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Study of multimode semiconductor lasers with buried mesas

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Abstract. **A buried-mesa AlGaAs/GaAs/GaInAs laser heterostructure emitting at a wavelength of 1050 nm is formed on a GaAs substrate by MOCVD. Mesa-stripe laser diodes with an aperture of 100 μm based on the obtained heterostructure are fabricated and studied. The internal optical losses of the laser diodes are 2.4 cm^{-1}. The output powers in both directions achieved at a cavity length of 2900 μm in the cw and pulsed regimes were 2.1 and 23 W, respectively.**

Keywords: *semiconductor laser, laser diode, heterostructure, MOCVD, buried mesa.*

1. Introduction

High-power semiconductor lasers are the most efficient sources of laser radiation [1, 2], because of which they are widely used for pumping the active media of fibre and solid-state lasers. At the same time, high reliability and output optical power make these sources attractive for solving the problems of material treatment without using intermediate laser amplification. However, efficient application of high-power systems based on semiconductor lasers is hindered by a low beam quality in the parallel plane, which is typical for high-power multimode lasers with a wide stripe contact [3, 4]. The use of weak lateral waveguides in multimode high-power lasers allows one to retain the lateral field quality but leads to the formation of closed mode structures [5, 6], which decreases the radiative efficiency. Thus, optimisation of the lateral waveguide structure of high-power multimode semiconductor lasers is a topical problem.

One of the ways of improving the mode structure of high-power semiconductor lasers is based on using the gain region localised only in the current injection region [7]. In the present work, we experimentally study the radiative characteristics of high-power multimode semiconductor lasers, in which the quantum-well gain region is localised due to two-stage epitaxial growth and selective etching. It is important to note that implementation of this approach requires both to investigate the technology of two-stage epitaxial growth for achieving high optical and electrical quality of the formed structures with a minimum amount of defects and to optimise the lateral waveguide structure, which is related to the choice of the composition of the epitaxial layers used for overgrowth, as well as of the buried region structure. We will focus on the results demonstrating the possibility of minimising such negative effects as an increase in nonradiative losses and a decrease in the internal quantum yield, which appear in the case of using two-stage epitaxial growth and selective etching.

2. Experimental samples

The experimental laser heterostructures were grown on n-GaAs (100) substrates by MOCVD using an EMCORE GS3100 setup with a vertical reactor and resistive heating of the substrate holder at a temperature of 750 °C. We used trimethylaluminum, trimethylgallium, and trimethylindium as the main III-group materials and arsine as a V-group element. Monosilane and bis-cyclopentadienyl magnesium were used as sources of n- and p-type impurity conduction, respectively.

The laser heterostructures were grown in two stages. At the first stage, we grown on a GaAs (100) substrate a part of the laser heterostructure, which included an n-$Al_{0.27}Ga_{0.73}As$: Si emitter layer (EL) 1 μm thick, a lower GaAs waveguide layer (WL) 0.4 μm thick, a GaInAs quantum well (QW) 9 nm thick, and a part of the upper GaAs WL 0.2 μm thick. Investigations of photoluminescence at $T = 500$ K showed that the spectral maximum for this GaAs QW lies at a wavelength of 1040 nm. On the obtained structure, we formed a photoresist mask, which made it possible to form mesa stripes with a width of 90 μm by liquid etching. Between the stripes, the structure was etched to a depth of 0.4 μm (Fig. 1). After etching, we performed the second stage of overgrowth of the obtained structure, which included the growth of the upper GaAs

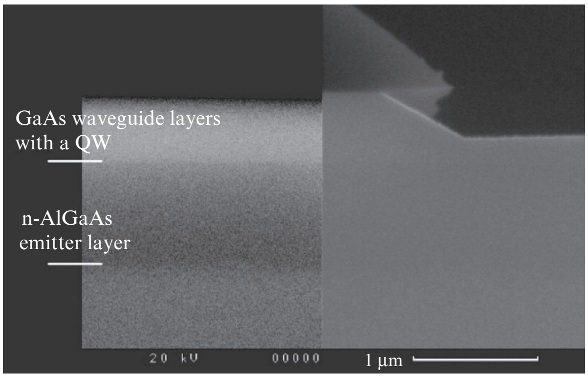

Figure 1. SEM image of the mesa-stripe structure fabricated by liquid etching of a heterostructure after the first growth stage.

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waveguide layer 0.2 μm thick, the upper p-$\mathrm{Al_{0.27}Ga_{0.73}As}$:Mg emitter layer 1 μm thick, and the p-GaAs:Mg contact layer 0.3 μm thick.

