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Longitudinal electro-kinetic waves in ion-implanted semiconductor plasmas

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Abstract. A comprehensive investigation of propagation of new longitudinal electro-kinetic modes and novel properties introduced due to presence of negatively charged colloids in semiconductor plasma is presented. By employing the multi-fluid balance equations, a compact dispersion relation for the cases in which wave phase velocity is either larger or smaller than electron thermal velocity is derived. This dispersion relation is used to study wave phenomena and electro-kinetic mode instability numerically. We find important modifications in electro-kinetic branch as well as the existence of new modes of propagation in colloids laden semiconductor plasma. The results of this investigation should be useful in understanding the characteristics of longitudinal electro-kinetic wave in colloids laden semiconductor plasmas whose main constituents are electrons, holes and negatively charged colloids.

PACS. 52.35.Fp Electrostatic waves and oscillations (e.g., ion-acoustic waves) – 72.30.+q High-frequency effects; plasma effects – 61.72.Ww Doping and impurity implantation in other materials – 82.70.Dd Colloids

1 Introduction

The word plasma is generally used to describe a medium consisting of mobile positive and negative charges. This medium may contain some additional micron or sub-micron sized fine solid particles, usually referred as "dust", which increases the complexity of the system. Hence termed as "dusty plasma" or "complex plasma". It is the most general form of the plasma found in space environments such as in the lower ionosphere of the earth, asteroid zones, and planetary atmospheres as well as in variety of low temperature plasma devices. The presence of the additional component i.e. "dust" inside the plasma introduces some unique potential structures and alter the properties and dispersion characteristics of various waves produced in it, when this additional component is charged due to different processes such as collection of electrons from surrounding, ultraviolet irradiations or sputtering of energetic ions etc. These charged dust particles are considered to have large mass significantly greater than that of positive ion masses and many orders of magnitude larger charges (positive or negative), which can fluctuate in time.

In the last decade, this field of dusty plasma has opened a new and fascinating research area. The formation of plasma crystal and the existence of noval types of waves in dusty plasma are the two interest receiving areas of studies. An ordered structure of heavy charge particles was first theoretically predicted by Ikezi [1]. After Ikezi's prediction, the dust Coulomb crystal formation has been demonstrated in a number of laboratory experiments. Recently Niels et al. [2] have experimentally pointed out that in strongly coupled dusty plasma, under some specific physical conditions the particle have the ability to organize themselves in the form of ordered spatial structures to form a new "plasma crystal". Hence finds wide applications in studying physical processes in condensed matter such as melting and phase transitions as well provides a strong motivation for investigating the collective properties in strongly coupled plasmas.

Since metals and semiconductors also contain large number of mobile charge carriers representing the system of plasma, which resembles the gaseous plasma regarding collective oscillations, but also expected to be different in many respects like collision frequency, carrier mobility and the frequency of excited modes. Thus to study the material structures a lot of researches have been reported on excitation of linear and non linear waves and their instabilities in solid state plasmas [3].

On the other hand a number of laboratory experiments have been carried out for colloid formation of metal ions (such as Ag^+, Cu^+, Fe^+, etc.) by ion implantation techniques in solid materials [4]. This implantation of metal ions in the host material would modify its high magnetic coercivity, nonlinear optical properties etc. These ions when implanted inside the host materials, gets neutralize and somehow agglomerate to form colloids. In this way, the presence of colloids in addition to mobile charge carriers present in semiconductors resembles the dusty

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gaseous plasma system. Though the role of dust particles in finding the new dust modes in gaseous plasma and plasma crystal formations have been studied extensively during last decade, but the study of these analogous phenomena in semiconductor plasmas remain untouched. Very recently, Salimullah et al. [5], first time predicted the possible Coulomb lattice formation in piezoelectric semiconductors. Later, in the same medium, the role of electron-phonon coupling in the formation of wake potential was also reported. But, wave propagation phenomena still remains untouched.

Due to the larger mass of ions compared with the mass of electrons in gaseous dusty plasma system only low frequency perturbations are seen, when the electron inertia became negligible whereas in semiconductors, the charge carriers, electrons and holes have high number densities and comparable masses. Therefore, it is expected that low as well as high frequency perturbations can be excited in the so-called "ion-implanted semiconductor plasma".

