MODULATION OF THE DIRECTION OF RADIATION EMITTED BY AN InAs/GaAs HETEROLASER WITH InAs QUANTUM DOTS UNDER THE INFLUENCE OF ACOUSTIC WAVE

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A theoretical model describing the modulation of a direction of radiation emitted by an InAs/GaAs heterolaser with InAs quantum dots under the influence of an acoustic wave has been developed. The character of the dependences of the emission deviation angle on the acoustic wave frequency and the geometric sizes of quantum dots has been determined.

1. Introduction

Future progress in the development of heterolasers is connected with the application of structures with quantum dots (QDs) in their active region [1, 2]. Semiconducting heterostructures InAs/GaAs with InAs QDs have a high quantum yield of photoluminescence, being a promising material for the creation of lasers in the near infrared spectral region [1, 3]. QD-based lasers demonstrate considerably better properties as compared with lasers based on quantum wells. The former have a higher laser gain, they are completely insensible to the lattice temperature, and the quantum energy of radiative recombination for them is much easier to be controlled [4]. The properties of those lasers were substantially improved owing to the engaging of vertically tunnel-coupled QDs [2, 5]. In Fig. 1,*a*, the diagram of the active region in a heterolaser containing InAs QDs in the GaAs matrix is shown [6]. Such lasers are, as a rule, surface-emitting lasers with the resonator length of several wavelengths [6].

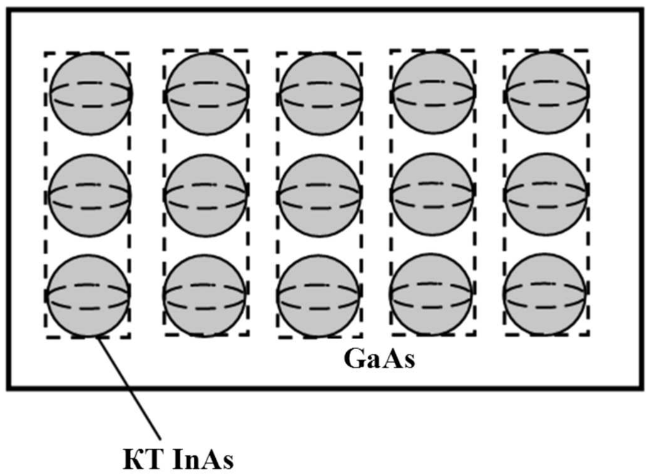

Fig. 1. Diagram of the active region of an InAs/GaAs heterolaser with InAs quantum dots

Sources of infrared radiation, which can quickly change the oscillation frequency and the emission direction, are important elements of high-resolution laser spectroscopy and optical communication systems [5, 7, 8].

Elastic deformations in the material of a heterostructure are an important factor that affects the spectral characteristics of a heterolaser, in particular, the state of light polarization [9] and the emission direction [8].

In this work, the theory of emission direction modulation under the influence of an acoustic wave has been developed for a heterolaser based on quantum dots. An acoustic wave, which is a source of elastic periodic nonuniform deformation, gives rise to a periodic variation in the components of the tensor of dielectric permittivity for the material of the heterostructure. Hence, the acousto-optical interaction invokes not only variations of the refractive index in time, but also its non-uniform spatial distribution in the direction perpendicular to the resonator. That is why the heterolaser emission direction changes in time as well.

2. Model

Consider an InAs/GaAs nanoheterosystem with stressed InAs quantum dots subjected to the influence of an acoustic wave (Fig. 2). The local surface stress induced by QDs in the multilayered structure is accumulated and, as a consequence, manifests itself in the form of a columnar arrangement of islands (QDs), the phenomenon being observed for InAs/GaAs [10]. Therefore, this system, which is the active region of an optical resonator, can be presented in the form of a cylindrical GaAs matrix with the base radius R_1, which includes a cylinder with the base radius equal to the QD radius R_0. The height of the inner cylinder L is equal to the resonator length (Fig. 2). The cylinder axis coincides with the optical emission direction in the absence of an acoustic wave, and the angle $\alpha(t)$ is the angle, by which the heterolaser emission direction deviates under the action of a non-uniform deformation created by an acoustic wave.

