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Anisotropy of the Velocity and Attenuation of Acoustic Waves in Gallium Arsenide Crystals

Farkhad R. AKHMEDZHANOV and Ibrat Sh. TOSHPULATOV
Institute of Ion-plasma and Laser Technologies of the Academy of Sciences of Uzbekistan,
33 Durmon yuli, 100125 Tashkent, Uzbekistan
Tel.: +998 902121998
E-mail: akhmedzhanov.f@gmail.com

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Abstract: The anisotropy of acoustic wave characteristics in gallium arsenide crystals was studied in the frequency range from 30 to 1200 MHz at room temperature. The measured values of the acoustic wave velocity and attenuation coefficient along the principal cubic directions [100], [110], and [111] were used to determine the real and imaginary components of the elasticity tensor. These data enabled construction of anisotropy surfaces for velocity and attenuation in the (001) and (110) crystallographic planes. Additionally, deviations in polarization and energy flux vectors from the wave vector direction were quantified, including the angle of internal conical refraction for degenerate transverse waves. Compared with earlier preliminary results, this study provides a comprehensive and extended analysis of the anisotropy of acoustic wave characteristics in GaAs crystals, which will be useful in the development of acousto-optic and ultrasonic devices.

Keywords: Anisotropy, Velocity and attenuation of acoustic waves, Gallium arsenide crystals, Energy flux vector, Polarization, Real and imaginary elastic constants.

1. Introduction

In this article, we investigate the anisotropy of acoustic characteristics in a non-centrosymmetric crystal of gallium arsenide (GaAs, point symmetry group 43 *m*), which, unlike silicon, is a semiconductor with a direct band gap, i.e., transitions between the valence and conduction bands require only a change in energy, making them a useful material for the manufacture of LEDs and semiconductor lasers [1, 2]. In addition, GaAs crystals exhibit optical transparency over a wide wavelength range (1-15 μm), as well as good elastic and photoelastic properties [2-4]. Thus, during light diffraction ((λ = 1.15 μm) on longitudinal acoustic waves, GaAs crystals have an acousto-optic quality factor M_2 equal to approximately $10^4 \cdot 10^{-15}$ s^3/kg [3].

The piezoelectric properties of GaAs crystals lead to strong interactions between acoustic and electronic processes, which is used to create acoustic and acousto-optic filters, as well as acoustoelectric oscillators. Combined with low acoustic losses, the high electron mobility of GaAs enables the creation of high-frequency, low-noise devices [5, 6].

One of the challenges in developing acousto-optic devices such as modulators, deflectors, and filters is determining the velocity anisotropy and attenuation coefficient of acoustic waves in crystals. Knowledge of the anisotropy of these characteristics allows for the selection of the most optimal crystal cuts used as the active medium in such devices [5, 6]. However, to date, the anisotropy of acoustic properties in these crystals has not been studied in detail. Preliminary results of our research were published in [7].

2. Experimental Methods

Gallium arsenide crystals with n-type conductivity and a room-temperature resistivity of $\rho = 3 \cdot 10^{-4}$ Ohm·m have been investigated. The samples were parallelepiped-shaped, approximately 12·6·5 mm in size, and were processed using mechanical grinding and polishing according to optical standards. The long side of the samples was oriented along the [100], [110], and [111] axes with an accuracy of no worse than 1^0. The non-parallelism of the faces perpendicular to the direction of acoustic wave propagation was no more than 30 arc seconds.

To excite longitudinal and transverse acoustic waves in the frequency range of 30–1200 MHz, quartz transducers of X- or Y-cut, respectively, with a natural resonant frequency of 30 or 40 MHz and a 4×4 mm aperture, were used. The fundamental and odd harmonics of these transducers were used. Acoustic contact between the sample and the piezoelectric transducer was created using organosilicon oil.

