JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Acousto-optic nonlinear interactions in diffusive semiconductor quantum plasmas

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Abstract: We studied the Fermi degenerate case and acousto-optic (AO) gain profile by employing the quantum hydrodynamic (QHD) model of diffusive semiconductor quantum plasma via a non-dimensional quantum parameter H. The QHD model generalised the fluid model with the inclusion of particle degeneracy pressure and Bohm potential (quantum diffraction). The numerical estimations are made for $n-BaTiO_3$ diffusive semiconductor plasma medium. The results indicate that quantum parameter H reduces the magnitude of AO gain coefficient in diffusive semiconductor plasma. The study also reveals that AO gain coefficient is several order high as varied the wave vector k_0 and the AO gain coefficient is highly dependent on the quantum parameter H.

Keywords: Nonlinear (NL) interactions, Semiconductor plasma, Quantum hydrodynamic (QHD) model, Non-dimensional quantum parameter H, Quantum diffraction.

Introduction:

Today, progress in plasma based techniques greatly influenced variety of physical systems, the quantum effects become very important due to its potential applications in miniaturisation of semiconductor quantum devices such as spintronics, quantum dots and quantum wells [1, 2]. The quantum effects are considered in these semiconductor devices when the wavelength of charged carriers is small or comparable the de Broglie wavelength and the effect of quantum tunneling reduces the size of devices used in microelectronics [3, 4]. The high power lasers play a new role in fields of research of nonlinear (NL) interactions in semiconductor plasma. In solid state plasma with high power laser the NL effects are easily observable. Piezoelectric semiconductors are assuring applicant for transform mechanical energy into electric energy. An acoustic perturbation in lattice gives a rise to coupling between acoustic phonons and plasmons i.e. acousto-optic (AO) coupling through piezoelectricity [5-10]. The parallel development in advanced theoretical and numerical methods has become possible to compare the meaningful results between experiment and theory [11, 12].

The quantum hydrodynamic (QHD) models have become essential to study the transport of electrons in extremely high electric field in semiconductor plasmas. QHD is appropriate for the study of the short-range collective phenomena of NL parametric interactions and wave instabilities [13, 14]. QHD model includes the terms of quantum diffraction i.e. the Bohm potential and statistical degeneracy pressure. The Fermi distance is very small than the de Broglie wavelength in semiconductor plasmas.

Quantum plasma (QP) is the most recent research area and important subfield of physics, the quantum effects can be seen in plasmas includes the high densities and low temperature. The standard quantum scales are the time, the length and the thermal speeds of the charge particles which are crucially different from those in classical plasmas. [15-17].

In the present paper, we study the AO gain of $n-BaTiO_3$ diffusive semiconductor plasma by a dimensionless quantum parameter H within the criteria of Fermi degenerate case and the effect of quantum diffraction is considered in the dispersion relation.

Theoretical Formulation:

In order to study AO gain coefficient derived from dispersion relation in diffusive semiconductor plasmas, we use QHD model of plasmas composed of degenerate electrons. A spatially pump field is applied to semiconductor plasmas. The hydrodynamics model of homogeneous semiconductor plasma of infinite range has been put out into QHD model with quantum corrections as Bohm potential and statistical degeneracy pressure effects. QHD consist set of equations such momentum transfer, lattice vibration, space charge and equation of continuity [18]. We have considered n-type semiconductor plasma having strain depend dielectric constant (SDDC).

In semiconductor media due to stress T and strain S produces lattice displacement u can be related as: $S\left(=du/dx\right)$ following White [19] and Steele and Vural [20].

The strain, electric field, coupling coefficient and electrical displacement can be connected as: $D=\varepsilon.E(1+g.S)$ and $\varepsilon=\varepsilon_0.\varepsilon_s$ being permittivity of the medium where D is the electric displacement, ε_0 is the absolute permittivity, ε_s is dielectric constant in absence of any strain S, and $g\left(=\varepsilon_s/3\right)$ is coupling constant semiconductor plasmas having SDDC [21].

