Laser parameters of n − i − p − i crystals

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ABSTRACT

The rate of spontaneous radiative recombination and gain coefficient for the high-doping superlattices versus the pump current are calculated in the model with no k-selection rule. Results for the inversion current density and differential gain at suitable design of superlattice parameters are presented.

Keywords: doping superlattices, radiative recombination rate, inversion current, gain, emission spectra

1. INTRODUCTION

Doping superlattices, or n − i − p − i crystals, and their modifications are among quantum electronics elements of a new type. Injection lasers have been developed, using δ - doped superlattices. [1] Characteristics of such lasers are completely determined by the potential energy profile of the doping superlattices, whose optical and electric parameters change in a wide range under excitation and can be varied through the choice of thicknesses and doping degree of the crystal layers. The familiar properties of doping superlattices are described in the review by Döhler. [2] The gain and spontaneous emission spectra in a model with the k-selection rule were accomplished in our previous works. [3,4] In this paper, a new approach to studying the properties of n − i − p − i crystals is proposed.

2. THEORETICAL MODEL

A high doping level for lasers based on n − i − p − i crystals requires the consideration of the violation of the k-selection rule for electron transitions at the analysis of spectral and other characteristics. In this case, the rate of spontaneous emission recombination at the light frequency ν can be represented in the following form

$$r_{sp}(h\nu) = \frac{A}{d} \int\limits_{0}^{d} \int\limits_{E_{c0}+E_{c00}}^{E_{v0}(z)+h\nu} \sum_{n} \sum_{\mu} |\psi_{cn\mu}(z)|^2 \rho_{cn\mu}(E) \times \rho_v(E-h\nu, z) f_e(E) f_h(E-h\nu)\, dE\, dz. \tag{1}$$

Here, $A = 32\pi a_0^3 A_{cv}$ is the probability of optical transitions with no k-selection rule, A_{cv} is the Einstein coefficient for interband transitions, a_0 is the effective Bohr radius of impurities, $d = d_n + d_p + 2d_i$ is the period of the superlattice, d_n, d_p, and d_i are the thicknesses of n-, p-, and i-layers, respectively, f_e and f_h are the functions of distribution of electrons and holes, $\psi_{cn\mu}$ is the wave function in the conduction band for the subband with the quantum number n and for the miniband with the quantum number μ, E_{c00} is the ground state energy in the conduction band. In the electron band we use the two-dimensional density of states which for any miniband with the quantum numbers n, ν has the form

$$\rho_{cn\mu}(E) = \frac{m_c}{\pi\hbar^2 N_p} H(E - E_{c0} - E_{cn\mu}), \tag{2}$$

where E is the energy of levels participating in the transitions, E_{c0} is the conduction band bottom, $E_{cn\mu}$ is the dimensional quantization level energy, m_c is the effective mass of electrons, H is the Heaviside step function, N_p is the number of superlattice periods. The quantity $\rho_v(E, z)$ is the density of states in the impurity band overlapping with the valence band edge. Without regard for the tail of the density of states, the first approximation to $\rho_v(E, z)$ can be assumed to be the volume density of states

$$\rho_v(E, z) = \frac{(2m_v)^{3/2}}{2\pi^2\hbar^3} \left(E_{v0}(z) - E\right)^{1/2}, \tag{3}$$

where E_{v0} is the valence band top, m_v is the hole effective mass. The energy E_{v0} follows the superlattice potential relief along the z-axis.

The total recombination rate is evaluated by the integrating of Eq.(1) over all energies of emitted photons and is equal to

$$R_{sp} = \frac{A}{d} \int_0^d n(z)p(z)dz, \quad (4)$$

where $n(z)$ and $p(z)$ are the volume concentrations of electrons and holes at some z-coordinate of the potential relief.

3. LASER CHARACTERISTICS

Among important laser parameters there are inversion and zero currents, gain factor, internal optical losses, and quantum efficiency. The inversion current gives the minimum value of the laser threshold. This value is determined in conditions where the difference of the quasi-Fermi levels for electrons and holes ΔF reaches the minimum energy of emitted quanta $h\nu_{min}$ which is related to the effective energy gap of the superlattice. The last characteristic can be varied through the choice of the doping concentrations of donors N_d and acceptors N_a and the thicknesses d_n, d_p, and d_i of n-, p-, and i-layers.

