RP Current Trends In Applied Sciences (e-ISSN: 2583-7486)
Vol. 4, No. 3 (July – September 2025) pp. 55–62

Cite this article: Pravesh, Gain characteristics of the acoustic wave in the homogeneous semiconductor quantum plasma, *RP Cur. Tr. Appl. Sci*. **4** (2025) 55–62.

Original Research Article

Gain characteristics of the acoustic wave in the homogeneous semiconductor quantum plasma

Pravesh*

Department of Physics, Baba Mastnath University, Asthal Bohar, Rohtak – 124021, Haryana, India
*Corresponding author, E-mail: praveshlamba004@gmail.com

ARTICLE HISTORY
Received: 8 May 2025
Revised: 31 July 2025
Accepted: 1 August 2025
Published: 2 August 2025

KEYWORDS
Quantum hydrodynamic model; Phonon-plasmon interaction; Acoustic wave gain; Density gradient; Quantum parameter (H).

ABSTRACT
The quantum hydrodynamic model is used to report the phonon-plasmon interaction in a magnetized inhomogeneous semiconductor quantum plasma. An evolution equation for the acoustic wave's gain coefficient is obtained by using a quantum modified dispersion relation. The scale length of density variation parameter (L) and the non-dimensional quantum parameter (H) are used in this work to account for inhomogeneity and quantum effects, respectively. These factors, along with the angular frequency ω, magnetic field orientation θ, and propagation distance z, are examined in relation to the acoustic wave's gain characteristics. These studies are conducted both with and without a magnetic field for density patterns that fluctuate linearly and quadratically. The findings suggest that the gain characteristics of the acoustic wave in the inhomogeneous semiconductor quantum plasma would be determined mostly by the magnetic field and linearly or quadratically variable density structures.

1. Introduction

The ability of acoustic waves to interact significantly with plasma particles is their dynamical property in plasma environments, setting them apart from other electromagnetic spectrum waves [1-4]. In order to explain the electronic, optical, and transport properties of semiconductor materials and their use in the fabrication of devices at the ultrasonic range, it is crucial to have a thorough understanding of the interaction between the plasma wave and lattice vibrations (acoustic wave) in the semiconductor plasma [5–9]. By exchanging energy between phonons and plasmons, this interaction amplifies or attenuates acoustic waves in semiconductor plasma medium. Acoustic wave amplifiers [10–12], acoustic charge transport [13] based on the acousto-electric effect, acoustic wave resonators [14], and other intriguing and noteworthy phenomena have been better understood as a result of this. It has been discovered that the collective oscillation of the lattice can readily be coupled strongly with plasma wave through piezoelectricity in piezoelectric semiconductors, which are excellent candidates for converting mechanical energy to electrical energy or vice versa [15–17]. Furthermore, the crucial spectral features of the acoustic wave propagation in the semiconductor plasma are provided by the medium's piezoelectricity. Based on the piezoelectric interaction between phonons and plasmons, a number of acoustic wave characteristics have been thoroughly investigated in this context [14, 18].

The study of many facets of acoustic waves in plasma medium has attracted a lot of attention because of its possible uses in the production of acoustic devices. Numerous studies have been conducted to examine the properties of acoustic waves in plasma from different perspectives [19–22]. However, the plasma medium is typically taken to be homogeneous in the majority of these findings. However, the majority of genuine plasmas are not homogenous, and the properties of waves alter depending on the local environment as they pass through them. Temperature and/or density gradients may be the cause of the plasma's inhomogeneity. Therefore, it is interesting to investigate the potential implications of inhomogeneity on the basic behavior of acoustic waves non plasma medium. A lot of scholars have recently focused on studying acoustic phenomena in inhomogeneous plasma medium [23–25].

However, a significant area of study has been the properties of acoustic wave propagation in the magnetized plasma. Since the properties of plasmas can change when the magnetic field is applied, it is well known that plasmas are significantly influenced by the magnetic field [26–28]. One of the earliest areas of study in plasma physics is the behavior of various waves in plasmas when a magnetic field is present. As a result, numerous physicists have written pertinent studies using a variety of plasma models [29–31].

The electrical characteristics of semiconductor devices are the most significant and far-reaching technological implications of contemporary solid state physics. The semiconductors used in the majority of these devices have non-uniform carrier concentrations. It is well known that the existence of a Lorentz force prevents a system from achieving perfect homogeneity under crossed fields geometry. Additionally, a complete homogenous crystal cannot be grown experimentally. Conversely, non-uniform doping or exposure to non-uniform radiation can cause a material to become inhomogeneous. A plasma current or particle drift is present if the system has a gradient of density, temperature, pressure, magnetic field, etc.; if not, the gradient alters the particle drift or plasma current when a dc electric field is present. In semiconductors, impurity doping can typically result in the development of linearly or quadratically changing plasma density patterns. These kinds of structures with different plasma densities increase the energy of drifting carriers by several orders of magnitude. In order to investigate the phonon-plasmon interaction through piezoelectricity and its effects, we choose the inhomogeneous semiconductor plasma as our medium in this research. Impurities in the semiconductor make it denser by injecting free plasma carriers in excess. Quantum effects are also not negligible in such a thick plasma [32–34]. Because of its enormous nano-scale applicability, semiconductor quantum plasma has thus garnered a lot of interest from plasma researchers for over 10 years [35, 36]. Furthermore, when a uniform magnetic field is present in the surrounding environment, the semiconductor quantum plasma may support a range of plasma waves. However, there aren't many reports in the literature about this topic [37–39]. The ratio of the plasmon energy to the Fermi energy of free carriers is how the non-dimensional quantum parameter-H affects plasma media. According to recent findings [40, 41] that mention the quantum parameter-H, its existence may have a major impact on the wave properties of semiconductor plasmas. Therefore, it would appear beneficial to thoroughly examine how the magnetic field, quantum parameter-H, and inhomogeneity affect the phonon-plasmon interaction in the piezoelectric semiconductor plasma.

