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## Wide and Flat Waveguide Gain Spectrum in the $\text{Ga}_{1-x}\text{In}_x\text{As}_y\text{Sb}_{1-y}/\text{Al}_x\text{Ga}_{1-x}\text{As}_y\text{Sb}_{1-y}$ Asymmetric Multiple-Quantum-Well Heterostructures

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For asymmetric multiple-quantum-well heterostructures based on  $\text{Ga}_{1-x}\text{In}_x\text{As}_y\text{Sb}_{1-y}/\text{Al}_x\text{Ga}_{1-x}\text{As}_y\text{Sb}_{1-y}$  semiconductors it is shown that a wide and almost flat waveguide gain spectrum can be obtained over the 2.3–2.84  $\mu\text{m}$  spectral range. Main attention is devoted to the results obtained under study of spectral characteristics of two-, three- and four- quantum-well structures with active region layers of different widths. Numerical simulation for band diagrams of the active region and shape of the waveguide gain spectra are performed.

**Key words:**  $\text{Ga}_{1-x}\text{In}_x\text{As}_y\text{Sb}_{1-y}/\text{Al}_x\text{Ga}_{1-x}\text{As}_y\text{Sb}_{1-y}$  heterostructure, multiple-quantum-wells, band diagram, inhomogeneous excitation, wide waveguide gain spectra.

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### Introduction

The GaSb-based quaternary semiconductor alloys are important materials for lasers emitting in the spectral range 2–5  $\mu\text{m}$  for trace gas sensing, molecular spectroscopy, night vision, as well as medical applications [1, 2]. These structures are also perspective for long-wavelength photodetectors [3] and thermophotovoltaic applications. On the basis of asymmetric multiple quantum well (QW) heterostructures with inhomogeneous excitation of quantum wells it is possible to realize wide and nearly flat gain spectra [4–7]. The main principals of engineering of such structures for GaAs/AlGaAs semiconductor system were shown in the papers [4–6].

In the present work results of numerical simulation of energy band diagrams and gain spectra for the asymmetric quantum well heterostructures based on  $\text{Ga}_{0.6}\text{In}_{0.40}\text{As}_{0.36}\text{Sb}_{0.64}/\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}_{0.03}\text{Sb}_{0.97}$  compound

are presented.

### I. Theoretical Consideration

In quantum well heterostructures generation wavelength corresponding to the interband optical transitions depends on the width and component composition of the active and barrier layers, as well as on excitation level of semiconductor. Usually gain coefficient is calculated in model of direct optical transitions in view of polarization dependence of probability of interband optical transition and taking into account spectral broadening of emission lines due to finiteness of the intrasubband carrier relaxation time [8]. For a QW with the width  $d$ , the gain coefficient  $K$  at the frequency  $\nu$  is described by the relation [8, 9]

$$K(\nu) = \frac{A_{cv}}{\pi \hbar^2 \nu p d} \sum_n \sum_i m_{ri} \int \left( 1 - \exp\left(-\frac{E_{cv} - \Delta F}{kT}\right) \right) f_e(E_{cni}) f_h(E_{vni}) \alpha_{ni}(E_{cv}) L(\hbar\nu - E_{cv}) dE_{cv}, \quad (1)$$

where  $f_e$  and  $f_h$  are the Fermi-Dirac distribution functions for electrons and holes,  $E_{cni}$  and  $E_{vni}$  are the energies of the subband levels associated with direct optical transitions

$$\begin{aligned} E_{cni} &= E_{c0} + \frac{m_{ri}}{m_c} (\hbar\nu - E_g) + \frac{m_{ri}}{m_{vi\perp}} E_{cn} - \frac{m_{ri}}{m_c} E_{vin}, \\ E_{vni} &= E_{v0} + \frac{m_{ri}}{m_{vi\perp}} (\hbar\nu - E_g) + \frac{m_{ri}}{m_{vi\perp}} E_{cn} - \frac{m_{ri}}{m_c} E_{vin}, \end{aligned} \quad (2)$$

$E_{c0}$  и  $E_{v0}$  – conduction-band bottom and valence band

**Table 1.**Input parameters for  $\text{Ga}_{0.6}\text{In}_{0.40}\text{As}_{0.36}\text{Sb}_{0.64}$  and  $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}_{0.03}\text{Sb}_{0.97}$  semiconductors

