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PHYSICS OF SEMICONDUCTOR DEVICES

Acoustoelectron Interaction in Quantum Laser Heterostructures

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Abstract—The effect of ultrasonic deformation on the polarization properties of semiconductor quantum-well laser radiation is experimentally and theoretically studied at room temperature. It is shown that the observed rotation of the polarization plane is caused by mixing of the light- and heavy-hole levels in the quantum well. Data on the splitting energy of these levels are obtained. The unique capability of the ultrasonic technique for obtaining data on the value and distribution of technological strains in the heterostructure is shown.

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1. INTRODUCTION

Currently, of great interest are the phenomena caused by modulation of the energy and wave functions of electron states of semiconductor nanostructures by external alternating strains, since this makes possible the direct detection of spectroscopic effects accompanying such modulation [1–7]. In [1, 2], the results of studying the optical properties of semiconductor structures in the presence of acoustic solitons at liquid-helium temperature are presented. However, these studies are rather exclusive in view of very difficult experiments.

Previously, we were the first to begin studies of ultrasonic deformation on the spectral characteristics of the generated radiation of InGaAsP/InP heterolasers [3–7] at room temperature. The main results of the studies are as follows.

(i) Demonstrating that rapid and continuous periodic tuning of the heterolaser spectrum in the studied structures, whilst retaining the spectral distribution and a constant emission intensity, can be performed.

(ii) Revealing that the contributions of acousto-electron and acousto-optic interactions are close in efficiency and operate in-phase.

(iii) Revealing the possibility of controlling the direction of the generated radiation.

Recently, our attention has been directed to a new aspect of the deformation effect of ultrasonic waves [8, 9], i.e., the effect of ultrasonic deformation on the fine spectrum of quantum states of carriers in the active region of the laser heterostructure. It is known that strong spin-orbit coupling in most cubic semiconductors forms the valence band and determines the existence of levels in the quantum well, which differ in their projection of the total hole angular momentum on the quantization axis [10]. Elastic mechanical stresses change the values of the quantum-size splittings and mix heavy- and light-hole states; as a result, both the frequency and polarization characteristics change. The introduction of alternating strain can cause the additional splitting of light- and heavy-hole levels and corresponding changes in the radiation polarization characteristics with the periodicity of ultrasonic deformation. Studying the effect is of interest not only from the fundamental point of view, but also as it offers new opportunities for use in data processing devices.

We were the first to begin investigation into the effect of ultrasonic deformation on the polarization characteristics of InGaAsP/InP heterolaser radiation at room temperature. Such experiments are attractive by their relative simplicity and the feasibility of uniaxial deformation in the quantum well of the active (laser) heterostructure at various orientations with respect to the quantization axis. In this case, ultrasonic studies allow real-time observation of the processes.

2. EXPERIMENTAL

As objects of study, we used InGaAsP/InP structures operating at room temperature in the pulsed mode with a duration of up to 3 μs at an emission wavelength of 1.48 μm. The threshold current was ~35 mA; the operating currents were varied from the threshold to two times its value. The space–energy diagram of the structure and its detailed parameters are given in [4]. A diagram of the energy levels in the quantum well of the active layer of the heterostructure and the experimental configuration are shown in Fig. 1.

To perform the studies, an experimental setup was developed, whose block diagram is shown in Fig. 2. Alternating elastic strain was induced by exciting pulses of longitudinal ultrasonic waves up to 3 μs in duration in the frequency range $F = 5–20$ MHz using resonant piezoelectric ceramic plates. The transducer

