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Influence of features of QW InGaAs/(Al)GaAs heterostructures grown by MOCVD on the emission spectrum of single-mode laser diodes

P.V.Bulaev, O.I.Govorkov, I.D.Zalevskii, V.G.Krigel, A.A.Marmalyuk, D.B.Nikitin, A.A.Padalitsa, A.B.Petrovskii

***Abstract*. Laser heterostructures with an active layer consisted of two strained InGaAs quantum wells are fabricated by the MOCVD epitaxy method. Single-mode laser diodes with a 3–4-μm wide stripe contact are made of the heterostructures and their spectral characteristics are studied. It is found that the spectrum of the diodes consists of two groups of longitudinal modes, which cause the spectral broadening. The power distribution between these groups of modes depends on time, the pump current and the temperature of the active region. It is assumed that such a behavior of the diode spectra is explained by the asymmetry of the composition of the diode active region, which arises due to the segregation of In because of the complicated mechanism of its penetrating in the solid solution during the epitaxial growth. This assumption was confirmed by the study of the active region using a modified Auger spectroscopy method.**

Keywords: *MOCVD epitaxy, laser diode, quantum well, Auger spectroscopy.*

1. Introduction

A great attention has been presently paid to the development of laser diodes (LDs) emitting a single spatial mode in the 900–1000-nm range and having the output power of 100 mW and higher. Such diodes produce the output beam with a low divergence and high power density. As a rule, these LDs are fabricated based on the AlGaAs/GaAs heterostructures with InGaAs ultra thin active layers (quantum wells).

In this paper, LDs emitting 100 mW at 980 nm were fabricated of the double quantum-well heterostructures. Much attention was paid to the study of the emission spectrum of the LD, which had two groups of longitudinal modes, resulting in a considerable broadening of the spectrum. This broadening, along with the dependence of the power distribution between the modes on temperature of the active region and the pump current, may prove to be critical factors for some applications of such lasers. The assumption that the spectrum depends on a composition asymmetry of the quantum wells was caused by the peculiarities of In penetration during the epitaxial growth confirmed by the study of the LD active region using a modified Auger spectroscopy method. The modified method based on the optimisation of the energy and angle of incidence of the etching ion beam and pump electron beam provided a sufficiently high resolution and allowed us to analyse the heterostructure profile, including the ultrathin layers of the active region, which were about ~ 5 nm thick.

P.V.Bulaev, O.I.Govorkov, I.D.Zalevskii, V.G.Krigel, A.A.Marmalyuk, D.B.Nikitin, A.A.Padalitsa, A.B.Petrovskii M.F.Stel'makh Polyus Research & Development Institute, ul. Vvedenskogo 3, 117342 Moscow, Russia

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2. Experimental

The heterostructures for single-mode laser diodes emitting at 980 nm were grown by the low-pressure MOCVD epitaxy. The growth was performed in a system with a horizontal rectangular quartz Sig-MOC-130 reactor, which was developed by researchers of SigmPlus, Ltd. Substrates were placed on a rotating graphite substrate holder. The holder was rotated using a gas flow to provide good homogeneity of the structures. The growth temperature of the structures was 650–750 °C. A typical operating pressure at the reactor chamber was 60–70 Torr. Triethyl gallium, trimethyl aluminium, and trimethyl indium were used as sources of the third group elements. The source of the fifth group elements was 100 % arsine (AsH_3). Diethyl zinc and monosilane were used as *p*- and *n*-type dopants, respectively.

Before feeding into the gas chamber, arsine was doubly cleaned by blowing through zeolite and the 'Sigma-CHEM-1.0' supercleaner. This reduced the concentration of oxygen and water in arsine down to 0.1 ppm. Hydrogen, which was cleaned by the method of diffusion through a Pd filter heated to 450 °C, was used as a gas-carrier. Hydrogen had the dew point lower than −100 °C. The growth was performed on GaAs substrates doped with Si. The substrates were oriented on the (100) plane and were slightly disoriented (by 1–2°) in the [100] direction.

A typical structure consisted of two $In_zGa_{1-z}As$ quantum wells ($z = 0.15 - 0.18$) surrounded by intermediate GaAs layers, waveguide $Al_xGa_{1-x}As$ layers ($x = 0.18$–0.24), and emitter $Al_yGa_{1-y}As$ layers. A heavily doped GaAs layer was used as a contact layer. The optimisation of the growth regime, the doping profile, and the layer composition provided low optical losses and high internal quantum efficiency.

Laser diodes with a cavity length of 600–800 μm and stripe width of 3–4 μm were fabricated of the grown heterostructures. The reflection coefficients of the coatings on the front and back facets of the chip were 5 % – 7 % and 96 % – 97 %. The threshold current was 15 – 20 mA, the output power was 100 mW for the pump current of 130 – 150 mA. The emission distributions in the far-field zone could be well approximated by Gaussians at the planes parallel and perpendicular to the $p-n$ junction. This implies that the LD emission had one spatial mode. At the same time, the emission spectrum of the LD consisted of two well-pronounced groups of longitudinal modes (Fig. 1).

