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Asymmetric multiple-quantum-well heterostructures with a wide flat amplification spectrum

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Due to asymmetric quantum-well heterostructures new possibilities to control spectral, power, and temporal properties of laser diodes and to widen their functionality are opened up. In the paper, main attention is devoted to the results obtained under study of spectral characteristics of quantum-well lasers with active region layers of different widths and compositions. Simulation examples are given for band diagrams of the active region, shape of the gain spectrum, and tuning curves. Attractiveness of designed laser sources for special applications is mentioned.

Key words. Quantum-well heterostructure, laser diode, band diagram, gain spectrum, tuning curve.

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Introduction

Since development of semiconductor injection lasers the considerable improvement of their characteristics has been achieved. It widens the use of laser diodes in different fields of science and technique. Investigations in the field of injection lasers are carried out in three main directions, that is search of new materials, theory simulation of physical processes in the active region including low-dimensional effects, and the designing of novel type heterostructures and devices. Quantum-well (QW) injection lasers differ from traditional laser diodes in a series of such positive virtues, as extremely small power consumption, low noise level, small threshold currents, weak sensitivity to ambient temperature fluctuations, sufficiently great values of lasing radiation power and efficiency, additional resources in control of emission characteristics.

From this point of view, laser heterostructures with varied QWs in the active region being called asymmetric systems have big prospects. There are several ways of deriving the asymmetric multiple-quantum-well (AMQW) heterostructures. The active layers can differ in the width, component composition, and in the order of location relative to each other or to emitters.

Basic principals of the conception of AMQW heterostructure lasers are presented in [1, 2]. Various designs of the active region of the AMQW heterostructures with tunable lasing spectra were proposed and simulated [3–5]. Using an asymmetric bi-QW heterostructure, the continuously tunable from 766 to 856 nm laser diode in a grating coupled ring cavity was demonstrated [6]. The tuning range of 911 to 981 nm was obtained for a laser with three QWs of different widths in an external cavity of the Littrow configuration [7]. Design of tunable AMQW laser diodes in the Littman and Metcalf cavity configuration is described as well [4, 5, 8]. Possible ways to obtain a widely flat gain spectrum based on the AMQW heterostructure conception are analyzed in [9]. In the present work, examples of different designs of the band structure in the active region of the QW laser diodes for obtaining widen tunable gain spectra are discussed and results of simulation of tuning curves are presented.

I. Principals of widening the gain spectrum and tuning curves

In QW heterostructures, the wavelength corresponding to interband radiative transitions depends on the width and component composition of the active and barrier layers. Therefore in the AMQW heterostructures different active layers amplify radiation in different wavelength regions. Hence, the sum amplification spectrum of a heterostructure laser with unequal active QW layers can cover a rather wide wavelength range.

Here, band diagrams of the AMQW heterostructures, waveguide gain spectra, tuning curves, and component design of lasers, which contain up to 17 layers and provide a wide flat emission spectrum, are presented. For example, for a laser diode which contains two differ width QW layers [6] it is not possible to get the flat form gain spectrum because in this laser the homogeneous excitation of the active QW layers is realized that is caused by the use of an undoped and quite thin barrier layer. The problem of getting the wide flat gain spectrum can be solved, in particular, by using the AMQW heterostructures [1].

The band diagram of such a laser diode (type 1 structure) under forward bias is shown in Fig. 1. The layer composition is specified in the GaAs–Al$_x$Ga$_{1-x}$As system [3, 4]. The active region consists of four QW layers of widths $d_1 = 15$ nm, $d_2 = 4.5$ nm, $d_3 = 5$ nm, and $d_4 = 7$ nm. The gain maximum of the d_1-thick layer falls at the wavelength of 850 nm while layers of d_2- and d_3-thicknesses at 800 nm (Fig. 2). As the thickest QW layer does not amplify but absorbs at wavelengths near 800 nm, two active QW layers of approximately equal widths are added in the laser for compensation of optical losses in this wavelength range. The d_4-thick QW layer smoothes a dip in the total gain spectrum at wavelengths near 830 nm.

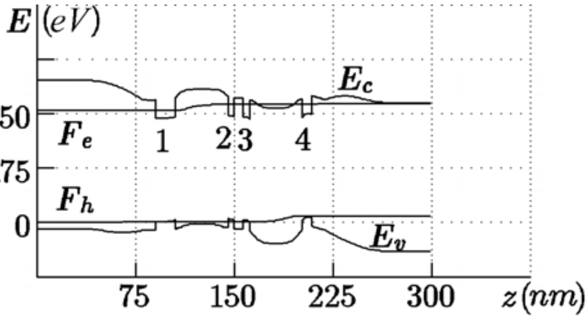

Fig. 1. Band diagram $E(z)$ of type 1 laser AMQW heterostructure under the forward bias 1.64 V. F_e and F_h are the electron and hole quasi-Fermi levels, E_c and E_v are the conduction and valence band edge energies.

