

PACS numbers: 42.55.Px; 78.66.–w; 43.35.Pt; 42.25.Ja
DOI: 10.1070/QE2013v043n05ABEH015157

Diagnostics of the fine spectrum of a quantum well in laser heterostructures using ultrasonic deformation

L.A. Kulakova, N.S. Averkiev, A.N. Darinskii, E.Z. Yakhkind

Abstract. **This paper describes a new acoustoelectronic effect in laser nanoheterostructures, which is caused by hole energy modulation and intermixing of hole wave functions in the quantum well of a laser structure in response to ultrasonic deformation. Experimental data are presented which indicate that the laser output intensity and polarisation direction vary periodically, with the acoustic wave period. Theoretical analysis of experimental data is used to assess parameters of the quantum well and the strain distribution in the heterostructure.**

Keywords: *acoustoelectronic interaction, heterostructure laser emission polarisation, hole states in a quantum well.*

1. Introduction

Tunable IR sources are an important component of ultra-high resolution laser spectroscopy and optical communication systems. Monitoring systems for fast processes and optical communication systems need techniques for rapidly tuning the frequency, polarisation and direction of radiation. In this connection, there is great interest in phenomena related to the modulation of the energy and wave functions of electronic states in semiconductor laser nanostructures by external alternating strain because this enables direct detection of the spectroscopic effects accompanying such modulation [1–7]. Akimov et al. [1] examined the optical properties of semiconductor structures (including resonance structures) exposed to acoustic solitons at liquid helium temperature. Such studies are, however, rather rare because of the complex experimental procedure.

We were the first to initiate research, continuing at present, into the effect of ultrasonic deformation on the room-temperature spectral characteristics of InGaAsP/InP heterostructure laser emission. Such experiments are easy to carry out and offer the possibility of producing uniaxial strain in a quantum well of an active (laser) heterostructure having different orientations relative to the quantisation axis. Moreover, ultrasonic studies enable real-time observation of various processes.

L.A. Kulakova, N.S. Averkiev, E.Z. Yakhkind A.F. Ioffe Physical-Technical Institute, Russian Academy of Sciences, Politekhnicheskaya ul. 26, 194021 St. Petersburg, Russia;
e-mail: L.Kulakova@mail.ioffe.ru, averkiev.les@mail.ioffe.ru;
A.N. Darinskii A.V. Shubnikov Institute of Crystallography, Russian Academy of Sciences, Leninsky prosp. 59, 119333 Moscow, Russia

Received 22 February 2013; revision received 3 April 2013
Kvantovaya Elektronika **43** (5) 410–413 (2013)
Translated by O.M. Tsarev

It follows from previous results [2–6] that, in semiconductor structures, one can control rapid and continuous periodic tuning of the spectrum of heterostructure lasers, while maintaining the spectral distribution, intensity and direction of the laser output unchanged.

In recent years, much of our attention has focused on a new aspect of the action of deformation: the influence of ultrasonic deformation on the fine spectrum of quantum states of charge carriers in the active zone of a laser heterostructure. It is known that, in most cubic semiconductors, strong spin–orbit coupling plays a key role in determining their valence band and is responsible for the presence of levels in a quantum well, which differ in the projection of the total magnetic moment of a hole onto the quantisation axis. Elastic stresses change quantum size splittings and intermix heavy and light hole states, thus changing both frequency and polarisation characteristics of the radiation. Alternating strain may lead to further splitting and the corresponding variation in the polarisation characteristics of the radiation with ultrasonic deformation periodicity. The study of this effect is of fundamental interest and opens up new possibilities for utilising it in information processing systems.

We are currently investigating the effect of ultrasonic deformation caused by bulk waves on the room-temperature polarisation characteristics of InGaAsP/InP heterostructure laser emission. It has been shown [7] that ultrasound causes intensity modulation of linearly polarised light and rotates its plane of polarisation. Note that the light remains linearly polarised and that the plane of polarisation is rotated with the period of the acoustic wave. The effect is the consequence of the strain-induced intermixing of the wave functions of heavy and light holes. We have determined the energy splitting of the hole levels in the quantum well and estimated the engineering strain in the heterostructure.

In this paper, we report new findings regarding the strain effect on the polarisation parameters of radiation due to surface acoustic waves in an InGaAsP/InP quantum well laser heterostructure.

2. Experimental

We used InGaAsP/InP structures operating at room temperature in pulsed mode (pulse duration up to 3 μs; emission wavelength of 1.48 μm). Rayleigh surface acoustic waves (SAWs) (alternating strain source, $F = 10$ MHz) were excited by interdigital transducers deposited onto a Y-cut single-crystal $LiNbO_3$ piezoelectric substrate (Fig. 1). After the substrate was coated with a thin metallic film, a laser structure was mounted on it.

