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Piezoelectrically active acoustic waves confined in a quantum well and their amplification by electron drift

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Abstract. Recently we have studied how the drift of two-dimensional electrons amplifies the acoustic waves confined in quantum wells. The electron-phonon interaction was considered to be due to deformation potential. Here we generalize the theory for the case of piezoelectric electron-phonon interaction. For transverse piezoelectrically active waves in sphalerite-type crystals we obtained solution in the form of localized waves and determined the amplification factor α under the drift of two-dimensional electrons. At frequencies of the order of tens GHz and drift fields of several V/cm α is about tens of cm^{-1}.

Keywords: acoustic waves, two-dimensional electrons, quantum well, piezoelectric electron-phonon interaction.

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1. Introduction

In a previous paper [1] we considered mixed acousto-charge waves localized in a quantum well. The electron-phonon interaction was assumed to realize via deformation potential. It was shown that the localized acoustic waves could be efficiently amplified at high frequencies by the drift of two-dimensional (2D) electrons.

Here we deal with a similar problem for the case of piezoelectric electron-phonon interaction in crystals. This case is of particular interest, since the most advanced technology exists for the quantum heterostructures based on III-V compounds that demonstrate considerable piezoelectric effect [2, 3].

2. Model and basic equations

Let us consider a cubic crystal of sphalerite type (crystal symmetry class T or T_d). In such a crystal its piezoelectric modulus $\beta = -\left(\frac{\partial \sigma}{\partial E}\right)_u = \frac{1}{4\pi}\left(\frac{\partial D}{\partial u}\right)_E$ has the only independent component $\beta_{14} = \beta_{25} = \beta_{36} = \beta$ (here σ, u, E, D are the stress tensor, strain tensor, electric field and electric displacement, respectively). In a bulk material there exist two piezoelectrically active acoustic modes, namely, longitudinal and transverse (polarized in the [001] azimuth), oriented along the [111] and [110] directions, respectively. In what follows we shall consider the transverse mode only.

Let us define the coordinate system in the following way: the coordinate axes X, Y, Z are oriented along the [110], [001] and [1$\bar{1}$0] directions, respectively. There is a layer $2d$ thick in the XY-plane. The matter density, ρ, in this layer differs from the density $\bar{\rho}$ in the rest of the bulk. (In what follows all the quantities beyond the layer will be marked with an overscribed bar.) Let the ratio $\rho/\bar{\rho}$ be equal to g; the elastic modulus is $C_{44} \equiv C = \bar{C}$, the piezoelectric modulus is $\beta = \bar{\beta}$ and the permittivity is $\varepsilon = \bar{\varepsilon}$.

Our model closely resembles the following heterostructure: GaAs layer in AlAs bulk, with elastic moduli and densities differing by 1% and 40%, respectively. There are charge carriers in the layer whose concentration is a sum of the equilibrium concentration, N, and a nonequilibrium term $n(x, z, t) = n(z)\, e^{iqx - i\omega t}$. $n(z)$ is an even function of z (it will be specified later); at the layer boundaries $n(\pm d) = 0$. The dependence of n on x, t is assumed to be the same as that of all the variable quantities. In the coordinate system used the elastic displacement vector, $\vec{U}$, has the only nonzero component, $U_y \equiv U$.

The problem studied is homogeneous along the Y-axis. The electric field $\vec{E} = -\nabla\phi$ is assumed to lie in the XZ-plane.

In the defined coordinate system the equations of state for the medium are of the following form:

$$\sigma_{xy} = C\frac{\partial U}{\partial x} - \beta E_x\ ;\ \sigma_{yz} = C\frac{\partial U}{\partial z} + \beta E_z\ ;$$

$$D_x = \varepsilon E_x + 4\pi\beta\frac{\partial U}{\partial x}\ ;\ D_z = \varepsilon E_z - 4\pi\beta\frac{\partial U}{\partial z}\ . \quad (1)$$

