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Efficiency of GaInAs/GaAs quantum-well lasers upon inhomogeneous excitation of quantum wells

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Abstract. **A model for calculating the power characteristics of laser structures taking into account inhomogeneous excitation of quantum wells (QWs), recombination in the barrier regions, and nonlinear gain effects is developed. It is shown that, with increasing number of QWs, the output power of the $Ga_{0.8}In_{0.2}As/GaAs/InGaP$ structures at first considerably increases and then slightly decreases. In a wide range of injection currents, the optimal number of QWs is 5 ± 1. The inhomogeneity of QW excitation increases with increasing injection current and decreases the laser power compared to homogeneous excitation.**

Keywords: *GaInAs/GaAs laser, quantum well, inhomogeneous excitation, lasing efficiency.*

1. Introduction

In high-power lasers, one uses ultrawide waveguides of various designs [1–3], which must have a high accuracy in the thickness of layers and in the position of active quantum wells (QWs) for suppressing multimode lasing. Leaky-mode lasers [4–6] also have some advantages. They have a large emission aperture and always operate at the fundamental mode. In addition, the large aperture of these lasers leads to a narrower directional pattern and to a decrease in the radiation load on the mirrors, which makes it possible to achieve higher output powers.

The first leaky-mode laser based on the GaAs/InGaAs/InGaP heterosystem was demonstrated in [7]. In [8, 9], the optical scheme of the GaAs/InGaAs/InGaP laser was optimised and its energy parameters were improved by increasing the substrate thickness and decreasing its doping.

In the present work, we analize the dependence of lasing intensity in the $Ga_{0.8}In_{0.2}As/GaAs/GaInP$ laser structure on the number of QWs. In modelling, we take into account the inhomogeneous excitation of QWs, as well as recombination in the barrier regions and nonlinear gain effects, whose role becomes much more important at high injection currents.

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2. Rate equations and inhomogeneous excitation of QWs

The output characteristics of a multilayer quantum-well laser were analysed similarly to [10, 11] based on the single-mode rate equations

$$\frac{\mathrm{d}n_{\mathrm{b}i}}{\mathrm{d}t} = \frac{\eta_i j}{e} - R_{\mathrm{b}i} - \frac{n_{\mathrm{b}i}}{\tau_{\mathrm{cap}}}\left[1 - \exp\left(\frac{\Delta F_{\mathrm{w}i} - \Delta F_{\mathrm{b}i}}{kT}\right)\right]\frac{d_{\mathrm{w}i}}{L_i}, \quad (1)$$

$$\frac{\mathrm{d}n_{\mathrm{w}i}}{\mathrm{d}t} = \frac{n_{\mathrm{b}i}}{\tau_{\mathrm{cap}}}\left[1 - \exp\left(\frac{\Delta F_{\mathrm{w}i} - \Delta F_{\mathrm{b}i}}{kT}\right)\right]\frac{d_{\mathrm{w}i}}{L_i} - R_{\mathrm{w}i} - v_{\mathrm{gr}} G_i S, \quad (2)$$

$$\frac{\mathrm{d}S}{\mathrm{d}t} = v_{\mathrm{gr}}\left(\sum_i G_i - k_{\mathrm{th}}\right)S + \beta\sum_i R_{\mathrm{w}i}. \quad (3)$$

Here, t is the time, $n_{\mathrm{b}i}$ and $n_{\mathrm{w}i}$ are the two-dimensional concentrations of current carriers in the ith barrier region with the length L_i and in the QW with the thickness $d_{\mathrm{w}i}$, S is the two-dimensional photon density in the lasing mode, j is the pump current density, $R_{\mathrm{w}i}$ and $R_{\mathrm{b}i}$ are the recombination rates in QWs and adjacent barrier regions with the corresponding Fermi quasi-levels $\Delta F_{\mathrm{w}i}$ and $\Delta F_{\mathrm{b}i}$, η_i is the efficiency of current carrier injection into the ith barrier region, kth is the optical loss coefficient, β is the factor determining the contribution of spontaneous radiation to the lasing mode, v_{gr} is group velocity of light, τ_{cap} is the effective carrier capture time in QWs, and G_i is the mode gain. The ratio $d_{\mathrm{w}i}/L_i$ takes into account the decrease in the capture time with increasing barrier length. The injection of charge carriers is taken into account in Eqns (1), (2) by the exponential term. This term turns the resulting capture–emission rate to zero in the case of identical Fermi quasi-levels ($\Delta F_{\mathrm{w}i} = \Delta F_{\mathrm{b}i}$).

