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# High-power laser diodes based on triple integrated InGaAs/AlGaAs/GaAs structures emitting at 0.9 μm

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*Abstract*. **Ternary vertically integrated lasers based on the InGaAs/AlGaAs/GaAs heterostructure grown by the method of MOS hydride epitaxy in a single epitaxial process are studied. The typical slope of the watt – ampere characteristic for a triple laser diode is 2.6 W A$^{-1}$. The frequency characteristics and temperature dependences of the optical power on the pump power demonstrate good homogeneity of the grown structures. Laser diodes based on the triple laser heterostructure (the stripe contact width is 200 μm and the cavity length is 1 mm) emit 80 W at 0.9 μm in the pulsed regime at the injection current of 40 A.**

***Keywords***: *integrated heterostructures, laser diode, metal-organic vapour phase epitaxy.*

## 1. Introduction

Modern semiconductor epitaxial technologies such as molecular beam epitaxy (MBE) and metal-organic vapour phase epitaxy (MOVPE) allow the growth of a many epitaxial layers with a high degree of control of their thickness, doping level, and the sharpness of interfaces. As a result, in the last decades a number of optoelectronic devices and functional schemes have been developed in the world, and in particular in our country, which are based on complicated multilayer semiconductor nanoheterostructures and combine various physical phenomena and principles. These are vertical-cavity surface-emitting lasers (VCSELs) [1, 2], quantum-well IR photodetectors [3, 4], unipolar and bipolar quantum-cascade lasers [5 – 7], photonic crystal waveguide lasers [8, 9], etc.

The achievement of the high radiation brightness and the increase in the output optical power and in the service life of semiconductor laser diodes (LDs) are the foremost problems in applications in optical communication, for control and monitoring of transport means, in technological processing and pumping of solid-state lasers, etc.

Several methods have been proposed for increasing the output power of a single LD, which include the use of separate-confinement heterostructures with wide and superwide waveguides [10], heterostructures with the asymmetrically positioned active region [11], the use of the profile doping of emitter layers [12], the development of lasers with large optical cavities, etc. [13].

Aside from these methods, the output power of semiconductor lasers can be further increased by adding the output powers of individual LDs, for example, by manufacturing horizontal linear LD arrays (parallel connection) [14]. However, in this case the output power is restricted by the possibilities of pump sources (power supplies).

This restriction can be surmounted by fabricating vertical LD arrays (series connection). However, it should be noted that during the fabrication of such arrays, additional contact resistances appear between LDs, which restrict the time response of the device and the maximum pulse repetition rate. One of the variants of the vertical LD array, which is devoid of these drawbacks, is a structure in which epitaxially integrated LDs grown in one technological process are used [15 – 17]. The main advantages of a device with several active regions are the high radiation brightness , which is determined by the number of emitting regions, and the absence of additional contact resistances, which considerably reduce the efficiency and the maximum pulse repetition rate.

The aim of this paper is to study the radiation parameters of integrated laser heterostructures for high-power LDs emitting at 0.9 μm.

## 2. Experimental

Epitaxial heterostructures for integrated InGaAs/GaAs/AlGaAs LDs were grown by the method of MOVPE on (100) GaAs substrates at a low pressure in a quartz horizontal reactor on a SIGMOS-130 setup with a rotating graphite substrate holder. The sources of the third group elements were TEG ($Ga(C_2H_5)_3$), TMA ($Al(CH_3)_3$) and TMI ($In(CH_3)_3$), the source of the fifth group elements was high-pure arsine ($AsH_3$). The carrier gas was hydrogen purified by the diffusion method through a palladium filter heated up to 450 C°, with the dew point not higher than −100 C°.

Silicon and carbon were used as doping impurities to fabricate highly efficient tunnelling contacts. These impurities have low diffusion coefficients and low activation energy, their initial reagents have no ‘memory effect’ and

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they are suitable for growing high-quality epitaxial structures by the MOS hydride epitaxy [18]. They were obtained from silane ($SiH_4$) and carbon tetrachloride ($CCl_4$), respectively.

