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Dependence of lasing wavelength on optical loss in quantum dot laser

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The dependence of the lasing line position on optical loss is investigated for stripe lasers with different numbers of planes of dense InGaAs/GaAs quantum dots (quantum well-dots). An analytical expression is obtained that explicitly establishes the relationship between the peak position of the gain spectrum and the value at the peak gain for an array with a Gaussian density of states. Reasonable agreement between the model predictions and experimental data is demonstrated. The saturated mode gain is estimated as $51\,\text{cm}^{-1}$ per layer.

Keywords: quantum dots, semiconductor laser, gain spectrum, inhomogeneous broadening.

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Advances in the technology of semiconductor microlasers and silicon lasers are largely associated with the use of epitaxial arrays of quantum dots (QDs) as their active regions [1–3]. Data on the relations between the pump current density, the optical gain, and the spectral position of the gain maximum are of great practical importance, since these relations specify the basic device characteristics of a laser (threshold current density and lasing wavelength) as functions of optical losses. The effect of pumping on optical gain was examined in detail for QD lasers, and several approximating expressions making due allowance for the linear dependence within the initial section and subsequent gain saturation were put forward [4,5]. It was proposed to use a Gaussian function for the density of states of a QD array [6] to determine the shape of the QD gain spectrum. At the same time, a model providing an explicit description of the relation between the spectral position of the gain maximum and the maximum gain magnitude is lacking. In the present study, the dependence of the position of the lasing line of a dense array of InGaAs/GaAs QDs on optical losses in stripe lasers with a Fabry−Pérot cavity is investigated both experimentally and with the use of the obtained analytical expression.

The studied heterostructures were synthesized by metalorganic vapor-phase epitaxy on n^+-GaAs substrates tilted by 6° from the (100) plane. The active region contained $N_{\text{QD}} = 2$, 4, or 6 QD layers formed by $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$ deposition (approximately 2 nm) and separated by 40-nm-thick GaAs spacers. Such QDs, which are also called quantum well-dots, are characterized by high density and, consequently, high material gain (approximately $1.5 \cdot 10^4\,\text{cm}^{-1}$ per layer [7]). This gain is more typical of quantum wells, which is why they got their name. The total thickness of the waveguide layer was close to $0.8\,\mu$m. The $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ cladding layers had a thickness of $1.5\,\mu$m and were subjected to gradient doping with Zn (p) and Si (n). The optical confinement factor for this laser waveguide design is approximately equal to 0.37% per QD layer [7], suggesting that saturated modal gain G_{sat} should be close to $55\,\text{cm}^{-1}$.

Stripe lasers had a width of $100\,\mu$m and length L varying from 0.25 to 4 mm. Faces were cleaved and were not coated with a dielectric. Figure 1, a shows threshold current density J_{th} and emission wavelength λ_{th} at the lasing threshold measured at room temperature as a function of the cavity length. It can be seen that J_{th} increases and λ_{th} shifts toward shorter wavelengths as L decreases. Laser diodes with a greater number of QD layers have a higher threshold current density and a longer-wavelength emission line.

The output losses were calculated: $\alpha_{out} = \ln(R^{-1})/L$, where reflectance R of faces was assumed to be equal to 0.3. Internal losses $\alpha_{in} = 1.0$, 1.5, and $1.9\,\text{cm}^{-1}$ for $N_{\text{QD}} = 2$, 4, and 6 were determined based on the dependence of the external differential efficiency on L. The modal gain per QD layer needed to initiate lasing was then calculated: $G_{th} = (\alpha_{out} + \alpha_{in})/N_{\text{QD}}$. It is shown in Fig. 1, b as a function of the pump current density per a single QD layer: $j_{th} = J_{th}/N_{\text{QD}}$. In lasers with $N_{\text{QD}} = 2$ and 4, these dependences are close to each other and do not reveal any noticeable saturation. We believe that this is due to the smallness of the measured G_{th} values in comparison with G_{sat}, which makes it impossible to determine the latter value. Lasers with $N_{\text{QD}} = 6$ are characterized by higher current densities, which may be attributed to a more intense nonradiative recombination in this epitaxial structure. Thus, despite the nominal equivalence of all QDs, the $G_{th}(j_{th})$ dependences corresponding to lasers with different N_{QD} vary in shape.