2. Theoretical formulations

Our goal is to examine how the magnetic field affects the phonon-plasmon interaction in the quantum plasma of an inhomogeneous semiconductor. For this, we consider an n-type piezoelectric semiconductor as medium, whose carrier charge and effective mass are $-e$ and m and assume the shear acoustic wave and electron plasma wave to be propagating in the z-direction. Furthermore, the medium is subjected to a dc electric field $\vec{E}_0$ along the negative z-direction and magneto-static field $\vec{B}_0$ at an arbitrary orientation θ with propagation direction z in the x-z plane. Under plane wave approximation, we assume that all perturbed quantities, responsible for the interaction of phonons and plasmons, vary as: $\exp[i(\omega t - kx)]$; here, ω and k are the angular frequency and wave vector, respectively.

Using a scale length of density variation parameter $L(z)(= n_0)/\nabla n_0(z))$, we take into account the consequences of inhomogeneity in our investigation of the phonon-plasmon interaction in inhomogeneous plasma media. Here, $\nabla n_0(z)$ is the varying plasma density structure, essentially a function of propagation distance z. The variation in the plasma density structure $(n_0(z))$ may be considered either as linear or quadratic along the direction of wave propagation. The plasma density structures are given by

$$n_0(z) = n_0[1 + f(z)];$$

in which $f(z) = \dfrac{z}{L(z)}$ is for the linearly varying profile,

and $f(z) = \dfrac{z^2}{L^2(z)}$ is for the quadratically varying profile.

Here, n_0 is the ambient plasma density at $z = 0$.

We have taken into consideration the quantum hydrodynamic description of the plasma in order to characterize the nature of plasmons in the medium. The continuity and momentum transfer equations are the two key components of this paradigm. The addition of components related to Fermi degenerate pressure and Bohm potential to the momentum transfer equation distinguishes the quantum hydrodynamic (QHD) model from the classical fluid model. Therefore, the QHD model's set of linearized equations for an inhomogeneous medium with a magnetic field present can be expressed as follows:

$$\frac{\partial n_1}{\partial t} + n_0(z)(\nabla.\vec{v}_1) + \vec{v}_0(\nabla.n_1) + \vec{v}_1(\nabla.n_0(z)) = 0 \tag{1}$$

$$\left(\frac{\partial \vec{v}_1}{\partial t} + \vec{v}_0 \nabla.\vec{v}_1\right) + \nu\vec{v}_1 + (\vec{v}_1 \times \omega_c) = -\frac{e}{m}(\vec{E}_1) - \frac{1}{mn_0(z)}\left(\nabla P_1(z) - \frac{\hbar^2 \nabla(\nabla^2 n_1)}{4m}\right) \tag{2}$$

Here, n_1, v_0, ν, and $\hbar$ stand for the perturbed electron number density, drift velocity of electrons due to dc electrostatic field E_0, momentum transfer collision frequency, and Planck constant, respectively. $\omega_c (= eB_0/m)$ is the electron cyclotron frequency due to applied magnetic field $\vec{B}_0$. $P_1(z) = mv_F^2 n_1$ is the Fermi pressure with $v_F = (2k_B T_F/m)^{1/2}$ as the Fermi velocity; k_B and T_F are the Boltzmann constant and Fermi temperature.

In the present theory, we consider non-dimensional quantum parameter $H(z)$ (= plasmon energy/Fermi energy) and scale length of density variation $L(z)$ as important parameters. The quantum parameter- takes care of the effects of quantum corrections through Fermi degenerate pressure and Bohm potential. Hence, continuity and momentum transfer equations of the QHD model in terms of parameters $L(z)$ and $H(z)$, under plane wave approximation, may now be rewritten as:

$$\frac{n_1}{n_0(z)} = \frac{\left[\vec{k}.\vec{v}_1\left\{1 + \frac{i}{(kL(z))}\right\}\right]}{\left[\omega - \vec{k}.\vec{v}_0\left\{1 - \frac{i}{(kL(z))}\right\}\right]} \tag{3}$$

$$\left(\frac{\partial \vec{v}_1}{\partial t}+\vec{v}_0\nabla.\vec{v}_1\right)+\nu\vec{v}_1+(\vec{v}_1\times\vec{\omega}_c)=-\frac{e}{m}(\vec{E}_1)-v_F^2\left(1+\frac{k^2v_F^2}{4\omega_p^2(z)}H^2(z)\right)\frac{\nabla n_1}{n_0(z)}\ . \tag{4}$$

Here, $\omega_p(z)=[e^2n_0(z)/m\varepsilon]^{1/2}$ is the electron plasma frequency, in which $\varepsilon(=\varepsilon_0\varepsilon_L)$ is the permittivity of the medium with lattice dielectric constant ε_L. $H(z)=\hbar\omega_p(z)/2k_BT_F$ is the non-dimensional quantum parameter measuring the relevance of quantum effects and is proportional to quantum diffraction.

As we are interested in electrostatic or space-charge branch of the spectrum, we will consider only the z-component of time varying velocity v_z, which may be determined by using the QHD relation (Eq. (4)) for the considered field geometry, as:

$$v_z=\frac{i(e/m)}{F_Q(\omega,k)}E_z \tag{5}$$

$$F_Q(\omega,k)=\left[\omega-kv_0-i\nu-\nu D_Fk^2\left(1+\frac{k^2v_F^2}{4\omega_p^2(z)}\right)H^2(z)\frac{\left(1+\frac{i}{(kL(z))}\right)}{\omega-kv_0\left(1-\frac{i}{(kL(z))}\right)}\right]+\left(\frac{\omega_{cx}^2(\omega-kv_0-i\nu)}{\omega_{cx}^2-(\omega-kv_0-i\nu)^2}\right)$$

Here, $\omega_{cx}=\omega_c\sin\theta$, $\omega_{cz}=\omega_c\cos\theta$, and $D_F=v_F^2/\nu$ stands for the diffusion constant at Fermi temperature.

