Modified Acousto-Electric Interactions in Colloids Laden Semiconductor Quantum Plasmas

Aartee Sharma, Nishchhal Yadav, S. Ghosh

School of Studies in physics, Vikram University, Ujjain-456010 (M. P.) India

Abstract- Using quantum hydrodynamic (QHD) model, a comprehensive investigation of propagation of longitudinal acousto-electric wave in colloids laden semiconductor plasmas is presented. It is noticed that the Bohm potential in the wave spectrum of the semiconductor plasma enhances the gain and also modifies the amplification characteristics of sound wave for both cases in which colloidal particles are either stationary **(**$\vartheta_{0d} = 0$**)** or streaming **(**$\vartheta_{0d} \neq 0$**).** The result of this investigation would be useful in understanding the characteristics of longitudinal electro-acoustic wave in magnetized n-type piezoelectric semiconductor quantum plasma and would be helpful in the fabrication of acousto-electric devices.

Index Terms- Acousto-electric interaction, Bohm potential, colloidal plasma, semiconductor plasma.

I. Introduction

Dusty plasma has opened up a completely new field of research in the domain of plasma physics. In addition to electrons, ions and neutrals in "ordinary" plasmas, dusty plasmas contain massive particles of nanometer to micrometer size. Dusty plasmas are widespread in astrophysical situations like in the rings of Saturn, in cometary tails or in interstellar clouds [1, 2]. In technological plasmas processing, dust particles grow from molecules in reactive gases to nanometer size particles [3, 4]. The removal of such plasma-grown particles is an essential issue in computer chip manufacturing. In contrast, materials with novel properties, such as solar cells with much improved efficiency, can be manufactured from thin films with incorporated dust particles.

A fascinating property of dusty plasma is that the particles can arrange in ordered crystal-like structure, so called plasma crystals [5, 6]. In the plasma, the particles acquire net negative charge equivalent to that of hundreds/thousands of elementary charges due to the inflow of electrons and ions. Then, the system becomes strongly coupled because the coulomb interaction of neighboring particles by far exceeds their thermal energies. The spatial and time scales of the particles motion allow easy observation by video microscopy. Weak frictional damping ensures that the dynamics and kinetics of individual particles becomes observable. Thus, dusty plasmas enable the investigation of crystal structure, solid and liquid plasmas, phase transitions, waves and many more phenomena on the kinetic particle level. On the other hand, the presence of dust in the plasma not only modifies the existing modes but also gives rise to new novel modes [7-11], even if dust particles do not participate in the perturbation. In most of the studies, a fluid description is used and the dust is considered as an additional component of the plasma, which can support low-frequency perturbations.

Salimullah et al. [12] predicted, first time, the possible lattice formation of charged dust grains in piezoelectric semiconductors. Later the influence of electron-phonon coupling on the lattice formation of negatively charged colloids resulting from ion-implantation in piezoelectric semiconductor were also reported [13]. This entirely new material, where phase transition and crystalline structure are expected to be confirmed by X-rays or electron microscope, may become a valuable tool for studying physical processes in condensed matter, such as melting, annealing and lattice defects. It also provides a strong motivation for investigating the collective properties in solid-state plasma media. As per the knowledge of the authors; it is an area which has remained very rarely explored so far.

Due to the larger mass of ions compared with the mass of electrons in gaseous dusty plasma system, depletion of electron densities may be almost complete. As a result, only low frequency perturbations are seen, when the electron inertia become negligible. In semiconductors, the charge carriers (electrons and holes) have high number densities and comparable masses. Therefore, the electron density should be reduced by small amount and it is expected that low as well as high frequency perturbations can be excited in the so–called " colloids laden semiconductor plasmas". At low frequency, all the three carrier species participate, while at high frequency, only electrons and holes can respond and the dust remains stationary in the background.

The interaction between mobile carriers and acoustic vibrations is one of the fundamental interaction processes in solids. This interaction gives useful information regarding the band structure of the host medium. The amplification of sound waves by the application of dc electric field has been commercially exploited for the fabrications of delay-lines, acousto-electric amplifiers and oscillators etc. The underlying physics of sound wave amplification in piezoelectric semiconductors is as follow: if the ion-implanted piezoelectric semiconductor is subjected to a large dc electric field below the breakdown value, a large beam of streaming electrons (due to their larger mobility than holes) will charge the neutral colloid particles to make them negatively charged colloidal ions. Thus, the semiconductor plasma will behave like dusty plasma [14] with electrons, vibrating lattice ions and dust like colloid ions.

As we know that, the temperature and density are the two basic parameters of the plasma. For quantum effects to be significant in plasmas, it is often assumed that the temperature over density ratio must be small. In such situation where density is too high and temperature is below the Fermi temperature, quantum mechanical effect can no longer be ignored. Such a system where quantum mechanical corrections are needed to describe the system completely is referred to as "Quantum Plasma". The peculiar property of quantum plasma is that it increasingly approaches the more collective (ideal) behavior as its density increases.