Using the structure obtained after the second stage, we fabricated deep-mesa laser diodes with a stripe contact width of 100 μm and etching depth to the GaAs waveguide layer. Figure 2 shows a photograph of a cleavage of the laser diode and the schematic of its structure. The figure shows three regions, namely, (1) the stripe contact region (emitting aperture) containing the active region, (2) the mesa-stripe region, in which the active region is absent due to its etching after the first growth stage, and (3) the mesa-groove region.

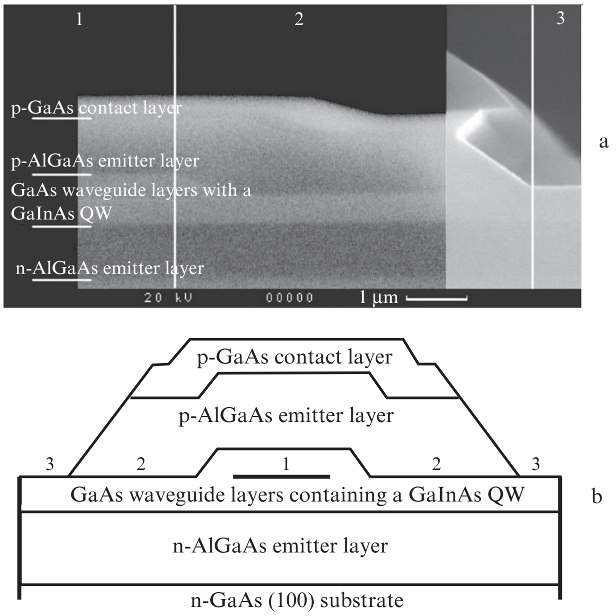

Figure 2. (a) SEM image of a laser diode based on a buried heterostructure and (b) scheme of the heterostructure: (1) part of the mesa-stripe with a quantum well, (2) part of the mesa-stripe without an active region, and (3) mesa-groove.

The ohmic contacts were deposited on the mesa-stripe structure using standard overgrowth procedures. The fabricated laser diodes had mirrors formed by natural cleavage faces.

3. Experimental results and discussion

The laser characteristics were studied at a heat-sink temperature of 25 °C. We studied laser diodes with the stripe contact width W = 100 μm and the cavity length L in the range 1000–4000 μm.

Based on the light–current characteristics (LCCs) measured in the near-threshold regime (when thermal heating can be neglected), we plotted the dependence of the reciprocal differential efficiency on the cavity length. From this dependence, we determined the internal quantum yield of stimulated emission η_{i} and internal optical losses α_{i} to be 95% and 2.4 $\mathrm{cm^{-1}}$, respectively. The found quantum yield η_{i} was close to the maximum value and corresponds to standard yields for high-power semiconductor lasers [1]. At the same time, the optical losses α_{i} are noticeably higher than that for laser heterostructures with broadened waveguides, which is caused by high losses in heavily-doped emitters due to strong optical limiting taking place in narrow-waveguide structures. From the dependence of the threshold current density on the reciprocal cavity length, we determined the minimum threshold current density J_0 at the cavity length $L \to \infty$, which corresponds to zero losses on coupling out of the Fabry–Perot resonator. The obtained value $J_0 = 270\ \mathrm{A\ cm^{-2}}$ is higher than that for the structures of high-efficiency semiconductor lasers, which may be related both to higher internal optical losses [8] and to the mode leakage effect, which will be considered below.

Figure 3 shows the LCC of a laser diode (W = 100 μm, L = 2900 μm) operating in a pulsed regime (pulse repetition rate 1 kHz, pulse duration 100 ns). The maximum output peak power in both directions was 23 W. The inset in Fig. 3 shows the LCC of the same laser in a cw regime; the maximum output power in both directions in this case was 2.1 W. The LCC curve deviates from linear in both lasing regimes. This deviation in the cw lasing regime is related to heating of the laser and appears at a pump current exceeding 3.5 A. In the pulsed regime, the LPCC linearity is retained up to a pump current of 35 A, while further increase in the current leads to a decrease in radiative efficiency due to increasing internal optical losses [9].