The compositions of emitter and waveguide layers and the thickness and composition of the active region were selected to provide a narrow radiation pattern in a plane perpendicular to the p – n junction at 0.9 µm. The thickness of the intermediate layers (GaAs tunnelling contacts) was 0.1 µm, and their doping level was $5 \times 10^{19} - 1 \times 10^{20}$ cm$^{-3}$.

For power measurements, lasers with stripe contacts of width 200 µm and cavity length 1 – 1.6 µm were fabricated. The reflectance $R_{\rm front}$ of the front face of the cavity with an optical coating was 0.03 – 0.05, while the reflectance $R_{\rm rear}$ of the rear face was no less than 0.95.

## 3. Results and discussion

The design of a triple epitaxially integrated heterostructure for high-power lasers is shown in Fig. 1.

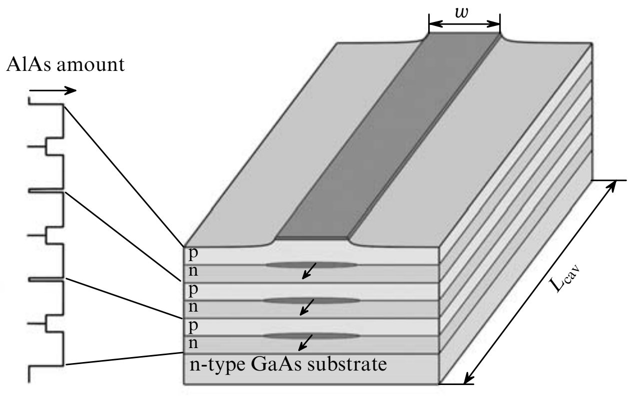

**Figure 1.** Typical geometry of a laser element with three active regions.

We fabricated [7] high-power pulsed lasers based on double epitaxially integrated heterostructures and showed that, to create devices with a low voltage drop across the average back-biased p – n junction, it is necessary to introduce a special low-resistance tunnelling transition between two adjacent LDs. To provide the voltage drop across the back-biased p – n junction lower than 0.1 V, the doping levels of epitaxial layers on the tunnelling contact should be no less than $10^{19} - 10^{20}$ cm$^{-3}$.

The characteristics of lasers based on triple integrated InGsAs/AlGaAs/GaAs heterostructures (LDs with three active regions) were measured upon pumping by 100-ns pulses at pulse repetition rates from 10 to 50 kHz.

Typical cut-off voltages of the direct branch of the volt – ampere characteristic were 1.35 – 1.4 V for a single LD, 2.8 – 2.9 V for a double LD, and 4.1 – 4.3 V for a triple LD (Fig. 2a), i.e. the LD cut-off voltage increases proportionally to the number of successively grown LDs.

The full widths at half-maximum (FWHM) of the radiation pattern measured for a single LD in the planes perpendicular ($\Theta_\perp$) and parallel ($\Theta_{||}$) to the p – n junction were 22° and 8°, respectively. The divergence of radiation from the fabricated lasers with two and three active regions in a plane perpendicular to the active layers was 20° – 23°, coinciding with the radiation divergence for a LD with one active layer. Therefore, the radiation pattern of an integrated laser emitter is determined by the radiation pattern of s single laser.