Quantum hydrodynamic (QHD) models become important and necessary to model and simulate electron transport, affected by extremely high electric fields. Generally the QHD model consists of a set of equations describing the transport of charge, momentum and energy in a charged particle system interchanging through a self consistent electrostatic potential. Mathematically, the QHD model generalizes the fluid model for plasmas with the inclusion of a quantum correction term, i.e., Bohm potential. This extra term can appropriately describe negative differential resistivity in resonant tunneling diodes. Such kind of quantum mechanical phenomena cannot be simulated by classical hydrodynamic models. The advantage of the microscopic quantum hydrodynamic model is that they are able to describe directly the dynamics of physical observable and simulate the main characters of quantum effect. This motivates the development of quantum transport model for charged particle systems.

Ghosh and his coworkers [15-18] studied the acousto-electric interactions in ion-implanted semiconductor plasmas. They have reported the origin of a number of new modes and effective modifications in the characteristic of the existing modes.

Motivated by the pioneer work of Ghosh and Khare [16-18] and the importance of the quantum effect on wave spectrum, in the following section of the present paper, we present an analytical study of the quantum modifications in wave spectrum of electro-acoustic modes in n-type piezoelectric semiconductor plasma embedded with colloidal grains.

II. THEORETICAL FORMULATION

To study the modification in longitudinal phonon-plasmon interaction using quantum hydrodynamic model (QHD), we consider an n-type piezoelectric semiconductor sample of infinite extent in the presence of colloidal particles. The medium is subjected to a dc electric field (applied along the negative z-axis) and a longitudinal magnetostatic field B_0 (applied in x-z plane) making an arbitrary angle θ with z-axis. We consider an acoustic wave to be propagating along the z-axis of the medium. The uniform flow of the electrons due to dc electric field can charge the neutral colloids negatively in the host material. The average size of the colloids is assumed to be much less than the inter-grain distance, the electron Debye radius as well as the wavelength under study, so that they can be treated as point masses [19]. Hence the material can be safely treated as the multi-component plasma consisting of electrons and negatively charged colloids under hydrodynamic limit.

For the wave, we assume all variables to be of the form $\exp[i(\omega t-kz)]$ in which (ω,k) are the frequency and wave number of the wave. The wave equation in an elastic piezoelectric medium, using Newton's equation of lattice vibration and other related equations, for the field geometry under study, may be written as

$$(-\rho\omega^2+ck^2)u_x=ik\beta E_z\ , \tag{1}$$

where β is the piezoelectric coefficient of the medium and all other symbols have the same meanings as given by Steele and Vural [20].

In deriving equation (1), we have assumed that the considered medium has a cubic symmetry, which has simplified the involved tensor components without diluting the physical significance of the problem under study. The sound wave is taken as a shear wave that propagates along z-axis, which is <011> axis of the crystal. The lattice displacement $\vec{u}$ is taken along the propagation direction. This geometry is appropriate to many piezoelectric compound semiconductors of III-V class.

In the present configuration the electrons and charged colloids acquire perturbed motion in accordance with first-order equations of motion and continuity of the quantum hydrodynamic (QHD) model which are as follows

$$m_j n_{0j}\left[\frac{\partial}{\partial t}+\left(\vec{\vartheta}_j\cdot\nabla\right)\right]\vec{\vartheta}_j+\upsilon_j\vec{\vartheta}_j=-en_{0j}\left[\vec{E}+(\vec{\vartheta}_j\times\vec{B})\right]-\nabla\vec{p}_j+\frac{\eta^2}{4m_j}\nabla(\nabla^2\vec{n}_j) \tag{2}$$

$$\frac{\partial n_j}{\partial t}+\nabla.(n_j\vec{\vartheta}_j)=0 \tag{3}$$

($j=e,d$ for electrons and dust)

Here, $p_j=\frac{m_jV_{F\,j}^2n^3}{3n_{0e}^2}$ is the Fermi pressure and, $V_{F\,j}^2=\frac{2K_BT_{Fj}}{m_j}$ with K_B and T_{Fj} being the Boltzmann constant and Fermi temperature of carriers. With the help of equations (2) and (3) we obtained the perturbed velocity components for electrons and charged colloids as

$$\vartheta_{ez}=\frac{i(e/m_e)E_{1z}}{F(\omega,k)} \tag{4}$$

and

$$\vartheta_{dz}=\frac{i(z_de/m_d)E_{1z}}{G(\omega,k)} \tag{5}$$

where,

$$F(\omega,k)=\left[(\omega-k_{0e}-i\upsilon_e)-\frac{k^2}{(\omega-k\vartheta_{0e})}V_F^2(1+\Gamma_e)\right]+\left[\frac{\omega_{ce}^2\sin^2\theta(\omega-k\vartheta_{0e}-i\upsilon_e)}{\omega_{ce}^2\cos^2\theta-(\omega-k\vartheta_{0e}-i\upsilon_e)^2}\right] \tag{6}$$

$$G(\omega,k)=\left[(\omega-k_{0d}-i\upsilon_d)+\frac{\omega_{cd}^2\sin^2\theta(\omega-k\vartheta_{0d}-i\upsilon_d)}{\omega_{cd}^2\cos^2\theta-(\omega-k\vartheta_{0d}-i\upsilon_d)^2}\right] \tag{7}$$

Here, e and z_de are the charges on electrons and colloids, respectively, in which $z_d=q_d/e$ is the ratio of the charge q_d

on a colloidal grain to the electron charge e. ϑ_{0d} and υ_d are the drift velocity and momentum transfer collision frequency of the colloids. The expression for $F(\omega,k)$ contains $\Gamma_e = \frac{\eta^2 k^2}{8 m_e K_B T_{Fe}}$, which represents the inclusion of quantum effect in the interaction. The colloid cyclotron frequency ω_{cd} is given by $z_d e B_0/m_d$. All other symbols have their usual meanings as given by Steele and Vural [20] except for the subscript e which denotes the parameter for electrons.