Let us present the equation of movement, $\rho\frac{\partial^2 U}{\partial t^2} = \frac{\partial\sigma_{xy}}{\partial x} + \frac{\partial\sigma_{yz}}{\partial z}$, and equation for the electric displacement, $\operatorname{div}\vec{D} = 4\pi en$ (here e is the carrier charge), within the layer ($|z| < d$) in the following form:

$$U'' - k_s^2 U - \frac{\beta}{C}\left(q^2\phi + \phi''\right) = 0 \quad (2)$$

$$\frac{4\pi\beta}{\varepsilon}\left(U'' + q^2 U\right) + \phi'' - q^2\phi = -\frac{4\pi e}{\varepsilon}n \quad (3)$$

(here prime denotes derivative with respect to z). Outside of the layer ($|z| > d$) the equations are of similar form but with zero right-hand side ($\bar{n} = 0$).

Let us also introduce the following notation:

$$q_s^2 = \frac{\omega^2}{V_s^2} = \frac{\rho\omega^2}{C}\ ;\ q_p^2 = \frac{q_s^2}{1+K^2} = \frac{\omega^2}{V_p^2}\ ;\ K^2 = \frac{4\pi\beta^2}{\varepsilon C}\ ;$$

$$k_{s,p}^2 = q^2 - q_{s,p}^2\ ;\ \bar{q}_{s,p}^2 = \frac{1}{g}q_{s,p}^2\ . \quad (4)$$

After eliminating ϕ'' from equations (2), (3), one obtains the following expression for the potential:

$$\phi = \frac{C}{2\beta q^2\left(1-K^2\right)}\left[U'' - \left(k_p^2 - 2q^2K^2\right)U\right] + \frac{1}{2q^2}\frac{4\pi e}{\varepsilon}n\ . \quad (5)$$

Substitution of (5) to (2) gives the following equation in $U(z)$:

$$U'''' - \left(q^2 + k_p^2 - 4q^2K^2\right)U'' + q^2k_p^2U = -\frac{4\pi e}{\varepsilon}\frac{\beta}{C}\left(1-K^2\right)\left(n'' + q^2 n\right) \quad (6)$$

The characteristic equation

$$P(\alpha) \equiv \alpha^4 - \left(q^2 + k_p^2 - 4q^2K^2\right)\alpha^2 + q^2k_p^2 = 0 \quad (6a)$$

determines four roots α_i: $\alpha_{1,2} = \pm\alpha_+$; $\alpha_{3,4} = \pm\alpha_-$. If one neglects the terms proportional to K^4 and higher powers of K, then one obtains the following approximate expressions for these roots:

$$\alpha_+ = q\left(1 - \frac{2q^2}{q_p^2}K^2\right);\ \alpha_- = k_p\left(1 + \frac{2q^2}{q_p^2}K^2\right). \quad (7)$$

The right-hand side of Eq. (6) is an even function of z. Assuming that all the roots of the characteristic equation are simple (a possibility of multiple roots will be discussed later) and selecting from the general solution of the homogeneous equation the even part only, one gets the even solution of the inhomogeneous Eq. (6):

$$U(z) = A\cosh\alpha_+ z + B\cosh\alpha_- z + Y(z) \quad (8)$$

$$Y(z) = \frac{4\pi e\beta}{\varepsilon C}\frac{1-K^2}{\alpha_+^2 - \alpha_-^2}\Bigg[n(0)\left(\cosh\alpha_+ z - \cosh\alpha_- z\right) - \frac{\alpha_+^2 + q^2}{2\alpha_+}J_-(\alpha_+, z) + \frac{\alpha_-^2 + q^2}{2\alpha_-}J_-(\alpha_-, z)\Bigg] \quad (9)$$

According to (5), one obtains the following expression for potential:

$$\phi(z) = \frac{C}{2\beta q^2}\left(Q_- A\cosh\alpha_+ z + Q_+ B\cosh\alpha_- z\right) + \frac{4\pi e}{2\varepsilon q^2}\frac{1-K^2}{\alpha_+^2 - \alpha_-^2}\Bigg(Q_-\left[n(0)\cosh\alpha_+ z - \frac{\alpha_+^2 + q^2}{2\alpha_+}J_-(\alpha_+, z)\right] - Q_+\left[n(0)\cosh\alpha_- z - \frac{\alpha_-^2 + q^2}{2\alpha_-}J_-(\alpha_-, z)\right]\Bigg) \quad (10)$$

Here the notation

$$Q_\pm = q^2\left(1 - K^2\right) - \alpha_\pm^2\left(1 + K^2\right) \quad (11)$$

is used. The integrals $J_-(\alpha_\pm, z)$ and their properties are given in [1].