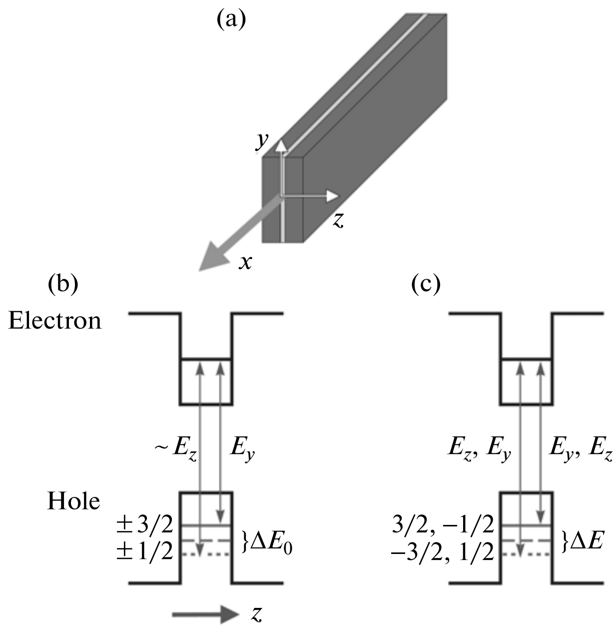

Fig. 1. (a) Experimental configuration, (b) optical transitions in an unstrained well, (c) optical transitions in a strained well. E_z and E_y are electric-field components of the emitted wave; ±3/2 and ±1/2 are the projections of the total hole momentum onto the growth axis.

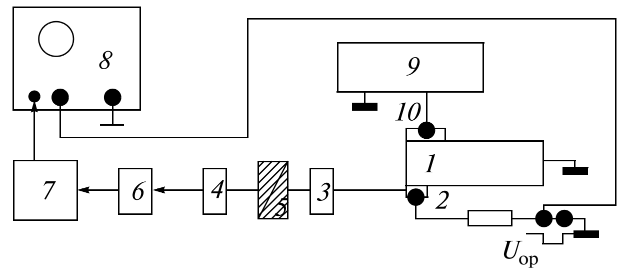

Fig. 2. Block diagram of the setup: (*1*) metal substrate, (*2*) laser heterostructure, (*3*, *4*) focusing systems, (*5*) polarization analyzer, (*6*) photodiode, (*7*) amplifier, (*8*) oscilloscope, (*9*) microwave generator, and (*10*) piezoelectric transducer.

size of 0.7 × 1.2 mm (dictated by the necessity of achieving the maximum sound intensity) is closest to the planar size of the heterostructure. Due to this, an intensity of up to 300 W/cm^2 (a strain amplitude up to 1.1×10^{-4}) was achieved. The wave propagates perpendicular to the active layer of the heterostructure. In this case (as before), all experiments were performed in the configuration of an infinitely narrow laser cavity in comparison with the acoustic wavelength Λ_s, $a \ll \Lambda_s$. This approximation is consistent with the conditions of the present experiments: $a \approx 6$ μm, $\Lambda_s \geq 250$ μm. Such a configuration makes it possible to implement the mode of almost constant spatial distribution of the elastic strain at each time point. This means that the strain $\varepsilon(t)$ varies in time with the periodicity of the acoustic wave, $S \approx S_0 \sin\Omega t$, $\Omega = 2\pi F$. The duration and delay of the sound pulses could vary to provide various modes of total or partial overlapping with the operating-current pulse of the heterolaser. To record the generated radiation, a preliminarily collimated beam passed through a polarization analyzer (Glan prism) was focused and detected by fast photodiodes with a photocurrent rise time of no longer than 5 ns. The electric signal from the photodiode was sent to a broadband amplifier and was then visualized using an oscilloscope (with a band of 200 MHz). The distribution of the radiation's spectral intensity was measured using a Fabry–Perot etalon (with a resolution to tenths of Å) in the wavelength range of ±9 Å with respect to the position of the intensity peak [5, 6]. To broaden the dynamic range to ±300 Å (±17 meV), an acoustooptic filter based on TeO_2 was used [11]. The measurements were performed in the quasi-single-frequency lasing mode [5, 6] in the operating current range from the threshold to twice its value. The width of the amplification line was up to 0.2 meV.

3. EXPERIMENTAL RESULTS

The shape of the radiation pulse in the equilibrium state is close to rectangular (Fig. 3a, curve *1*). The dependence of the radiation intensity on the angle α (α is the angle of deflection of the analyzer-output-polarization direction from the polarization direction of the maximum laser radiation intensity, which coincides with the *y* axis direction with an accuracy of up to 1°) is well described by the dependence $I = I^0\cos^2\alpha = I_0(1 + \cos 2\alpha)$, $I_0 = I^0/2$ (Fig. 4a). This fact indicates that the laser under study provides linear polarization in a wide range of variations in the operating current (I_{op}).

