Phonon spectrum of GaAs–InAs superlattices

V. A. Gaĭsler, A. O. Govorov, T. V. Kurochkina, N. T. Moshegov, S. I. Stenin, A. I. Toropov, and A. P. Shebanin

Institute of Semiconductor Physics, Siberian Branch of the Academy of Sciences of the USSR, Novosibirsk
(Submitted 9 April 1990)
Zh. Eksp. Teor. Fiz. **98**, 1081–1092 (September 1990)

Results are given of an experimental and theoretical investigation of the phonon spectrum of stressed GaAs–InAs superlattices. The results of Raman scattering of light are in good agreement with the theoretical models. Beside the singularities observed in the Raman spectra due to folding of the acoustic phonon branches and to localization of optic phonons, it is predicted that localized phonons should exist in the GaAs–InAs system. A specific feature of the superlattice phonon system of GaAs–InAs, compared with the GaAs–AlAs superlattice, is pointed out: it consists of the absence of strong localization of optic phonons in the GaAs layers which is due to the partial overlapping of the GaAs and InAs optic phonon branches, induced by strong mechanical stresses in the superlattice.

1. INTRODUCTION

Semiconductor superlattices (SL) are essentially new phonon systems which have a vibrational excitation spectrum very different from the spectra of the semiconducting materials which form the SL. This has given rise to great interest in theoretical and experimental investigation of the phonon spectra of SL's.[1-4] The most informative experimental method is Raman scattering (RS) spectroscopy. Results in recent years verify that together with the most important fundamental characteristics of the phonon spectra of SL's, the RS method can also yield a number of practically important parameters, such as the value of the SL periods and the fluctuation in periods, and the value of the mechanical stresses.[2,5,6]

Up to now the most thoroughly studied are SL's with alternating layers of GaAs and AlAs.[1-4] It turned out to be a model system for the experimental verification of ideas about folding of the acoustic phonon branches (FAPB), the localization of optic phonons (LOP) and the existence of surface mode phonons (SP) in semiconductor superlattices.[1] Investigation of the phonon spectrum of GaAs–InAs SL's is a more complicated problem compared with GaAs–AlAs SL's for several reasons. Unlike GaAs–AlAs, where the optic phonon branches of GaAs and AlAs do not overlap, which considerably simplifies the analysis of the spectrum, in GaAs–InAs SL's the frequencies of the optic phonons differ to a smaller extent and the optic phonon branches partially overlap.

Strong mechanical stress in the layers of GaAs–InAs SL, produced by mismatch, to the extent of 7%, of the lattice parameters of GaAs ($a_1 = 5.65$ Å) and InAs ($a_2 = 6.04$ Å) leads to an additional approach of the optic phonon frequencies. The large mismatch in the lattice parameters of GaAs and InAs also imposes a limit on the possible values of the ratio of the thicknesses of GaAs and InAs layers in the SL. It is possible to synthesize an SL with period $(GaAs)_m(InAs)_n$ containing simultaneously ultrathin layers of GaAs and InAs on a semiconductor substrate with lattice parameter a ($a_1 < a < a_2$); then $m \approx n$ and does not exceed tens of monomolecular layers.

Experimental results of investigating RS by a SL of a type such as $(InAs)_3(GaAs)_4$, grown on an InP substrate ($a = 5.86$ Å) are given by Gérard *et al.*[7] Another variant of growing GaAs–InAs SL's, enabling a greater variety of structures to be obtained, consists of the synthesis of a SL with period $(GaAs)_k(InAs)_l$ on GaAs substrates or SL's with period $(InAs)_k(GaAs)_l$ on InAs substrates, where l is not more than two monomolecular layers and k is not less than five and has no upper limit.

In the present work the phonon spectrum of GaAs–InAs SL's is studied experimentally (by the RS method) and theoretically for the first time, using as examples SL's with period $(GaAs)_k(InAs)_l$ and $(InAs)_k(GaAs)_l$, i.e. GaAs–InAs SL's containing ultranarrow layers of material of one type ($l = 1,2$) and relatively thick layers of material of the other type. Peaks are found in the RS spectra corresponding to FAPB and LOP in GaAs–InAs SL's. Investigation of SL's with a large ratio of thicknesses of neighboring layers $d_1/d_2 \gg 1$ ($d_1 + d_2 = d$ the SL period) made it possible to observe the FAPB process in a considerable part of the acoustic range and to obtain a spectrum containing up to seven FAPB doublets. Peaks were observed in the optic spectral region, corresponding to LOP in the GaAs layer, including LO_{13}, where 13 is the order of quantization of a longitudinal optic phonon. The theoretical dispersion relation obtained in this work, taking account of the deformation of the SL layers, describes well the set of experimental RS results and predicts the folding effect of the optic phonon branches (FOPB) and the localization of acoustic phonons (LAP) in GaAs–InAs SL's.