Using equations (1) to (7) and the usual relations for the continuity and electrical displacement for a longitudinal wave, we get the dispersion relation for phonon-plasmon interactions using QHD model as

$$(\omega^2 - k^2\vartheta_s^2)\left[1 - \frac{\omega_{pe}^2}{(\omega - k\vartheta_{0e})F(\omega,k)} - \frac{\omega_{pd}^2}{(\omega - k\vartheta_{0d})G(\omega,k)}\right] = K^2 k^2 \vartheta_s^2, \quad (8)$$

where, $K^2 = (\beta^2/c\varepsilon)$ is the dimensionless electromechanical coupling coefficient. The plasma frequencies for electrons and colloids are given as $\omega_{pe}^2 = \frac{e^2 n_{0e}}{\varepsilon m_e}$ and $\omega_{pd}^2 = \frac{z_d^2 e^2 n_{0d}}{\varepsilon m_d}$ in which $n_{0e,d}$ are the unperturbed number densities of electrons and colloids, respectively.

In absence of piezoelectricity $(\beta = 0)$, the coupling parameters on RHS of equation (8) vanishes and we get two independent modes as

$$(\omega^2 - k^2\vartheta_s^2) = 0 \quad (9a)$$

and

$$\left[1 - \frac{\omega_{pe}^2}{(\omega - k\vartheta_{0e})F(\omega,k)} - \frac{\omega_{pd}^2}{(\omega - k\vartheta_{0d})G(\omega,k)}\right] = 0 \quad (9b)$$

Equation (9a) is the usual sound mode propagating through an elastic medium and equation (9b) represents the electro-kinetic mode modified due to the presence of charged colloids and quantum effect in the host material.

In absence of charged colloids $(\omega_{pd} = 0)$ and quantum effect ($\Gamma_e = 0, V_F \to V_{th}$, thermal velocity), equation (8) reduces to equation (8-20) of Steele and Vural [20] and represents the phonon-plasmon interaction in magnetized piezoelectric semiconductor plasma. Hence equation (8) represents the phonon-plasmon interaction modified due to the presence of charged colloids and quantum effect in magnetized piezoelectric semiconductor plasma.

In the collision dominated regime $(\omega << \upsilon_e, \upsilon_d$ and $k\vartheta_{0e} << \upsilon_e, k\vartheta_{0d} << \upsilon_d)$, equation (8) is solved with the standard approximation $k\vartheta_s/\omega = 1 + i\alpha$ [21], where the gain per radian α is << 1. Therefore, one gets,

$$\alpha = \frac{\frac{1}{2}K^2\gamma_e\left(\frac{\omega_{\mathrm{Re}}}{\omega\phi_e}\right)\left[1 + \frac{\omega_{Rd}\phi_e\gamma_e}{\omega_{\mathrm{Re}}\phi_d\gamma_d} + \left(\frac{k^2V_F'^2}{\omega\phi_e}\right)^2 \frac{\omega_{Rd}}{\omega_{\mathrm{Re}}}\frac{\phi_e}{\phi_d\gamma_e\gamma_d\upsilon_e^2}\right]}{\left(\frac{\omega_{\mathrm{Re}}}{\omega\phi_e}\right)^2\left[1 + \frac{\omega_{Rd}\phi_e\gamma_e}{\omega_{\mathrm{Re}}\phi_d\gamma_d} + \frac{k^2V_F'^2}{\omega_{\mathrm{Re}}\upsilon_e}\right]^2 + \gamma_e^2\left[1 - \frac{k^2V_F'^2\omega_{Rd}}{\omega^2\phi_e\phi_d\gamma_e\gamma_d\upsilon_e}\right]^2} \quad (10)$$

in which

$V_F'^2 = V_F^2(1+\Gamma_e)$, $\gamma_{e,d} = (\vartheta_{0e,d}/\vartheta_s - 1)$, $\omega_{\mathrm{Re},d} = \omega_{pe,d}^2/\upsilon_{e,d}$

and

$$\phi_{e,d} = \frac{1 + (\omega_{ce,d}^2/\upsilon_{e,d}^2)}{1 + (\omega_{ce,d}^2\cos^2\theta/\upsilon_{e,d}^2)}.$$

The subscripts 'e' and 'd' are used to represent quantities related to electrons and charged colloids, respectively. It can be infer from equation (10) that quantum effects appear in the parameter V_F'.

Sound mode amplification-

The sound wave is amplified only when gain per radian α is positive. Now we will discuss the amplification characteristics of sound wave for two distinct cases in which charged colloids are either stationary or streaming. In both the cases we will discuss the quantum correction effect on the amplification characteristics of sound mode.