Since the lattice constant of the grown material InAs ($a_1 = 0.608$ nm) is larger than that of the GaAs matrix ($a_2 = 0.565$ nm), InAs undergoes the squeezing, and GaAs undergoes the stretching at the heteroepitaxial growth of InAs on the GaAs layer in the pseudomorphic growth limits. Therefore, there emerges a deformation in the InAs/GaAs heterosystem induced by both the action of the acoustic wave and the mismatch between the lattice parameters in contacting materials.

For the determination of components of the strain tensor, it is necessary to find the displacement vectors $\mathbf{u}^{(i)}(t,\mathbf{r})$ (hereafter, $i = 1$ for InAs and 2 for GaAs) in the quantum dot and matrix materials, which satisfy the equation

$$\rho^{(i)}\frac{\partial^2 u_i^{(i)}}{\partial t^2} = \sum_j \frac{\partial \sigma_{ij}^{(i)}}{\partial x_j}, \tag{1}$$

where $\rho^{(i)}$ is the density of the i-th material;

$$\sigma_{ij}^{(i)} = K^{(i)}\sum_k \xi_{kk}^{(i)}\delta_{ij} + 2\mu^{(i)}\left(\xi_{ij}^{(i)} - \delta_{ij}\frac{1}{3}\sum_k \xi_{kk}^{(i)}\right) \tag{2}$$

are components of the stress tensor for the i-th material; $K^{(i)}$ and $\mu^{(i)}$ are the corresponding bulk and shear, respectively, moduli; and

$$\xi_{ij}^{(i)} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{3}$$

are the strain tensor components. We seek the displacement vector $\mathbf{u}^{(i)}(t,\mathbf{r})$ as a sum of two terms, $\mathbf{u}^{(i)}(t,\mathbf{r}) = \mathbf{u}_l^{(i)}(t,\mathbf{r}) + \mathbf{u}_T^{(i)}(t,\mathbf{r})$, the latter satisfying the conditions

$$\operatorname{rot}\mathbf{u}_l^{(i)}(t,\mathbf{r}) = 0,\ \operatorname{div}\mathbf{u}_T^{(i)}(t,\mathbf{r}) = 0.$$

As a result, we obtain

$$\Delta\mathbf{u}_l^{(i)} = \frac{1}{c_l^{(i)2}}\frac{\partial^2 \mathbf{u}_l^{(i)}}{\partial t^2}, \quad \Delta\mathbf{u}_T^{(i)} = \frac{1}{c_T^{(i)2}}\frac{\partial^2 \mathbf{u}_T^{(i)}}{\partial t^2}, \tag{4}$$

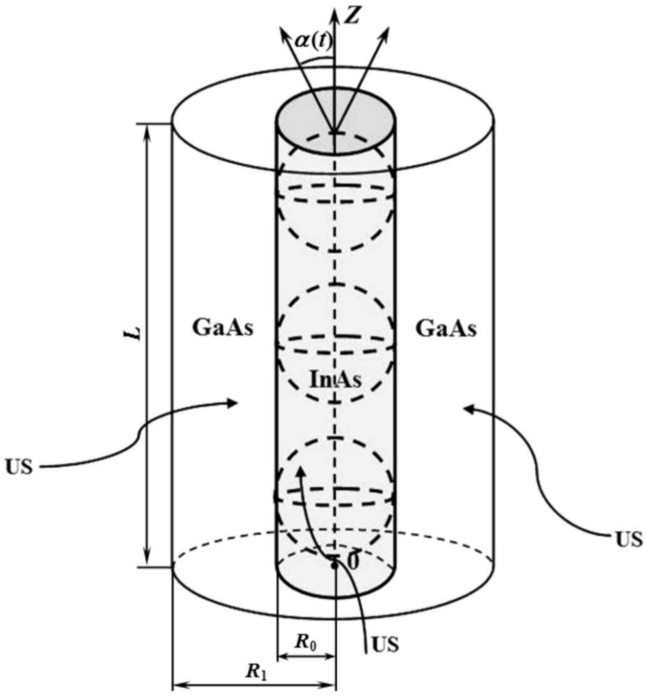

Fig. 2. Model of an InAs/GaAs heterostructure with vertically tunnel-coupled InAs QDs