Measurements of the velocity and attenuation coefficient of acoustic waves at relatively low frequencies (up to 100 MHz) were carried out using a modified Williams-Lamb "pulse interference" method [8, 9], the peculiarity of which lies in the comparison of the phases of acoustic waves that have passed different paths in the studied sample. The interference zeros or maxima of the amplitude of acoustic pulses observed when changing the frequency of these waves make it possible to determine the value of the acoustic wave velocity in the sample V from the relation [8, 9]:

$$V = 2L \cdot \Delta\nu, \quad (1)$$

where L is the sample length, and $\Delta\nu$ is the difference between two adjacent frequencies of the radio generator used to generate the acoustic waves. This difference was determined using a digital frequency meter with an absolute accuracy of 10 Hz. The accuracy of determining the acoustic wave velocity was limited by the accuracy of the sample length measurement and was ~0.01 %.

Measurements of the velocity and attenuation coefficient of acoustic waves at higher frequencies (above 100 MHz) were made using the standard pulse-echo method [8]. The attenuation coefficient of acoustic waves α_{exp} was determined from the measured values of the amplitudes of adjacent pulses A_1 and A_2:

$$\alpha_{exp} = \frac{20\, lg(A_1/A_2)}{2L} \quad (2)$$

When determining the attenuation coefficient of an acoustic wave, various types of acoustic energy loss, caused by so-called geometric factors, were taken into account. In general, the value of the true attenuation coefficient α (in units of dB/cm), taking these factors into account, is written as [8]:

$$\alpha = \alpha_{exp} - \alpha_d - \alpha_n, \quad (3)$$

where α_{exp} is the experimentally determined attenuation from relation (2), α_d is the diffraction loss, the contribution of which is large at low frequencies, and α_n is the apparent attenuation caused by the non-parallelism of the reflecting faces. The values of α_d and α_n are determined by the expressions [8]:

$$\alpha_d = 1.7 \frac{V}{a^2 \cdot \nu}, \quad (4)$$

$$\alpha_n = \frac{8.68\pi^2 \nu^2 a^2 \theta^2 n}{V^2 L}, \quad (5)$$

where a is the diameter of the piezoelectric transducer, θ is the angle between the reflecting faces, n is the number of the selected reflections and ν is the frequency of the acoustic wave.

From formulas (4) and (5), it is clear that as the frequency of the acoustic wave increases, the contribution of diffraction losses decreases, while the effect of the non-parallelism of the reflecting faces on the measured attenuation value increases significantly. Overall, the accuracy of determining the attenuation coefficient α was ~10 %.

3. Experimental Results and Discussion

The characteristic surfaces of the velocity and attenuation coefficient of acoustic waves, describing the anisotropy of these characteristics, can be constructed if all real c'_{ijkl} and imaginary c''_{ijkl} components of the complex elasticity tensor c_{ijkl} are known [10-12]:

$$c_{ijkl} = c'_{ijkl} + i c''_{ijkl}. \quad (6)$$

For crystals with cubic symmetry, such as GaAs crystals, knowledge of three such independent components of the elasticity tensor are necessary. These components are easily determined if the values of the effective elastic constants $c'_{эфф}$ and $c''_{эфф}$ are known for longitudinal and transverse acoustic waves propagating along the crystal's symmetry axes.

In our studies, the values of the specified constants were determined based on the results of measuring the velocity and attenuation coefficient of acoustic waves along the main crystallographic directions [100], [110] and [111]. The obtained values are presented in Table 1, in which the following notations are introduced: **q** is the wave vector of the acoustic wave, and **η** is the polarization vector.

The values of the attenuation coefficient of acoustic waves at a frequency of 1 GHz, presented in Table 1, were obtained by extrapolating the attenuation values at a frequency of 450 MHz, assuming a quadratic dependence of attenuation on frequency, according to the Akhiezer mechanism [8]. Numerous experimental data on the attenuation of acoustic waves in crystals confirm such dependence in the frequency range from 100 MHz to 1–2 GHz [8, 9]. The attenuation coefficient values obtained by such extrapolation for some directions of gallium arsenide crystals are in good agreement with the data presented in [2].