CASE-1: **Stationary colloids** $(\vartheta_{0d} = 0)$

It is a well-known fact that, unless one considers the lowest part of the grain mass spectrum and very-very low frequency modes, the conclusion is that the grain dynamics can be ignored with respect to the electron dynamics [22]. Thus, for ultrasonic frequency regime and robust colloidal grains, we can safely assume $\vartheta_{0d} = 0$ and consequently $\gamma_d = -1$. Under this approximation equation (10) reduces to

$$\alpha \approx \frac{\frac{1}{2}K^2\gamma_e\left(\frac{\omega_{\mathrm{Re}}}{\omega\phi_e}\right)\left[1 - \frac{\omega_{Rd}\phi_e\gamma_e}{\omega_{\mathrm{Re}}\phi_d}\left\{1 + \left(\frac{k^2V_F'^2}{\omega\phi_e}\right)^2\frac{1}{\gamma_e^2\upsilon_e^2}\right\}\right]}{\left(\frac{\omega_{\mathrm{Re}}}{\omega\phi_e}\right)^2\left[1 - \frac{\omega_{Rd}\phi_e\gamma_e}{\omega_{\mathrm{Re}}\phi_d} + \frac{k^2V_F'^2}{\omega_{\mathrm{Re}}\upsilon_e}\right]^2 + \gamma_e^2\left[1 + \frac{k^2V_F'^2\omega_{Rd}}{\omega^2\phi_e\phi_d\gamma_e\upsilon_e}\right]^2} \quad (11)$$

One can immediately infer from equation (11) that this mode will be amplified $(\alpha > 0)$ only when

$$\gamma_e > 0 \quad (12a)$$

and

$$\omega < \frac{k^2V_F'^2}{\phi_e\gamma_e\upsilon_e}\left[\sqrt{\frac{\omega_{\mathrm{Re}}}{\omega_{Rd}}\frac{\phi_d}{\phi_e\gamma_e}} - 1\right]^{-1} \quad (12b)$$

In absence of charged colloids, it was reported by White [21] that the condition for gain is $\gamma_e > 0$ or $(\vartheta_{0e}/\vartheta_s) > 1$. We have found that in an n-type semiconductor consisting of colloid particles an extra condition (12b) is imposed to achieve the amplifying wave. This extra condition actually comes into picture due to the presence of charged colloids and Bohm potential (i.e., quantum correction) in the fluid model of plasmas. This condition actually imposed a limit on the frequency of the wave, which may be amplified. It is also found that the value of gain is also modified by the presence of quantum correction term in the regime where colloids are stationary. Hence one gets modified longitudinal phonon-plasmon interaction in the n-type piezoelectric semiconductor quantum plasma even in presence of robust colloidal grains.

CASE-2: **Streaming colloids** $(\vartheta_{0d} \neq 0)$

Now, if one includes dynamics of colloidal grains into consideration the expression for gain per radian will be exactly same as given in equation (10). To study the amplification characteristics of the wave, we shall discuss different velocity regimes as follows:

(a)When $\gamma_e > 0$ ***and*** $\gamma_d > 0$ ***i.e.*** $\vartheta_{0e} > \vartheta_s < \vartheta_{0d}$ **:**

Under this velocity regime, the expression for gain reduces to

$$\alpha \approx \frac{\frac{1}{2}K^2|\gamma_e|\left(\frac{\omega_{\mathrm{Re}}}{\omega\phi_e}\right)\left[1+\frac{\omega_{Rd}\phi_e|\gamma_e|}{\omega_{\mathrm{Re}}\phi_d|\gamma_d|}+\left(\frac{k^2V_F'^2}{\omega\phi_e}\right)^2\frac{\omega_{Rd}}{\omega_{\mathrm{Re}}}\frac{\phi_e}{\phi_d|\gamma_e||\gamma_d|\upsilon_e^2}\right]}{\left(\frac{\omega_{\mathrm{Re}}}{\omega\phi_e}\right)^2\left[1+\frac{\omega_{Rd}\phi_e|\gamma_e|}{\omega_{\mathrm{Re}}\phi_d|\gamma_d|}+\frac{k^2V_F'^2}{\omega_{\mathrm{Re}}\upsilon_e}\right]^2+|\gamma_e^2|\left[1-\frac{k^2V_F'^2\omega_{Rd}}{\omega^2\phi_e\phi_d|\gamma_e||\gamma_d|\upsilon_e}\right]^2} \tag{13}$$

It is clear from the equation (13) that under this velocity regime the wave will always be of amplifying nature but the value of gain per radian is modified due to presence of quantum potential through the modified Fermi velocity term $V_F^{'}$.