The introduction of sound leads to the appearance of an ac component with acoustic-wave periodicity (Fig. 3a, curve *2*), and a clear change in the modulation phase to the opposite one is observed as the analyzer is rotated by 90° with respect to the direction of maximum intensity (Fig. 3b, curves *1* and *2*).

The ac signal amplitude is ~0.5 V. However, since the ac signal frequency is equal to the sound frequency, this contribution can be easily separated with high accuracy and independently analyzed. The angular dependences of the amplitude $I_{\sim}$ of this component are presented in Fig. 4b. An analysis of the experimental data shows that the angular dependences of the dc signal and the ac-signal amplitude are well approximated by the expressions

$$I_{=} = A_{=}(1 + \cos 2\alpha), \quad (1)$$

$$I_{\sim} = A_{\sim}(1 + \cos 2\alpha) + B_{\sim}\sin 2\alpha, \quad (2)$$

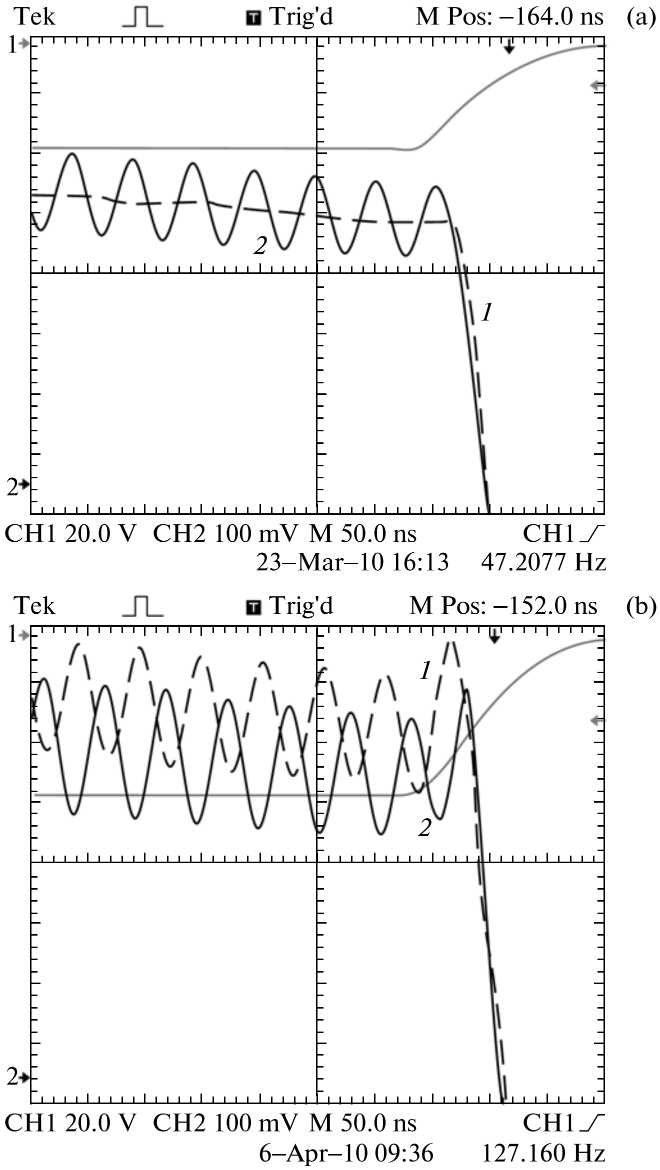

Fig. 3. Oscillograms; upper and lower beams show the operating current and radiation-intensity pulses, respectively: (a) equilibrium radiation (*1*) and in the presence of sound (*2*); (b) $\alpha = 84$ deg (*1*), $\alpha = 96$ deg (*2*).

