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Research Article

LONGITUDINAL ELECTROKINETIC WAVES IN SEMICONDUCTOR PLASMAS CONSISTING OF A SINGLE NANOPARTICLE

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ABSTRACT
We have described the propagation characteristics of longitudinal electrokinetic wave in semiconductor plasma consisting of a single nanoparticle. The interaction is studied using hydrodynamical model of infinite plasmas. We found that for collisionless or nearly collisionless plasma, nanoparticle modifies only the dispersion characteristic of the modes. But in collision dominated region, gain characteristics of both the modes of propagation get modified due to the presence of nanoparticle.

Keywords: *Semiconductor Plasma, Hydrodynamical Model of Plasma, Electrokinetic Wave, Propagation Characteristics, Nanoparticles*

INTRODUCTION
Plasmas host wide range of electrostatic and electromagnetic waves. The propagation of comparatively high frequency plasma oscillations (depending upon free carrier density of plasma medium) are among the fundamental electrostatic modes that has great attraction of plasma researchers for their simple mechanism and wide range of applications in space and laboratory plasmas (Koepke, 2002; Cranmer *et al.*, 2007; Liu *et al.*, 2009; Castro *et al.*, 2010). The semiconductor materials, on the other hand, consist of the electrons-holes. Due to their dilute nature, in terms of parameters of interest, they are found to be more appropriate materials among all solid state plasmas to study the wave propagation characteristics. In the semiconductor materials the separation of charges due to polarisation between semiconductor plasma species, results in an oscillation called plasma oscillations (Suryanarayanan *et al.*, 2010). Under certain favourable physical situation, these oscillations propagate through semiconductor plasma as fundamental electrostatic mode. The experimental studies have been done for the electrostatic modes in many materials like Ge, Si, InSb and GaAs. However, a lot of primitive work is still matter of comprehensive experimental and theoretical studies.

One of the recently emerging multidisciplinary research fields in plasma is plasma nano-science. The ongoing research in this direction is very relevant and expected to substantially expand to competitively contribute to the solution of many grand challenges. Recently strong interests are emerging for development of solid state devices operating at little higher frequency region for possible applications in radio astronomy, industry and defense (Mustafa and Hashim, 2010). The existing gap cannot be filled by using conventional electron approach or transit time devices due to the limitation that comes from the carrier transit time where extremely small feature sizes are required. One way to overcome this limitation is to employ the properties of nanoparticles in already existing plasma media.

Nanoparticles are of great technological importance because their inclusion makes significant changes in the properties of bulk materials. Nanoparticles often possess unexpected optical and dielectric properties as they are small enough to confine orbital electrons and produce quantum effects. Other size dependent properties those change with nanoparticles include quantum confinement in semiconductors, surface plasmon resonance in some metal particles and super magnetism in magnetic materials. Several workers have reported the wave-nanoparticle interaction and found some interesting results those are useful in electronic-device manufacturing. Wei *et al.*, (2004) reported experimental and theoretical studies on the plasmon resonances of finite one-dimensional chains of Au nanoparticles excited by evanescent light waves with polarisation parallel to the chains. They showed that the plasmon resonance peak wavelengths are significantly red-shifted in comparison to that of single Au nanoparticle. Weber and Ford (2004) derived the dispersion relation for dipolar modes propagating along a chain of metal nanoparticles treating nanoparticles as point dipoles. They found large deviations from previous quasi-static results. Govorov *et al.*, (2006) described the physical properties of excitons in hybrid complexes composed of semiconductor and metal nanoparticles. They revealed the interaction between individual nanoparticles as an enhancement or suppression of emission. Lindberg *et al.*, (2007) studied the dipole-dipole coupling between two fluorescent molecules in the presence of a chain of metallic nanoparticles. Their result shows that for certain resonant wavelengths the coupling strength between the molecules is greatly enhanced and is strongly polarisation sensitive. Recently Jain and Parashar (2011) reported the propagation characteristics of electrostatic and electromagnetic waves in medium consisting of (i) a single nanoparticle, (ii) collection of nanoparticles and (iii) periodically arranged nanoparticles. They have also reported the effect of particle density, size and electron density on the propagation of these waves.

Motivated we study theoretically the propagation characteristics of electrostatic mode through semiconductor plasma medium consisting of a single metal nanoparticle doped inside the material. We found very important alteration in the characteristic of this elementary excitation.