2. SPECIMEN CHARACTERISTICS AND EXPERIMENTAL METHOD

In this work specimens of superlattices with periods $(GaAs)_k(InAs)_l$ and $(InAs)_k(GaAs)_l$ were studied, grown by the molecular beam epitaxy method developed in this Institute. The orientation of the substrate and SL layers was [100]. The growth of each layer was monitored by the method of high-energy electron diffraction and ended at the moment when the maximum intensity of the mirror beam was reached, which corresponded to the maximum filling of the upper monolayer.[8] Type I SL's with period $(GaAs)_k(InAs)_l$, where $l = 2$, $k = 6$, 10, 19, 22, 40 were grown on GaAs substrates; type II SL's with period $(InAs)_k(GaAs)_l$ where $l = 2$, $k = 10$, 19, 35, 50 were grown on InAs substrates. In addition, a set of structures

 0038-5646/90/090603-07$03.00

with $l = 1$ was grown, and also aperiodic structures. The number of periods in the SL's varied from specimen to specimen and on the average amounted to 30–40. The structures grown were examined by x-ray diffraction and electron microscopy and the results confirm the existence of additional periodicity and give evidence of the sharpness of the heterojunction.

The RS spectra were excited by light from an Ar^+ laser and a DCM dye laser and were recorded with DFS-52 and U-1000 spectrometers. Brewster quasi-backscattering geometry was used with parallel (xx) and crossed (xy) polarizations of the incident and scattered light, the x and y axes were parallel respectively to the crystallographic [100] and [010] directions. The specimens were in a vacuum and the investigations were carried out in the temperature interval from 10 to 295 K.

3. ANALYSIS OF PHONON DISPERSION RELATIONS IN GaAs–InAs SUPERLATTICES

In a strict discussion the phonon spectrum of SL's cannot be reduced to the spectra of the materials forming the SL, nevertheless a comparative analysis of the dispersion relations of the bulk materials is highly informative for understanding the mechanisms for the formation of the SL's phonon spectrum. The dispersion relations for longitudinal-type vibrations in GaAs, InAs and also, for comparison, in AlAs[1)] are shown in Fig. 1.

The dispersion relations are obtained from the solution of the problem of the vibrations of a linear chain of atoms, the normalization being accomplished for values of the longitudinal optic phonon frequencies with $k = 0$. The real and imaginary parts of the phonon wave vector are plotted along the horizontal axis in units of π/ε, where $\varepsilon = a/2$, a being the crystal lattice constant. The quantity $(\mathrm{Im}\,k)^{-1}$, the inverse of the value of the imaginary part of the wave vector, characterizes the penetration depth of the vibrational excitation into the crystal. The vertical dashed lines in Fig. 1 show

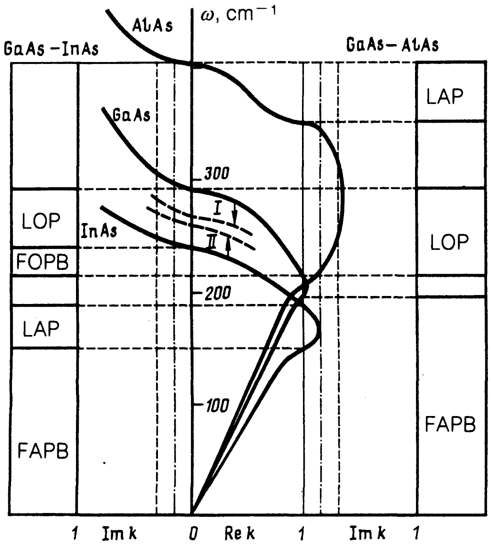

FIG. 1. Dispersion relations for the bulk materials AlAs, GaAs and InAs in the regions of real and imaginary values of the wave vectors. The vertical dashed and dashed-dot lines denote values of $(\mathrm{Im}\,k)^{-1}$ corresponding to attenuation of the vibrations in, respectively, one and two monomolecular layers.

values of Im k which correspond to a penetration depth the thickness of one monolayer (~ 3 Å), the vertical dashed-dot lines are for two monolayers (~ 6 Å).

It can be seen in the figure that in the low-frequency region the phonon branches overlap over a wide interval, so that the SL phonon spectrum contains delocalized vibrational excitations, the dispersion of which can be obtained fairly accurately by convolution of the acoustic phonon branches within the limits of the Brillouin minizone with boundaries π/d (Refs. 1, 2). This applies to practically the whole range of acoustic frequencies of the GaAs–AlAs pair; unlike that, there is a range of frequencies for the GaAs–InAs pair (roughly from 150 to 180 cm^{-1}), where the dispersion of InAs phonons is located in the region of imaginary wave vectors, i.e., vibrations with frequencies in this interval are attenuated in InAs. The penetration depth in InAs for an acoustic phonon in GaAs of frequency ~ 160 cm^{-1} is, according to Fig. 1, two monolayers (~ 6 Å). Thus, in this frequency range in the GaAs–InAs SL local acoustic phonons can be formed in GaAs layers.

The optic branches of the GaAs–AlAs pair are spaced over a large distance on a frequency scale, so the vibrations are strongly localized in GaAs and AlAs layers, the penetration depth according to Fig. 1 is not more than one monolayer. In the GaAs–InAs system the optic branches partially overlap and in this region there can be folding of the optic phonon branches. In the range where there is no overlap the conditions are satisfied for local optic phonons to arise. Large compressive and dilatation stresses, produced by mismatch of the lattice parameters of GaAs and InAs, lead to appreciable shifts in the dispersion relations. The dashed lines in Fig. 1 denote the optic phonon wings of stretched GaAs (curve I) and compressed InAs (curve II). In both cases deformation of 7% was used. The shifts of optic phonon frequencies under the action of the deformation were determined here and in further discussion in accordance with the data of earlier work.[11] The strong approach of the optic phonon branches leads to redistribution on the frequency scale of the FOPB and LOP regions, and also changes the conditions for phonon localization in a GaAs layer.

