

Electron-electron two stream instability in n -GaAs plasma embedded with a nanoparticle

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Electron-electron two stream instability in many valley semiconductors like n -GaAs embedded with a nanoparticle has been studied in hydrodynamic regime. The ingredients of this study are the consideration of polar optical phonon as the dominant intravalley scattering mechanism and a drifted Maxwellian distribution for the carriers in each valley of the medium. A dispersion relation has been developed by the self consistent solution of the momentum transfer, continuity and Maxwell's equations. Typical values of the parameters of n -GaAs at room temperature are considered for analyzing the dispersion relation of the electrostatic wave. Detail qualitative analysis of the convective instability of possible four modes of propagation reveals that the dispersion, propagation and gain profiles of all the four modes have been affected profoundly by the presence of a nanoparticle in the medium via electron plasma frequency of electron cloud present in the nanoparticle.

Keywords: Two stream instability, Semiconductor plasma, Many valley semiconductor

1 Introduction

Pair plasmas have been significant media of research for plasma physicists. The term pair plasma is denoting large ensembles of charged matter consisting of free charged particle populations bearing either opposite or similar charge signs. When a semiconductor is excited by a short laser pulse or a dc electric field having amplitude well below the damage threshold of the medium, electrons absorb the energy and transit from the valence band to the conduction band, depending on the photon or the drift energy and the band gap energy. This inter-band transition of the electrons creates holes in the valence band and this state may satisfy the plasma conditions to create electron-hole plasmas¹. This electron-hole plasma in a semiconductor offers a promising medium to study instability due to oppositely charged streams under the influence of applied dc electric field or due to two counter streaming particle beams²⁻⁷. On the other face of the coin, in case of many valley semiconductors like n -GaAs, with more than one conduction band minimum, it is possible to establish a double-humped electron distribution which can be approximated by the two-electron stream model⁸. Here the transferred electron mechanism actually creates two electron streams. If no drift field is applied to semiconductor like GaAs crystal, all the electrons will be on the

bottom of the central valley. But at applied electric field, if the electrons gain more energy than the energy gap between the central and satellite valleys, some of them will cross over to satellite valley and hence there will be significant number of electrons in both central and satellite valley in the conduction band. Thus in semiconductors like n -GaAs the two stream instability arises due to the interaction between these two streams of electrons having different effective masses. The two stream instability is instability with respect to density perturbation in the medium; under certain conditions, density perturbation in the medium with co propagating carriers will initially grow exponentially. Instabilities in many valley semiconductors using the peculiarities of its band structure have been discussed at length in the literature⁸. Field induced electron transfer mechanism is responsible to achieve negative differential resistivity, Gunn effect in strong signal limit and amplification of space charge wave in weak signal limit. Hence, the different types of two-stream instabilities are very interesting field of research in semiconductor plasma physics. It can very easily be induced by an energetic particle beam shined upon the system, or setting a current (drift velocity) along the medium so different species (e-h, e-p, e-e etc.) may acquire different drift velocities and can lead to excitation of space charge mode through energy exchange phenomenon.

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Recent days, modern nanotechnology is locking almost all the sub disciplines of science and engineering making the subject area rather interdisciplinary in nature. The past two decades have witnessed a dramatic progress in experimental and theoretical methods and application of nanoparticles encompassing their utility in opto-electronics and photovoltaic⁹, biomedicine¹⁰, catalysis¹¹, cosmetics¹², etc. Nanoparticles act as bridge between bulk materials and atomic and nuclear structures, i.e., the structural feature of a nano-sized material lies between bulk macroscopic material and that of isolated atoms giving rise to various interesting novel optical, electrical, chemical and mechanical properties due to their increased surface to volume ratio. There have been many experimental and theoretical investigations of localized collective oscillations of nanoparticles and nanotubes. These oscillations can be excited by charge particles due to electrostatic and electromagnetic perturbations in a plasma medium and their interaction may significantly alter the instabilities produced in a plasma medium^{13,14}.

As nanoparticles inherit various novel optical and electrical properties and it is hoped that their presence in any medium would alter the medium properties significantly. Following this idea, we have investigated the effect of single and group of nanoparticles impinged within a semiconductor plasma medium on dispersion and absorption characteristics of electrostatic^{15,16} and acoustic wave¹⁷ interacting with the medium. The above survey of literature reveals the importance of nanoparticle embedded semiconductor plasma medium and the utility of two-stream (e-e) instability phenomena in fabrication of travelling space charge amplifier and oscillator. Motivated by this in present report, we have investigated the effect of a nanoparticle, embedded in *n*-GaAs semiconductor, on electron-electron two-stream instability produced within the medium.

