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***Research Article***

# LONGITUDINAL PHONON-PLASMON INTERACTIONS IN QUANTUM SEMICONDUCTOR PLASMAS WITH NON-PARTICIPATING COLLOIDS

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## ABSTRACT
Using the quantum hydrodynamic model for quantum semiconductor magnetoplasma, the acousto-electric wave spectrum has been investigated in detail in presence of non-participating negatively charged colloidal grains in addition to usual electrons and holes. The present analysis predicts that the quantum correction and presence of non-participating charged colloids significantly affect the wave spectrum of acousto-electric mode in semiconductor plasmas.

***Keywords:*** *Phonon-Plasmon Interactions, Quantum Hydrodynamic Model, Semiconductor Plasma, Non-Participating Colloids, Bohm Potential, Fermi Pressure*

## INTRODUCTION
Dusty gaseous plasmas (Verheest, 2000; Shukla and Mamun, 2002) and colloids laden semiconductor plasmas (Ghosh *et al.*, 2004; Salimullah *et al.*, 2005) both have become outstanding and challenging research areas because of their ubiquity, versatile applications, and complexities. The physics of these media has not only introduced a great variety of new phenomena associated with waves and instabilities (Rosenberg, 1996; Merlino *et al.*, 1998), but also it has initiated a number of new experimental discoveries. The most important experimental discoveries in dusty plasmas are dust plasma crystals (Chu and Lin, 1994; Thomas *et al.*, 1994; Hayashi and Tachibana, 1994), dust mach cones (Samsonov *et al.*, 1999), dust voids (Morfill *et al.*, 1999; Samsonov and Goree, 1999) etc.
Moreover in recent years, there has been growing enthusiasm in quantum effects in these complex plasma media (Mishra and Chowdhury, 2006; Moslem *et al.*, 2007; Chaudhary *et al.*, 2013a,b) because of their importance in microelectronics and electronic devices with nanoelectronic components (Hass *et al.*, 2003), dense astrophysical system (Chabrier *et al.*, 2002) and laser produced plasmas (Marklund and Shukla, 2006). When a plasma is cooled to an extremely low temperature, the de-Broglie wavelengths of the plasma particles could be at least comparable to the scale lengths, such as Debye length or Larmor radius, in the system. In such systems, the ultracold dense plasma would behave as a Fermi gas and quantum mechanical effects might play a vital role in the behaviour of the charge carriers of these plasmas under extreme conditions. Normally researchers consider the quantum effect through the Bohm potential only, which is valid for a relatively low-density quantum plasma and a short wavelength perturbation. For high-density plasmas and relatively larger wavelength, the Fermi degenerate pressure will dominate over the Bohm potential term in the equation of motion. Hence to study the whole possible scale of wavelengths, one should include both Bohm potential and Fermi degenerate pressure in the equation of motion as induced in quantum hydrodynamical model of plasmas.
The colloids present in nearly compensated semiconductor plasma usually acquire negative charge due to high mobility of electrons in comparison to positively charged holes. As a result, the balance of charge is altered by the presence of colloids and a charge imbalance parameter $\delta$ comes into play. It is also worth mentioning here that charging of colloids causes depletion of species of higher mobility (electrons in this case), however, the ratio of number densities of the electrons to that of the holes cannot be, in general, less than the square root of the ratio of their effective masses (Shukla and Mamun, 2002) i.e.

$$\delta = \frac{n_{0e}}{n_{0h}} \geq \sqrt{\frac{m_e}{m_h}} .$$

It is also expected that the presence of charged colloids can have a strong influence on the characteristics of usual plasma wave modes, even at a frequency where colloidal grains do not participate in wave motion. In these cases, the colloids may simply provide an immobile charge neutralizing background. Hence, they are expected to add new dimensions to well studied semiconductor plasma medium; as the charged dust grains do in case of gaseous plasma.

Recently Ghosh et al. (Chaudhary *et al.*, 2013(a); 2013(b); Sharma *et al.*, 2013) have reported the quantum effect on dispersion and absorption characteristics of electro-kinetic and acousto-electric modes in colloids laden semiconductor plasma with participating negatively charged particulates.

Motivated we have reported in this paper the quantum modification of acousto-electric wave characteristics in colloids laden semiconductor plasma with non-participating negatively charged colloids. Here we have considered Bohm potential and Fermi degenerate pressure both in our calculation to extend the validity of our results to whole possible range of wave number.

The rest of the present paper is organized as follows. In section 2, the dispersion relation is studied. A brief discussion of the results is given in section 3. Finally the conclusion is presented in section 4.

