Charge-Carrier Drift Influence on the Electroacoustic Interactions in Piezoelectric Semiconductors with Induced Chiral Properties

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Abstract

Effects of charge-carrier drift on the electroacoustic interactions in piezoelectric semiconductors with spatial dispersion and induced chiral properties is studied. The wave numbers and ellipticities of eigenmodes of acoustic waves are found and effects of charge-carrier drift are investigated. Boundary-value problem for a slab under rotating electric field influence is solved.

1. Introduction

In the literature, electroacoustic interactions in media having dielectric and conducting properties are well known. A possibility to control acoustic wave polarization by electric field inducing artificial spiral anisotropy was shown by Belyi and Sevruk [1]. The availability of charge carriers in semiconductors allows to influence on the character of interaction of acoustic waves with external electric fields. Charge carriers interact with the electric field of waves in crystal. The character of interaction can be changed by external constant electric field with strength $\mathbf{E}'$. Under the action of this field, the electrons in a crystal start moving. Their averaged motion is described as electron drift with the velocity $\mathbf{v}_0 = -\mu\mathbf{E}'$, where μ is the electron mobility in the crystal. The objective of this study is to take into account a complex of various effects, i.e., the charge-carrier drift influence on the electroacoustic interaction in piezoelectric semiconductors with induced chiral properties and spatial dispersion. Below, we report the results of the study of electroacoustic interactions in piezoelectric semiconductors with spatial dispersion in rotating electric fields with due regard for the charge-carrier drift influence.

2. Theory and Discussion

Rotating bias electric field can be created by the electrodes which are placed on the wall of a waveguide [2]. The phase shift between the fields in electrode pairs is determined by the number of electrodes, and for the case two pairs of electrodes is $\frac{\pi}{2}$. We assume that the electric field rotates around the x axis and the incident wave propagates also along the same x axis. In practice, the change of the elastic constant of media under external electric field influence can reach 10 per cent. Acoustic properties of a semiconductor crystal (without a center of symmetry) which is placed into a rotating electric field can be described by the following constitutive relations taking into account spatial dispersion and piezoelectric effect [2]:

$$\sigma = c\gamma + b\frac{\partial\gamma}{\partial x} + g\mathbf{E}_0\varepsilon_0\varepsilon\mathbf{E}, \qquad \mathbf{D} = \varepsilon_0\varepsilon\mathbf{E} - \varepsilon_0\varepsilon g\mathbf{E}_0\gamma. \tag{1}$$

Here σ, γ, c, and b are tensors of tensions, deformations, elastic constants and acoustic gyration, respectively (scalar multiplication of tensors is implied). g is a tensor of rank four, $g\mathbf{E}_0$ is tensor of rank three, taking into account piezoelectric effect induced by the rotating electric field, ε_0 is the electric constant, ε is the relative permittivity of the medium. Electric field of propagating wave $\mathbf{E}$ consists of two components:

$$\mathbf{E} = \mathbf{E}_1 + \mathbf{E}', \tag{2}$$

where $\mathbf{E}_1$ is the longitudinal electric field created by piezoelectric effect, and $\mathbf{E}'$ is the external constant longitudinal electric field. $\mathbf{E}_0$ is the strength vector of the rotating electric field. The equation for the current density should contain terms that take into account the interaction of acoustic wave with external longitudinal electric field:

$$\mathbf{j} = -e(N_0 + n)(\mathbf{v}_0 + \mathbf{v}) \approx -eN_0 - eN_0\mathbf{v}_0 - en\mathbf{v}_0, \tag{3}$$

where n is the change in electron concentration induced by the acoustic wave, e is the unit charge. Electron velocity is $\mathbf{v}_0 + \mathbf{v}$, where $\mathbf{v}_0$ is velocity component due to the drift in bias electric field $\mathbf{E}'$, and N_0 is the equilibrium carrier concentration. In accordance to [2], the solution to the equation of elastic wave propagation is sought in the form of coupled plane monochromatic waves:

$$\mathbf{u} = [A_+\mathbf{n}_+e^{-i(\omega-\Omega)t} + A_-\mathbf{n}_-e^{-i(\omega+\Omega)t}]e^{ik(\omega)x} \tag{4}$$

having equal wavenumbers $k(\omega)$, different frequencies $\omega \pm \Omega$ and opposite circular polarizations described by vectors $\mathbf{n}_\pm = (\mathbf{y}_0 \mp i\mathbf{z}_0)/\sqrt{2}$, where $\mathbf{y}_0$ and $\mathbf{z}_0$ are the unit vectors of the Cartesian coordinate system. Here ω_0 is the incident acoustic wave frequency, Ω is the rotating electric field frequency, and $\omega = \omega_0 - \Omega$. As a result, we can arrive at the system of equations for the amplitudes which allows to determine the wavenumbers and ellipticities of eigenmodes. We have considered the case when on the crystal border $x = 0$ circularly polarized acoustic wave

