1.55 µm range edge-emitting laser diodes based on InGaAs/InGaAlAs superlattice and InGaAs quantum wells

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Abstract. Two laser heterostructures with active region based on seven InGaAs quantum wells and on InGaAs/InGaAlAs superlattice were grown on InP substrates by molecular beam epitaxy. Both active regions were designed for vertical-cavity surface-emitting lasers of 1535-1565 nm spectral range and had total thickness about 80-90 nm. Characteristics of edge-emitting laser diodes fabricated from grown laser heterostructures were studied and compared.

1. Introduction
The improvement of performance of a semiconductor laser active region is related to optical gain amplification and at the same time on current density reduction. For that purpose, such approaches as the use of double heterostructures and an active region dimension reduction with the use of quantum wells (QWs) and quantum dots (QDs) were used [1]. Although, the use of QWs and QDs allows to achieve small values of current density several QW or QD layers must be used for an edge-emitting laser optical gain amplification. In an edge-emitting laser a light wave interacts with a QW along the entire length of the cavity but in a vertical-cavity surface-emitting laser (VCSEL) a light wave interacts with a QW only in a small fraction of cavity [2] which is about 90 nm. Hence, the number of located in an active region of VCSEL QWs is usually varies from six to eight because QWs must be separated from each other by barriers.

Typically, for VCSEL operation in a 1.3-1.55 µm wavelength spectral range quantum wells are used. Strained QWs provide an increase in the coefficient of differential optical gain, which leads to a decrease in the current density at the threshold of optical radiation generation and to an increase of a small-signal modulation frequency of VCSELs [3]. QWs get strained by lattice mismatch between QWs and barriers. Thus, to prevent dislocations formation it is necessary to increase the thickness of the barrier. Unfortunately, light amplification is absent in potential barriers dividing strained QWs that is why a significant part of a VCSEL active region does not participate in a light amplification [4].

As an alternative, potential barriers can be used in light amplification in a short-period superlattice. Thus, with use of short-period superlattice as an active region for 1.3-1.55 µm VCSELs, modal gain of the device can be increased because of miniband formation in semiconductor layers since the presence
of a miniband makes it possible to significantly increase the overlap integral of a standing light wave with a region that amplifies light [5], compared to heterostructures based on QWs.

In this work we present the results of investigation of structural and optical properties of 1.55 µm edge-emitting laser diodes based on 7 strained QWs and short-period superlattice.

2. Experiment

Two laser heterostructures were grown by molecular beam epitaxy (MBE) on InP (100) substrates by using a Riber 49 machine. Laser heterostructures consisted of an n-type In0.52Al0.48As emitter with a thickness of 1000 nm, an In0.53Ga0.27Al0.2As waveguide with a thickness of 600 nm containing an active region in its center, a p-type In0.52Al0.48As emitter with a thickness of 1500 nm, and a contact layer made of p-type In0.51Ga0.47As with a thickness of 200 nm. Active region of heterostructure H1 consisted of 7 strained In0.74Ga0.26As QWs sandwiched between In0.53Ga0.27Al0.2As barriers [6]. Active region of heterostructure H2 consisted of 29 period In0.60Ga0.40As/In0.52Ga0.27Al0.21As superlattice.

To analyze the structural properties of heterostructure H2 X-ray diffraction technique was used. The analyses were made using PANalytical X’pert Pro diffractometer in parallel geometry of the X-ray beam and obtained in the vicinity of the symmetric (004) reflex of InP. Thereby, the most intense peak among X-ray diffraction experimental curve (Figure 1) corresponds to the InP substrate. In the region of the smaller angels, which is on the left of the InP peak, are located the peaks from InAlAs emitter layer (more close to the central peak from the InP substrate) and from InGaAs/InGaAlAs short-period superlattice. Simulation of the experimental curve determined the parameters of the epitaxial layers of the heterostructure H2 coinciding with the design values. The average molar content of In in the superlattice was 0.56.

![Figure 1. X-ray diffraction curves for heterostructure with an InGaAs/InGaAlAs short-period superlattice (heterostructure H2).](image)

Both laser heterostructures were used for 100-µm wide edge-emitting laser diodes fabrication with a cavity length of 1000 µm. The devices were mounted p-side down on a copper heat sink for temperature stabilization at 25 °C.