A survey of available literature [4,6–9] indicates that the optical properties of implanted colloids formed within the host materials have been thoroughly investigated. Nevertheless, to the best of our knowledge, no attempt has yet been made to study the effect of implanted colloids on the properties of the host semi-conducting medium. The presence of implanted colloids creates a charge imbalance in the plasma of the host medium and is expected to modify waves and instabilities phenomena. Since, a study of wave propagation through a medium can provide tremendous insight regarding properties of ion-implantated semiconductor, comprehensive efforts in this direction are much needed.

The presence of implanted charged colloids can have a strong influence on the characteristics of the usual plasma wave modes, even at frequencies, where the colloidal grains do not participate in the wave motion. In this case, the colloids simply provide an immobile charge neutralizing background. However, when one considers frequencies well below the typical characteristic frequencies of electron plasma, new dust mode appears in dispersion relation derived using multi-fluid model of plasmas. Some of these new modes are very similar to those found in negative ion plasmas, but with some important differences unique to these media.

Motivated by the present status and the works of Salimullah et al. [5], in the present paper, we have focused our attention on the dispersion and absorption characteristics of the simplest mode i.e. longitudinal electro-kinetic wave in the ion-implanted semiconductor plasma. The paper is organized in the following manner. In Section 2, we outline the basic equations describing electro-kinetic wave propagation and derive a dispersion relation for electro-kinetic wave in the ion-implanted semiconductor plasma using multi-fluid plasma model. The dispersion relation reveals that the presence of colloids not only causes new mode of propagation but also modifies the existing modes. In Section 3, we present numerical appreciations of the results obtained and discussions. The important conclusions drawn from the study are listed in Section 4.

2 Theoretical formulation

In the present model, we have considered an ion-implanted semiconductor plasma system, consisting of electrons, holes and negatively charged colloids. Both electrons and holes may be collected by the dust grains, but since the electrons move more swiftly than the holes, therefore we have considered that the grains tend to acquire a negative charge. These charged colloids act as a third species or foreign particles inside the medium, but have significant effect on the behaviour of plasma. Hence, now the plasma that contains electrons, holes and negatively charged colloids may be treated with "multi-component plasma" model.

Here we have assumed that all the colloids are of uniform size. This size is assumed to be smaller than the wavelength of perturbations, inter grain distance as well as electron Debye radius, then these colloids can be treated as negatively charged point masses [10].

It is well-known fact that unless one considers the lowest part of the grain mass spectrum and very low frequency modes, the conclusion is that the grain dynamics can be ignored with respect to the electron / hole dynamics. Hence, the medium can be safely treated as multi-component plasma consisting of electrons, holes and stationary negatively charged colloids under hydrodynamic limit.

In the present model, we have studied the linear dispersion relation for low frequency electrostatic waves in unmagnetized semiconductor plasma. For this let us consider an n-type semiconductor sample of infinite extent in presence of implanted colloidal particles, and the carrier motion is assumed to be entirely along the z-direction. Then the condition for charge neutrality in plasma with negatively charged colloids is given as:

$$z_h n_{0h} = z_e n_{0e} + z_d n_{0d}, \tag{1}$$

where n_α ($\alpha = e,\ h,\ d$) is the number density, z_α is the charge states of electrons, holes and colloids respectively, in which $z_{ed} = q_d/e$ is the ratio of negative charges q_d resided over the colloidal grains to the charge e on electrons and it is assumed that $z_e = -1$ and $z_h = 1$ for further calculations.

If each component has a mass m_α, charge state z_α, density n_α, thermal velocity $\upsilon_{t\alpha}$, momentum transfer collision frequency ν_α, and charge density ρ_α, then this multi-component plasma system is described by their continuity and momentum equations as

$$\frac{\partial n_\alpha}{\partial t} + \frac{\partial}{\partial z}\left(n_\alpha \upsilon_\alpha\right) = 0, \tag{2}$$

$$\frac{\partial \upsilon_{z1\alpha}}{\partial t} = \frac{z_\alpha q_\alpha}{m_\alpha} E_{z1} - \nu_\alpha \upsilon_{z1} - \frac{\upsilon_{t\alpha}^2}{\rho_{0\alpha}} \frac{\partial \rho_{1\alpha}}{\partial z}. \tag{3}$$

