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The rotation of the polarization plane of quantum-well heterolasers emission under the ultrasonic strain

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ABSTRACT

The paper is devoted to an acousto-electron effect in the nanodimensional laser heterostructures. The effect results in a modulation of the laser emission intensity as well as in a turn of the emission polarization by the sound strain. Theoretical treatment of the experimental data is presented.

1. Introduction

Recently ultrasonic techniques of controlling spectral and transport properties of semiconductor structures become relevant. Changes in optical properties of microcavities caused by introducing of acoustic solitons are investigated in detail in [1–4]. Photocurrent pump-and-probe measurements in semiconductor devices under the ultrasonic strain are presented in [13]. Quantum-well- and quantum-dot-based laser properties are commonly discussed, and the emission properties are the subject of essential scientific interest [5–8]. The present work combines these matters and devoted to the controlling of quantum well heterolasers emission properties through the introduction of ultrasonic waves in the active region. The ultrasonic strain effect on spectral characteristics of InGaAsP/InP heterolasers was studied [9–13]. The principal results of research in the structures under study are: (a) fast and continuous periodic tuning of laser wavelength can be controlled without changing intensity of emission; (b) possibility of modulation of the laser emission direction by an ultrasonic strain.

In the work we first demonstrate results of straining effect of ultrasonic waves on the fine structure of quantum states of carriers in active region of the heterostructure. Elastic mechanical stresses change the quantum-sized splitting and mix heavy and light hole states [13] that results in changing of frequency and polarization characteristics. Introduction of an alternating strain may lead to additional splitting of heavy and light hole levels and corresponding changes in polarization characteristics of the laser emission with the periodicity of the alternating strain. Study of the effect is not only of the interest from the fundamental point of view but also discovers new possibilities of application in information processing devices.

We have started the studies of ultrasonic strain effect on polarization characteristics of InGaAsP/InP heterolasers at room temperature. These experiments attract not only for relative simplicity but also for the opportunity of realization of uniaxial strain in quantum well of the active heterostructure at different orientations relative to the quantization axis. At the same time ultrasonic researches allow to observe processes in the real-time scale.

2. The experimental techniques

The InGaAsP/InP laser heterostructures have been studied operating at room temperatures at the emission wavelength of 1.48 μm in the operation pulse mode of a duration time up to 3 μs. Threshold current had a value ~35 mA, operating current was changed in the range from threshold value to double threshold value.

The energy diagram of the quantum well of the active region and experiment scheme are illustrated in Fig. 1(a)–(c). The detailed characteristics of the structures and experimental set-up are presented in [10].

The alternating elastic strain was produced introducing longitudinal (bulk) ultrasonic waves with the intensity up to 100 W/cm^2 (strain amplitude ε_0 up to 10^{-4}) in pulse mode. The wave propagation direction is normal to the active region of the heterostructure. At the same time (as it is in early studies) the wavelength is sufficiently greater than the thickness of the active region. This scheme allows us to operate in the regime of almost constant spatial distribution of elastic strain in every moment of

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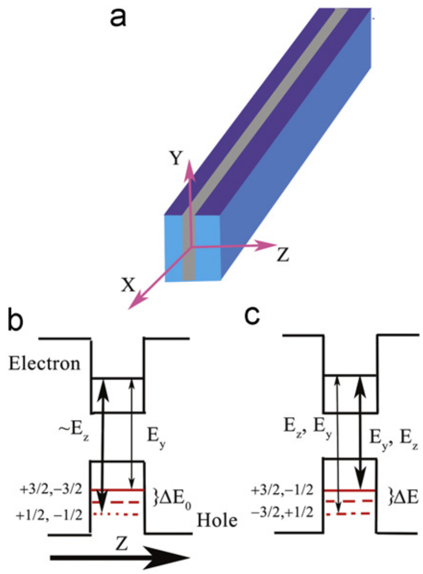

Fig. 1. (Color online) Experiment geometry (a): a laser emission propagates along X; scheme of the energy states in the quantum well of heterestructure active layer; (b) an unsteressed quantum well; (c) a quantum well under the mechanical stresses; Z is the quantization axis.