Using the above relations of stress T and strain S, the wave equation may be written in elastic medium as;

$$\frac{\partial T}{\partial x}=\rho\frac{\partial^2 u}{\partial t^2}=c\frac{\partial^2 u}{\partial x^2}-\varepsilon.g\frac{\partial E_1^*}{\partial x} \qquad (1)$$

Equation (1) describes the lattice vibration in semiconductor plasmas. In this equation the acoustic velocity $v_a=\sqrt{\frac{c}{\rho}}$; where c is elastic constant and ρ is density of the medium. The acoustic wave in crystal is responsible for coupling of sound mode with the electron motion through the fields E_1. Now we start with the following basic momentum transfer equations:

$$\frac{\partial v_0}{\partial t} + \upsilon v_0 = \frac{-eE_0}{m} \qquad (2)$$

$$\frac{\partial v_1}{\partial t} + v_0 \nabla v_1 + \upsilon v_1 = \frac{-e[E_1 + (v_1 \times B_0)]}{m} - V_F^2 \left(1 + \frac{k^2 V_F^2 H^2}{4\omega_p^{\ 2}}\right) \frac{\Delta n_1}{n_0} \qquad (3)$$

Equation (2) and (3) represents momentum transfer equation of unperturbed and perturbed oscillatory fluid velocities of an electron charge e and m mass. In equation (3) the last term differentiate the QHD model from the classical hydrodynamic model. This pressure term represents the quantum effects via quantum diffraction and quantum statistics in plasma system. Here n_0 and n_1 are the equilibrium and perturb transfer collision frequency and $P_F = \frac{mV_F^{\ 2} n_1^{\ 3}}{3n_0^{\ 2}}$ is Fermi pressure with $V_F = \left(\frac{2k_B T_F}{m}\right)^{\frac{1}{2}}$ as Fermi velocity, k_B and T_F are the Boltzmann constant and Fermi temperature [22]. In our derivation, we have considered a non-dimensional quantum parameter $H\left(= \frac{\hbar\omega_p}{2k_B T_F}\right) =$ Plasmon energy / Fermi energy, which provide the mixed effects of degeneracy pressure and Bohm potential. In which

$\omega_p = \sqrt{\frac{n_o e^2}{m\varepsilon}}$ is electron plasma frequency.

$$\frac{\partial n_1}{\partial t} + n_0 \frac{\partial v_1}{\partial x} + v_0 \frac{\partial n_1}{\partial x} + D \frac{\partial^2 n_1}{\partial x^2} = 0 \qquad (4)$$

Here $D = \frac{V_F^2}{\nu}$ is diffusion constant.

$$\frac{\partial E_1}{\partial x} = -\frac{n_1 e}{\varepsilon} - gE_0 \frac{\partial^2 u}{\partial x^2} \qquad (5)$$

In the continuity equation (4) the diffusion coefficient is $D = \frac{k_B T_F}{e}\mu$ where $\mu\left(= \frac{e}{m\upsilon}\right)$ is electron mobility. Due to diffusion the movement of charge carriers increased and produces the charge separation in strong space charge field. This space charge field is determined by the Poisson's equation (5). The electromagnetic pump wave parametrically generated the acoustic waves (phonons) and electron density perturbation, which turns into an electron plasma wave (photons) in medium thus by solving equations (1) to (5) and using standard approach [23], we obtain the relation as:

$$\frac{\partial^2 n_1}{\partial t^2} + \upsilon \frac{\partial n_1}{\partial t} + \omega_R^2 n_1 + \frac{ik^3 \omega_P^2 g^2 \varepsilon \bar{\varepsilon} E_1 E_0}{e\rho(\omega_a^{\ 2} - k^2 v_a^{\ 2})} = ikn_1 E_b \qquad (6)$$