2 Theoretical Formulations

The polar optical phonon scattering becomes a dominant intravalley scattering mechanism when *n*-GaAs is considered at room temperature (300 K), which has been supported by a large number of reports^{18,19}. This scattering mechanism becomes responsible for transfer of energy and momentum between carriers of the medium. The distribution function has been approximated by assuming the drifted Maxwellian distribution for

carriers in each valley to determine effective electron temperature and collision frequencies^{20,21}. The momentum and energy balance equations have also been applied to obtain field dependent collision frequencies and effective electron temperature at central and satellite valley. The results have been found to be fairly in good agreement with experimental observations²². Hence following Stratton²⁰, the drift velocity $\mathcal{G}_{0,j}$ in either valley is given by²³:

$$\mathcal{G}_{0,j} = 3k_B\theta_D(m_j x_{ej})^{-1} \times \left[1 + \left\{ K_{1j} \left(e^{x_0 - x_{ej}} + 1 \right) \right\} \left\{ K_{0j} \left(e^{x_0 - x_{ej}} - 1 \right) \right\}^{-1} \right] \quad \dots (1)$$

where j can be replaced by 1 and 2, for central and satellite valley respectively. k_B is Boltzmann's constant, θ_D is Debye temperature of crystal, m_j is effective mass of electron, $x_0 = \hbar\omega_l/k_B T_0$, $x_{ej} = \hbar\omega_l/k_B T_{ej}$; T_0 and T_{ej} be the lattice and effective electron temperature, $\hbar\omega_l$ is optical phonon energy in which ω_l represents longitudinal optical phonon frequency. K_{0j} and K_{1j} are the modified Bessel's functions of second kind of zeroth and first order, respectively, those can be approximated as²⁴:

$$K_{0j} = -\left[\ln(x_{ej}/4) + \gamma \right] \text{ and } K_{1j} = 2/x_{ej}$$

here, $\gamma = 0.5772$ is Euler's constant.

Using displaced Maxwellian distribution function of electron, for polar optical phonon scattering, the momentum transfer collision frequency for electrons of central and satellite valley ν_j is given as²⁰:

$$\nu_j = 2/3 \times eE_{0j} N_l (2\pi m_j k_B \theta_D)^{-1/2} x_{ej}^{3/2} e^{x_{ej}/2} \times \left[K_{1j} \left(e^{x_0 - x_{ej}} + 1 \right) + K_{0j} \left(e^{x_0 - x_{ej}} - 1 \right) \right] \quad \dots (2)$$

where e is charge on electron, $E_{0j} = (1/\epsilon_\infty - 1/\epsilon_l) m_j e \hbar \omega_l / \hbar^2$ represents an electric field characterizing the strength of the polar mode scattering, ϵ_l and ϵ_∞ are static and optical dielectric constants, respectively, $N_l = [\exp(\theta_D/T_0) - 1]^{-1}$ is number of phonons with wave vector \vec{k} .

Now, in order to formulate carrier concentrations in different valleys, we assume like Hilsum²⁵ and McCumber and Chynoweth²⁶ that the entire electron

distribution thermalizes with electron temperature of central valley, as electron temperature of satellite valley is found to remain close to lattice temperature²¹. Thus electron density in satellite valley n_2 is given as²⁵:

$$n_2 = n \left\{ 1 + (m_1/m_2)^{3/2} \exp(\Delta/k_B T_{e1}) \right\}^{-1} \quad \dots (3)$$

where n is total carrier concentration given by $n = n_1 + n_2$ in which n_1 is carrier concentration in central valley. m_1 and m_2 are effective masses of electrons in central and satellite valley respectively and Δ is the energy gap between central and satellite valley.

Now let us assume n -GaAs semiconductor plasma of infinite extent impinged with a nanoparticle of radius r and electron density n_{0n} . This two valley semiconductor medium is subjected to an external dc electric field E_{dc} applied along z -axis parallel to wave vector k . The free electrons of both valleys in the conduction band of n -GaAs semiconductor acquire average drift \mathcal{G}_{0j} due to externally applied dc electric field E_{dc} . Under plane wave approximation $\exp[i(\omega t - kz)]$ and using first-order momentum transfer and continuity equations of the hydrodynamic model of plasma:

$$[i(\omega - \vec{k} \cdot \vec{\mathcal{G}}_{0j}) + \nu_j] \vec{\mathcal{G}}_1 = (-e/m_j) \vec{E}_1 + i\mathcal{G}_{\theta_j}^2 (n_1/n_{0j}) \vec{k} \quad \dots (4)$$

$$(n_1/n_{0j}) = \frac{\vec{k} \cdot \vec{\mathcal{G}}_{1j}}{\omega - \vec{k} \cdot \vec{\mathcal{G}}_{0j}} \quad \dots (5)$$

We may obtain the perturbed velocity \mathcal{G}_{1j} of electrons along z -axis as:

$$\mathcal{G}_{1j} = \frac{ie}{m_j} \frac{(\omega - k\mathcal{G}_{0j})}{(\omega - k\mathcal{G}_{0j})(\omega - k\mathcal{G}_{0j} - i\nu_j) - \mathcal{G}_{\theta_j}^2 k^2} E_{1z} \quad \dots (6)$$