(b)When $\gamma_e > 0$ ***and*** $\gamma_d < 0$ ***i.e.*** $\vartheta_{0e} > \vartheta_s > \vartheta_{0d}$ **:**

In this regime equation (10) reduces to,

$$\alpha \approx \frac{\frac{1}{2}K^2|\gamma_e|\left(\frac{\omega_{\mathrm{Re}}}{\omega\phi_e}\right)\left[1-\left\{\frac{\omega_{Rd}\phi_e|\gamma_e|}{\omega_{\mathrm{Re}}\phi_d|\gamma_d|}+\left(\frac{k^2V_F'^2}{\omega\phi_e}\right)^2\frac{\omega_{Rd}}{\omega_{\mathrm{Re}}}\frac{\phi_e}{\phi_d|\gamma_e||\gamma_d|\upsilon_e^2}\right\}\right]}{\left(\frac{\omega_{\mathrm{Re}}}{\omega\phi_e}\right)^2\left[1-\frac{\omega_{Rd}\phi_e|\gamma_e|}{\omega_{\mathrm{Re}}\phi_d|\gamma_d|}+\frac{k^2V_F'^2}{\omega_{\mathrm{Re}}\upsilon_e}\right]^2+|\gamma_e^2|\left[1+\frac{k^2V_F'^2\omega_{Rd}}{\omega^2\phi_e\phi_d|\gamma_e||\gamma_d|\upsilon_e}\right]^2} \tag{14}$$

From equation (14) one can infer that α will be positive only when the expression within square bracket in numerator is positive. The expression within square bracket is dominantly controlled by the quantum term $V_F^{'}$. Thus the gain per radian in this velocity region will be

$$\alpha \approx \frac{\frac{1}{2}K^2|\gamma_e|\left(\frac{\omega_{\mathrm{Re}}}{\omega\phi_e}\right)}{\left(\frac{\omega_{\mathrm{Re}}}{\omega\phi_e}\right)^2\left[1-\frac{\omega_{Rd}\phi_e|\gamma_e|}{\omega_{\mathrm{Re}}\phi_d|\gamma_d|}+\frac{k^2V_F'^2}{\omega_{\mathrm{Re}}\upsilon_e}\right]^2+|\gamma_e^2|\left[1+\frac{k^2V_F'^2\omega_{Rd}}{\omega^2\phi_e\phi_d|\gamma_e||\gamma_d|\upsilon_e}\right]^2} \tag{15}$$

It may be concluded that even when $\gamma_d < 0$ i.e. charged colloids moves slowly in comparison with acoustic phonon speed, one gets the amplification of sound wave in a frequency regime given as

$$\omega < \frac{k^2V_F'^2}{\phi_e|\gamma_e|\upsilon_e}\left[\sqrt{\frac{\omega_{\mathrm{Re}}}{\omega_{Rd}}\frac{\phi_d|\gamma_d|}{\phi_e|\gamma_e|}}-1\right]^{-1} \tag{16}$$

This frequency regime is very much decided by the Bohm potential correction through $V_F^{'}$. Hence, the gain characteristic is sharply modified by the presence of quantum correction term even in this velocity regime also.

(c)When $\gamma_e < 0$ ***and*** $\gamma_d > 0$ ***i.e.*** $\vartheta_{0e} < \vartheta_s < \vartheta_{0d}$ **:**

For this velocity regime, gain per radian may be expressed using equation (10) as

$$\alpha \approx \frac{\frac{1}{2}K^2|\gamma_e|\left(\frac{\omega_{\mathrm{Re}}}{\omega\phi_e}\right)\left(\frac{\omega_{Rd}}{\omega_{\mathrm{Re}}}\right)\left[\frac{\phi_e|\gamma_e|}{\phi_d|\gamma_d|}+\left(\frac{k^2V_F'^2}{\omega\phi_e}\right)^2\frac{\phi_e}{\phi_d|\gamma_e||\gamma_d|\upsilon_e^2}\right]}{\left(\frac{\omega_{\mathrm{Re}}}{\omega\phi_e}\right)^2\left[1-\frac{\omega_{Rd}\phi_e|\gamma_e|}{\omega_{\mathrm{Re}}\phi_d|\gamma_d|}+\frac{k^2V_F'^2}{\omega_{\mathrm{Re}}\upsilon_e}\right]^2+|\gamma_e^2|\left[1+\frac{k^2V_F'^2\omega_{Rd}}{\omega^2\phi_e\phi_d|\gamma_e||\gamma_d|\upsilon_e}\right]^2} \tag{17}$$

Hence, for this velocity regime we found that α will be positive only when

$$\omega > \frac{k^2V_F'^2}{\phi_e|\gamma_e|\upsilon_e}\left[\sqrt{\frac{\omega_{\mathrm{Re}}}{\omega_{Rd}}\frac{\phi_d|\gamma_d|}{\phi_e|\gamma_e|}}-1\right]^{-1}. \tag{18}$$

It can be inferred that in a frequency region defined by equation (18), we may get sound amplification even if the electron drift is less than the acoustic speed. From equation (17), it is found that this gain is not possible in absence of colloids $(\omega_{Rd} = 0)$; therefore, this mode may be termed as colloids induced sound mode amplification in piezoelectric semiconductor. This novel mode strongly depends on the quantum correction made through $V_F^{'}$.

(d) When $\gamma_e < 0$ ***and*** $\gamma_d < 0$ ***i.e.*** $\vartheta_{0e} < \vartheta_s > \vartheta_{0d}$ **:**

In this velocity regime one will get a decayed mode $(\alpha < 0)$ always; hence it is of no importance here.