Assuming that the injection efficiency and quantum yield of luminescence are close to 1, for the inversion current density we have

$$j_{inv} = edR_{sp}|_{\Delta F = h\nu_{min}}. \quad (5)$$

Here, the inversion current density is determined per one period of the superlattice.

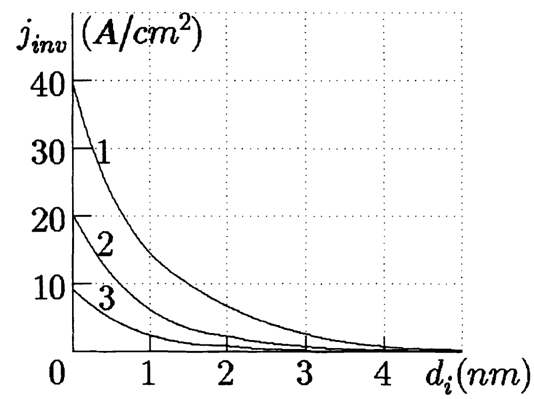

Fig. 1. Dependence of the inversion current density j_{inv} on the width of intrinsic layers d_i at different concentrations of donor impurities (1) $N_d = 5 \times 10^{18}$ cm^{-3}, (2) $N_d = 6 \times 10^{18}$ cm^{-3}, and (3) $N_d = 7 \times 10^{18}$ cm^{-3}. $N_a = 10^{19}$ cm^{-3}, $d_n = d_p = 10$ nm, $T = 300$ K.

Calculations were performed in the GaAs system. The parameter j_{inv} versus the thickness d_i is shown in Fig. 1. The inversion current density decreases with increasing the superlattice period because of increasing spatial separation of electrons and holes. Due to weak overlapping the wave functions, the inversion current density values do not exceed several tens A/cm^2.

The gain and emission spectra have been calculated and their transformation with pump are represented in Fig. 2. The level of excitation of the structure can be described by the factor $r = n_1/N_d d_n$, where n_1 is the two-dimensional concentration of electrons. The gain coefficient $k(\nu)$ is determined from Eq. 1 according to the standard relation between the spontaneous emission recombination rate and absorption (gain) coefficient. It is seen that the maximum value of the gain coefficient k_{max} reaches up to 10^3 cm^{-1} at room temperature.

To find the internal laser parameters, consider results in Fig. 3. If k_{max} is above 400 cm^{-1}, the dependence of k_{max} on r can be approximately described by a linear function $k_{max} = \kappa(r - r_0)$. Here, the zero pump factor $r_0 \approx 0.6$ and $\kappa \approx 7000$ cm^{-1} for the structure under study. Using the relation between r and n_1, we estimate the differential gain $g = \partial k_{max}/\partial n_1$. For the examined laser superlattice the value of g is about 10^{-9} cm. The two-dimensional concentration of nonequilibrium current carriers corresponding to the zero pump conditions reaches 4.2×10^{12} cm^{-2}.

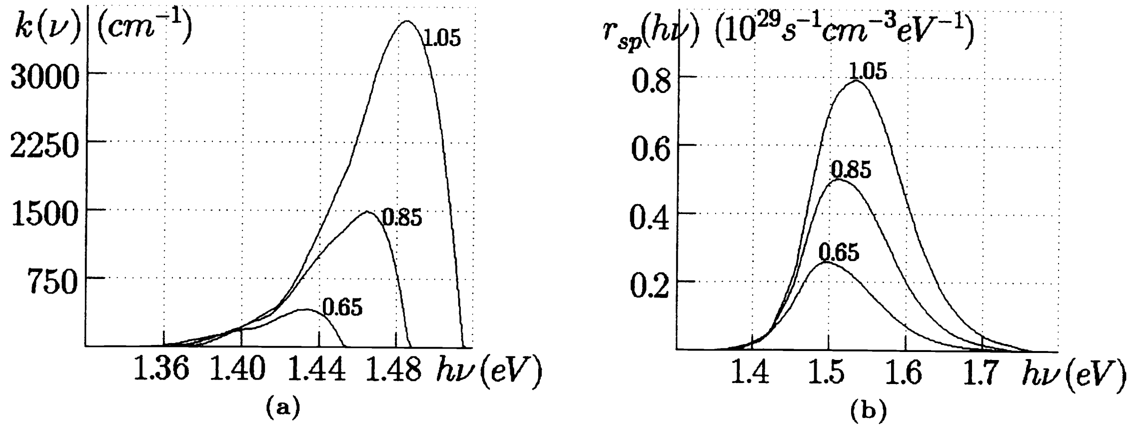

Fig. 2. (a) Gain and (b) emission spectra for different values of the pump factor r (numbers on the curves). $N_a = 10^{19}$ cm^{-3}, $N_d = 7 \times 10^{18}$ cm^{-3}, $d_p = d_n = 10$ nm, $d_i = 0$, $T = 300K$.

