Parameters of Laser Diodes Radiation in Different Temperature Intervals

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ABSTRACT
The article deals with experimental studies that have been carried out in order to study the radiation characteristics of commercially available semiconductor laser diodes and to analyze the reasons that cause changes in the characteristics of laser radiation. The need for such studies is connected with the search for expanding the possibilities of using semiconductor lasers in various appliances and devices operating in different conditions. The article presents experimental study results of the features of laser diodes emission spectra made on the basis of AlGaInP solid quadruple solution in the temperature range (50-300) K. The influence of temperature on the characteristics of the radiation spectrum was studied. The temperature was stabilized in a Cryomech ST15 closed-cycle vacuum helium cryostat. The radiation spectrum was investigated using a MDR-23 monochromator with a CCD detector installed. It is shown that the spectral characteristics of the emission spectrum (the predominance of stimulated or induced radiation, the wavelength of the radiation) depend on the operating temperature of the laser diode. Information is obtained that in the temperature range (50-300) K certain processes take place in the semiconductor laser diode material that lead to a change in the width of the forbidden band by approximately (4.2-4.5) % of the value corresponding to a temperature of 50 K. Data is given that the the temperature coefficient value of the change in the forbidden band width varies in absolute magnitude in 2-3 times within the investigated temperature interval. The authors propose an experimental method for determining the ionization energies of exciton levels localized in the region of the p-n junction of a laser diode. This method can find practical application for quality control of material in the manufacture of semiconductor lasers. The advantage of the proposed method is that it provides information on the exciton spectrum of a laser diode material in the narrow zone of the p-n junction in which laser radiation is formed.

1. INTRODUCTION

Semiconductor lasers based on heterostructures are used in various fields of science, engineering, and medicine. In the operation process of mass production semiconductor lasers, features of their operational characteristics are manifested, which are not reflected in the passport data [1, 2]. At the same time, these features can manifest themselves in the practical use of semiconductor lasers.

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Currently, there is further search for expanding the possibilities of using semiconductor lasers in various devices and devices operating in a wide temperature range. One of essential aspects of such research is the study of the effect of temperature on the parameters of laser radiation. The work is devoted to the study of the radiation characteristics of commercially available semiconductor laser diodes in a wide range of temperatures, from 50 K to 300 K, and to the analysis of the causes of change in laser radiation characteristics.

2. MATERIAL AND METHOD

In the work, commercially available semiconductor laser diodes (manufactured on the basis of AlGaInP solid quadruple solution) of two brands with similar performance characteristics were investigated: low output power (about 5 mW); wavelength of about 635 nm; working voltage not exceeding 2.3 V for laser diode 1 (L1) and 2.8 V for laser diode 2 (L2); operating current was less than 23 mA (for L1) and less than 35 mA (for L2). The effect of temperature on the nature of the radiation spectrum and the wavelength λ of the radiation was studied. The temperature was stabilized in a Cryomech ST15 closed-loop vacuum helium cryostat. The radiation spectrum was studied using an MDR-23 monochromator with an installed CCD detector.

3. RESULTS

It is shown that for any temperature considered, the emission spectrum is multimode (Fig. 1), including the working temperature range (233-313) K specified in the laser passport data. It is noted that the general contour of the emission spectrum changes as the temperature changes (Fig. 2). As can be seen in Fig. 2, in the temperature range (270-298) K, the laser radiation is spontaneous. Lowering the temperature leads to the suppression of some radiation modes, and the proportion of induced radiation increases. From fig. 2, we can conclude that the working temperature range indicated in the passport data corresponds to both spontaneous and partially induced radiation.