Dispersion Relation

We consider n-type semiconductor plasma of infinite extent and assumed that a single metal nanoparticle of radius r and electron density n_{0n} is impinged within this medium. The medium is subjected to an external dc electric field due to which the free electrons of semiconductor plasma gets drifted along z-axis with an average drift velocity ϑ_{0z}. To discuss the simplest mode supported by an infinite semiconductor plasma consisting of a single nanoparticle, we assume that this mode is due to longitudinal oscillations of free charges (classical plasma mode) controlled by plasma frequency $\omega_{pe}\left[= \left(n_{0e}q^2/m_e\varepsilon\right)^{1/2}\right]$. A perturbation $E_{1z} = \hat{E}_{1z}\exp\left[i(\omega t - kz)\right]$ is imposed on the medium in which ω is angular frequency and k is the wave number.

Following Steele and Vural (1969) and by obtaining self consistent solution of the basic equations of hydrodynamical model of plasmas, the conduction current density in absence of nanoparticle is derived as

$$J_{1z} = -i\frac{q^2 n_{0e}}{m_e}\frac{\omega E_{1z}}{\left[(\omega - k\vartheta_{0z})(\omega - k\vartheta_{0z} - i\nu_e) - \vartheta_\theta^{\,2}k^2\right]} \qquad (1)$$

Here, ν_e is the momentum transfer collision frequency and ϑ_θ is the thermal velocity.

Under the influence of the wave electric field, the electron cloud of the nanoparticle is displaced by an amount Δ. The displacement of electron cloud is governed by the equation of motion

$$\frac{d^2\Delta}{dt^2} + \frac{\omega_{pn}^{\;2}}{3}\Delta = -\frac{eE}{m}, \qquad (2)$$

where $\omega_{pn} = \sqrt{e^2 n_{0n}/m}$ is the plasma frequency of the electron cloud present within nanoparticle.

On solving equation (2) we obtain the expression for current density as

$$J_{np} = i\frac{e^2 n_{0n}}{m}\frac{\omega E_1}{\left(\omega^2 - \dfrac{\omega_{pn}^2}{3}\right)} \qquad (3)$$

The resultant current density $\vec{J}_1 = \vec{J}_{1z} + \vec{J}_{np}$ becomes

$$J_1 = -i\varepsilon\omega\left[\frac{\omega_{pe}^2}{(\omega - k\vartheta_{0z})(\omega - k\vartheta_{0z} - i\nu_e) - \vartheta_\theta{}^2 k^2} - \frac{\omega_{pn}^2}{\left(\omega^2 - \frac{\omega_{pn}^2}{3}\right)}\right]E_1 \tag{4}$$

Substituting equation (4) in general wave equation we obtain the general dispersion relation for longitudinal electrokinetic waves propagating through n-type semiconductor plasma consisting of a single nanoparticle as

$$\varepsilon(\omega, k) = \left[1 - \frac{\omega_{pe}^2}{(\omega - k\vartheta_{0z})(\omega - k\vartheta_{0z} - i\nu_e) - \vartheta_\theta{}^2 k^2} + \frac{\omega_{pn}^2}{\left(\omega^2 - \frac{\omega_{pn}^2}{3}\right)}\right] = 0 \tag{5}$$

In absence of nanoparticle $(\omega_{pn} = 0)$, the above dispersion relation reduces to equation (4-36) of Steele and Vural (1969). Hence it may be infer from equation (5) that the presence of a single nanoparticle modifies the dispersion as well as amplification characteristics of modes due to longitudinal oscillations of charges supported by plasma oscillations.

RESULTS AND DISCUSSION

We may rewrite dispersion relation (5) as polynomial in k as

$$A_2 k^2 + A_1 k + A_0 = 0 \tag{6}$$

in which,

$$A_0 = \omega^4 - i\omega^3\nu_e + \frac{2}{3}\omega^2\omega_{pn}^2 - \frac{2}{3}i\omega\nu_e\omega_{pn}^2 - \omega_{pe}^2\omega^2 + \frac{\omega_{pe}^2\omega_{pn}^2}{3}$$

$$A_1 = -2\omega^3\vartheta_{0z} + i\vartheta_{0z}\nu_e\omega^2 - \frac{4}{3}\omega\vartheta_{0z}\omega_{pn}^2 + \frac{2}{3}i\vartheta_{0z}\nu_e\omega_{pn}^2$$

$$A_2 = \omega^2\vartheta_{0z}^2 - \omega^2\vartheta_\theta^2 + \frac{2}{3}\vartheta_{0z}^2\omega_{pn}^2 - \frac{2}{3}\vartheta_\theta^2\omega_{pn}^2$$

