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Semiconductor AlGaInAs/InP lasers (λ = 1450–1500 nm) with a strongly asymmetric waveguide

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Abstract. **Semiconductor lasers based on AlGaInAs/InP heterostructures with a strongly asymmetric waveguide are studied. It is shown that the use of such a waveguide simultaneously with an increased quantum well energy depth provides conditions for increasing the output laser power. The semiconductor AlGaInAs/InP lasers based on a strongly asymmetric waveguide with a stripe contact width of 100 μm demonstrated an output optical power of 5 W (pump current 11.5 A) in a continuous-wave regime and 19 W (100 A) in a pulsed regime (100 ns, 1 kHz) at a wavelength of 1450–1500 nm at room temperature. The obtained data are compared with the output characteristics of lasers based on a symmetric waveguide.**

Keywords: *semiconductor laser, heterostructure, AlGaInAs/InP, asymmetric waveguide.*

1. Introduction

The application fields of semiconductor lasers are continuously expanding and, in many cases, one of the main required characteristics is an increased optical output power. An increase in the output power can be achieved by broadening the waveguide [1–3], increasing the energy depth of quantum wells (QWs) [4, 5], using additional barrier layers near the active region [6–8], and increasing the breakdown threshold of cavity mirrors [9–11]; recently, a positive influence of waveguide doping was also noted [12–14]. It was shown that, for high-power multielement lasers (laser diode bars and arrays), it is reasonable to use narrow waveguides, which leads to lower heat release and better heat removal from the active region of the heterostructure [5, 15]. In [16, 17], it was shown that an important factor restricting the output power of semiconductor lasers is the accumulation of charge carriers in the p-side of the waveguide with increasing pump current and, correspondingly, an increase in the internal optical losses. This effect can be reduced in lasers with extremely narrow waveguides [18–20], as well as with strongly asymmetric waveguides, in which QWs are close to the p-emitter [21–25].

When developing high-power semiconductor lasers emitting in the spectral range 1400–1600 nm, it is important to pay attention to decreasing the Auger recombination probability, which, as a rule, is achieved by using strained QWs [26].

The design with QWs shifted to the p-emitter is extensively used for fabricating semiconductor lasers of the spectral range 800–1100 nm in the InGaAs/AlGaAs/GaAs material system [21–23, 27–29]. The authors of [21], apart from shifting QWs to the p-emitter, used a wide n-waveguide (leakage layer) confined by the n-emitter with a low refractive index gap and called this structure laser with leaking emission. Theoretical analysis of such a heterostructure performed in [30] showed the possibility of increasing the output power and narrowing the directional pattern. It is important to emphasise that the considered variant suggests emission leakage into the n-waveguide rather than into the substrate as in some leaky-mode lasers [31, 32]. An idea of a heterostructure with double asymmetry, when the InGaAs QW is shifted to the p-waveguide (QW position asymmetry) and the waveguide itself is sandwiched between AlGaAs emitter layers with different compositions and, hence, with different refractive indices (asymmetry of sandwiching layers), was proposed in [22, 27, 28]. This structure was developed to decrease the optical losses, to reduce the electrical and thermal resistance, and to increase the differential quantum efficiency. This design was later modified into a heterostructure with triple-asymmetry, which additionally included different barrier layers adjacent to the QW [23, 29]. The aim of this modification was to increase the optical confinement factor in the QW for decreasing the threshold current density and increasing the temperature stability.

As applied to the spectral range 1400–1600 nm, we should note the works of two research groups. The researchers of the first group studied the QW shift to the p-emitter in terms of the traditional design of a double AlGaInAs/InP separate confinement heterostructure of the considered spectral range and avoided the appearance of high-order modes [24, 33]. The authors of works of the second group [34, 35] also used a shift of the active region, but considered the heterostructure based on the InGaAsP/InP material system. To optimise the output parameters of emitters, it was proposed to use a bulk active region instead of QWs and additionally to decrease the refractive index gap at the waveguide/n-emitter interface (heterostructure with double asymmetry).

The present work continues the approach of [34, 35] but differs by the use of a strongly asymmetric waveguide with a deeper QW to reduce the carrier leakage and a thinner

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p-emitter to improve heat removal from the active region as in [36]. The aim of this work is to study the possibility of increasing the output power of semiconductor lasers with a strongly asymmetric waveguide emitting in the range 1450–1500 nm.