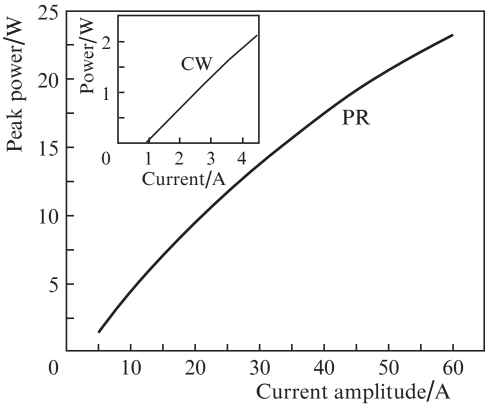

Figure 3. Light–current characteristic of the laser diode in a pulsed regime (PR) (1 kHz, 100 ns). The inset shows the LCC of the laser diode in a cw regime. The power is measured in both directions; W = 100 μm, L = 2900 μm.

Figure 4 demonstrates the changes occurring in the emission spectrum with increasing pump current for the laser diode in the cw regime. The spectral maximum shifts by 4 nm as the current increases from 1.1 to 3.3 A, which confirms thermal heating of the laser crystal.

Figure 5 presents typical beam divergence patterns of the laser diode in the planes parallel [curves (*1*, *2*)] and perpendicular [curve (*3*)] to the p–n junction. The beam divergence in the plane parallel to the p–n junction was measured at pump currents of (*1*) 1 and (*2*) 3.5 A. One can see that the divergence (FWHM) in the plane parallel to the p–n junction increases from 3.5° to 14.6° as the pump current increases from 1 to 3.5 A. In our opinion, this increase in divergence is caused by the effect of deep mesa-grooves forming the lateral waveguide, which allows the laser mode fields to extend in the transverse direction. However, at low pump currents, when the lateral waveguide is bounded only by the quantum-well region, the radiation divergence is lower than the divergence typical for high-power semiconductor lasers [10]. This circumstance indicates that the use of the technology of two-

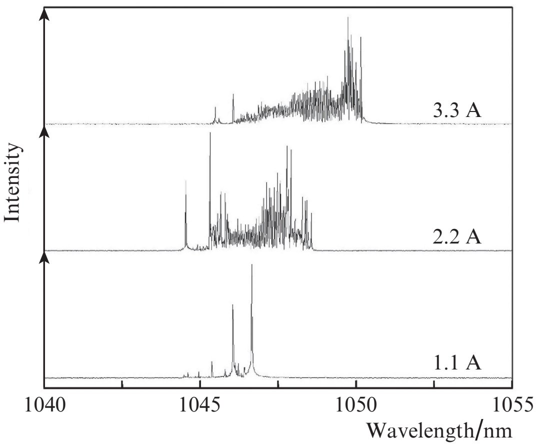

Figure 4. Emission spectra of the laser diode in a cw regime at different pump currents.

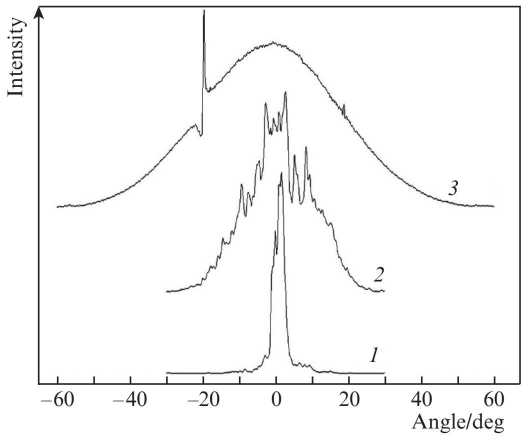

Figure 5. Laser diode divergence (FWHM) in the planes (*1*, *2*) parallel and (*3*) perpendicular to the p–n junction at pump currents of (*1*) 1 and (*2*, *3*) 3.5 A.

stage epitaxial growth and selective etching is promising for achieving further decrease in the divergence in the parallel plane and that optimisation of the lateral waveguide structure is an important task.

The FWHM divergence of the laser diode radiation in the plane perpendicular to the p–n junction at a pump current of 3.5 A is 39° [Fig. 5, curve (*3*)]. The shown divergence curve in the plane perpendicular to the p–n junction is typical and does not change in the studied range of pump currents. This curve exhibits two peaks, at angles of –20° and 19°. The peak on the substrate side is most intense. We believe that this peak is related to the mode leaking into the substrate.

4. Conclusions

It is shown that the use of the two-stage growth for fabricating high-power multimode semiconductor lasers causes no considerable deterioration of such radiative characteristics as internal quantum yield and threshold current density. It is important to note that etching and subsequent overgrowth of the strained quantum well allowed us to retain the high optical quality of the laser structure, which is confirmed by a high (95%) internal quantum yield of stimulated recombination and by the possibility of pumping the laser by current pulses with an amplitude of 60 A without irreversible degradation of the laser crystal. This testifies to a weak nonradiative recombination at the interface between the quantum well and the buried layer.

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