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InGaAs/AlGaAs/GaAs semiconductor lasers (λ = 900–920 nm) with broadened asymmetric waveguides and improved current–voltage characteristics

N.A. Volkov, T.A. Bagaev, D.R. Sabitov, A.Yu. Andreev, I.V. Yarotskaya, A.A. Padalitsa, M.A. Ladugin, A.A. Marmalyuk, K.V. Bakhvalov, D.A. Veselov, A.V. Lyutetskii, N.A. Rudova, V.A. Strelets, S.O. Slipchenko, N.A. Pikhtin

Abstract. **Semiconductor lasers based on double separate-confinement InGaAs/AlGaAs/GaAs heterostructures with a broadened waveguide are studied. The experimentally obtained samples of lasers with undoped and doped waveguide layers are compared. The differences in their current–voltage characteristics are analysed. It is found that a decrease in the series resistance and the cutoff voltage of the current–voltage characteristic makes it possible to delay the beginning of the output optical power saturation and increase the efficiency of the studied semiconductor lasers to 70%–72%.**

Keywords: *semiconductor laser, asymmetric waveguide, doping, output power.*

1. Introduction

High-power semiconductor lasers are required for many practical applications. Such lasers are traditionally based on double separate confinement heterostructures with one or several quantum wells (QWs) in the active region. A well-proven solution for achieving higher output powers of semiconductor lasers is the use of a broadened waveguide, which provides a decrease in internal optical losses and thus allows one to increase the differential quantum efficiency and to use longer laser cavities [1–3]. An additional advantage of this design is a decrease in the laser radiation density on the cavity faces, which delays the catastrophic optical degradation of mirrors.

Unfortunately, the use of broadened waveguides may lead to an increase in the series resistance of the structure and, as a result, to a higher heat release, which decreases the efficiency of semiconductor lasers and restricts the maximum achievable power. Moreover, it was noted in [4] that the cutoff voltage of the current–voltage characteristic (CVC) increases with increasing waveguide width, which also negatively affects the efficiency and thermal characteristics of lasers.

It was shown in [5, 6] that an important reason for the saturation of the output optical power of semiconductor lasers with increasing pump current in a cw lasing regime is the delocalisation of charge carriers from the active region into the waveguide layers. In this case, a special role is played by ejection of electrons and their accumulation in the p-waveguide [7, 8]. The authors of [9] have demonstrated that an effective method to decrease the delocalization of charge carriers into the waveguide is to increase the QW depth. In the case of InGaAs/AlGaAs/GaAs heterostructures, this approach consists in the use of wide-bandgap AlGaAs waveguide layers with an increased mole fraction of AlAs. However, widening of the band gap with increasing AlAs mole fraction in the AlGaAs layers is accompanied by an increase in their series electric and thermal resistances, which negatively affects the temperature stability of lasers.

A way to use the advantages of broadened waveguides under these conditions is to create laser heterostructures with a doped waveguide. Doping of waveguide layers makes it possible to decrease the series resistance and working voltage of semiconductor lasers. In this case, selection of the doping profile may provide a sufficiently low level of internal optical losses [10]. Heterostructures with doped waveguides were successfully used to fabricate semiconductor lasers emitting at wavelengths from 800 to 1550 nm [7, 10–15]. In each case, the proposed doping profiles of waveguide layers varied depending on the chosen system of materials and the general design of the laser heterostructure.

The temperature stability of the threshold current density and the delocalisation of charge carriers in semiconductor lasers with a broadened asymmetric waveguide emitting in the range 900–920 nm were studied in [16, 17]. The present work is aimed at improving the CVCs of these lasers in order to increase their optical output power and efficiency.