The mode gain with allowance for the nonlinearity was calculated according to

$$G_i = \frac{\Gamma_i g_i}{1 + \varepsilon_i S}, \quad (4)$$

were g_i is the material gain of the ith QW at the lasing wavelength λ, Γ_i is the optical confinement factor, and ε_i is the nonlinear gain. The recombination rate in the barrier regions was calculated as

$$R_{\mathrm{b}i} = A_{\mathrm{cv}} N_{\mathrm{r}} \exp\left(\frac{\Delta F_{\mathrm{b}i} - E_{\mathrm{gb}}}{kT}\right) L_i, \quad (5)$$

where A_{cv} is the Einstein coefficient for spontaneous transitions, while N_{r} and E_{gb} are the normalised bulk density of states and the bandgap width in the barrier layers. Here, recombination was taken into account in the entire GaAs waveguide layer and the boundaries of the barrier regions were drawn through the centre between QWs. The laser wavelength was determined by the maximum of the resulting gain spectrum.

Our estimates of the capture–emission of carriers in QWs showed that, at a comparatively small depth of QWs in the $Ga_{0.8}In_{0.2}As/GaAs$ system, the inhomogeneity of excitation of the barrier regions and QWs is insignificant. Therefore, the recombination rate in the barrier regions can be included into the recombination rate of carriers R_{spi} in the neighbouring QWs. Then, Eqns (1) and (2) in the system of equations (1)–(3) can be summed and substituted by the equation [11, 12]

$$\frac{dn_i}{dt} = \frac{\eta_i j}{e} - R_{spi} - \frac{v_{gr}\Gamma_i g_i S}{1+\varepsilon_i S} \qquad (6)$$

where $R_{spi} = R_{wi} + R_{bi}$ is the resulting recombination rate in QWs and adjacent barrier regions.

The output laser power was calculated as

$$P = h\nu v_{gr} k_r LWS, \qquad (7)$$

where W is the width of the stripe contact of the diode, L is the cavity length, and k_r is the effective loss coefficient. A decrease in the external quantum yield due to the absorption in the substrate was disregarded as unimportant for determination of the optimum.

As a rule, the barrier layers between QWs are undoped. In this case, the concentrations of electrons and holes in wide barriers can be taken to be identical. Due to a high electron mobility, the Fermi quasi-level in the structure is almost constant, and the inhomogeneous excitation of QWs occurs due to a change in the Fermi quasi-level for holes. The efficiency of carrier injection into the ith QW is determined as

$$\eta_i = \frac{j_{i+1,i} - j_{i,i-1}}{j}, \qquad \frac{j_{i,i-1}}{e} = D\frac{n_{bi-1}^{3D} - n_{bi}^{3D}}{L_{i-1}/2 + L_i/2}, \qquad (8)$$

where D is the hole diffusion efficiency. The bulk concentration n_{bi}^{3D} of curriers in the ith barrier region for approximate Boltzmann distribution can be calculated as

$$n_{bi}^{3D} = \sqrt{N_c N_v}\exp\left(\frac{\Delta F_{bi} - E_{gb}}{2kT}\right). \qquad (9)$$

Here, N_c and N_v are the effective bulk densities of electron and hole states in the barrier layers, and $n_{bi} = L_i n_{bi}^{3D}$.

The excitation inhomogeneity increases with decreasing effective density of diffusion current, which depends on the thickness of barrier layers and on the diffusion coefficient. Depending on the concentration, the mobility of holes in GaAs is 40–400 $cm^2\,V^{-1}\,s^{-1}$, which, at room temperature, corresponds to a diffusion coefficient of $\sim$1–10 $cm^2\,s^{-1}$.

3. Calculation of gain

When calculating the energy levels and wave functions of stressed $Ga_{0.8}In_{0.2}As/GaAs$ compounds, one must take into account the valence subband mixing. The calculations are performed using the four-band $\boldsymbol{k{\cdot}p}$ method [13, 14]. The gain $g(\nu)$ in a model with the wave vector selection rule for a QW with the thickness d_w was calculated as [13]

$$g(\nu) = \frac{e^2}{c\varepsilon_0 m_e^2 n_a \nu d_w}\int\frac{dk_{\parallel}}{(2\pi)^2}$$

$$\times\sum_{n,i}|M_{nn}|^2[f_e(E_{cn}(k_{\parallel})) + f_h(E_{vin}(k_{\parallel})) - 1]F(h\nu - h\nu_0), \qquad (10)$$