The dependences of modal gain at the lasing threshold versus pump current density for the lasers fabricated from heterostructures H1 and H2 are presented in Figure 2. The mode gain coefficient \( G_{\text{mod}} \) was calculated from the equation:

\[
G_{\text{mod}} = \alpha_{\text{in}} + \alpha_{\text{out}}
\]
where \( \alpha_{\text{in}} \) are losses inside the cavity and \( \alpha_{\text{out}} \) are losses related to the radiation output from the cavity and depending on cavity length and reflectivities of the cavity mirrors and from the equation:

\[
\eta_d = \frac{\eta_{\text{int}} \alpha_{\text{out}}}{\alpha_{\text{in}} + \alpha_{\text{out}}}
\]

(2)

where \( \eta_{\text{int}} \) is the internal quantum efficiency of the stimulated emission which can be assumed as \( \eta_{\text{int}} \approx 1 \) because of identity in the laser diodes design differing from each other only by active region.

![Figure 2](image)

**Figure 2.** Modal gain versus current density of edge-emitting laser diodes fabricated with use of heterostructure H1 (circles) and heterostructure H2 (triangles) at the wavelength \( \lambda = 1550 \) nm.

Thus, the active region of heterostructure H2 demonstrates a higher gain at equal values of the pump current density compared to the active region of heterostructure H1. For example, when the pump current density is 3000 A/cm\(^2\), which is typical value for VCSELs lasing threshold, the gain in the heterostructure H2 is 49 cm\(^{-1}\), whereas the heterostructure H1 demonstrates only 33 cm\(^{-1}\), which is about 1.5 times lower.

Figure 3 illustrates the dependences of threshold current density \( J_{th} \) and differential quantum efficiency (\( \eta_{\text{diff}} \)) versus temperature. Threshold current density and differential quantum efficiency were measured for both laser diodes fabricated from heterostructures H1 and H2 in the temperature range 15-70 °C. It can be seen from Figure 3 that from 30 to 70 °C lasers based on heterostructure H1 demonstrates weaker temperature sensitivity for \( J_{th} \) and \( \eta_{\text{diff}} \), compared to the lasers based on heterostructure H2. Characteristic temperatures \( T_0 \) and \( T_1 \) were estimated with use of follow equations:

\[
J_{th} (\Delta T) = J_{th}(0) \exp \left( \frac{\Delta T}{T_0} \right), \eta_{\text{diff}} (\Delta T) = \eta_{\text{diff}}(0) \exp \left( -\frac{\Delta T}{T_1} \right)
\]

(3)

where \( \Delta T \) – temperature range, \( T_0 \) – characteristic temperature of threshold current density and \( T_1 \) – characteristic temperature of differential quantum efficiency.
Figure 3 (a,b). (a) Dependences of threshold current density versus temperature for edge-emitting laser diodes fabricated from heterostructure H1 (circles) and heterostructure H2 (triangles); (b) Dependences of differential quantum efficiency versus temperature for edge-emitting laser diodes fabricated from heterostructure H1 (circles) and heterostructure H2 (triangles).

The threshold current density for the lasers fabricated from heterostructure H2 is slightly higher, and the differential quantum efficiency is slightly lower in comparison with the lasers fabricated from heterostructure H1. For the lasers from heterostructure H1 characteristic temperatures were \( T_0 = 59 \) K and \( T_1 = 65 \) K, while for the lasers from heterostructure H2 characteristic temperatures \( T_0 \) and \( T_1 \) were 44 K and 53 K, respectively.

3. Conclusion
The obtained results clearly indicate that replacing the active region of 1.5 \( \mu \)m range VCSEL based on 7 QW by an active region based on the short-period InGaAs/InGaAlAs superlattice should improve the performance of VCSELs, reduce the threshold current and increase the frequency of small signal modulation of VCSELs [7] and will not lead to a significant change in temperature stability of laser characteristics.

Acknowledgments
This work was supported by the Ministry of Science and Higher Education of Russian Federation, research project no. 2019-1442.

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