From fig. 1 and 2, it can be seen that the laser diode radiation at any temperature lies in a certain wavelength range. Further on, the laser radiation wavelength at a specific temperature will be considered as the wavelength corresponding to the maximum value of the laser radiation intensity in the spectrum measured at this temperature. As is known, the width of the forbidden zone is related to the wavelength of laser radiation by the following relation (h is Planck's constant, c is the speed of light in vacuum) [3]:

$$E_g = \frac{hc}{\lambda} \quad (1)$$

The band gap of semiconductors, as a rule, decreases with increasing the temperature [4, 5]. This was confirmed by the results of our experiment (Fig. 3, a) for lasers based on AlGaInP solid quadruple solution. It is shown that in the investigated temperature range the dependence is nonlinear. Quantitatively, the effect of temperature on the width of the forbidden zone is estimated by the temperature coefficient of the forbidden zone width variation [4]:

$$\beta = \frac{E_{g2} - E_{g1}}{T_2 - T_1} \quad (2)$$

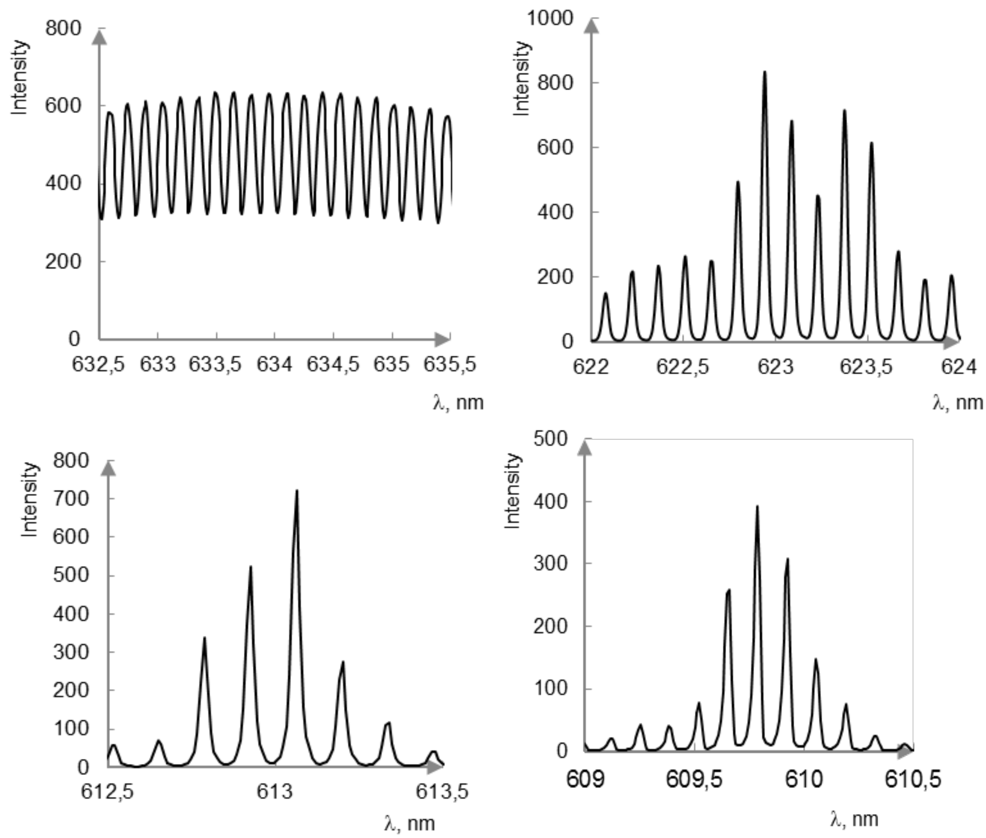

Fig.1. Temperature effect on the spectral composition of radiation semiconductor laser diode (AlGaInP).