The even solution outside of the layer ($|z| > d$) that is damping as $z \to \pm\infty$ is:

$$\bar{U}(z) = \bar{A}e^{-\bar{\alpha}_+|z|} + \bar{B}e^{-\bar{\alpha}_-|z|}; \quad (12)$$

$$\bar{\phi}(z) = \frac{C}{2\beta q^2}\left[\bar{Q}_-\bar{A}e^{-\bar{\alpha}_+|z|} + \bar{Q}_+\bar{B}e^{-\bar{\alpha}_-|z|}\right] \quad (13)$$

The four constants (A, B, $\bar{A}$, $\bar{B}$) may be determined from the boundary conditions at $z = d$:

1) $U = \bar{U}$; 2) $\phi = \bar{\phi}$; 3) $\frac{\partial\phi}{\partial z} = \frac{\partial\bar{\phi}}{\partial z}$; 4) $\frac{\partial U}{\partial z} = \frac{\partial\bar{U}}{\partial z}$.

3. Free piezoelectrically active acoustic waves

Since the expressions for boundary conditions are too cumbersome, we do not present them here. Only the determinant D of the corresponding set of equations is given for the case of small half-width d ($qd << 1$):

$$D = -e^{-(\bar{\alpha}_+ + \bar{\alpha}_-)d}\left(\bar{\alpha}_+ - \bar{\alpha}_-\right)\left(\alpha_+^2 - \alpha_-^2\right)\left(\Delta_0 + d\Delta_1\right); \quad (14)$$

$$\Delta_0 = q\bar{k}_p\left(\bar{\alpha}_+ + \bar{\alpha}_-\right)\left(1 + K^2\right)^2; \quad (14a)$$

$$\Delta_1 = q\bar{k}_p\left(1+K^2\right)\left\{q^2\left(1-3K^2\right)+\left(1+K^2\right)\bar{k}_p^2\right\}+ \\ +q^2\left(1+K^2\right)^2\left(k_p^2+\bar{k}_p^2\right) \quad (14b)$$

Expressions for the case of arbitrary d are not given because (i) they are too cumbersome, (ii) the piezoelectric interaction is essential at lower frequencies (i.e., at smaller q) than the interaction via deformation potential. For a piezoelectric the free waves in our layered medium are qualitatively similar to those in the case of deformation potential [1].

Of special interest is the case of resonance when, at a preset frequency ω, the wave vector is close to those values that turn the determinant D (14) into zero. This condition determines a dispersion law for the free localized waves that can propagate in our composite medium. If one of the factors in parentheses in the expression (14) for D turned into zero, this would mean that there exist multiple roots of the characteristic polynomial (6a), either in the layer ($\alpha_+ = \alpha_-$) or outside of it ($\bar{\alpha}_+ = \pm\bar{\alpha}_-$). We have constructed the general solution in the case of multiple roots and found that a new determinant of the set of equations for boundary conditions does not turn into zero. This means that no such free waves exist in our medium at small d.

Thus, when D turns into zero, this means that $\Delta_0 + d\Delta_1 = 0$ (14a, 14b). Since we are searching for localized solutions, then $\bar{k}_p$ (or $\bar{\alpha}_-$) has to be real, i.e., $q > \bar{q}_p$. Therefore $\Delta_0 > 0$ and it should be that $\Delta_1 < 0$. The term in braketes in (14b) is positive. So the case $\Delta_1 < 0$ might be realized when $k_p^2 < 0$ (i.e., $q < q_p$). Hence it follows that $q_p^2 > \bar{q}_p^2$. This means that the localized wave may exist only at $g = \frac{\rho}{\bar{\rho}} > 1$, i.e., the inner medium has to be «heavier».