To make conditions for non-homogeneous excitation of the active region, the barrier layers are doped with acceptors and donors in the proper manner. Distribution of the doping impurities across the laser structure is shown in Fig. 3. At forward bias, the potential barrier arising in the conduction band due to the acceptor doping of the layer between QW layers 1 and 2 partially blocks the electron transport into QW layer 1. The potential barrier arising in the valence band because of the donor doping of the barrier layer between QWs 3 and 4 impedes hole carrying into QW layer 4. Thus, varying parameters of barrier layers (width, component composition, doping extent and type) it is possible to control the excitation level of corresponding QW layers. Design parameters of type 1 laser structure are listed in Tabl. 1.

Attractive characteristics are also displayed by AMQW heterostructures which contain active layers of equal widths but different component compositions (Tabl. 2). The QW layers are assumed to be of the 15 nm-thick. The Al mole fractures in the active layers are $x_1 = 0$, $x_2 = 0.07$, $x_3 = 0.08$, and $x_4 = 0.04$. Corresponding gain spectra and tuning curves (power P in dependence on wavelength λ) for type 2 laser structure are shown in Figs. 4 and 5.

Table 1

Type 1 structure.

No.	d (nm)	x	N_a (cm^{-3})	N_d (cm^{-3})
1	50	0.5	5×10^{17}	
2	30	0.5→0.3		
3	10	0.3		
4	15	0		
5	5	0.3→0.35		
6	30	0.35	3.3×10^{18}	
7	5	0.35→0.3		
8	4.5	0		
9	7	0.3		
10	5	0		
11	5	0.3→0.35		
12	30	0.35		2.6×10^{18}
13	5	0.35→0.3		
14	7	0		
15	10	0.3		
16	30	0.3→0.35		
17	50	0.5		5×10^{17}

Table 2

Type 2 structure.

No.	d (nm)	x	N_a (cm^{-3})	N_d (cm^{-3})
1	50	0.5	5×10^{17}	
2	30	0.5→0.3		
3	10	0.3		
4	15	0		
5	5	0.3→0.35		
6	30	0.35	1.7×10^{18}	
7	5	0.35→0.3		
8	15	0.07		
9	8	0.3		
10	15	0.08		
11	5	0.3→0.35		
12	25	0.35		2.2×10^{18}
13	5	0.35→0.3		
14	15	0.04		
15	10	0.3		
16	30	0.3→0.35		
17	50	0.5		5×10^{17}

Finally, in Fig. 6 it is shown the band diagram of an AMQW heterostructure containing the active layers differed in both thicknesses and component compositions [9]. Parameters of the QW active layers are assumed equal to $d_1 = 15$ nm, $x_1 = 0$, $d_2 = 10$ nm, $x_2 = 0.07$, $d_3 = 15$ nm, $x_3 = 0.07$, $d_4 = 10$ nm, and $x_4 = 0.03$. The tuning curves for type 3 laser structure are resulted in Fig. 7.

For the radiation tuning it is possible to use an external selective cavity (for example, of the Littman and Metcalf configuration) or to apply a fiber Bragg reflector. The tuning range of the lasing spectrum for AMQW heterostructures in the GaAs–Al$_x$Ga$_{1-x}$As system reaches up to 60 nm and the output power above 7 mW in the broad-band spectral diapason can be produced. Transferring the emission spectrum to another required

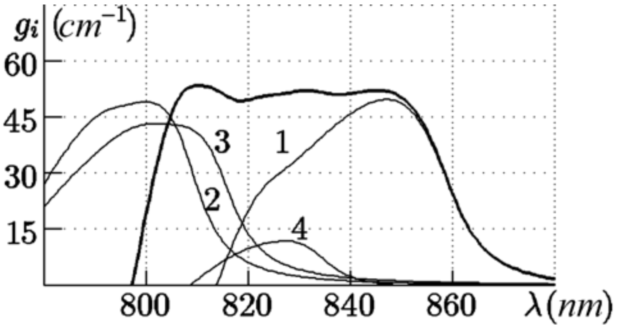

Fig. 2. Waveguide gain spectra $g_i(\lambda)$ for the TE mode. The bold curve corresponds to the laser total gain. The figures at the curves are the QW layer numbers. j = 1.3 kA/cm^2.

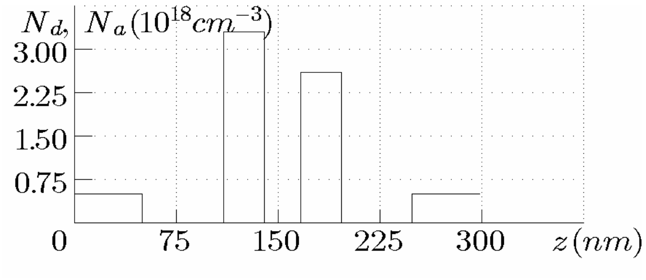

Fig. 3. Distribution of doping impurity concentrations in the laser diode along z-axis. N_a and N_d are acceptor and donor concentrations.