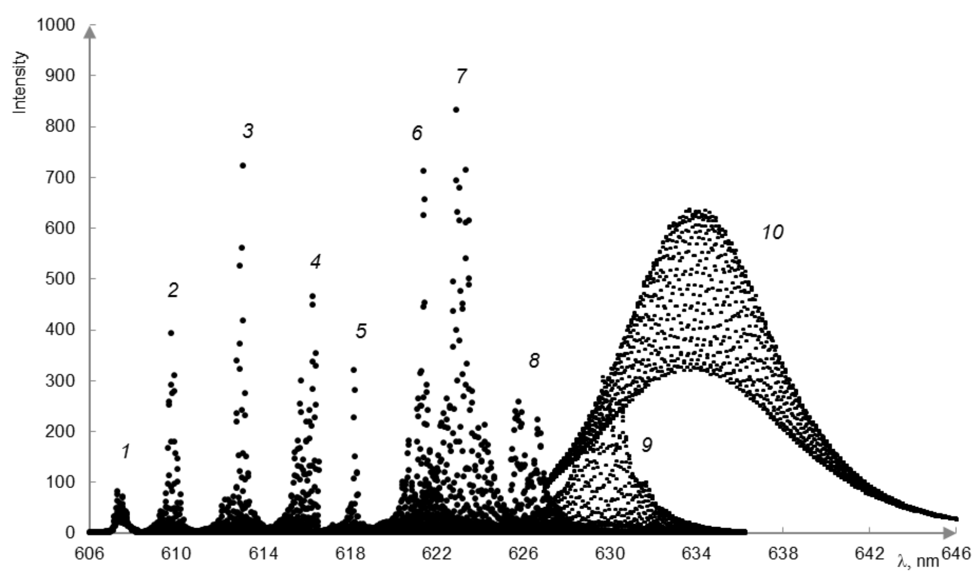

Fig. 2. Emission spectra of the AlGaInP (L2) semiconductor laser diode at various temperatures (the pump current is 1.2 of the threshold current value): 1 - 50 K; 2 - 90 K; 3 - 130 K; 4 - 160 K; 5 - 180 K; 6 - 210 K; 7 - 230 K; 8 - 250 K; 9 - 210 K; 10 - 290 K

where E_{g1} and E_{g2} are the band gap of a semiconductor at the temperature T_1 and T_2, respectively.

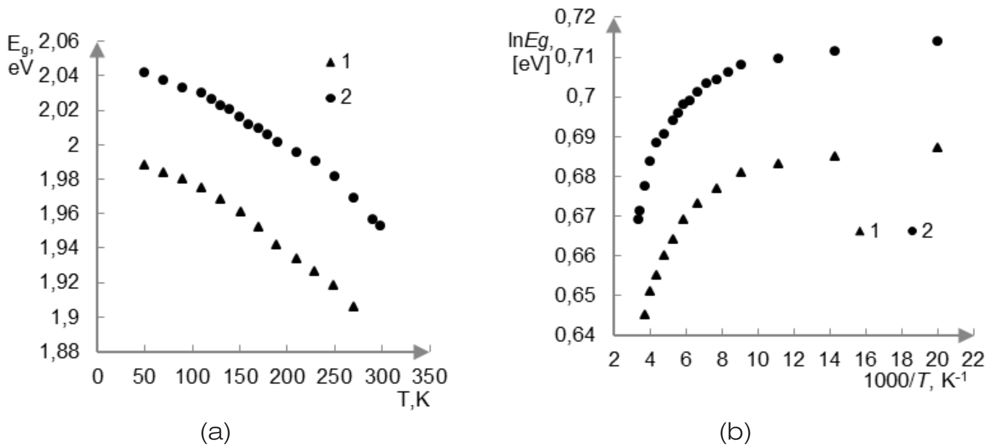

Fig. 3. Dependence of the band gap Eg on the temperature (a) and the natural logarithm of the band gap width lnEg from the inverse temperature (b) for AlGaInP semiconductor laser: 1 - L1 diode; 2 - L2 diode.

For L1 laser, two temperature ranges with different β values can be selected on the graph $E_g(T)$: the first – in the temperature range from 50 K to 130 K; the second – in the range from 150 K to 270 K (Fig. 3, a, curve 1). The magnitude of the temperature coefficient of variation of the band gap is β = - 2.38 · 10^{-4} eV / K for the low temperature region and β = - 4.62 · 10^{-4} eV / K for the high temperature region.

In the literature we did not find information on the β coefficient for AlGaInP solid quadruple solutions. The materials widely used in the manufacture of semiconductor lasers have the same order of magnitude of β which we obtained in the experiment, namely: β = –5.0 · 10^{-4} eV / K (GaAs) and β = –5.5 · 10^{-4} eV / K (AlSb) [4].