In this work we use a model in which elastic properties are the same in the layer and outside of it, but the densities differ. When elastic constants are different for the media in the layer and outside of it, then the localized wave is realized (even at the same densities) if the inner medium is more «soft». At different elastic constants a passage to the limit (vacuum) is possible inside the layer. In this case the wave turns into two Gulyaev-Bleustein waves [4, 5] in the upper and lower half-spaces. These two waves that are coupled through the vacuum with electric field make the so-called slot wave. It has been considered by a number of authors (see [6, 7]).

From the equation $\Delta_0 + d\Delta_1 = 0$ it follows that $\bar{k}_p \propto d$. Therefore, being within the framework of linear (in d) approximation, we have to omit $\bar{\alpha}_- \approx \bar{k}_p$ (but leave $\bar{\alpha}_+ \approx q$) in Δ_0 and omit in D_1 all the terms that are $\bar{k}_p \propto d$. As a result, we obtain that near the resonance:

$$\Delta_0 + d\Delta_1 = q^2\left[\bar{k}_p - q^2(g-1)d\left(1+2K^2\right)\right] \equiv q^2 F_1(q).$$

Thus the dispersion law for the zero branch is determined by the following equation:

$$F_1(q) \equiv \bar{k}_p - q^2(g-1)d\left(1+2K^2\right) = 0. \quad (15)$$

This equation is completely similar to the Eq. (16) [1] for deformation potential.

At a fixed frequency the solution of the Eq. (15) is:

$$q_0 = \bar{q}_p\left[1 + \frac{1}{2}\bar{q}_p^2 d^2 (g-1)^2\left(1+2K^2\right)^2\right]. \quad (16)$$

4. Amplification of localized acoustic waves

When an interaction with charge carriers exists, then in Eq. (15) a nonzero right-hand side, $R_1(q)$, appears. (Its explicit form will be given later.) As a result, we obtain

$$\bar{k}_p = q_0^2(q-1)d\left(1+2K^2\right) + R_1(q) \quad (17)$$

instead of (15). Solution of equation (17) at a fixed frequency determines wave vector $q(\omega)$:

$$q - q_0 = R_1(q_0)\left[q_0(g-1)\left(1+2K^2\right)d + \frac{R_1(q_0)}{2q_0}\right] \quad (18)$$

Substituting in (10), (12) and (13) the constants found from the set of equations for boundary conditions, one obtains the expressions for $\phi(z)$ in the layer and $\bar{\phi}(z)$, $\bar{U}(z)$ outside it. It is easy to verify that to calculate interaction with charge carriers in the case of a thin layer one needs only to know the potential (or longitudinal effective field $E^* = -iq\phi$) value at $z = 0$.

Near the resonance one gets after straightforward but cumbersome operations:

$$E^*(0) = -i\frac{4\pi e}{2\varepsilon}\left(1 - K^2\frac{q}{F_1(q)}\right)n_s, \quad (19)$$

Here the 2D concentration of charge carriers is introduced:

$$n_s = \int_{-d}^{d} n(z)dz \quad (20)$$

The solutions outside of the layer ($|z| > d$) are as follows:

$$\overline{U}(z)=\frac{4\pi e}{\varepsilon}\frac{\beta}{C}\frac{n_s}{2R_1(q)}\times$$
$$\times\left[2\frac{\overline{k}_p}{q}e^{-q\left(1-2K^2\right)\left(|z|-d\right)}-e^{-\overline{k}_p\left(1+2K^2\right)\left(|z|-d\right)}\right]; \qquad (21)$$

$$\overline{\phi}(z)=\frac{4\pi e}{\varepsilon}\frac{n_s}{2R_1(q)}\times$$
$$\times\left[\frac{\overline{k}_p}{q}e^{-q\left(1-2K^2\right)\left(|z|-d\right)}-e^{-\overline{k}_p\left(1+2K^2\right)\left(|z|-d\right)}\right] \qquad (22)$$

One can see that they involve two terms. The first term, of small amplitude (near the resonance $\overline{k}_p \propto d$) is damping rather quickly at distances about q^{-1}. The second one is of bigger amplitude; it is damping (slower than the first term) at distances $\sim \overline{k}_p^{-1}$.