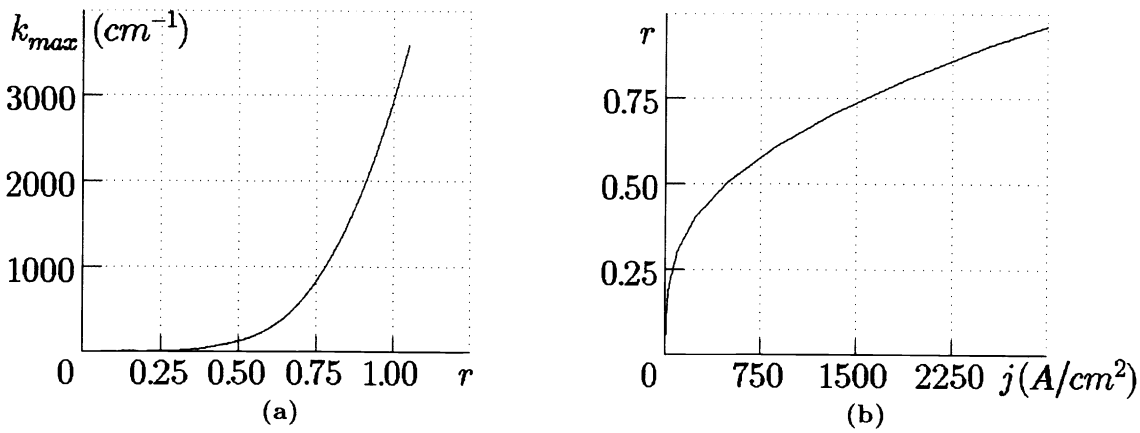

Fig. 3. (a) Dependence of the maximum gain coefficient k_{max} on the pump factor r and (b) the relation $r(j)$. $N_a = 10^{19}$ cm^{-3}, $N_d = 7 \times 10^{18}$ cm^{-3}, $d_p = d_n = 10$ nm, $d_i = 0$, $T = 300$ K.

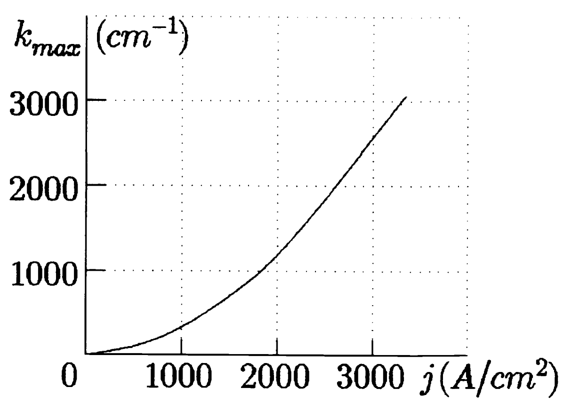

Fig. 4. Dependence of the maximum gain coefficient k_{max} on the current density j. $N_a = 10^{19}$ cm^{-3}, $N_d = 7 \times 10^{18}$ cm^{-3}, $d_p = d_n = 10$ nm, $d_i = 0$, $T = 300$ K.

In general, the dependence of the gain on the injection current in the doping superlattices is nonlinear in a wide interval of k_{max} (Fig. 4). But, in the practical important interval of the gain values $1000 - 3000$ cm^{-1}, an ordinary linear function $k_{max} = \beta(j - j_0)$ gives a good fitting for the gain behaviour versus pump. For the structure under study, we obtain $j_0 \approx 1100$ A/cm^2 and $\beta \approx 1.4$ cm/A. These values correspond to one period of the superlattice. The performed calculations of the internal parameters permit to optimize laser $n - i - p - i$ structures.

4. CONCLUSION

Characteristics of lasers based on doping superlattices were considered in a model with no k-selection rule. Transformation of gain and spontaneous emission spectra with the pump current has been investigated. For the GaAs superlattices, it is shown that the maximum gain can exceed 10^3 cm^{-1} at room temperature and depends linearly on the injection current.

5. ACKNOWLEDGMENT

This work was partly supported by the Belarussian Republican Foundation for Fundamental Research.

6. REFERENCES

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