$$\mathbf{u}_e = u_0\mathbf{n}_- \exp[-i\omega_0 t] \tag{5}$$

with frequency $\omega_0 \approx \Omega$ is incident. Displacement vector of this acoustic wave has the same rotation direction as the external electric field. This wave can interact in resonance with rotating electric field because its frequency is near to the rotation frequency of the anisotropy structure formed by the electric field. As a result of interaction of propagating wave with rotating electric field in crystal amplification of the transmitted wave and generation of reverse wave are possible [1, 2]. The displacement vectors of these waves on the crystal borders ($x = 0$ and $x = L$, L is the crystal thickness) can be described as follows:

$$\mathbf{u}_\tau = u_\tau\mathbf{n}_- \exp[-i\omega_0 t + ik_0L], \quad \mathbf{u}_c = u_c\mathbf{n}_+ \exp[-i(\omega_0 - 2\Omega)t]. \tag{6}$$

Acoustic field in the crystal can be represented in the form of a superposition of two eigenmodes:

$$\mathbf{u} = \sum_{m=1}^{2} A_m \left(\mathbf{n}_-e^{-i\omega_0 t} + \xi_m^{-1}(\omega_0 - \Omega)\mathbf{n}_+e^{-i(\omega_0-2\Omega)t} \right) e^{ik_m(\omega_0-\Omega)x} \tag{7}$$

where $\xi_m = \frac{A_-}{A_+}$ is the ratio of the amplitudes of eigenwaves.

¿From the condition of continuity of the displacement vectors on the crystal borders we can obtain system of the following equations:

$$\sum_{m=1}^{2} A_m = u_0, \quad \sum_{m=1}^{2} A_m\xi_m^{-1}(\omega_0 - \Omega)e^{ik_m(\omega_0-\Omega)L} = 0,$$

$$\sum_{m=1}^{2} A_m e^{ik_m(\omega_0-\Omega)L} = u_\tau e^{ik_0L}, \quad \sum_{m=1}^{2} A_m\xi_m^{-1}(\omega_0 - \Omega) = u_c. \tag{8}$$

The solution of this system allows to determine the amplitudes of reflected and transmitted acoustic waves.

3. Numerical results

Calculations have been made with the following values of parameters [2]: $m^* = 0.0145\ m_e$ (m_e is the electron mass), $\Omega = 10^9$ radn/s, $\nu = 10^{13}\ \mathrm{s}^{-1}$, $T = 300$ K, $c = 10^{11}\ \mathrm{N/m^2}$, $\rho = 5.7{\cdot}10^3\ \mathrm{kg/m^3}$, $\beta = 10^{-2}$, $b = 14.4$ N/m. The dependence of the wavenumbers of eigenmodes on the frequency is presented in Figure 1 (left). ¿From Figure 1(left) we can see that charge-carrier drift influence is displayed as a shift of diagrams. The dependence of the intensity of the transmitted waves normalized to the intensity of the incident waves (transmission coefficients) on the frequency is presented in Figure 1 (right). Analysis of numerical results leads us to the conclusion that charge-carrier drift influence can be a cause of a shift of the maximum of the transmission coefficients. The direction of the shift depends on the direction of carrier drift. When charge-carrier drift direction coincides with the incident wave propagation direction we can see an increase of the transmission coefficient. This effect can be explained by interaction of acoustic wave and electron "clouds". When charge-carrier drift direction is the opposite to the incident wave propagation direction we can see a shift of maxima of the transmission coefficient to the lower frequency region. The dependence of the intensity of the reflected waves as functions of the crystal thickness is presented in Figure 2 (left) in the logarithmic scale (the basis of logarithm is 10). When the crystal thickness L corresponds to the resonance condition [2], the reflection coefficients have periodic resonances. Spatial dispersion influence can be a cause of a decrease of the crystal thickness corresponding to maxima of the reflection coefficients. The influence of electron drift on the changing of the crystal thickness corresponding to maximum of reflection coefficients is much smaller than the spatial dispersion influence. Rotation of the polarization plane dependence on the incident wave frequency is presented in Figure 2 (right). The influence of charge-carrier drift exhibits as a change of the angle of rotation of the polarization plane in the case of resonant interaction. Charge-carrier drift influence leads to a shift of diagrams, and the relative change of the maximal rotation power can reach 2. Natural acoustic activity is comparable with the chiral properties of crystal induced by rotating electric fields.

4. Conclusion

Wave numbers and ellipticities of acoustic eigenmodes in semiconductors without a center of symmetry which are placed into rotating electric field have been found. So called *two-wave approximation* has been used to find the solution of the boundary-value problem. The transmission and reflection coefficients dependence on the incident wave frequency and crystal thickness have been studied. Found characteristics of transmitted and reflected waves have been compared with the results for semiconductors with spatial dispersion without charge-carrier drifts. The obtained results can be used for the design of devices that can rotate the polarization plane of ultrasound [3].