where $c_l^{(i)} = \sqrt{\frac{3K^{(i)}+4\mu^{(i)}}{3\rho^{(i)}}}$ and $c_T^{(i)} = \sqrt{\frac{\mu^{(i)}}{\rho^{(i)}}}$ are the longitudinal and transverse, respectively, velocities of acoustically induced vibrations in the quantum dot or matrix substance.

The transverse acoustic wave – $\mathbf{u}_T^{(i)}$ in Eq. (4) – does not change the volume [11], because $\operatorname{div}\mathbf{u}_T^{(i)}(t,\mathbf{r}) = 0$. The propagation of a longitudinal wave is accompanied by the expansion and the squeezing of the volume.

We consider elastic vibrations in the heterosystem with quantum dots against the background of static stresses, which arise owing to a parameter mismatch between the lattices of contacting materials. Let the displacement look like

$$\mathbf{u}_l^{(i)}(\mathbf{r},t) = \mathbf{u}_0^{(i)}(\mathbf{r}) + \mathbf{u}_{1l}^{(i)}(\mathbf{r},t), \tag{5}$$

where $\mathbf{u}_0^{(i)}(\mathbf{r})$ is the static displacement in the quantum dot or matrix material, which arises owing to the mismatch between the lattice parameters of contacting materials. In this work, we calculate the heterolaser emission deviation angle. Therefore, we confine the consideration to the calculation of displacement components $\mathbf{u}_{1l}^{(i)}(\mathbf{r},t)$ in the quantum dot and matrix materials caused by the action of an acoustic wave.

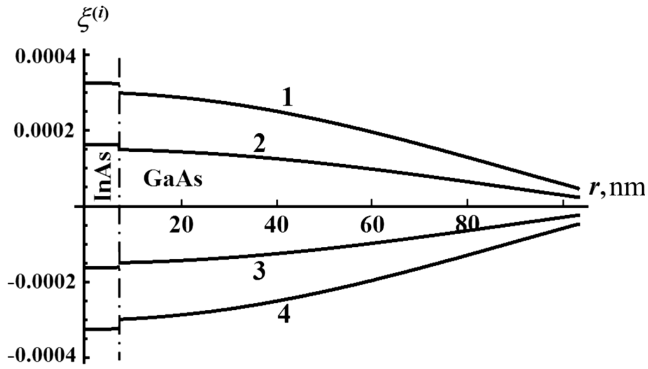

Fig. 3. Spatial distributions of the uniform deformations $\xi(r)$ in the QD and matrix materials at various time moments, $\omega t = \frac{\pi}{2}$ (1), $\frac{\pi}{6}$ (2), $\frac{7\pi}{6}$ (3), and $\frac{3\pi}{2}$ (4)

For an axially symmetric system, the radial stress looks like

$$\sigma_{rr}^{(i)} = \left(K^{(i)} + \frac{4}{3}\mu^{(i)}\right)\frac{\partial u_r^{(i)}}{\partial r} + \left(K^{(i)} - \frac{2}{3}\mu^{(i)}\right)\frac{u_r^{(i)}}{r}. \quad (6)$$

Changing to the scalar potential $\varphi^{(i)}$, using the formula $\mathbf{u}_{1l}^{(i)} = \boldsymbol{\nabla}\varphi^{(i)}$, and taking Eq. (5) into account, we can write Eq. (4) as follows:

$$\Delta\varphi^{(i)} = \frac{1}{c_l^{(i)2}}\frac{\partial^2\varphi^{(i)}}{\partial t^2}. \quad (7)$$