The last term in the expression of $F_Q(\omega,k)$ stands for the contribution made by cyclotron frequency of electrons in the medium induced due to the presence of external magnetostatic field $\vec{B}_0$ applied at an arbitrary angle θ with propagation direction z in the x-z plane. This term results from the $\vec{v}_1\times\vec{\omega}_c$ term on the LHS of the QHD relation (Eq. (4)). We may infer from this last term that for $\theta=0$, $\omega_{cx}(=\omega_c\sin\theta)$ becomes equal to zero, then this term vanishes. Hence, one may conclude that applied external magneto-static field $\vec{B}_0$ does not affect the interaction when $\theta=0$ ($\vec{B}_0 \parallel \vec{k} \parallel \hat{z}$ in our case) or in other words when magneto-static field $\vec{B}_0$ is applied along the direction of wave propagation. Therefore, the magnetic field (B_0) should be applied across the direction of wave propagation in order to evaluate its effect on the wave spectrum. It has been discovered that transverse magneto-static fields significantly improve the acousto-electric effect, especially in III-V semiconductors like InSb, GaSb, and GaAs. This is because a sufficiently large transverse magnetic field can induce the creation of high resistance domains. For a given B_0, the enhancement of the acousto-electric effect becomes greater as the electron mobility increases. The particular case of n-InSb is of interest because, without B_0, avalanche breakdown occurred before any acousto-electric effects could be observed.

Now under plane wave approximation, substituting Eqs. (3) and (5) in Maxwell's equation $\nabla.\vec{D}=-en_1$, the displacement vector may be obtained as:

$$D=\frac{(n_0(z)e^2/m)}{F_Q(\omega,k)}\frac{\left(1+\frac{i}{(kL(z))}\right)}{\omega-kv_0\left(1-\frac{i}{(kL(z))}\right)}E_z\ . \tag{6}$$

It is one of the two relations that we require in order to obtain the dispersion relation that we desire.

Coherent lattice vibrations cause the acoustic wave to travel through semiconductors. Phonons can be used to explain these vibrations. Through the piezoelectricity of semiconductor media, the plasma wave efficiently accompanies the acoustic wave. The lattice is displaced when the semiconductor medium is subjected to stress T because of its elastic nature. We employ the phenomenological theory created by White [10] and Steele and Vural [42] to describe the equations that control such displacements and the waves connected to them. Because we have considered shear acoustic wave propagating along the z-direction, we may consider its displacement u_x in the x-direction that is related to a strain component S following the relation:

$$S=\frac{1}{2}\frac{\partial u_x}{\partial z}\ . \tag{7}$$

The lattice and electric displacement motion can be represented using the one-dimensional piezoelectric crystal electromechanical equations as follows:

$$(-\rho\omega^2+Ck^2)u_x=ik\bar{e}E_z \tag{8}$$

$$D=\varepsilon E_z+2\bar{e}S\ . \tag{9}$$

The electric displacement component in terms of phonons can now be determined by applying Eqs. (7) and (8) in (9).

$$D=\varepsilon E_z\left[1+\frac{\bar{e}^2k^2}{\varepsilon(-\rho\omega^2+Ck^2)}\right]. \tag{10}$$

The required phonon-plasmon interaction in the piezoelectric inhomogeneous semiconductor quantum plasma in the presence of a magnetic field is expressed by the quantum modified dispersion relation, which may be obtained by comparing Eqs. (6) and (10).

$$(\omega^2-k^2v_s^2)\left[1-\frac{\left(1+\frac{i}{(kL(z))}\right)\omega_p^2(z)}{\left\{\omega-kv_0\left(1-\frac{i}{(kL(z))}\right)\right\}F_Q(\omega,k)}\right]=K^2k^2v_s^2 \tag{11}$$

Here, $K^2 = \bar{e}^2/\varepsilon C$ is the dimensionless electro-mechanical coupling constant and $v_s = (C/\rho)^{1/2}$ is the velocity of sound in the medium. Relation (11) suggests that the coupling between acoustic and quantum plasma waves in an inhomogeneous semiconductor plasma medium is caused by this electromechanical coupling constant. It also serves as a gauge for piezoelectric strength. As $\bar{e} \to 0$, i.e., in the absence of piezoelectricity, the coupling parameter vanishes and Eq. (11) leads to two independent modes, which are:

$$(\omega^2 - k^2 v_s^2) = 0 \tag{12}$$

$$\left[1 - \frac{\left(1 + \frac{i}{(kL(z))}\right)\omega_p^2(z)}{\left\{\omega - kv_0\left(1 - \frac{i}{(kL(z))}\right)\right\}F_Q(\omega,k)}\right] = 0\,. \tag{13}$$

Inhomogeneity, quantum correction, and magnetic field have no effect on the normal sound mode propagating through an elastic medium, as represented by Eq. (12). In contrast, the plasma mode, represented by Eq. (13), is significantly impacted by inhomogeneity, quantum parameter-H, and magnetic field. Therefore, the interaction between electrons and acoustic vibrations in the medium is represented by Eq. (11).

One of the basic interaction processes in piezoelectric semiconductors is the interaction between mobile electrons and acoustic vibrations. The interaction provides valuable insights into the host medium's band structure. Commercial applications of the amplification of acoustic waves through the application of a dc electric field to piezoelectric semiconductors include the creation of oscillators, delay lines, and acousto-electric amplifiers. The following is the fundamental physics of acoustic wave amplification in piezoelectric semiconductors: In essence, the regularly stressed areas in a piezoelectric semiconductor create an ac electric field when an auditory wave passes over them. This causes conduction electrons to react, which causes the electrons to be redistributed in space. At the same face where the sonic wave leaves the sample, the electrons ultimately group together. A dc field is created in the sample as a result. The acoustic wave is attenuated if a dc electric field is allowed to flow because it transfers energy from the wave to electrons. Conversely, if the electrons' drift velocity is somewhat greater than the wave velocity, a dc current will amplify an acoustic wave. On the potential curve's back slopes, the electrons will subsequently clump.