	$E_g, \text{eV}$	$\Delta E_c, \text{eV}$	$\Delta E_v, \text{eV}$	$m_c/m_0$	$m_h/m_0$	$m_l/m_0$	$m_{hl}/m_0$	$m_{ll}/m_0$
$\text{Ga}_{0.6}\text{In}_{0.40}\text{As}_{0.36}\text{Sb}_{0.64}$	0,369			0,033	0,289	0,030	0,039	0,092
$\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}_{0.03}\text{Sb}_{0.97}$	1,167	0,519	0,279	0,075	0,295	0,058		

top energy,  $\Delta F = F_e - F_h$  is the quasi-Fermi level difference between quasi-Fermi levels for electrons  $F_e$  and holes  $F_h$ ,  $v$  is the velocity of light in the crystal,  $\rho$  is the mode density of electromagnetic field,  $m_{ri} = m_c m_{vi\perp} / (m_c + m_{vi\perp})$  are the reduced masses containing transverse effective masses for heavy ( $i=h$ ) and light ( $i=l$ ) holes,  $L(h\nu - E_{cv}) - \text{Gaussian}$  function which define the shape of the emission line. The summation in (1) is made with respect to the quantum number  $n$  and states of heavy and light holes ( $i=h, l$ ). Integration in (1) is performed within the limits of the energy  $h\nu_{ni}$ , from which optical transitions begin for subbands with the quantum number  $n$ , to the energy equal to the band gap in emitters.

Energy levels subbands in quantum well are given as follows [10]:

$$E_{cv,n} = E_{cv,n}^\infty n^2 \left( n + \frac{2}{\pi} \sqrt{\frac{m_{cv,b}}{m_{cv}}} \frac{E_{cv,n}^\infty}{U_0} \frac{e^{\kappa d_b} + (-1)^{n+1}}{e^{\kappa d_b} - (-1)^{n+1}} \right)^{-2}, \quad (3)$$

where  $\kappa = \sqrt{2m_{cv,b}(U_0 - E_{cv,n})}/\hbar$ ,  $U_0$  is potential barrier height,  $n$  is the quantum numbers of subbands,  $m_{cv}$  and  $m_{cv,b}$  are the effective masses for electrons ( $cv=c$ ), heavy ( $cv=h$ ) and light ( $cv=l$ ) holes in quantum wells and barrier layers correspondingly,  $d$  and  $d_b$  are the thicknesses of the quantum wells and barrier layers,

$$E_{cv,n}^\infty = \frac{(\pi\hbar)^2}{2m_{cv}d^2} n^2 \text{ are define the energy levels subbands}$$

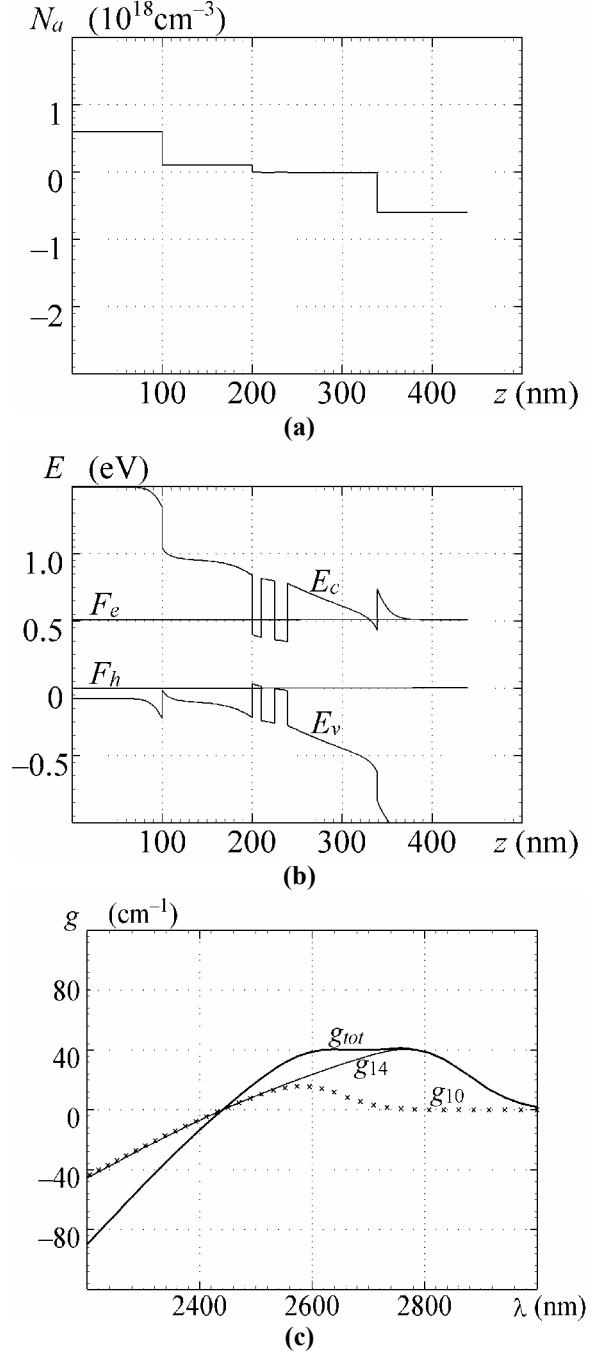
in case of infinite potential barriers height.