Apart from the regions of FAPB, LAP, FOPB and LOP, marked in Fig. 1, surface-mode phonons (SP) can arise in the frequency intervals between longitudinal and transverse optic vibrations in the semiconductor SL's. For SL's with large relative contacting layer thicknesses studied in the present work, we find in accordance with the expressions for the calculation of SP frequencies,[2] that the SP frequencies coincide or are close to the longitudinal and transverse optic vibration frequencies in bulk crystal.

We have carried out a stricter discussion of the form of the dispersion relation for phonons in GaAs–InAs SL's using expressions specially derived for SL's containing alternate layers of material of one type of any thickness d_1 and ultrathin layers of material of the other type of thickness d_2, equal to one or two monolayers. The dispersion relation obtained on solving the problem of the vibrations of a linear chain of atoms is shown in the upper part of Fig. 2. It is of the following form:

$$A \sin k\varepsilon \cos qd = B \sin[k(d_1-\varepsilon)] + C \sin[k(d_1-2\varepsilon)] + D \sin[k(d_1-3\varepsilon)], \qquad (1)$$

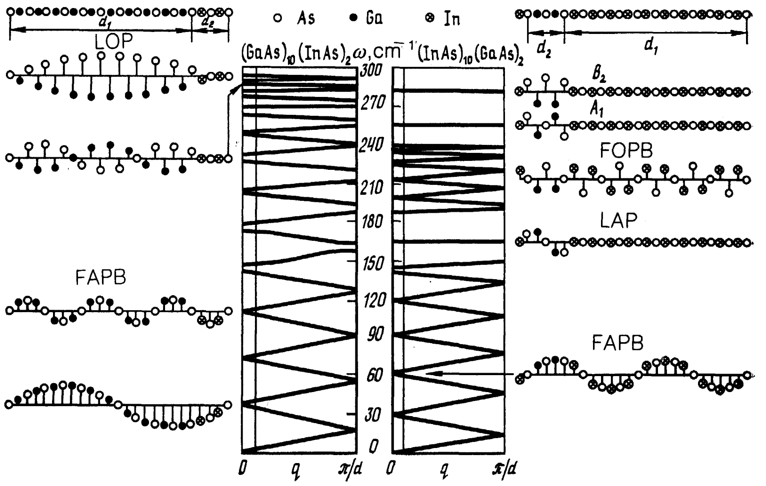

FIG. 2. Theoretical dispersion relations for the SL's $(GaAs)_{10}(InAs)_2$ and $(InAs)_{10}(GaAs)_2$.

where q and k are, respectively, the complex wave vectors of phonons in the SL and in bulk material entering into the SL in the form of layers of thickness d_1. For $(GaAs)_k(InAs)_l$ SL's in the case of $l = 1$ the coefficients in Eq. (1) are of the form

$$A=\eta\chi\gamma,\quad B=(\nu-\psi-\eta)(\varphi+\gamma)^2+2\eta\chi(\varphi+\gamma),$$
$$C=2\gamma[(\nu-\psi-\eta)(\varphi+\gamma)+\eta\chi],\quad D=(\nu-\psi-\eta)\gamma, \tag{2}$$

in the case of $l = 2$

$$A = \nu\eta\chi\gamma,$$
$$B=(\psi^2-\nu^2)(\varphi+\gamma)^2-2\chi\psi\eta(\varphi+\gamma)+\eta^2\chi^2, \tag{3}$$
$$C=2\gamma[(\psi^2-\nu^2)(\varphi+\gamma)-\eta\psi\chi],\quad D=(\psi^2-\nu^2)\gamma^2.$$

The symbols used in Eqs. (2) and (3) are

$$\nu=\frac{-\beta}{m_{As}\omega^2-2\beta},\quad \eta=\frac{-\beta}{m_{As}\omega^2-\alpha-\beta},\quad \chi=\frac{-\alpha}{m_{As}\omega^2-\alpha-\beta},$$
$$\gamma=\frac{-\alpha}{m_{As}\omega^2-2\alpha},\quad \varphi=\frac{m_{Ga}\omega^2-2\alpha}{\alpha}+\chi, \tag{4}$$
$$\psi=\frac{m_{In}\omega^2-2\beta}{\beta}+\eta+\nu,$$

where m_{As}, m_{Ga}, m_{In} are the masses of As, Ga, In atoms, α and β are stiffness constants for GaAs and InAs respectively (for unstrained GaAs, InAs $\alpha = 0.907\cdot 10^5$ dyn/cm, $\beta = 0.764\cdot 10^5$ dyn/cm).

The obvious substitutions $\alpha\leftrightarrow\beta$, $m_{In}\leftrightarrow m_{Ga}$ are made in Eqs. (1)–(4) to describe $(InAs)_k(GaAs)_l$ SL's with $l = 1,2$. The dispersion relations obtained from the solution of Eq. (1), without taking account of stresses in the layers are shown for the SL's $(GaAs)_{10}(InAs)_2$ and $(InAs)_{10}(GaAs)_2$ in Fig. 2. The displacement of the atoms is also shown on them, corresponding to longitudinal phonons of different types. For clarity, the amplitude of the longitudinal displacements is shown laid out perpendicular to the direction of the wave vector. The value of the phonon wave vector arising in the RS process, $q\approx 4n_0\pi/\lambda$ (n_0 is the refractive index, λ the wavelength of the exciting light) is shown by the vertical lines on the dispersion curves.