If the dispersive and dissipative properties are completely understood, the medium's properties and wave characteristics may be better explained. Since the principle aim of this paper is to achieve a better insight to these properties, we shall study the amplification characteristics of the acoustic wave in piezoelectric semiconductor medium by evaluating its attenuation coefficient (α). The dispersion relation Eq. (11) is a fourth order polynomial with the complex coefficient in terms of complex wave vector $\vec{k}$. The real part of $\vec{k}$ will deliver the dispersive properties whereas the imaginary part will cater the dissipative property of the wave. It is not easy to solve a fourth order polynomial analytically. Hence, we evaluate the acoustic gain per unit length ($\alpha\omega/v_s$) in the piezoelectric inhomogeneous semiconductor quantum plasma by following the method reported by White under the assumption that collision frequency dominates over all other frequencies ($\omega, k\bar{v}_0 \ll \nu$) [10]. Under this physically valid approximation for the semiconductor, the dispersion relation (Eq. (11)) may be rewritten as:

$$1 - \left(\frac{kv_s}{\omega}\right)^2 = iK^2\left[\omega - kv_0\left(1 - \frac{i}{(kL(z))}\right) - \frac{iD_F k^2}{\varphi}\left(1 + \frac{k^2 v_F^2}{4\omega_p^2(z)}H^2(z)\right)\left(1 + \frac{i}{(kL(z))}\right)\right]$$
$$\times\left[\left(\frac{\omega_R(z)}{\varphi}\right)\left(1 + \frac{i}{(kL(z))}\right) + i\left\{\omega - kv_0\left(1 - \frac{i}{(kL(z))}\right) - \frac{iD_F k^2}{\varphi}\left(1 + \frac{k^2 v_F^2}{4\omega_p^2(z)}H^2(z)\right)\left(1 + \frac{i}{(kL(z))}\right)\right\}\right]^{-1}. \tag{14}$$

Here, $\omega_R(z) = \omega_p^2(z)/\nu$ is the dielectric relaxation frequency and $\varphi = (1 + \omega_c^2/\nu^2)/(1 + \omega_{cz}^2/\nu^2)$.

Now to obtain the solution of the above dispersion relation (Eq. (14)), we will follow the standard approximation reported by Steele and Vural [42], which is $(kv_s/\omega) = 1 + i\alpha$, where α, the gain per radian, $\ll 1$. Using this approximation, the dispersion relation (Eq. (14)) leads to an expression for gain per unit length in terms of attenuation coefficient $\ll 1$, which may be obtained as follows:

$$\left[1 - (1 + i\alpha)^2\right] = iK^2\left[\omega - kv_0\left(1 - \frac{i}{(kL(z))}\right) - \frac{iD_F k^2}{\varphi}\left(1 + \frac{k^2 v_F^2}{4\omega_p^2(z)}H^2(z)\right)\left(1 + \frac{i}{(kL(z))}\right)\right]$$
$$\times\left[\left(\frac{\omega_R(z)}{\varphi}\right)\left(1 + \frac{i}{(kL(z))}\right) + i\left\{\omega - kv_0\left(1 - \frac{i}{(kL(z))}\right) - \frac{iD_F k^2}{\varphi}\left(1 + \frac{k^2 v_F^2}{4\omega_p^2(z)}H^2(z)\right)\left(1 + \frac{i}{(kL(z))}\right)\right\}\right]^{-1}$$

$$[-2i\alpha + \alpha^2] = iK^2\left[\omega - kv_0\left(1 - \frac{i}{(kL(z))}\right) - \frac{iD_F k^2}{\varphi}\left(1 + \frac{k^2 v_F^2}{4\omega_p^2(z)}H^2(z)\right)\left(1 + \frac{i}{(kL(z))}\right)\right]$$

$$\times\left[\left(\frac{\omega_R(z)}{\varphi}\right)\left(1+\frac{i}{(kL(z))}\right)+i\left\{\omega-kv_0\left(1-\frac{i}{(kL(z))}\right)-\frac{iD_Fk^2}{\varphi}\left(1+\frac{k^2v_F^2}{4\omega_p^2(z)}H^2(z)\right)\left(1+\frac{i}{(kL(z))}\right)\right\}\right]^{-1}.$$

Since $\alpha^2 \ll 1$, therefore by neglecting α^2 from LHS and then equating the imaginary parts from both sides, the above equation reduces to the following form:

$$\frac{\alpha\omega}{v_s}=\frac{\frac{1}{2}K^2\frac{\omega_R(z)}{v_s\varphi}\left(\gamma-\frac{v_0}{\omega kL^2(z)}\right)}{\left(\frac{\omega_R(z)}{\omega\varphi}\right)^2\left\{1+\frac{\omega^2\left(1+\frac{k^2v_F^2}{4\omega_p^2(z)}H^2(z)\right)}{\omega_R(z)\omega_{DF}}-\frac{v_0\varphi}{L(z)\omega_R(z)}\right\}^2+\left\{\gamma-\frac{D_Fk}{\omega L(z)\varphi}\left(1+\frac{k^2v_F^2}{4\omega_p^2(z)}H^2(z)\right)-\frac{\omega_R(z)}{\omega kL(z)\varphi}\right\}^2}. \tag{15}$$

Positive values of $\alpha\omega/v_s$ imply the amplification of the acoustic wave, and negative values stand for attenuation

or loss. Here, $\omega_{DF}=v_s^2/D_F$ is the diffusion frequency at Fermi temperature and $\gamma=(v_0/v_s)-1$. The above equation expresses the gain coefficient, which decides the amplification of the acoustic wave, in terms of quantum parameter-*H*, scale length of density variation L, and magnetic parameter φ.