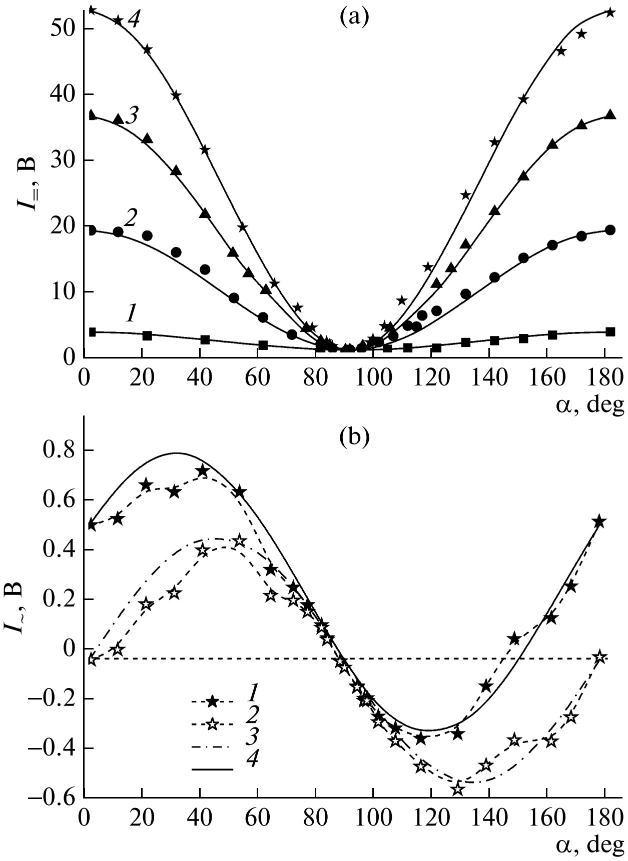

Fig. 4. Angular dependences of the intensities: (a) equilibrium radiation $I_=$, symbols refer to experimental data at (*1–4*) I_{op}/I_{th} = 1.04, 1.25, 1.6 and 1.9, respectively, the solid curves refer to approximations by the dependence $\cos^2\alpha$; (b) amplitudes of the alternating radiation component ($I_{op}/I_{th} = 1.9$), symbols refer to experimental data for (*1*) $I_\sim$, (*2*) $[I_\sim - A_\sim(1 + \cos 2\alpha)]$; line refers to calculated data: (*3*) dependence $B_\sim \sin 2\alpha$ and (*4*) expression (2).

where $A_=$, $A_\sim$, and $B_\sim$ depend on the current and are 25.75, 0.27, and 0.5 V, respectively, at $I_{op}/I_{th} = 1.9$. The total intensity can be written as

$$I = I_= + I_\sim$$
$$= (A_= + A_\sim)\left(1 + \cos 2\alpha + \frac{B_\sim}{A_= + A_\sim}\sin 2\alpha\right). \quad (3)$$

From relation (3), we can draw two main conclusions.

(i) In the presence of ultrasonic deformation, modulation of the radiation intensity is observed.

(ii) Linear polarization of the radiation is retained. The additional term $\frac{B_\sim}{A_= + A_\sim}\sin 2\alpha$ determined by variable strain appears due to radiation-polarization rotation by the angle $\varphi_\sim$,

$$\sin 2\varphi_\sim = \frac{B_\sim}{(A_= + A_\sim)},$$

$$\varphi_\sim \approx \frac{B_\sim}{2(A_= + A_\sim)} \approx 10^{-2} = 0.55 \text{ deg}.$$

This means that the rotation angle varies within 1.1 deg for half the acoustic wave period. The acoustic-wave periodicity is inherent to both effects. It should be noted that the factor in front of $\cos 2\alpha$ should be $\cos 2\varphi_\sim = 1 - 2\sin^2\varphi_\sim$ in the case of polarization-plane rotation. In the case under study (small rotation angle), the correction $2\sin^2\varphi_\sim$ is the second-order of smallness appearing at the limit of measurement accuracy; with this accuracy, it should be thought that the coefficient in front of $\cos 2\alpha$ in (3) is unity.

4. THEORETICAL ANALYSIS OF THE RESULTS OBTAINED

As a result of the performed experiment, the dependences of the laser-radiation intensity on the polarizer rotation angle with and without controlled ultrasonic deformation ($I_=$ and I, respectively) were obtained. We note that the signal I is not informative for estimating strains and their effect on the structures under study, since the difference of $I_=$ from it is small in comparison with $I_=$. However, the use of differential techniques allows high-accuracy measurements of the difference between I and $I_=$, which forms the signal $I_\sim$.