***Theoretical Formulation***

We consider an infinitely extended high density three components quantum dusty plasma containing electrons, holes and non-participating negatively charged colloidal grains, in the presence of a dc electric field $\vec{E}_0 \, ll \, \hat{z}$ and a magnetostatic field $\vec{B}_0$ applied in the $x-z$ plane making an arbitrary angle $\theta$ with $\hat{z}$. Under the influence of the dc electric field, electrons will acquire drift along $-z$ direction and holes will acquire drift along $+z$ direction and the wave is propagating along the $z$ axis of the medium.

The mass of the colloidal particle is much larger than the mass of the holes and more so of the electron. Therefore, the colloidal particles can be taken as stationary for frequencies far exceeding the characteristic frequency of the dusty plasma component, forming only a stationary neutralizing background for the perturbations propagating in the plasma. Thus, at equilibrium overall charge neutrality condition implies

$$(z_d n_{0d}/n_{0e}) = (n_{0h}/n_{0e}) - 1 \quad (1)$$

where $n_{0h}$, $n_{0e}$ and $n_{0d}$ are the unperturbed concentrations of holes, electrons and dust particles respectively; $z_d$ is the number of the electron charge on the grain surface. When the grain size is much smaller than the wavelength of any perturbations and the inter-particle distance, then the colloidal grains can be treated as negatively charged point masses (Ostrikov *et al.*, 2000).

The amplification characteristics of the acoustic mode in a quantum plasma are governed by the QHD model. By using this model and following the procedure adopted by Steele and Vural (1969), we obtained the dispersion relation for acoustic wave in quantum dusty plasma with non-participating colloidal grains as

$$(\omega^2-\kappa^2\vartheta_s^2)\left[1-\omega_{ph}^2\left\{\frac{(\delta/m)}{(\Omega_e)(\Omega_e-i\nu_e)-\frac{\kappa^2}{\Omega_e}V_F^2(1+\Gamma_e)+\frac{\omega_{ce}^2\sin^2\theta(\Omega_e-i\nu_e)}{\omega_{ce}^2\cos^2\theta-(\Omega_e-i\nu_e)^2}} + \frac{1}{(\Omega_h)(\Omega_h-i\nu_h)-\frac{\kappa^2}{\Omega_h}V_F^2(1+\Gamma_h)+\frac{\omega_{ch}^2\sin^2\theta(\Omega_h-i\nu_h)}{\omega_{ch}^2\cos^2\theta-(\Omega_h-i\nu_h)^2}}\right\}\right] = K^2\kappa^2\vartheta_s^2 \quad (2)$$

where $K^2 = (\beta^2/c\varepsilon)$ is the dimensionless electromechanical coupling coefficient which is used to measure piezoelectric activity in the semiconducting medium, $\omega_{ce} = eB_0/m_e$ and $\omega_{ch} = qB_0/m_h$ are the cyclotron frequencies of electrons and holes respectively, $\omega_{ph}^2 = q^2 n_{0h}/\varepsilon m_h$ is the plasma frequency for holes. From equation (2) one can easily notice that at $\beta = 0$, the usual uncoupled sound mode and the electro-kinetic mode modified due to the presence of static dust particles and Bohm potential are obtained by equating to zero the first and second factors of the L.H.S respectively. In the collision dominated regime $(\omega << \nu_e, \nu_h \text{ and } k\vartheta_{0e} << \nu_e, k\vartheta_{0h} << \nu_h)$ and by using standard approximation $k\vartheta_s/\omega = 1 + i\alpha$ (White, 1962). From equation (2) we obtain the expression for gain as:

$$\alpha = \frac{\frac{1}{2}K^2\left(\frac{\omega_{Rh}}{\omega}\right)\frac{\zeta_e^2}{\phi_h\zeta_h}\left[\left\{\frac{(k^2V_F^{'2})^2}{\omega^2\phi_e^2\nu_e^2\zeta_e^2}+1\right\}-\frac{\omega_{ph}^2(\delta/m)}{\omega_{Rh}\nu_e\zeta_e\zeta_h}\frac{\phi_h}{\phi_e}\left\{\frac{(k^2V_F^{'2})^2}{\omega^2\phi_h^2\nu_h^2}+1\right\}\right]}{\left[\frac{k^2V_F^{'2}}{\omega\phi_e\nu_e}-\frac{k^2V_F^{'2}\zeta_e}{\omega\phi_h\nu_h\zeta_h}+\frac{\omega_{ph}^2(\delta/m)}{\omega\phi_e\nu_e}-\frac{\omega_{Rh}\zeta_e}{\omega\phi_h\zeta_h}\right]^2+\left[\zeta_e+\frac{(k^2V_F^{'2})^2}{\omega^2\phi_e\phi_h\zeta_h\nu_e\nu_h}+\frac{\omega_{ph}^2(\delta/m)k^2V_F^{'2}}{\omega^2\phi_e\phi_h\zeta_h\nu_e\nu_h}+\frac{\omega_{Rh}k^2V_F^{'2}}{\omega^2\phi_e\phi_h\zeta_h\nu_e}\right]^2} \quad (3)$$

Equation (3) reflects the principal aim of the report, representing the modified gain characteristics of the acousto-electric wave due to quantum correction in magnetized, piezoelectric quantum colloids laden semiconductor plasma. Here, $V_F^{'2} = V_F^2(1+\Gamma_e)$ is a quantum parameter, $\zeta_{e.h} = (\vartheta_{0e.h}/\vartheta_s \pm 1)$ is a measure of the ratio of the drift velocities of electrons and holes to the velocity of sound and other symbols have their usual meaning and explained well in ref. (Sharma *et al.*, 2013).