The solution of Eq. (7) is determined in each region of the heterostructure with regard for the boundary conditions

$$\begin{cases} \sigma_{rr}^{(1)}(t)\left|_{r=R_0}\right. = \sigma_{rr}^{(2)}(t)\left|_{r=R_0}\right. ; \\ u_r^{(1)}(t)\left|_{r=R_0}\right. = u_r^{(2)}(t)\left|_{r=R_0}\right. ; \\ \sigma_{rr}^{(2)}(t)\left|_{r=R_1}\right. = -\sigma_{us}\sin\omega t. \end{cases} \quad (8)$$

The last boundary condition in system (8) determines the influence of the acoustic wave on the stressed state of the nanosystem as the action of a periodic driving force with frequency ω. Here, σ_{us} is the amplitude of the mechanical stress created by an acoustic wave at the matrix surface. The directions of this external periodic force and the elastic force that arises in the nanoheterosystem under its influence are opposite to each other at any moment, which is responsible for the sign choice in the second equation of system (8).

Therefore, in view of Eqs. (6)–(8) and the relation $u_r^{(i)} = \frac{\partial\varphi^{(i)}}{\partial r}$, we obtain the following expressions for the radial components of displacement vectors in the quantum dot and the matrix:

$$u_r^{(1)}(r,t) = C_1\frac{\omega}{c_l^{(1)}}J_1\left(\frac{\omega r}{c_l^{(1)}}\right)\sin\omega t, \quad (9)$$

$$u_r^{(2)}(r,t) = C_2\frac{\omega}{c_l^{(2)}}J_1\left(\frac{\omega r}{c_l^{(2)}}\right)\sin\omega t +$$

$$+ C_3\frac{\omega}{c_l^{(2)}}Y_1\left(\frac{\omega r}{c_l^{(2)}}\right)\sin\omega t, \quad (10)$$

where J_1 and Y_1 are the Bessel functions of the 1-st and 2-nd kinds, respectively. The constants C_1, C_2, and C_3 are determined from the boundary conditions (8). Solution (9) was selected to provide its regularity at the point $r = 0$.

The components of the strain tensors for the quantum dot and matrix materials are

$$\xi_{rr}^{(i)} = \frac{\partial u_r^{(i)}}{\partial r^{(i)}},\ \ \xi_{\varphi\varphi}^{(i)} = \frac{u_r^{(i)}}{r^{(i)}},\ \ \xi_{zz}^{(i)} = -\frac{\nu^{(i)}}{1-\nu^{(i)}}\left(\xi_{rr}^{(i)} + \xi_{\varphi\varphi}^{(i)}\right),$$

$$\xi^{(i)} = \mathrm{Sp}\xi^{(i)} = \xi_{rr}^{(i)} + \xi_{\varphi\varphi}^{(i)} + \xi_{zz}^{(i)}, \quad (11)$$

where $\nu^{(i)}$ are Poisson's ratios for the quantum dot and matrix materials.

3. Modulation of the direction of radiation emitted by a heterostructure with quantum dots

Consider the propagation of a light beam in an InAs/GaAs heterostructure with InAs quantum dots subjected to an axially symmetric deformation under the action of an acoustic wave (Fig. 2). Figure 3 illustrates the results of calculations for the spatial distribution of the uniform deformation in the material of InAs/GaAs heterostructure with InAs quantum dots at various time moments for an acoustic wave frequency of 10^9 Hz. The calculations were carried out using the following parameter values [12]: $R_1 = 100$ nm, $K^{(1)} = 0.58$ Mbar, $\mu^{(1)} = 0.19$ Mbar, $K^{(2)} = 0.79$ Mbar, $\mu^{(2)} = 0.33$ Mbar, $\rho^{(1)} = 5680$ kg/m^3, $\rho^{(2)} = 5320$ kg/m^3, $\nu^{(1)} = 0.352$, $\nu^{(2)} = 0.318$, and $\sigma_{us} = 10$ bar.

