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EFFECT OF COMPOSITION OF BARRIER LAYERS REGION ON POLARIZATION RADIATION CHARACTERISTICS OF QUANTUM-WELL HETEROLASER

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Effect of componental composition of quantum-well heterostructures' barrier waveguide layers in GaAs–$\mathrm{Al}_x\mathrm{Ga}_{1-x}$As system on the polarization degree of spontaneous and stimulated radiations is investigated. It is shown, that given x at frequencies near the basic optical transitions, a spontaneous radiation polarization degree sign change occurs. In the oscillating mode, depending on a waveguide layer componental composition, the generation of the entirely polarized radiation of TE- or TM-type is possible.

Keywords: quantum-well heterolaser, polarization of radiation, gain, TE- and TM-modes

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1. Introduction

Quantum-well injection lasers have an essential advantage against traditional laser diodes due to the improved lasing characteristics that allow the lasers of this type to be widely applied in various fields of science and technology. Polarization properties of amplification spectra of this type of lasers are connected with the dependence of probability of optical transitions to the heavy and light electron hole states on the type of mode [1], orientation, geometry, and size of lasing regions [2–4]. The analysis of influence of componental content variations of quantum-well heterostructure layers on light polarization characteristics has a doubtless interest as regards the optimization of light output characteristics and the making of laser diodes with required polarization type.

2. Theory

The major influence on spectral characteristics of quantum well radiation have the states of initial levels of electron E_{cn} and electron hole E_{vin} subbands which are found from expressions [5]

$$E_{cn} = \frac{E_{cn}^{\infty}}{n^2}\left(n - \frac{2}{\pi}\mathrm{arccot}\sqrt{\frac{m_c}{m_{cb}}}\sqrt{\frac{E_{cb}}{E_{cn}} - 1}\right)^2, \quad (1)$$

$$E_{vin} = \frac{E_{vin}^{\infty}}{n^2}\left(n - \frac{2}{\pi}\mathrm{arccot}\sqrt{\frac{m_{vil}}{m_{vilb}}}\sqrt{\frac{E_{vb}}{E_{vin}} - 1}\right)^2,$$

where $E_{cn}^{\infty} = \pi^2\hbar^2 n^2/(2m_c d^2)$ and $E_{vin}^{\infty} = \pi^2\hbar^2 n^2/(2m_{vil} d^2)$ are the electron and hole subband level values calculated in the infinite barrier approach, m_c and m_{cb} are effective masses of the electrons in active region and barrier layers accordingly, m_{vil} and m_{vilb} are longitudinal components of hole effective masses in the active and waveguide layers, $i = h, l$ is an index designating heavy and light holes, respectively, E_{cb} and E_{vb} are the potential barrier heights in the quantum well, $n = 1, 2, 3, \ldots$ is a quantum number.

For the considered quantum-well heterostructure in the $\mathrm{Al}_x\mathrm{Ga}_{1-x}$As/GaAs system the height of potential barrier practically linearly depends on aluminium molar concentration x [5]. At the point Γ of the Brillouin band the band-gap width E_g depends on x at $T = 300$ K as $E_g = (1.424 + 1.155x + 0.37x^2)$ eV, and the potential barrier heights in the conduction and valence bands are $E_{cb} = 0.848x$, $E_{vb} = 0.399x$ eV, respectively. Effective mass of the electron at the bottom of the conduction band depends on x as $m_c = (0.067 + 0.083x)m_e$. For the holes, besides division into light and heavy ones, it is necessary to take into account the mass anisotropy.

The level position of the hole subbands in the quantum well is determined by longitudinal component of

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the effective mass. For the heavy holes the value of longitudinal effective mass depends on x as $m_{vhl} = (0.34 + 0.42x)m_e$, and for the light holes – as $m_{vll} = (0.094 + 0.043x)m_e$.