where $\omega_R^2 = \omega_P^2 \left(1 + \frac{\omega_c^2}{e(\omega_0^2 - \omega_c^2)} + \frac{k^4 V_F^4 H^2}{4\omega_p^4}\right)$ is modified plasma frequency and $\bar{\varepsilon} = \left(\varepsilon + \frac{\omega_c^2}{e(\omega_0^2 - \omega_c^2)}\right)$, $E_b = \frac{eE_0}{m}$ We can use rotating wave approximation to obtain the slow component:

$$n_s^* = \frac{k^4 \omega_p^{\ 2} \varepsilon \bar{\varepsilon} g^2 E_1 |E_0|^2}{m\rho(\omega_a^{\ 2} - k^2 v_a^{\ 2})} \left[\frac{(k^2 E_b^{\ 2} - \delta_a^{\ 2}\delta_0^{\ 2} - \nu\omega_a\omega_0) + i\nu(\omega_a \delta_0^{\ 2} - \omega_0 \delta_a^{\ 2})}{(k^2 E_b^{\ 2} - \delta_a^{\ 2}\delta_0^{\ 2} - \nu\omega_a\omega_0)^2 + \nu^2(\omega_a \delta_0^{\ 2} - \omega_0 \delta_a^{\ 2})^2}\right] \qquad (7)$$

where $\delta_a^{\ 2} = \omega_R^{\ 2} - \omega_a^2$ and $\delta_0^{\ 2} = \omega_R^{\ 2} - \omega_0^{\ 2}$

In order to study the role of diffusion on the nonlinearity of the medium, we express the induced current density by the relation:

$$J_d(\omega_0) = eD \frac{\partial n_s^*}{\partial x} \qquad (8)$$

In above relation the nonlinear component of induced current density is due to coupling amongst three interacting waves. The induced acousto-optic nonlinear polarization $P_{ao}(\omega_0)$ may be treated as the time integral of the induced nonlinear current density $J_d(\omega_0)$ i.e. the used polarization as time integral current density can be written as-

$$P_{ao} = \int J(\omega_0)dt = -\frac{J(\omega_0)}{i\omega_0}$$

$$P_{ao} = \frac{k^5 \omega_p^{\ 2} eD\varepsilon \bar{\varepsilon} g^2 E_1 |E_0|^2}{\omega_0 m\rho\left(\omega_a^{\ 2} - k^2 v_a^{\ 2}\right)} \left[\frac{(k^2 E_b^{\ 2} - \delta_a^{\ 2}\delta_0^{\ 2} - \nu\omega_a\omega_0) + i\nu(\omega_a\delta_0^{\ 2} - \omega_0\delta_a^{\ 2})}{(k^2 E_b^{\ 2} - \delta_a^{\ 2}\delta_0^{\ 2} - \nu\omega_a\omega_0)^2 + \nu^2(\omega_a\delta_0^{\ 2} - \omega_0\delta_a^{\ 2})^2}\right] \tag{9}$$

$$P_{ao} = \varepsilon_0 \chi_{ao}^3 E_1 |E_0|^2$$

Thus the third order acousto-optic nonlinear susceptibility of the medium induced by the carrier diffusion can be obtained as

$$\chi_{ao}^3 = -\frac{k^5 \omega_p^{\ 2} eD\varepsilon_s \bar{\varepsilon} g^2}{\omega_0 m\rho\left(\omega_a^{\ 2} - k^2 v_a^{\ 2}\right)} \left[\frac{(k^2 E_b^{\ 2} - \delta_a^{\ 2}\delta_0^{\ 2} - \nu\omega_a\omega_0) + i\nu(\omega_a\delta_0^{\ 2} - \omega_0\delta_a^{\ 2})}{(k^2 E_b^{\ 2} - \delta_a^{\ 2}\delta_0^{\ 2} - \nu\omega_a\omega_0)^2 + \nu^2(\omega_a\delta_0^{\ 2} - \omega_0\delta_a^{\ 2})^2}\right] \tag{10}$$

