Electron-Phonon coupling in magnetized semiconductor quantum plasmas

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Abstract. Present paper deals with electron-phonon coupling in piezoelectric n-type magnetized semiconductor plasma under quantum regime. A quantum modified dispersion relation is derived for the evolution of desired electron-phonon coupling in semiconductor plasma using quantum hydrodynamic (QHD) model. The main ingredients of this study are the role of non-dimensional quantum parameter $H$ and externally applied magneto-static field. The presence of quantum parameter $H$ includes the contributions of Fermi degenerate pressure and quantum diffraction. It represents the ratio of plasmon energy to Fermi energy of the system, hence is a function of doping concentration $n_0$. An expression for gain coefficient of acoustic wave is obtained in terms of quantum parameter $H$ and magnetic field under the collision dominated limit. We present the effects of doping in medium and orientation of magnetic field on gain profile of acoustic wave. The results show that the presence of magnetic field and quantum effects through quantum parameter $H$ effectively modifies the gain per unit length of acoustic wave.

1. Introduction
Dynamics of acoustic phonons in semiconductor plasma has been discussed from many angles. Plasma physicists and device engineers have mainly emphasized on the interaction of acoustic wave with free carriers of semiconductor [1-4]. Electron-phonon coupling in semiconductor plasma medium subsequently generate an intense acoustic flux due to background lattice vibrations which finally give rise to a gain of acoustic wave when the electron drift becomes supersonic i.e. $\mathcal{v}_d > \mathcal{v}_s$ (here $\mathcal{v}_d$ and $\mathcal{v}_s$ are electron drift and sound velocities, respectively). Piezoelectric semiconductors are found to be natural candidates for converting mechanical energy to electric energy or vice versa due to coupling between electrons and acoustic phonons through piezoelectricity [5-6]. Thus phenomena of electron-phonon coupling in piezoelectric semiconductor plasma have become one of the extremely important areas of study in plasma physics.

In addition, the propagation of acoustic wave in magnetized plasma has been a topic of important research. It is well known that the plasmas are strongly influenced by magnetic field [7-8] because the plasma parameter may vary with the application of magnetic field. The study of behavior of different waves in plasmas in presence of magnetic field is among the oldest field in plasma physics. Therefore many physicists have published relevant papers about it based on various models [9-10].

Since semiconductors may be doped with external impurities which make it denser by introducing free charge carriers in excess. In such dense medium, quantum effects become unavoidable. Thus semiconductor quantum plasma has gained significant attention from plasma researchers for more than a decade due to their tremendous nano-scale applications [11-12]. Moreover semiconductor quantum plasma can host a variety of plasma waves in the presence of an ambient static uniform magnetic field. But in this context, very few reports have been found [13-14] in the literature. Therefore, in the present paper, we aim to investigate the electron-phonon coupling in semiconductor quantum plasma in...
presence of magnetic field and quantum corrections through quantum parameter- H which represents the ratio of plasmon energy to Fermi energy of the carriers under the field geometry defined in Steele and Vural [15].

2. Theoretical formulation

The coupling between electrons and acoustic phonons in piezoelectric semiconductor quantum plasma is governed by the macroscopic model of piezoelectric media and quantum hydrodynamic (QHD) model. Hence following Steele and Vural [15], a quantum modified dispersion relation, in terms of quantum parameter - H and magneto-static field via electron cyclotron frequency, is derived as

\[
\left( \omega^2 - k^2 \alpha^2 \right) \left( 1 - \frac{\alpha^2}{(\omega - k \alpha_0)} F_Q (\omega, k) \right) = K^2 k^2 \beta^2
\]

(1)

where \( F_Q (\omega, k) = \frac{\omega^2}{(\omega - k \alpha_0)} \)

Here \( H = \frac{\hbar \omega_r}{2K_\beta T_r} \) is the non-dimensional quantum parameter, measuring the relevance of quantum effects, and is proportional to quantum diffraction. \( \delta_f = \frac{2K_\beta T_r}{\hbar} \) is Fermi velocity and \( D_f = \frac{\delta_f}{\nu} \) is diffusion constant at Fermi temperature \( T_r \). Other symbols have their usual meaning.

The first bracket of L.H.S. of the equation (1) represents an acoustic mode while second bracket is a quantum modified electro-kinetic mode. The term on R.H.S. represents the coupling between electron and phonon through \( k^2 = \frac{\epsilon}{\epsilon_r} \), the dimensionless electro-mechanical coupling constant, and \( \beta = \sqrt{\epsilon_r \rho c} \) the acoustic velocity in the medium.

Now using the approximation \( \frac{k \beta_\phi}{\omega} = 1 + i a \) [15], where the gain per radian \( a << 1 \), in the collision dominated regime \( (\omega, k \beta_\phi << \nu) \), equation (1) reduces to

\[
\alpha = \frac{1}{2} K^2 \gamma \frac{\omega_r}{\omega \varphi}
\]

(2)

Where \( \omega_r = \frac{\omega^2}{\nu} \) is dielectric relaxation frequency, \( \omega_{DF} = \frac{\beta_f^2}{D_f} \) is diffusion frequency at Fermi temperature, \( \gamma = \frac{\beta_\phi}{\beta_r} - 1 \) and \( \varphi = \frac{1 + \frac{\omega^2}{\nu^2}}{1 + \frac{\omega^2}{\nu^2} \cos^2 \theta / \nu^2} \). The above expression represents attenuation coefficient in terms of quantum parameter- H, and magnetic parameter \( \varphi \). At \( a > 0 \) i.e. when attenuation coefficient becomes positive, one obtains the amplification of acoustic wave.

3. Results and discussions

For the numerical estimation of our results, we consider n-InSb as our study medium. Using the typical parameters of n-InSb, we investigate the dependency of gain per unit length \( (\alpha \varphi / \beta_\phi) \) of acoustic wave on the doping concentration \( (n_\text{d}) \) and orientation angle \( (\theta) \) of magnetic field and are presented in the following figures.
One may infer from figure 1 that $\alpha_0/\theta_z$ varies with $n_0$ in identical manner both in presence and absence of magnetic field. It increases initially, attains maxima and then starts decreasing with $n_0$. The magnitude of $\alpha_0/\theta_z$ is found to be high in presence of magnetic field. Hence, the presence of magnetic field becomes favourable for achieving higher gain.

The gain per unit length of acoustic wave as a function of orientation angle of magnetic field is depicted in figure 2 with quantum effect as parameter. Figure shows that on enhancing the value of $\theta$, $\alpha_0/\theta_z$ increases, attains maxima at $\theta \approx 72^\circ$ and then starts decreasing with $\theta$. It is also observed from this figure that the magnitude of $\alpha_0/\theta_z$ is found to be low as one includes the quantum corrections through quantum parameter-$H$ and its effect on $\alpha_0/\theta_z$ becomes vanished as $\theta$ approaches $84^\circ$.

4. Conclusions
The electron-phonon coupling in magnetised semiconductor plasma is studied under quantum regimes in which quantum effects are considered through non-dimensional quantum parameter-$H$. The results
of present study reveal that the quantum parameter-$H$ and magnetic field significantly modify the dispersion relation and gain coefficient of acoustic wave. It is also found that higher gain can be obtained in presence of magnetic field and in absence of quantum parameter-$H$. Authors may conclude that this study may be useful in designing of many electronic devices such as acoustic wave amplifier, acousto-electric oscillators, acoustic filters etc.

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