2. Experiment

The AlGaInAs/InP laser heterostructures were grown by MOCVD. We used two types of heterostructures differing by the QW position in the waveguide. The first (basic) heterostructure, which was similar to the heterostructure used in [19], consisted of an active region with two strain-compensated InGaAs QWs in the centre of a broadened AlGaInAs waveguide. The QW parameters were chosen so that lasing occurred in the spectral range of 1450–1500 nm. The waveguide was sandwiched between InP emitter layers. To decrease leakage, AlInAs blocking barrier layers isoperiodic with the InP substrate were formed on the waveguide–emitter interface. In the second heterostructure, the p-waveguide thickness was decreased so that (by analogy with [35]) the QWs turned out to be in the immediate vicinity of the p-emitter. The energy band diagrams of both types of studied heterostructures are presented in Fig. 1.

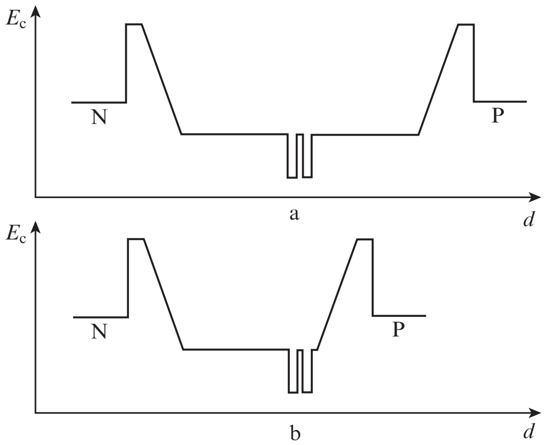

Figure 1. Schematic band diagram of the active region of AlGaInAs/InP semiconductor lasers with (a) symmetric and (b) asymmetric waveguides.

Based on the grown heterostructures, we fabricated semiconductor lasers with a stripe contact width of 100 μm and a cavity length of 2000–3000 μm. The cavity faces were coated with antireflection and reflection layers with reflection coefficients $R_1 \sim 0.05$ and $R_2 \sim 0.95$. The crystals were mounted onto a copper heat sink, and their output characteristics were studied in pulsed (pulse duration 100 ns, repetition rate 1 kHz) and cw regimes at a heat sink temperature of 25 °C.

3. Results and discussion

The light–current characteristics (LCCs) of both studied laser types are shown in Fig. 2. One can see that their threshold currents are similar but the LCCs are different even at the initial stage. An increase in the differential quantum efficiency of the laser with an asymmetric waveguide is related to the use of QWs with an increased energy depth. With increasing the

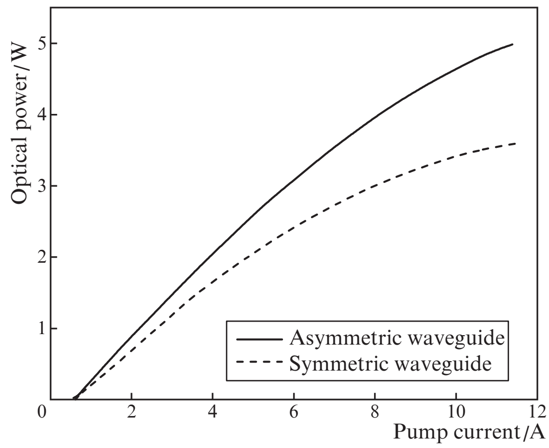

Figure 2. Light–current characteristics of semiconductor lasers based on AlGaInAs/InP heterostructures with asymmetric and symmetric waveguides in a cw regime.

pump current, the LCC of the laser with shifted QWs saturates more slowly due to a decrease in the internal optical losses on charge carriers accumulated in the p-waveguide. The maximum achievable optical power at a pump current of 11.5 A, a stripe contact width $w = 100$ μm, and a cavity length $L = 2000$ μm was 3.6 W for the samples with a symmetric waveguide and 5.0 W for the samples with a strongly asymmetric waveguide.

The transparency current density ($J_0 = 120–150$ A cm^{-2}) and the internal quantum efficiency ($\eta_i = 0.95–0.96$) were similar in the studied lasers, while the internal optical losses in the sample with an asymmetric waveguide ($\alpha_i = 1.0–1.5$ cm^{-1}) was lower than in the sample with a symmetric waveguide ($\alpha_i = 2.0–2.5$ cm^{-1}). Owing to this, the increase in the cavity length from 2000 to 3000 μm positively affected the output power of the latter.