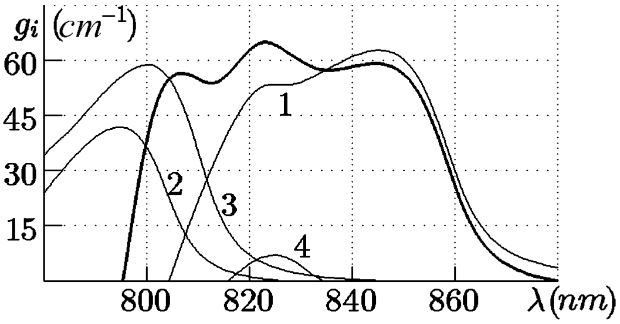

Fig. 4. Waveguide gain spectra $g_i(\lambda)$ for the TE mode. The bold curve corresponds to the total gain of the heterostructure. The figures at the curves are the QW layer numbers. j = 1.7 kA/cm^2.

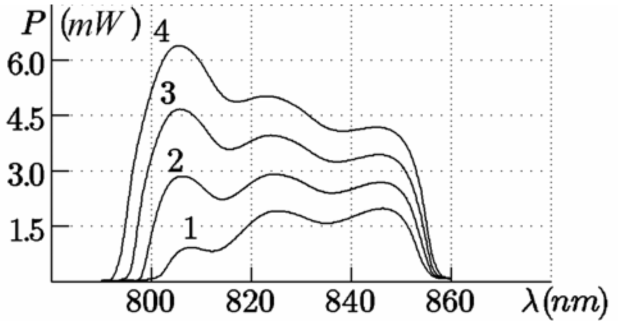

Fig. 5. Tuning curves $P(\lambda)$ of the laser radiator at various pump current densities (1) j = 1.6, (2) 1.7, (3) 1.8, and (4) 1.9 kA/cm^2.

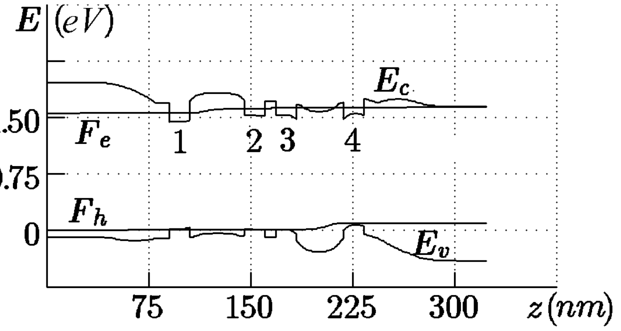

Fig. 6. Band diagram $E(z)$ of type 3 laser structure, which contains the QW layers of different widths and compositions, under the forward bias 1.64 V.

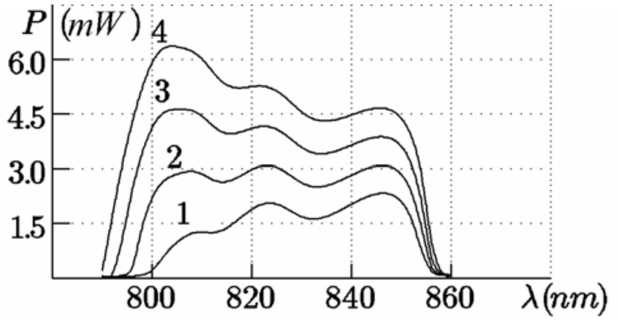

Fig. 7. Tuning curves $P(\lambda)$ of the laser radiator at various pump current densities (1) j = 1.5, (2) 1.6, (3) 1.7, and (4) 1.8 kA/cm^2.

diapason occurs by choose of suitable materials in the active region, e. g., ternary or quaternary compounds. In particular, the GaInAsP semiconductor is appropriate for the range 1.3–1.6 μm [10].

Conclusion

The AMQW heterostructure approach is one of the most advantageous conceptions of the band-gap engineering. The modeling simulation of the laser performance allows to chose the active region parameters for required regimes of operation and to extend gain spectra and tuning curves under the non-uniform excitation conditions. There are some designs of the widely tunable AMQW heterostructure laser diodes. In the active region, QW and barrier layers can differ in thicknesses and component compositions and in arrangement as well. Laser sources based on the AMQW heterostructures are attractive for a number of special applications, including coherent spectroscopy, metrology, and multi-channel fiber optical communications.

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Асиметричні багатоквантові точкові гетероструктури із широкою площиною підсилення спектру

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Через відкриття асиметричних гетероструктур на квантових точках з'явилися нові можливості керувати спектральними, енергетичними та часовими властивостями лазерних діодів та розширити їх функціональні можливості. У роботі, в основному приділена увага результатам, отриманим при дослідженні спектральних характеристик лазерів на квантових точках квантових з активними шарами області різної ширини та складу. Змодельовані діаграми смуг активної області, форма спектра підсилення, настроюваних кривих. Відзначена актуальність розроблених лазерних джерел для спеціальних пристроїв.