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Laser Diodes with a Wide Flat Modal Gain Spectrum in the (1–3)-μm Range

I. S. Manak, D. V. Ushakov, and V. S. Belyavskii

Belarussian State University, ul. Nezavisimosti 4, Minsk, 220030 Belarus
e-mail: manak@bsu.by

Abstract—The gain spectra of multilayer quantum-well heterostructures on the basis of GaInAs/GaInPAs and GaInAsSb/AlGaAsSb compounds have been analyzed. The possibility of implementing of wide and almost flat spectrum of modal gain in the near IR range upon inhomogeneous excitation of quantum wells in such compounds is shown.

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Laser diodes operating in the wavelength range 1–3 μm are necessary to develop high-efficiency fiber optical communication and data transfer systems, as well as perform environmental monitoring, and precise long-range optical measurements. Injection lasers on multilayer asymmetric quantum-well (QW) heterostructures based on the GaInPAs and GaInAsSb quaternary compounds are most promising for solving the noted problems. Such lasers provide a wide modal gain spectrum and make it possible to implement optical units with different lasing frequencies and the same lasing power.

It is well known that the transmission spectrum of the atmosphere has transparency windows in the ranges 1.2–1.3, 1.55–1.7, and 2–2.3 μm, as well as fairly effective transparency bands at wavelengths of 2.3–2.5 and 2.85–3 μm [1]. At the same time, the laser radiation decay coefficient in a quartz fiber at $\lambda = 1.27$ μm is about 0.2 db nm^{-1}, while germanate glass GeO_2 doped with antimony oxide Sb_2O_3 and free of OH hydroxyls, transition-metal ions, and other foreign impurities provides a line attenuation of 0.1 db nm^{-1} in the wavelength range 1.8–2.5 μm [2]. These characteristics should be taken into account in design of two-color optical units based on GaInPAs and GaInAsSb compounds and operating in the (1–3)-μm range.

In QW heterostructures, the wavelength corresponding to radiative interband transitions, depends on the thickness and composition of the active and barrier layers. Therefore, individual QWs in such structures amplify radiation in different wavelength ranges. Selective doping of barrier layers with donor or acceptor impurities is performed to provide conditions for inhomogeneous QW excitation [3, 4]. Then, the total gain spectrum of a multilayer heterostructure with inhomogeneously excited active layers can cover a fairly wide wavelength range.

By the example of AlGaAs/GaAs compounds, it was previously shown that there are several techniques for obtaining asymmetric multilayer QW heterostructures [3, 4]. The active layers of a structure may have different thicknesses, composition, and order of arrangement with respect to each other and to the emitters.

The gain spectra of the structures based on the GaInPAs and GaInAsSb quaternary compounds are analyzed and a possibility of implementing a wide flat modal gain spectrum in these compounds is demonstrated here. In the case of the former compound, the calculations were performed for an asymmetric QW heterostructure with three or four QWs of different thickness, generating in the (1.3–1.6)-μm band. The $Ga_{0.17}In_{0.83}As_{0.4}P_{0.6}$ compound was used for barrier layers, and the QW material was $Ga_{0.45}In_{0.55}As$. The parameters of the active and barrier layers were chosen according to [5], so as to match the lattice constants; the semiconductor was chosen to be direct-gap, with a band gap corresponding to the interband transitions in the range 1.3–1.6 μm.

For these QW heterostructures in calculation of the band energy diagram, it is necessary to take into account the effect of hole-state mixing; therefore, the energy levels and the wave functions of the valence band were calculated within the approximation of the four-band *kp* method [6].

The characteristics of heterostructures with QWs of different width are considered in this study. The active region of a heterostructure consisted of three or four QWs with the widths $d_1 = 4$ nm, $d_2 = 9$ nm, $d_3 = 14$ nm, and $d_4 = 5$ nm. The QWs were chosen so as to make the wavelengths of the optical transitions of electrons to the heavy- and light-hole levels in different QWs to be slightly spaced and overlap the desired wavelength range.