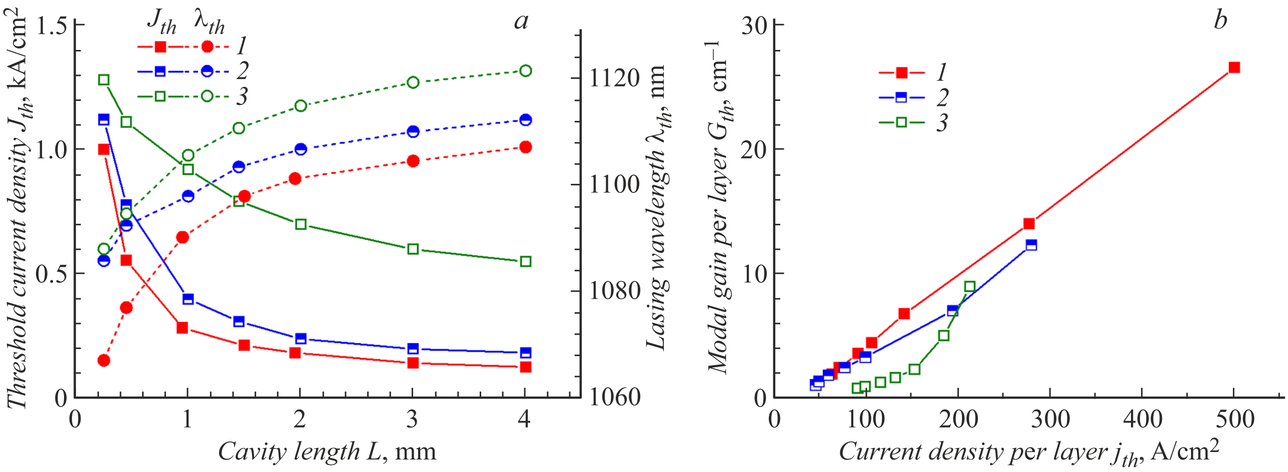

Figure 1. Dependences of the threshold current density (squares) and the wavelength at the lasing threshold (circles) on the cavity length (*a*) and the modal gain on the current density (*b*) for lasers with QD layer number $N_{QD} = 2$ (*1*), 4 (*2*), and 6 (*3*).

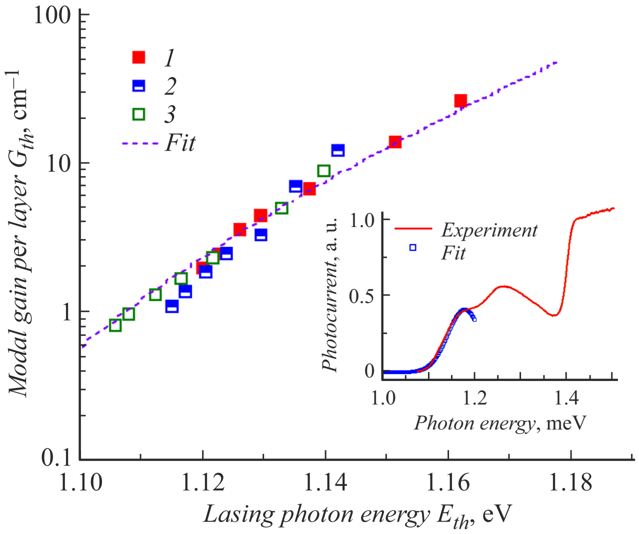

Figure 2. Modal gain at the lasing threshold per QD layer as a function of radiation energy. The dotted curve is the result of approximation by formula (3), while symbols represent experimental data: $N_{QD} = 2$ (*1*), 4 (*2*), and 6 (*3*). The photocurrent spectrum (curve) and the Gaussian approximation (squares) are shown in the inset.