Temperature effect on the band structure of a crystal is caused by two main phenomena: thermal expansion of the lattice, associated with the dependence of the carrier energy levels on the volume of the unit cell, and electron-phonon interaction [6]. It should be noted that other factors are also considered in the full theory. We assumed that analysis of the dependence $\ln(E_g) / (1/T)$ will provide the opportunity to determine the activation energy of the processes affecting the change in the forbidden zone width. Indeed, construction of the dependences of the band gap $\ln(E_g)$ natural logarithm on the inverse temperature (shown in Fig. 3, b) in an "extended scale" allowed us to more accurately determine the activation energy E_i of the processes affecting the change in the band gap. Activation energy E_i in a specific temperature range was determined by the ratio:

$$E_i = \frac{k\left(\ln(E_{g2}) - \ln(E_{g1})\right)}{\frac{1}{T_2} - \frac{1}{T_1}} \quad (3)$$

where E_{g1} – the width of the forbidden zone corresponding to the beginning of the temperature interval, E_{g2} – the width of the forbidden zone corresponding to the end of the temperature interval, k is the Boltzmann constant.

Since the radiation of a laser diode is formed due to the recombination of an electron and a hole in the p – n junction, we turn our attention to the factors influencing this process. Several recombination mechanisms are considered, where radiation occurs in a semiconductor [7]. During direct recombination, an electron is transferred from the conduction band to the valence band, where it recombines with a hole, resulting in radiation with a wavelength associated with the forbidden band width by relation (1). Other possibilities are discussed. Instead of direct recombination with a hole, an electron can first form an exciton with it, after a while the exciton can annihilate, emitting a quantum of light with an energy smaller than the forbidden band width. The peculiarity of this mechanism is that the exciton can remain stationary for a long time and not contribute to radiation; nevertheless, a significant proportion of recombination radiation can be caused precisely by this process [7]. For example, in pure silicon (at a temperature of 83 K), approximately 5/6 of the recombination radiation is caused by recombination through excitons [7]. It is noted that AIIIBV compounds doped with various impurities also exhibit radiation resulting from the annihilation of excitons bound to various imperfections of the crystal lattice.

We have analyzed the possibility of correlating the values of the activation energy E_i, which was found in our experiment with the energy spectrum of excitons. The energy spectrum of the Wannier-Mott exciton has the following form [7]:

$$E = -\frac{R_{ex}}{n^2} \quad (4)$$

where n is an integer; R_{ex} is the ionization energy of an exciton, which is measured from the bottom of the conduction band to a state with $n = 1$ (the ground energy state of the exciton).

The results of experimental data processing are presented in Table. 1 (for L1 laser) and in Table. 2 (for L2 laser). It follows from the calculations that the value of R_{ex} = 26.512 meV for the L1 laser and R_{ex} = 52.375 meV for the L2 laser. In columns II and III, the calculated values of the numbers of levels and the values of the ionization energies of the exciton are given, satisfying the relation with a sufficient degree of accuracy (4).

Table 1. The numbers of levels n and the calculated values of the ionization energy E_{cal}, as well as experimentally determined values E_i of the excitons ionization energy for semiconductor laser L1, corresponding to different temperature ranges

Temperature range, K	**Number level**	**E_i, meV**	**E_{cal}, meV**	$\frac{\lvert Ei - Ecal \rvert}{Ecal}$, %
I	**II**	**III**	**IY**	**Y**
270-249	4	1,657	1, 657	0
249-210	5	1,04	1,06	1,9
210-170	6	0,692	0,732	5,5
170-151	8	0,442	0,411	7,5
151-130	9	0,335	0,327	2,45
130-110	10	0,254	0,265	4,15
110-90	18	0,0853	0,082	5,56
90-70	22	0,0543	0,0548	0,91
70-50	30	0,0302	0,0295	2,37

Table 2. The numbers of levels n and the calculated values of the ionization energy E_{cal}, as well as experimentally determined values E_i of the excitons ionization energy for semiconductor laser L2, corresponding to different temperature ranges

