Quantum Electronics **47** (4) 291 – 293 (2017)

LETTERS

https://doi.org/10.1070/QEL16365

Laser diode bars based on AlGaAs/GaAs quantum-well heterostructures with an efficiency up to 70 %

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Abstract. **The results of the development and fabrication of laser diode bars (λ = 800 – 810 nm) based on AlGaAs/GaAs quantum-well heterostructures with a high efficiency are presented. An increase in the internal quantum and external differential efficiencies together with a decrease in the working voltage and the series resistance allowed us to improve the output parameters of the semiconductor laser under quasi-cw pumping. The output power of the laser diode bars with a 5-mm transverse length reached 210 W, and the efficiency was ~70 %.**

Keywords: *laser diode bars, efficiency, quantum-well heterostructures, MOCVD, AlGaAs/GaAs.*

1. Introduction

Semiconductor lasers emitting in the spectral range 790 – 810 nm have been widely used in the key fields of science and engineering for a long time. In particular, they are used for optical pumping of various active media of solid-state lasers, in range finding and communication systems (navigation, location), in car and ship manufacturing, and in electronic, optomechanical, and other branches of industry. Improvement of the parameters of laser diodes, bars, and arrays allowed one to directly use them for technological purposes, because of which these sources began to play a more important role in such fields as materials processing, medicine, and printing industry.

The significant advance in the creation of high-power semiconductor lasers discussed in the present work was achieved owing to the development and upgrade of the main technological stages of their fabrication including MOCVD of high-quality quantum-well heterostructures (HS’s), formation of active elements with a higher radiation resistance of output faces, and assembling of laser diode bars (LDBs).

The present work continues the series of studies [1 – 6] aimed at increasing the output optical power, efficiency, and temperature stability of lasers, in particular, of LDBs with wavelengths of 800 – 810 nm. The main goals of this work were to choose the optimal design and the technology of production of AlGaAs/GaAs quantum-well HSs and to decrease the electrical and thermal resistances of active elements in order to increase the total electrical-to-optical power conversion efficiency.

2. Experiment and results

The semiconductor $Al_xGa_{1-x}As$/GaAs HS’s with single quantum wells were grown by MOCVD. As an active region material in our experiment we used AlGaAs, GaAsP, and InAlGaAs quantum wells. The waveguide layers had different thicknesses (from 0.2 to 1.7 μm) and mole fractions of AlAs in the ternary solid solution $Al_xGa_{1-x}As$ ($x = 0.25 - 0.55$). Special attention was paid to doping of waveguide, emitter, and contact layers to ensure, on the one hand, a low series resistance of HS layers and, on the other hand, low internal optical losses. All parameters of the laser HS were optimised to achieve the maximum total efficiency at the working point, i.e., at pump currents corresponding to the required power and wavelength. In addition, it was important to avoid a sharp decrease in the efficiency after passing the maximum (especially at pump currents $I_p \sim 10 I_{th}$), because of which, apart from a high external differential efficiency of the laser HS, a particular attention was paid to achieving a low series resistance of the laser.

From the well-known equation relating laser efficiency to pump current, threshold current, cutoff voltage, series resistance, and internal efficiency, which is determined by the cavity parameters and internal losses [7],

$$\eta_c = \eta_d \frac{h\nu}{q} \frac{I - I_{th}}{I(V_0 + IR_s)}, \tag{1}$$

where

$$\eta_d = \eta_i \left(\frac{1}{2L} \ln \frac{1}{R_f R_r}\right) \Big/ \left(\alpha_i + \frac{1}{2L} \ln \frac{1}{R_f R_r}\right),$$

we can obtain the following equation for the pump current corresponding to the maximum efficiency:

$$I_{max} = I_{th}\left(1 + \sqrt{\frac{V_0}{I_{th} R_s} + 1}\right). \tag{2}$$

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Received 17 March 2017
Kvantovaya Elektronika **47** (4) 291 – 293 (2017)
Translated by M.N. Basieva

Then, at the LDB contact width $W = 100$ μm, the cavity length $L = 1000$ μm, the LDB transverse length $l_{\rm LDB} = 5$ mm, as well as at typical threshold currents $I_{\rm th} = 12-14$ A, cutoff voltage $V_0 = 1.54-1.60$ V, and series resistance $R_{\rm s} = 3-4$ mΩ, we obtain $I_{\rm max} \approx 80-90$ A. If needed, $I_{\rm max}$ can be decreased, for example, to 60–70 A, by decreasing L or W. Vice versa, to shift this parameter to larger values, for example, to 110–120 A, one should increase L or W. In our case, the laser optimisation and the choice of the mentioned parameters were performed so that the working pump current was ~95–100 A.