Thus the radiation is not entirely localized in the active layers because of their small thicknesses, we calculated the waveguide gain  $g(h\nu) = \Gamma K(\nu)$ , where  $\Gamma$  is the optical confinement factor. The optical confinement factor for the  $j$ -th quantum well of multilayer quantum well heterostructures for radiation of the TE- and TM-polarization can be evaluated in equivalent three-layer waveguide model [11]

$$\Gamma_{\text{TE}} = \frac{d_j}{d + \frac{2}{d(\epsilon_a - \epsilon_c)} \left( \frac{\epsilon_c}{\epsilon_j} \right)^{1/2} \left( \frac{\lambda}{2\pi} \right)^2}, \quad (4)$$

$$\Gamma_{\text{TM}} = \frac{d_j}{d + \frac{2}{d(\epsilon_a - \epsilon_c)} \left( \frac{\epsilon_a}{\epsilon_c} \right) \left( \frac{\epsilon_j}{\epsilon_c} \right)^{3/2} \left( \frac{\lambda}{2\pi} \right)^2}$$

Radiation wavelength  $\lambda$  is determined by narrow band semiconductor energy gap width. As an effective active area permittivity  $\epsilon_a$  use variables  $\epsilon_a = d^{-1} \int \epsilon(z) dz$  for the TE and  $\epsilon_a^{-1} = d^{-1} \int \epsilon^{-1}(z) dz$  TM modes. Total waveguide gain of multilayer heterostructure on



**Fig. 1.** (a) Distribution of doping impurity concentrations in the laser diode with 2 QWs, (b) Band diagram  $E(z)$  under the forward bias 0.51 V and (c) TE mode waveguide gain spectra  $g(\lambda)$  for the quantum well widths 10 ( $g_{10}$ ) and 14 nm ( $g_{14}$ ) and total gain  $g_{\text{tot}}$ .  $F_e$  and  $F_h$  are the electron and hole quasi-Fermi levels,  $E_c$  and  $E_v$  are the conduction and valence band edge energies.

frequency  $\nu$  is set by expression

$$g(\nu) = \sum_j g_j(\nu) = \sum_j \Gamma_j K_j(\nu), \quad (5)$$

The basic equation system for calculations of electrophysical parameters of QW heterostructures includes the Poisson and current continuity equations defining electrostatic potential  $\phi$  and electronic  $j_e$  and holes  $j_h$  currents [10].

$$\begin{aligned} \frac{\partial^2 \phi}{\partial z^2} &= -\frac{e}{\epsilon \epsilon_0} (p - n + N_d - N_a) \\ \frac{\partial j_e}{\partial z} &= eR, \quad j_e = \mu_e n \frac{\partial F_e}{\partial z}, \\ \frac{\partial j_h}{\partial z} &= -eR, \quad j_h = \mu_h p \frac{\partial F_h}{\partial z} \end{aligned} \quad (6)$$

