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Improvement of the current–voltage performance of broadened asymmetric waveguide InGaAs/AlGaAs/GaAs semiconductor lasers (λ = 940–980 nm)

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Abstract. **The purpose of this work is to improve the current–voltage (I–V) performance of semiconductor lasers based on broadened asymmetric waveguide InGaAs/AlGaAs/GaAs separate-confinement double heterostructures. We analyse the effect of AlGaAs waveguide layer composition on the output characteristics of the lasers and demonstrate that the decrease in the series resistance of the lasers and the threshold voltage of their I–V characteristic as a result of a decrease in the percentage of AlAs in the waveguide layers shifts the drop in the differential quantum efficiency of the lasers to higher pump currents, despite the decrease in the energy depth of the quantum wells in the active region.**

Keywords: *semiconductor laser, asymmetric waveguide, current–voltage characteristic, quantum well, output power.*

1. Introduction

The ability to raise the output power of semiconductor lasers emitting in the range 940–980 nm is critical for a large number of important practical applications [1]. The use of broadened waveguide heterostructures in various ways stands out among the approaches proposed to date for raising the power of light sources [2–5]. Such a geometry of structures allows one to lower the level of intrinsic optical losses in lasers and maintain their differential quantum efficiency as the cavity length increases, which helps raise the maximum achievable power. Vinokurov et al. [6] proposed the use of a broadened waveguide having a slight asymmetry with respect to the position of quantum wells (QWs) in order to improve high-order mode selection.

In recent years, there has been great interest in highly asymmetric waveguide laser structures in which the active region is located as close as possible to the p-emitter [4, 5, 7] because reducing the p-region of the waveguide reduces the accumulation of electrons ejected from the active region and prevents an increase in internal optical loss with increasing pump current [8]. Despite the promising potential of this approach, broadened symmetric or slightly asymmetric waveguide heterostructure designs continue to be widely used. Since optical power saturation of semiconductor lasers in continuous mode is of a thermal nature, reducing the heat release during operation of such lasers should help raise their output power. As shown by Gavrina et al. [9] using direct optical probing measurements, accumulation of charge carriers ejected to the waveguide is responsible for the increase in internal optical loss with increasing pump current. According to Shashkin et al. [10], increasing the QW depth helps reduce carrier delocalisation in waveguide layers. In the case of InGaAs/AlGaAs/GaAs heterostructures, this approach is implemented by increasing the mole fraction of AlAs in the AlGaAs waveguide layers, but this change is accompanied by a rise in series resistance [11], which increases heat release during operation of the laser and leads to a lower saturation threshold of its light–current (L–I) characteristic. Thus, there are two opposite factors. On the one hand, a transition to wide-gap waveguide layers impairs the current–voltage (I–V) performance and efficiency of the lasers. On the other, the use of wide-gap waveguides reduces carrier ejection from QWs and raises the optical output power saturation threshold. In many studies aimed at making high-power semiconductor lasers based on the heterostructures under consideration, it was proposed that carrier localisation in the active region be improved by using QWs with an energy depth ΔE for electrons (separation between the first size quantisation level for electrons and the QW potential-barrier top) above 250 meV [12–14]. By contrast, in this work we ensure conditions for reducing carrier localisation in QWs in order to improve I–V parameters of lasers and assess the effect of these factors on their output characteristics.

2. Experimental

InGaAs/AlGaAs/GaAs separate-confinement laser heterostructures were grown by metal-organic vapour phase epitaxy. The main parameters of the heterostructures were the same as in a previous study [15]. Their active region consisted of an InGaAs QW located in a broadened asymmetric waveguide. We studied three distinct designs, in which the waveguide layers differed in composition from the base layer: the mole fraction of AlAs was reduced by a factor of 2 and 3. Thus, the waveguide composition was $Al_{0.3}Ga_{0.7}As$ in one heterostructure, $Al_{0.15}Ga_{0.85}As$ in another, and $Al_{0.1}Ga_{0.9}As$ in

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the third. The waveguide layers were doped to $10^{16}-10^{17}$ cm^{-3}. The waveguide width and the composition of the emitter layers were chosen so as to ensure a vertical output beam divergence angle of the order of 30° FWHM. The heterostructures were used to fabricate semiconductor lasers with a 100-μm-wide stripe contact. The laser cavity length was varied from 3 to 4 mm. The cavity facets were coated with antireflective and reflective layers having reflectivities $R_1 \approx 0.05$ and $R_2 \approx 0.99$. The output facet was passivated with a silicon nitride layer 2–3 nm in thickness. The lasers were mounted on a copper heat sink. Their output characteristics were measured in continuous mode at a heat sink temperature of 25 °C.