It is characteristic for the dispersion relation of $(GaAs)_{10}(InAs)_2$ SL (and other SL's of this type) that all the phonon branches, including the branches describing vibrations at the limiting optic frequencies, have a slope $V = d\omega/dq\neq 0$. Thus, even for the limiting optic frequencies, which are in the LOP region in accordance with Fig. 1, the condition for strong localization is not satisfied, an optic phonon partially penetrates into the neighboring layer. In contrast, the dispersion relation for $(InAs)_{10}(GaAs)_2$ SL (and other SL's of this type) contains three non-dispersive branches, two of which correspond to strongly localized optic-type vibrations in a narrow GaAs layer (B_2 is an antisymmetric vibration while A_1 is symmetric), the third is a localized acoustic phonon in a GaAs layer, the possibility of this arising was mentioned above.

The dispersion relations (Fig. 2) obtained by using Eq. (1) demonstrate the main features of the phonon spectrum of the superlattices studied: the existence of regions of localized optic and acoustic phonons and regions of folded branches of optic and acoustic phonons. However, for a quantitative analysis of the experimental results the introduction of a number of corrections is required, in particular to take account of mechanical stresses, which will be described below.

4. ACOUSTIC REGION OF THE SPECTRUM

The folding of the acoustic phonon branches (FAPB) within the limits of a Brillouin minizone is manifest in RS spectra in the form of a set of double peaks, the frequencies of which are determined by the points of intersection of the vertical lines, giving the phonon wave vector in the process of Raman scattering by the phonon dispersion branches (Fig. 2). It was shown in our previous work[5] that for SL's with large ratios of neighboring layers the intensities of the FAPB doublets depend weakly on the doublet number, which enables the FAPB process to be observed over an appreciable part of the acoustic range. In Fig. 3 the RS spectra of SL's with different thickness ratios of GaAs and InAs layers are shown. The dashed lines indicate the broad features which arise due to disordering of the crystal structure (DATA, DALA[2)]).[2] On their background the FAPB doublets are clearly seen, the number of which increases with increasing ratio d_1/d_2. In the RS spectrum of a $(GaAs)_{22}(InAs)_2$ SL specimen ($d_1/d_2 = 11$) 7 FAPB doublets are observed (Fig. 3, e).

The experimental values of the FAPB doublet frequencies agree well with theoretical values obtained from Eq.

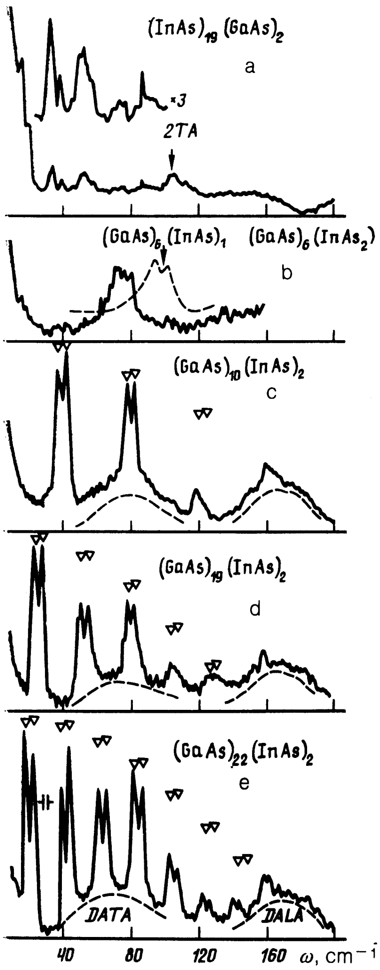

FIG. 3. RS spectra ($T = 295$ K) in the acoustic frequency region for (a) type II SL's and (b, c, d, e) type I SL's.

(1), although somewhat better agreement is given by the expression which we obtained specially[5] for FAPB, since exact values for the velocity of sound in GaAs and InAs phonons are used, normalized to the frequency of longitudinal optic phonons (Fig. 1) with some error in the acoustic region. Taking account of the deformation of the layers does not lead to a noticeable change in the theoretical value of the FAPB peak frequencies. The theoretical values of the frequencies and intensities[2,5] of the FAPB peaks are indicated in Fig. 3 by triangles. Good agreement between the theoretical and experimental values of the FAPB frequencies, and also an appreciable frequency shift for a small change in SL period (Fig. 3, b–e) enables the results of RS to be used to determine the parameter d of the SL to high accuracy (not worse than ~ 0.5 Å).

The low-frequency spectra of type II SL's also contain a number of FAPB peaks (Fig. 3, a). The poor quality of the spectrum is due to its low intensity, determined by the high attenuation of the light in InAs and the less perfect structure of the $(InAs)_{19}(GaAs)_2$ SL. Only the first two of the five FAPB doublets observed could be spectrally resolved, the first doublet is on the wing of the laser line.