Laser radiation is known to be the combination of spontaneous and stimulated radiations. The intensity of spontaneous radiation is specified by the velocity of spontaneous transitions [6, 7]:

$$r^{\gamma}_{\mathrm{sp}}(h\nu) = \frac{A_{cv}}{\pi\hbar^2 d}\sum_n\sum_i m_{rit} \tag{2}$$

$$\times \int f_e(E_{cni}) f_h(E_{vni}) L(h\nu - E_{cv}) \alpha^{\gamma}_{ni} \mathrm{d}E_{cv}\,,$$

where A_{cv} is Einstein coefficient, d is the width of the quantum well, $m_{rit} = m_c m_{vit}/(m_c + m_{vit})$ is the reduced mass associated with the respective transversal components of the heavy or light holes ($i = h, l$), parameter α^{γ}_{ni} characterizes polarization dependence of the probability of the optical transitions and depends on the type of modes (TE or TM), levels involved (heavy or light holes), and transition energy $E_{cv} = E_{cni} - E_{vni}$ [6]; $f_e(E_{cni})$ and $f_h(E_{vni})$ are Fermi–Dirac distribution functions of the electrons and holes of the states E_{cni} and E_{vni} participating in the optical transitions [8]:

$$E_{cni} = E_{c0} + E_{cn} + \frac{m_{rit}}{m_c}(E_{cv} - h\nu_{ni})\,,$$

$$E_{vni} = E_{v0} - E_{vin} - \frac{m_{rit}}{m_{vit}}(E_{cv} - h\nu_{ni})\,. \tag{3}$$

E_{c0} and E_{v0} are the energies of the bottom of conduction band and the top of valence band, respectively, E_{cn} and E_{vin} are the ground levels of subbands with number n for the electrons and heavy or light holes, $h\nu_{ni} = E_g + E_{cn} + E_{vin}$ is the energy of initial optical transitions with a participation of these states, $\Delta F = F_e - F_h$ is difference of the quasi-Fermi levels, T is temperature. Function $L(h\nu - E_{cv})$, which takes into account the broadening of spectral lines in semiconductor lasers, is approximated by a Lorentzian

$$L(h\nu - E_{cv}) = \frac{1}{\pi}\frac{\Gamma_{cv}}{(h\nu - E_{cv})^2 + \Gamma^2_{cv}}\,. \tag{4}$$

Equations (1–4) are also supplemented with the requirement of electroneutrality of active region [7].

The degree of radiation polarization is given by the formula

$$P = \frac{I^{\mathrm{TE}} - I^{\mathrm{TM}}}{I^{\mathrm{TE}} + I^{\mathrm{TM}}}\,, \tag{5}$$

where I^{TE} and I^{TM} are intensities of the corresponding polarization radiation; in case of spontaneous radiation $I^{\gamma} \sim r^{\gamma}_{\mathrm{sp}}$.

The radiation intensity of the quantum-well laser with nonselective resonator in the oscillation mode can be calculated using the rate equations [8]

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{j}{ed} - R_{\mathrm{sp}} - \sum_{\gamma}\sum_{m} \nu\Gamma^{\gamma} k^{\gamma}_m S^{\gamma}_m\,,$$

$$\frac{\mathrm{d}S^{\gamma}_m}{\mathrm{d}t} = \nu(\Gamma^{\gamma} k^{\gamma}_m - k^{\gamma}_1) S^{\gamma}_m + \beta R_{\mathrm{sp}}\,, \tag{6}$$

where N is concentration of nonequilibrium carriers in the active region, S^{γ}_m is a photon density, j is pump current density, $R_{\mathrm{sp}} = \int r_{\mathrm{sp}}(h\nu)\mathrm{d}(h\nu)$ is rate of spontaneous recombination, k^{γ}_1 is loss coefficient, Γ^{γ} is optical confinement factor, β is coefficient showing the contribution of spontaneous emission transitions to the laser mode, $\gamma = \mathrm{TE}, \mathrm{TM}$ is mode polarization index, m is longitudinal mode number, and the expression for gain factor $k^{\gamma}_m(\nu)$ is given by

$$k^{\gamma}_m = k_0 \sum_n\sum_i \frac{m_{rit}}{m_e} \int \left[1 - \exp\left(\frac{E_{cv} - \Delta F}{kT}\right)\right] \tag{7}$$

$$\times f_e(E_{cni}) f_h(E_{vni}) L(h\nu_m - E_{cv}) \alpha^{\gamma}_{ni}(E_{cv}) \mathrm{d}E_{cv}\,,$$

