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Double integrated nanostructures for pulsed 0.9-μm laser diodes

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***Abstract*. Double integrated laser InGaAs/GaAs/AlGaAs heterostructures grown by the method of metal-organic vapor phase epitaxy (MOVPE) in a single epitaxial process are studied. Typical slopes of the watt – ampere characteristic for a single laser diode were 1.08 – 1.15 W A^{-1}, while these slopes for the double integrated laser diode proved to be considerably higher (1.88 – 2.01 W A^{-1}). The manufactured double laser diodes emitting ~0.9 μm, 100-ns pulses at a pulse repetition rate of 10 kHz produce an output power of 50 W at pump current of 30 A.**

Keywords: *laser diode, integrated nanostructures, metal-organic vapor phase epitaxy.*

1. Introduction

Semiconductor laser diodes (LDs) are used at present in a variety of fields in science and technology. Interest in LDs continues to increase due to their high efficiency, smallness, effectiveness, reliability, and flexibility of their manufacturing technology. Such devices are especially required in cases when a high output radiation power is needed.

The output power of semiconductor radiation sources can be increased by using laser bars and arrays [1]. A set of LDs in a bar produces the output power proportional to their number. A set of LDs is most often fabricated by connecting individual LDs by the vertical or horizontal methods.

In the case of the horizontal method of laser bar fabrication, all the diodes are connected in parallel. A disadvantage of this variant of connection is the restricted possibilities of pump sources (power supplies) used for obtaining high input currents, which are required for achieving the high output power.

To obtain high output powers at low injection currents, it is preferable to use the vertical connection method. In this case, LDs are connected is series with the help of soldered contacts. An important disadvantage of the vertical connection is that radiation beams emitted from the active regions of lasers forming a stack are not strictly parallel to each other, and the greater the number of such LDs in the set, the greater disorientation of emitting active regions. Another disadvantage of this connection is additional resistances appearing in contacts.

At present the most promising method of increasing the output power of a radiation source is the use of vertical integrated LDs grown in one epitaxial process. This method for manufacturing LD sets was first proposed in [2]. A radiation source is fabricated in the form of a monolithic cascade semiconductor heterostructure laser with several active regions (Fig. 1). Two or more LDs are connected with the help of special low-resistance contact layers between them. Recently, interest in such devices strongly increased [3, 4].

The main advantages of a radiation source with several active regions are the high radiation brightness, which is determined by the number of active regions, the absence of additional contact resistances, which considerably reduce the laser efficiency and the maximum pulse repetition rate, and also the reduced expenses of production because the initial epitaxial structure already includes all the contact connections between LDs. At present the main difficulties in the development of integrated radiation sources are the elaboration of appropriate heterostructures, in particular, contact layers between adjacent lasers and the fabrication of highly homogeneous unstrained multilayer structures with a precision control of the thickness, composition, and doping level of the layers with distinct interfaces between heterostructures.

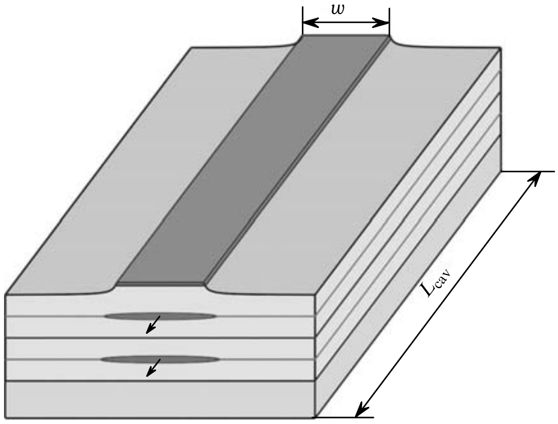

Figure 1. Geometry of a laser element with two active regions.

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This paper is devoted to the development and study of such an integrated structure used in a high-power pulsed two-cascade laser diode emitting at 0.9 μm.

2. Physical principle of the operation of an integrated LD

The principle of operation of an integrated laser, whose energy band diagram is shown schematically in Fig. 2, has been discussed in many previous papers [2, 5, 6]. An electron, injected into the conduction band of the first laser at the left of Fig. 2 and then emitting a photon during the transition to the valence band, tunnels into the conduction band of the second laser through a specially designed contact junction and again emits a photon. Any injected electron in the ideal case will produce the number of photons equal to the number of LDs contained in the entire epitaxial structure, thereby increasing the output power. The quantum efficiency of this device can be considerably increased and even can exceed unity.

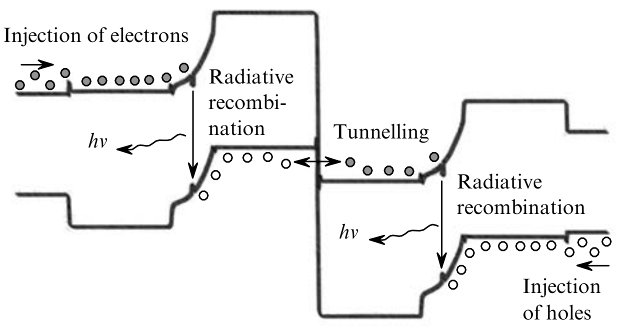

Figure 2. Energy band diagram of an integrated LD to which a voltage is applied.