A localized acoustic phonon in a GaAs layer does not appear in the RS spectra (Fig. 3, a), since for a SL of the type $(InAs)_k(GaAs)_2$, the LAP is symmetric (Fig. 2) and consequently inactive in RS. The observation of LAP in RS spectra is possible, in our opinion, in SL's of another configuration, for example, in SL's of the type $(InAs)_k(GaAs)_3$.

5. EFFECTS OF LOCALIZATION OF OPTIC PHONONS

Localized optic phonons in layers of SL's appear in RS spectra in the form of a set of peaks located in the low-frequency region relative to peaks of optic phonons of bulk materials forming a superlattice.[1-4] The experimental results for SL's of the $(GaAs)_k(InAs)_2$ type are shown in Figs. 4 and 5. The RS spectra are shown in Fig. 4 for a specimen with the smallest period $(GaAs)_6(InAs)_2$. The spectrum contains two peaks for crossed polarization. In agreement with the selection rules[1,3,6] odd-parity LOP's (LO_1, LO_3 etc.) should appear in a crossed polarization geometry xy, since they have B_2 symmetry. In the parallel xx geometry odd-parity LOP's are forbidden, but under resonance conditions in xx geometry even-parity LOP's (LO_2, LO_4 etc.) of A_1 symmetry appear because of the Fröhlich mechanism. The lower spectrum of Fig. 4 was recorded in xx geometry under resonance conditions ($E_0 + \Delta_0$ for GaAs) and contains one peak which also partially appears in the spectrum of non-resonance excitation ($\lambda = 488$ nm) in xx geometry. From the polarization and resonance investigations carried out, the observed features of the RS spectra can be ascribed to the appearance of the LOP's LO_1, LO_2, and LO_3 (in the order of decreasing frequency of the peaks in Fig. 4). Figure 5 consists of the RS spectra of other $(GaAs)_k(InAs)_2$ structures, in which LOP's appear, including LO_{13} for the SL with the greatest period $(GaAs)_{22}(InAs)_2$.

The results of comparing the theoretical and experimental values of the LOP frequencies are shown in Fig. 6. The shift in LOP frequency relative to the LO phonon frequency in bulk GaAs is along the ordinate axis; the open symbols (triangles, circles and squares) are the theoretical values, the dark symbols are experimental values. Curve 1 in Fig. 6 is the theoretical LO phonon dispersion relation in bulk GaAs shown in Fig. 1 and used to construct the disper-

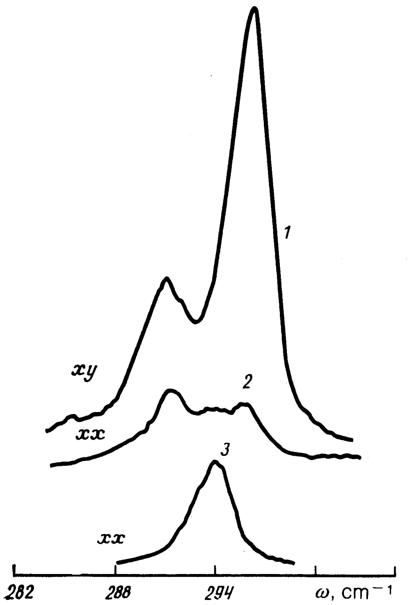

FIG. 4. Spectra of the SL $(GaAs)_6(InAs)_2$ at $T = 10$ K in the optical frequency region (1, 2—$\lambda_i = 488$ nm, 3—$\lambda_i = 652.8$ nm).

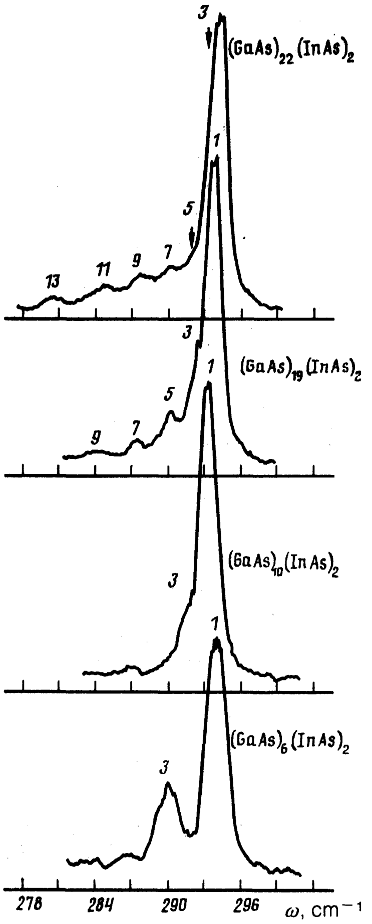

FIG. 5. RS spectra in the optical frequency region of type I SL's; xy geometry, $T = 77$ K, $\lambda_i = 488$ nm.

layers. The value $q = n\pi/d_1$ is plotted on the wave vector axis in Fig. 6 for the LOP LO_n, corresponding to the condition for strong localization of a phonon in a GaAs layer of thickness d_1. The calculation of the LOP frequencies carried out using Eq. (1) showed that the theoretical dispersions shown in the form of curves 1 and 2 in Fig. 6 do not allow the set of experimental results on LOP in GaAs layers to be described. Analogous results have been obtained[12] for GaAs–AlAs SL's. Application of the dispersion relation shown as curve 3 of Fig. 6, and also taking account of mechanical stresses in InAs layers, enabled dispersion relations in SL's to be obtained with the help of Eq. (1), which describe well the experimental values of the frequencies (Fig. 6). Fragments of such dispersion relations for the SL's $(GaAs)_6(InAs)_2$ and $(GaAs)_{22}(InAs)_2$ are shown in Fig. 7.

sion of phonons in GaAs–InAs SL's (Fig. 2). Curve 2 is the theoretical LO phonon dispersion relation of bulk GaAs, constructed on the basis of results of cold-neutron scattering and used[1] to analyze localization effects of phonons in GaAs

Two facts must be noted:

1. The slope of the phonon branches relative to the wave vector axis, $d\omega/dq \neq 0$, can be clearly seen in Fig. 7.