We analyze equation (3) for the case when the drift velocity of electrons and holes both are greater than the acoustic wave speed, i.e. $\zeta_{e,h} > 0$ .

For the amplification of acoustic wave in this velocity regime, following condition must be satisfied

$$\delta < m\left[\frac{\omega_{Rh}}{\omega_{ph}^2}\frac{\zeta_e\zeta_h\phi_e\nu_e}{\phi_h}\right]\cdot\frac{\left\{\frac{(k^2V_F^{'2})^2}{\omega^2\phi_e^2\nu_e^2\zeta_e^2}+1\right\}}{\left\{\frac{(k^2V_F^{'2})^2}{\omega^2\phi_h^2\nu_h^2}+1\right\}}, \quad (4)$$

i.e., the term in the numerator of equation (3) which depends upon charge imbalance parameter $\delta$, must be positive. Since, it is clear from the above analysis that in this velocity regime the amplification of acoustic wave strongly depends on the charge imbalance parameter $\delta$, and the wave spectrum is effectively modified by the presence of immobile colloidal particles and by quantum parameter $V_F'$ .

## RESULTS AND DISCUSSION

We have solved numerically the expression for gain per radian $\alpha$ for the case when $\zeta_{e,h} > 0$. In order to have some numerical appreciation of our analytical result, we consider parameters of magnetized piezoelectric semiconductor quantum dusty plasma, n-InSb: where $\varepsilon_L = 17.54\,(77K)$, $n_{0e} = n_{0h} = 10^{24}\,m^{-1}$, $m_e = 0.014m_0$, $m_h = 0.40m_0$ ($m_0$ is the free electron mass), $\beta = 0.054Cm^{-2}$, $\rho = 5.8\times10^3\,kgm^{-3}$, $\nu_e = 3.5\times10^{11}\,s^{-1}$ and $\nu_h = 4.4\times10^{11}\,s^{-1}$. The results are displayed in Figures 1-3.

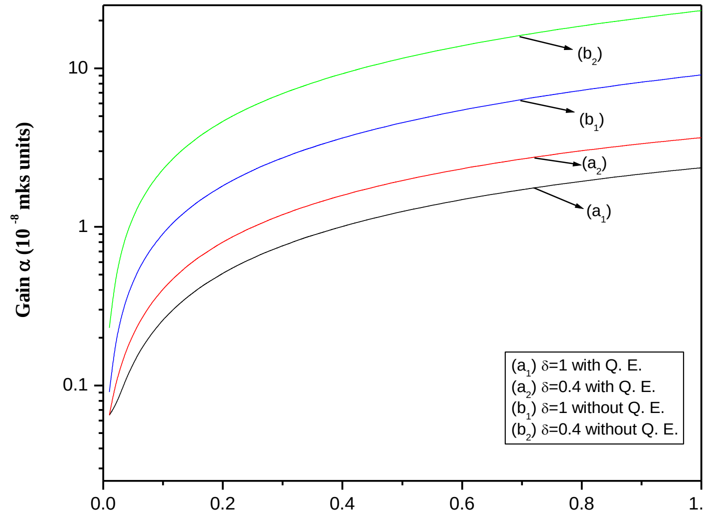


**Fig. 1: The gain $(\alpha)$ of acoustic wave is plotted against the wave frequency $(\omega)$ for different values of $\delta$**

The variation of gain per radian $(\alpha)$ with acoustic wave frequency $(\omega)$ is depicted in Fig. 1 at different values of charge imbalance parameter $(\delta)$. It follows that the gain of the acoustic wave increases parabolically with frequency in both cases (with as well as without quantum effect). When a fraction of colloidal particles is charged, a charge imbalance $(\delta < 1)$ is created in the medium. As a result, the value of gain constant is significantly modified. Fig. 1 revels that the presence of charge imbalance causes to achieve higher values of gain constant in both cases. On the other hand, in absence of colloidal particles, the plasma has equal number densities of electrons and holes i.e., for $\delta = 1$; Fig. shows the same nature of variation of sound wave for lower values of gain constant in both cases. Hence it is quite evident that the charge imbalance created by the presence of colloidal particles in medium causes effective modification in amplification characteristics whereas quantum effect causes to reduce the value of gain $(\alpha)$.

