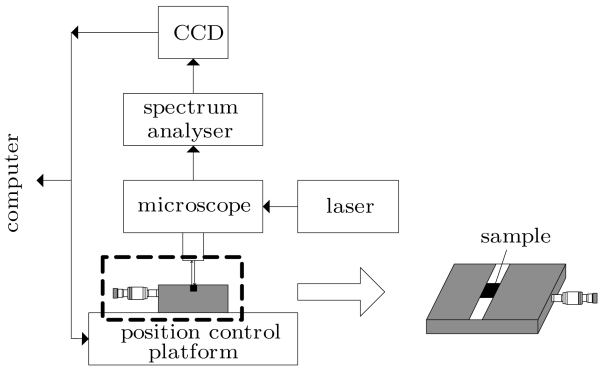


Fig. 3. Schematic diagram of the pressure-loading experimental system.

For PL measurements on the testing sample, PL spectra were recorded in backscattering geometry using a RENISHAW inVia Raman spectrometer equipped with a 3000 l/mm grating. An Ar^+ laser with a wavelength of 514.5 nm was used as the excitation source, and the power of the laser directed onto the sample was set to 5 mW. All the measurements were performed at room temperature (300 K).

3. Experimental results and discussion

The PL spectra as a function of pressure in the back side of the testing sample are presented in Fig. 4. From this result, the electronic states of the testing materials are illustrated to display a series of transitions and broadenings of the lines as a function of external pressure.

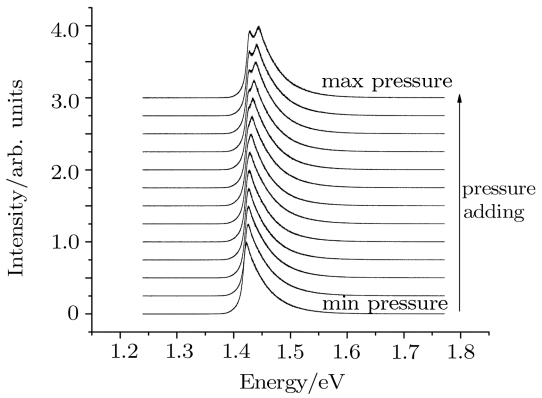


Fig. 4. The PL spectra of the back side of the testing sample.

With increasing external uniaxial pressure applied on the testing sample, the energy peak has blue shifts, which means that the energy gap E_g of the testing sample increases, as shown in Fig. 5 and a new peak appears on the left side of the original energy peak at about 1.43654 eV. Also, the splitting of these two peaks becomes more apparent under the increasing pressure, as shown in Fig. 6. The strain caused by compressive pressure along the [110] direction causes the shift of valence bands to higher energy, and the top valence band is the heavy hole band,[12] as shown in Fig. 7. The different rates of the above-mentioned peak shifts lead to the split with increasing applied pressure. The magnitude of the energy gap proportional to the hydrostatic component of the pressure can be expressed as[13]

$$\Delta E = (11.5 - 1.3x)10^{-3}P \ \ (\text{eV}), \qquad (1)$$

where P is pressure.

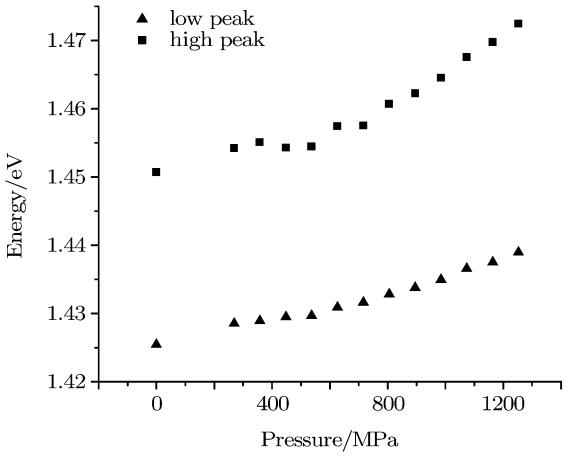


Fig. 5. Energy of low peak and high peak versus pressure.

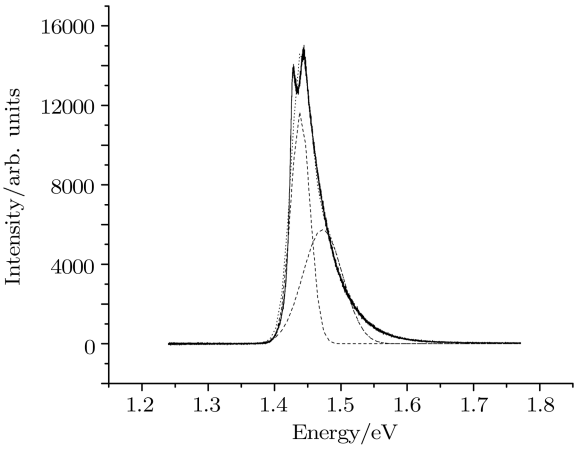


Fig. 6. The splitting of the energy band peak under external uniaxial pressure.

