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The effect of external stress on the properties of AlGaAs/GaAs single quantum well laser diodes

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ABSTRACT

The change of spectrum of the AlGaAs/GaAs single quantum well laser diode is measured under the application of uniform uniaxial in-plane tensile and compressive stress. In the range of the tensile stress we apply (up to 597 MPa), the wavelength increases linearly at a rate of 5.3 nm GPa^{-1}. The energy band gap decreases with the tensile stress with the slope of −10 meV GPa^{-1}, which is close to the theoretical change of the heavy hole band edge with respect to the conduction band edge. There is a shorter wavelength peak existing on the spectrum as the tensile stress increases, suggesting a transition from the conduction band to a higher energy valence band. For the compressive stress (up to −516 MPa), the wavelength decreases with the stress, but it shows an abrupt reduction from −162 to −200 MPa. The threshold current also varies as a result of the change of the energy band structure.

1. Introduction

Laser diode bars (LDBs) with AlGaAs active regions have a wide range of applications including solid-state laser pumping, materials processing, optical communications, and printing machines [1–3]. The device structures consist of very thin active layers epitaxially grown on appropriate substrates. There usually exist residual stresses in the thin film layer due to the thermal and lattice mismatches between the epilayer and substrate [4,5]. The stress can also be introduced from the packaging processes, as a result of the differences in the thermal expansion coefficients between the chip and heat sink materials [6–9]. Previous investigations have revealed that the performance, such as the wavelength, threshold, optical gain, and reliability of laser diodes are affected by the residual stresses [10,11]. Furthermore, the energy band structure of III–V semiconductor materials have been found to change with the lattice mismatch stresses, which result from the variation of the composition of the semiconductor materials [12–15]. The band gap increases when under compression and decreases under tension [12–17]. Therefore, for the AlGaAs/GaAs single quantum well laser diodes which are of wide application interest, it is desirable to study in detail the effect of external mechanical stress on the properties for a better understanding of the device performance, for interpretation of experimental results, and for optimization of the device design. However, it is difficult to apply a uniform stress either in-plane or out-of-plane on a laser chip, especially when the stress level is much larger than 1 MPa. Adams and colleagues [10] applied an in-plane stress on a unbounded InGaAsP/InP laser chips by supporting it on two diamonds apart while pushing a probe against the back side of the substrate. They observed the threshold current and wavelength increased under in-plane tensile stress and decreased under in-plane compressive stress. The same approach has also been used in other works [18]. However, the in-plane stress applied by such a method is not uniform across a sample and hence the measured results depend not only on the applied force but also the relative position of a device on the sample.

In this work, we present the results on the change of spectrum of the unbounded 808-nm AlGaAs/GaAs laser chips under external mechanical stresses. By using a four point bending test rig, a uniform uniaxial in-plane stress (both tensile and compressive) can be applied to the lasers. The change of the energy band structure is also investigated based on the properties change.

2. Experiments

The laser diodes studied in this work are grown by metalorganic chemical vapor deposition (MOCVD) on (100) GaAs substrate and consist of a single quantum well AlGaAs structure. The active region has a thickness of 9 nm which is made up of AlInGaAs. The output and reverse facets are asymmetrically coated with Al_2O_3 and Al_2O_3/Si. The chip dimensions are ~130 μm (bar thickness) × 900 μm (cavity length) × 2765 μm (total lateral

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width), sawed from a 2 in. wafer. The laser bar contains 5 emitters with a width of ~500 μm. To avoid heating effect, the lasers are operated with 30 μs current pulses at a duty cycle of ~0.3%.

The uniform in-plane tensile stress is provided by a four-point bending test rig shown in Fig. 1. Because the sample is too small to be loaded, it is bonded on the center region of a sheet of spring steel which is 30 mm (length) × 8 mm (width) × 0.26 mm (thickness) using the indium solder. To make sure the bonding is tight enough, we use the uv-cured optical adhesive on the periphery of the sample. The steel sheet with the adhered sample is put between the two sets of center aligned upper and lower rollers. When the height of adjustable platform is increased, the sample would start to bend. The advantage of this method is that the in-plane stress induced between the two lower rollers is intrinsically uniform. The lower roller stage is supported by a sensor placed on the platform, which is connected with a monitor to read the force loaded on the sample. The measurement accuracy can reach 0.01 N. When we apply a load on a sample using two sets of rollers as shown in Fig. 1, the bending moment is constant between the two lower rollers. Hence, the in-plane strain and stress at the sample top surface is uniform. The derivation of the in-plane stress from the loading force is described in the previous work [19]. The active region of most lasers is located closer to the top surface of the sample. Therefore, either tensile or compressive stress can be produced within the active region depending whether the laser chip is positioned with the active region up or down. In our experiment, the maximum stress level we apply is less than 600 MPa before the sample breaks up. We increase the stress gradually from 0 to ~600 MPa (tensile or compressive), and then reduce it from ~600 MPa to 0. To confirm the reliability of the results, we repeat the experiment for two samples.