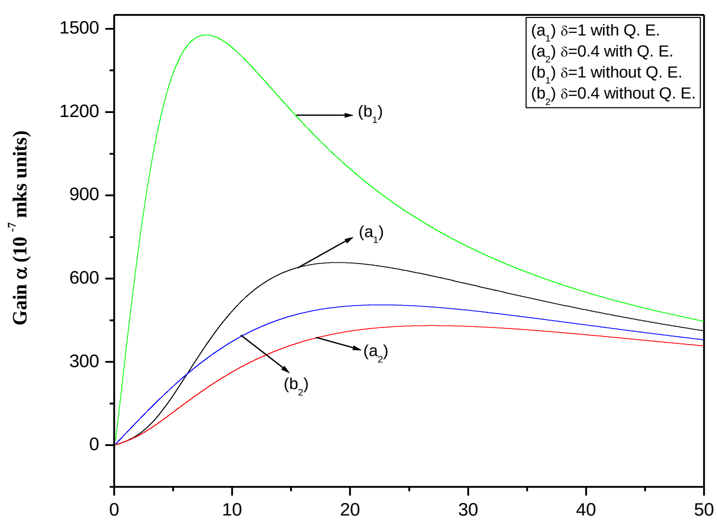


**Fig. 2: The gain $(\alpha)$ of acoustic wave is plotted against the electric field $(E_0)$ for different values of $\delta$**

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Fig. 2 displays the plot between the electric field $(E_0)$ and the acoustic gain per radian $(\alpha)$ for different values of charge imbalance parameter $\delta$. The value of gain constant first increases with the increase in electric field and for the higher values of $E_0$ it tends to saturate. It is observed that in absence of quantum effect and charge imbalance $(\delta = 1)$ the increase in gain constant is quite rapid at lower values of the electric field than at higher ones, while the presence of quantum effect decreases the value of gain for $\delta = 1$. It is also found that the presence of charge imbalance $(\delta < 1)$ is responsible for the decrement in the value of gain constant for both (with and without quantum effect) cases. Hence, it is clear from this graph that externally applied dc electric field is favourable to achieve desirable acoustic gain when quantum effect and charge imbalance both are absent in the medium.

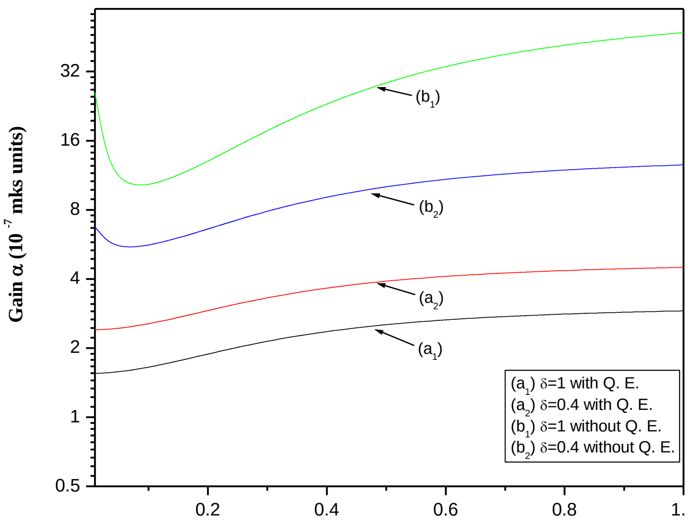


**Fig. 3: The gain $(\alpha)$ of acoustic wave is plotted against the magnetic field $(B_0)$ for different values of $\delta$**

Fig. 3 shows the dependence of the gain constant $(\alpha)$ on the applied magnetic field $(B_0)$ at different values of charge imbalance parameter $\delta$. Under the considered velocity regime all the effects of magnetic field appear through the parameter $\phi_{e,h}$. It is seen that the gain of the acoustic mode increases with the increase of applied magnetic field and the maximum value of gain is obtained in absence of quantum effect for $\delta = 1$. Hence for this velocity regime we found quantum effect is not favourable for achieving higher acoustic gain.

***Conclusion***

In this paper, the dispersion relation for longitudinal phonon-plasmon interaction is investigated by employing the quantum hydrodynamic (QHD) model. It is found that the quantum Bohm potential effect and presence of non-participating negatively charged colloids significantly alters the dispersion characteristics of the acousto-electric wave in the plasmas under consideration. It is also observed that the charge imbalance increases the acoustic gain constant whereas quantum effect reduces it. The possible applications of such type of quantum plasma systems can be found in dense astrophysical objects and micro- and nanoelectromechanical systems, where the charged dust impurities can exist.

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