One can easily obtain real and imaginary part of the acousto-optic susceptibility-

$$\left(\chi_{ao}^3\right)_R = -\frac{k^5 \omega_p^{\ 2} eD\varepsilon_s \bar{\varepsilon} g^2}{\omega_0 m\rho\left(\omega_a^{\ 2} - k^2 v_a^{\ 2}\right)} \left[\frac{(k^2 E_b^{\ 2} - \delta_a^{\ 2}\delta_0^{\ 2} - \nu\omega_a\omega_0)}{(k^2 E_b^{\ 2} - \delta_a^{\ 2}\delta_0^{\ 2} - \nu\omega_a\omega_0)^2 + \nu^2(\omega_a\delta_0^{\ 2} - \omega_0\delta_a^{\ 2})^2}\right]$$

(11a)

$$\left(\chi_{ao}^3\right)_I = -\frac{i\nu k^5 \omega_p^{\ 2} eD\varepsilon_s \bar{\varepsilon} g^2}{\omega_0 m\rho\left(\omega_a^{\ 2} - k^2 v_a^{\ 2}\right)} \left[\frac{(\omega_a\delta_0^{\ 2} - \omega_0\delta_a^{\ 2})}{(k^2 E_b^{\ 2} - \delta_a^{\ 2}\delta_0^{\ 2} - \nu\omega_a\omega_0)^2 + \nu^2(\omega_a\delta_0^{\ 2} - \omega_0\delta_a^{\ 2})^2}\right]$$

(11b)

From the imaginary part of susceptibility, following relation can study the phenomena of the acousto-optic (AO) gain coefficient:

$$g_{ao} = -\frac{k}{2\varepsilon_s} \chi_{imag.}^{(3)} |E_0|^2 \tag{12}$$

Analysis and discussion:

We will discuss the numerical calculations of AO gain profile of acousto-optic interactions in high mobility $(n - BaTiO_3)$ semiconductor at 77K irradiated by $10.6\mu m$ CO_2 laser. The following parameters are; $m = 0.014m_0$, $\varepsilon_s = 2000$, $\varepsilon = 1.77\times10^{-8}$, $v_a = 4.5\times10^3 ms^{-1}$, $n_0 = 10^{18} - 10^{24} m^{-3}$, $\omega_a = 2\times10^{11} s^{-1}$, $\omega_0 = 1.78\times10^{14} s^{-1}$. The necessary criteria for Fermi degenerate case for medium become quantum plasma is $n_0\lambda_B^3 \geq 1$ hence $\upsilon << \omega_p$ when $T << T_F$ [24]. As per above physical parameters the electron concentration range may be deal with the quantum plasma.

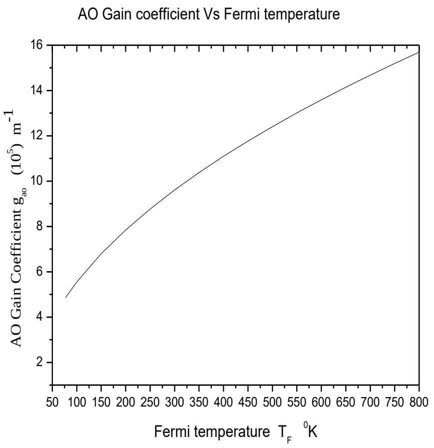

Figure 1: Variation of AO gain coefficient g_{ao} Vs Fermi temperature T_F .

Figure 1 shows the variation of the AO gain coefficient g_{ao} with respect to Fermi temperature T_F. It can be seen from figure that AO gain coefficient g_{ao} increases with increase the Fermi temperature T_F in regime when $\omega_a^{\ 2} > k^2 v_a^{\ 2}$. Initially at $T_F \approx 77^0 K$ the AO gain is $g_{ao} \approx 4.868 \times 10^5 m^{-1}$ as we increase the Fermi temperature the AO gain coefficient increases, the AO gain coefficient become $g_{ao} \approx 1.5 \times 10^6 m^{-1}$ at $T_F \approx 800^0 K$. However the doping should not exceed the limit i.e. $\omega_p^{\ 2} << \omega_1^{\ 2}$. Figure 2 depicts the variation of AO gain coefficient g_{ao} Vs Cyclotron frequency ω_c. The AO gain coefficient g_{ao} decreases as we increase the Cyclotron frequency ω_c. Initially at $\omega_c = 6.279 \times 10^{12} s^{-1}$, the AO gain coefficient is $g_{ao} = 2.38 \times 10^{-17} m^{-1}$. As we increase the Cyclotron frequency, the AO gain coefficient decreases abruptly up to $\omega_c = 1.88 \times 10^{13} s^{-1}$ further increase in ω_c , g_{ao} decreases slowly (when $\omega_a^{\ 2} > k^2 v_a^{\ 2}$).