In the pulsed regime (100 ns, 1 kHz), the lasers with a strongly asymmetric waveguide demonstrated an increase in the output power by 50% (Fig. 3). In particular, at a pump current of 60 A, $w = 100$ μm, and $L = 3000$ μm, the output power of lasers with an asymmetric waveguide reached 16 W

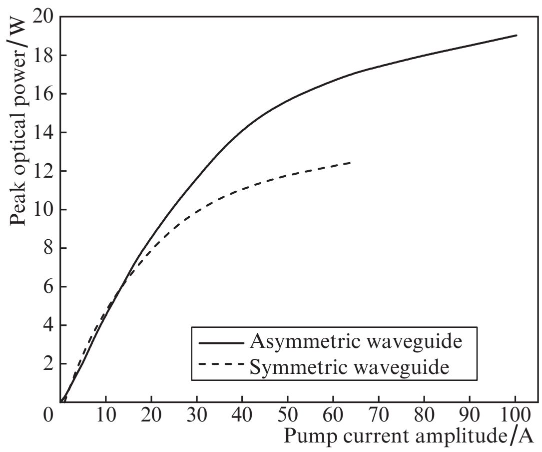

Figure 3. Light–current characteristics of semiconductor lasers based on AlGaInAs/InP heterostructures with asymmetric and symmetric waveguides in a pulsed regime (100 ns, 1 kHz).

versus 12.5 W for the samples with a symmetric waveguide. An increase in the pump current to 100 A allowed us to increase the output power of the samples with an asymmetric waveguide to 19 W, while an increase in the pump current for the sample with a symmetric broadened waveguide caused no increase in the output power due to the LCC saturation.

The wavelength of the studied lasers varied in the range of 1450–1480 nm depending on the pump conditions. The typical spectral characteristics of the laser with an asymmetric waveguide in the cw regime at different pump currents are presented in Fig. 4. The FWHM far-field divergence angle of these lasers was 40–43° in the plane perpendicular to the p–n junction and 7–9° in the plane parallel to the p–n junction.

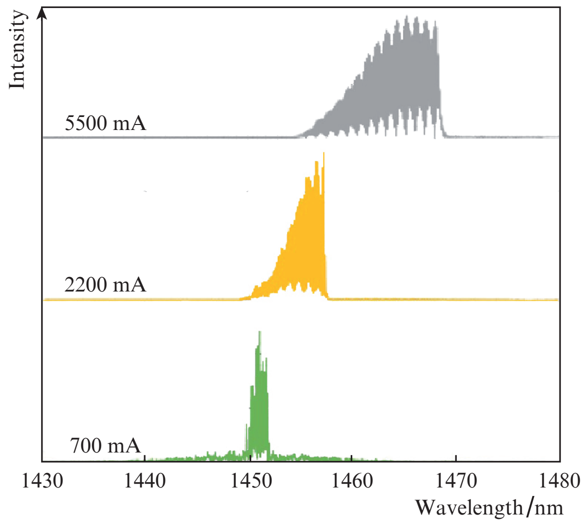

Figure 4. Typical spectral characteristics of a semiconductor laser based on the AlGaInAs/InP heterostructure with an asymmetric waveguide in a cw regime at injection currents of 0.7, 2.2, and 5.5 A.

Thus, our measurements show that a shift of the active region of a semiconductor laser to the p-emitter simultaneously with an increase in the QW energy depth and a decrease in the p-emitter thickness makes it possible to increase the output power. The creation of conditions for reducing the charge carrier accumulation in the p-waveguide and improving heat removal from the active region allowed us to achieve a maximum output power of 5 W in the cw operation regime at a wavelength of 1450–1500 nm.

4. Conclusions

In this work, we presented the results of comparative experimental studies of semiconductor lasers based on AlGaInAs/InP heterostructures with waveguides of different designs. In a strongly asymmetric waveguide, a shift of the QW to the p-emitter with a decreased thickness decreases the carrier accumulation in the p-waveguide and improves heat removal, while the simultaneous increase in the QW depth improves electron localisation in the active region and increases the differential quantum efficiency. This leads to an increase in the output power of these lasers approximately by 1.5 times in comparison with the lasers having the same but symmetric waveguide at identical geometric dimensions of the emitting region and pump currents both in pulsed and cw operation regimes.

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