Now following Steele and Vural²⁷ and using Eq. (6), the conduction current density $J_{zj} (= -n_{0j} e \mathcal{G}_{1j})$ of medium electrons may be obtained as:

$$J_{zj} = -i\varepsilon\omega_{pj}^2 (\omega - k\mathcal{G}_{0j}) \times \left[(\omega - k\mathcal{G}_{0j})(\omega - k\mathcal{G}_{0j} - i\nu_j) - \mathcal{G}_{\theta_j}^2 k^2 \right]^{-1} E_{1z} \quad \dots (7)$$

Here, $\omega_{pj} = \sqrt{e^2 n_{0j} / m_j \varepsilon}$ with $\varepsilon = \varepsilon_0 \varepsilon_l$; ε_0 and ε_l are permittivity of free space and lattice dielectric constant, and \mathcal{G}_{θ_j} represents thermal velocities of

electrons in central and satellite valley. The semiconductor embedded with a nanoparticle has been developed by several workers, e.g., Schultz and Palmstrom²⁸, Kawasaki *et al.*²⁹, etc. Thus, we have considered n -GaAs doped with a metal nanoparticle as our medium of study. The equation of motion for displacement X of electron cloud of the nanoparticle is given as³⁰:

$$\frac{d^2 X}{dt^2} + \frac{\omega_{pn}^2}{3} X = -\frac{eE_{1z}}{m} \quad \dots (8)$$

where, $\omega_{pn} = \sqrt{e^2 n_{0n} / m \varepsilon}$ is plasma frequency of electron cloud present within the nanoparticle with electron effective mass as m . On solving Eq. (8), we obtain current density for electron cloud within the nanoparticle as:

$$J_{np} = -i\varepsilon\omega_{pn}^2 \omega \left(\omega^2 - \frac{\omega_{pn}^2}{3} \right)^{-1} E_{1z} \quad \dots (9)$$

Hydrodynamically, the displacement velocity of free electrons of nanoparticle cloud and drift velocities of free electrons of both valleys of semiconductor resulted into an average conduction current density for electron that is vector sum of these two conduction currents. Now, as the two valley semiconductor (n -GaAs) impinged with a metallic nanoparticle is acted upon by dc electric field E_{dc} , the resultant conduction current density may be expressed by using Eqs (7) and (9), as:

$$J_{1j} = -i\varepsilon\omega \left[\begin{array}{l} \omega_{pj}^2 \left\{ (\omega - k\mathcal{G}_{0j}) \times \right. \\ \left. \times (\omega - k\mathcal{G}_{0j} - i\nu_j) - \mathcal{G}_{\theta_j}^2 k^2 \right\}^{-1} \\ \left. + \omega_{pn}^2 \left(\omega^2 - \frac{\omega_{pn}^2}{3} \right)^{-1} \right] E_{1z} \quad \dots (10)$$

Substituting Eq. (10) in wave equation $\omega \varepsilon_0 \varepsilon_l E_{1z} = iJ_{1j}$ for present field geometry, we may obtain dispersion relation for electrostatic wave for two streams of electrons in n -GaAs semiconductor plasma medium doped with a nanoparticle as:

$$\varepsilon(\omega, k) = \left[\begin{array}{l} \left\{ (\omega - k\mathcal{G}_{0j}) \times \right. \\ \left. 1 - \omega_{pj}^2 \times (\omega - k\mathcal{G}_{0j} - i\nu_j) - \right. \\ \left. - \mathcal{G}_{\theta_j}^2 k^2 \right\}^{-1} \\ \left. - \omega_{pn}^2 \left(\omega^2 - \frac{\omega_{pn}^2}{3} \right)^{-1} \right] = 0 \quad \dots (11)$$

The contribution of the nanoparticle to the dispersion characteristics of electron-electron two stream interactions is evident from third factor within the square bracket in Eq. (11). This additional term depends on plasma frequency of electron cloud of nanoparticle and frequency of the propagating mode.

The main objective of this paper is to report convective behavior of different propagating modes by solving the dispersion relation expressed as Eq. (11). In order to investigate the convective nature of instability produced, we rewrite Eq. (11) in polynomial form in terms of complex wave number $k = k_{\text{Re}} + ik_{\text{Im}}$ and real wave angular frequency ω as:

$$A_4 k^4 + A_3 k^3 + A_2 k^2 + A_1 k + A_0 = 0 \quad \dots (12)$$

where,

$$\begin{aligned} A_4 &= (\mathcal{G}_{01}^2 - \mathcal{G}_{01}^2)(\mathcal{G}_{02}^2 - \mathcal{G}_{02}^2)\left(\omega^2 - \frac{4}{3}\omega_{pn}^2\right) \\ A_3 &= -\left[\mathcal{G}_{02}(\mathcal{G}_{01}^2 - \mathcal{G}_{01}^2)(2\omega - i\nu_2) + \mathcal{G}_{01}(\mathcal{G}_{02}^2 - \mathcal{G}_{02}^2)(2\omega - i\nu_1)\right] \times \left(\omega^2 - \frac{4}{3}\omega_{pn}^2\right) \\ A_2 &= (\mathcal{G}_{01}^2 - \mathcal{G}_{01}^2) \left\{ \frac{\omega(\omega - i\nu_2)\left(\omega^2 - \frac{4}{3}\omega_{pn}^2\right) - \omega_{p2}^2\left(\omega^2 - \frac{\omega_{pn}^2}{3}\right)}{-\omega_{p2}^2\left(\omega^2 - \frac{\omega_{pn}^2}{3}\right)} \right\} + \\ &+ (\mathcal{G}_{02}^2 - \mathcal{G}_{02}^2) \left\{ \frac{\omega(\omega - i\nu_1)\left(\omega^2 - \frac{4}{3}\omega_{pn}^2\right) - \omega_{p1}^2\left(\omega^2 - \frac{\omega_{pn}^2}{3}\right)}{-\omega_{p1}^2\left(\omega^2 - \frac{\omega_{pn}^2}{3}\right)} \right\} + \\ &+ \mathcal{G}_{01}\mathcal{G}_{02}(2\omega - i\nu_1)(2\omega - i\nu_2)\left(\omega^2 - \frac{4}{3}\omega_{pn}^2\right) \\ A_1 &= -\left[\mathcal{G}_{01}(2\omega - i\nu_1) \left\{ \frac{\omega(\omega - i\nu_2)\left(\omega^2 - \frac{4}{3}\omega_{pn}^2\right) - \omega_{p2}^2\left(\omega^2 - \frac{\omega_{pn}^2}{3}\right)}{-\omega_{p2}^2\left(\omega^2 - \frac{\omega_{pn}^2}{3}\right)} \right\} + \right. \\ &\left. + \mathcal{G}_{02}(2\omega - i\nu_2) \left\{ \frac{\omega(\omega - i\nu_1)\left(\omega^2 - \frac{4}{3}\omega_{pn}^2\right) - \omega_{p1}^2\left(\omega^2 - \frac{\omega_{pn}^2}{3}\right)}{-\omega_{p1}^2\left(\omega^2 - \frac{\omega_{pn}^2}{3}\right)} \right\} \right] \\ A_0 &= \omega^2(\omega - i\nu_1)(\omega - i\nu_2)\left(\omega^2 - \frac{4}{3}\omega_{pn}^2\right) - \\ &- \omega\left(\omega^2 - \frac{\omega_{pn}^2}{3}\right)\left\{\omega_{p1}^2(\omega - i\nu_2) + \omega_{p2}^2(\omega - i\nu_1)\right\} \end{aligned}$$

Equation (12) is a quadratic equation in complex wave number k that indicates the existence of four possible modes of propagation and can be solved for real positive values of ω to study the convective instability of space charge or electrostatic modes propagating through two valley *n*-GaAs plasma medium embedded with a metallic nanoparticle. In

absence of nanoparticle ($\omega_{pn} = 0$), the order of polynomial does not change. Hence, it may be concluded that no new mode of electrostatic wave is induced due to the presence of nanoparticle. A look at the complex coefficients of Eq. (12) yields that the behavior of the existing modes are significantly modified by the presence of a metallic nanoparticle in the considered semiconductor medium.

3 Results and Discussion

In deriving dispersion relation (Eq. (12)), we have considered the perturbations of electrostatic wave of the form $\exp[i(\omega t - kz)]$ and so the wave would be growing in space when $k_{\text{Im}} > 0$ and decaying when $k_{\text{Im}} < 0$. Two stream instability is an example of general class of instabilities that can occur in a conservative system. Such instabilities have been referred to as reactive. A reactive instability occurs when two wave modes of the linear system couple at a frequency, where one of the modes carries positive energy and the other negative energy. To estimate the propagation and gain profiles of all four possible modes, Eq. (12) has been solved numerically for *n*-GaAs at room temperature. The numerical magnitudes of required physical parameters of *n*-GaAs at room temperature have been collected from the literature and are listed in Table 1.