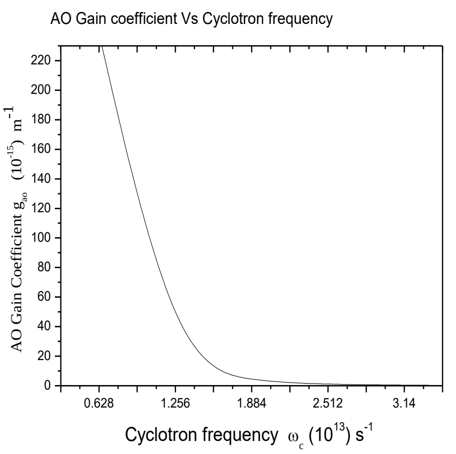

Figure 2: Variation of AO gain coefficient g_{ao} Vs Cyclotron frequency ω_c .

Now we will discuss the variation of AO gain coefficient g_{ao} as a function of pump electric field E_0 with and without quantum effect.

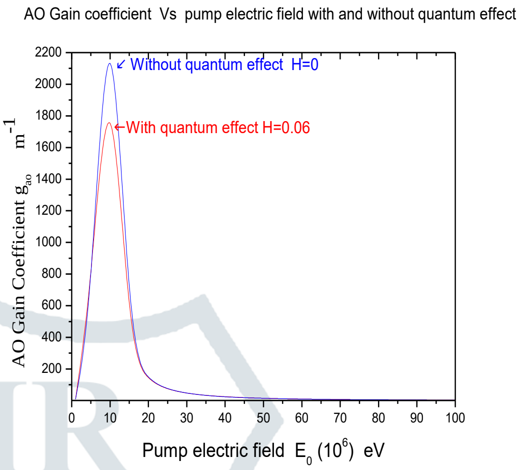

Figure 3: Variation of AO gain coefficient g_{ao} Vs Pump electric field E_0 with ($H = 0.06$) and without quantum ($H = 0$) effect.

Figure 3: represents the change in AO gain coefficient g_{ao} profile with the pump electric field E_0 for the case of classical ($H = 0$) and quantum ($H = 0.06$) plasma. It can be infer from figure that in the low regime of pump field when $k^2 E_b^2 << \delta_0^2 \delta_a^2$ the g_{ao} increase rapidly up to $k^2 E_b^2 \approx \delta_0^2 \delta_a^2$, the gain attains its maximum value for both the cases of classical $(H = 0)$ $g_{ao} \approx 2.982 \times 10^3 m^{-1}$ and quantum $(H \neq 0)$ $g_{ao} \approx 2.381 \times 10^3 m^{-1}$. Hence it is also deduces from figure that magnitude of AO gain coefficient is lower in quantum parameter H i.e. quantum diffraction shift. The analysis of factors reveals that on further increase in the applied pump electric field, AO gain coefficient decreases quite rapidly in both classical and quantum effect.

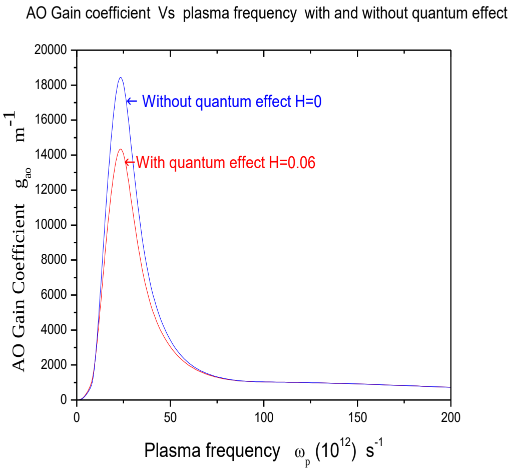

Figure 4: Variation of AO gain coefficient g_{ao} as a function of carrier concentration n_0 (via plasma frequency ω_p) with ($H = 0.06$) and without quantum ($H = 0$) effect.