References

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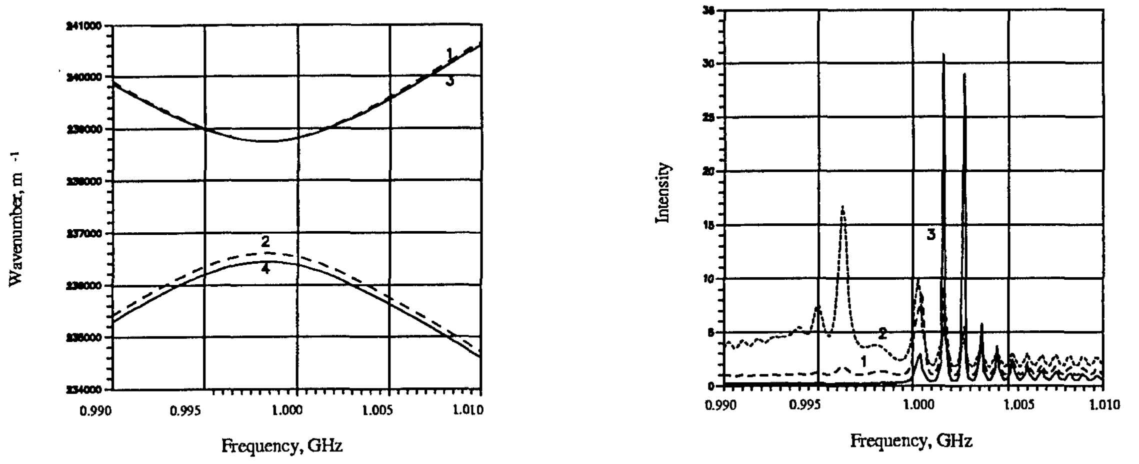

Figure 1: left)The wavenumbers of eigenmodes as functions of the frequency. Dashed lines (1 $-k_1$, 2 $-k_2$) correspond to the crystal without charge-carrier drifts, and solid lines (3 $-k_1$, 4 $-k_2$) correspond to the crystal with a charge-carrier drift; right) The intensity of the transmitted wave as a function of the frequency. 1 corresponds to the intensity of the transmitted wave without charge-carrier drift; 2 corresponds to the intensity of the transmitted wave taking into account charge-carrier drift ($v_0 = -10v_t$); 3 corresponds to the intensity of the transmitted wave taking into account charge-carrier drift ($v_0 = 10v_t$).

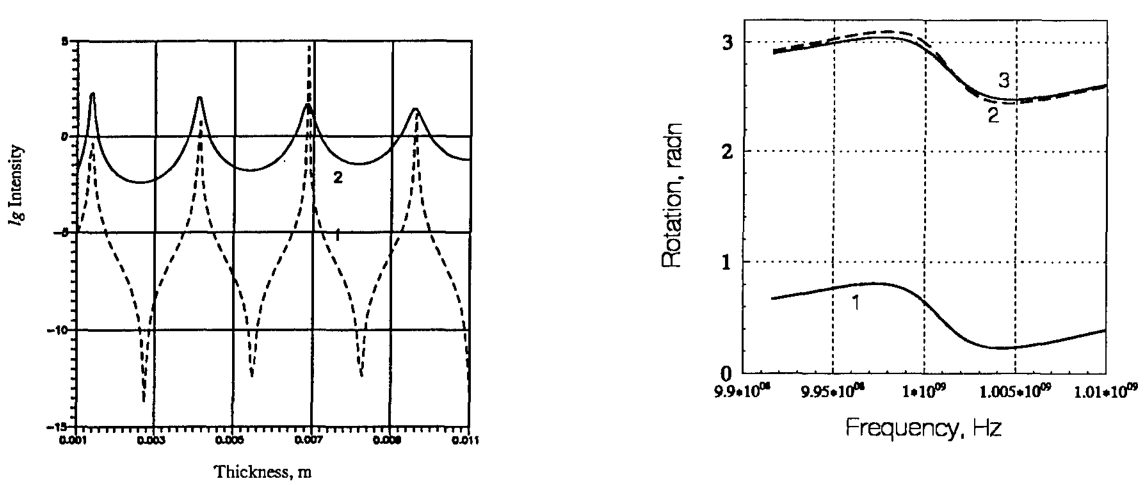

Figure 2: left) The intensity of the reflected waves as a function of the crystal thickness. 1 corresponds to the intensity of the reflected wave without charge-carrier drifts, and 2 corresponds to the intensity of the reflected wave taking into account charge-carrier drift ($v_0 = \pm 10v_t$); right) Rotation of the polarization plane dependence on the incident wave frequency ω: 1 corresponds to the crystal with the charge-carrier drift direction which is opposite to the incident wave propagation direction; 2 corresponds to the crystal with charge-carrier drift direction which coincides with the incident wave propagation direction; 3 corresponds to the crystal without charge-carrier drift.