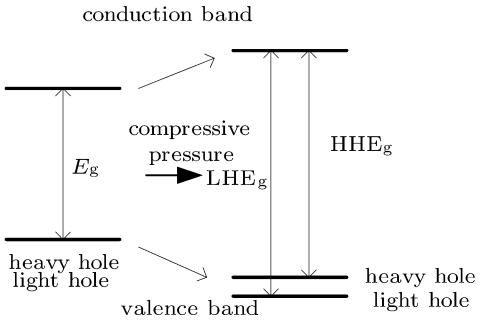


Fig. 7. Schematic diagram of energy shifts and split under external uniaxial pressure.

Research on resonant tunnelling current requires the calculation of the transmission probability under various biasing conditions, described by the two-band $k \cdot p$ model which is expressed as[14]

$$\frac{\hbar^2 k^2}{2m_0} = \frac{(E - E_c)(E - E_v)}{E_p}, \qquad (2)$$

where $E_{\rm p} = 2P^2/m_0$ is the normalized squared interband momentum matrix element which is determined by setting $E_{\rm g}/E_{\rm p} = m^*/m_0$; here, $E_{\rm g}$ is the weighted average of the gaps between the conduction band and the valence band.

The tunnelling current density J was calculated by integrating over the energy associated with the longitudinal motion of the electrons $E_{\rm z}$ and expressed as[15]

$$J = \frac{emkT}{2\pi^2\hbar^3}\int_0^{\infty} \tau^*\tau \times \ln\left(\frac{1+\exp[(E_{\rm f}-E_{\rm z})/kT]}{1+\exp\{[E_{\rm f}-(E_{\rm z}+eV_{\rm a})]/kT\}}\right) {\rm d}E_{\rm z}, \tag{3}$$

where e is the electron charge, k is the Boltzmann constant, T is the temperature, $E_{\rm f}$ is the Fermi energy, $V_{\rm a}$ is the externally applied bias voltage. From expressions (1)–(3), we found that the shift of the energy gap has an influence on the tunnelling current density. Comparing the shift trends of the current density and the energy gap, as shown in Figs. 2 and 5, we found that the current density increases under the same outer bias voltage with increasing energy gap under conditions of increasing external pressure.

Meanwhile, the peak voltages shift to more positive values under certain outer bias voltages, when the pressure is applied parallel to the [110] direction, which can be explained by the piezoelectric effect. The shift of the energy gap shows that internal strain exists under external pressure to make polarized charges appear at the interface between GaAs and AlAs, because of the existing different piezoelectric constant between GaAs and AlAs. Thus, the internal electric field ε is generated, as shown in Fig. 8, with an opposite direction to the outer bias electric field $E_{\rm a}$, to offset the influence of the outer bias voltages on the I–V performance to some extent; therefore, more positive voltages are needed to achieve the same current. Thus, the obvious shift of the I–V curve to the right side appears.

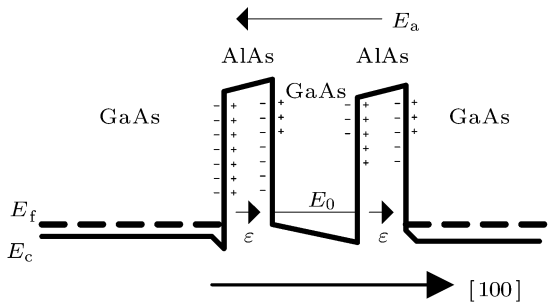


Fig. 8. Schematic diagram of energy band and polarized charge distribution under internal strain along the [110] direction.[9]

Figure 9 shows the full width at half maximum (FWHM) broadening of these two PL peaks as a function of increasing pressure. The external stress influences the phonons related to luminescence, and the strain or stress caused by the phonon frequency shifts changes the symmetry of the carrier density, leading to broadening of the PL spectra.[16]

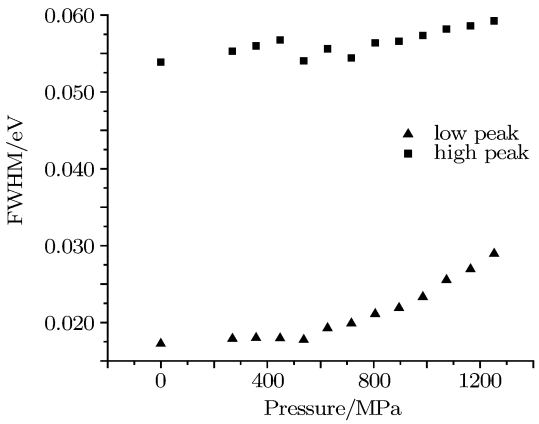


Fig. 9. FWHM broadening of the low peak and high peak versus pressure.

4. Conclusions

PL measurements of GaAs-based RTS under external uniaxial pressure display energy band shifts and split and FWHM broadening as a function of increasing pressure. The strain caused by compressive pressure causes the shift of valence bands to higher energy, and the different rates of peak shift lead to the split. Blue shift and splitting of the luminescence peaks were observed, which have some influences on the I–V curve of RTS from the point of view of the energy gap. Also, inhomogeneous strain or stress related to phonon frequency shifts result in the broadening of FWHM.

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