2. Laser design

The double separate confinement heterostructures InGaAs/AlGaAs/GaAs were grown by MOVPE. The basic heterostructure design was taken from [17]. The active region consisted of two InGaAs QWs asymmetrically positioned in a broadened AlGaAs waveguide. We studied the samples with intentionally undoped [$(1-5)\times10^{15}$ cm^{-3}] and doped

N.A. Volkov, T.A. Bagaev, D.R. Sabitov, A.Yu. Andreev, I.V. Yarotskaya, A.A. Padalitsa, M.A. Ladugin Sigm Plus Ltd, ul. Vvedenskogo 3, 117342 Moscow, Russia;
e-mail: volkov_n_a@mail.ru;
A.A. Marmalyuk Sigm Plus Ltd, ul. Vvedenskogo 3, 117342 Moscow, Russia; National Research Nuclear University MEPhI, Kashirskoe sh. 31, 115409 Moscow, Russia;
K.V. Bakhvalov, D.A. Veselov, A.V. Lyutetskii, N.A. Rudova, V.A. Strelets, S.O. Slipchenko, N.A. Pikhtin Ioffe Institute, Russian Academy of Sciences, ul. Politekhnicheskaya 26, 194021 St. Petersburg, Russia

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($10^{16}-10^{17}$ cm^{-3}) waveguide layers. As doped waveguides, we used $Al_{0.25}Ga_{0.75}As$ layers, which have narrower gaps, and the $Al_{0.3}Ga_{0.7}As$ layers with wider gaps were used as undoped waveguides. The asymmetric waveguide width and the composition of emitter layers were chosen so that the radiation divergence along the fast axis at half maximum was about 30°. The grown heterostructures were used to fabricate semiconductor lasers with a stripe contact width of 100 μm. The cavity length was 3 mm. The cavity faces were coated with antireflection and reflection layers with reflectivities $R_1 \approx 0.05$ and $R_2 \approx 0.95$. The crystal was mounted onto a copper heat sink. The output laser characteristics were studied in a cw operation regime at a heat sink temperature of 25 °C.

3. Results and discussion

A considerable part of electromagnetic radiation in semiconductor lasers with broadened waveguides propagates within the waveguide layers, which, as a rule, are intentionally undoped to ensure low optical losses. The saturation of the output optical power in the cw regime of these lasers has a thermal nature and depends on the laser efficiency and the conditions of heat removal from the active region. In this case, an increased thickness of waveguide layers may lead to an increase in the series resistance and deteriorate the temperature characteristics of semiconductor lasers. At the same time, doping of waveguide layers may provide a balance between a decrease in the series resistance and an increase in the internal optical losses. Therefore, in this work we study semiconductor lasers with both undoped and doped asymmetric broadened waveguides.

The ways to improve the CVCs without considerable deterioration of radiative characteristics of heterostructures with doped waveguides were searched using waveguide and emitter layers with narrower gaps. In this case, although the QW depth for electrons becomes smaller than that of structures with undoped waveguides, it still exceeds 230 meV, which is sufficient for weakening the effect of delocalization of carriers [18]. It was expected that a decrease in the mole fraction of AlAs in the layers of the AlGaAs laser heterostructure along with doping of the waveguides will improve the CVCs of these devices.

The transparency current density of emitters with an undoped waveguide (J_0 = 160–190 A cm^{-2}) turned out to be slightly lower than that of the samples with doped waveguides (J_0 = 180–210 A cm^{-2}), while the internal quantum efficiency (η_i = 0.95–0.98) and the level of internal optical losses (α_i = 0.2–0.4 cm^{-1}) in the studied lasers were close for laser of both types. Figure 1 shows the experimental dependences of the inverse differential quantum efficiency on the cavity length for the studied samples, which made it possible to determine the internal quantum yield and internal optical losses.

Despite doping of waveguides, the internal optical losses in the samples almost did not increase due to the chosen doping profile. In addition, the lasers with doped waveguides demonstrated a decrease in the series resistance (to R_s = 55–70 mΩ versus R_s = 95–110 mΩ for lasers with undoped waveguides) and a decrease in the cutoff voltage of the CVC (U_0 = 1.41–1.44 V versus 1.50–1.53 V) (Fig. 2).

All other conditions being equal, the improvement of the CVC should lead to a delay of the saturation of the output optical power at high pump currents due to a higher efficiency. Figure 3 presents the light–current characteristics (LCCs) of the studied lasers.