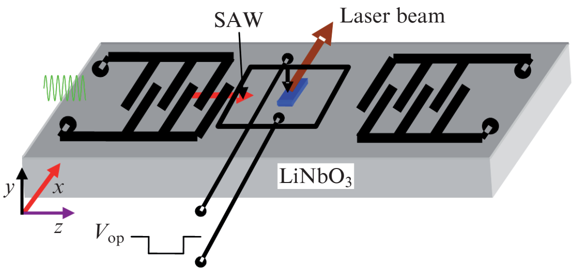

Figure 1. Schematic of surface acoustic wave excitation.

Figure 2 shows energy level diagrams of a quantum well in the active layer. The laser structure and experimental setup were described in detail previously [2, 5, 7]. A wave propagates along the active layer (along the z axis of the substrate). As in previous experiments, the acoustic wavelength (350 μm) considerably exceeds the width of the active layer (~6 μm) along the SAW direction. Under such conditions, the strain can be thought to be constant along the quantum well and to vary only with time, with the SAW period: $\varepsilon(t) \approx \varepsilon_0 \sin\Omega t$.

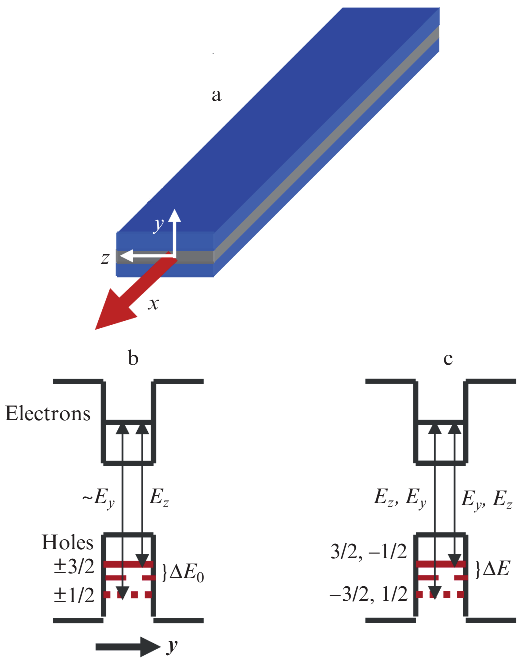

Figure 2. (a) Laser structure: radiation propagates along the x axis. Energy level diagrams of (b) an unstrained quantum well in the active layer of the heterostructure and (c) a quantum well in the presence of mechanical stress (y is the quantisation axis).

A collimated laser beam passes through a polarisation analyser (Glan prism) and is then detected by a high-frequency photodiode (photocurrent rise time within 5 ns). After a broadband amplifier, the photodiode signal is visualised using a Tektronix TDS 2022B 200-MHz oscilloscope. The signal is measured with an accuracy of 20 mV. The sensitivity threshold in averaging mode approaches the measurement accuracy of the oscilloscope. The experiments were carried out in repetitive-pulse mode (pulse repetition rate of 100 Hz). The signal was locked to the trailing edge of the operating current pulse. The measurements were made in quasi-single-frequency lasing mode [5, 6] at operating currents (I_{op}) from the threshold level (I_{th}) to $2I_{th}$ (output power near 100 mW). The gain bandwidth reached 0.2 meV.

3. Results and discussion

Without ultrasound, the pulse shape was nearly rectangular (Fig. 3a) and the variation of the output intensity with α (the angle between the polarisation direction at the analyser output and the polarisation direction corresponding to the maximum laser output intensity, which coincided with the direction of the z axis to within 1°) was well represented by the relation $I_= = 2I_0\cos^2\alpha = I_0(1 + \cos 2\alpha)$ (Fig. 4a). This suggests that the laser output was linearly polarised in a wide range of operating currents.