3. Results and discussion

Fig. 2(a) and (b) shows the spectra measured at different levels of in-plane tensile and compressive stress, respectively. The change of the peak wavelength is plotted in Fig. 3(a), displaying a linear increasing relationship with the tensile stress within the stress level. The linear slope is about 5.3 nm GPa^{-1}. For the compressive stress (Fig. 3(b)), the wavelength decreases first linearly, but shows a rapid and big decrease at around 200 MPa. Afterwards, it changes following a similar trend as before. Moreover, when the stress is removed from the sample (represented by the open symbol in Fig. 3), the wavelength can return to their original values with no measurable hysteresis, suggesting that the in-plane stress we apply does not cause any plastic deformation in our sample. The peak wavelengths of the two samples show the changing characteristics under the external stress consistent with each other, although their magnitude deviates from each other which is due to the samples intrinsic difference. The corresponding energy band gap can be derived from the relationship $E_g = hc/\lambda$,

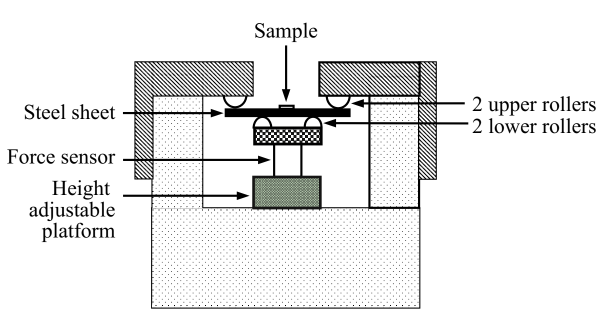

Fig. 1. The sketch of the four-point bending test rig.

where h is the Planck's constant, c the speed of light, and λ the wavelength. The linear slope of the energy band gap with respect to the external stress is about −10 meV GPa^{-1} (or the linear slope of the energy band gap with respect to the strain is about −1 eV). It has been known that the stress defeats the symmetry of the semiconductor and results in removal of the degeneracy at the top of the valence band with a splitting between the heavy and light hole states. The energy difference between the bottom of the conduction band and the top of the degenerate valence band under the biaxial stress has been discussed and calculated in the literature [12–17]. For the uniaxial stress in our case, the corresponding energy difference is given by [20]

$$\Delta E_{hh} = -a(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}) + \frac{b}{2}(\varepsilon_{xx} + \varepsilon_{yy} - 2\varepsilon_{zz}) \tag{1}$$

$$\Delta E_{lh} = -a(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}) - \frac{b}{2}(\varepsilon_{xx} + \varepsilon_{yy} - 2\varepsilon_{zz}) \tag{2}$$

where ΔE_{hh} is the shift in the heavy hole valence band edge with respect to the conduction band edge, ΔE_{lh} is the shift in the light hole valence band edge with respect to the conduction band edge, ε_{xx}, ε_{yy}, and ε_{zz} are the strain components, a and b are the hydrostatic deformation potential and the shear deformation potential, respectively. In the experiment, the uniaxial stress is applied along the x direction in the layer plane (ie. xy-plane); neither the stress along the growth axis (z-axis) nor the shear stresses are imposed on the sample. Therefore, the in-plane uniaxial stress are expressed as

$$\sigma_{xx} = \sigma \tag{3}$$

$$\sigma_{yy} = \sigma_{zz} = 0 \tag{4}$$

$$\sigma_{xy} = \sigma_{yz} = \sigma_{zx} = 0 \tag{5}$$

where σ_{ij} is the stress components. The strains due to the stress are given by

$$\varepsilon_{xx} = \varepsilon \tag{6}$$

$$\varepsilon_{yy} \neq 0 \quad \varepsilon_{zz} \neq 0 \tag{7}$$

$$\varepsilon_{xy} = \varepsilon_{yz} = \varepsilon_{zx} = 0 \tag{8}$$

The strain and stress are related by

$$\sigma = C_{11}\varepsilon + C_{12}\varepsilon_{yy} + C_{12}\varepsilon_{zz} \tag{9}$$

$$0 = C_{12}\varepsilon + C_{11}\varepsilon_{yy} + C_{12}\varepsilon_{zz} \tag{10}$$

$$0 = C_{12}\varepsilon + C_{12}\varepsilon_{yy} + C_{11}\varepsilon_{zz} \tag{11}$$

giving that

$$\varepsilon_{yy} = \varepsilon_{zz} = \frac{-C_{12}}{C_{11} + C_{12}}\varepsilon \tag{12}$$

$$\sigma = \left(C_{11} - \frac{2C_{12}^2}{C_{11} + C_{12}}\right)\varepsilon \tag{13}$$

where C_{ij} is the elastic stiffness coefficients. From Eqs. (1) and (2) we obtain

$$\Delta E_{hh} = -a(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}) + \frac{b}{2}(\varepsilon_{xx} + \varepsilon_{yy} - 2\varepsilon_{zz}) = \left[-a\frac{C_{11} - C_{12}}{C_{11} + C_{12}} + b\frac{(C_{11} + 2C_{12})}{2(C_{11} + C_{12})}\right]\varepsilon \tag{14}$$

$$\Delta E_{lh} = -a(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}) - \frac{b}{2}(\varepsilon_{xx} + \varepsilon_{yy} - 2\varepsilon_{zz}) = \left[-a\frac{C_{11} - C_{12}}{C_{11} + C_{12}} - b\frac{(C_{11} + 2C_{12})}{2(C_{11} + C_{12})}\right]\varepsilon \tag{15}$$

Using the numerical values for AlGaAs (a = −8.2 eV, b = −2 eV, C_{11} = 118.8 GPa, C_{12} = 53.8 GPa) [20,21], Eqs. (14) and (15) yield for AlGaAs, $\Delta E_{hh} = 1.8\varepsilon$, $\Delta E_{lh} = 4.4\varepsilon$. It can be seen that the linear slope of the energy band gap with respect to the uniaxial tensile