Since the dispersion relation (6) is only of second degree in k with complex coefficient, it infers two longitudinal modes with wave number k_1 and k_2 for a given frequency ω. We shall now discuss the characteristics of these modes analytically in detail

1) For cold and collisionless plasma $(\vartheta_\theta = \nu_e = 0)$, we found

$$k_1 = k_f = \frac{\omega}{\vartheta_{0z}} - \frac{\omega_{pe}\left[\omega^4 + \frac{1}{3}\omega^2\omega_{pn}^2 - \frac{2}{9}\omega_{pn}{}^4\right]^{1/2}}{\vartheta_{0z}\left(\omega^2 + \frac{2}{3}\omega_{pn}^2\right)} \tag{7a}$$

$$\vartheta_f = \frac{\omega}{k_f} = \frac{\vartheta_{0z}}{1 - \frac{\omega_{pe}\left[\omega^4 + \frac{1}{3}\omega^2\omega_{pn}^2 - \frac{2}{9}\omega_{pn}^4\right]^{1/2}}{\omega\left(\omega^2 + \frac{2}{3}\omega_{pn}{}^2\right)}} \tag{7b}$$

and

$$k_2 = k_s = \frac{\omega}{\vartheta_{0z}} + \frac{\omega_{pe}\left[\omega^4 + \frac{1}{3}\omega^2\omega_{pn}{}^2 - \frac{2}{9}\omega_{pn}{}^4\right]^{1/2}}{\vartheta_{0z}\left(\omega^2 + \frac{2}{3}\omega_{pn}{}^2\right)} \quad (8a)$$

$$\vartheta_s = \frac{\omega}{k_s} = \frac{\vartheta_{0z}}{1 + \frac{\omega_{pe}\left[\omega^4 + \frac{1}{3}\omega^2\omega_{pn}^2 - \frac{2}{9}\omega_{pn}^4\right]^{1/2}}{\omega\left(\omega^2 + \frac{2}{3}\omega_{pn}{}^2\right)}} \quad (8b)$$

Equations (7) and (8) are the familiar fast and slow space charge modes of cold collisionless (or nearly collisionless) semiconductor plasma modified due to presence of a single nanoparticle.

2) Assuming $\vartheta_\theta = 0$, $\nu_e \neq 0$ and $\nu_e < 2\omega_{pe}$, we found

$$k_{1,2} = \frac{\omega \mp \omega_{pe}X\left[1 - \nu_e{}^2/4\omega_{pe}^2X^2\right]^{1/2}}{\vartheta_{0z}} - \frac{i\nu_e}{2\vartheta_{0z}} \quad (9)$$

In this case, the two modes may still be classified as modified fast and slow space charge waves having phase velocities

$$\vartheta_f = \frac{\vartheta_{0z}}{1 - \frac{\omega_{pe}}{\omega}\left[1 - \nu_e{}^2/4\omega_{pe}^2X^2\right]^{1/2}} \quad (10a)$$

and

$$\vartheta_s = \frac{\vartheta_{0z}}{1 + \frac{\omega_{pe}}{\omega}\left[1 - \nu_e{}^2/4\omega_{pe}^2X^2\right]^{1/2}} \quad (10b)$$

in which $X^2\left[= \frac{\omega^2 - \frac{1}{3}\omega_{pn}^2}{\omega^2 + \frac{2}{3}\omega_{pn}^2}\right]$ being the correction factor for effective plasma frequency due to the presence of a single nanoparticle in semiconductor plasma medium. This factor is responsible to produce lower effective plasma frequency and becomes responsible for reduction of phase velocity of fast mode and enhancement of it in case of slow mode.