where $h\nu_0 = E_g + E_{cn}(k_{\parallel}) - E_{vin}(k_{\parallel})$; E_g is the bandgap width; $E_{cn}(k_{\parallel})$ and $E_{vin}(k_{\parallel})$ are the energies of levels participating in the radiative electron–hole recombination; M_{nn} are the matrix elements of direct interband transitions; f_e and f_h are the Fermi–Dirac distribution functions for electrons and holes; n_a is the refractive index of the active region of the structure; and $F(h\nu - h\nu_0)$ is the line broadening function. In expression (10), in addition to the selection rule for the wave vectors k_x and k_y, the selection rule for the quantum number n was applied. The calculations were performed for the TE polarisation.

The gain $g(\nu)$ and the spontaneous recombination rate $r_{sp}(h\nu)$ are related by a universal relation [15]. Then, the total recombination rate in a QW R_{wi} is found by integrating $r_{sp}(h\nu)$ over all frequencies.

The gain spectra were calculated taking into account the hydrostatic and shear stresses [16] in the $Ga_{0.8}In_{0.2}As$ layers. The hydrostatic shifts of the valence and conduction band edges $\Delta E_{v,av}^{hyd}$ and ΔE_c^{hyd} were included into the bandgap width,

$$E_g = E_{g0} + \Delta E_{v,av}^{hyd} + \Delta E_c^{hyd}, \qquad (11)$$

where E_{g0} is the bandgap width of the unstressed structure. The shear stresses were taken into account in the calculations of energy levels.

Figure 1 shows the results of numerical calculations of the material gain for the TEM mode. The structure parameters are listed in Table 1.

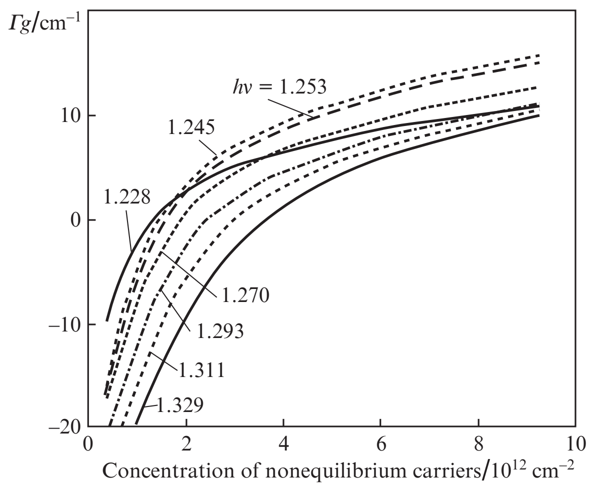

Figure 1. Dependence of the TE mode gain of one QW $\Gamma g(h\nu)$ on the concentration of nonequilibrium carriers for different laser photon energies $h\nu$, d_w = 9 nm, and Γ = 0.008.

4. Numerical calculation and discussion of results

The power characteristics of a $Ga_{0.8}In_{0.2}As$ structure 9 nm thick with 2–10 QWs for different currents J were determined by numerically solving the system of balance equations taking into account the dependence of the efficiency of carrier injection into QWs on the level of their excitation. The power characteristics calculated from the stationary equations (1)–(3) are shown in Figs 2, 3. The calculations were done

Table 1. Structure parameters used in calculations.

Layer	E_g (300 K)/eV	m_c/m_e	m_{vl}/m_e	m_{vh}/m_e	m_{vlt}/m_e	m_{vht}/m_e	ΔE_v/meV	ΔE_c/meV
GaAs	1.422	0.062	0.090	0.350	0.203	0.111	0	0
$Ga_{0.8}In_{0.2}As$	1.211	0.053	0.061	0.346	0.160	0.077	71	172

Note: m_c is the effective electron mass, m_{vl} is the light hole effective mass, m_{vh} is the heavy hole effective mass, m_{vlt} is the light hole effective mass in the transverse direction, m_{vht} is the heavy hole effective mass in the transverse direction.

using the following parameters: $\Gamma_i = 8 \times 10^{-3}$, $\beta = 2 \times 10^{-6}$ [5], $\varepsilon_i = 10^{-12}$ cm^2, $\tau_{cap} = 10^{-12}$ s [17], $W = 360$ μm, and $L = 1$ mm. The gain was taken in the maximum of the spectral distribution at T = 300 K, which, according to Fig. 1, lies at $h\nu$ = 1.245 eV and corresponds to the transition from the first electron level to the first heavy hole level. The thickness of the GaAs waveguiding layer was taken to be 2.1 μm.