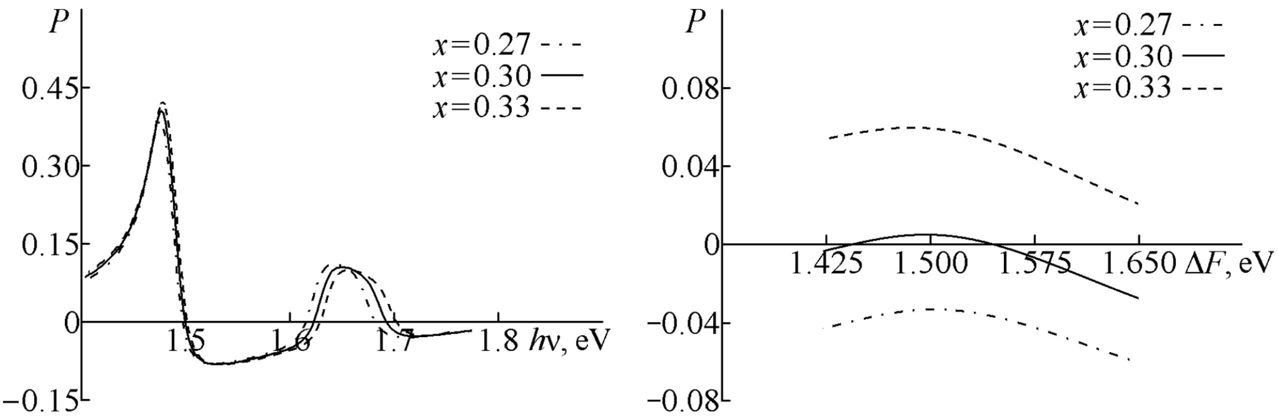
where $k_0 = A_{cv} m_e/(\pi\hbar^2 v\rho d) = 8.0{\cdot}10^4$ cm^{-1}, ρ is density of the electromagnetic modes. The stationary combined equations (6) ($\mathrm{d}N/\mathrm{d}t = 0$, $\mathrm{d}S^{\gamma}/\mathrm{d}t = 0$) are supplemented with the equation for the optical confinement factor Γ^{γ} [8].

The intensity of the mode with order number m is supposed to be

$$I^{\gamma}_m = h\nu_m v S^{\gamma}_m\,. \tag{8}$$

Calculations were carried out with the following values of parameters: $d = 8$ nm, $v = c/n_a$, $n_a = 3.6$, $\Gamma^{\mathrm{TE}} = 2.29\cdot 10^{-2}$, $\Gamma^{\mathrm{TM}} = 1.80\cdot 10^{-2}$ at $\lambda = 825$ nm, $k^{\mathrm{TE}}_1 = 30$ cm^{-1}, $k^{\mathrm{TM}}_1 = 25$ cm^{-1}, $\beta = 10^{-4}$, $\Gamma_{cv} = 10$ meV, $T = 300$ K.

Figure 1 shows dependences of the spontaneous radiation polarization degree on (a) energy of emited quantum $h\nu$ and (b) quasi-Fermi level difference ΔF. As can be seen, the increase of aluminium molar concentration x in the barrier waveguide layers leads to a shift of a graphic chart of the polarization degree P to the short-wave area. This fact can be explained by the shift of the initial subband levels of electrons and holes to the high-energy area as x increases. It is of particular interest when the polarization degree changes a sign



(a) (b)

Fig. 1. Dependence of spontaneous radiation polarization degree P on (a) quantum energy $h\nu$ (at $\Delta F = 1.555$ eV) and (b) quasi-Fermi level difference ΔF (at $h\nu = 1.4797$ eV, $\lambda = 828.2$ nm).