On solving polynomial given in Eq. (12) for real positive ω , the obtained modifications due to presence of nanoparticle in convective nature of possible four modes have been depicted in Figs 1-6. In Figs 1 and 2, the dispersion characteristics of all four modes of propagation are depicted in presence (Fig. 1) and in absence (Fig. 2) of nanoparticle. From these figures one may yield that in absence of nanoparticle, all the possible modes follow normal dispersion characteristics (Fig. 2). Due to the presence of nanoparticle these normal dispersive modes reflect anomalous behavior as seen in Fig. 1. Figure 1 also depicts that all four modes show resonant behavior at

Table 1 – Basic parameters of GaAs at room temperature

| | |
|---|-------------|
| Mass of electron in central valley ³¹ m_1 | 0.072 m_0 |
| Mass of electron in satellite valley ³¹ m_2 | 0.364 m_0 |
| Static dielectric constant ³¹ ϵ_f | 13.5 |
| Optical dielectric constant ³¹ ϵ_∞ | 11.6 |
| Energy gap ³¹ Δ (eV) | 0.36 |
| Optical phonon energy ³¹ $\hbar\omega_l$ (eV) | 0.036 |
| Debye temperature ³² θ_D (K) | 420 |

$\omega \approx 10^6 \text{ s}^{-1}$. It may also be inferred from Fig. 1 that, I and II modes are contrapropagating whereas III and IV modes are copropagating in nature, in presence of nanoparticle.

Figure 2 displays that in absence of nanoparticle, I, II and III modes are contrapropagating whereas IV mode is copropagating in nature. Hence one may infer that nanoparticle converts the nature of propagation of at least one mode, i.e., III mode from contra to copropagation. The phase velocity of a mode is defined as $\left(\frac{\omega}{|k_{\text{Re}}|} \right)$, that is always inversely proportional to k_{Re} at a particular value of wave frequency ω . Thus we have considered $\omega = 10^6 \text{ s}^{-1}$ drawing all the propagation and gain characteristics (Figs 3-6) because we obtained a resonance at this frequency

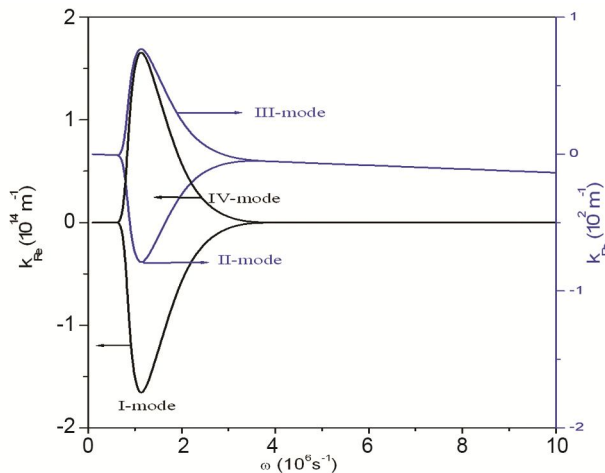


Fig. 1 – Dispersion characteristics of all four modes in presence of nanoparticle

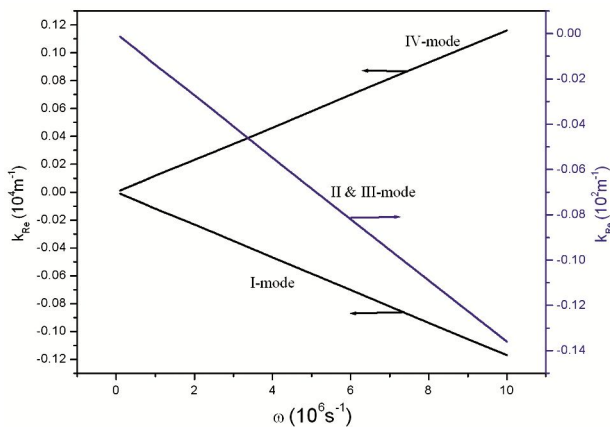


Fig. 2 – Dispersion characteristics of all four modes in absence of nanoparticle

evident from Fig. 1. One may infer from Fig. 3(a) that the phase velocity of I-mode is an increasing parameter with applied electric field E_{dc} . The inclusion of a nanoparticle within the semiconductor plasma medium changes its characteristic. Initially its phase velocity increases up to $E_{\text{dc}} = 2.2 \times 10^6 \text{ Vm}^{-1}$, acquires a maximum and starts reducing with further increase in E_{dc} . The presence of nanoparticle within the medium is found to enhance phase velocity by 6 orders in magnitude. Curves in Fig. 3(b) reflects that the mode is evanescent in nanoparticle free medium, but it becomes amplifying due to inclusion of nanoparticle within the medium and its amplification coefficient is a reducing function of external electric field E_{dc} .