3) Assuming $\vartheta_\theta = 0$, and $\nu_e > 2\omega_{pe}$,

$$k_{1,2} = \frac{\omega}{\vartheta_{0z}} - \frac{i\nu_e}{2\vartheta_{0z}}\left[1 \pm \left\{1 - 4\omega_{pe}^2X^2/\nu_e{}^2\right\}^{1/2}\right] \quad (11)$$

Here, both modes have the same phase velocity that is equal to the drift velocity and are independent of the presence of nanoparticle. The presence of nanoparticle only modifies the imaginary part of k of both the modes and hence the gain characteristics get altered due to its presence.

If we now assume $\nu_e >> 2\omega_{pe}$ in equation (11), we obtain

$$k_1 = \frac{\omega}{\vartheta_{0z}} - \frac{i\nu_e}{\vartheta_{0z}}\left\{1 - \omega_{pe}^2X^2/\nu_e{}^2\right\} \quad (12a)$$

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And

$$k_2 = \frac{\omega}{\vartheta_{0z}} - \frac{i\omega_{pe}^2 X^2}{\nu_e \vartheta_{0z}} \tag{12b}$$

Here k_1 mode is heavily damped and since $\nu_e >> \omega$ in this collision dominated regime we have real part of k_1 very very smaller than imaginary part of it and consequently the excitation does not have reasonable life time. Hence k_1 is not a meaningful excitation of the system and we are left with only one collective mode k_2 expressed as equation (12b).

4) Assuming that $\nu_e >> 2\omega_{pe}$, $\vartheta_\theta \neq 0$ and $\frac{\vartheta_\theta}{\vartheta_0} << 1$, the two modes reduce to

$$k_1 = \frac{\omega}{\vartheta_{0z}}\left(1 + \frac{2\vartheta_\theta^{\ 2}}{\vartheta_{0z}^{\ 2}}\right) - i\left(\frac{\nu_e}{\vartheta_{0z}} - \frac{\omega_{pe}^2 X^2}{\nu_e \vartheta_{0z}}\right)\left(1 + \frac{\vartheta_\theta^2}{\vartheta_{0z}^2}\right) \tag{13a}$$

and

$$k_2 = \frac{\omega}{\vartheta_{0z}} - \frac{i\omega_{pe}^2 X^2}{\nu_e \vartheta_{0z}}\left(1 + \frac{\vartheta_\theta^2}{\vartheta_{0z}^2}\right) \tag{13b}$$

Here we may infer that whereas the first order effect of diffusion under collision dominated regime, enhances the losses of both the modes, the presence of nanoparticle enhances the losses of second mode k_2 but shrinks the losses of first mode k_1.

Collision frequency is found to play an important role in modification of dispersion and gain characteristics. It is revealed in this study that when collisionless plasma is considered, or collisions are less effective, dispersion characteristics of propagating modes are modified due to the presence of nanoparticle, whereas in case of collision dominant plasma, inclusion of nanoparticle modifies the gain characteristics of both propagating modes.