For classical homogeneous plasma medium ($H\rightarrow 0$, $\nabla n_0(z)\rightarrow 0$, this dispersion relation (Eq. (15)) reduces to Eq. (8-44) of Steele and Vural [42]. Hence, this quantum modified dispersion relation for inhomogeneous medium is expected to give modified results.

3. Results and discussion

Our main goal in this research is to investigate the acoustic wave gain profiles in the magnetized inhomogeneous semiconductor quantum plasma. This can be achieved by considering inhomogeneity and quantum corrections through the scale length of density parameter L and non-dimensional quantum parameter-*H*. n-InSb semiconductor, subjected to an external magnetic field, is taken as a suitable medium for our numerical study. The typical parameters of the n-InSb semiconductor plasma at 77K are: $m=0.014m_0$, where m_0 is the free electron mass, $\varepsilon_L=17.54$, $\nu=3.5\times10^{11}$ s^{-1}, $\bar{e}=0.054$ Cm^{-2}, and $\rho=5.8\times10^3$ kgm^{-3}.

We have displayed in Figures 1–5 the dependence of gain per unit length $\alpha\omega/v_s$ on quantum parameter-*H*, scale length of density variation parameter-L, propagation distance z, angular frequency ω, and orientation angle θ of magnetic field (B_0). All these curves are drawn both for linearly and quadratically varying density structures (LVDS and QVDS).

Figure 1 depicts the change in gain per unit length $\alpha\omega/v_s$ due to non-dimensional quantum parameter-*H*. Four curves in the figure correspond to the absence ($B_0=0$) and presence ($B_0\neq 0$) of the magnetic field, for LVDS and QVDS. The figure infers that the magnitude of ($\alpha\omega/v_s$) is a decreasing function of quantum parameter-*H* in all cases. The decreasing nature of ($\alpha\omega/v_s$) reflects that as the magnitude of quantum parameter-*H* increases, the rate of transfer of energy between phonons and plasmons reduces, which in turn makes the plasma wave more energetic and subsequently acoustic wave becomes more stable. It is also observed from this figure that, at lower values of *H*, ($\alpha\omega/v_s$) is larger for LVDS, while for QVDS, ($\alpha\omega/v_s$) is larger towards higher *H*. This figure also illustrates that the magnitude of ($\alpha\omega/v_s$)is smaller for $B_0\neq 0$ for both the density structures, i.e., LVDS and QVDS. Hence, one may conclude that the applied magneto-static field has a stabilizing effect on phonon-plasmon interaction in the inhomogeneous semiconductor quantum plasma.

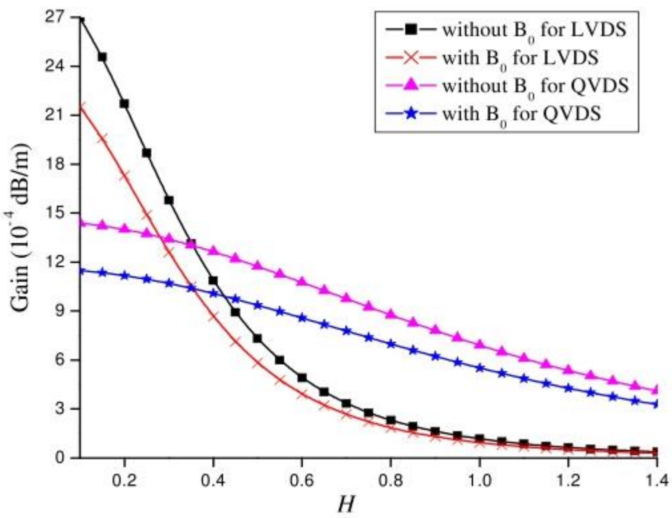

Figure 1: $\alpha\omega/v_s$ versus H at $L=0.005$ m, $z=0.02$ m, $B_0=0.5$ T, and $\theta=\pi/3$.

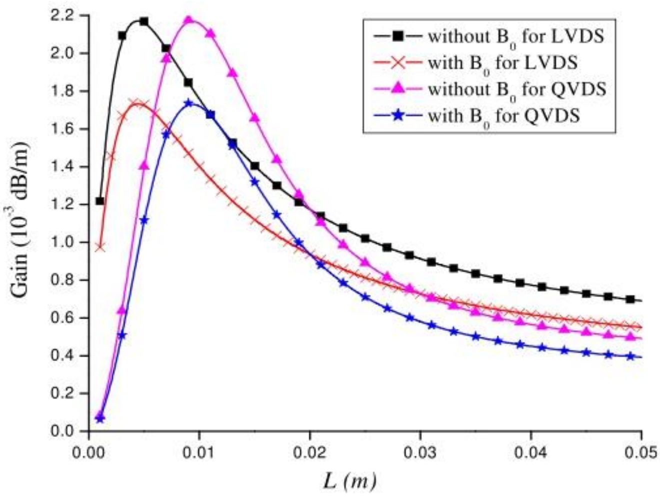

Figure 2: $\alpha\omega/v_s$ versus L at $H=0.2$, $z=0.02$ m, $B_0=0.5$ T, and $\theta=\pi/3$.

Figure 2 highlights the response of gain per unit length ($\alpha\omega/v_s$) of the acoustic wave with increasing scale length of density variation parameter L in magnetized ($B_0 \neq 0$) and un-magnetised ($B_0 = 0$) inhomogeneous semiconductor quantum plasmas. Initially with L, all the four curves start increasing sharply with different inclinations, reach to a maximum value, and then start decreasing slowly. For $L > 0.035$ m, the gain per unit length of the acoustic phonons becomes nearly independent of density gradient through scale length L. The influence of the magnetic field on ($\alpha\omega/v_s$) is found to be of retarded nature. It is also observed that the magnitude of maximum gain is identical in both cases, i.e., for LVDS and QVDS. But the magnitude of L corresponds to maximum gain, shifts toward higher values for QVDS.