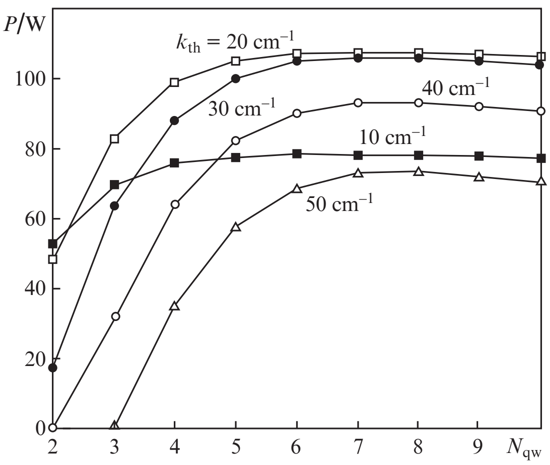

Figure 2. Dependence of the laser power on the number of QWs N_{qw} in the active region of the $Ga_{0.8}In_{0.2}As$/GaAs quantum-well laser heterostructures at different loss coefficients k_{th}, $h\nu$ = 1.245 eV, J = 160 A, d_b = 115 nm, and D = 10 cm^2 s^{-1}.

At a small number of QWs, the threshold concentration of carriers in QWs can considerably exceed the inverse population due to the gain stabilisation with increasing concentration of carriers and to nonlinear gain. At the same time, the recombination in the barrier regions is significant due to their associated population. With increasing number of QWs, the stabilisation effect weakens, but more and more injected carriers are spent for creating the population inversion in QWs.

At low loss coefficients in a structure with one QW, the lasing threshold can be close to inversion current, and the laser power at high injection currents almost does not depend on the number of QWs. At high loss coefficients, due to the gain stabilisation, the structures with a small number of QWs (from one to three) are less efficient (Fig. 2). In these structures, at intense excitation of QWs, the population of the barrier regions is significant. At a large number of QWs (from six to ten), the laser power almost does not depend on the number of QWs. The optimal loss coefficient is ~20 cm^{-1}.

One can see from Fig. 3 that the power characteristics calculated based on the system of Eqns (1)–(3) taking into account the capture–emission of charge carriers almost completely coincide with the results of calculations for a model with homogeneous excitation of barrier regions and QWs based on Eqns (3), (6). This is caused by the fact that, at a comparatively small depth of QWs, the difference between

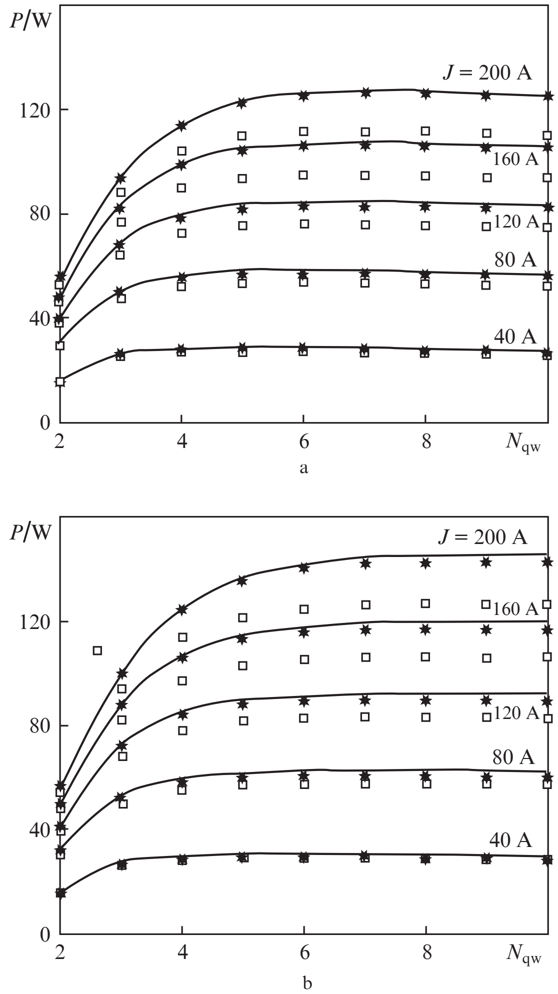

Figure 3. Dependence of the laser power on the number of QWs N_{qw} in the active region of the $Ga_{0.8}In_{0.2}As$/GaAs quantum-well laser heterostructures at different currents J for the photon energy $h\nu$ = 1.245 eV in the case of approximately homogeneous (solid lines, D = 10 cm^2 s^{-1}) and inhomogeneous (squares, D = 6 cm^2 s^{-1}) excitation of QWs at d_b = (a) 115 and (b) 30 nm. The asterisks denote the powers calculated in the model with homogeneous excitation of barrier layers and QWs based on Eqns (3), (6); k_{th} = 20 cm^{-1}.