Note that for the [100] direction, the effective elastic constants c'_{eff} and c''_{eff} coincide, respectively, with the elasticity tensor components c'_{11} and c''_{11} for longitudinal waves and c'_{12} and c''_{12} for transverse waves. The values of the components c'_{12} and c''_{12} were determined from the values of the velocity and attenuation coefficient of transverse acoustic waves along the [110] direction with polarization along the $[1\bar{1}0]$ axis. Based on these data, the values of the real (c'_{eff}) and imaginary (c''_{eff}) effective elastic constants for these transverse waves were calculated, and then the components c'_{12} and c''_{12} were calculated using the relations:

$$c'_{12} = c'_{11} - 2c'_{eff}, \tag{7}$$

$$c''_{12} = c''_{11} - 2c''_{eff}. \tag{8}$$

The following values were obtained for these components: c'_{12} = 5.28 10^{10} $N{\cdot}m^{-2}$, and c''_{12} = 3.80 10^{7} $N{\cdot}m^{-2}$.

Table. 1. Velocity of acoustic waves in GaAs crystals, acoustic attenuation (ν = 1 GHz), effective real and imaginary elastic constants at room temperature.

q	η	V, 10^3 м·с$^{-1}$	c'_{eff}, 10^{10} N·m^{-2}	α, dB·cm^{-1}	c''_{eff}, 10^7 N·m^{-2}
[100]	[100]	4.73	11.8	21.1	8,70
	[001]	3.34	5.90	19.2	2.80
[110]	[110]	5.24	14.6	16.4	9,20
	$[1\bar{1}0]$	2.48	3.26	41.1	2,45
	[001]	3.35	5.96	19.4	2.85
[111]	[111]	5.40	15.5	15.2	9,35
	[110]	2.80	4.16	30.0	2,50

It should be noted that the values of the real components of the elasticity tensor c'_{11}, c'_{12} and c'_{44} are given in many studies. The values we obtained are in good agreement with the values given in [2, 3, 7]. The accuracy of determining the real and imaginary components of the elasticity tensor was 1 % and 10 %, respectively.

The results of calculating the anisotropy of the velocity of longitudinal, fast transverse and slow transverse acoustic waves propagating in the $(1\bar{1}0)$ plane are shown in Fig. 1. Note that the concepts of "fast" and "slow" applied to transverse acoustic waves are conditional.

It is evident that the strongest velocity anisotropy is observed for slow transverse waves whose polarization vector lies in the $(1\bar{1}0)$ plane under consideration. For this wave, the ratio of the maximum to minimum velocity is 1.4.

When determining the acoustic wave attenuation coefficient in gallium arsenide crystals, in addition to energy losses due to so-called geometric factors, it is necessary to consider the energy loss of the acoustic wave due to its interaction with various elementary excitations [5, 6]. The main mechanism responsible for the attenuation of acoustic waves in crystals is the Akhiezer mechanism, caused by the interaction of acoustic waves with thermal phonons [13, 14]. A distinctive feature of this attenuation mechanism is the quadratic dependence of the attenuation coefficient on the acoustic wave frequency. Studies of attenuation by the Akhiezer mechanism make it possible, in principle, to determine such interesting characteristics of phonon spectra as anharmonicity constants and relaxation times [14].

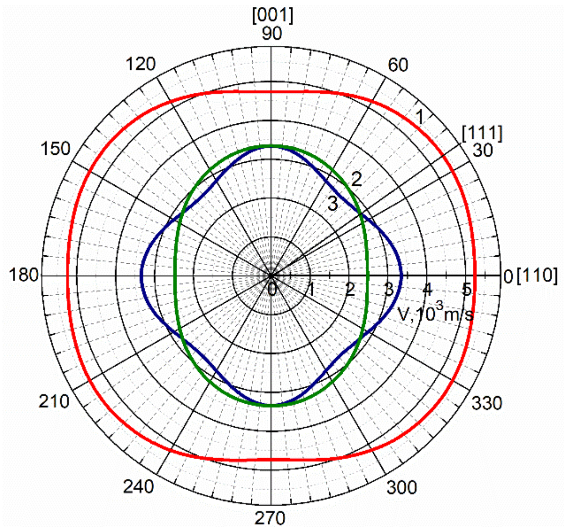

Fig. 1. Anisotropy of the velocity of longitudinal (1), slow (2) and fast (3) transverse acoustic waves in the $(1\bar{1}0)$ plane.

