Novel modes in electron-electron two stream interactions in semiconductor plasma embedded with a nanoparticle

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Abstract. The temporal behaviour of electron-electron two stream instability in two valley semiconductor plasma embedded with a nanoparticle has been investigated. The analytical results obtained for nanoparticle embedded n-GaAs at 300K revealed the possibility of six electrostatic modes of propagation, out of which two modes are found to be induced by the nanoparticle present in the medium. We found that the temporal behaviour of four pre-existing modes does not depend on the signature of nanoparticle present within the medium whereas nanoparticle induced two novel modes are found to be evanescent and stable by nature. Both the new modes are found to be propagating with equal phase velocities but in opposite directions.

1. Introduction

The development of solid state devices operating at higher frequency region gained tremendous attention due to their possible applications in radio astronomy, industry and defence [1]. Here extremely small feature sizes are required, but to achieve required small sizes, carrier transit time always imposes limitations and these limitations could not be overcome by using conventional approaches. Modern workers proposed that to overcome this limitation, one has to explore the properties of nanoparticles embedded in existing plasma media. The presence of nanoparticle in the medium, due to their inherent properties, supposed to induce significant changes in bulk material. Recently, in few theoretical and experimental papers [2-7], we found the reports on the modifications in the thermal properties of bulk semiconductors when embedded with a metallic nanoparticle.

When dc electric field is applied on a semiconductor plasma medium doped with nanoparticle, the conduction electrons of the semiconductor medium acquire drift velocity, whereas the electrons of the cloud of nanoparticle get displaced from their equilibrium position. These two velocities get imposed to give an average velocity of electron. Hydrodynamically, it is the vector sum of these two velocities. On the other side, due to displacement in electron cloud of nanoparticle, a restoring force is also resulted. Due to this restoring force, electrons of the cloud start collective oscillations identical to plasma oscillations of free electrons of semiconductor medium. This effect is equivalent to making the spring constant stiffer, and therefore, leads to a higher plasma frequency. These two phenomena, resulted due to the presence of nanoparticle in semiconductor plasma medium, may become the cause of modifications in the dispersion and amplification characteristics of wave propagation.

Presently, using these unique properties of nanostructures, the present authors [8-10] have investigated the wave phenomena in semiconductor plasma doped with a nanoparticle. Ghosh and Dubey [8] have investigated the convective instability of longitudinal electrokinetic wave in semiconductor plasma consisting of a nanoparticle. They found that, for collisionless or nearly collisionless plasma, nanoparticle modifies only the dispersion characteristics of the modes, whereas in collision dominated region, gain characteristics of both the modes get modified. Ghosh and Dubey [9] studied the temporal instability of longitudinal electrokinetic wave in a nanoparticle impinged semiconductor plasma medium and found that two new modes are induced within the medium due to...
the inclusion of a nanoparticle. They have also explored the carrier drift and wave number dependency of spectral characteristics of all four propagating modes and reported modification due to impinged nanoparticle. The effect of a nanoparticle within the piezoelectric semiconductor on electro-acoustic wave spectrum is studied in detail and recently reported by Dubey and Ghosh [10]. They found significant modification in gain per radian of acoustic wave in terms of velocity ratio, wave frequency and free electron density of semiconductor medium. In presence of nanoparticle the resonant frequency is found to be higher than that found in absence of it, but attenuation to amplification crossover point is found unaffected. Motivated by these, in present study, we have investigated the electron-electron two stream instability in two valley semiconductor (n-GaAs) and hoped that it may attribute to the fundamental knowledge being the very first attempt in this direction.

It is well known fact that the observation of electron-electron two stream instability in a solid depends on the existence of a double-humped electron distribution which could be approximated by a two-stream model. In semiconductors, with more than one conduction band minimum, like GaAs, it is possible to establish a double humped electron distribution [11]. Instabilities in n-GaAs using the peculiarities of its band structure have been proposed by a large number of workers [e.g., 12]. In the strong signal limit, it leads to Gunn effect [13] whereas in the small-signal limit, it leads to amplification of space charge or electrostatic waves. Such an amplification can be described in terms of two-stream instabilities [e.g., 12] and with proper feedback can lead to oscillations [14].

In present analytical investigation, we assumed that, the transferred electron mechanism creates two electron streams. Accordingly, at an applied static electric field greater than the threshold, the central and satellite valleys in the conduction band would be populated by significant number of electrons and these electrons would acquire different drift velocities because of different effective masses. Thereby, we get two-stream system of electrons in the medium.