Here the subscripts 0 and 1 in equations (2) and (3) represent zero and first order quantities, respectively. Assuming the first order quantities varying as $\exp\left[i\left(\omega t - kz\right)\right]$ [where ω and k are frequency and wave number of the propagating mode respectively], and following the procedure adopted by Steele and Vural [11], the dispersion relation for longitudinal electro-kinetic wave is obtained as:

$$\varepsilon(\omega,k) = 1 + \frac{\omega_{pe}^2}{\left(\omega^2 - i\nu_e\omega - k^2\lambda_{De}^2\omega_{pe}^2\right)} + \frac{\omega_{ph}^2}{\left(\omega^2 - i\nu_h\omega - k^2\lambda_{Dh}^2\omega_{ph}^2\right)} + \frac{\omega_{pd}^2}{\omega^2} = 0, \quad (4)$$

where

$$\omega_{pe}^2 = \frac{e^2 n_{0e}}{\varepsilon m_e}, \quad \omega_{ph}^2 = \frac{e^2 n_{0h}}{\varepsilon m_h}, \quad \omega_{pd}^2 = \frac{z_d^2 e^2 n_{0d}}{\varepsilon m_d},$$

and $\varepsilon = \varepsilon_0\varepsilon_L$; ε_L being the lattice dielectric constant.

Comparing equation (4) with the equation (4-3b) of Steele and Vural [11], we find that the last two terms of R.H.S. of above equation (4) are the additional terms representing the contributions of holes and charged colloids in the medium. The third term is responsible for the modified character of electro-kinetic waves in colloids laden semiconductor plasma. Hence, if we neglect the presence of holes and charged colloids our equation (4) reduces to equation (4-3b) of Steele and Vural [11].

Now we shall focus our attention towards the principal point of this paper i.e. instability characteristics of the longitudinal electrostatic mode in colloids laden semiconductor plasma medium. Hence, we shall study the dispersion relation under two different physical situations.

2.1 Case 1: Slow electro-kinetic mode ($\omega \ll k\upsilon_{te}, k\upsilon_{th}$)

If the phase velocity of the wave is less than the thermal velocities of electrons and holes both, the mode may be termed as slow electro-kinetic mode. Therefore, for slow electro-kinetic mode, under collision dominated or low frequency regime ($\omega \ll \nu_e,\ \nu_h$), dispersion relation (4) reduces to

$$1 - \frac{\omega_{pe}^2}{\left(k^2\lambda_{De}^2\omega_{pe}^2 + i\omega\nu_e\right)} - \frac{\omega_{ph}^2}{\left(k^2\lambda_{Dh}^2\omega_{ph}^2 + i\omega\nu_h\right)} + \frac{\omega_{pd}^2}{\omega^2} = 0. \quad (5)$$

Equation (5) may written in the form of polynomial in ω as

$$\begin{aligned}\omega^4 &- i\omega^3\left[\omega_{Re}\left(k^2\lambda_{De}^2 - 1\right) + \omega_{Rh}\left(k^2\lambda_{Dh}^2 - 1\right)\right] \\ &- \omega^2\left[k^2\left(k^2\lambda_{De}^2\lambda_{Dh}^2 - \lambda_{De}^2 - \lambda_{Dh}^2\right)\omega_{Re}\omega_{Rh} - \omega_{pd}^2\right] \\ &- i\omega\left[k^2\omega_{pd}^2\left(\lambda_{De}^2\omega_{Re} + \lambda_{Dh}^2\omega_{Rh}\right)\right] \\ &- k^4\lambda_{De}^2\lambda_{Dh}^2\omega_{pd}^2\omega_{Re}\omega_{Rh} = 0. \quad (6a)\end{aligned}$$

where $\omega_{Re,h} = \omega_{pe,h}^2/\nu_{e,h}$, is the dielectric relaxation frequencies of electrons and holes, respectively.

One can infer from equation (6a) that in absence of charged colloids ($\omega_{pd} = 0$) the polynomial reduces to

$$\begin{aligned}\omega^2 &- i\omega\left[\omega_{Re}\left(k^2\lambda_{De}^2 - 1\right) + \omega_{Rh}\left(k^2\lambda_{Dh}^2 - 1\right)\right] \\ &- \left[k^2\left(k^2\lambda_{De}^2\lambda_{Dh}^2 - \lambda_{De}^2 - \lambda_{Dh}^2\right)\omega_{Re}\omega_{Rh}\right] = 0. \quad (6b)\end{aligned}$$

It can very clearly demonstrated by equations (6) that the presence of colloids introduces two new modes of propagation in the system.