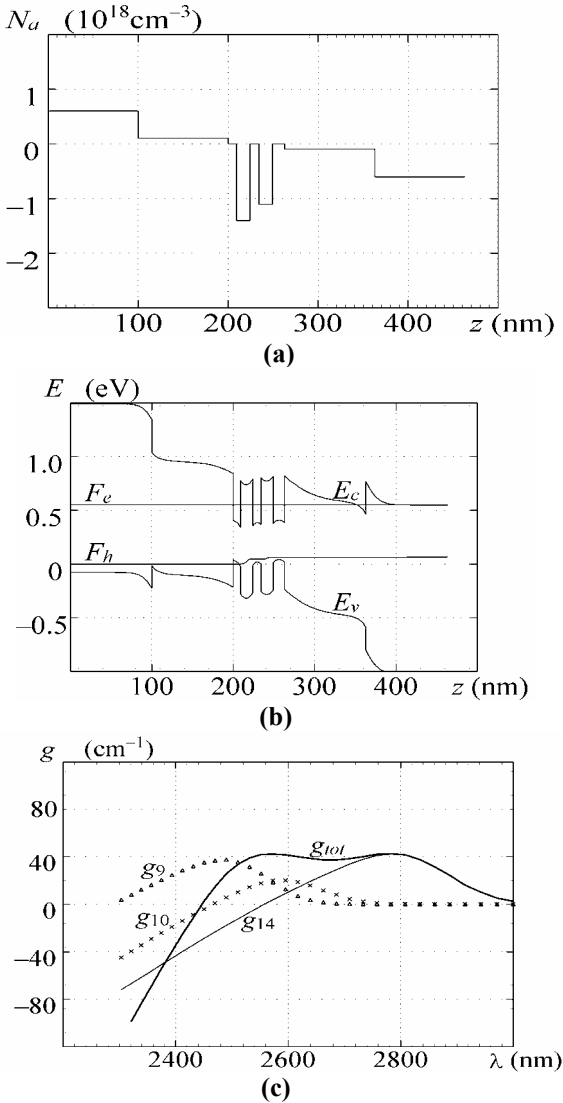
where  $n$  and  $p$  are electron and hole concentrations;  $N_a$  and  $N_d$  are concentrations of ionized acceptors and

donors;  $\epsilon$  – dielectric constant;  $R$  is the recombination rate;  $\mu_e$  and  $\mu_h$  are the electron and hole mobilities.

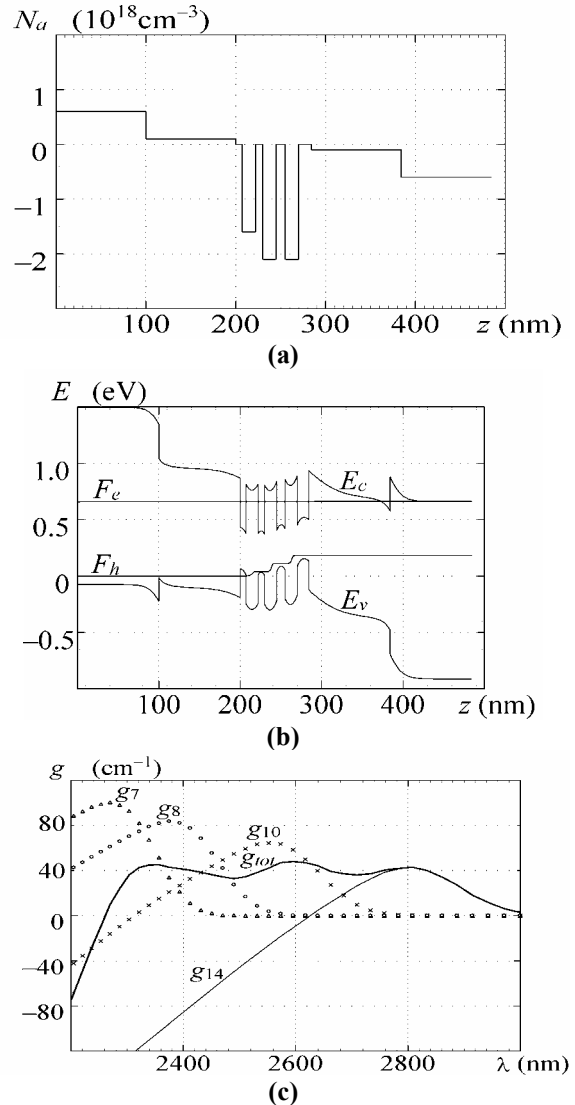
## II. Results of the Numerical Calculations

To receive a flat spectrum of the gain in a wide wavelength interval, the control of the excitation level of each QWs is necessary. For obtaining the conditions of non-uniform excitation of the active region, definite doping of the barrier layers with donors and acceptors must be accomplished [4–6]. We consider performances of heterostructures with quantum wells of a different width for which optical wave lengths transitions to levels of heavy and light holes of different quantum wells will be a little separated and cover all desired wave length range.