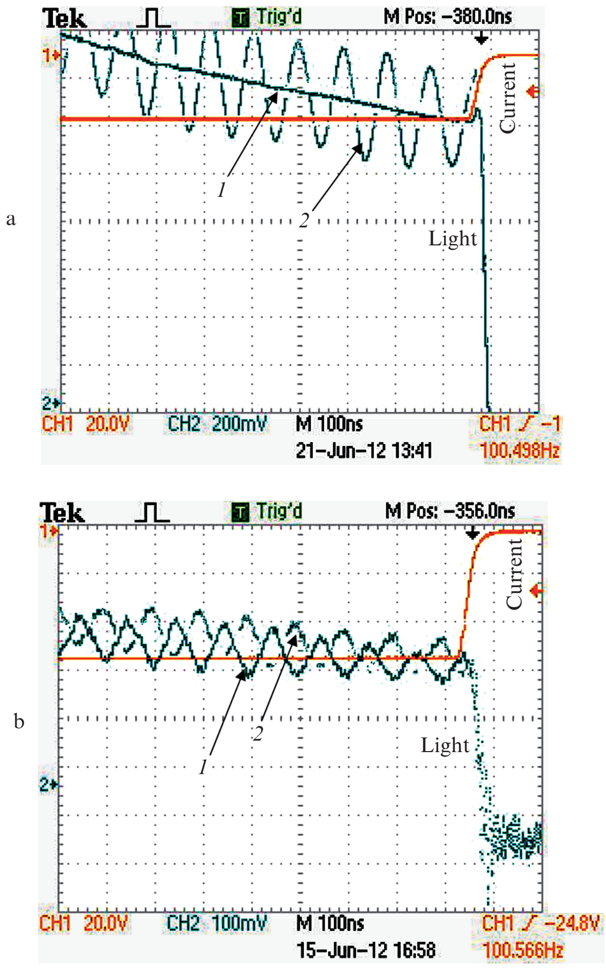

Figure 3. Oscilloscope traces of an operating current pulse and the output intensity at (a) $I_{op} \approx I_{th}$ (*1*) without ultrasound and (*2*) in the presence of ultrasound and (b) at $I_{op} \approx 2I_{th}$ in the presence of ultrasound for α = (*1*) 85° and (*2*) 95°.

At $I_{op} \approx I_{th}$ ($I_{th} \approx$ 40 mA), ultrasound causes strong modulation of the laser output intensity with the period of the acoustic wave (Fig. 3a), and the angular dependence of the amplitude of the alternating component ($\tilde{I}$) is the same as without ultrasound. With increasing operating current, $\tilde{I}$ ($\alpha = 0$) decreases rapidly, to below the sensitivity threshold at $I_{op} \approx 2I_{th}$. The alternating component of the output intensity is only observed at nonzero α values. Also, the modulation

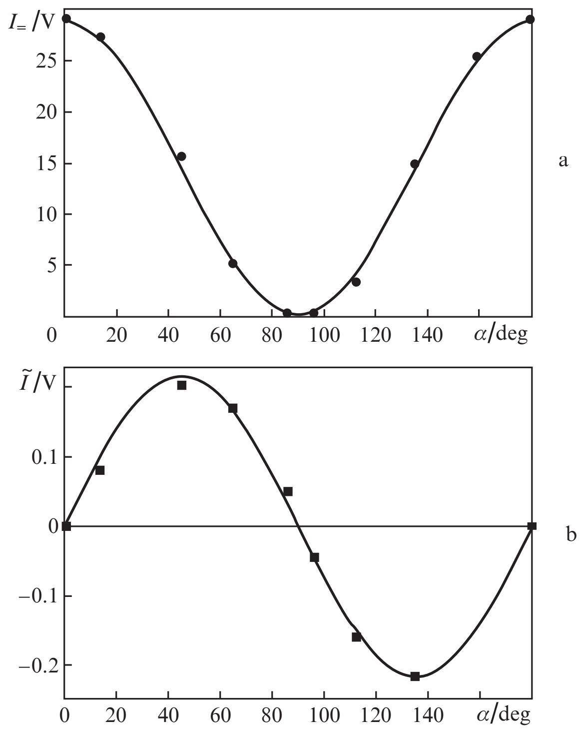

Figure 4. Angular dependences of the output intensity at $I_{\rm op} \approx 2I_{\rm th}$ (a) without ultrasound (the points represent the experimental data and the solid line shows the best fit to $2I_0\cos^2\alpha$, with I_0 = 14 V) and (b) in the presence of ultrasound (the points represent the experimental data and the solid line shows the best fit to $\tilde{B}\sin2\alpha$, with $\tilde{B}$ = 0.22 V).

phase changes sharply to the opposite one when the analyser is rotated through 90° relative to the maximum intensity direction (Fig. 3b), and the intensity amplitude has maxima at α = 45° and 135° (Fig. 4b). At $I_{\rm op} \approx 2I_{\rm th}$, the angular dependence of the amplitude of the alternating intensity component is well represented by the relation $\tilde{I} \approx \tilde{B}\sin2\alpha$, where $\tilde{B}$ = 0.22 V. Thus, the total intensity can be represented in the form

$$I = I_0[1 + \cos2\alpha + (\tilde{B}/I_0)\sin2\alpha]. \quad (1)$$

It follows from (1) that, at $\alpha = 0$, SAWs cause no intensity modulation, in contrast to bulk waves [7, 8]. However, like in the case of bulk waves, the polarisation rotates with the SAW period through an angle whose amplitude is $\varphi \approx \tilde{B}/2I_0 \approx 7 \times 10^{-3}$ rad ≈ 0.4°. This relation persists for $I_{\rm op} > I_{\rm th}$.