2.2 Case 2: Fast electro-kinetic mode ($k\upsilon_{th} \ll \omega \ll k\upsilon_{te}$)

If the phase velocity of the mode is less than electron thermal speed but more than the hole thermal speed, the mode may be termed as fast electro-kinetic mode. Thus for fast electro-kinetic mode the dispersion relation (4) reduces to

$$1 - \frac{\omega_{pe}^2}{\left(k^2\upsilon_{te}^2 + i\nu_e\omega\right)} + \frac{\omega_{ph}^2}{\left(\omega^2 - i\nu_h\omega\right)} + \frac{\omega_{pd}^2}{\omega^2} = 0. \quad (7)$$

Equation (7) may be rewritten in the term of polynomial in ω as

$$\begin{aligned}\omega^4\omega_{Rh} &- i\omega^3\left[\left(k^2\lambda_{De}^2 - 1\right)\omega_{Re}\omega_{Rh} + \omega_{ph}^2\right] \\ &- \omega^2\left[\left(k^2\lambda_{De}^2 - 1\right)\omega_{Re}\omega_{ph}^2 - \omega_{Rh}\left(\omega_{ph}^2 + \omega_{pd}^2\right)\right] \\ &- i\omega\left[k^2\lambda_{De}^2\omega_{Re}\omega_{Rh}\left(\omega_{ph}^2 + \omega_{pd}^2\right) + \omega_{ph}^2\omega_{pd}^2\right] \\ &- k^2\lambda_{De}^2\omega_{ph}^2\omega_{pd}^2\omega_{Re} = 0. \quad (8a)\end{aligned}$$

In absence of colloids ($\omega_{pd} = 0$) we get from equation (8a) as

$$\begin{aligned}i\omega^3\omega_{Rh} &+ i\omega^2\left[\left(k^2\lambda_{De}^2 - 1\right)\omega_{Re}\omega_{Rh} + \omega_{ph}^2\right] \\ &- i\omega\left[\left(k^2\lambda_{De}^2 - 1\right)\omega_{Re}\omega_{ph}^2 - \omega_{Rh}\omega_{ph}^2\right] \\ &+ k^2\lambda_{De}^2\omega_{ph}^2\omega_{Re}\omega_{Rh} = 0. \quad (8b)\end{aligned}$$

It can be inferred from equations (8) that the presence of charged colloids induces one additional mode of propagation for fast electro-kinetic wave in the host medium.

3 Result and discussions

We have considered the longitudinal electro-kinetic wave is of the form $\exp[i(\omega t - kz)]$ and so the wave may be growing in time when $\omega_i < 0$ so that the power is being extracted by the wave from the medium which causes temporal instability. On the other hand the wave may be decaying in time when $\omega_i > 0$ so that power is being absorbed from the wave by the medium so that wave would suffer an attenuation. We have discussed in this paper the effect of charged colloids on the phase and attenuation constants of the wave.

Equations (6a) and (8a) being of fourth degree in complex wave frequency ($\omega = \omega_r + i\omega_i$) with complex coefficients is not easy to solve analytically and so we have solved it numerically. In numerical calculations the following parameters have been used: $m_e = 0.0815 m_0$, m_0 being the free electron mass, $m_h = 4m_e$, $m_d = 10^{-27}$ kg, $\varepsilon_L = 15.8$, $n_{0e} = 10^{19}$ m^{-3}, $n_{0h} = 5 \times 10^{19}$ m^{-3}, $\nu_e = 3.463 \times 10^{11}$ s^{-1}, $\nu_h = 1.194 \times 10^{11}$ s^{-1} and $\nu_d = 3.422 \times 10^8$ s^{-1} at 77 K.

