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Threshold current of etched-well vertical-cavity surface-emitting diode lasers

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The threshold analysis of etched-well vertical-cavity surface-emitting diode lasers is carried out in the present work. In the analysis, a current-spreading effect and reflections from internal boundaries are taken into account and the self-consistent method of calculations is used. Optimal thicknesses of the active layer determined in this work as a function of resonator mirror reflectivities are greater than those predicted in earlier papers and a dramatic increase in a threshold current density is anticipated when this layer is made thinner.

1. Introduction

Hitherto known threshold analyses [1]–[4] of etched-well vertical-cavity surface-emitting (VCSE) lasers suffer from three important disadvantages: (1) they completely ignore a current-spreading effect, (2) they do not take into consideration reflections from internal boundaries, and (3) they are not self-consistent analyses, i.e., they do not take into account an important fact that free-carrier losses within active areas are directly proportional to carrier concentrations. The first results of the new, complete, self-consistent model of the threshold behaviour of a VCSE laser is presented in this work. The model is a generalized case of all hitherto known models. It is not, however, applicable to lasers with quantum-well active layers and to microresonators because of a different threshold condition.

2. Model

The gain threshold current density $j_{TH,G}$ i.e., this part of a supply threshold current density which is to fulfil the gain threshold condition, is related to the total supply threshold current density j_{TH} with the aid of the following formula:

$$j_{TH,G} = j_{TH} a_{INJ} \tag{1}$$

with [5]

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$$a_{\mathrm{INJ}} = \frac{R_{\mathrm{P}}}{R_{\mathrm{P}}-R_{\mathrm{N}}} - \sqrt{\frac{8\pi(R_{\mathrm{P}}-R_{\mathrm{N}})+\beta R_{\mathrm{P}}R_{\mathrm{N}}\pi r_{\mathrm{A}}^2 j_{\mathrm{TH}}}{\pi r_{\mathrm{A}}^2 \beta j_{\mathrm{TH}}(R_{\mathrm{P}}-R_{\mathrm{N}})^2}} \tag{2}$$

where

$$\beta = e/(mk_{\mathrm{B}}T), \tag{3}$$

R_{P} and R_{N} are the sheet resistances of the P-type and the N-type, respectively, cladding layers, e is the unit charge, k_{B} is the Boltzmann constant, r_{A} is the radius of the active area, and m is the parameter (for GaAs/(AlGa)As structures, [6], [7], $m = 2$).

Assuming bimolecular radiative recombination process, the gain threshold current density may be expressed in a following form:

$$j_{\mathrm{TH,G}} = \frac{eB_{\mathrm{E}}d_{\mathrm{A}}}{A^2}(g_{\mathrm{TH}}+B)^2 \tag{4}$$

where g_{TH} is the threshold value of the local gain, A and B are the parameters of assumed linear relationship between a local gain and carrier density concentration (for $\lambda = 0.883$ μm [8]: $A = 3.3\times10^{-20}$ m^2 and $B = 3.7\times10^{-4}$ m^{-1}), B_{E} is the effective recombination constant ($B_{\mathrm{E}} = 1.5\times10^{-16}$ m^3/s [9]), and d_{A} is the thickness of the active layer.

For resonators without internal boundaries (Fig. 1**a**), g_{TH} may be expressed as [1]–[4]

$$g_{\mathrm{TH}} = \alpha_{\mathrm{A}} + (\alpha_{\mathrm{N}}d_{\mathrm{N}}+\alpha_{\mathrm{P}}d_{\mathrm{P}})/d_{\mathrm{A}} + (1/2d_{\mathrm{A}})\ln(1/R_{\mathrm{F}}R_{\mathrm{R}}) \tag{5}$$

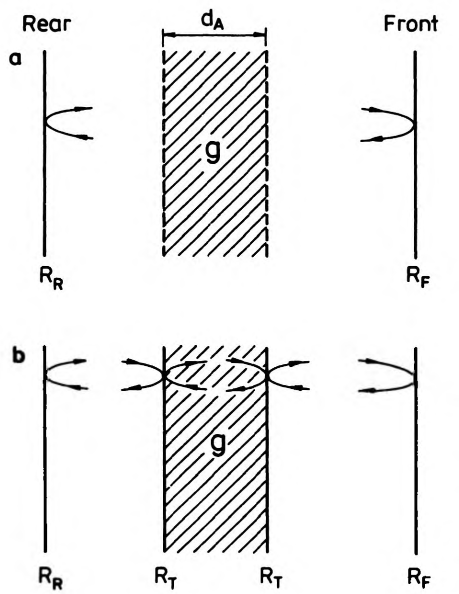

Fig. 1. Laser resonators with a single active layer and without (**a**) or with (**b**) internal boundaries reflecting radiation. R_{F}, R_{R} and R_{T} – reflection coefficients of the front mirror, of the rear mirror, and of internal boundaries, respectively. Shaded areas indicate regions (active areas), where radiation is gained. All reflections considered in the analysis are indicated

where α_A is the free-carrier absorption coefficient in the active area, α_N and α_P are the absorption coefficients in the N-type and the P-type, respectively, cladding layers, d_N and d_P are their thicknesses, and R_F and R_R are the reflectivities of the front and the rear, respectively, resonator mirrors.

The absorption within the active area is assumed to be a linear function of free-carrier (n and p) concentrations [10]

$$\alpha_A = a_N n + a_P p \tag{6}$$

where, for GaAs at room temperature [11], $a_N = 3\times10^{-18}$ cm^{-3} and $a_P = 7\times10^{-18}$ cm^{-3}.