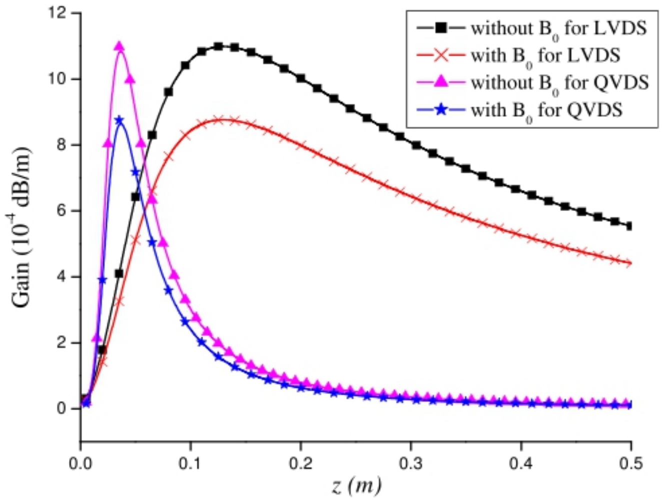

Figure 3: $\alpha\omega/v_s$ versus *z* at $H = 0.6$, $L = 0.01$ m, $B_0 = 0.5$ T, and $\theta = \pi/3$.

The gain per unit length ($\alpha\omega/v_s$) of the acoustic wave, as a function of propagation distance *z*, is depicted in Figure 3 in the presence and absence of B_0 in the inhomogeneous semiconductor quantum plasma. One may infer from this figure that increment in *z* consistently makes interaction more and more intense resulting in the increment in the magnitude of gain per unit length, up to $z = 0.13$ m for LVDS and $z = 0.035$ m for QVDS. This results in a shift of maximum gain point towards smaller *z* for QVDS. On further increasing *z*, ($\alpha\omega/v_s$)starts decreasing for all combinations. The nature of such reduction is slow in the case of LVDS and rapid for QVDS. Further, it is observed that as the propagation distance increases, magnetic field dominates the instability characteristics of phonon-plasmon interaction by reducing ($\alpha\omega/v_s$). For QVDS, gain characteristics become independent of applied magnetic field for $z \geq 0.4$ m.

The effect of wave angular frequency ω on ($\alpha\omega/v_s$) in the case of $B_0 \neq 0$ and $B_0 = 0$ for LVDS and QVDS is depicted in Figure 4. It is found that the gain per unit length of the acoustic wave varies with x in an identical manner for all combinations of parameters. It increases initially, attains maxima, and then starts decreasing with ω. The magnitude of ω at which maximum gain occurs can be expressed by

$$\omega^2 = \omega_R(z)\omega_{DF}/3\left(1 + \frac{k^2 v_F^2}{4\omega_p^2(z)} H^2(z)\right).$$

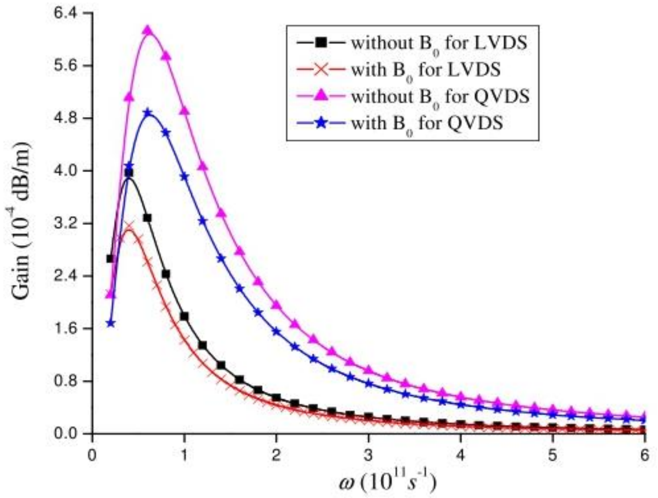

Figure 4: $\alpha\omega/v_s$ versus ω at $H = 0.6$, $L = 0.01$ m, $L = 0.02$ m, $B_0 = 0.5$ T, and $\theta = \pi/3$.

This condition infers that the frequency corresponding to maximum gain is not influenced by magnetic field and this fact is in concurrence with the depiction in figure. Furthermore, the presence of magnetic field reduces the magnitude of $\alpha\omega/v_s$ and its effect vanishes at $\omega \approx 5.5\times10^{11}$ s^{-1} in the case of LVDS. When one considers QVDS, the magnitude of ($\alpha\omega/v_s$) and frequency of maximum gain both shift towards higher values.

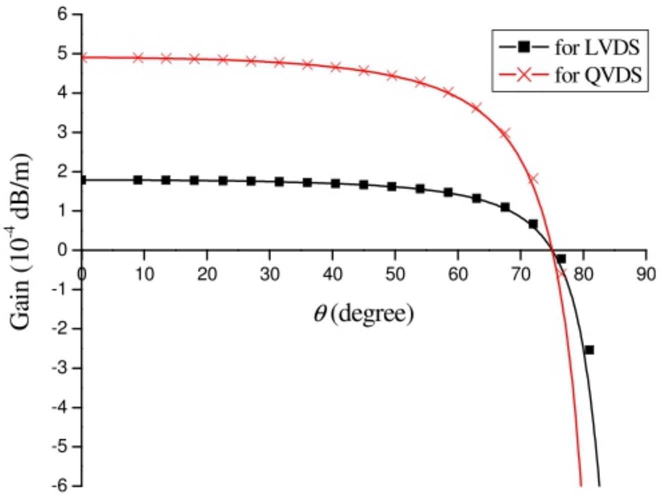

Figure 5: $\alpha\omega/v_s$ versus θ at $H = 0.6$, $L = 0.01$ m, $L = 0.02$ m, and $B_0 = 0.5$ T.