Propagation and amplification characteristics of II mode are depicted in Fig. 4(a,b). Curves in the figures infer that the mode is decaying in presence as well as absence of nanoparticle. In absence of nanoparticle

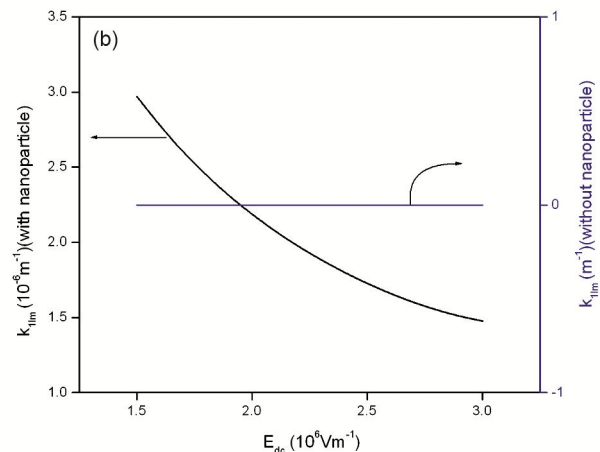
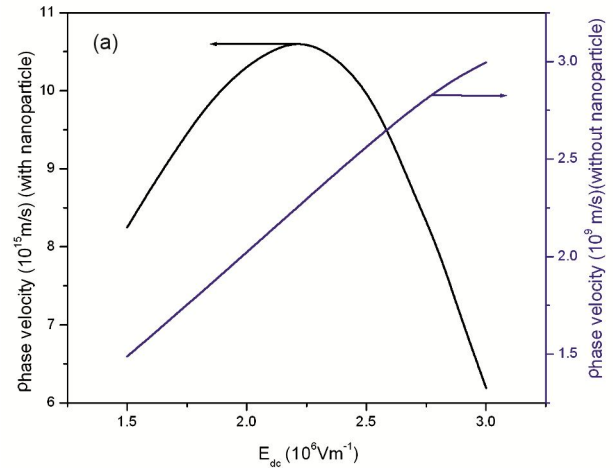


Fig. 3 – (a) Variation of phase velocity of I-mode with E_{dc} and (b) variation of gain coefficient of I-mode with E_{dc}

the phase velocity increases with applied electric field, whereas when the medium is doped with a metal nanoparticle it initially increases to a maximum at $E_{dc} = 2.2 \times 10^6 \text{Vm}^{-1}$ and then starts decreasing with E_{dc} . The gain profile reveals that the decay constant is increasing with increase in applied electric field (E_{dc}) in absence of nanoparticle; while the presence of nanoparticle within the medium enhances the decay constant by 4 orders in magnitude and it is a decreasing function of applied electric field E_{dc} .

Figure 5(a) infers that propagation characteristic of III-mode is unaffected by the presence of the metal nanoparticle within the semiconductor plasma medium. The phase velocity increases almost linearly with varying electric field E_{dc} . Curves in Fig. 5(b) reflect that the presence of a metal nanoparticle converts the character of III-mode from amplifying to decaying. Its gain coefficient has similar

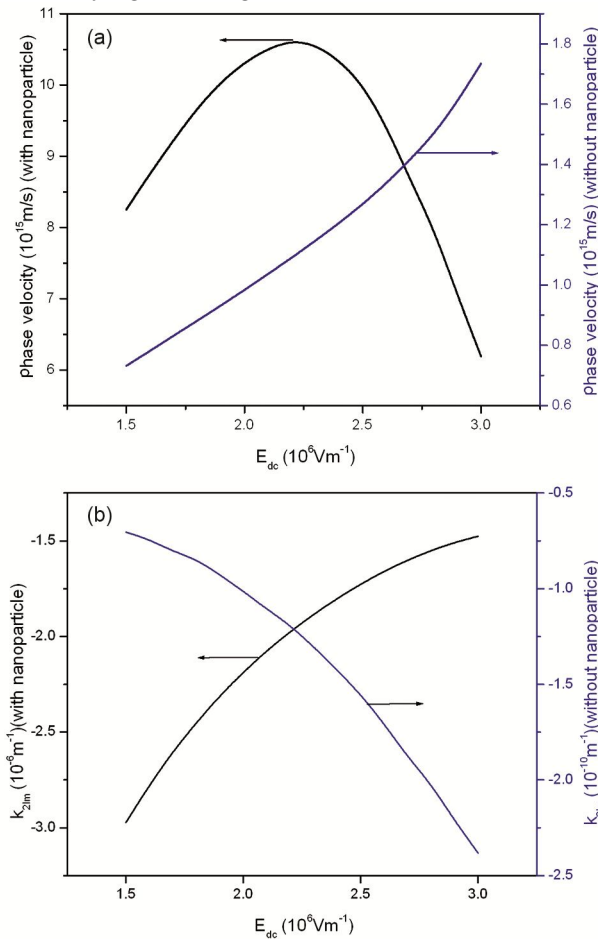


Fig. 4 – (a) Variation of phase velocity of II-mode with E_{dc} and (b) variation of gain coefficient of II-mode with E_{dc}

quantitative variation in both the physical situations and found to be enhanced with increasing electric field E_{dc} .