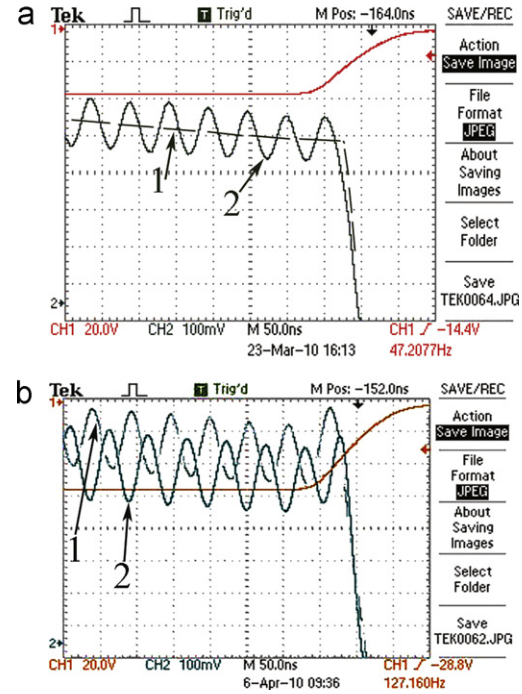

Fig. 2. (Color online) Oscillograms, top and bottom beams i.e., pulses of the operating current and the emission intensity, respectively: (a) (1) equilibrium emission, (2) with the sound strain F=20 MHz., (b) (1) α=84 degrees, (2) α=95 degrees.

time. So the strain changes in time with the periodicity of the sound i.e., $\varepsilon \sim \varepsilon_0 \sin\Omega t$, Ω being the sound frequency.

Duration and delay of ultrasonic pulses may vary in order to provide different regimes of full or partial overlap with the pulse of heterolaser operating current. The laser emission pre-collimated beam was passed through the polarization analyzer (Glan prism), focused and detected by a high frequency photodiode with rise time of photocurrent not more than 5 ns. Signal from photodiode was directed to wideband amplifier and then visualized by an oscilloscope with 200 MHz band.

3. Results and discussion

3.1. Experimental results

The shape of the equilibrium emission pulse is close to the rectangular one (Fig. 2(a) (1)). The introduction of the sound causes occurrence of an alternating component with a periodicity of the sound wave (Fig. 2(a), (2)). But what is more striking there is change of the phase of the modulation to the opposite one is observed when the analyzer is rotated by 90° relative to the polarization direction of the maximum intensity (Fig. 2(b) (1, 2)).

In the absence of the sound dependence of the emission intensity on angle α is well described by expression $I_= = I_0\cos^2\alpha$ (Fig. 3(a)).α is the angle of deviation of direction of output analyzer polarization from the polarization direction of maximum intensity which is matching the direction the Y-axis within 1°. This fact indicates that the studied laser emission is linearly polarized in wide range of operating currents (I_{op}). Maximum value $I_{\sim\max}$ of the alternating signal amplitude is about 0.5 V, that is much less then I_0 (approximately 50 V). However, since the frequency of the alternating signal coincides with the sound frequency, we can distinguish this contribution with great accuracy, and analyze it separately. Angular dependence of the amplitude of this component ($I_\sim$) are shown in Fig. 3(b) (1–3).

Analysis of experimental data shows that the angular dependences of $I_\sim$ and $I_=$ are well approximated by the expressions:

$$I_= = I_0(1+\cos(2\alpha)) \quad (1)$$

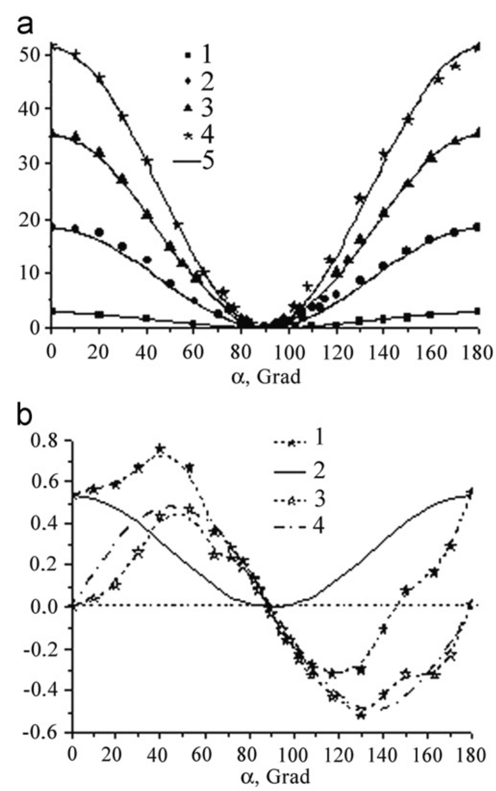

Fig. 3. Emission intensities of the angle : (a) equilibrium emission : points are experiment, (1)–(4) $I_{\min}/I_{\rm rh}$=1.04,1.25,1.6 and 1.9, respectively, solid lines are approximation in accordance with $\cos^2\alpha$ and (b) alternating component amplitudes (at I_{op}/I_{th}=1.9); points are experiment (1) I , (2) calculation $2B\cos^2\alpha$, (3) I–$2B\cos^2\alpha$, (4) calculation $C\sin 2\alpha$.