To this point it was assumed that both the force with which electrons are acting on the crystal lattice and electron concentration are preset. To obtain explicit forms of these functions, one has to solve a problem: how to construct the electron states and electron transport in the layer. This problem has been solved in [1] for the case when the electron-phonon interaction was realized via deformation potential, with the following suppositions. The longitudinal motion of electrons in the layer was considered using the quasi-classical approach. The transverse motion was considered for the two limiting cases, namely, (i) quantum well – the potential well is so narrow that there is the only (lowest) filled subband, and one can neglect the transitions to higher subbands; (ii) classical well – the number of filled subbands is so great that the transverse motion may be also considered using the quasi-classical approach.

In [1] the longitudinal acoustic wave has been considered, while here we deal with the transverse one. Nevertheless, the calculation of electron kinetics under drift in the field of a sonic wave is quite similar to that in [1], and so will not be presented here. Several replacements, however, are to be made in the expressions of [1]. They are as follows.

1. First of all, one has to replace in all the expressions of [1] the velocity of longitudinal wave, V_L, with that of transverse piezoelectrically active wave, V_P: $V_L \to V_P$.

2. Second, from comparison between the dispersion equation (16) for free waves given in [1] and that presented in this work (15) one may conclude that the following replacement has to be made in the expressions of [1]: $(h-1) \to (g-1)(1+2K^2)$.

3. And, at last, comparing the expression (51) for the effective field given in [1] to that given in this work (19), one may find the following replacement for the coupling constants: $G\omega^2 \to K^2$.

In this work we restricted ourselves by consideration of the most urgent case of a quantum well and high frequencies when $ql > 1$ (here l is the electron mean free path). After performing the above replacements in expression (55) of the work [1], one obtains that the function $R_1(q)$ (that enters expression (17)) is of the following form:

$$R_1(q)=qK^2Lq\frac{1+\frac{1+\eta^2}{Lq}+i\eta}{(1+Lq)^2+\eta^2}, \qquad (23)$$

$$\eta=\frac{V_P}{V_F}\left(1-\frac{V_d}{V_P}\right) \qquad (24)$$

Here we introduced the shielding length in 2D electron gas, $L=\frac{\hbar^2\varepsilon}{2e^2m}$; 2D Fermi velocity, $V_F=\frac{\hbar}{m}\sqrt{2\pi N_s}$; equilibrium surface concentration of electrons, N_s; electron effective mass, m; drift velocity, $V_d = mE_0$; constant electric field, E_0; mobility, μ.

At a fixed frequency the wave vector is determined by expression (18). Let us omit the second term in the right-hand side of (18) (this term is of essence for a medium that is uniform from the very beginning). According to (16), one obtains $q_0 \approx \overline{q}_p$. The left-hand side of expression (18) may be presented as

$$q-\overline{q}_P=-\frac{\Delta\overline{V}_P}{\overline{V}_P}\overline{q}_P+i\frac{\alpha}{2} \qquad (25)$$

Let us define the sound velocity renormalization:

$$\frac{\Delta\overline{V}_P}{\overline{V}_P}=\frac{\overline{V}_P'-\overline{V}_P}{\overline{V}_P},$$

Here $\overline{V}_P$ ($\overline{V}_P^{\prime}$) is the initial (renormalized) velocity of an acoustic wave outside of the layer. Then one can get from (23):

$$\frac{\Delta\overline{V}_P}{\overline{V}_P}=-K^2(qd)(g-1)\left(1+2K^2\right)\frac{1+Lq+\eta^2}{(1+Lq)^2+\eta^2},$$
$$q=\overline{q}_P(\omega) \qquad (26)$$

For the absorption coefficient (amplification factor) one obtains

$$\alpha(\omega)=2K^2q(qd)Lq(g-1)(1+2K)\frac{\eta}{(1+Lq)^2+\eta^2},$$
$$q=\overline{q}_P(\omega) \qquad (27)$$

When $V_d > V_P$, then, according to expression (24), $h < 0$ and $\alpha < 0$, i.e., we get amplification of the acoustic wave localized in a quantum well. The amplification factor a grows monotonically with frequency. The power of this dependence is less by two than in the case of deformation potential [1].