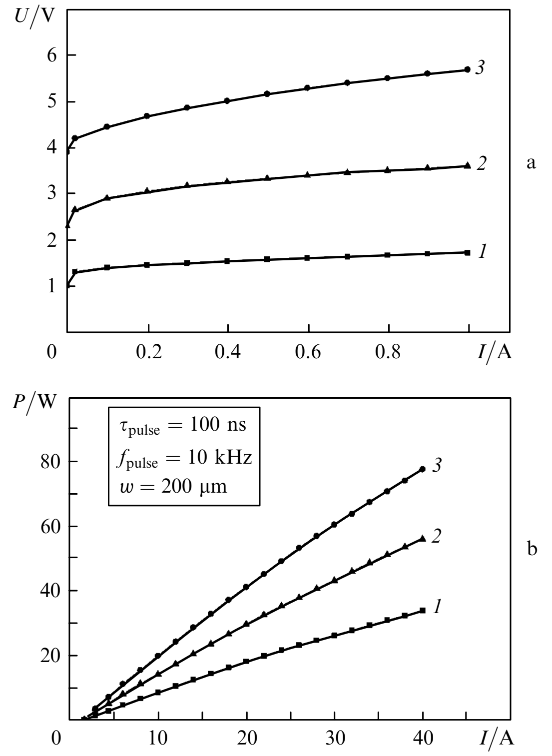

**Figure 2.** Volt – ampere (a) and watt – ampere (b) characteristics of epitaxially integrated lasers: single LD (1), double LD (2), and triple LD (3).

The watt – ampere characteristics of a single, double, and triple laser emitters based on integrated InGaAs/AlGaAs/GaAs heterostructures are presented in Fig. 2b.

The typical slope of the watt – ampere characteristic in the initial part of the curve for a triple LD was 2.4 – 2.6 W A$^{-1}$. The fabricated lasers had the threshold current of 1.5 – 2 A. The approximate equality of threshold currents and the linearity of the watt – ampere characteristic in a broad pump current range for single, double, and triple LDs demonstrates the good homogeneity of the grown epitaxial heterostructures with identical active regions.

Figure 3 shows the dependence of the optical power of each separately emitting active region of the triple LD on the pump current. To perform these measurements, the image of radiation from an individual active region on the output mirror face of the LD was magnified in a microscope and separated with the help of a slit behind which a detector was mounted. For the pump current of 20 A, the output power of each LD was about 15 W, while the typical slope of the watt – ampere characteristic was in the range 0.8 – 0.9 W A$^{-1}$. It follows from Fig. 3 that the entire laser structure was heated rather uniformly. This is also demonstrated by the dependence of the emission spectrum of the LD with several active regions on the pump current in Fig. 4. The thermal characteristics of pulsed laser emitters with several active regions are close to these of single LDs because the crystal is not heated considerably with increasing the pump current amplitude.

Figure 5 presents the dependences of the average output pulse power on the pump pulse repetition rate. One can see that the decrease in the output power with increasing the

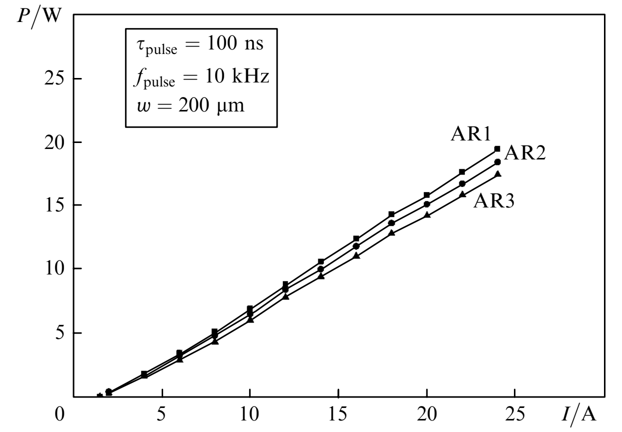

**Figure 3.** Dependences of the optical power of individual emitting active regions (ARs) of the triple LD on the pump current.