2. As has been remarked, the value $q = n\pi/d_1$ has been plotted along the wave vector axis in Fig. 6. Appreciably better agreement between the experimental results for $(GaAs)_6(InAs)_2$ and $(GaAs)_{10}(InAs)_2$ SL's and curve 3 is obtained on using $q' = n\pi/d$, the substitution of q' for q is shown by arrows in Fig. 6 for the specimens, the crosses denote the experimental values corresponding to q'. For SL's with large period, replacement of d_1 by d in the expression for q does not lead to a noticeable change in the magnitude of q and is not shown in the figure.

These two facts indicate the absence of strong localization of phonons in GaAs layers and the penetration of phonons into the neighboring InAs layer, which is due to partial overlap of the phonon branches of GaAs and InAs and their further approach under the action of large mechanical stress in the pseudomorphic InAs layers. Thus, for the optic phonons in SL's of the type $(GaAs)_k(InAs)_2$, the intermediate case between LOP and FOPB is realized.

In ideal $(GaAs)_k(InAs)_l$ SL's grown on GaAs substrates, the deformations must be concentrated in pseudo-

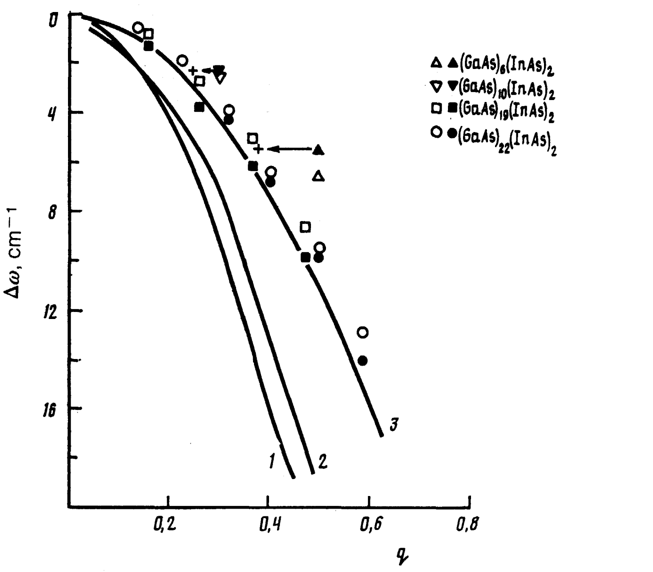

FIG. 6. Theoretical dispersion curves (1,2) of bulk GaAs; 3) a curve constructed from the results of slow neutron scattering in bulk GaAs; the points are experimental (open) and theoretical (dark) values of the frequencies of localized optic phonons in type I SL's.

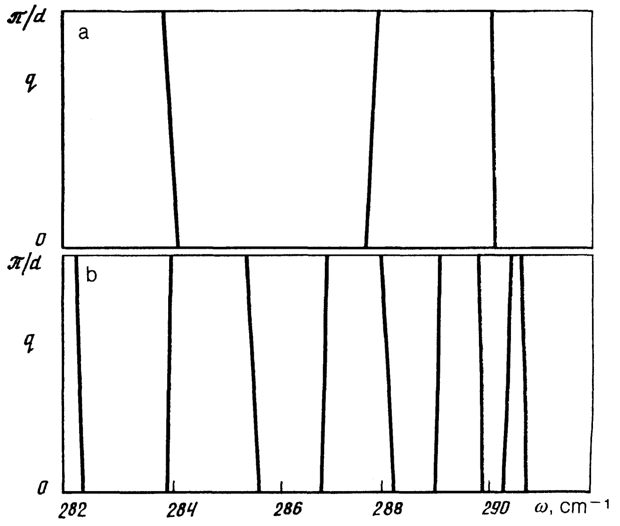

FIG. 7. Fragment of theoretical dispersion curves for the SL's a) $(GaAs)_6(InAs)_2$ and b) $(GaAs)_{19}(InAs)_2$ taking account of mechanical stresses in an InAs layer.