Temperature range, K	**Number level**	E_i**, meV**	E_{cal}**, meV**	$\frac{\lvert Ei - Ecal \rvert}{Ecal}$**, %**
I	**II**	**III**	**IY**	**Y**
298-270	5	2,095	2,095	0
270-230	6	1,438	1,455	1,16
230-190	10	0,533	0,524	1,72
190-170	10	0,565	0,524	7,8
160-150	11	0,432	0,433	0,23
150-130	14	0,266	0,267	0,37
130-110	15	0,228	0,233	1,72
110-90	27	0,0708	0,0718	1,39
70-50	28	0,0691	0,0698	3,3

Analysis of the data presented in tables 1 and 2 allows to make a conclusion that there is a satisfactory agreement between the experimentally determined values of the activation energy E_i and the calculated values of the ionization energy of the exciton levels E_{cal}. This allows to conclude that the activation energies E_i obtained in the experiment represent precisely the ionization energies (or the depth relative to the bottom of the conduction band) of the exciton levels. It should be noted that formula (4) gives the exciton energy without taking into account the motion of its mass center. Taking into account the motion of the exciton mass center, according to [7], leads to the fact that the lines of the energy spectrum of the exciton expand into zones. In our opinion, this can explain the fact (Table 2) that in the temperature ranges (230-190) K and (190–170) K, similar values of ionization energy of the exciton level are observed: 0.533 meV and 0.565 meV. Perhaps these energies correspond to the same value of n, equal to 10.

Let us discuss the question of how excitons with low ionization energy (from hundreds of meV to tens of meV) can manifest themselves in radiation, determined by the energy of several eV? In our opinion, this experimental fact can be explained in the following way. As mentioned above, an electron can recombine with a hole not immediately, but forming an exciton first. In terms of the band diagram, this means that the exciton will occupy one of the energy levels, which differs by units (or unit fractions) of meV from the energy of the conduction band bottom. Later, when the exciton annihilates after some time, a quantum of radiation appears that differs in energy from the forbidden band width by an equally small amount. It is obvious that the emission spectrum associated with the exciton annihilation actually merges with the spectrum arising from interband recombination, and is determined, as mentioned above, by two main processes. In order that the exiton annihilation occurs, it is necessary that a sufficient number of excitons are accumulated at the appropriate level [7]. It can be assumed that the limiting process in two-step recombination through the intermediate exciton state is the filling of the exciton energy level. It is probably for this reason that the ionization energy of an exciton can be detected on an experimental dependence.

In our opinion, the suggested assumption requires further experimental and theoretical research. In [7], it was indicated that GaAs and GaP compounds, which are widely used in semiconductor technology, give a large variety of narrow-band emission spectra resulting from the annihilation of excitons coupled to various imperfections of the crystal lattice. Similar data for the AlGaInP quaternary solution were not found in the literature. Obviously, this will be the subject of future research.

4. CONCLUSIONS

1. The results obtained in this work indicate that in the temperature range (50-300) K in the semiconductor material from which the laser diode is made (AlGaInP solid four solution), certain processes take place that change the width of the forbidden zone by about 4.5%.
2. On the dependence $E_g(T)$, we can distinguish two (or three) temperature ranges corresponding to different temperature coefficient values of variation of the forbidden band width. The specified coefficient in the temperature range (50-300) K can change in absolute value in 2-3 times.
3. The value of the band gap in the temperature range of 50–300 K can vary by (4.2–4.5) % of the value corresponding to a temperature of 50 K.
4. An experimental method for determining the ionization energies of exciton levels has been proposed. From our point of view, this method can find practical application for quality control of material in the manufacture of semiconductor lasers. The advantage of the proposed method is that it allows obtaining information about the exciton spectrum of the laser diode material in the narrow p – n junction zone in which laser radiation is formed.

ACKNOWLEDGMENTS

The authors thank the administration of the Scientific Park of St. Petersburg State University for the opportunity to perform the measurements whose results are presented in this publication.

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