$$I_\sim = C_\sim(1+\cos(2\alpha)) + D_\sim \sin(2\alpha) \quad (2)$$

where I_0, $C_\sim$, $D_\sim$ are current-dependent and equal to: I_0 = 25.75 V, $C_\sim$=0.27 V, $D_\sim$=0.5 V at I_{op}/I_{th}=1.9. The total intensity can be represented by the following expression

$$I = I_{=} + I_{\sim} = (I_0 + C_{\sim})(1 + \cos(2\alpha) + \frac{D_{\sim}}{I_0 + C_{\sim}}\sin(2\alpha)) \quad (3)$$

It means that: 1. the intensity of emission is modulated in the presence of ultrasonic strain; 2. emitted light keeps linear polarization and in the presence of sound light polarization plane is rotated by an angle ϕ, determined by coefficient of sin2α: $\sin 2\phi = (D_{\sim}/I_0 + C_{\sim})$,

$\phi = (D_{\sim}/2(I_0 + C_{\sim})) \cong 10^{-2}$. It should be noticed that in the case of rotation coefficient of cos2α is equal to $\cos(2\phi) = 1 - 2\sin^2\phi$. In our case of small rotation angle 2 $\sin^2 \varphi$ is a second-order correction and is out of the limit of accuracy of measurements, and with given accuracy the dependence (3) is true.

3.2. Theoretical treatment and results

We have obtained the dependencies of laser intensity on analyzer polarization angle in the absence ($I_{=}$) and presence (I) of the controlled ultrasonic strain. Note that signal I is not informative for the evaluation of the strains and their effect on the studied structures, since difference between $I_{=}$ and I is small in comparison with the value of $I_{=}$. However, the use of differential methods allows us to measure $I - I_{=} = I_{\sim}$ with high accuracy. We have calculated the dependence of the signals $I_{\sim}$ and $I_{=}$ on the parameters of the investigated structure. The active region consists of 2 quantum wells separated by a barrier [10]. It can be shown that for given values of the thickness of the quantum wells and the barrier height and width one can consider quantum wells unrelated and study only one of them to analyze the emission properties. Quantum wells were considered infinitely deep because the transitions under study are referred to the levels that are close to the bottom of the quantum well. The calculations show that in the case that in-plane wave vector of the carriers in quantum well is significantly different from zero the polarization degree is significantly different from 1; since the experimentally observed degree of polarization is close to 100%, below we assume that $k \sim 0$ for induced optical transitions under study. It is well-known that in the structure radiative transitions occur between the conduction band and levels in the valence band corresponding to heavy holes, leading to the absolute polarization of the outcoming emission along the axis y. In case of weak strains in the system heavy-hole and light-hole states are slightly mixed that change the splitting between the energy sublevels and the thickness of the quantum well. The transitions between the conduction band and the light hole states are characterized by polarization of the emission along the axis z. As a result, in the case of weak mixing of states (due to elastic strain) polarization plane can be rotated while the degree of polarization keeps equal to 1. Investigation of the waveguide properties of the structure shows that the observed wavelength corresponds to a TE, and TM mode, and hence the waveguide imposes no restrictions on the polarization properties of light.

In the calculations we consider direct-band radiative transitions between conduction band and valence band with $k = 0$. Wave functions in the conduction band are transformed by the irreducible representation Γ_6 and wave functions in the valence band are transformed by the irreducible representation Γ_8. We assume that in the absence of strain there are only transitions between states in the conduction band and heavy-hole states in valence band. In the presence of strain states in valence band are characterized by Bir–Pikus Hamiltonian [14]. In the case of small strain we can carry out the calculations of radiative transitions in terms of perturbation theory in the first and second order of magnitude of an internal(«technological») deformations and an ultrasonic strains

Energy splitting between the sublevels of light and heavy holes in the case of arbitrary strain can be described by the formula [15]:

$$\Delta E = 2\sqrt{\left(\frac{b\delta}{2} + B\frac{\pi^2}{a^2}\right)^2 + (d^2(\varepsilon_{yz}^2 + \varepsilon_{xy}^2 + \varepsilon_{xz}^2) + (br)^2)},$$

$$r = -\frac{\sqrt{3}}{2}(\varepsilon_{xx} - \varepsilon_{yy}), \quad \delta = \left[(\varepsilon_{zz} - \varepsilon_{xx}) + (\varepsilon_{zz} - \varepsilon_{yy})\right], \quad (4)$$

where b, d are the absolute values of the deformation potential constants, a is the quantum well thickness, B is a parameter, which can be expressed through the masses of light and heavy holes in the following way $B = \hbar^2 \frac{m_{hh} - m_{lh}}{4 m_{hh} m_{lh}}$ (for simplicity, here we used a spherical approximation to describe the states in the valence band).

Expression (4) shows that in the heterostructures grown along the (0 0 1), the splitting between the states of heavy and light holes is determined by the size quantization effect and technological strains along the growth axis. Experimental data show that all other deformations are small and the value of the splitting ΔE can be considered equal to:

$$\Delta E = b\delta_0 + 2B\frac{\pi^2}{a^2}, \quad (5)$$

where δ_0 is a part of δ containing only the "technological" strains.