III. Results and Discussion

To study absorption characteristics of sound modes in the colloid laden semiconductor quantum plasma, we may employ the expressions for gain per radian (α) derived for different cases in the preceding section of this paper. For the same we have considered the following set of parameters for n-InSb at 77K as a representative case : $m_e = 0.014 m_0$ (m_0 is the free electron mass), $m_d = 10^{-27} kg$, $\in_L = 17.54$, $\beta = 0.054 Cm^{-2}$, $\rho = 5.8 \times 10^3 kg\, m^{-3}$, $n_{0e} = 10^{19} m^{-3}$, $n_{0d} = 10^{17} m^{-3}$, $\upsilon_e = 3.5\times10^{11} s^{-1}$, $\upsilon_d = 3.248\times10^{10} s^{-1}$, $B_0 = 0.5T$. The results of our calculations are depicted in the form of curves in the Figures 1-4.

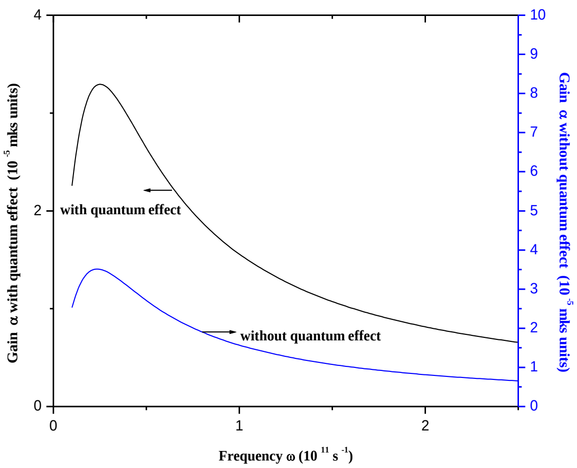

Fig.1 Variation of gain α with wave frequency ω for case (1) In which $\vartheta_{0d} = 0$ (stationary colloids) and $\vartheta_{0e} > \vartheta_s$ at $B_0 = 0.5T$ and $\theta = 45°$.

Figure 1 shows the dependence of gain α (with and without quantum effect) on the wave frequency ω . It is found that the gain for stationary colloids ($\vartheta_{0d} = 0$) is strongly affected by the quantum corrections. For the velocity regime ($\vartheta_{0e} > \vartheta_s$) i.e., when the electron drift velocity is greater than the acoustic speed we always get amplification of sound wave and it is a well known fact that in absence of colloids one can achieve sound gain only when $\vartheta_{0e} > \vartheta_s$; hence in the presence of charged colloids one gets a new amplifying mode from phonon-plasmon interaction in piezoelectric semiconductor. Here, we also found that the inclusion of quantum effect enhances the value of gain, it is observed that in both the cases gain first increases up to $\alpha \approx 3.52\times10^{-5}$ mks units at $\omega \approx 2.55\times10^{10} s^{-1}$ (with quantum effect) and $\alpha \approx 3.1\times10^{-5}$ mks units at $\omega \approx 2.4\times10^{10} s^{-1}$ (without quantum effect) and then decays gradually with increasing value of ω and towards the high frequency spectrum it saturates. In presence of quantum correction term gain per radian is always larger than those obtained in absence of quantum effect. Hence it may be inferred from Figure 1 that the presence of Bohm potential effectively increases the magnitude of gain per radian when the implanted colloids are static.

Figure 2 infers that, in homogeneous medium when $\vartheta_{0e} > \vartheta_s < \vartheta_{0d}$, the sound mode is always be of amplifying nature. In this velocity regime, natures of variation of α for both the cases (with and without quantum effect) are identical and gain is modified due to the presence of quantum effect. This figure depicts that the gain first increases with increase in frequency and attains its maximum ($\alpha \approx 3.5\times10^{-5}$ mks units) at $\omega \approx 7.55\times10^{10} s^{-1}$ (with quantum effect) and ($\alpha \approx 3.43\times10^{-5}$ mks units) at $\omega \approx 7.7\times10^{10} s^{-1}$ (without quantum effect).

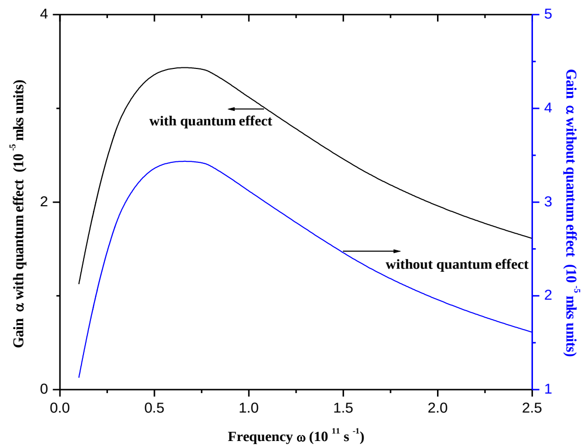

Fig.2 Variation of gain α with wave frequency ω for case 2(a) Under the velocity regime $\vartheta_{0e} > \vartheta_s < \vartheta_{0d}$, at $B_0 = 0.5T$ and $\theta = 45°$.