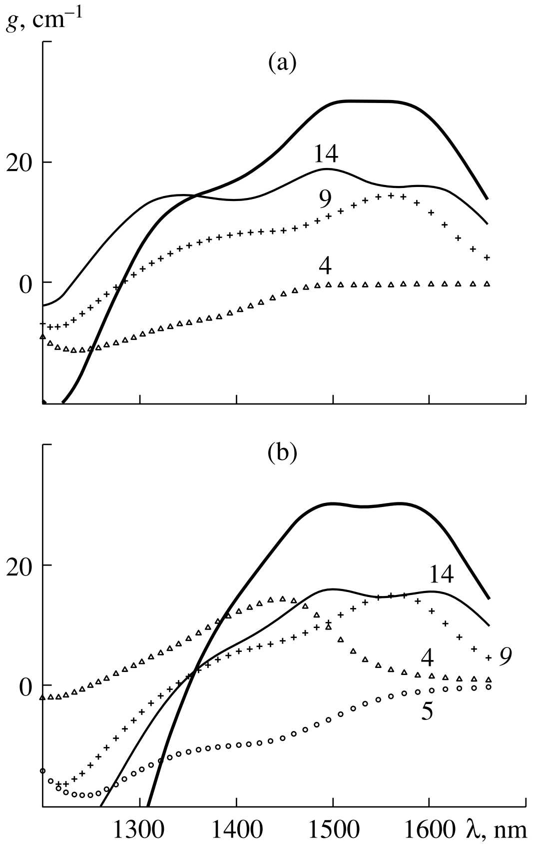

Fig. 1. Gain spectra for the TE mode in a $QWGa_{0.45}In_{0.55}As/Ga_{0.17}In_{0.83}As_{0.4}P_{0.6}$ structure with (a) three and (b) four QWs at different excitation levels and QW thicknesses d_w (numbers at curves in nm) and the total gain spectrum (thick line); (a) $d = 4$ nm, $\Delta F = 0.85$ eV, $\Gamma = 2.6 \cdot 10^{-3}$; $d = 9$ nm, $\Delta F = 0.97$ eV, $\Gamma = 5.9 \cdot 10^{-3}$; $d = 14$ nm, $\Delta F = 1.0$ eV, $\Gamma = 9.1 \cdot 10^{-3}$; (b) $d = 4$ nm, $\Delta F = 0.98$ eV, $\Gamma = 3.2 \cdot 10^{-3}$; $d = 5$ nm, $\Delta F = 0.80$ eV, $\Gamma = 4.0 \cdot 10^{-3}$; $d = 9$ nm, $\Delta F = 0.93$ eV, $\Gamma = 7.2 \cdot 10^{-3}$; $d = 14$ nm, $\Delta F = 0.93$ eV, $\Gamma = 11 \cdot 10^{-3}$.