The behaviour of AO gain coefficient g_{ao} profile varying with carrier concentration n_0 illustrates in figure 4 with quantum ($H = 0.06$) and classical ($H = 0$) effect. Figure shows that the AO gain coefficient of transversely modulated wave with quantum ($H = 0.06$) and classical ($H = 0$) effects increases with rise in carrier density of the medium. It is found that when plasma frequency at $\omega_p \approx 2.383 \times 10^{13} s^{-1}$, the AO gain coefficient g_{ao} attains maximum value in both the cases with quantum ($H = 0.06$) i.e. $g_{ao} \approx 2.018 \times 10^4 m^{-1}$ and classical ($H = 0$) effect i.e. $g_{ao} \approx 2.636 \times 10^4 m^{-1}$. If ω_p is further increased g_{ao} diminishes very rapidly. This behaviour again is found to be same figure 3.

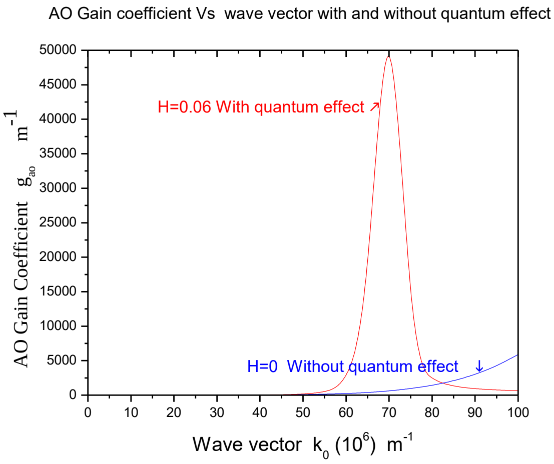

Figure 5: Variation of AO gain coefficient g_{ao} Vs Wave vector k_0 with ($H = 0.06$) and without quantum ($H = 0$) effect.

The influence of wave vector k_0 with AO gain coefficient is depicted in Figure 5 in both the terms of classical and quantum effect. In this figure AO gain coefficient g_{ao} is found to be several orders higher than lower value of wave vector k_0. The AO gain coefficient g_{ao} increase as increase in wave vector k_0 in both the cases in lower regime when $k^2 E_b^2 << \delta_a^2 \delta_0^2$ but in case of quantum ($H = 0.06$) effect at $k^2 E_b^2 \approx \delta_a^2 \delta_0^2$ when $k_0 \approx 6.5 \times 10^7 m^{-1}$ AO gain coefficient g_{ao} abruptly increase by several orders and attains maximum value $g_{ao} \approx 6.95 \times 10^4 m^{-1}$ on further increase in wave vector k_0 the g_{ao} decreases. On the other hand in case of classical ($H = 0$) effect when we increase the value of wave vector k0, increases the AO gain coefficient up to $g_{ao} \approx 5.903 \times 10^3 m^{-1}$.

On the basis of above discussion under criteria for Fermi degenerate case and AO gain profile properties through a dimensionless quantum parameter called H, is taken into account in the dispersion relation of the effect of quantum diffraction . By varying the parameters of the acousto-optic, the important inferences may be drawn as:

i. QHD model is used to investigate AO interactions in n-$BaTiO_3$ semiconductor plasma medium

ii. The magnitude of the acousto-optic gain coefficient is at the quantum parameter H i.e. the quantum diffraction shift, smaller.

iii. The AO gain coefficient is several order high as varied the wave vector and the AO gain coefficient is highly dependent on the quantum parameter H.

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