3. Experimental results and discussion

Carrier delocalisation from the active region to waveguide layers is the main cause of output power saturation with increasing pump current in semiconductor lasers in continuous mode. There is conclusive experimental evidence [11, 13, 16] that increasing the QW depth ΔE for electrons to above 250 meV considerably reduces the rate of this process. In particular, in the case of typically used $Al_{x_w}Ga_{1-x_w}As$ waveguide layers with a mole fraction of AlAs $x_w = 0.25-0.3$, the energy depth ΔE of QWs in the spectral range under consideration exceeds the above value. Therefore, electron delocalisation processes in lasers containing such QWs will be hindered, and this is expected to help raise the laser output power. On the other hand, as pointed out in a number of reports [12, 13, 15, 16] an important factor intensifying carrier delocalisation from the active region is the temperature of the device. With increasing temperature, the concentration of carriers ejected to the waveguide rises rapidly, so the self-heating of lasers during operation will have a significant effect on the delocalisation process. Moreover, raising the operating voltage at a constant pump current will increase this effect. Thus, in view of this, raising ΔE via an increase in the mole fraction of AlAs in the AlGaAs waveguide and, hence, emitter layers will be accompanied by an increase in operating voltage, increasing heat release and reducing laser efficiency, which may lead to a lower output power saturation threshold.

In this work, we studied lasers with the waveguide layer compositions $Al_{0.3}Ga_{0.7}As$, $Al_{0.15}Ga_{0.85}As$, and $Al_{0.1}Ga_{0.9}As$. In the case of the first composition, the lasers had $\Delta E >$ 250 meV, which was quite sufficient for hindering electron delocalisation processes. In the case of the second and third compositions, with a reduced mole fraction of AlAs, the QWs had $\Delta E \approx 150-200$ meV. This QW depth is insufficient for effective electron confinement, but lasers with such a waveguide would be expected to have an improved $I-V$ performance and, hence, be capable of retaining a constant slope of their $L-I$ curve in a wider range.

Figure 1 shows $I-V$ curves of the lasers studied. As was expected, reducing the mole fraction of AlAs in the AlGaAs layers reduced the series resistance of the lasers, as evidenced by the change in the slope of the $I-V$ curves. Similar behaviour was exhibited by the threshold voltage, which decreased from 1.4 to 1.32 and 1.29 V (at $x_w = 0.3$, 0.15, and 0.1, respectively).

All other conditions being the same, improving the $I-V$ performance of a laser should help reduce saturation of its output power at high pump currents. For comparison, Fig. 2 shows $L-I$ curves of the lasers with waveguide layers differing in composition.

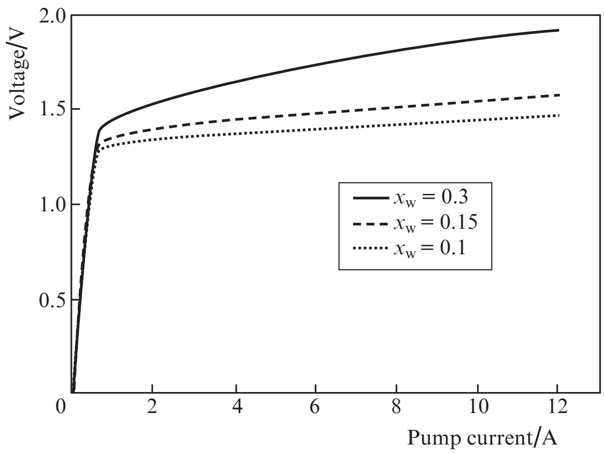

Figure 1. $I-V$ curves of the semiconductor lasers based on InGaAs/AlGaAs/GaAs heterostructures containing $Al_{x_w}Ga_{1-x_w}As$ waveguide layers differing in x_w.