We calculated the dependence of the signals $I_\sim$ and $I_=$ on the parameters of the structure under study. The active region represents two quantum wells separated by a barrier [3]. It can be shown that, at given quantum-well thicknesses and barrier heights and widths, the quantum wells can be considered uncoupled and, for analysis of the radiation, only one of them can be analyzed. In the calculation, the wells were considered as infinitely deep, since the ground-level position in them differs insignificantly from that in a well with infinitely high walls. The calculation shows that the degree of polarization significantly differs from unity in the case of the significantly nonzero wave vector k of carriers in the quantum-well plane. Since the experimentally observed degree of polarization is close to 100%, we further suppose that $k \approx 0$. Radiative transitions in the structure under study occur from the conduction-band to the valence-band levels corresponding to heavy holes, which results in one hundred-percent polarization of the output radiation along the y axis. In the case of weak strains in the system, light-hole states are mixed with heavy-hole states, and the value of the splitting between the energy sublevels and the quantum-well thickness change. The transitions from the conduction band to light-hole states are characterized by radiation polarization along the z axis. As a result of the weak admixture of light-hole states, rotation of the polarization plane becomes possible whilst retaining a degree of polarization equal to unity due to strain. Studying the waveguide properties of the structure shows that both TE and TM modes correspond to the observed wavelength, hence, the waveguide does not impose limitations on the polarization properties of the radiation.

The spectrum and hole wave functions in the quantum well were calculated in detail within perturbation theory, taking into account strain fields. The Hamiltonian H of carriers in cubic semiconductors at the top of the Γ_8-type valence band, taking into account the strain at the zero wave vector k in the quantum-well plane, in the structure configuration under consideration is given by [10]

$$H = \begin{pmatrix} f & h & j & 0 \\ h^* & g & 0 & j \\ j^* & 0 & g & -h \\ 0 & j^* & -h^* & f \end{pmatrix}, \tag{4}$$

where

$$f = a\mathrm{Sp}\hat{\mathscr{E}} - \frac{3}{2}b\varepsilon'_{zz} + (A-B)\hat{\mathbf{k}}_Z^2,$$

$$g = a\mathrm{Sp}\hat{\mathscr{E}} + \frac{3}{2}b\varepsilon'_{zz} + (A-B)\hat{\mathbf{k}}_Z^2,$$

$$h = -d(\varepsilon_{xz} + i\varepsilon_{yz}), \quad j = \sqrt{\frac{3}{2}}b(\varepsilon_{xx} - \varepsilon_{yy}) - id\varepsilon_{xy},$$

$$\mathrm{Sp}\hat{\mathscr{E}} = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}, \quad \varepsilon'_z = \varepsilon_{zz} - \frac{1}{3}\mathrm{Sp}\hat{\mathscr{E}},$$

$$\hat{\mathbf{k}}_Z^2 = \frac{1}{i}\frac{\partial}{\partial Z}.$$

Here, A and B are the Luttinger parameters defining the effective masses of holes in the valence band; ε_{ij} are strain-tensor components; a, b, and d are the strain-potential constants.

As noted above, for simplicity, we considered an infinitely deep rectangular quantum well, which allowed us to obtain analytical expressions for the size quantization energy and the radiation intensity in the presence of strains. The calculation shows that the energy spacing between the main sublevels of light and heavy holes in the case of random deformations is given by

$$\Delta E = 2\sqrt{\left(\frac{\delta}{2} + \langle B\rangle\frac{\pi^2}{c^2}\right)^2 + [d^2(\varepsilon_{yz}^2 + \varepsilon_{xy}^2 + \varepsilon_{xz}^2) + (br)^2]},$$

$$r = -\frac{\sqrt{3}}{2}(\varepsilon_{xx} - \varepsilon_{yy}), \quad \delta = \delta_0 + \delta(t), \tag{5}$$