2. Theoretical formulation
Assuming a one dimensional hydrodynamic model of a semiconductor plasma and small-signal approximation for a periodic perturbation proportional to exp[i(\omega t - kz)], we obtain the conduction current density for free electrons in two valley semiconductor like n-GaAs subjected to a static electric field $E_0$ in the direction of wave propagation as

$$J_z = -i\varepsilon \omega \left[ \frac{\omega_p^2}{(\omega - k\partial_{11})(\omega - k\partial_{11} - i\nu_1) - \partial_{11}^2 k^2} + \frac{\omega_p^2}{(\omega - k\partial_{22})(\omega - k\partial_{22} - i\nu_2) - \partial_{22}^2 k^2} \right] E_z$$

(1)

Subscripts 1 and 2 stand for central and satellite valleys respectively. Here, $\omega_p = \sqrt{e^2 n_j / m_e}$ with $\varepsilon = e_0 e_1$, $m_j$, $n_j$, $\nu_j$, $\partial_{ij}$ and $\partial_{ij}$ represent effective mass, number densities, collision frequencies, thermal velocities and drift velocities of electrons of $j$th-valley respectively.

For current density $J_{np}$ of the electron cloud of the impinged nanoparticle, we will use equation (3) of Ref. [8] which is as follows

$$J_{np} = -i\varepsilon \omega \frac{\omega_{pm}^2}{\left( \omega^2 - \frac{\omega_{pm}^2}{3} \right) E_z}$$

(2)

We obtain the resultant current density $J = J_z + J_{np}$ as

$$J = -i\varepsilon \omega \left[ \frac{\omega_{p1}^2}{(\omega - k\partial_{11})(\omega - k\partial_{11} - i\nu_1) - \partial_{11}^2 k^2} + \frac{\omega_{p2}^2}{(\omega - k\partial_{22})(\omega - k\partial_{22} - i\nu_2) - \partial_{22}^2 k^2} + \frac{\omega_{pm}^2}{\left( \omega^2 - \frac{\omega_{pm}^2}{3} \right) E_z} \right]$$

(3)

Using equations (3) in wave equation for present field geometry $(\omega e_0 e_1 E_z = iJ)$, we may derive the dispersion relation as-
\[\varepsilon(\omega, k) = \left[ 1 - \frac{\omega_p^2}{(\omega - k \delta_0_1)(\omega - k \delta_0_1 - i \nu_1) - \Omega_{g1}^2 k^2} \right] \left[ \frac{\omega_p^2}{(\omega - k \delta_0_2)(\omega - k \delta_0_2 - i \nu_2) - \Omega_{g2}^2 k^2} \right] + \frac{\omega_m^2}{(\omega - \Omega_{g2} - \omega_p^2 / 3)} = 0 \quad (4)\]

Above relation (equation (4)) represents modified dispersion relation in presence of a nanoparticle within the two valley semiconductor plasma medium. In absence of nanoparticle and by neglecting the effect of diffusion, this dispersion relation reduces to equation (1) of Guha and Sen [16]. The modification induced due to plasma frequency of electron cloud present within the nanoparticle is evident through fourth term in square bracket.

Now, to examine the temporal behaviour of electrostatic modes in the medium under study, we rewrite [equation (4)] in form of a polynomial in terms of complex angular frequency \( \omega \) as

\[A_0 \omega^6 + A_4 \omega^4 + A_2 \omega^2 + A_1 \omega + A_0 = 0 \quad (5)\]

where

\[A_0 = \left( -\frac{1}{2} \omega_p^2 \right) \left( k^2 \delta_{g1}^2 + ik \delta_{g1} \nu_1 - \delta_{g1}^2 k^2 \right) \left( k^2 \delta_{g2}^2 + ik \delta_{g2} \nu_2 - \delta_{g2}^2 k^2 \right) + \left( \frac{\omega_m^2}{3} \right) \left( k^2 \delta_{g1}^2 + ik \delta_{g2} \nu_2 - \delta_{g2}^2 k^2 \right) + \left( \frac{\omega_m^2}{3} \right) \left( k^2 \delta_{g2}^2 + ik \delta_{g1} \nu_1 - \delta_{g1}^2 k^2 \right) \]