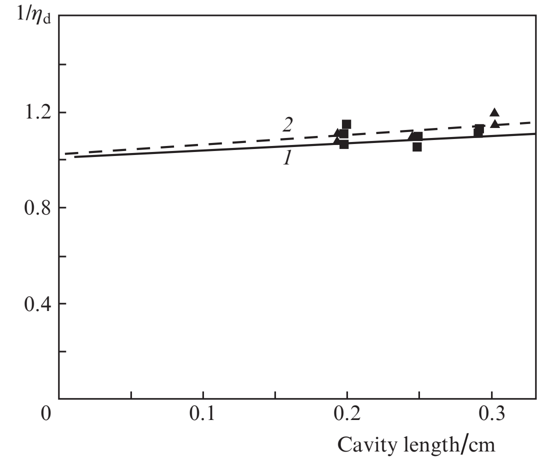

Figure 1. Dependences of the inverse differential quantum efficiency on the cavity length of semiconductor lasers based on InGaAs/AlGaAs/GaAs heterostructures with (*1*) undoped and (*2*) doped broadened asymmetric waveguides.

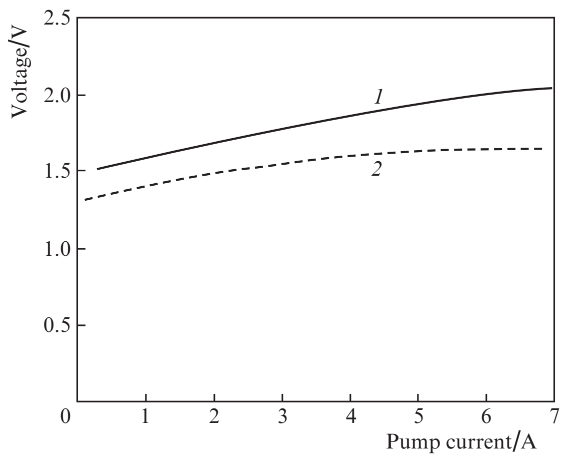

Figure 2. CVCs of semiconductor lasers based on InGaAs/AlGaAs/GaAs heterostructures with (*1*) undoped and (*2*) doped broadened asymmetric waveguides.

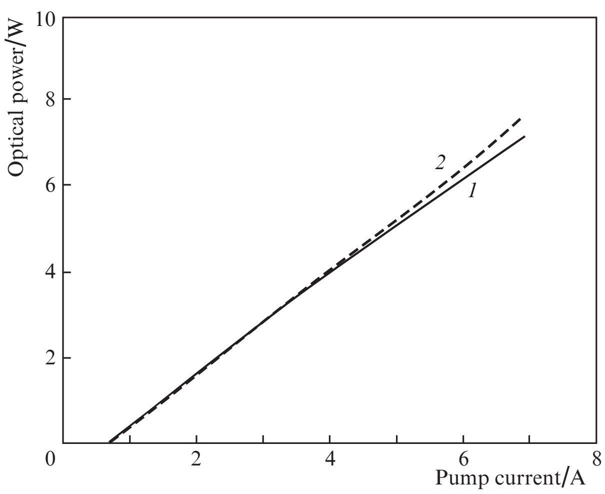

Figure 3. LCCs of semiconductor lasers based on InGaAs/AlGaAs/GaAs heterostructures with (*1*) undoped and (*2*) doped broadened asymmetric waveguides.

One can see that a decrease in the series resistance and in the cutoff voltage with unchanged internal optical losses allows the laser with a doped waveguide to retain the LCC slope at high pump currents. The character of the LCC saturation with increasing pump current is well seen in Fig. 4.

