Optica Applicata, Vol. XXXV, No. 3, 2005

Analysis of mounting induced strain in semiconductor structures by means of spatially resolved optical modulation techniques

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A wide range of applications of high-power diode lasers is connected with the tendency towards device miniaturization resulting in increased power densities. To manage the thermal load, the chips or arrays of chips (the so-called laser lines or cm–bars) have to be mounted with low thermal resistance on a heat sink of high thermal conductivity. These measures potentially introduce mechanical strain and defects into the semiconductor chips affecting the parameters of laser emission, *e.g.*, spectral position. The ability of optical modulation techniques to monitor spatial strain distribution along the devices was evaluated.

Keywords: electroreflectance, mounting induced strain, laser bar.

1. Introduction

Laser diodes providing high optical output power undergo rapid development as they find new ranges of applications. The tendency towards miniaturization and increase in optical power results in high power densities. Hence these devices work under extreme conditions. Managing the thermal load requires chips or laser diode arrays (also called cm–bars) to be mounted on heat sinks providing very high thermal conductivity allowing for effective management of thermal power dissipation. Proper heat dissipation requires mounting the device on a heat sink with low thermal resistance. Additionally, an active region of laser diodes must be brought in very close contact to the heat sink, *i.e.*, it must be mounted “epi-side down”. This is especially important when continuous work applications are considered. Different thermal coefficients of GaAs (6×10^{-6} K^{-1}) and heat sink material, usually copper (16×10^{-6} K^{-1}), introduce mechanical strain into the system, when the device is cooled down from soldering to ambient temperature.

The presence of stress in semiconductor material has an influence on its working characteristics, as well as on the device’s lifetime. Stress influences also the semiconductor’s band structure, changing band gap energy of the material and bands’ shapes (Fig. 1). All of that results in changing optical properties of the material.

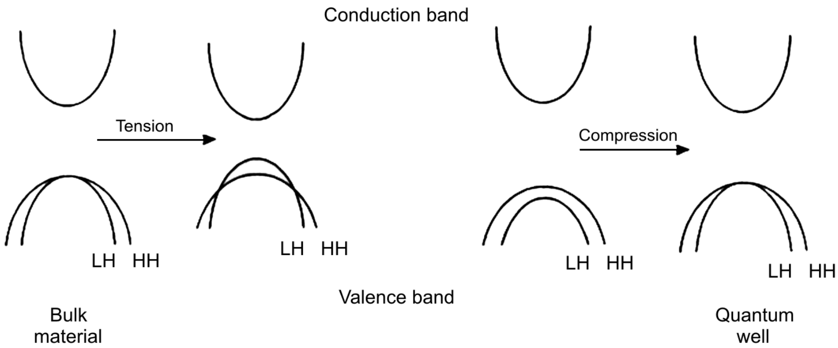

Fig. 1. Effects of tensile and compressive stress on semiconductors band structure.

Theoretical estimation of strain introduced into the system is difficult because of problems with determining the thickness of solder and final solder composition. Hence, it is important to determine this value experimentally. The goal of this paper is to present the electroreflectance method to investigate spatial stress distribution along the laser cm–bar.

2. Theory

Optical modulation spectroscopy is a well developed tool for characterizing band structure of semiconductors, as it is known since early sixties of the 20th century [1]. Using this method, one is able to obtain a derivative of optical spectrum (reflectance or transmittance) of the material through modification of measurement conditions. Spectral response of the sample can be modified directly by applying repeated

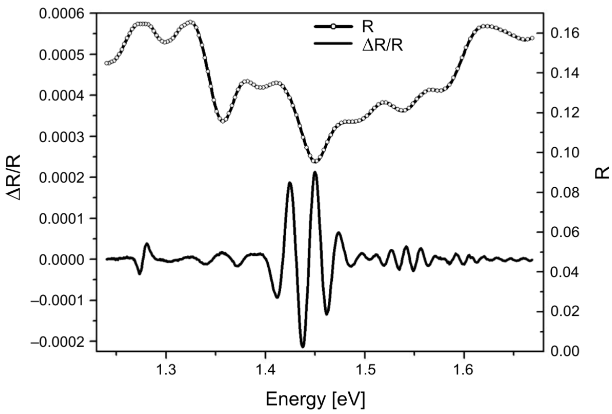

Fig. 2. Comparison of reflectance and photoreflectance spectra of full laser structure measured at room temperature.

perturbation such as electric field (electromodulation), heat pulse (thermomodulation) or deformation (piezomodulation). Periodic changes of measuring conditions result in sharp, differential spectra in the region of interband transitions. Thus, modulation spectroscopy emphasizes crucial features of spectrum suppressing effects connected with background (Fig. 2).

Analysis of spectra provides information about critical points energies, broadening parameter (connected with carrier lifetime) or values of built-in electric fields.

For an electron and hole in a periodic electric field, the wave function is given by:

$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V(\mathbf{r}) + e\xi\right]\Psi(\mathbf{r}) = E\Psi(\mathbf{r}). \tag{1}$$

Solutions of Eq. (1) are:

$$\Psi(\mathbf{r}) = CA_i\frac{-e\xi\mathbf{r} - V(\mathbf{r})}{\hbar\theta} \tag{2}$$

where A_i is the Airy function, and $\hbar\theta$ is an electro-optical energy defined as $(\hbar\theta)^3 = q^2\hbar^2F^2/2\mu_{||}$, where F is an electric field and $\mu_{||}$ is the reduced interband mass in the direction of the electric field.