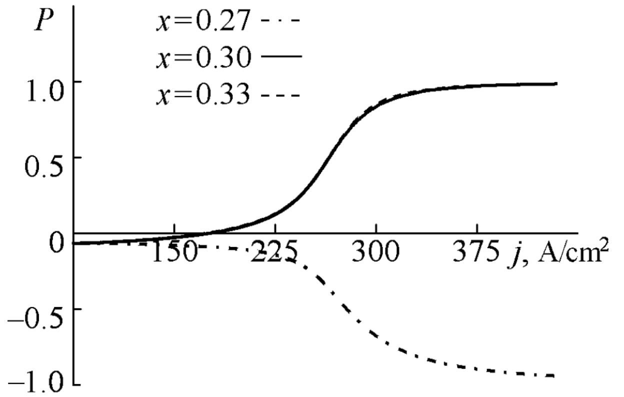


Fig. 2. Dependence of the polarization degree P on the pump current density j at various values of x.

at frequencies close to the initial optical transitions depending on the given value of x (Fig. 1(b)).

In Fig. 2 the dependences of the degree of radiation polarization P on the pump current density j are presented. As it was mentioned above, as x increases, the shift of the electron and hole subband levels to the high-energy area takes place and as a result the oscillation wave length moves to the short-wave area. Given the loss level, when x is crossing the value of 0.27, a change of the polarization from TM- to TE-type takes place. Besides, a shift of the electron and hole subband levels to the high-energy area leads to a decrease of the density of states in a quantum well, thus the threshold current density increases with x, too (Fig. 3).

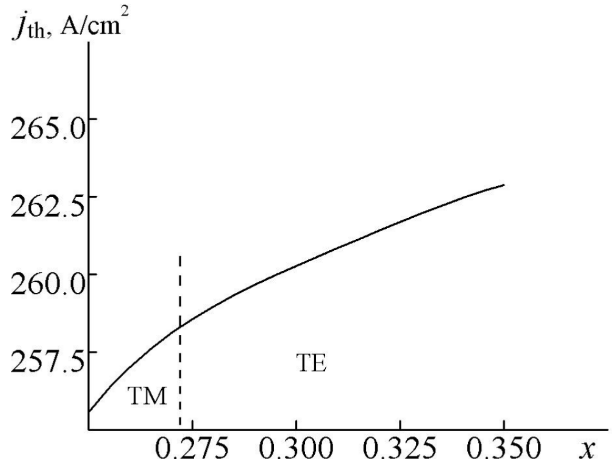


Fig. 3. Dependence of the threshold current density j_{th} on x.

3. Conclusions

On the basis of numerical modelling of polarization degree of spontaneous and stimulated radiation of quantum-well heterostructure, it is possible to make the following conclusions. The change of polarization degree of spontaneous radiation P, depending on an energy of the emitted quantum $h\nu$ at switching of emission transitions between heavy and light hole subbands, occurs step-wisely. Variations of the composition of barrier layers of heterostructure qualitatively do not influence the polarisation of spontaneous radiation. In an oscillating mode, by varying the molar fraction of aluminium in barrier layers of quantum-well heterostructures, semiconducting laser emiters with the specified polarisation type (TE or TM) at an optimum value of the generation threshold can be obtained.

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BARJERINIŲ SLUOKSNIŲ SRITIES SUDĖTIES ĮTAKA KVANTINIŲ DUOBIŲ HETEROLAZERIO SPINDULIUOTĖS POLIARIZACIJOS CHARAKTERISTIKOMS

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Santrauka

Tiriama kvantinių duobių heterosandarų barjerų bangolaidinių sluoksnių komponentinės sudėties įtaka savaiminės ir priverstinės spinduliuotės poliarizacijos laipsniui GaAs–Al_xGa_{1-x}As sistemoje. Parodoma, kad fiksuotam x dažnių srityje, artimoje optiniams šuoliams, įvyksta savaiminės spinduliuotės poliarizacijos laipsnio ženklo pokytis. Priklausomai nuo bangolaidinių sluoksnių komponentinės sudėties, osciliuojančioje modoje yra galima visiškai poliarizuotos TE ar TM tipo spinduliuotės generacija.