Figure 2 illustrates the relation between photon energy E_{th} corresponding to the lasing line and modal gain G_{th} at the lasing threshold. It is evident that an increase in E_{th} induces an increase in G_{th}. Notably, the dependences for laser structures with different N_{QD} are fairly close (within ± 2 meV). Optical losses in a laser with a Fabry–Pérot cavity (as well as a disk laser with a diameter that is not too small) do not depend on wavelength, and the spectral distance between adjacent cavity modes is small. In this case, the value of E_{th} is set by the maximum of modal gain spectrum $G(E)$, and the gain at maximum balances out the losses; i.e., $G(E_{th}) = G_{th}$. In turn, the gain spectrum is specified by the spectral form of reduced density of states $\rho(E)$ of a QD ensemble and the degree of population inversion: $G(E) = G_{sat}\rho(E)[f_e(E_e) + f_h(E_h) - 1]$. Here, $f_{e(h)}$ and $E_{e(h)}$ are the degree of filling and the energy of an electron (hole) QD level, and $E = E_e - E_h$. A spread in size (and other parameters) of QDs leads to inhomogeneous broadening of the density of states around average optical transition energy E_0. When a QD array is close to complete filling ($f_{e,h} \approx 1$), the gain spectrum maximum approaches E_0, while the gain at maximum becomes close to G_{sat}.

To obtain an explicit description of the relation between spectral position E_{th} of the lasing line and gain G_{th} (optical losses), we assume that $\rho(E)$ follows Gaussian function $\rho(E) = \exp[-(E - E_0)^2/(2\sigma^2)]$, where σ characterizes the magnitude of inhomogeneous broadening, at least on the long-wavelength side (at $E < E_0$). Let us also assume that the QD ensemble filling is equilibrium in nature [6] and $f_{e,h}$ may be expressed in terms of Fermi energies $F_{e,h}$ of electrons (holes): $f_{e,h} = [1 + \exp(\pm(E_{e,h} - F_{e,h})/E_T)]^{-1}$, where E_T is the thermal energy; the „plus" and „minus" signs correspond to electrons and holes, respectively. Finally, we require that local electroneutrality $f_e(E_e) = f_h(E_h)$, which is equivalent to $(E_e - F_e) = -(E_h - F_h)$, be satisfied. With these assumptions introduced, the normalized gain spectrum takes the form

$$g = \exp\left(-\frac{\varepsilon^2}{2s^2}\right)\left(\frac{2}{1 + \exp\left(\frac{\varepsilon - \varphi}{2}\right)} - 1\right), \qquad (1)$$

where $g \equiv G/G_{sat}$, $\varepsilon \equiv (E - E_0)/E_T$, $s \equiv \sigma/E_T$, and $\varphi \equiv (F_e - F_h - E_0)/E_T$. The inset in Fig. 3 illustrates the shape of the gain spectrum. Owing to inhomogeneous broadening, maximum $\varepsilon_{th} \equiv (E_{th} - E_0)/E_T$ of the gain spectrum is shifted to the left relative to the center of the density of states; i.e., $\varepsilon_{th} < 0$. As normalized Fermi energy φ rises, gain $g_{th} \equiv G_{th}/G_{sat}$ increases and approaches unity, while ε_{th} tends to zero.

Setting $dg/d\varepsilon = 0$, we find

$$\frac{\xi}{(1+\xi)^2} + \frac{\varepsilon_{th}}{s^2}\left(\frac{2}{1+\xi} - 1\right) = 0. \quad (2)$$

Here, $\xi \equiv \exp\big((\varepsilon_{th} - \varphi)/2\big)$. Solving (2) for ξ and inserting the result into (1), we obtain the sought-for explicit relationship between g_{th} and ε_{th}:

$$g_{th} = \left(\frac{4}{2 + s^2/\varepsilon_{th} + \sqrt{4 + s^4/\varepsilon_{th}^2}} - 1\right) \exp\left(-\frac{\varepsilon_{th}^2}{2s^2}\right). \quad (3)$$