$$\delta_0 = b[(\varepsilon_{zz} - \varepsilon_{xx}) + (\varepsilon_{zz} - \varepsilon_{yy})],$$

where $\langle B\rangle$ is the parameter expressed in terms of the masses of light and heavy holes as follows: $\langle B\rangle = h^2(m_{hh} - m_{lh})/4m_{hh}m_{lh}$ (for simplicity, we use the spherical approximation to describe the valence-band states) and c is the quantum-well width. In the absence of acoustic deformation, laser radiation is completely linearly polarized along the y axis, and the introduction of ultrasound does not change the polarization type. This circumstance and analysis (5) allow the conclusion that the splitting ΔE is mostly caused by size quantization effects and technological strains δ_0. This means that the internal shear strains ε_{ij}, the asymmetry of longitudinal strains in the quantum-well plane, and the alternating external strains $\varepsilon_{ij}(t)$ should be small,

$$d\varepsilon_{ij},\ br,\ \delta(t) \ll \Delta E \tag{6}$$

and the splitting ΔE can be considered to be

$$\Delta E = \delta_0 + 2\langle B\rangle \frac{\pi^2}{c^2}. \tag{7}$$

We note that in the case of structure compression, the strain $\varepsilon_{zz} < 0$ decreases the splittings; in the case of tension, $\varepsilon_{zz} > 0$, the initial splitting increases.

The ground-state wave functions for the perturbed system were calculated in the second order of the perturbation theory in small parameters (6). Therefore, we can calculate, in relative units of the radiation intensity with polarizations in the y and z directions, and obtain the following expression for the dependence of the radiation intensity on the angle α (reference point on the y axis)

$$I = I_0(1 + C\cos 2\alpha + D\sin 2\alpha), \tag{8}$$

$$I_0 = N\left\{1 + \frac{2br}{\sqrt{3}\Delta E} + \frac{\frac{5}{3}[d^2(\varepsilon_{yz}^2 + \varepsilon_{xy}^2 + \varepsilon_{xz}^2) + (br)^2]}{(\Delta E)^2} - \frac{2br\delta(t)}{3\sqrt{3}(\Delta E)^2}\right\} \tag{8a}$$

$$1 - C^2 - D^2 = \frac{16}{3}(\Delta E)^{-2}[d^2(\varepsilon_{xy}^2 + \varepsilon_{xz}^2) + (br)^2], \tag{8b}$$

$$C = 1 - \frac{8[d^2(\varepsilon_{yz}^2 + \varepsilon_{xy}^2 + \varepsilon_{xz}^2) + (br)^2]}{3(\Delta E)^2}, \tag{8c}$$

$$D = 1/3\frac{4d\varepsilon_{yz}\delta(t)}{\sqrt{3}(\Delta E)^2} - \frac{4d\varepsilon_{yz}}{\sqrt{3}\Delta E} + \frac{8d\varepsilon_{yz}br}{3(\Delta E)^2}, \tag{8d}$$

where N is the coefficient proportional to the matrix element of the momentum operator, calculated for transitions from the conduction band to the valence band. Expression (8) for the total intensity contains a time-independent term and a term varying in time with the ultrasonic frequency. Expression (8b) means that radiation depolarization appears only in the second order according to technological strains. Polarization rotation occurs only due to the shear strain ε_{yz}. In the approximation linear in technological strains, the polarization-plane rotation angle, according to (8d), is $\varphi_= = 2d\varepsilon_{yz}/\sqrt{3}\Delta E$. We recall that α in the experiment is the angle of deflection of the analyze-output-polarization direction from the polarization direction of the maximum laser-radiation intensity, which coincided with the y axis direction with an accuracy up to 1°. From this, we can conclude that $\varphi_=$ does not exceed the measurement error, i.e., $\varphi_= \le 10^{-2}$.