In addition to interaction with thermal phonons, interaction with free charge carriers can contribute to the attenuation of acoustic waves in semiconductor crystals [5]. For piezoelectric semiconductors, this interaction is determined by the fact that acoustic wave propagation in them is accompanied by alternating electric fields that act on free charge carriers [6]. For certain relationships between the frequency of acoustic waves ω and the Maxwell relaxation time $\tau_c = \varepsilon/\sigma$ (ε is the dielectric constant, σ is the electrical conductivity), when the condition $\omega\tau_c<1$ is satisfied, the expression for the electron-phonon attenuation α_{e-ph} (in units of dB/μs) is written as [5, 6]:

$$\alpha_{e-ph} = 4.34{\cdot}10^{-6}(\chi^2 \varepsilon\, \omega^2/\sigma), \tag{9}$$

where χ is the electromechanical coupling constant, ω is circular frequency of the acoustic wave/

In GaAs crystals, this mechanism can make the greatest contribution for purely transverse piezoelectric acoustic waves along the [110] direction. However, even in this case, due to the low value of the electromechanical coupling constant (on the order of $5{\cdot}10^{-2}$), the contribution of this mechanism to the attenuation of these waves can be neglected.

In addition to this interaction mechanism, which is unique to piezoelectric, the coupling of the acoustic wave with the carriers can be mediated by the strain potential, i.e., a change in the band gap width under the influence of elastic deformation. However, the latter mechanism typically results in attenuation that is significantly smaller than the attenuation caused by scattering by thermal phonons [5, 15].

Studies have shown that the frequency dependence of the attenuation coefficient of acoustic waves in gallium arsenide crystals in the studied frequency range follows a quadratic law. This dependence is valid in the range $\omega\tau \ll 1$ (where τ is the thermal phonon relaxation time), if the main attenuation mechanism is the Akhiezer mechanism, caused by phonon-phonon interaction [14].

According to this mechanism, the attenuation coefficient of acoustic waves (in units of c^{-1}) is expressed by the relation [5, 6, 8]:

$$\alpha = \frac{\beta \cdot \gamma^2 \lambda T \omega^2}{2\rho V^2 V_D^2} \tag{10}$$

Here, β is a factor of the order of unity, ρ is the density, λ is the thermal conductivity, T is the temperature, γ is the effective Grüneisen constant, and V_D is the average Debye velocity.

The effective constant of the phonon-phonon interaction (Grüneisen constant) γ^2 in (10) is determined by the expression [5, 8]:

$$< \gamma^2 > = \sum_{\vec{k},j} \gamma^2(\vec{k},j) C(\vec{k},j)/C_V, \tag{11}$$

where $C(k, j)$ is the heat capacity of the phonon branch and C_V is the heat capacity per unit volume.

According to expression (10), the temperature dependence of attenuation by the Akhiezer mechanism is determined by the temperature dependence of the thermal conductivity, and therefore the thermal phonon relaxation time. The temperature behavior of the effective anharmonicity constant can also contribute to the temperature dependence of acoustic attenuation.

The obtained values of the real and imaginary components of the elasticity tensor make it possible to calculate the attenuation of acoustic waves by the Akhiezer mechanism along an arbitrary direction of their propagation in gallium arsenide crystals, using the expression [10, 11].

$$\alpha = \frac{\omega}{2} \frac{c''_{eff}}{\cdot c'_{eff}} \tag{12}$$

In (12), the real and imaginary effective elastic constants are determined, respectively, through the components of the real c'_{ijkl} and imaginary c''_{ijkl} parts of the elasticity tensor using expressions [10].

$$c'_{эфф} = c'_{ijkl} \kappa_j \kappa_l \gamma_i \gamma_k, \tag{13}$$

$$c''_{эфф} = c''_{ijkl} \kappa_j \kappa_l \gamma_i \gamma_k, \tag{14}$$

where κ_j and γ_k are the direction cosines of the wave vector and displacement vector.