It should be noted that piezoelectric interaction between the acoustic wave and drifting 2D electrons has been considered in [3]. Our results differ from those obtained by the author of [3], since he dealt with bulk (non-localized) waves.

5. Discussion of results

To perform numerical estimations, let us consider the AlAs/GaAs/AlAs quantum heterostructure with the following parameters [2, 3, 8]: ρ = 5.317 g/cm^3; $\bar{\rho}$ = =3.76 g/cm^3; $g \equiv \frac{\rho}{\bar{\rho}} = 1.4$; C = 0.594×10^{12} dyne/cm^2; ε = 12.85; $m = 0.067 m_0$; $K^2 = 3.6\times10^{-3}$. Using the above values, one gets $L = 0.5\times10^{-6}$ cm. Let the equilibrium electron concentration N_s be equal to 2×10^{12} cm^{-2} and the layer half-width d be equal to 10^{-6} cm. Then Fermi velocity $V_F = \frac{\hbar}{m}\sqrt{2\pi N_s}$ = 5.6×10^7 cm/s and Fermi wavelength $\lambda_F = \sqrt{\frac{2\pi}{N_s}}$ =1.8×10^{-6} cm. At these values the quantum limit is realized for electrons. Let us take 25 GHz for frequency, i.e., ω = 1.57×10^{11} s^{-1}. Then q_p = 0.47× ×10^6 cm^{-1}, $\bar{q}_p$ = 0.39×10^6 cm^{-1}, $L\bar{q}_p$ = 0.195. At this frequency the sonic wavelength $\frac{2\pi}{\bar{q}_p}$ = 16×10^{-6} cm is over λ_F, so one may use the classical approach when considering the acoustic wave and its interaction with electrons. If one takes the mobility μ = 10^5 V·cm^2/s, then the electron mean free path l = 1.6×10^{-4} cm, i.e., the case ql >>1 is realized. Absorption gives way to amplification at a field E_0 = 3.35 V/cm. If one takes the value of 100 V/cm for field at the above parameter values, then the amplification factor is 10 cm^{-1}.

According to expression (25), the sound velocity renormalization is negative and equals about 0.05%. The power in the expression for transverse damping of the localized piezoelectrically active acoustic wave outside of the layer is determined by (21), (22). At the chosen parameter values the wave intensity is decreased by e times over a distance about six wavelengths.

For comparison with the interaction via deformation potential (considered in [1]), let us estimate also the amplification factor at the same frequency of 100 GHz that was chosen in [1]. Although the coupling constants are practically the same at this frequency (in [1] $G\omega^2$ = 3.9× ×10^{-3}, while K^2 = 3.6×10^{-3}), the amplification factor turns out to be 300 cm^{-1}, (i.e., five times as much). This is related primarily to the fact that in this paper we took into account a big (g = 1.4) difference between the densities of the layer with a quantum well and its surroundings, and also to the fact that the velocity of transverse wave is below that of longitudinal wave (considered in [1]).

Thus we have shown that at piezoelectric interaction the drifting 2D electrons may efficiently amplify the high-frequency acoustic vibrations localized near the layer with a quantum well. If the values of piezoelectric interaction parameters are those characteristic of the AlGaAs/GaAs heterostructures, then the sound amplification factor exceeds tens of cm^{-1} at frequencies over 25 GHz.

It is pertinent to note that quantum wells based on the AlGaN/GaN heterostructures are to demonstrate even higher amplification factors for high-frequency phonons, since for the wide-gap III-V compounds of GaN/AlGaN-type piezoelectric interaction is at least an order of magnitude bigger than that for AlGaAs/GaAs [9, 10].

Conclusions

We have shown that in piezoelectrically active crystals the drift of 2D electrons may serve as an efficient method for amplification (generation) of high-frequency acoustic phonons. Our method, along with those proposed in [11], demonstrates a novel approach to electrogeneration of coherent phonons (e.g., phonon generation with fast optical pulses).

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