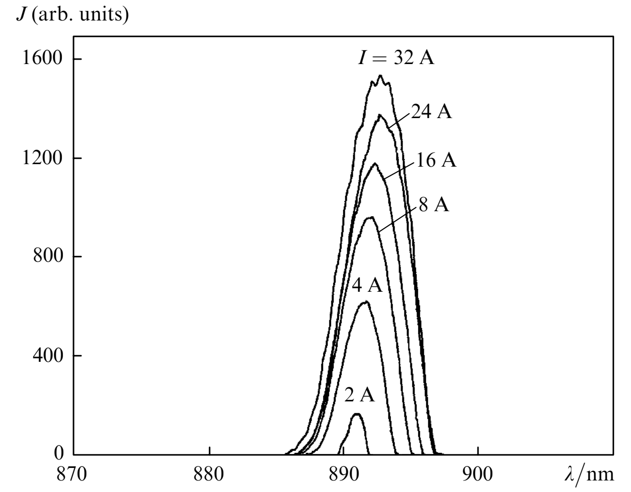

**Figure 4.** Emission spectra of the triple LD for different pump currents.

pump pulse repetition rate from 10 to 50 kHz does not exceed 10 %. The epitaxial integration of several LDs in one semiconductor crystal allows a considerable extension of the emission range of pulsed laser emitters, unlike LD arrays and linear arrays for which maximum pump pulse repetition rates do not exceed a few kilohertz.

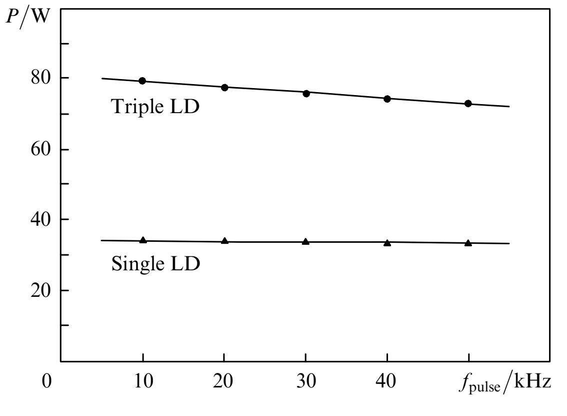

**Figure 5.** Output powers of a single LD and a triple integrated LD as functions of the pump pulse repetition rate ($I_{\text{pulse}} = 40$ A, $\tau_{\text{pulse}} =$ 100 ns).

Figure 6 shows the temperature dependences of the radiation power of a triple LD for the fixed pulse amplitude, which demonstrate that the triple integrated LD stably operates in a broad temperature range.

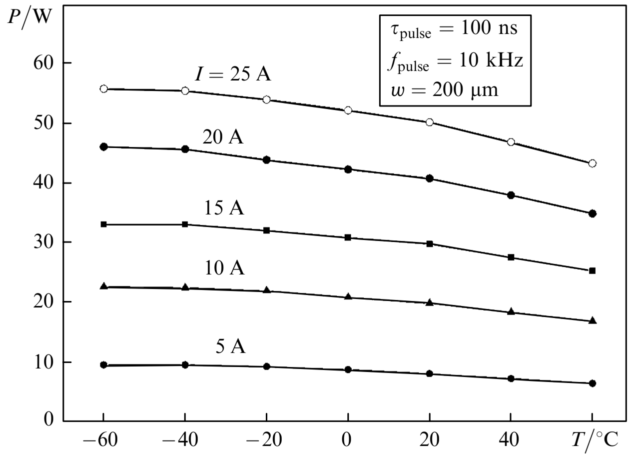

**Figure 6.** Dependences of the output power of the triple LD on the ambient temperature and the pump current.

Thus, the technology of epitaxially integrated emitters with several active regions studied in this paper, which insignificantly differ by their thermal and frequency characteristics from single pulsed LDs, is most preferable for the successive connection of LDs. The narrow radiation pattern providing the concentration of 70 % – 80 % of the output power within a 30° cone, and closely spaced emitting regions open up new possibilities for applications of these devices in highly bright emission sources.

## 4. Conclusions

We have shown that the modern technology of growing high-quality epitaxial layers by the method of MOS hydride epitaxy makes it possible to build small devices based on a semiconductor crystal. Laser diodes based on triple vertically integrated heterostructures provide a considerable increase in the optical power emitted by one crystal.

It has been shown that the emitter with three integrated LDs can operate with the pump pulse repetition rate no less than 560 kHz. The temperature range of the stable operation of the emitter is −60 °C ... + 60 °C. The watt – ampere characteristics of individual emitters demonstrate the high quality of the grown heterostructures. The total output power of the emitter at 0.9 μm achieved 80 W for the pump power of 40 A.