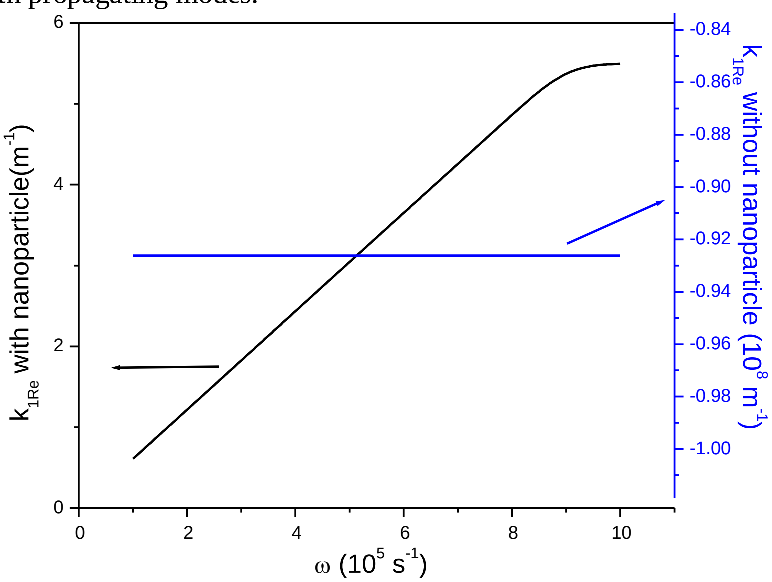

Figure 1a: Variation of phase constant of I-mode with wave frequency ω

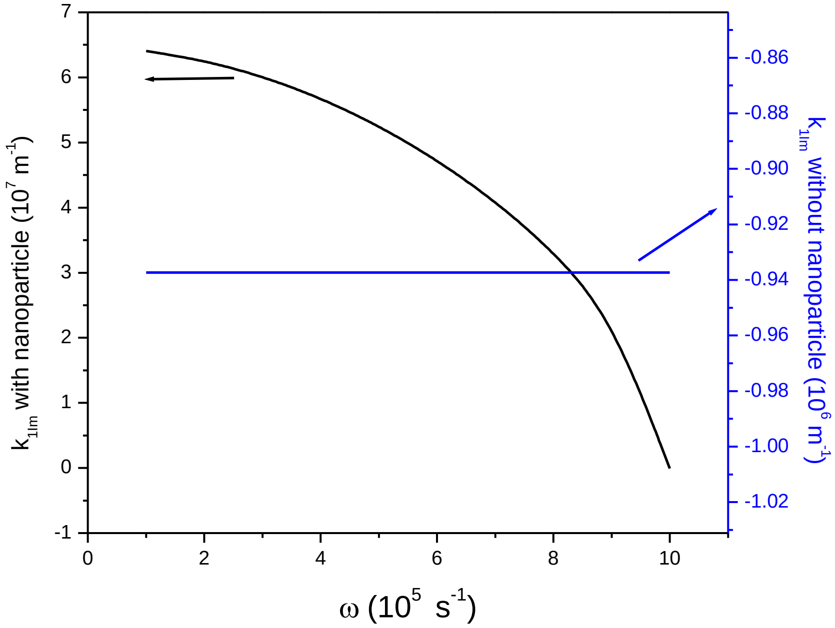

Figure 1b: Variation of growth rate of I-mode with wave frequency ω

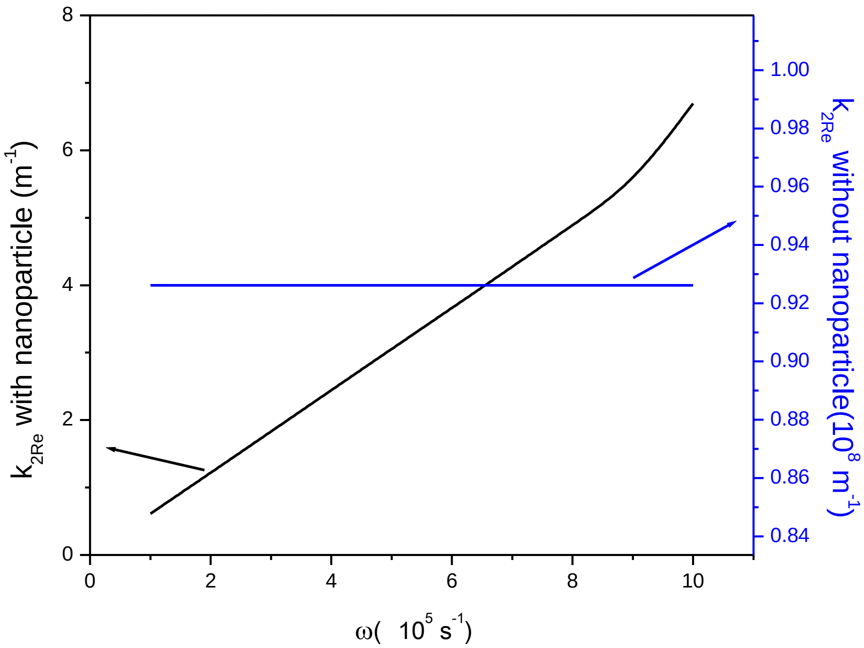

Figure 2a: Variation of phase constant of II-mode with wave frequency ω

Now to get some numerical appreciation, we solve the polynomial (equation (6)) numerically for n-Ge at room temperature using following set of parameters $m_e = 1.588m_0$, $\varepsilon_L = 15.8$, $n_{0e} = 2\times10^{24}$, $\nu_e = 3.076\times10^{11}$.