The calculations were based on experimental data and expressions (3), (4), (5), and (6). The anisotropy of the attenuation coefficient of longitudinal and transverse acoustic waves with a frequency of 1 GHz propagating in the (001) plane is shown in Fig. 2.

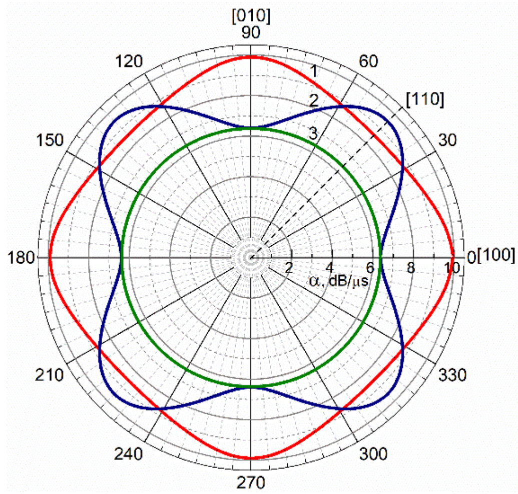

Fig. 2. Cross-section of the surface of the attenuation coefficient of longitudinal (1), slow transverse (2) and fast transverse (3) acoustic waves by plane (001).

It is evident that the strongest anisotropy of the attenuation coefficient in this plane is observed for slow transverse waves whose polarization lies in the same (001) plane. The ratio of the maximum to the minimum attenuation for these waves is 1.5.

The orientation dependences of the attenuation coefficient of longitudinal and transverse acoustic waves propagating in the $(1\bar{1}0)$ plane are shown in Fig. 3. It can be seen that in this plane, the strongest anisotropy of the attenuation coefficient of acoustic waves is observed for slow transverse waves, for which the ratio of the maximum to the minimum value is also equal to 1.5.

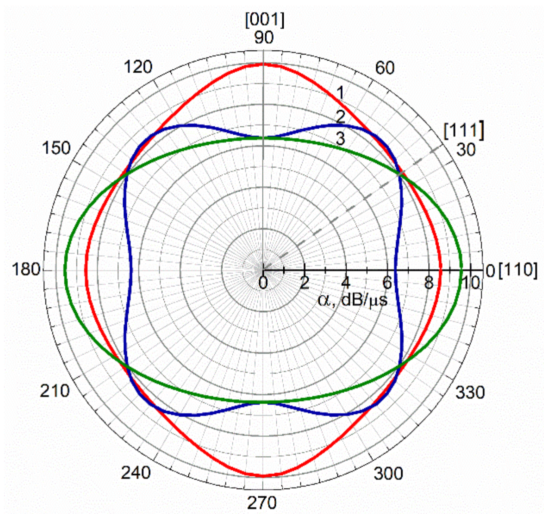

Fig. 3. Cross-section of the surface of the attenuation coefficient of longitudinal (1), fast transverse (2) and slow transverse (3) acoustic waves by plane $(1\bar{1}0)$.

Note that all three rotational symmetry axes of cubic crystals are represented in Fig. 3: [001], [110], and [111]. It is evident that the following regularities are observed for attenuation of longitudinal (α^L), fast transverse (α^{FS}), and slow transverse (α^{SS}) acoustic waves:

$$\alpha^L_{[001]} > \alpha^L_{[110]} > \alpha^L_{[111]}, \quad (15)$$

$$\alpha^{SS}_{[110]} > \alpha^{SS}_{[111]} > \alpha^{SS}_{[001]} = \alpha^{FS}_{[110]} \quad (16)$$

Such dependencies are characteristic of cubic crystals, in which the imaginary acoustic anisotropy parameter A'' is less than unity. This parameter is determined by the imaginary elastic constants using the expression:

$$A'' = \frac{c''_{11} - c''_{12}}{2c''_{44}} \quad (17)$$

Substituting the obtained values of the components of the imaginary part of the elasticity tensor into relation (17) yields for gallium arsenide crystals a value of A'' equal to 0.87. Thus, the nature of the anisotropy of the attenuation coefficient of longitudinal and transverse acoustic waves in any crystal of cubic symmetry can be determined in advance if the value of the imaginary parameter of acoustic anisotropy is known.