To analyse the data obtained, it is necessary to determine the magnitudes of and the relationship between the amplitudes of different alternating strain components, $|\varepsilon_{ij}(z)|$, that are excited by an SAW in the active layer of a heterostructure mounted on a Y-cut $LiNbO_3$ substrate (with metallic film) and propagate in the z-axis direction. The $|\varepsilon_{ij}(z)|$ distribution was calculated by the finite element method (details of the calculational approach can be found in Ref. [9]). In modeling the structure under consideration, we used parameters of single-crystal InP (Fig. 5), which is similar in elastic properties to the InGaAsP/InP structure. The laser measured 100 × 400 × 900 μm in dimensions (Fig. 5). The displacement amplitude of the SAW at the input end of the structure was taken to be 1 Å, and diffraction in the xz plane was left out of account. The calculated strain amplitude (ε_{ij})

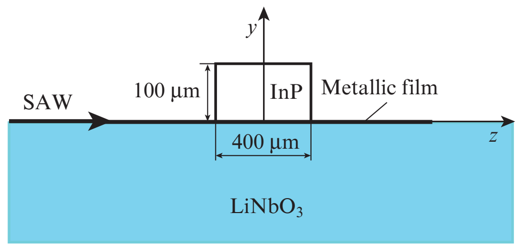

Figure 5. Schematic of the model configuration used to calculate the amplitudes of different strain components excited by an SAW in the structure under investigation.

distributions in the active zone of the laser (−5 μm < z < 5 μm, $y \approx$ 2 μm) are presented in Fig. 6. It follows from these data that SAWs excite three strain components in the structure. Detailed calculations of radiative transitions in a previous study [8] indicate that all these components should influence the polarisation parameters of light. According to theoretical predictions [8], the output intensity in the presence of a SAW (with allowance for all the strain components produced by the SAW) is given by

$$I = I_0(1 + \cos2\alpha + B\sin2\alpha), \quad (2)$$

where

$$I_0 \approx N\left\{1 + \frac{2b^2 r[2\varepsilon_{yy}(t) - \varepsilon_{zz}(t)]}{3\sqrt{3}\,\Delta E^2}\right\}, \quad r = -\frac{\sqrt{3}}{2}(\varepsilon_{xx} - \varepsilon_{zz}); \quad (3)$$

$$B \approx \frac{4d\varepsilon_{yz}(t)}{\sqrt{3}\,\Delta E};$$

the coefficient N is proportional to the matrix element of the momentum operator for the $k = 0$ transitions from the conduction band to the valence band; ΔE is the energy separation between the heavy and light hole states; b and d are constants in the deformation potential; and the parameter r quantifies the engineering strain asymmetry.

Analysis of the experimental data, calculation results (Fig. 6) and relations (3) and (4) leads us to the following conclusions:

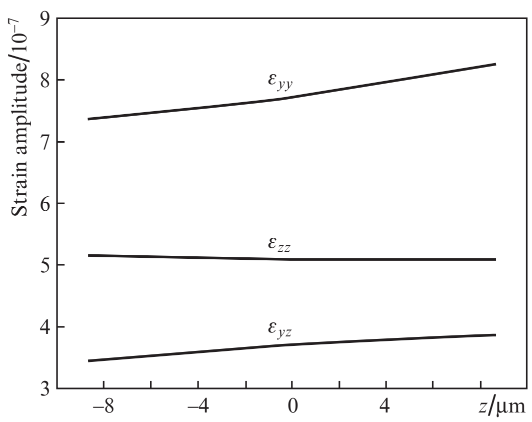

Figure 6. ε_{yy}, ε_{yz} and ε_{zz} ultrasonic strain amplitude distributions in the yz plane of the active zone of the heterostructure.

1. The rotation angle is $\varphi \approx B/2 \approx 7 \times 10^{-3}$ rad. Using the estimated energy splitting $\Delta E \approx 14$ meV [7, 8] and $d = 4$ eV, we obtain $|\varepsilon_{yz}| \approx 2 \times 10^{-5}$.

2. According to calculation of the relationship between the amplitudes of the other alternating strain components in the active layer of the laser (Fig. 6) with $\varepsilon_{yz} \approx 2 \times 10^{-5}$, these amplitudes are $\varepsilon_{zz} \approx 3 \times 10^{-5}$ and $\varepsilon_{yy} \approx 4 \times 10^{-5}$.