\[A_4 = \left( \frac{1}{2} \omega_p^2 \right) \left( 2k \delta_{g1} + i \nu_1 \right) \left( k^2 \delta_{g1}^2 + ik \delta_{g2} \nu_2 - \delta_{g2}^2 k^2 \right) + \left( 2k \delta_{g2} + i \nu_2 \right) \left( k^2 \delta_{g1}^2 + ik \delta_{g1} \nu_1 - \delta_{g1}^2 k^2 \right) - \left( \frac{\omega_m^2}{3} \right) \left( 2k \delta_{g1} + i \nu_1 \right) \left( 2k \delta_{g2} + i \nu_2 \right) + \left( \frac{\omega_m^2}{3} \right) \left( 2k \delta_{g2} + i \nu_1 \right) \left( 2k \delta_{g1} + i \nu_2 \right) \]

This polynomial infers that, for a particular \( k \), there exist six possible electrostatic modes of propagation in a two valley semiconductor plasma embedded with a single nanoparticle.

To appreciate the effect of embedded nanoparticle in the plasma medium, we write the dispersion relation (equation (4)) in polynomial form in terms of angular frequency \( \tilde{\omega} \) in absence of nanoparticle \( (\omega_p \to 0) \) and obtain

\[B_4 \omega^4 + B_3 \omega^3 + B_2 \omega^2 + B_1 \omega + B_0 = 0 \quad (6)\]

where,

\[B_0 = \left( k^2 \delta_{g1}^2 + ik \delta_{g1} \nu_1 - \delta_{g1}^2 k^2 - \omega_p^2 \right) \left( k^2 \delta_{g2}^2 + ik \delta_{g2} \nu_2 - \delta_{g2}^2 k^2 \right) - \omega_p^2 \left( k^2 \delta_{g1}^2 + ik \delta_{g1} \nu_1 - \delta_{g1}^2 k^2 \right) \]

\[B_1 = -\left( 2k \delta_{g1} + i \nu_1 \right) \left( k^2 \delta_{g1}^2 + ik \delta_{g2} \nu_2 - \delta_{g2}^2 k^2 - \omega_p^2 \right) - \left( 2k \delta_{g2} + i \nu_2 \right) \left( k^2 \delta_{g2}^2 + ik \delta_{g1} \nu_1 - \delta_{g1}^2 k^2 - \omega_p^2 \right) \]
\[ B_2 = (2k \vartheta_0 + i \nu_1)(2k \vartheta_0 + i \nu_2) + \left( k^2 \vartheta_0^1 + i k \vartheta_0 \nu_1 - \vartheta_0^2 k^2 \right) + \left( k^2 \vartheta_0^2 + i k \vartheta_0 \nu_2 - \vartheta_0^1 k^2 \right) - (\vartheta_0^1 + \vartheta_0^2) \]

\[ B_3 = -(2k \vartheta_0 + i \nu_1) - (2k \vartheta_0 + i \nu_2) \text{ and } B_4 = 1 \]

One may infer from equation (6) that, in absence of nanoparticle, only four modes of propagation of electrostatic wave is possible. Thus, one may conclusively interpret from equations (5) and (6) that the presence of a single nanoparticle induces two novel modes of propagation through plasma frequency of electron cloud of nanoparticle impinged in the two valley semiconductor.

3. Results and discussions

We have numerically solved the dispersion relation (equation (5)) for real positive \( k \approx 10^6 \text{m}^{-1} \) in n-GaAs. The physical parameters of n-GaAs are obtained from references [17, 18]. We found that the dispersion and amplification characteristics of all the four pre-existing electrostatic modes in two valley semiconductor (n-GaAs) plasma are unaffected by the presence of nanoparticle within the medium; hence of no interest. The two newly induced electrostatic modes are found to be propagating in opposite directions to each other i.e., one is forward and other is backward propagating mode. Both transmit through the medium with equal phase velocity \( \approx 2 \text{ms}^{-1} \) which is independent of the magnitude of applied electric field \( E_{dc} \). Due to slow phase velocities, they may be used as diagnostic tool by material scientists working with many valley semiconductors. While studying amplification characteristic of these two novel modes, we found that their gain coefficient is always zero for the range of electric field \( E_{dc} (10^3 - 10^6 \text{V/m}) \) considered here for the study. Hence, these two modes may be termed as stable propagating electrostatic modes or evanescent modes of propagation in the range of parameter under study.

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