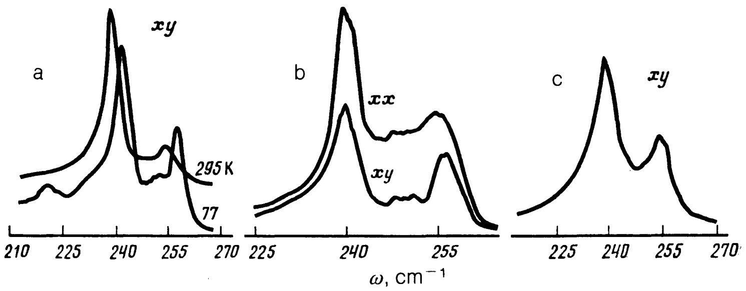

FIG. 8. RS spectra in the optic frequency region a, b) of the SL $(InAs)_{19}(GaAs)_2$ and c) an aperiodic SL: a—$\lambda_i = 488$ nm; b—$\lambda_i = 476.5$ nm, $T = 77$ K; c—$\lambda_i = 488$ nm, $T = 295$ K.

morphic InAs layers, while GaAs layers are undeformed. However, in real structures, because of the introduction of mismatch dislocations, not only the InAs layer (compressed by 7%) is deformed, but also the GaAs layer partially (stretching deformation). The magnitude of the residual deformation of the GaAs layers, characterizing the perfection of the structure, can be recorded by the low-frequency shift in the LO_1 peaks relative to the phonon frequencies in bulk GaAs, taking account of the contribution from LOP's, which is determined by solving Eq. (1). The magnitude of ξ varies from specimen to specimen (as can be seen in Fig. 5; the LO_1 peaks have several different frequencies). On the average ξ for the structures studied is 0.2%, which agrees well with the values of ξ determined in these SL's by electron microscopy methods.

The distribution of the deformation for type II SL's has an inverse character: a thin GaAs layer stretches (7% level of deformation), an InAs layer is undeformed. The optic region of the RS spectrum of the SL's $(InAs)_k(GaAs)_l$ for $l = 1, 2$ is shown in Figs. 8 and 10. Together with the peak, close in frequency to the LO phonon of bulk InAs (~ 240 cm^{-1}), the spectra contain an additional peak at a frequency ~ 255 cm^{-1}. On lowering the temperature this peak is strongly narrowed (Fig. 8, a) while the peak with $\omega \approx 240$ cm^{-1} is practically unchanged in half-width, which indicates their different nature. Polarization studies (Fig. 8, b) provide evidence that both peaks have identical symmetry, besides which a feature of different symmetry is observed in the frequency interval between them. RS studies in different specimens showed that the frequency of the additional peak (~ 255 cm^{-1}) is independent of the size of the SL period for considerable changes in it: from $(InAs)_{10}(GaAs)_2$ to $(InAs)_{50}(GaAs)_2$. The spectrum of an aperiodic SL $(InAs)_k(GaAs)_2$ ($k = 4 + 4N$, N is the layer number counted from the surface of the structure) is shown in Fig. 8, c. This spectrum also contains an additional peak at a frequency ~ 255 cm^{-1}. The set of results given enabled this peak to be attributed to an optic phonon localized in the $(GaAs)_2$ layer which has B_2 symmetry (see Fig. 2).

The dispersion relations that do not take account of mechanical stresses in $(InAs)_k(GaAs)_l$ SL's provide a value for the frequency of the B_2 vibration of ~ 285 cm^{-1}, which considerably exceeds the experimental value. Taking account of the extension deformation of the GaAs layer in $(InAs)_k(GaAs)_2$ SL by 7% enables a dispersion relation to be obtained (Fig. 9, b) which describes satisfactorily the experimental values of the B_2 frequencies. The feature of the spectrum at a frequency ~ 250 cm^{-1} (Fig. 8, a, b) evidently relates to an A_1 symmetry vibration (Figs. 2, 9).

We did not observe the appearance of FOPB in the RS spectra, which is evidently due to the existence of a low-frequency asymmetrical wing for the 240 cm^{-1} peak (Fig. 8), which masks the FOPB. This wing is typical of RS in bulk InAs and is associated with the features of the electron–phonon coupling in this material.[13]

Vibrational excitations in ultra-narrow $(GaAs)_l$ layers in the SL's $(InAs)_k(GaAs)_l$ are, in their nature, close to a local vibration of a Ga atom in InAs doped with gallium. The frequencies of vibrations in $(GaAs)_l$ layers change in a no-

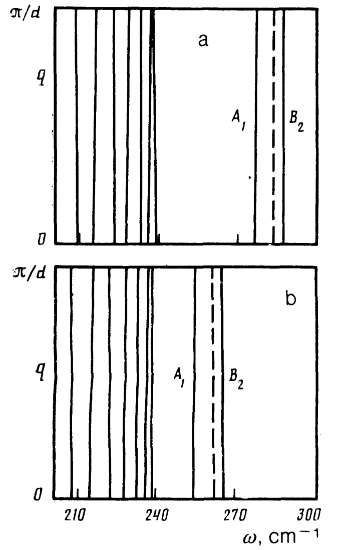

FIG. 9. Theoretical dispersion relation for the SL $(InAs)_{10}(GaAs)$ a) without taking account of mechanical stresses in a GaAs layer and b) taking account of a deformation $\xi \sim 7\%$ in a GaAs layer. The dashed lines indicate the solutions obtained for the SL $(InAs)_{10}(GaAs)_1$.