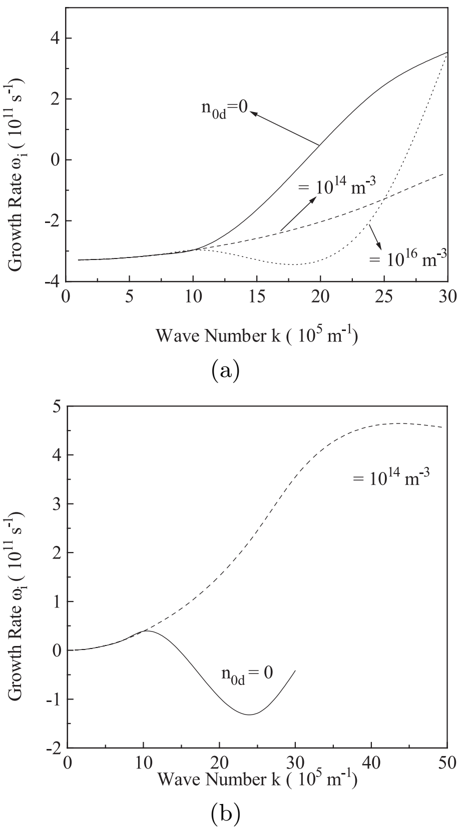

Fig. 1. (a) Variation of growth rates of first existing mode with wave number for slow electro-kinetic wave. (b) Variation of growth rates of second existing mode with wave number for slow electro-kinetic wave.

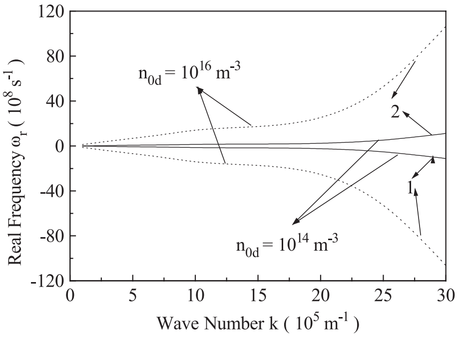

Fig. 2. Variation of real frequencies of two new modes with wave number for slow electro-kinetic wave.

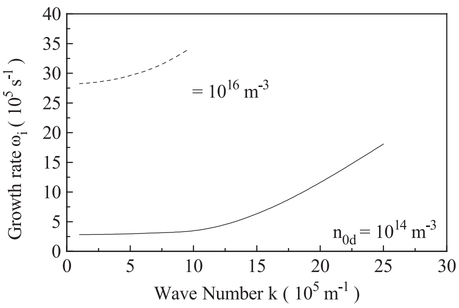

Fig. 3. Variation of growth rates of two new modes with wave number for slow electro-kinetic wave.

For slow electro-kinetic mode, one may infer from equations (6a) and (6b) that the presence of negatively charged colloids are responsible not only for two new modes but also for the modification of wave-spectrum of two existing modes. The variations of ω_r and ω_i with positive real values of k for this wave are illustrated in Figures 1–3. Figures 1a and 1b display the variations of growth rates (ω_i) of first and second existing modes with k with colloids concentration n_{0d} as parameter. These two modes are found to be aperiodic ($\omega_r = 0$) in nature in presence as well as in absence of charged colloids. Figure 1a infers that in absence of colloids this mode is growing in nature ($\omega_i < 0$) and its growth rate reduces with increasing k. At $k \approx 1.8\times10^6$ m $^{-1}$, ω_i becomes zero and beyond this point the mode becomes decaying in nature. It also infers that the presence of colloids do not have any effect on ω_i till $k \approx 1.1\times10^6$ m^{-1}. For $k \geq 1.1\times10^6$ m^{-1} the effects of charged colloids on attenuation characteristics are visible. Beyond $k > 1.1 \times 10^6$ m^{-1} the growth rate is higher than that found in absence of colloids. For $n_{0d} = 10^{14}$ m^{-3} the crossover from growing to decaying nature is not found in the k-region under study. But for $n_{0d} = 10^{16}$ m^{-3} we found that the mode crosses over from amplification to attenuation nature at $k \approx 2.6 \times 10^6$ m^{-1}. Figure 1b illustrates that the second mode has just opposite nature of variation of ω_i with k, as compared to first mode (Fig. 1a). Hence one may conclude that the wave spectrum of existing two modes are modified in presence of charged colloids beyond a certain value of k, but they remains aperiodic in nature. Figure 2 displays the variations of ω_r with k of two new modes introduced due to presence of colloids with n_{0d} as parameter. It is found that both the modes have exactly opposite nature of variations with k. Hence, if one propagates along positive z-direction then other one propagates along negative z-direction. But magnitude wise both have the identical phase constant. It may also be seen from this figure that the presence of charged colloids increases the magnitude of phase constants of both the modes. But the nature of variation does not change. Due to condition ($\omega \ll k\vartheta_{te}$, $k\vartheta_{th}$) imposed for the propagation of slow electro-kinetic wave, it is not possible to increase phase velocity of these two new modes indefinitely by increasing the colloids concentration. Hence, it may be inferred that the charged colloids induce two new modes of propagation for slow electro-kinetic wave that are not only periodic in nature but also propagate in opposite directions with equal phase speed.