As per propagation characteristic displayed in Fig. 6(a), IV mode is found to have the similar qualitative variation of phase velocity in both the physical conditions (presence and absence of nanoparticle). The phase velocity increases with increasing dc electric field. The amplification characteristic of IV-mode depicted in Fig. 6(b) reveals that it is a non-amplifying evanescent mode in nanoparticle free medium, but in presence of a nanoparticle within the medium, it is converted into a growing mode with gain coefficient as an increasing function of applied electric field E_{dc} . It is a very

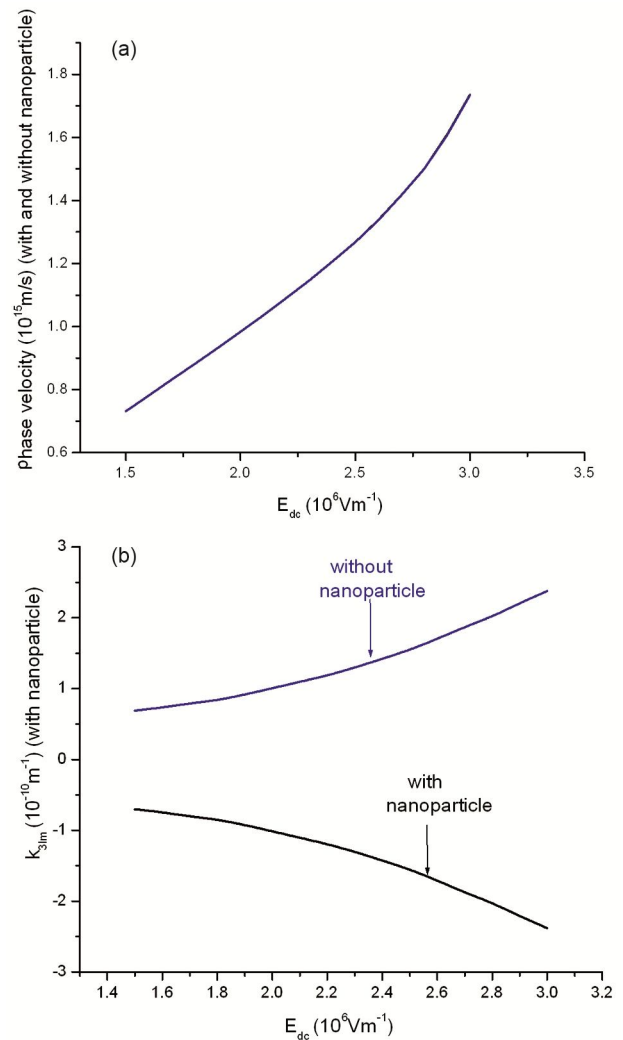


Fig. 5 – (a) Variation of phase velocity of III-mode with E_{dc} and (b) variation of gain coefficient of III-mode with E_{dc}

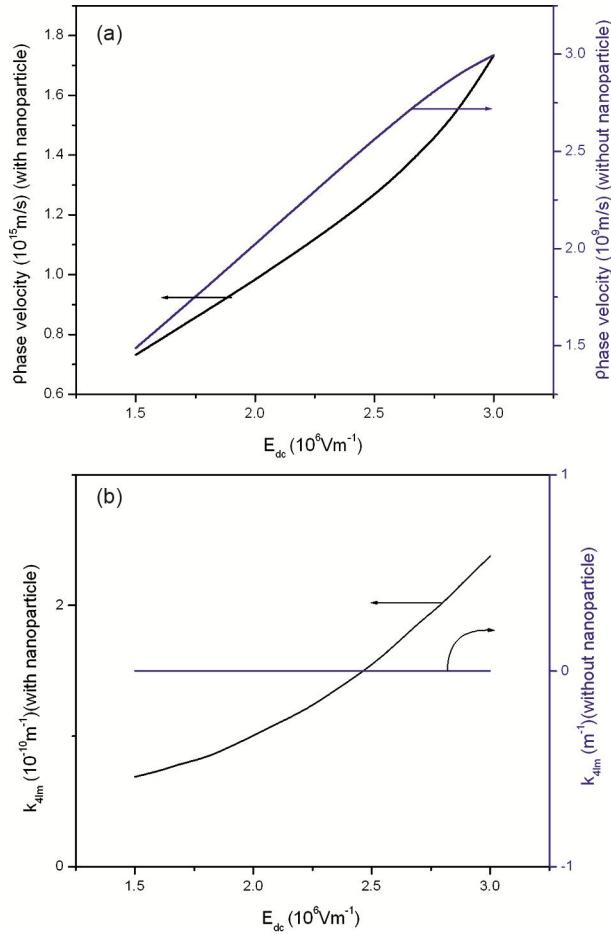


Fig. 6 – (a) Variation of phase velocity of IV-mode with E_{dc} and (b) variation of gain coefficient of IV-mode with E_{dc}

favourable modification induced by a nanoparticle present in the semiconductor medium.