the Fermi quasi-levels in the barrier regions (ΔF_{bi}) and in QWs (ΔF_{wi}) does not exceed 2 meV, which is much smaller than kT.

Inhomogeneous excitation of QWs leads to a decrease in the lasing efficiency, and the negative effect of this inhomogeneity increases with increasing injection current. This effect can be weakened by placing QWs close to each other. The calculations of the structure performed in [8] show that one can expect a 10% increase in the laser power when decreasing the distance between QWs from 115 nm (Fig. 3a) to 30 nm (Fig. 3b). Note that the experimental power obtained for an active region consisting of six QWs at the injection power

$J = 130$ A is 56 W [8]. This agrees with the calculated power ($\sim$85 W), if we additionally take into account the absorption of generated radiation in the substrate with a free-carrier absorption coefficient of $\sim 5\ \text{cm}^{-1}$.

It should be noted that the presented results are obtained at a constant temperature of 300 K. The calculations show that the allowance for heating of the active region leads to a decrease in the laser power by 10%–15% per each additional 50 K. At the same time, the position of the optimum in the dependence of the laser power on the number of QWs does not change within the range of 300–400 K.

At strongly inhomogeneous excitation, some of QWs may not participate in amplification of radiation. Therefore, the optimal number of quantum wells decreases in comparison with the case of homogeneous excitation. The number of amplifying QWs increases with increasing loss coefficient. As is seen from Fig. 4, the gain distributions over QWs for the laser structures with more than five QWs almost coincide. In addition, the mode gain for QWs from seventh to tenth is smaller than 1 cm^{-1} and tends to zero with increasing QW number. Thus, the optimal number of QWs with respect to the loss coefficient and the pump current is 5 ± 1.

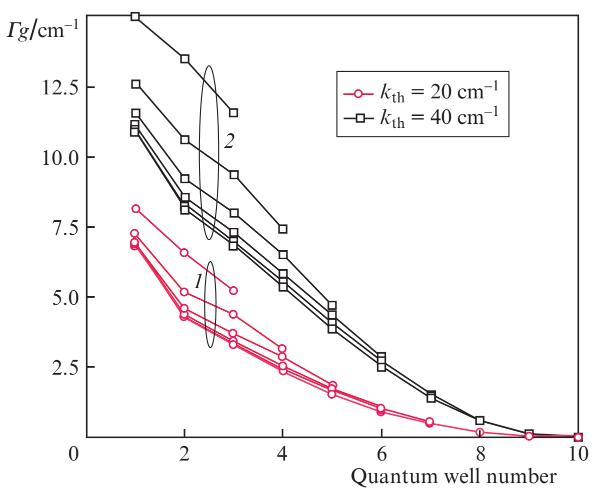

Figure 4. Distribution of the TE mode gain $\Gamma g(h\nu)$ over QWs for the active regions with different numbers of QWs (from three to ten) at the loss coefficients k_{th} = (*1*) 20 and (*2*) 40 cm^{-1}; $J = 160$ A, $d_b = 115$ nm, and $D = 6\ \text{cm}^2\,\text{s}^{-1}$.

5. Conclusions

Thus, we developed a model for calculating the power characteristics of laser structures taking into account inhomogeneous excitation of QWs, recombination in barrier regions, and nonlinear gain effects. It is shown that the output power of the $Ga_{0.8}In_{0.2}As/GaAs$ laser structures at first considerably increases with increasing number of QWs and then slightly decreases. The optimal number of QWs is 5 ± 1 in a wide range of injection currents. Inhomogeneous excitation of the structure leads to a decrease in the laser power compared to the case of homogeneous excitation. In the considered structure [8], a decrease in the thickness of barrier layers between QWs from 115 to 30 nm results in an increase in the laser power by 10%. The maximum powers at a pump current of 160 A are achieved at a loss coefficient of $\sim 20\ \text{cm}^{-1}$.

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