From numerical analysis, it is found that these two oppositely propagating new modes are decaying in nature and their attenuation constants (ω_i) are exactly identical. Figure 3 shows the variation of ω_i with k considering n_{0d} as parameter. The values of ω_i for both the modes increase with increments in k and n_{0d}. Hence, the instability characteristics of slow electro-kinetic wave are directly influenced by the presence of charged colloids.

Under the fast electro-kinetic wave limit, one gets three modes in absence and four modes in presence of colloids.

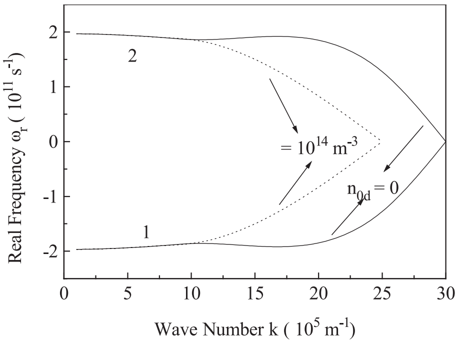

Fig. 4. Variation of real frequencies of two existing periodic modes with wave number for fast electro-kinetic wave.

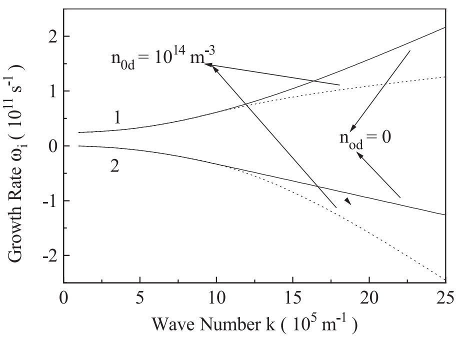

Fig. 5. Variation of growth rates of three existing modes with k for fast electro-kinetic wave [1 for aperiodic and counter-propagating mode; 2 for co-propagating mode].

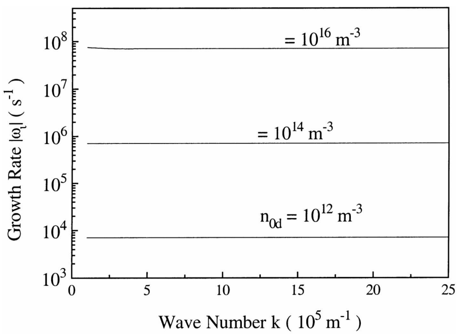

Fig. 6. Variation of growth rates of new mode with wave number for fast electro-kinetic wave.

Hence here only one new mode is induced by the presence of charged colloids. Out of common three modes one is found aperiodic in nature in absence as well as in presence of charged colloids. The variations of ω_r with k for different values of n_{0d} for remaining two modes are shown in Figure 4. Solid curves show the variation in absence ($n_{0d} = 0$) of colloids and dashed curves represent the variation in presence ($n_{0d} = 10^{14}$ m^{-3}) of colloids. From this figure one may infer that one mode is co-propagating whereas other is counter-propagating with wave propagation direction (z-axis). Phase speed of both the modes reduces to zero at $k \approx 3 \times 10^6$ m^{-1} in absence of colloids. In presence of colloids this critical value of k at which phase speed reduces to zero decreases nearly to 2.4×10^6 m^{-1}. The value of the phase constant for both the modes remain unaffected by charged colloids up to $k \approx 1.1 \times 10^6$ m^{-1} and beyond this value of k, phase constants decrease due to the presence of charged colloids. Hence the propagation characteristics of two existing periodic modes are modified by the presence of charged colloids.