The influence of the acoustic wave gives rise to the emergence of a deformation gradient and, hence, a gradient of the refractive index in the direction perpendicular to the optical resonator. As is seen from Fig. 3, not only the magnitude of deformation gradient, but also its direction change during the acoustic wave period. Therefore, it is evident that the trajectory of a light beam changes in time. In a non-uniform medium, it is described by the differential equation

$$\frac{d^2r}{dz^2} = \frac{1}{n^{(i)}}\frac{dn^{(i)}}{dr} \tag{12}$$

with the boundary conditions

$$\begin{cases} r(z=0) = r_0; \\ \dfrac{dr(z=0)}{dz} = 0. \end{cases} \tag{13}$$

The first condition determines the initial distance r_0 of the beam from the symmetry axis, the second one specifies that, in the plane $z = 0$, the beam propagates in parallel to the axis OZ.

Taking into account that the refractive index is determined by the relation $n^{(i)}(r,t) = \sqrt{\varepsilon^{(i)}(r,t)}$, where $\varepsilon^{(i)}(r,t)$ is the dielectric permittivity of a heterostructure material, Eq. (12) can be rewritten in the form

$$\frac{d^2r}{dz^2} = \frac{1}{2\varepsilon_0^{(i)}}\frac{d\varepsilon^{(i)}}{dr}, \tag{14}$$

where $\varepsilon_0^{(i)}$ is the dielectric permittivity of the homogeneous material in the heterostructure.

The dielectric permittivity $\varepsilon^{(i)}(r,t)$ of the QD material, which changes in time under the action of the acoustic wave, can be presented in the form [13]

$$\varepsilon^{(i)}(r,t) = \varepsilon_0^{(i)} + a^{(i)}\xi^{(i)}(r,t), \tag{15}$$

where $a^{(i)} < 0$ are elastooptical constants.

With regard for Eqs. (9), (11), and (15) in the approximation $\frac{\omega r}{c_l^{(1)}} \ll 1$, we can write Eq. (14) describing the beam path in the internal cylinder (see Fig. 2) in the form

$$\frac{d^2r}{dz^2} = \frac{1}{4\varepsilon_0^{(1)}}a^{(1)}\frac{1-2\nu^{(1)}}{1-v^{(1)}}C_1\left(\frac{\omega}{c_l^{(1)}}\right)^4 r\sin\omega t. \tag{16}$$

The solutions of the differential equation (16) obtained with regard for the boundary conditions (13) are

$$r(z,t) = r_0\cos\sqrt{|q|\sin\omega t}z,$$

$$2\pi n \le \omega t \le (2n+1)\pi, \;\; n = 0,1,2,... \tag{17}$$

$$r(z,t) = r_0\mathrm{ch}\sqrt{q\sin\omega t}z,$$

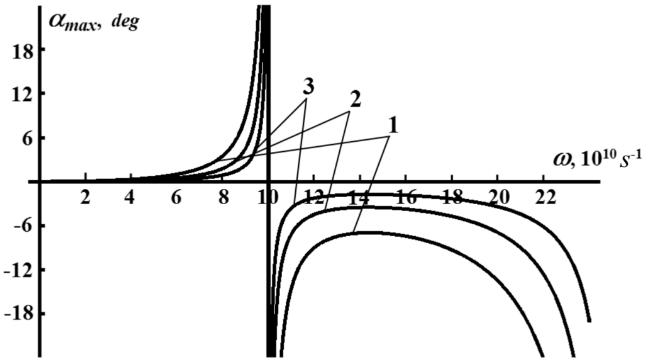

Fig. 4. Dependences of the deviation angle amplitude of emission from an InAs/GaAs heterolaser with InAs QDs on the acoustic wave frequency for various QD dimensions: R_0 = 3 (*1*), 6 (*2*), and 9 nm (*3*)

$$(2n+1)\pi \le \omega t \le 2\pi(n+1), \tag{18}$$

where

$$q = \frac{a^{(1)}}{4\varepsilon_0^{(1)}}\frac{1-2v^{(1)}}{1-v^{(1)}}C_1\left(\frac{\omega}{c_l^{(1)}}\right)^4.$$