Experimental data can be explained in the assumption that there are «technological» strains ε_{yz}, δ and r, and that sound creates alternating strains $\varepsilon_{yz}(t), \varepsilon_{xz}(t), \varepsilon_{zz}(t)$.

Then the expression for the total intensity is given by expression (3), and $I_{=}$, $I_{\sim}$ can be described by:

$$I_{=} = I_0(1 + \cos(2\alpha)) + D_{=}\sin(2\alpha), \quad (6)$$

$$I_{\sim} = C_{\sim}(1 + \cos(2\alpha)) + D_{\sim}\sin(2\alpha), \quad (7)$$

and in terms of the model

$$I_0 = N\left(1 + \frac{2br}{\sqrt{3}\Delta E}\right), \quad C_{\sim} = -N\left(\frac{2b^2 r \varepsilon_{zz}(t)}{\sqrt{3}(\Delta E)^2} + \frac{4d^2 \varepsilon_{yz}\varepsilon_{yz}(t)}{3(\Delta E)^2}\right),$$

$$D_{\sim} = -N\left(\frac{4d\varepsilon_{zy}(t)}{\sqrt{3}\Delta E}\right), \quad D_{=} = -N\left(\frac{4d\varepsilon_{zy}}{\sqrt{3}\Delta E}\right), \quad (8)$$

where N is the factor, characterized by the transition matrix elements

Deriving (6)–(8) we suggested that $\Delta E \gg d\varepsilon_{zy}(t)$, $b\varepsilon_{zz}(t)$ and hence all terms containing quadratic sound contributions were considered negligible.

Note that we take into account the second-order terms only calculating $C_{\sim}$. Expression (7) coincides with (2). Expression (6) does not correspond exactly the expression (1). This is due to the fact that in (6),(7) α is counted from Y-axis exactly, not from the direction of maximum intensity as it is in (1)–(3).

In terms of the assumption expressions (6)–(8) show that the polarization plane is rotated by an angle $\phi \approx \frac{2d\varepsilon_{zy}(t)}{\sqrt{3}\Delta E}$ due to the ultrasonic strain. In this case, we can estimate ΔE, basing on the possible values of $\varepsilon_{zy}(t)$, arising from the diffraction divergence of the sound wave. Our estimates give a value of $\varepsilon_{zy}(t)$ of about $3 \cdot 10^{-5}$ and for $d = 4$ eV, $\Delta E \approx 15$ meV However, theoretical approach shows that the value of ΔE without δ_0 is equal to 100 meV for typical effective mass values $m_{lh} = 0.026\ m_o$, $m_{hh} = 0.41\ m_o$, m_o is the free electron mass. We can assume that δ_0 has a magnitude about $3 \cdot 10^{-2}$ to approve the calculations and experimental data. We note that these strains have the crucial role in the geometry of the experiment. In this geometry in the absence of deformation $\varepsilon_{zy}(t)$ even in the presence of other strains polarization properties of emission do not change, and the light is linearly polarized along the y-axis (Fig. 2). The in-plane asymmetry defined by the parameter r is considered essential because it determines the value of $C_{\sim}$. On the basis of experimental data on $D_{\sim}/C_{\sim}$ we have obtained value of $r \approx 8 \cdot 10^{-3}$ at $b=3$ eV and$\varepsilon_{zz}(t) \approx 10^{-4}$.

Expressions (5)–(8) have been derived for transitions to states with $k=0$ and can be used for the cases that the operating current exceeds the threshold value of 200 percent, but for the cases that the operating current is over twice of the threshold value these expressions are not suitable. The precise calculation for different values of k may explain this dependence, but the results are cumbersome and are not given in the communication.

4. Conclusion

Thus, the effects of ultrasonic strain on the polarization properties of laser emission of a semiconductor laser on quantum well are experimentally and theoretically studied.

It is shown that

1. Maintaining the degree of polarization equal to 1, the sound rotates the polarization plane which is a consequence of light and heavy hole wave functions mixing in the presence of the sound strain.
2. The splitting energy value of hole states in quantum well is obtained.
3. A unique possibility of usage of ultrasonic techniques not only to study the effects of strain on spectrum in quantum well, but also to obtain data on the distribution of strain in the heterostructure is demonstrated.

Emphasize that in this paper, we studied the polarization properties of laser induced emission. Spontaneous emission spectrum has full width at half maximum 30 meV, which means that both light and heavy holes are involved in the radiative transitions. However, lasing in these structures is realized only between the conduction band and heavy-hole subband, that confirmed by the value of the laser line generation width, experimentally observed in [11,12].

Acknowledgments

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