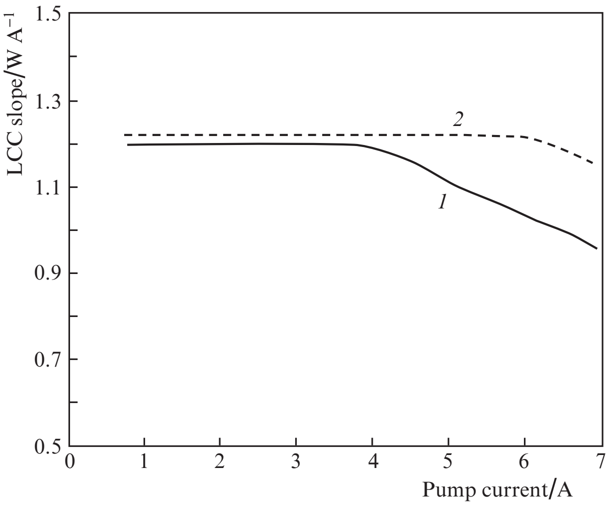

Figure 4. Dependences of the LCC slopes of semiconductor lasers based on InGaAs/AlGaAs/GaAs heterostructures with (*1*) undoped and (*2*) doped broadened asymmetric waveguides on the pump current in the cw regime.

The wavelength of the studied lasers varied from 900 to 920 nm depending on the pumping conditions as is shown in Fig. 5. The difference between the slopes of the curves indicates that the thermal load on the active region is higher for the laser with an undoped waveguide rather than with a doped one. This well agrees with the results of analysis of the dependences of LCC slopes of the studied lasers.

Note that the maximum efficiency reached 70%–72% for the samples with doped broadened asymmetric waveguides and only 55%–60% for the samples with undoped waveguides.

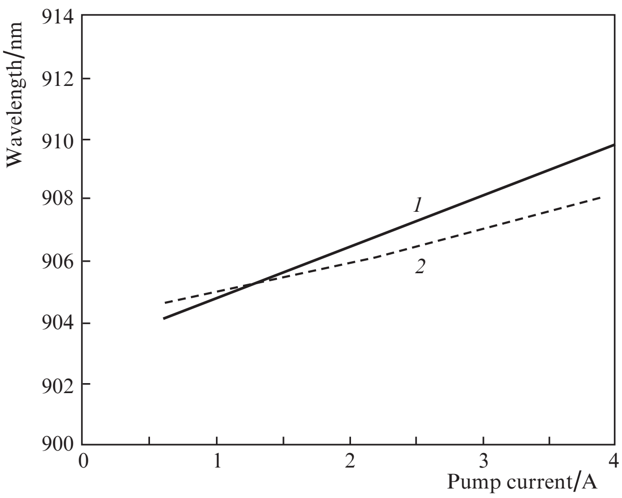

Figure 5. Dependences of the wavelength of lasers based on InGaAs/AlGaAs/GaAs heterostructures with (*1*) undoped and (*2*) doped broadened asymmetric waveguides on the pump current in the cw regime.

The beam divergence of the studied lasers with an undoped waveguide in the far field zone at half maximum was 30–32° in the plane perpendicular to the p–n junction and 3–15° in the plane parallel to the pn junction. At the same time, the divergence of the radiation of lasers with a doped waveguide was 28–30° in the plane perpendicular to the p–n junction and 3–8° in the plane parallel to it.

Our study shows that a decrease in the series resistance and in the cutoff voltage delays the LCC saturation with increasing pump current and increases the output optical power of semiconductor lasers with a broadened asymmetric waveguide. Despite a decrease in the energy barrier for electrons in QWs, the better CVCs lead to weaker self-heating of lasers at high working currents and to a less efficient delocalization of charge carriers from the active region into the waveguide. This approach to increasing the output power, which includes improvement of the CVCs, was also proved to be applicable for semiconductor lasers with ultra-narrow and strongly asymmetric waveguides [19, 20].

Thus, the present study of the output characteristics of semiconductor lasers based on InGaAs/AlGaAs/GaAs heterostructures with improved CVCs shows that the use of heterostructures with a decreased mole fraction of AlAs in the AlGaAs layers and with moderately doped waveguides (10^{16}–10^{17} cm^{-3}) makes it possible to use the advantages of broadened waveguides and to increase the efficiency of these lasers to 70%–72%.

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