Figure 5 displays the influence of orientation θ of magnetic field on gain per unit length ($\alpha\omega/v_s$) of the acoustic wave for both the density structures, i.e., LVDS and QVDS. It may be observed from this figure that as the orientation angle θ increases, ($\alpha\omega/v_s$) reduces up to $\theta \approx 72^{\circ}$ for both the density structures; but magnitude of ($\alpha\omega/v_s$) is always larger for QVDS. On further enhancing θ (i.e., $\theta > 72^{\circ}$), the acoustic wave suffers strong damping. The rate of damping is again large in the case of QVDS. The physical mechanism associated with such crossover from wave amplification to attenuation is that as the orientation angle θ increases, the magnitude of cyclotron frequency of electrons ($\omega_{cz} = \omega_c \cos\theta$)

along the direction of wave propagation reduces. This, in turn, decreases the drift velocity of electrons; therefore, reduction in gain of acoustic wave occurs. Furthermore, when drift velocity becomes smaller than acoustic velocity, the acoustic wave starts attenuating.

4. Conclusions

The phonon-plasmon interaction in the magnetized inhomogeneous semiconductor quantum plasma system is theoretically demonstrated in this paper. We have examined how the magnetic field affects this interaction for density configurations that fluctuate linearly and quadratically. We have used the QHD model to establish the quantum modified dispersion relation to address the interaction between phonons and plasmons. The gain coefficient under the collision-dominated limit has also been analytically computed. Calculations reveal that the gain coefficient is influenced by the density gradient and its variation patterns, as well as the magnetic field and its orientation. According to the current study, the linearly variable density structure (LVDS) has a large gain magnitude in weakly quantized plasma, or at lower values of H. In contrast, the quadratically varying density structure (QVDS) is found to be more effective in highly quantized plasma. Moreover, as one moves from LVDS to QVDS, the maximum gain point shifts towards lower values of propagation distance *z*, higher values of scale length of density variation L, and angular frequency ω. It is very interesting that the crossover from wave amplification to attenuation occurs as the orientation angle of magnetic field θ becomes more than 72°. Therefore, it is believed that the current findings would help unravel the origin of the acoustic wave and its stability/instability regimes in the semiconductor quantum plasma with magnetized inhomogeneity. One could draw the conclusion that our findings would be helpful in the creation of minuscule electronic devices such as traveling wave amplifiers.

Acknowledgements

The author is thankful to Dr. Manjeet Singh, Assistant Professor, Department of Physics, Government College, Matanhail (Jhajjar) India for many useful suggestions to carry out this work.

Authors' contributions

The author read and approved the final manuscript.

Conflicts of interest

The author declares no conflict of interest.

Funding

This research received no external funding.

Data availability

No new data were created.

References

[1] D.H. Ki, Y.D. Jung, Friedel screening effects on the entanglement fidelity for elastic collisions in degenerate quantum plasmas, *J. Phys. Soc. Jpn*. 80 (2011) 083501.

[2] A. Sharma, N. Nimje, N. Yadav, S. Ghosh, Effect of density gradient on longitudinal phonon-plasmon interactions in colloids laden semiconductor quantum plasmas, *Int. J. Appl. Phys*. **4** (2014) 37.

[3] A.K. Basak, H. Petek, K. Ishioka, E.M. Thatcher, C.J. Stanton, Ultrafast coupling of coherent phonons with a nonequilibrium electron-hole plasma in GaAs, *Phys. Rev. B* **91** (2015) 125201.

[4] P. Bury, I. Bellan, I. Jamnicky, J. Kudelcik, S. Hardon, Acoustoelectric effect in semiconductor structures - Tool for interface states investigation by complex acoustic spectroscopy, *Acta Acust. Acust*. **102** (2016) 652-662.

[5] S. Buyukkose, A.H. Mınguez, B. Vratzov, C. Somaschini, L. Geelhaar, H. Riechert, W.G.V. Wiel, P.V. Santos, High-frequency acoustic charge transport in GaAs nanowires, *Nanotechnology* **25** (2014) 135204.

[6] A. Bouhemadoua, R. Khenatab, S. Bin-Omranc, G. Murtazad, Y. Al-Dourie, Structural, elastic, electronic and optical properties of new layered semiconductor $BaGa_2P_2$, *Opt. Mater*. **46** (2015) 122-130.

[7] P. Ruello, V.E. Gusev, Physical mechanisms of coherent acoustic phonons generation by ultrafast laser action, *Ultrasonics* **56** (2015) 21-35.

[8] G. Potter, N. Tokranovaa, A. Rastegarb, J. Castracane, Design, fabrication, and testing of surface acoustic wave devices for semiconductor cleaning applications, *Microelectron. Eng*. **162** (2016) 100-104.

[9] Q. Fan, C. Chai, Q. Wei, Q. Yang, P. Zhou, M. Xing, Y. Yang, Mechanical and electronic properties of Si, Ge and their alloys in P42/mnm structure, *Mater. Sci. Semicond. Process*. **43** (2016) 187-195.

[10] D. L. White, Amplification of ultrasonic waves in piezoelectric semiconductors, *J. Appl. Phys*. **33** (1962) 2547-2554.

[11] J.S. Yang, H.G. Zhou, Acoustoelectric amplification of piezoelectric surface waves, *Acta Mech*. **172** (2004) 113-122.

[12] K. Shinokita, K. Reimann, M. Woerner, T. Elsaesser, R. Hey, C. Flytzanis, Strong amplification of coherent acoustic phonons by intraminiband currents in a semiconductor superlattice, *Phys. Rev. Lett*. **116** (2016) 075504.

[13] F.J.R. Schulein, K. Muller, M. Bichler, G. Koblmuller, J.J. Finley, A. Wixforth, H.J. Krenner, Acoustically regulated carrier injection into a single optically active quantum dot, *Phys. Rev. B* **88** (2013) 085307.

[14] V.J. Ghokhale, M.R. Zadeh, Phonon-electron interactions in piezoelectric semiconductor bulk acoustic wave resonators, *Sci. Rep*. **4** (2014) 5617.