It is found numerically that out of three existing modes counter propagating periodic mode and aperiodic mode have identical values of growth rate ω_i and they are decaying in nature. The co-propagating mode have different growth rate and is amplifying in nature. The variations of these ω_i with k for $n_{0d} = 0$ and $n_{0d} = 10^{14}$ m^{-3} is shown in Figure 5. It is seen that the growth rate of amplifying mode (i.e. co-propagating one) increases with the increase in k. On the other hand, the attenuation factor of aperiodic and counter-propagating modes is also increasing with the increase in k. The presence of colloids increases the growth rate of amplifying mode and decreases the attenuation factor of decaying modes beyond $k \approx 1.1 \times 10^6$ m^{-1}. Below $k = 1.1 \times 10^6$ m^{-1}, colloids do not affect the values of ω_i. Figure 6 displays the nature of variation of ω_i of the newly induced aperiodic mode with k for different values of n_{0d}. It may be seen from the graph that the growth rate $|\omega_i|$ of the new mode is unaffected by the increment in k; but increment in n_{0d} increases its value drastically. From Figures 5 and 6 one may infer that the charged colloids introduce one additional amplifying mode and modify the wave spectrum of existing three modes and hence a direct effect on the propagation and instability characteristics of the fast electro-kinetic wave has been seen.

To conclude, we have discussed a noval possibility for longitudinal electro-kinetic wave propagation in semiconductor plasma in presence of charged colloidal particles. We focused our attention on two different cases in which phase velocity of the wave are either larger or smaller than the thermal velocity of the free electrons. Both the cases correspond to the real laboratory experiment under different wave number regimes. We found that, there exists a strong resonant interaction between electro-kinetic wave and colloidal particles. In the case of slow electro-kinetic wave, it is found that the charged colloids induce two new modes of propagation which are periodic in nature but propagate in opposite directions with same phase speed. The instability characteristic is also found to be affected by the presence of charged colloids. Hence, charged colloids not only modify the wave spectrum of the slow electro-kinetic wave but also become responsible for the existence of two oppositely propagating noval modes.

In fast electro-kinetic wave regime, charged colloids become responsible for only one new mode of propagation that is found to be amplifying in nature. In this regime too, we found modifications in wave spectrum of three modes, which are available in absence of colloids also.

It may be mentioned here that the present theory provides a qualitative picture of wave spectrum of longitudinal electro-kinetic mode in semiconductor plasma in presence of charged colloids. We have not only found modification in electro-kinetic wave spectrum but also the existence of new modes is established. Thus for the experimental verification of our theoretical idea, we propose to initiate a serious laboratory experimental efforts using semiconductor plasma where the parameters of the medium could be varied over a wide range of values without much difficulty.

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References

1. H. Ikezi, Phys. Fluids **29**, 1764 (1986)
2. Niels F. Otani, A. Bhattacharji, Xio gang Wang, Phys. Plasma **6**, 409 (1999)
3. J. Pozhela, *Plasma and Current Instabilities in Semiconductors* (Pergamon, Oxford, 1981)
4. N. Matsunami, H. Hosono, Appl. Phys. Lett. **63**, 2050 (1993); H. Hosono, Y. Abe, N. Matsunami, Appl. Phys. Lett. **60**, 2613 (1992)
5. M. Salimullah, S.K. Ghosh, M.R. Amin, Pramana **54**, 185 (2000); M. Salimullah, P.K. Shukla, S.K. Ghosh, H. Nitta, Y. Hayashi, J. Phys. D **36**, 958 (2003)
6. D. Ila, E.K. Williams, S. Sarkisov, C.C. Smith, D.B. Poker, D.K. Hensley, J. Nucl. Instr. Meth. B **141**, 289 (1998)
7. S.S. Sarikisov, E. Williams, M. Curley, D. Ila, P. Venkateshwarlu, D.B. Poker, D.K. Hensley, J. Nucl. Instr. Meth. B **141**, 294 (1998)
8. J.C. Cheang-Wong, A. Oliver, A. Crespo, J.M. Hernandez, E. Munoz, R. Espejel-Morales, J. Nucl. Instr. Meth. B **161**, 1058 (2000)
9. G.L. Zhang, W.H. Liu, F. Xu, W.X. Hu, Appl. Phys. Lett. **61**, 2527 (1992)
10. K.N. Ostrikov, S.V. Vladimirov, M.Y. Yu, G.E. Morfill, Phys. Plasmas **7**, 461 (2000)
11. M.C. Steele, B. Vural, *Wave Interactions in Solid State Plasmas* (Mc-Graw Hill, New York, 1969), p.45.