The band diagrams and gain spectra of the



**Fig. 2.** (a) Distribution of doping impurity concentrations in the laser diode with 3 QWs, (b) Band diagram  $E(z)$  under the forward bias 0.55 V and (c) TE mode waveguide gain spectra  $g(\lambda)$  for the quantum well widths 9 ( $g_9$ ), 10 ( $g_{10}$ ) and 14 nm ( $g_{14}$ ) and total gain  $g_{tot}$ .  $F_e$  and  $F_h$  are the electron and hole quasi-Fermi levels,  $E_c$  and  $E_v$  are the conduction and valence band edge energies.



**Fig. 3.** (a) Distribution of doping impurity concentrations in the laser diode with 4 QWs, (b) Band diagram  $E(z)$  under the forward bias 0.66 V and (c) TE mode waveguide gain spectra  $g(\lambda)$  for the quantum well widths 7 ( $g_7$ ), 8 ( $g_8$ ), 10 ( $g_{10}$ ) and 14 nm ( $g_{14}$ ) and total gain  $g_{tot}$ .  $F_e$  and  $F_h$  are the electron and holes quasi-Fermi levels,  $E_c$  and  $E_v$  are the conduction and valence band edge energies.

asymmetric two-, three- and four-QW heterostructure is shown in Figs. 1–3. For calculations values of the effective energy band gap  $E_g$ , effective masses of electrons and holes for  $\text{Ga}_{0.6}\text{In}_{0.4}\text{As}_{0.36}\text{Sb}_{0.64}$  and  $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}_{0.03}\text{Sb}_{0.97}$  semiconductors are taken from data in [1, 2, 12] and presented in Table 1.

For the two-QW heterostructure we used QWs with 10 and 14 nm widths which amplify radiation near 2.57 and 2.76  $\mu\text{m}$  correspondingly. It is seen in Fig. 1 that the waveguide gain spectrum is flat in 2.6–2.8  $\mu\text{m}$  range for the loss coefficient equal to 40  $\text{cm}^{-1}$ . The excitation level of QWs is controlled by the width and doping of the barrier layer between QWs.

If we add 9 nm QW for the three- QW heterostructure and select excitation level to enhance radiation near 2.48, 2.60 and 2.78  $\mu\text{m}$  for the 9, 10 and 14 nm QWs correspondingly, the waveguide gain spectrum is flat near the 2.52–2.82  $\mu\text{m}$  (See Fig. 2).

To achieve nearly flat gain spectrum for the four-QW heterostructure we used QWs with 7, 8, 10 and 14 nm widths which amplifies radiation near 2.37, 2.48,

2.56, and 2.8  $\mu\text{m}$  correspondingly. It is seen in Fig. 3 that the range of gain tuning for this structure reaches up to 540 nm. The waveguide gain spectrum is nearly flat on the interval of 2.30–2.84  $\mu\text{m}$  with deviations less than 5  $\text{cm}^{-1}$ .

Thus, selecting the parameters of the barriers, QW widths and the excitation levels in the  $\text{Ga}_{1-x}\text{In}_x\text{As}_y\text{Sb}_{1-y}/\text{Al}_x\text{Ga}_{1-x}\text{As}_y\text{Sb}_{1-y}$  asymmetric multiple-quantum-well heterostructures with inhomogeneous excitation of quantum wells it is possible to receive wide and almost flat waveguide gain spectrum over the range of 2.30–2.84  $\mu\text{m}$ . Described sources allow realizing double- and multifrequency modules which can be used for special purposes of coherent light spectroscopy, chemical analysis, metrology, and environment monitoring.

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## Широкий і плоский хвильовід – підсилення спектру в асиметричній складній квантовій ямі гетероструктури $\text{Ga}_{1-x}\text{In}_x\text{As}_y\text{Sb}_{1-y}/\text{Al}_x\text{Ga}_{1-x}\text{As}_y\text{Sb}_{1-y}$

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Для асиметричної складної квантової ями, створеної на гетероструктурних напівпровідниках  $\text{Ga}_{1-x}\text{In}_x\text{As}_y\text{Sb}_{1-y}/\text{Al}_x\text{Ga}_{1-x}\text{As}_y\text{Sb}_{1-y}$  показано, що приріст спектра широко і плоского хвильоводу може бути одержаний в області 2,3–2,84  $\mu\text{m}$  спектральних ліній. Головна увага приділяється результатами, одержаним при вивченні спектральних характеристик дво-, трьо- і чотирирозмірної розмірної квантової ями з активними шарами різної ширини. Представлено математична модель для зонних діаграм активної ділянки і форми хвильоводних спектрів.