One of the first steps in the creation of epitaxial HS's in this work was to choose the design and growth technology of the active quantum-well region, which, for emission in the given spectral range, was based on AlGaAs, InAlGaAs, and GaAsP. On the whole, the best parameters were demonstrated by the best studied and reliable AlGaAs quantum wells, although in a series of experiments they were inferior in some parameters to lasers with compressively strained InAlGaAs and tensile strained GaAsP quantum wells (threshold current, slope of the light–current characteristic, or ultimate output power). The thickness, composition, and growth regimes of the quantum-well material were selected so that it had the lowest transparency threshold and an internal quantum efficiency close to 100%.

In previous studies [5, 6], we experimentally demonstrated an advantage of deep quantum wells, as well as of narrow (0.2–0.4 μm) waveguides compared to broadened ones (1.5–2.5 μm), which concludes in a better temperature stability of the parameters of bars operating at high pulsed currents in a wide temperature range (from –40 to +50 °C). The characteristic temperature T_0 of lasers based on HS's with a narrow waveguide was higher than the characteristic temperature of lasers with a broadened waveguide [6].

However, we also should mention the drawbacks of HS's with a narrow waveguide. The ultimate output power of lasers based on these HS's is noticeably lower than that of lasers made of HS's with a broad waveguide. In addition, the fundamental mode field deeply penetrates into the doped emitter layers, which leads to an increase in the internal optical losses on free charge carriers. In this case, the injection layers should be sufficiently thick (1.5–2.0 μm) to efficiently keep the fundamental mode field and prevent its penetration into contact layers [8]. At the same time, the epitaxial layers should not be too thick, because this can reduce heat removal from the active region.

Taking into account the advantages of HS's with narrow and broadened waveguides, in the present work we proposed a HS with an intermediate waveguide thickness (0.6–1.0 μm). Owing to the quantum well with an increased energy depth and to the corresponding decrease in the probability of delocalisation of charge carriers at high pump currents (as described in [5, 9]), these HS's retained a good temperature stability of threshold current and external differential efficiency, while a slight broadening of the waveguide led to an increase in the ultimate output power and a decrease in the internal optical losses (to 0.7 cm^{-1}). The simultaneously proposed profiled doping of waveguide layers and strong doping of the emitter and contact layers allowed us to decrease the cutoff voltage and the series resistance of the laser [10].

We performed corresponding modifications in fabrication of active elements and formation of low-resistance contacts, as well as increased the radiation resistance of the output faces, which affects the ultimate characteristics of developed sources.

Stripe active elements (30 pieces) with an emitting region width of about 120 μm were formed on a length of 5 mm. The filling factor, i.e., the ratio of the total width of laser channels to the total length of the LDB was 72%. To increase the ultimate power, we used a scheme with non-pumped cavity regions near the mirrors [11].

Semiconductor lasers with a high output optical power density require special treatment of emitting surfaces in order to decrease the nonradiative recombination rate at the interface between the semiconductor crystal and the optical coating. In the present work, we used ion treatment of the emitting face in a vacuum chamber of the evaporation system directly before the deposition of the optical coating. The reflection coefficients of the input and output mirrors were $R_1 = 0.05-0.10$ and $R_2 = 0.95-0.99$, respectively.

Owing to the high doping level of the contact layers, the ohmic contacts were made using a combination of metal films Ti–Pt–Au, which was successfully used to develop high-power semiconductor devices [12]. As a result, the cutoff voltage for the LDB turned out to be close to the theoretical value (V_0 = 1.54–1.56 V), and the series resistance $R_{\rm s}$ was about 2–3 mΩ (Fig. 1).

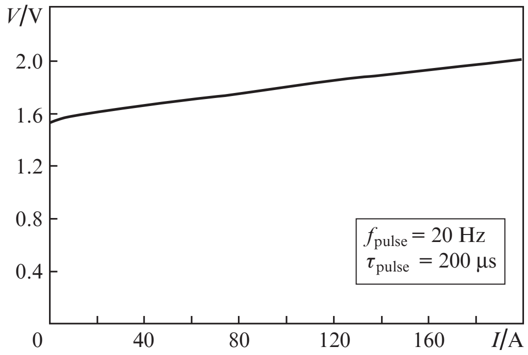

Figure 1. Typical current–voltage characteristic of the LDB ($l_{\rm LDB}$ = 5 mm).