The numerical results so obtained are illustrated in Figures 1 to 4. Figures 1a and 1b correspond to variations in k_{1Re} and k_{1Im} with wave frequency ω for I mode of propagation. The dispersion characteristics of I mode as illustrated in Figure 1a infers that in absence of nanoparticle the mode is

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contra-propagating while in presence of nanoparticle it changes its direction of propagation by 180° and becomes co-propagating.

The presence of nanoparticle enhances the phase velocity by eight orders in magnitude and it decreases with the increment in ω upto $\omega \approx 9\times10^5$ s^{-1} beyond this value of ω the phase velocity becomes nearly independent. We obtain a constant phase velocity in the frequency regime under study in absence of nanoparticle.

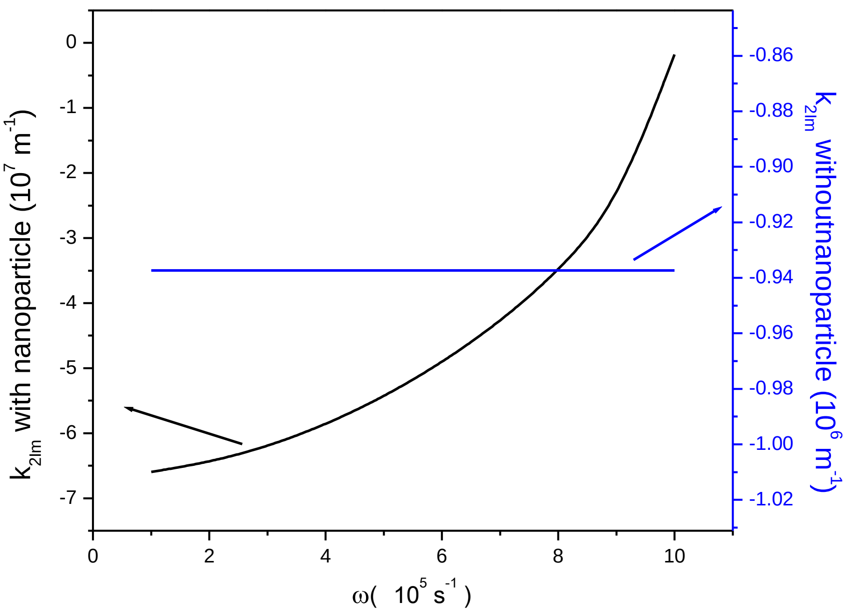

Figure 2b: Variation of growth rate of II-mode with wave frequency ω

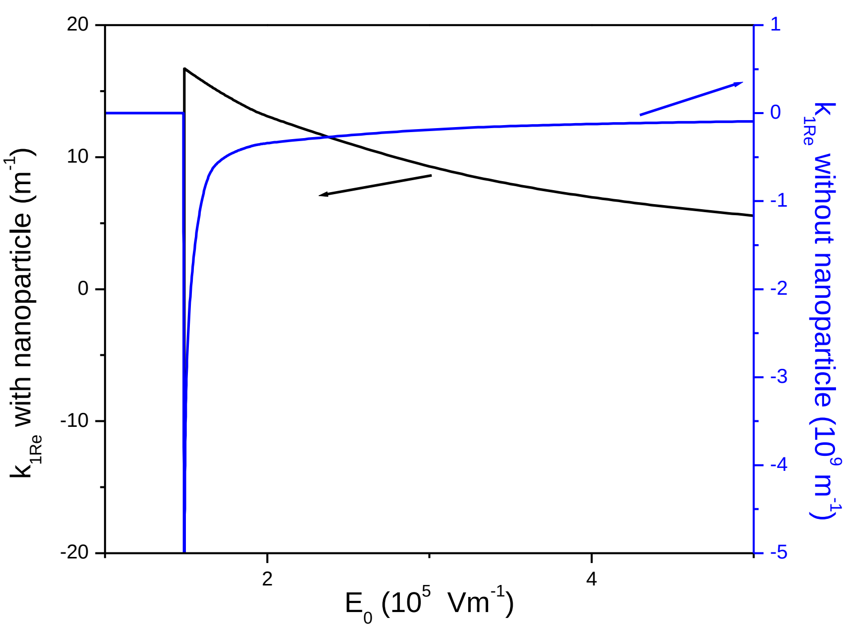

Figure 3a: Variation of phase constant of I-mode with electric field E_0

The characteristics of II mode with respect to wave frequency ω is displayed in Figures 2a and 2b.This mode is always co-propagating in both the physical situations (with and without nanoparticle). In absence of nanoparticle the phase velocity is independent of ω whereas in presence of it velocity decreases with

ω; but its magnitude enhanced by a significant amount. Figure 2b infers that II mode is always decaying in nature whether the nanoparticle is present or not. But in presence of nanoparticle the decay constant decreases with ω whereas in absence of nanoparticle it is independent of ω.