At the output of the optical resonator with length L, the emission deviation angle amplitude $\alpha_{\max}$ from the initial propagation direction is described by the formula

$$\mathrm{tg}\,\alpha_{\max} = \frac{dr(z=L)}{dz} = r_0 q(\omega, R_0)L,$$

or, taking into account that $\sqrt{|q|}L \ll 1$, by the formula

$$\alpha_{\max} \approx r_0 q(\omega, R_0)L. \tag{19}$$

Hence, the beam deviation angle is proportional to the distance between the beam and the axial axis. Therefore, an optical resonator subjected to the action of an acoustic wave behaves itself as a lens (within a half-period as a collective and within the other half-period as a diverging one) with the focal length $f = \pm\left(|q|\,L\sqrt{|\sin\omega t|}\right)^{-1}$, which changes in time.

In Fig. 4, the dependences of the deviation angle amplitude for the radiation emitted by a heterolaser based on InAs/GaAs with InAs quantum dots on the acoustic wave frequency are depicted for various values of quantum dot radius ($\varepsilon_0^{(1)} = 12.8$, $L = 2$ μm, $r_0 = 1$ μm).

The acousto-optical constant $a^{(i)}$ can be determined experimentally. While calculating, the constant $a^{(i)}$ was so selected that the angle deviation amplitude for the radiation emitted by an InAs/GaAs heterolaser with InAs quantum dots 3 nm in radius should be 3° at an acoustic wave frequency of 10^{10} Hz.

The emission direction modulation amplitude is governed by the deformation gradient, which depends on both the acoustic wave frequency and the deformation amplitude. If the acoustic wave frequency ω increases from 10^7 s^{-1} to 6×10^{10} s^{-1}, the angle deviation amplitude grows as $\alpha_{\max} \sim \omega^3$. The further increase of the acoustic wave frequency is accompanied by a nonmonotonous variation of the heterolaser-emission deviation angle, with a maximum located at the frequency $\omega \approx 10^{11}$ s^{-1}, which is associated with the growth of a deformation amplitude in the QD material. The growth of a deformation occurs as a result of the approach of the acoustic wave frequency to the characteristic vibration frequency of QD atoms [14]. The divergence of the solution at $\omega \approx 10^{11}$ s^{-1} is connected with the neglect of the vibration damping in the elastic medium.

If the acoustic wave frequency ω falls within the interval from 10^7 to 5×10^{10} s^{-1}, the amplitude of the directed emission modulation for a InAs/GaAs heterolaser with InAs QDs practically does not depend on the QD dimensions. At higher acoustic wave frequencies, $\omega > 5 \times 10^{10}$ s^{-1}, a monotonous increase of the deviation angle is observed for a reduction of the QD radius. It can be explained by the fact that quantum dots with smaller dimensions are more sensitive to the influence of external mechanical stresses.

4. Conclusions

A theoretical model for the direction modulation of emission from an InAs/GaAs heterolaser with InAs quantum dots under the influence of an acoustic wave has been developed. The increase of the acoustic wave frequency was found to result in a monotonous growth of the deviation angle amplitude of the emission direction according to the law $\alpha_{\max} \sim \omega^3$ in the range 10^7 s^{-1} $< \omega < 5 \times 10^{10}$ s^{-1}. At frequencies $\omega > 5 \times 10^{10}$ s^{-1}, this dependence has a nonmonotonous character. As the QD dimensions become smaller, the direction modulation amplitude for the emission from an InAs/GaAs heterolaser grows, which is explained by an increase of the deformation gradient in the QD material.

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МОДУЛЯЦІЯ НАПРЯМКУ ВИПРОМІНЮВАННЯ ГЕТЕРОЛАЗЕРА З КВАНТОВИМИ ТОЧКАМИ InAs ПІД ВПЛИВОМ АКУСТИЧНОЇ ХВИЛІ

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Р е з ю м е

Побудовано теоретичну модель процесу модуляції напрямку випромінювання гетеролазера InAs/GaAs з квантовими точками InAs під впливом акустичної хвилі. Встановлено характер залежності амплітуди кута відхилення гетеролазера від частоти акустичної хвилі та геометричних розмірів квантової точки.