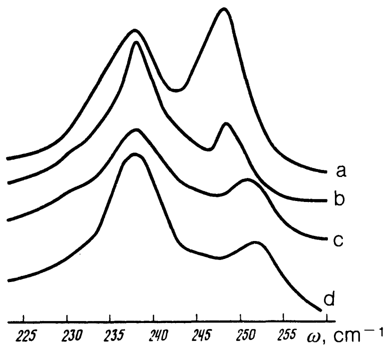

FIG. 10. RS spectra of a) solutions $In_xGa_{1-x}As$ for $x = 0.95$ and the SL's b) $(InAs)_{10}(GaAs)_{0.5}$, c) $(InAs)_{10}(GaAs)_1$, d) $(InAs)_{10}(GaAs)_2$ in xy geometry at $T = 295$ K.

ticeable way on reducing the layer thickness and in the limiting case of ultra-narrow layers approach the frequency of a local vibration of a Ga atom in InAs.[14] This evolution is reflected in Fig. 10 where RS spectra are shown for SL's with periods $(InAs)_{10}(GaAs)_2$, $(InAs)_{10}(GaAs)_1$, $(InAs)_{10}(GaAs)_{0.5}$ and also the RS spectrum of the solid solution $In_{0.95}Ga_{0.05}As$ (Fig. 10, d, c, b, a respectively). We constructed theoretical dispersion curves for the SL $(InAs)_{10}(GaAs)_1$ which contain only one branch in the LOP region shown by the dashed lines in Fig. 9, which refer to a local vibration of a Ga monolayer in InAs. The shift of this branch relative to the B_2 branch of the SL $(InAs)_{10}(GaAs)_2$ (Fig. 9) agrees well with the experimental difference between the frequencies of the RS peaks of Fig. 10, c, d. The frequencies of the peaks of vibrations of Ga atoms in a SL containing 0.5 Ga monolayer and in the solution $In_{0.95}Ga_{0.05}As$ practically coincide (Fig. 10, a, b).

CONCLUSIONS

In the present work the main features of the phonon spectrum of GaAs–InAs SL's due to folding of the acoustic phonon branches and localization of optic phonons have thus been analyzed theoretically and experimentally for the first time. It was established that built-in mechanical stresses which do not noticeably influence the acoustic spectral region, appreciably modify the optic region which, in particular, is manifest in the absence of strong localization of optic phonons in GaAs layers in $(GaAs)_k(InAs)_l$ for $l = 1, 2$. The suggestion is formulated of localized acoustic phonons in GaAs–InAs SL's for the detection of which further investigations are essential. The possibility of using results of RS spectroscopy for determining the SL period and the magnitude of the residual mechanical stresses in SL layers is demonstrated.

The authors thank A. O. Minaev for help with the computations, A. K. Gutakovskiĭ and S. M. Pintus for providing the results of electron microscope investigation of GaAs–InAs SL's.

[1)] We have limited our discussion to longitudinal vibrations since transverse vibrations do not appear in RS of SL's in the [100] orientation, but are observed in RS in SL's in other orientations.[9,10]

[2)] *DATA* and *DALA* are abbreviations for: disorder-activated *TA*-, *LA*-phonons

[1] M. Cordona, Superlattices and Microstructures **5**, 27 (1989).
[2] C. Colvard, T. A. Gant, M. V. Klein, R. Merlin, R. Fischer, H. Morkoç, and A. C. Gossard, Phys. Rev. **B31**, 2080 (1985).
[3] B. Kh. Baĭramov, T. Gant, M. Deleneĭ, Yu. É. Kitaev, M. V. Klein, D. Levi, H. Morkoç, and R. A. Évarestov, Zh. Eksp. Teor. Fiz. **95**, 2200 (1989) [Sov. Phys. JETP **68** (6), 1271 (1989)].
[4] B. H. Bairamov, R. A. Evarestov, I. P. Ipatova *et al.*, Superlattices and Microstructures **6**, 227 (1989).
[5] A. P. Shebanin, V. A. Gaĭsler, T. V. Kurochkina *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **49**, 349 (1989) [JETP Lett. **49** (6), 399 (1989)].
[6] M. Holtz, K. Syassen, and K. Ploog, Phys. Rev. **B40**, 2988 (1989).
[7] J. M. Gérard, J. Y. Marzin, B. Jusserand, F. Glas, and J. Primot, Appl. Phys. Lett. **54**, 30 (1989).
[8] T. Sakamoto, H. Finubashi, K. Ohta, T. Nakagawa, N. J. Kawai, and T. Kojima, Jpn. J. Appl. Phys. **23**, L657 (1984).
[9] Z. V. Popović, M. Cardona, E. Richter, D. Strauch, L. Tapfer, and K. Ploog, Phys. Rev. **B40**, 3040 (1989).
[10] V. A. Markov, O. P. Pchelyakov, L. V. Sokolov, and V. A. Gaĭsler, Pis'ma Zh. Eksp. Teor. Fiz. **49**, 42 (1989) [*sic*].
[11] F. Cerdeira, C. J. Buchenauer, F. H. Pollock, and M. Cardona, Phys. Rev. **5**, 580 (1972).
[12] A. K. Sood, J. Menendez, M. Cardona, and K. Ploog, Phys. Rev. Lett. **54**, 2111 (1985).
[13] E. L. Ivchenko, D. N. Mirlin, and I. I. Reshina, Fiz. Tverd. Tela (Leningrad) **17**, 2282 (1975) [Sov. Phys. Solid State **17**, 1510 (1975)].
[14] G. Lucovsky and M. F. Chen, Solid State Commun. **8**, 1397 (1970).

Translated by Robert Berman