The gain characteristics of I mode (Figure 1b) reveals that the mode is decaying in nature in absence of nanoparticles and its decay constant is independent of wave frequency ω. In presence of nanoparticle I mode gets amplified and its gain decreases with increase in wave frequency ω.

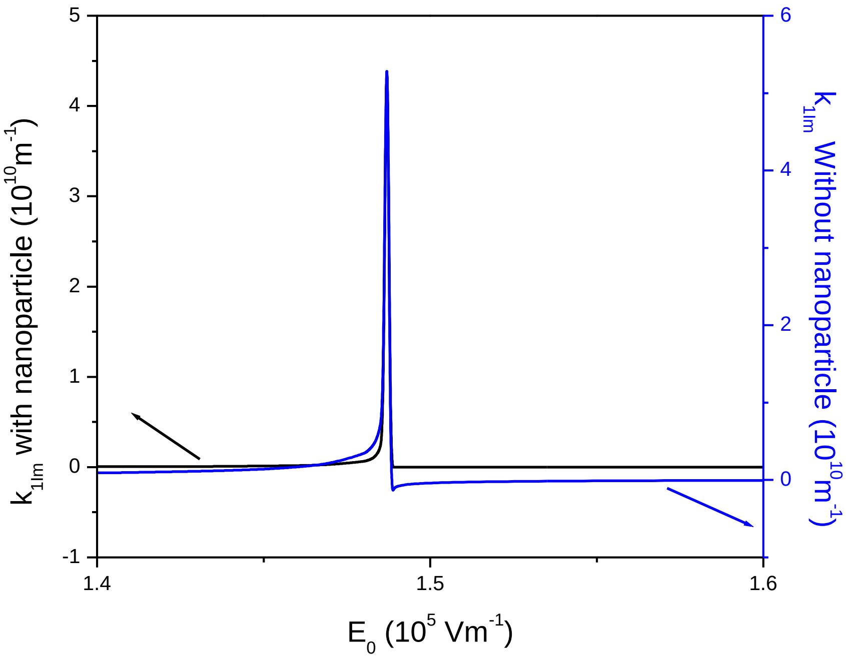

Figure 3b: Variation of growth rate of I-mode with electric field E_0

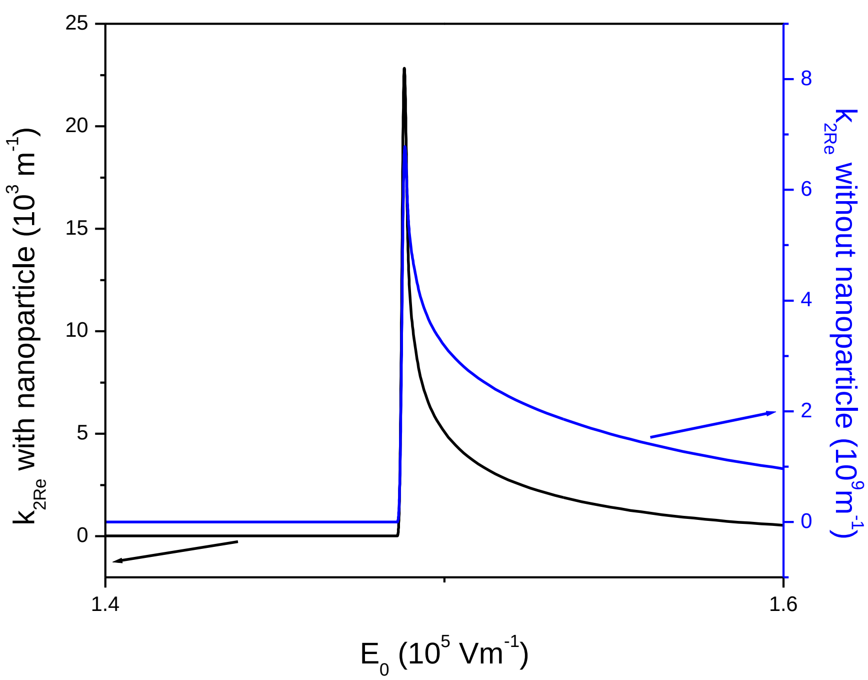

Figure 4a: Variation of phase constant of II-mode with electric field E_0

The propagation characteristics of both modes with respect to applied dc electric field E_0 are depicted in Figures 3 and 4.Figure 3a illustrates $k_{1\text{Re}}$ Vs E_0 curves for I mode. In absence of nanoparticle I mode is contra-propagating for all the values of E_0 we have considered. Initially its phase velocity is independent of E_0 and suddenly at $E_0 \approx 1.5\times10^5\,\text{Vm}^{-1}$, it touches its minimum value. If we tune the value of E_0 a little more than $1.5\times10^5\,\text{Vm}^{-1}$, it abruptly increases up to $E_0 \approx 2\times10^5\ \text{Vm}^{-1}$ and then increases slowly with E_0.

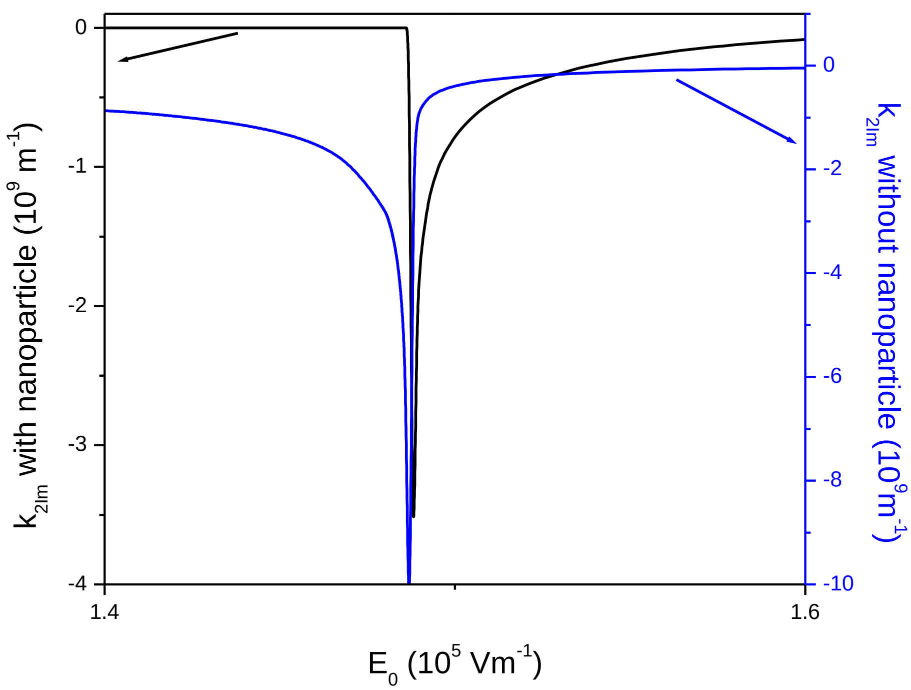

Figure 4b: Variation of growth rate of II-mode with electric field E_0

In presence of nanoparticle I mode turns out to be co-propagating. Its phase velocity initially decreases till $E_0 \approx 1.5\times10^5\,\text{Vm}^{-1}$ and then afterwards it increases smoothly. I mode is always growing in nature and its gain profile is nearly identical in presence as well as in absence of nanoparticle. Figure 4a infers that the II mode is always co-propagating in nature. Its phase velocity in presence as well as absence of nanoparticle is nearly same till $E_0 < 1.5\times10^5\,\text{Vm}^{-1}$. When $E_0 > 1.5\times10^5\,\text{Vm}^{-1}$, we found that the phase velocity in presence of nanoparticle is always faster than that in absence of nanoparticle. II mode is always decaying in nature for the regime of E_0 under study and qualitatively the variation with E_0 is almost identical in presence as well as in absence of nanoparticle.
To summarize, we have shown that the propagation characteristics of longitudinal electrostatic wave is modified strongly by the presence of a metal nanoparticle in semiconductor plasma. We have also shown that the characteristic is sensitive to external parameters and nanoparticle semiconductor plasma medium and may have useful device properties.

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