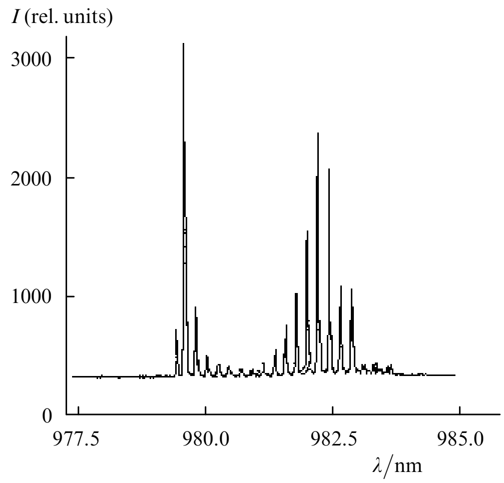

Figure 1. Typical emission spectrum of an LD with two groups of longitudinal modes.

The active region of the grown structures was studied using Auger spectroscopy at the Analytical Center of Polyus Research & Development Institute. The concentration profile of the composition was obtained with a PHI-560 scanning Auger spectrometer (Physical Electronics, Inc, USA). A modified design of the sample holder allowed us to perform ion etching at a sliding angle (80° with respect to the normal to the sample plane), a precise adjustment and combining of the ion and electron beams at the focal plane of the analyser. This provided a high spatial resolution of the Auger profiles obtained over the depth. The energy of the Ar^+ ion beam was 1.5 keV. The upper layers of the sample (the contact and *p*-emitter layers) were removed using ion etching in order to achieve an enhanced resolution at the depth of the active layers [1].

3. Results and discussion

A typical concentration profile of the sample under study is presented in Fig. 2. The concentration profile of In is shifted with respect to the profile of Al in a direction towards the sample surface. This shift (the width of the intermediate region under the heteroepitaxy) is about 3 nm. A similar concentration shift of In was found in Refs [2 – 4]. It follows from Fig. 2 that the concentration of In at the upper quantum well is higher than at the lower one. A possible reason for such a concentration profile of In may be the segregation of In atoms during the epitaxial growth [5]. It is known that indium atoms are accumulated at the surface layer until their equilibrium concentration is achieved [6]. After that, the composition of the solid solution becomes equivalent to the gas phase composition.

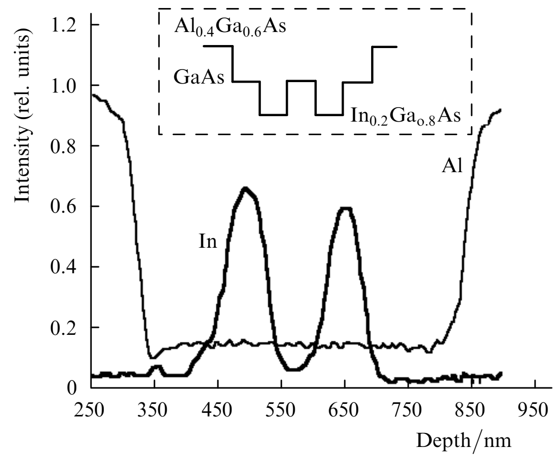

Figure 2. Typical Auger profile of the active region of an LD. The conduction-band profile is shown in the inset.

The segregation effect results in the broadening of the intermediate quantum well – barrier layer, in a distortion (the deviation from the ideal rectangular shape) of the potential profile of the well, and in the enhancement of the indium content in the second adjacent quantum well. All these is explained by a rather long time of residual incorporation of indium into the crystal lattice from the surface layer of the accumulated atoms.

We calculated positions of quantum levels in two adjacent quantum wells using the Schrödinger equation. The potential energy profiles of the wells were described taking into account the Auger spectra of the samples. We neglected in calculations the bias voltage, which was applied to the structure during the injection pumping of the laser diode. Nevertheless, the results of the calculations can explain the appearance of two groups of modes in the emission spectrum.

The ground quantum level both in the valence band and in the conduction band of each quantum well splits into two sublevels due to the presence of two quantum wells. These two sublevels take part in the radiative transitions. Because of this, emitted photons have slightly different energies, the difference being equal to the ground-level splitting, which is of about 1 nm in the case of the identical wells. According to our estimates, the difference is about 3 – 4 nm provided the wells have different depths (as in a real Auger spectrum in Fig. 2) due to different concentrations of indium in them. This results in the appearance of two distinct groups of longitudinal modes in the spectrum.

4. Conclusions

We have shown in this paper that the emission spectrum of laser diodes fabricated of heterostructures with the active region formed by two strained InGaAs quantum wells consists of two groups of longitudinal modes separated by about 3 nm. The study of the active region of the LD using the modified Auger spectroscopy has shown that the indium content in the quantum wells is not the same due to specific features of indium incorporation during the epitaxial growth. The analysis of the potential energy profile of the active region of the heterostructure has explained the spectral features of the laser diodes. It follows from our study that the parameters of laser diodes can be improved by developing special technological methods for the epitaxial growth of ultrathin strained InGaAs layers for suppression of the indium segregation.

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