To fully describe the anisotropy of a crystal's acoustic properties, it is necessary to know the nature and extent of the deviation of the polarization vector and energy flow vector directions in an acoustic wave from the direction of the wave vector itself.

The most interesting case is the propagation of longitudinal and transverse waves (generally, quasilongitudinal and quasitransverse) in the $(1\bar{1}0)$ plane of symmetry, in which the deviations of the polarization and energy flow vectors are located in the same plane.

The direction of the polarization vector of a quasilongitudinal wave propagating in the $(1\bar{1}0)$ plane will be characterized by the angle ψ_L, which is the angle between the direction of this vector and the [110] axis. This angle is determined using an expression easily obtained from the Green-Christoffel system of equations by substituting the corresponding values of the real part of the effective elastic constant and the real components of the Green-Christoffel tensor Γ'_{ik} [2, 4]. As a result, we obtain the expression:

$$\psi = arctg\left(\frac{\sqrt{2}\Gamma'_{13}}{c'_{eff} - \Gamma'_{13}}\right) \quad (18)$$

The component Γ'_{13} in expression (18) is determined by the relation:

$$\Gamma'_{13} = \frac{1}{\sqrt{2}}(c'_{12} + c'_{44}) sin\varphi \cdot cos\varphi, \quad (19)$$

where the angle φ specifies the direction of the wave vector of the longitudinal acoustic wave in the $(1\bar{1}0)$ plane relative to the [110] axis.

It is obvious that the direction of the polarization vector of a quasi-transverse wave propagating in the same plane $(1\bar{1}0)$ and determined by the angle ψ_S will differ from the corresponding angle ψ_L all the time by +90 or -90 degrees (the choice is ours), due to the condition of mutual perpendicularity of the polarization vectors of these waves.

The calculation results in the form of dependence of the deviation of the polarization vectors of quasilongitudinal and quasitransverse waves on the direction of their propagation in the plane $(1\bar{1}0)$ are shown in Fig. 4 (curves 1 and 3). Since this plane is perpendicular to the axis of symmetry of the second order, the calculation data are presented in the range of angles from 0 to 180 degrees. Angles are measured from the [110] direction.

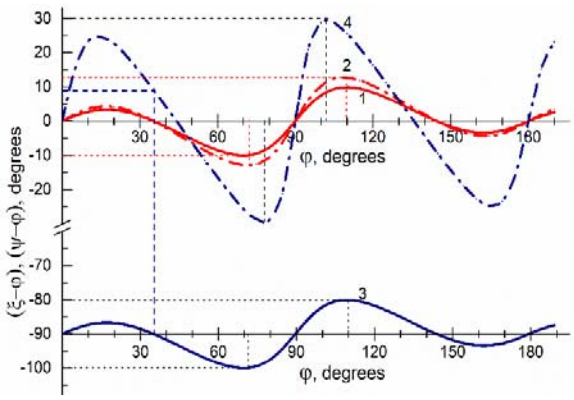

Fig. 4. Deviation of the directions of polarization and energy flow of quasilongitudinal (1, 2) and quasitransverse (3, 4) waves from the direction of their propagation in the $(1\bar{1}0)$ plane. Angles are measured from the [110] direction.

It is evident that for these waves the maximum deviation of the polarization vector from the wave normal, equal to approximately ±10 degrees, is observed when the wave normal is directed in the plane $(1\bar{1}0)$ at angles close to 72 or 110 degrees relative to the [110] axis.

One of the characteristics of acoustic waves in crystals, in addition to velocity and polarization, is the direction of energy flow in the acoustic wave (the Umov-Poynting vector). Knowing the direction of energy flow is essential when conducting experiments with acoustic waves, and especially when measuring the velocity and attenuation of acoustic waves.