Let us analyze the derived relations under experimental conditions. The longitudinal acoustic wave along the z axis causes a corresponding uniaxial strain ($\varepsilon_{zz}(t) \approx 10^{-4}$). This means that $\varphi_\sim$ is defined by the first term (8d),

$$\varphi_\sim = \frac{2d\varepsilon_{yz}\delta(t)}{\sqrt{3}(\Delta E)^2},$$

where $\delta(t) = 2b\varepsilon_{zz}(t)$. Since it follows from the above estimate that $2d\varepsilon_{yz}/\sqrt{3}\Delta E \le 10^{-2}$, agreement with experimental data ($\varphi_\sim \approx 10^{-2}$) is possible only if $\Delta E \le 0.6$ meV. However, as estimations show, ΔE defined by size quantization, is ~100 meV, which disagrees with the experimental value by two orders of magnitude.

Agreement with the experiment can be achieved assuming that not only the longitudinal component $\varepsilon_{zz}(t)$, but also the shear component $\varepsilon_{yz}(t)$ are excited. Such an assumption is natural, if we consider the transducer configuration (dictated by the necessity of achieving the maximum sound intensity) at which the size along the y axis does not exceed 0.7 mm. Our calculations and experimental modeling show that the shear strain $\varepsilon_{yz}(t) \approx 3 \times 10^{-5}$ appears due to diffraction divergence. Then the rotation angle of the polarization plane due to ultrasound is mostly controlled by the term linear in the strain (8d)

$$\varphi_\sim = \frac{2d\varepsilon_{yz}(t)}{\sqrt{3}\Delta E}.$$

In this case, we can estimate the splitting of hole levels in the quantum well of the structures under study,

$$\text{at} \quad d = 4\ \text{eV}, \quad \Delta E \approx 14\ \text{meV}. \tag{9}$$

This result suggests that, in addition to size quantization, the splitting is significantly affected by internal technological strains; in this case, compressive strains ε_{zz} along the well growth axis are basic and accompanied by tensile strains in the well plane due to elastic properties. Taking 100 meV as the contribution of size quantization to ΔE, using (5) and (7), we can obtain the internal strains caused (9)

$$\text{at} \quad b = 3\ \text{eV}, \quad -(2\varepsilon_{zz} - \varepsilon_{xx} - \varepsilon_{yy}) \approx 3 \times 10^{-2}. \tag{10}$$

Then, from (8a) and (8d), we can obtain the relation for the experimental coefficients $B_\sim$ and $A_\sim$ defining the polarization-plane rotation and the radiation-intensity modulation by ultrasonic deformation,

$$\frac{B_\sim}{A_\sim} = -\frac{6d\varepsilon_{yz}(t)\Delta E}{br\delta(t)}.$$

Using the experimental data, we obtain the estimate for the asymmetry r in the quantum-well plane,

$$r \approx 3 \times 10^{-3}. \quad (11)$$

We note that the crucial role of these strains is associated with the experimental configuration. In the used configuration, in the absence of strain ε_{yz}, even in the presence of other strains, the polarization properties of the radiation remain unchanged, and radiation is linearly polarized along the y axis. The asymmetry in the quantum-well plane, defined by the parameter r is essential, since it is responsible for the experimental value of $A_{\sim}$ for all operating currents.

Expressions (5)–(8) were derived for the transitions to states with $k = 0$ and cannot be applied in analyzing the dependence of $I_{\sim}$ on the degree of supercriticality. An accurate calculation for nonzero values of k can explain this dependence, but it seems cumbersome and is omitted in this paper.

5. CONCLUSIONS

The effect of ultrasonic deformation on the polarization properties of the radiation of a semiconductor quantum-well laser was experimentally and theoretically studied. It was shown that:

(i) Whilst retaining linear polarization, the sound rotates the polarization direction.

(ii) The value of the splitting of hole states in the quantum well of the laser heterostructures under study was determined.

(iii) The unique opportunity of the ultrasonic technique in studying not only the effect of strain on the fine spectrum of states in the quantum well of laser heterostructures, but also in obtaining data on the distribution of technological strains in a heterostructure was shown.

It should be emphasized that the performed fine analysis of the ultrasonic effect is possible only for induced (laser) radiation. The width of the spontaneous-emission spectrum is ~30 meV. This means that both light and heavy holes are involved in radiative transitions in this case. However, lasing in such structures is achieved only between the conduction band and the heavy-hole subband, which is confirmed by the narrow linewidth of lasing in the structures under study [5, 6].

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