Following conclusions of hitherto obtained analyses [1], [4], [12]–[16], we neglect in our model diffraction losses, absorption within the output mirror and an impact of amplified spontaneous emission.

Let us consider a resonator with internal boundaries (Fig. 1**b**). Constructive interference of incident and reflected beams takes place only then when both the phase and the amplitude conditions are fulfilled. Usually thicknesses of layers are not specially designed to fulfil the above conditions. Therefore, for a purely destructive interference, i.e., assuming that all radiation reflected back at these boundaries is lost, the gain threshold condition takes the form

$$g_{TH} = \alpha_A + (\alpha_N d_N + \alpha_P d_P)/d_A + \alpha_{DES} \tag{7}$$

with

$$\alpha_{DES} = (1/2d_A)\ln\{[(1-R_T)^4 R_F R_R]^{-1}\} \tag{8}$$

where R_T is the reflection coefficient for the internal boundaries.

In the above calculations, we assume that the radiation reflected back from the internal boundaries is lost to the dominant radiation mode. But anyway it may fulfil another phase condition (another wavelength) and another amplitude condition (another gain) at the output mirror, so it can create another (side) radiation mode, not considered, however, in this paper.

3. Self-consistent method of calculations

We assume after Kinoshita et al. [2] for the standard VCSE laser without internal boundaries and with an active layer of a thickness $d_{A,N} = 2$ μm that at the threshold electrons and holes are injected into the active area with concentrations as high as 3×10^{18} cm^{-3} and then the threshold current density equals $j_{TH,N} = 28.6412$ kA/cm^2. Therefore, according to Eq. (6), the absorption within the active area is assumed to be

$$\alpha_A = (30\ \text{cm}^{-1})(j_{TH}/j_{TH,N})(d_{A,N}/d_A). \tag{9}$$

The calculations are repeated as long as a difference between threshold current densities calculated in two successive loops of our procedure is within an acceptable range.

4. Results

Some of the results of our calculations carried out for the $GaAs/Al_{0.3}Ga_{0.7}As$ VCSE lasers are compared with experimental data in Fig. 2. Assuming that some discrepancy of earlier results of KINOSHITA et al. [2] is of technological nature, it seems to be justified to note that the experimental results confirm the validity of our model. They seem to confirm also the validity of hitherto known models but it should be remembered that the new one, being undoubtedly more exact, is a generalized case of all of them.

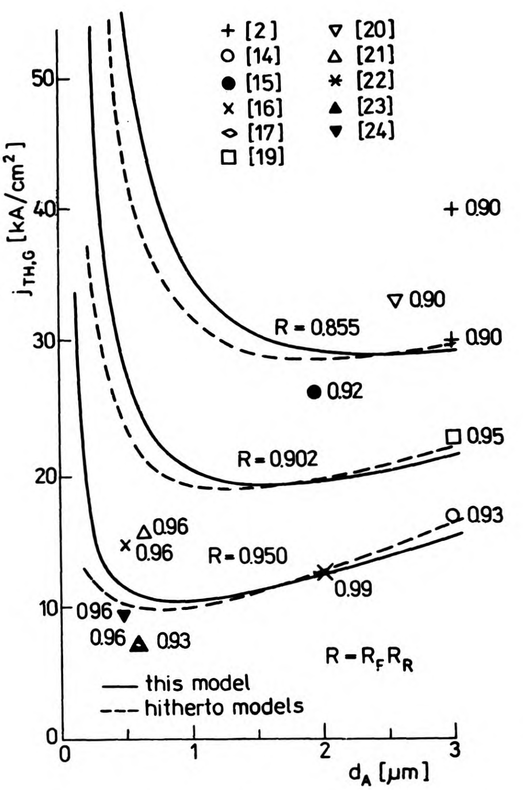

Fig. 2. Plots of $j_{TH,G}$ versus d_A dependences for various values of the mirror reflectivity product, i.e., $R = R_FR_R$: solid lines – this model, dashed lines – hitherto known models. Results of experiments [2], [14]–[17], [19]–[24] are also shown

From plots in Figure 2 it is also shown that the higher the mirror-reflectivity product ($R = R_FR_R$) is, then the lower value of the active layer thickness corresponds to the minimal threshold current density of the VCSE lasers. It is in a good agreement with experimental results [1]–[3], [14], [16]–[18].

The most noteworthy feature in our results is that optimal thicknesses of the active layer (from the point of view of achievement of minimal threshold current densities), determined in this work as a function of resonator mirror reflectivities are thicker than it was anticipated in earlier papers [1]–[14]. A dramatic increase in threshold current densities is anticipated when this layer is made thinner.

5. Conclusions

Detailed threshold analysis of etched-well vertical-cavity surface-emitting diode lasers has been carried out in the present work. Our principal conclusion is that the higher the reflectivities of resonator mirrors, the thinner the active layers which are beneficial from the low-threshold-current-density operation point of view. Optimal thicknesses of the active layer are greater than those predicted in earlier papers.

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Пороговый ток в поверхностно излучающемся лазерном диоде вертикального и вытравленного колодцев

В настоящей работе сделан пороговый анализ поверхностно излучающегося лазерного диода травленного и вертикального колодцев. Во время анализа учтен эффект распределения тока и отражения от внутренних предельных слоев, а также употреблен самосогласованный метод. Оптимальные толщины активного слоя, определенные в настоящей работе как зависимые от отражающей способности зеркал резонатора, больше определенных в предыдущих работах на эту тему. Предусмотрено резкое повышение порогового тока для более тонкого активного слоя.

Перевел Станислав Ганцаж