Such an integrated LD can also emit at different wavelengths as was demonstrated in papers [7, 8].

A special tunnelling junction (TJ) located between adjacent LDs provides good electric contact. Although such tunnelling junctions are also widely used in other optoelectronic devices (photodetectors, vertical-cavity surface-emitting lasers, solar batteries), it is necessary to pay a special attention to their development and growing because TJs determine the operation of an integrated LD as a whole. The necessity of fabricating heavily doped degenerate TJs is explained by the fact that the tunnelling current through the junction drastically increases with increasing the doping level of the p- and n-type conduction layers. A clear understanding of the principle of operation of this part of the integrated structure and its technological accomplishment strongly influence the total efficiency of the laser structure. For example, in paper [6] devoted to the fabrication of integrated lasers of this type, breaks in watt–ampere characteristics were observed due to the development of lasing in two sections at different threshold currents. This was explained by a poor electric contact between LDs.

It follows from the above discussion that the development and fabrication of integrated nanostructures for high-power LDs is a complicated problem requiring the consideration of various factors affecting their operation.

3. Experimental

Epitaxial heterostructures for integrated InGaAs/AlGaAs/GaAs emitting at 0.9 μm were grown by the MOVPE method at a reduced pressure in a quartz horizontal reactor in a SIGMOS-130 setup with a rotating graphite substrate support. The sources of the third group elements were triethylgallium $Ga(C_2H_5)_3$, trimethylaluminum $Al(CH_3)_3$ and trimethylindium, while the fifth group element was obtained from high-purity (100 %) arsine AsH_3. The carrier gas was hydrogen purified by diffusion through a palladium filter heated up to 450 °C, with the dew point of no more than −100 °C.

To fabricate highly efficient tunnelling contacts, heavily doped (for obtaining the degeneracy) epitaxial layers of both conduction types are required. In addition, dopants should have as low diffusion coefficients and activation energy as possible and should not have the so-called memory effect. We used silicon and carbon as dopants for these purposes. They were obtained from silane SiH_4 and carbon tetrachloride, respectively. These impurities have the above-mentioned advantages and are suitable for growing high-quality epitaxial structures by the MOVPE method [9].

Figure 3 shows the typical geometry of the grown epitaxial integrated laser diode.

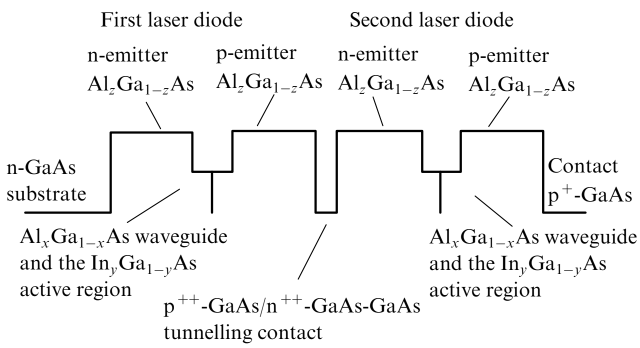

Figure 3. Energy band diagram of a grown double LD.

The compositions of the emitter and waveguide layers and thicknesses of the waveguide and active region were selected to provide the angular divergence of the radiation pattern not exceeding 20° (FWHM) in the plane perpendicular to the p–n-junction [10]. The geometry of the quantum-well active region was selected to provide lasing at 900 nm.

The thickness of emitter layers (∼ 1.5 μm) was chosen so that to avoid the penetration of radiation from the active region to a heavily doped TJ because it leads to the absorption of radiation.

To measure the radiative and electric characteristics, we fabricated laser elements with contacts of width $w = 100$ μm and the resonator length $L_{cav} = 1000$ μm. The reflectivities of the front (R_{fr}) and rear (R_{rear}) ends of the resonator with optical coatings were 0.03–0.05 and no less than 0.95, respectively.

4. Results and discussion

All the measurements were performed upon pumping by 100-ns current pulses at a pulse repetition rate of 10 kHz. As expected, in the case of vertical connection of diodes in series, the voltage drop across the entire laser structure increased proportionally to the number of integrated LDs. A small additional voltage drop across the TJ between diodes also added to this voltage drop. The volt – ampere characteristic presented in Fig. 4 shows that the voltage drop in the integrated heterostructure of the double laser approximately doubled. Typical cut-off voltages for single and double LDs were 1.35 – 1.4 and 2.8 – 3.0, respectively.

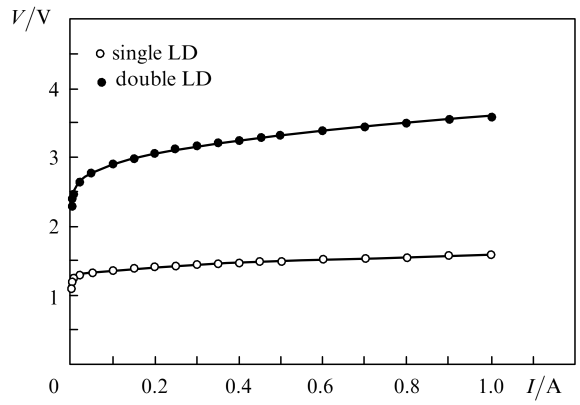

Figure 4. Volt – ampere characteristic of single and double LDs.