For bulk materials in the presence of weak electric fields, the electromodulation (photo- or electroreflectance) spectrum is given by:

$$\frac{\Delta R}{R} \cong (\hbar\theta)^3\mathrm{Re}\left[\frac{A\exp(i\phi)}{(E - E_g + i\Gamma)^n}\right]. \tag{3}$$

A detailed information and analysis of modulation techniques is provided elsewhere [2–4].

3. Experiment

Figure 3 presents an electroreflectance setup used in our experiment. It is a typical electroreflectance setup [2].

An examined sample is placed on a stage, which enables measuring different points along the device. Modulating external electric field is applied through contacts. Properties of this signal can be adjusted by programmable power supply.

Tungsten lamp is a source of analyzing beam which after leaving a monochromator is focused on an examined sample. Light reflected form the sample is collected by the silicon photodiode. Because changes in the signal are of order of 10^{-4}–10^{-6}, it is necessary to use a lock-in amplifier.

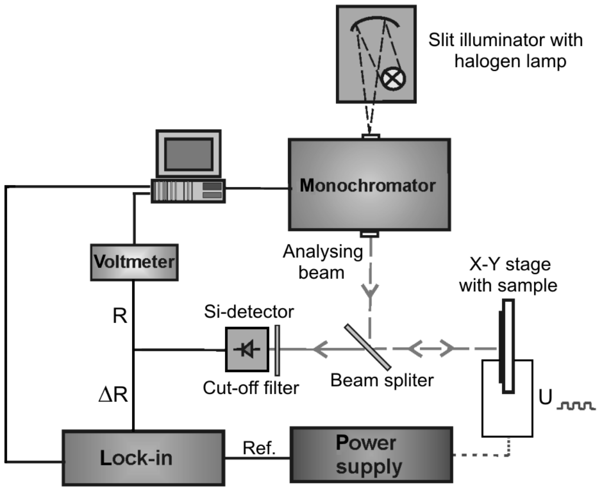

Fig. 3. Electroreflectance experimental setup.

Figure 4 presents the epitaxial structure of examined laser bars. It is a single quantum well separate confinement heterostructure (SQW SCH) with 8 nm InGaAs QW.

Electroreflectance measurement requires applying contacts to the structure. For structures mounted epi-side down thin Au contact is applied to the substrate, and the other contact is AuGe/Ni/Au.

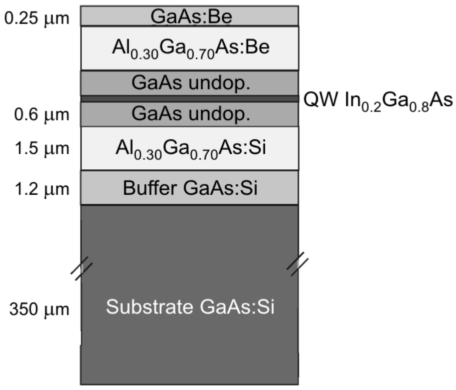

Fig. 4. Scheme of epitaxial structure.

Two series of measurements were done: first before and second after mounting the device on the heat sink. Each dataset contained eight spectra measured at the same points along the laser bar. For each point the fit was performed, resulting in the value of transition energy. Points were measured beginning in the centre of the bar and ending at its edge.

4. Results

A key to interpretation of the results is fitting the experimental spectra using an appropriate model. In this case a nonlinear fit was performed using Levenberg –Marquardt procedure. A model function was Aspnes third derivative functional form.

For the mounted device a shift of spectra towards higher energies is observed. This is due to the compressive strain induced during the packaging procedure. Comparison of the datasets is shown in Fig. 5. The value of induced stress is estimated using relation 1 nm = 16 MPa [5], *i.e.*, a shift of the band gap energy of 1 nm is due to applied pressure of 16 MPa.

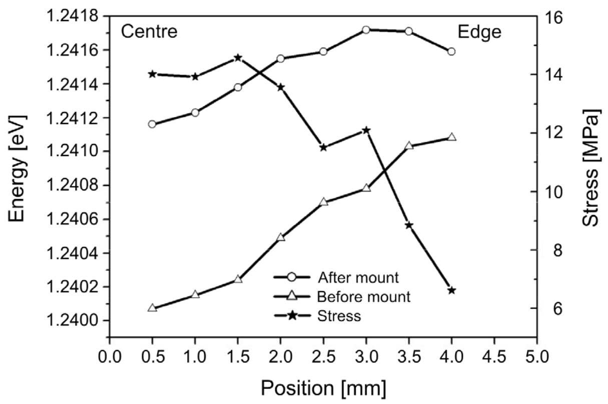

Fig. 5. Comparison of datasets and stress distribution.

It appears that the device is more strained in the centre than at the edges. This is in an agreement with results of other research results conducted on this subject [6, 7].

Electroreflectance ability to monitor packaging induced strain was estimated. It is a promising technique useful in spatially resolved measurements of stress along the laser bars.

5. Summary

Laser cm–bars were examined in order to assess packaging induced strain by means of optical modulation techniques, namely electroreflectance. This method proved to be useful in detecting subtle changes in bandgap energy, caused by mounting induced strain. From shifts in that energy stress can be estimated. The device mounted to a heat sink using indium solder, tend to be more strained in the center of the bar. Stress is weakening towards the edges.

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Received June 6, 2005
in revised form November 11, 2005