Longitudinal acoustic waves propagating along the axes of symmetry [001], [110], and [111] are purely longitudinal, and therefore also ordinary. The direction of energy transfer (the direction of the acoustic ray) in them coincides with the direction of wave propagation [5, 6]. At the same time, a transverse acoustic wave along these axes, while remaining purely transverse, will be ordinary only when propagating along the axes

[001] and [110]. When propagating along the [111] axis, the energy flow in it will be deflected due to the phenomenon of internal conical refraction [16].

In this case, when the polarization vector in a transverse wave rotates around a third-order axis, the energy flux vector describes a cone around this axis [4, 8]. For cubic crystals, the opening angle of this cone θ for transverse acoustic waves propagating along the third-order symmetry axis [111] is given by the formula [16]:

$$\theta = arctg\left[\frac{c'_{11}-c'_{12}-2c'_{44}}{\sqrt{2}(c'_{11}-c'_{12}+c'_{44})}\right] \quad (20)$$

When the displacement vector in such a wave is in the $(1\bar{1}0)$ plane, the energy flux vector lies in the same plane at an angle of θ/2 to the direction of propagation. Calculation using formula (20) yielded a value of 9.32 degrees for this angle.

For other directions of propagation of quasilongitudinal and quasitransverse waves in the $(1\bar{1}0)$ plane, the direction of the energy flow vector in them was determined by the angle ξ between the direction of this vector and the [110] axis. This direction was determined through the components of the group velocity vector $\boldsymbol{V}_g$ of an acoustic wave with a wave normal **κ** and polarization $\boldsymbol{\eta}$ [6, 12]:

$$V_{gi} = \frac{1}{\rho V} c'_{ijkl}\kappa_k \eta_j \eta_l \quad (20)$$

The calculated dependencies showing the deviation of the direction of the energy flow from the direction of the wave vector of quasilongitudinal (curve 2) and quasitransverse (curve 4) acoustic waves in the plane $(1\bar{1}0)$ are also shown in Fig. 4. It can be seen that in the plane under consideration, the maximum deviation of the energy flux vector in a quasilongitudinal wave from the wave normal, equal to approximately 13 degrees, is observed when the wave normal is directed in the $(1\bar{1}0)$ plane at angles close to 72 or 110 degrees relative to the [110] axis. Thus, for quasilongitudinal waves in this plane, the directions of the maximum deviation of polarization and energy flux from the wave vector coincide.

For quasitransverse waves, the maximum deviation of the energy flux vector from the wave normal, equal to approximately 30 degrees, is observed when these waves propagate at angles close to 78 or 102 degrees relative to the [110] axis.

4. Conclusions

The velocity and attenuation coefficient of acoustic waves propagating along the main symmetry axes in gallium arsenide crystals were determined. These values were used to obtain the real and imaginary components of the elasticity tensor, allowing for the analysis of the anisotropy of acoustic wave characteristics.

It is shown that the greatest anisotropy of the velocity and attenuation coefficient is observed for purely transverse acoustic waves propagating in the $(1\bar{1}0)$ plane with polarization along the [100] axis. For these waves, the attenuation coefficient changes by a factor of one and a half when the direction of propagation changes from the [110] axis to the [001] axis.

The directions of maximum deviation of the polarization vector and energy flow from the wave vector of quasilongitudinal and quasitransverse acoustic waves propagating in the plane $(1\bar{1}0)$ have been determined. It was shown that for quasilongitudinal waves this maximum deviation is 10 degrees, and for quasitransverse waves it is 30 degrees. The angle of internal conical refraction for transverse waves propagating along the three-fold axis [111] in gallium arsenide crystals has been determined to be 9.32 degrees.

The revealed features of the anisotropy of the velocity and attenuation coefficient of acoustic waves can be used in the development of acoustic delay lines, acousto-optic modulators and deflectors in the infrared region of light based on GaAs crystals.

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