With the g_{th} value remaining unchanged, the greater normalized broadening s of the density of states is, the further spectrum maximum ε_{th} is shifted away from zero (Fig. 3). When $|\varepsilon_{th}| \gg s^2$, the pre-exponential factor in (3) is simplified to the form $-s^2/(4\varepsilon_{th})$; when $|\varepsilon_{th}| \ll s^2$, it takes the form $(1 + \varepsilon_{th}/s^2)/(1 - \varepsilon_{th}/s^2)$. These limiting cases are represented in Fig. 3 by dashed and dotted curves, respectively. If relation $\varepsilon_{th}^2 \ll s^2$ also holds, the exponential function may be replaced by unity.

The inset in Fig. 2 shows the photocurrent spectrum [8] of a 0.2-mm-long waveguide photodiode fabricated from a heterostructure similar to the examined ones and containing a single QD layer. With a small length of the absorption region, the photocurrent spectrum is shaped by the absorption spectrum, which, in turn, is $\propto \rho(E)$. Fitting the long-wavelength edge of the spectrum with a Gaussian function, we determined $E_0 = 1179 \pm 2\,\text{meV}$ and $\sigma = 35 \pm 2\,\text{meV}$ ($s = 1.353$). The value of saturated gain G_{sat} is also needed to calculate the absolute values of G_{th} and E_{th} by formula (3). The closest agreement between the calculated values and the entire set of experimental data was obtained at $G_{sat} = 51\,\text{cm}^{-1}$ per layer (Fig. 2). The inaccuracy of determination of E_0 translates into a roughly $5\,\text{cm}^{-1}$ error in the determination of G_{sat}.

Thus, it was found that the dependence of threshold gain (per a single QD layer) on the lasing line position is reproduced under a varying number of layers of dense InGaAs/GaAs QD (quantum well-dot) arrays. A model providing an opportunity to characterize this dependence analytically for QDs of any kind with a Gaussian density of states was proposed. The slope of the dependence is specified by the ratio of energy broadening of the optical QD transition to the thermal energy. The calculations performed provided a satisfactory fit to experimental data (including the data for lasers with their dependence of gain on the current density deviating from the common behavior). The saturated modal gain, which was estimated at $51 \pm 5\,\text{cm}^{-1}$ per layer, is the only fitting parameter. The model allows one to predict the change in spectral position of the emission line induced by a modification of the laser cavity and estimate the magnitude of optical losses based on the position of the lasing line. The latter is important in those cases where the exact relation between the cavity design parameters and losses is unknown (e.g., in microdisk cavities).

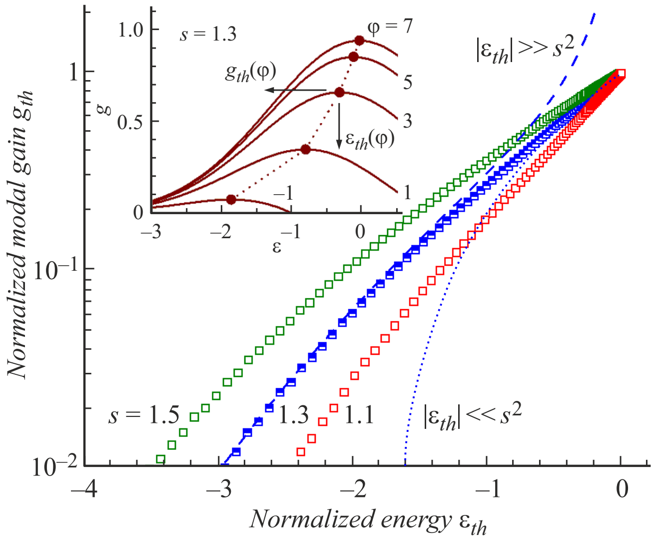

Figure 3. Dependence of normalized gain on normalized energy. Symbols represent the results of calculation by formula (3) with different values of broadening s, while curves are the limiting cases for $s = 1.3$. The gain spectra calculated using (1) for different normalized Fermi energy φ values are shown in the inset.

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Conflict of interest

The authors declare that they have no conflict of interest.

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