After achieving maximum values the gains in both the cases remain stationary for a while. These portions of the curves display quasi-stationary character of the amplification curve. Beyond this region gains decrease gradually in both cases and become frequency independent towards higher value of frequency. In this velocity regime also, quantum correction is found responsible for the increment in α , the gain per radian.

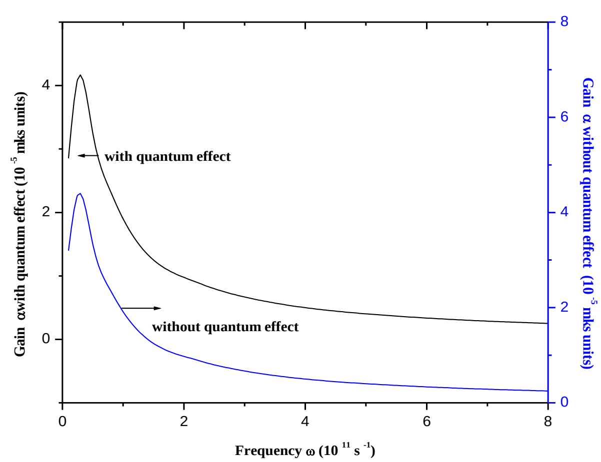

Fig.3 Variation of gain α with wave frequency ω for case 2(b)

Under the velocity regime $\vartheta_{0e} > \vartheta_s > \vartheta_{0d}$, at $B_0 = 0.5T$ and $\theta = 45°$.

Figure 3 displays the variation of gain α as a function of wave frequency ω, under the velocity regime $\vartheta_{0e} > \vartheta_s > \vartheta_{0d}$. We have drawn two curves in presence and absence of quantum correction. When $\vartheta_{0e} > \vartheta_s$, we always get amplification of sound mode in both (with and without quantum effect) the cases. But colloids impose an additional condition on amplification criterion in terms of frequency as predicted by equation (16), in absence of quantum effect due to this restriction on allowed frequency range, we get amplification only upto $\omega \leq 1.4 \times 10^{11} s^{-1}$. Here gain first increases sharply with frequency achieve a maximum and then decreases sharply due to slight tuning in frequency. As soon as we include Bohm potential, the frequency range for which gain of sound mode is possible, increases enormously. The nature of variation is found to be identical with the case when quantum effect is absent. Hence in this velocity regime quantum effect not only increases the gain value but also modifies the amplification condition.

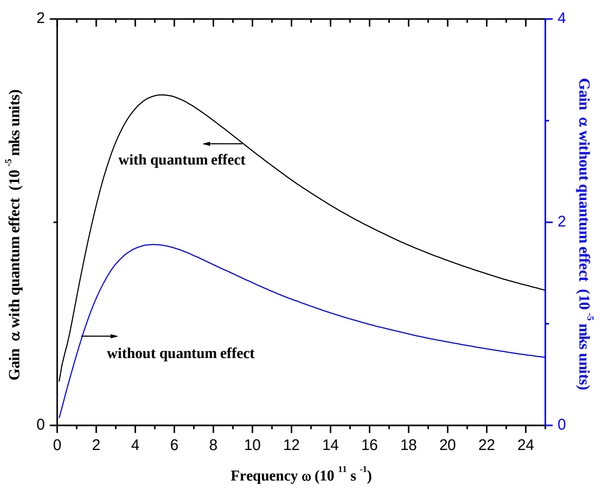

Fig.4 Variation of gain α with wave frequency ω for case 2(c) Under the velocity regime $\vartheta_{0e} < \vartheta_s < \vartheta_{0d}$, at $B_0 = 0.5T$ and $\theta = 45°$.

In colloid laden semiconductor plasma, we get amplifying sound mode even when electron velocity is less than the velocity of sound. Hence the nature of variation of gain in this interesting velocity regime $(\vartheta_{0e} < \vartheta_s < \vartheta_{0d})$ is studied numerically by us and depicted in Figure 4. For both the cases we found that the gain first increases with frequency, achieves a maximum value and then decreases slowly with the increase in frequency. With quantum effect we always get larger gain for the sound mode throughout the frequency spectrum under study. Hence one may control the gain value by tuning the Fermi velocity of electron in the medium for colloids induced sound mode in piezoelectric semiconductors.

IV. CONCLUSION

To conclude, we have presented a novel possibility of controlling longitudinal phonon-plasmon interactions in magnetized n-type piezoelectric semiconductor quantum plasma in presence of charged colloid particles. We focused our attention on two different cases in which colloidal particles are either robust $(\vartheta_{0d} = 0)$ or dynamic $(\vartheta_{0d} \neq 0)$. We also studied the cases when quantum correction through Bohm potential is included or excluded from the interaction process. All of these cases correspond to the real laboratory experiments under different frequency regimes depending upon the size of the colloidal particles and temperature of the free electrons. We found that, there exists a strong resonant interaction between acoustic mode and quantum mechanically modified electro kinetic mode due to piezoelectric nature of the medium in presence of charged colloidal particles. Hence we hope that the present theory provides a qualitative picture of modification and amplification of sound mode in magnetized n-type piezoelectric semiconductor quantum plasma.