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## References

1. Iga K. *Jap. J. Appl. Phys.*, **47**, 1 (2008).
2. Maleev N.A., Kovsh A.R., Zhukov A.E., Vasil'ev A.P., Mikhrin S.S., Kuz'menkov A.G., Bedarev D.A.,

Zadiranov Yu.M., Kulagina M.M., Shernyakov Yu.M., Shulenkov A.S., Bykovsky V.A., Solov'ev Yu.M., Moller C., Ledentsov N.N., Ustinov V.M. *Fiz. Tekh. Poluprovodn.*, **37**, 1265 (2003).

3. Rogalski A., Chrzanowski K. *Opto-Electron. Rev.*, **10**, 2, 111 (2002).
4. Esaev D.G., Marchishin I.V., Ovsyuk V.N., Savchenko A.P., Fateev V.A., Shashkin V.V., Sukharev A.V., Padalitsa A.A., Budkin I.V., Marmalyuk A.A. *Avtometriya*, **44**, 112 (2007).
5. Yu J.S., Slivken S., Darvish S.R., Evans A., Gokden B., Razeghi M. *Appl. Phys. Lett.*, **87**, 041104 (2005).
6. Biryukov A.A., Zvonkov B.N., Nekorin S.M., Demina P.B., Semenov A.N., Aleshkin V.Ya., Gavrilenko V.I., Dubinov A.A., Marem'yanin K.V., Morozov S.V., Belyanin A.A., Kocharovskii V.V., Kocharovskii Vl.V. *Fiz. Tekh. Poluprovodn.*, **41**, 1226 (2007).
7. Zverkov M.V., Konyaev V.P., Krichevskii V.V., Ladugin M.A., Marmalyuk A.A., Padalitsa A.A., Simakov V.A., Sukharev A.V. *Kvantovaya Elektron.*, **38**, 989 (2008) [*Quantum Electron.*, **38**, 989 (2008)].
8. Krauss T.F., De La Rue R.M. *Progr. Quantum Electron.*, **23**, 51 (1999).
9. Blokhin S.A., Usov O.A., Nashchekin A.V., Arakcheeva E.M., Tanklevskaya E.M., Konnikov S.G., Zhukov A.E., Maksimov M.V., Ledentsov N.N., Ustinov V.M. *Fiz. Tekh. Poluprovodn.*, **40**, 833 (2006).
10. Al-Muhanna A., Mawst L.J., Botez D., Garbuzov D.Z., Martinelly R.U., Conolly J.C. *Appl. Phys. Lett.*, **73**, 1182 (1998).
11. Andreev A.Yu., Leshko A.Yu., Lyutetskii A.V., Marmalyuk A.A., Nalet T.A., Padalitsa A.A., Pikhtin N.A., Sabitov D.R., Simakov V.A., Slipchenko S.O., Khomylev M.A., Tarasov I.S. *Fiz. Tekh. Poluprovodn.*, **40**, 628 (2006).
12. Belenky G.L., Donetsky D.V., Reynolds C.L., Kazarinov R.F., Shtengel G.E., Luryi S., Lopata J. *IEEE Photon. Tech. Lett.*, **9**, 1558 (1997).
13. Knauer A., Erbert G., Staske R., Sumpf B., Wenzel H., Weyers M. *Semicond. Sci. Technol.*, **20**, 621 (2005).
14. Botez D., Scifres D.R. *Diode Laser Arrays* (Cambridge: Cambridge Univ. Press, 1994) p. 448.
15. Van der Ziel J.P., Tsang W.T. *Appl. Phys. Lett.*, **41**, 499 (1982).
16. Patterson S.G., Lau E.K., Pipe K.P., Kolodziejski L.A. *Appl. Phys. Lett.*, **77**, 172 (2000).
17. Garcia Ch., Rosencher E., Collot Ph., Laurent N., Guyaux J.L., Vinter B., Nagle J. *Appl. Phys. Lett.*, **71**, 3752 (1997).
18. Stringfellow G.B. *Organometalic Vapor-Phase Epitaxy: Theory and Practice* (San Diego: Acad. Press, 1999) p. 585.