3. The modulation depth of the linearly polarised alternating intensity component, $\tilde{I}_0/I_0$, is determined by the second term in (3) and is $\sim 2 \times 10^{-3}$ at $b = 3$ eV and $r = 3 \times 10^{-3}$ [8]. We failed to detect this alternating component, which was probably the consequence of the insufficient sensitivity (detection limit $\tilde{I}_0/I_0 \sim 10^{-3}$) because of uncertainties in our calculations.

An increase in the excitation efficiency using either electronic means for increasing the SAW intensity or complex excitation configurations (e.g. simultaneous excitation of both bulk and surface waves) would allow more detailed information to be gained.

Of special note is that the birefringence induced by external shear deformation may have a significant effect on the polarisation of light that passes through the Fabry–Perot cavity of a semiconductor laser. The rotation angle of the plane of polarisation is determined by the photoelastic constant p_{44} of the waveguide material and (in passive mode) by the waveguide length. Estimates for GaAs crystals (basic to the heterostructure under consideration) far away from their absorption edge for $\varepsilon_{yz} \approx 2 \times 10^{-5}$ and the experimental conditions of this study (0.9-mm-long heterostructure) give a rotation angle of $\sim 1.5°$. This means that, when there is alternating strain, the effect in question should be observed even below threshold, but no effect was detected below or near threshold for bulk or surface waves.

On the other hand, the p_{44} of cubic semiconductors is known to depend on the wavelength of light. In particular, the p_{44} of gallium arsenide near its optical absorption edge is almost zero. This fact was analysed experimentally and theoretically by Higginbotham et al. [10].

That the induced birefringence has no effect on the rotation angle of the plane of polarisation confirms that a considerable rotation in the lasing regime via multiple photon passes through the cavity would lead to lasing breakdown because of the rotation of the plane of polarisation through 90° and that optical transitions with light polarisation parallel to the growth axis of the quantum well (the y axis in our experiments) are forbidden. Lasing breakdown caused by an acoustic wave through the structure would show up at least as appreciable modulation of the laser output intensity at twice the ultrasound frequency, but nothing of the kind was detected.

All this leads us to conclude that, in our experiments, induced birefringence played no significant role.

4. Conclusions

We have studied the effect of Rayleigh surface acoustic waves on the polarisation properties of the output radiation of a quantum well semiconductor laser. The results demonstrate that, like in the case of bulk waves, the SAW-induced strain rotates the polarisation direction (but the light remains linearly polarised), which is the consequence of the intermixing of the wave functions of heavy and light holes. Using measured rotation angles, we have estimated the amplitude of the shear component of the SAW-induced strain. We have calculated the distribution of the SAW-induced strain components in a model laser structure and determined all the SAW-induced ultrasonic strain components in the laser structure studied.

Acknowledgements. We are grateful to I.S. Tarasov and his colleagues at the Ioffe Physical Technical Institute, Russian Academy of Sciences, for kindly providing the high-quality laser heterostructures.

This work was supported by the Russian Foundation for Basic Research (Grant No. 11-02-00729) and the Russian Academy of Sciences (Programme Nos 24 and 27).

References

1. Akimov A.V., Scherbakov A.V., Yakovlev D.R., Bayer M., Kent A. *J. Lumin.*, **131**, 404, (2011).
2. Kulakova L.A., Tarasov I.S. *Pis'ma Zh. Eksp. Teor. Fiz.,* **78**, 67 (2003).
3. Kulakova L.A., Pikhtin N.A., Slipchenko S.I., Tarasov I.S. *Zh. Eksp. Teor. Fiz.*, **131**, 790 (2007).
4. Kulakova L.A. *Fiz. Tverd. Tela*, **51**, 73 (2009).
5. Kulakova L.A. *Appl. Opt.*, **48**, 1128 (2009).
6. Kulakova L.A., Lyutetskii A.V., Voloshinov V.B. *Pis'ma Zh. Tekh. Fiz.*, **36**, 48 (2010).
7. Kulakova L., Gorelov V., Lutetskiy A., Averkiev N. *Solid State Commun.*, **152**, 1690 (2012).
8. Kulakova L.A., Averkiev N.S., Lyutetskiy A.V., Gorelov V.A. *Fiz. Tekh. Poluprovodn.*, **47**, 137 (2013).
9. Darinskii A.N., Weihnacht M., Schmidt H. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, **57**, 2042 (2010).
10. Higginbotham C.W., Cardona Manuel, Pollak F.H. *Phys. Rev.*, **184** (3), 821 (1969).