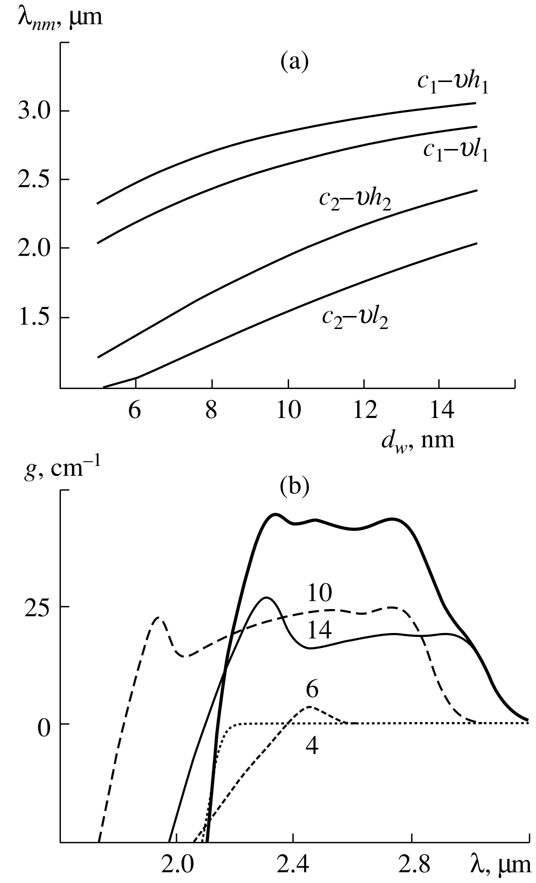

Fig. 2. (a) Wavelengths λ_{nm} of the optical transitions in a QW $Ga_{0.60}In_{0.40}As_{0.36}Sb_{0.64}$/ $Al_{0.35}Ga_{0.65}As_{0.03}Sb_{0.97}$ structure between the electron and light-hole levels, depending on the QW thickness d_w and (b) gain spectra for the TE mode in a QW structure with four QWs at different excitation levels and QW thicknesses d_w (numbers at curves in nm), and the total gain spectrum (bold line); $d = 4$ nm, $\Delta F = 0.50$ eV; $d = 6$ nm, $\Delta F = 0.52$ eV; $d = 10$ nm, $\Delta F = 0.68$ eV; $d = 14$ nm, $\Delta F = 0.59$ eV.

The difference ΔF in the Fermi quasi-levels of QWs of different thickness was optimized to obtain a wide and almost flat total spectrum of modal gain. The results of the calculations of the gain spectra for the TE-mode with due regard to the optical limitation Γ factor for the active region with different numbers of QWs are shown in Fig. 1. As can be seen in Fig. 1b, a wide QW amplifies in the long-wavelength region, while a narrow (4 nm) QW amplifies in the range 1.35–1.5 μm. To obtain a wide and flat gain spectrum, one needs a narrow amplifying QW and an absorbing QW. For the TE mode, a 4-nm-thick QW is amplifying, and a 5 nm-thick QW is absorbing. A 9-nm-thick QW is used to increase the total heterostructure gain in the range 1.5–1.6 μm. Calculations show that, for an active region with four QWs, the width of the gain spectrum with an almost constant maximum value of ~30 cm^{-1} is ~120 nm in the range 1.48–1.6 μm. As can be seen in Fig. 1a, the decrease of the number of QWs to three narrows the constant-gain range. An increase in the number of QWs to five leads to an increase in the maximum gain; however, the plateau region narrows as well.

The QW thicknesses and excitation levels for the heterostructures based on narrow-gap GaInAsSb semiconductors can be chosen in the same way. The calculations of the energy levels were performed for the $Ga_{0.60}In_{0.40}As_{0.36}Sb_{0.64}/Al_{0.35}Ga_0.65As_{0.03}Sb_{0.97}$ system with the corresponding effective masses in the QWs ($m_c = 0.033m_e$, $m_{\upsilon l} = 0.030m_e$, $m_{\upsilon h} = 0.289m_e$) and barrier layers ($m_c = 0.075m_e$, $m_{\upsilon l} = 0.059m_e$, $m_{\upsilon h} = 0.295m_e$).

As can be seen in Fig. 2a, for the QWs with widths from 5 to 15 nm, the wavelengths of the main optical transitions lie in the range 2–3 μm. The optimized modal gain spectra for the structure with four QWs are shown in Fig. 2b. According to the calculations, the width of the range of almost constant gain at a level of 43 cm^{-1} is ~490 nm.

Thus, the use of asymmetric multilayer QW heterostructures based on the GaInPAs and GaInAsSb quaternary compounds with inhomogeneously excited active layers of different thickness allows one to obtain a wide and almost flat modal gain spectrum in the near-IR range. The gain spectra of such structures were analyzed for different excitation levels. At inhomogeneous excitation of QWs of differing thickness, a wide and almost flat modal gain spectrum was obtained. It is shown that the structure with four QWs is optimal for obtaining a wide and flat modal gain spectrum.

Injection lasers based on AlGaAs, GaInPAs, and GaInAsSb compounds with a wide flat modal gain spectrum make it possible to implement two-color units, if they are connected with a fiber containing two Bragg gratings, or emitters continuously tuned in a wide frequency band, when external dispersive elements are used.

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