ACKNOWLEDGMENT

The financial assistance from the Madhya Pradesh Council of Science and Technology, Bhopal, India under a research project is gratefully acknowledged. One of the authors (Aartee Sharma) thanks Ms. Sandhaya Chaudhary for her help during the course of this work.

REFERENCES

[1] C. K. Goertz, Dusty plasmas in the solar system, *Rev. Geophysics*. 27, 1989, pp. 271-292.

[2] F. Verheest, "*Waves in Dusty space plasmas* (kluver Academic publishers, Dordrecht)", 2000.

[3] G. S. Selwyn, J. E. Heidenreich and K. L. Haller, Rasterd lasre light scattreing studies during plasma processing: Particle contamination trapping phenomena, *J. Vac. Sci. Technol*. A9, 1991, pp. 2817-2824.

[4] *Dusty Plasmas*, edited by A. Bouchoule (John Wiley & Sons, Chichester, 1999).

[5] J. H. Chu and L. I, Direct observation of coulomb crystals and liquids in strongly coupled rf dusty plasmas, *Phys. Rev. Lett*. 72, 1994, pp. 4009-4012.

[6] H.Thomas, G. E. Morfill, V. Demmel, J. Goree, B. Feuerbacher and D. Mohlmann, Plasma Crystal: Coulomb Crystallization in a Dusty Plasma, *Phys. Rev. Lett*. 73, 1994, pp. 652-655.

[7] N. N. Rao, P. K. Shukla and M. Y. Yu, Dust-acoustic waves in dusty plasmas, *Planet space Sci*. 38, 1990, pp. 543-546.

[8] P. K. Shukla and V. P. Sillin, Dust ion-acoustic wave, *Phys. Scr*. 45, 1992, pp. 508.

[9] M. Salimullah and M. Salahuddin, Dust-acoustic waves in a magnetized dusty plasma, *Phys. Plasmas* 5, 1998, pp. 828-829.

[10] M. K. Islam, Y. Nakashima, K. Yastu and M. Salimullah, On low frequency dust-modes in a collisional and streaming dusty plasma with dust charge fluctation, *Phys. Plasmas* 10, 2003, pp. 591-595.

[11] J. Pramanik, G. Prasad, A. Sen and P. K. Kaw, Experimental Observations of Transverse Shear Waves in Strongly Coupled Dusty Plasmas, *Phys. Rev. Lett.* 88, 2002, pp. 175001-175004.

[12] M. Salimullah, S. Ghosh and M. R. Amin, Possible lattice formation of new materials within a piezoelectric semiconductor plasma, *Pramana* 54, 2000, pp. 785-789.

[13] M. Salimullah, P. K. Shukla, S. K. Ghosh, H. Nitta and Y. Hayashi, Electron-phonon coupling effect on wake fields in piezoelectric semiconductors, *J. Phys. D: Appl. Phys*. 36, 2003, pp. 958.

[14] P. K. Shukla, and A. A. Mamun, "*Introduction to Dusty plasma physics* (IOP, Bristol)", 2002.

[15] S. Ghosh, G. R. Sharma, Pragati Khare and M. Salimullah, Modified interactions of longitudinal phonon-plasmon in magnetized piezoelectric semiconductor plasmas, *Physica B* 315, 2004, pp. 163-170.

[16] S. Ghosh and Pragati Khare, Acousto-electric wave instability in ion-implanted semiconductor plasma, *Eurp. Phys. J. D* 35, 2005, pp. 521-526.

[17] S. Ghosh and Pragati Khare, Effect of Density Gradient on the Acousto-Electric Wave Instability in Ion-Implanted Semiconductor Plasmas, *Acta Physica Polonica A* 109, 2006, pp. 187-197.

[18] S. Ghosh and Pragati Khare, Acoustic wave amplification in ion-implanted piezoelectric semiconductor, *Ind. J. Pure & Appl. Phys*. 44, 2006, pp. 183-187.

[19] K. N. Ostrikov, S. V. Vladimirov, M. Y. Yu and G. E. Morfill, Low-frequency dispersion properties of plasmas with variable-charge impurities, *Phys. Plasma* 7, 2000, pp. 461-465.

[20] M.C. Steele and B. Vural, "*Wave Interactions in Solid State Plasmas* (Mc-Graw Hill, New York)", 1969, pp. 134-147.

[21] D.L. White, Amplification of Ultrasonic Waves in Piezoelectric Semiconductors, *J. Appl. Phys*. 33, 1962, pp. 2547-2554.

[22] U. de Angelis, The physics of dusty plasmas, *Phys. Scripta* 45, 1992, pp. 465.

AUTHORS

First Author – Aartee Sharma, M.Phil., School of Studies in Physics, Vikram University, Ujjain (M. P.) 456010 India and email: aartee.sharma08@gmail.com
Second Author – Dr. Nishchhal Yadav, Ph.D., School of Studies in Physics, Vikram University, Ujjain (M. P.) 456010 India and email: somyadav@gmail.com
Third Author – Prof. Sanjay K. Ghosh, Ph.D., School of Studies in Physics, Vikram University, Ujjain (M. P.) 456010 India and email: sanjayghosh.ssp@gmail.com

Correspondence Author – Aartee Sharma, email aartee.sharma08@gmail.com, Mob. No. +91-9926583496.