The laser diodes were soldered with Ag-Sn and Au-Sn eutectic solders on CuW heat sinks, whose thermal expansion coefficient is close to that of GaAs. The achieved output optical powers of the developed and fabricated LDBs operating under quasi-cw pumping ($\tau_{\rm pulse} \approx 200$ μs, $f_{\rm pulse} \approx 20$ Hz) were 200–210 W at $l_{\rm LDB} = 5$ mm and up to 400 W at $l_{\rm LDB} = 10$ mm. The slope of the light–current characteristics shown in Fig. 2 was 1.3–1.35 W A^{-1} at the initial stage and slightly decreased (to 1.2–1.25 W A^{-1}) as the pump current approached 100–200 A.

The LDB was designed so that the efficiency maximum (Fig. 3) was observed at the pump currents $I_{\rm p} \approx$ 95–100 A, which ensured the required level of the output power. As a result, the efficiency for most samples was 65%–68% and reached 70% for the best samples. The threshold pump current at 20 °C was 13–14 A and slightly increased as the environmental temperature increased to +50 °C. The parameter T_0, which characterises this temperature sensitivity, was ~110 K.

Along with the total efficiency, the temperature of the LDB active region is an important characteristic determining

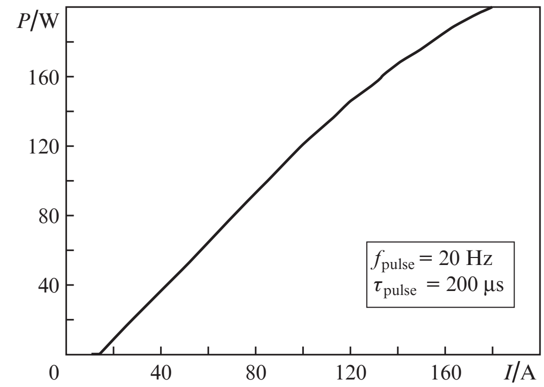

Figure 2. Typical light–current characteristic of the LDB (l_{LDB} = 5 mm).

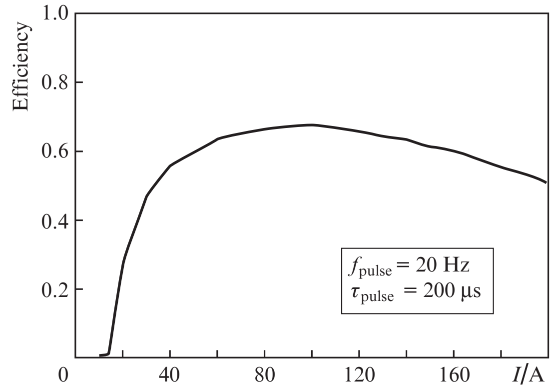

Figure 3. Dependence of the LDB efficiency on the pump current (l_{LDB} = 5 mm).

the efficiency of control of thermal processes in the laser scheme. This temperature can be calculated from the wavelengths $\lambda_{\max}$ measured in the single-pulse and steady-state regimes (Fig. 4). In our case, the active region temperature exceeded the heat sink temperature by only 3 °C. The calculated thermal resistances of the LDB were ~0.1–0.2 K W^{-1}. The lifetime tests of the bars demonstrated stable operation for 10^8–10^9 pulses without degradation of the output parameters.

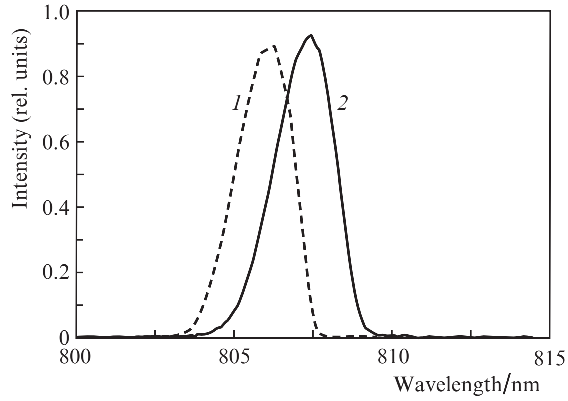

Figure 4. Wavelength ($\lambda_{\max}$) of the 5-mm LDB in (*1*) single-pulse and (*2*) steady-state regimes.

Thus, in the course of optimisation of the scheme and the fabrication technology of the lasers emitting in the range of 800–810 nm, we have developed and grown AlGaAs/GaAs quantum-well heterostructures with a high differential efficiency and low optical losses, proposed an improved scheme of the active element with low contact resistances, and developed a technology of assembling laser bars with efficient heat removal. The output optical power of 5-mm bars reached 210 W, and the efficiency was ~70%.

Acknowledgements. This work was partially supported by the Competitiveness Programme of the National Research Nuclear University 'MEPhI'.

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