[15] M. Willatzen, J. Christensen, Acoustic gain in piezoelectric semiconductors at ε-near-zero response, *Phys. Rev. B* **89** (2014) 041201.

[16] P. Li, F. Jin, J. Yang, Effects of semiconduction on electromechanical energy conversion in piezoelectrics, *Smart Mater. Struct*. **24** (2015) 025021.

[17] C.L. Zhang, X.Y. Wang, W. Chen, J. Yang, Carrier distribution and electromechanical fields in a free piezoelectric semiconductor rod, *J. Zhejiang Univ. Sci. A: Appl. Phys. Eng*. **17** (2016) 37-44.

[18] P. Dubey, S. Ghosh, Modified longitudinal phonon-plasmon interactions in nanoparticle doped piezoelectric semiconductors, *Acta Acust. Acust*. **102** (2016) 436.

[19] B. Ghosh, S. Banerjee, S.N. Paul, Effect of non-thermal electrons and warm negative ions on ion-acoustic solitary waves in multi-component drifting plasma, *Ind. J. Pure Appl. Phys*. **51** (2013) 488-493.

[20] E.F. El-Shamy, Nonlinear ion-acoustic cnoidal waves in a dense relativistic degenerate magnetoplasma, *Phys. Rev. E* **91** (2015) 033105.

[21] M. McKerr, F. Haas, I. Kourakis, Ion-acoustic envelope modes in a degenerate relativistic electron-ion plasma, *Phys. Plasmas* **23** (2016) 052120.

[22] F. Iikawa, A. Hernandez-Minguez, M. Ramsteiner, P.V. Santos, Optical phonon modulation in semiconductors by surface acoustic waves, *Phys. Rev. B* **93** (2016) 195212.
[23] D.-L. Xiao, J.X. Ma, Y.-F. Li, Y. Xia, M.Y. Yu, Evolution of nonlinear dust-ion-acoustic waves in an inhomogeneous plasma, *Phys. Plasmas* **13** (2026) 052308.
[24] A.E. Mowafy, W.M. Moslem, Ion-acoustic waves in an inhomogeneous plasma with negative ions, *J. King Saud Univ., Sci.* **24** (2012) 343-349.
[25] W.F. El-Taibany, M.M. Selim, N.A. El-Bedwehy, O.M. Al-Abbasy, Linear and nonlinear dust acoustic waves in an inhomogeneous magnetized dusty plasma with nonextensive electrons, *Phys. Plasmas* **21** (2014) 073710.
[26] M. Dutta, S. Ghosh, R. Roychoudhury, M. Khan, N. Chakrabarti, Nonlinear electron acoustic cyclotron waves in presence of uniform magnetic field, *Phys. Plasmas* **20** (2013) 042301.
[27] C. Li, Z. Wu, W. Yang, P.K. Chu, Surface electromagnetic wave equations in a warm magnetized quantum plasma, *Phys. Plasmas* **21** (2014) 072114.
[28] G.A. Hoshoudy, Rayleigh-Taylor instability in magnetized plasma, *World J. Mech.* **4** (2014) 260-272.
[29] M.R. Amin, Modulation of a compressional electromagnetic wave in a magnetized electron-positron quantum plasma, *Phys. Rev. E* **92** (2015) 033106.
[30] M.M. Selim, A. El-Depsy, E.F. El-Shamy, Bifurcations of nonlinear ion-acoustic travelling waves in a multicomponent magnetoplasma with superthermal electrons, *Astrophys. Space Sci.* **360** (2015) 66.
[31] A. Vyas, R.K. Singh, R.P. Sharma, Effect of the magnetic field on coexisting stimulated Raman and Brillouin backscattering of an extraordinary mode, *Phys. Plasmas* **23** (2016) 012107.
[32] M.R. Amin, Quantum effects on compressional Alfven waves in compensated semiconductors, *Phys. Plasmas* **22** (2015) 032303.
[33] F. Haas, B. Eliasson, A new two-stream instability mode in magnetized quantum plasma, *Phys. Scr.* **90** (2015) 088005.
[34] H. Schamel, B. Eliasson, On the correct implementation of Fermi–Dirac statistics and electron trapping in nonlinear electrostatic plane wave propagation in collisionless plasmas, *Phys. Plasmas* **23** (2016) 052114.
[35] A. Rasheed, M. Jamil, M. Siddique, F. Huda, Y.-D. Jung, Beam excited acoustic instability in semiconductor quantum plasmas, *Phys. Plasmas* **21** (2014) 062107.
[36] M.R. Amin, Modulation of electrostatic Langmuir waves in quantum electron-hole semiconductor plasmas, *Phys. Scr.* **90** (2015) 015601.
[37] Pravesh, S. Dahiya, N. Singh, M. Singh, Dispersion, threshold and gain characteristics of Brillouin scattered Stokes mode in ion-implanted semiconductor quantum plasmas, *Optik* **293** (2023) 171452.
[38] Renu, Sanjay, M. Singh, Hot carrier effects on Brillouin gain coefficients of magnetoactive doped semiconductors, *J. Opt.* **51** (2022) 386-396.
[39] A. Rasheed, M. Jamil, F. Areeb, M. Siddique, M. Salimullah, Low frequency hybrid instability in quantum magneto semiconductor plasmas, *J. Phys. D: Appl. Phys.* **49** (2016) 175109.
[40] P. Chatterjee, K. Roy, S.V. Muniandy, S.L. Yap, C.S. Wong, Effect of ion temperature on arbitrary amplitude ion acoustic solitary waves in quantum electron-ion plasmas, *Phys. Plasmas* **16** (2009) 042311.
[41] A. Muley, S. Ghosh, Effect of quantum parameter–H on longitudinal electro–kinetic wave characteristic in magnetized semiconductor plasma, *Int. J. Eng. Sci. Res. Technol.* **4** (2015) 88-95.
[42] M.C. Steele, B. Vural, Wave Interactions in Solid State Plasmas, Mc-Graw Hill, New York (1969), pp. 136–146.