The watt – ampere characteristics of single and double LDs are shown in Fig. 5. All the laser elements had the threshold current of about 1 A. Above the lasing threshold, the slope of the curve $P(I)$ for the epitaxial structure consisting of two lasers is approximately 1.75 time greater than the slope of the curve for the structure containing one LD.

The absence of breaks in the watt – ampere characteristic means that the threshold currents in both sections of the integrated laser are equal, which demonstrates good homogeneity of the grown epitaxial structures. The minimisation of electric losses in TJs and current leaks improved the operation of the integrated LD. Typical slopes of the watt – ampere characteristic at the initial part of the curve (below 10 A) for single and double LDs were 1.08 – 1.15 and 1.88 – 2.01 W A^{-1}, respectively.

It should be emphasised that watt – ampere characteristics measured for single and double LDs did not change up to a pulse repetition rate of 20 kHz.

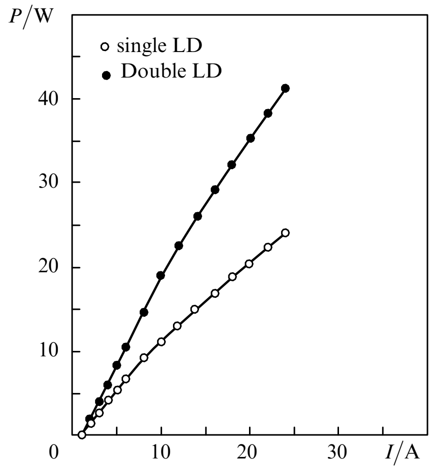

Figure 5. Typical watt – ampere characteristics of single and double LDs.

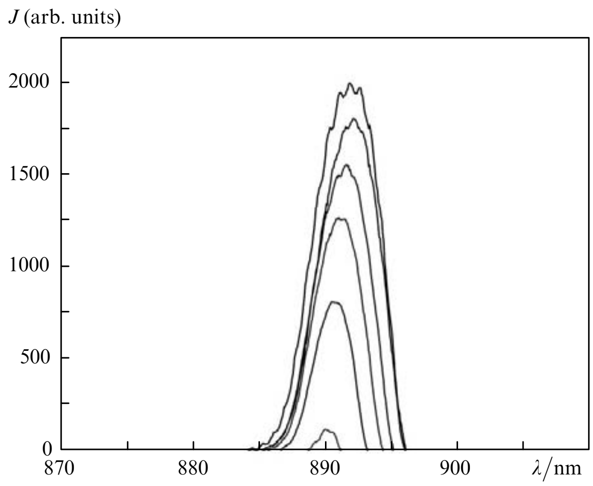

Figure 6. Emission spectra of a double LD at different pump currents.

Figure 6 shows that the emission spectra of a double LD only weakly change with increasing pump current. This suggests that the heating of the crystal mounted on a heat sink is weak.

The far-field pattern for the double integrated LD is shown in Fig. 7. The radiation divergence angles in planes perpendicular ($\Theta_{\perp}$) and parallel ($\Theta_{\parallel}$) to the p – n junction were 18° and 8°, respectively. The value of $\Theta_{\perp}$ well agrees with the calculated divergence angle in the vertical plane (18° – 20°) obtained by using epitaxial heterostructure layers fabricated in the study.

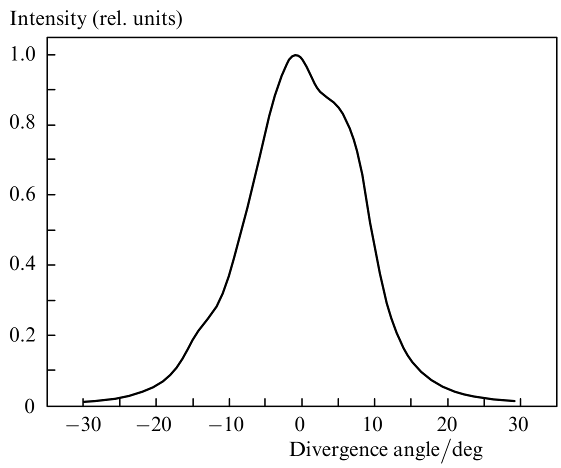

Figure 7. Radiation pattern of a double LD in a plane perpendicular to the p – n junction.

5. Conclusions

Double integrated laser InGaAs/GaAs/AlGaAs heterostructures grown by the MOVPE method in a single epitaxial process studied in our paper can be used for the development of promising radiation sources – integrated laser diodes. The slope of the watt – ampere characteristic for the epitaxial heterostructure consisting of two lasers increased by a factor of 1.75 compared to that for the structure containing one LD.

We have built high-power pulsed laser diodes with several active regions emitting 50 W at $\sim$0.9 μm at the pump current 30 A.

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