Here two kinds of semiconductors are investigated namely n -GaAs and a metal nanoparticle embedded n -GaAs. We found certain important behavioral modifications of different modes due to two stream (e-e) interactions in n -GaAs embedded with a single nanoparticle. The deviation in character due to the presence of nanoparticle may be summarized as:

(i) In nanoparticle free n -GaAs medium, it is found that phase velocities of all the four modes are increasing function of applied dc electric field E_{dc} (Figs 3(a), 4(a), 5(a) and 6(a)). Being an energy conservative system, the energy supplied externally by dc electric field, actually transferred to these modes via carrier drift and hence increases their kinetic energy (phase velocities).

- (ii) The I and IV modes of propagation through n -GaAs in absence of nanoparticle are found to be evanescent in nature (Figs 3(b) and 6 (b)). This nature may be attributed to the fact that these two interacting modes propagate with nearly identical speed that is equal to the drift velocity of the carriers of satellite valley. Thus, the energy of these two modes and satellite carriers are equal and hence the reactive interaction between them is not possible. Resultantly, they are stable modes.
- (iii) The Doppler shift of II and III modes in absence of nanoparticle, with respect to both valley carriers are nearly negligible, thus they are interactive modes. Now based on the gain characteristics of these modes (Figs 4(b) and 5(b)), it may very safely concluded that due to this interaction, energy is transferred from II mode to the III mode. Because of this energy transfer, II mode decays whereas III mode amplifies. Their decay constant and amplification constant also increase with increasing dc electric field E_{dc} . Hence II and III modes in absence of nanoparticle may be termed as positive energy carrying and negative energy carrying modes, respectively.
- (iv) When a metallic nanoparticle is impinged within the semiconductor medium, because of the resulted restoring force due to displacement in electron cloud of nanoparticle, the electrons of the cloud start collective oscillations identical to plasma oscillations of free electrons of semiconductor medium. This is equivalent to making the spring constant stiffer and therefore, leads to higher plasma frequency which subsequently shifts the centre of interaction towards higher frequency. This phenomena induced due to the presence of nanoparticle may be attributed for the modifications in the propagation and amplification characteristics of all the four electrostatic modes.
- (v) In case of nanoparticle impinged n -GaAs, we found that the phase velocities of all the four modes increase with increasing E_{dc} (Figs 3(a), 4(a), 5(a) and 6(a)) but the phase velocities of I and II modes (Figs 3(a) and 4(a)) achieves maximum value at $E_{dc} = 2.2 \times 10^6 \text{ Vm}^{-1}$ and then start decreasing. This unusual behavior may be attributed to the fact that at this magnitude of

dc electric field ($\approx 2.2 \times 10^6 \text{ Vm}^{-1}$), the drift velocity of carriers of central valley becomes resonant with its thermal velocity.

- (vi) From the gain characteristics of I and III modes of propagation through nanoparticle impinged *n*-GaAs semiconductor, it is found that I mode is amplifying in nature with decreasing gain constant (Fig. 3(b)) with applied electric field E_{dc} , whereas III mode is decaying in with increasing decay constant (Fig. 5(b)) with applied electric field E_{dc} . This varying nature may be assigned to the fact that a reactive interaction may occur through the coupling of these two modes of linear system, when III mode carries positive and I mode carries negative energy. Being a conservative system, III mode loses whereas I mode gains energy resulting in decay and amplification of these modes, respectively.
- (vii) Similarly, it may be presumed that II and IV modes of this conservative system couple when II mode is positive and IV mode is negative energy carrying modes. During interaction, II mode loses energy and hence become a decaying mode (Fig. 4(b)) whereas IV mode gains energy to become an amplifying mode (Fig. 6(b)).

4 Conclusions

We have devoted a significant amount of our efforts to study the two-stream instability in a nanoparticle impinged semiconductor medium because this material may be useful in fabrication of good infrared radiation sources. This type of reactive interaction might be seen in a device in which electrons are injected into a relatively short doped base region from a tunnel barrier. Such a device is called the tunneling hot-electron transfer amplifier. When the device is biased, electrons from the emitter tunnel through the barrier into the base region. These injected electrons are essentially monoenergetic, and they stream quasi-ballistically relative to the cold electrons that are present in the base. This situation could lead to electron-electron two stream instability. It is hoped that the physics of the two stream instability in such a device may be explained satisfactorily with the aid of the work presented here.

In this field induced instability, the relaxation time approximation was extensively used. These

interactions are responsible for the negative mobility of minority carriers in photo excited quantum wells, as the majority carriers dragged the minority carriers along in their wake. The presence of these scatterings would unfortunately tend to decrease the possibility of the two-stream instability, since they would reduce the mobility of both species. Future investigations into the two-stream instability using Monte-Carlo or other such numerical techniques could include the more realistic scattering terms and carrier-carrier scattering.

Conclusively, it is hoped that these important modifications in the propagation and gain characteristics of two stream instability due to the presence of a nanoparticle may be useful in understanding the physics of the phenomena and several of these modifications may be helpful in the fabrication of useful new infrared radiation sources and travelling wave devices.

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