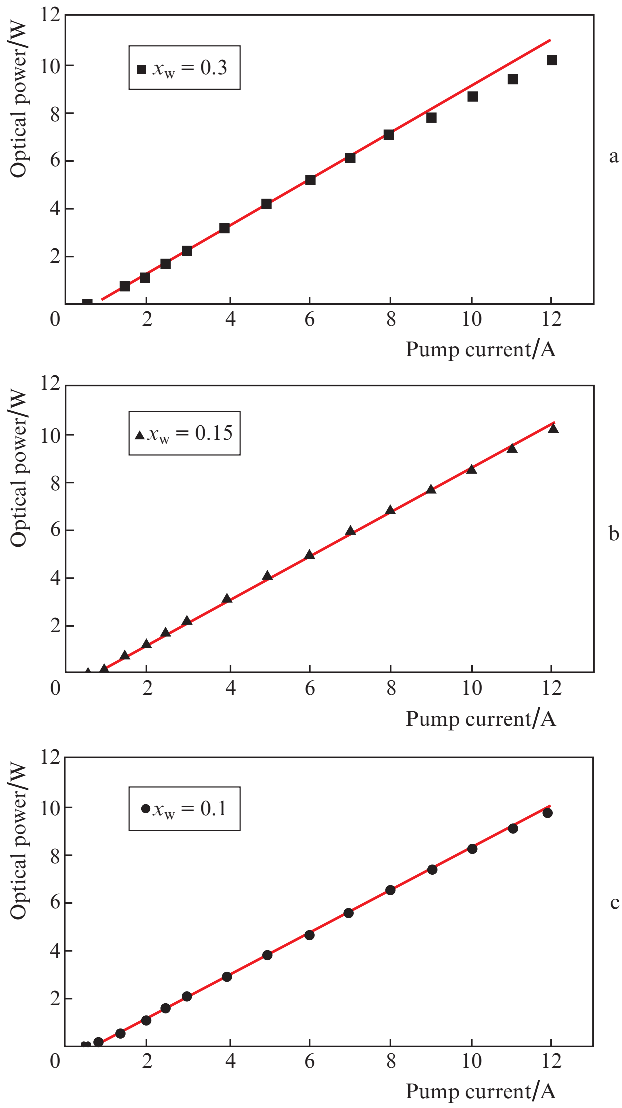

Figure 2. $L-I$ curves of the semiconductor lasers based on InGaAs/AlGaAs/GaAs heterostructures containing $Al_{x_w}Ga_{1-x_w}As$ waveguide layers differing in x_w.

Comparison of the $L-I$ curves of the lasers (Fig. 2) indicates that the lower series resistance and threshold voltage of the lasers with the reduced fractions of AlAs lead to a higher saturation threshold in their $L-I$ characteristics and allow the slope of their $L-I$ curves to remain constant as the operating current increases. This is well seen in Fig. 3.

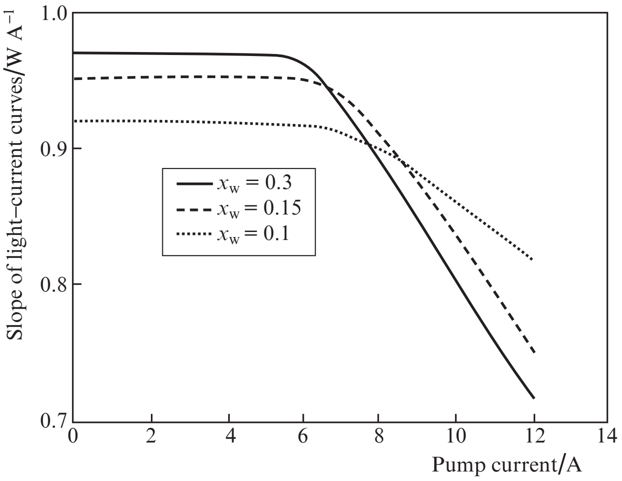

Figure 3. Slope of light–current curves as a function of pump current for the semiconductor lasers based on InGaAs/AlGaAs/GaAs heterostructures containing $Al_{x_w}Ga_{1-x_w}As$ waveguide layers differing in x_w.

All the lasers emitted in the spectral range 970–975 nm. At a pump current of 12 A, the lasers with the reduced percentage of AlAs in the waveguide layer ($x_w = 0.1-0.15$) had similar temperature shifts of their wavelength, 14.8–15.0 nm, which corresponded approximately to an increase in the temperature of the active region by 49–50 °C. At the same pump current, the wavelength of a laser with a standard design and $x_w = 0.3$ was shifted by about 17.5 nm, which corresponded to heating by ~58 °C. All this demonstrates that reducing the mole fraction of AlAs in the composition of the waveguide layers has an advantageous effect on laser operation efficiency.

4. Conclusions

The present results demonstrate that reducing the series resistance and threshold voltage allows the slope of the $L-I$ curve to persist at higher pump currents and ensures a higher output power of broadened asymmetric waveguide semiconductor lasers even at a reduced QW energy depth. The improvement of $I-V$ parameters with decreasing AlAs concentration in the $Al_{x_w}Ga_{1-x_w}As$ waveguide layer owing to the decrease in the series resistance of the laser diode can compensate for the degradation of its $L-I$ performance as a result of the decrease in QW depth. In a previous study [17], this approach was shown to be effective. Thus, despite the decrease in QW depth, the use of narrower gap and moderately doped waveguide layers allows the slope of the $L-I$ curve to persist at higher pump currents.

Further optimisation of the relationship between the above parameters, with the low level of internal optical losses retained, will make it possible to raise the maximum achievable output power.

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