Wave Interaction in Two species Ion-Implanted Semi-Conductor Plasma

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Abstract:
The present paper is aimed to report the analytical study of wave interaction in two species (InSb, GaAs) ion implanted semiconductor plasma. Considering that the third order optical susceptibility χ^3 arising from the nonlinear wave interaction and using couple mode theory an analytical investigation of two species with ion-implantation has been presented. We have studied the threshold (E_{0th}) and gain characteristics (α) with number density (n_0) and wave vector (k) respectively. It can be seen that, in the case of GaAs shows a favourable enhancement in steady-state as well as the gain coefficient of the generated acoustic mode.

Keywords: Two-species ion-implanted plasma, Semiconductor plasma, Wave interaction, Ion implantation, Plasma waves, Electrostatic waves etc.

Introduction

It is well known fact that the optical properties of any material are not get affected when a light beam propagates through it, but when the intensity of light beam is abundantly sizeable then optical properties of the medium such as absorption, refractions etc. will depend on intensity and give rise to the non linear optical (NLO) interaction phenomena (Bloembergen, 1965) (1). The significant studies of wave-wave interaction and wave-particle interaction in plasma have been carried out substantially during last three decennium. Such effects are considered as NLO effect and many researchers have been carried out in a form of publication to understand its various phenomena's.

The NLO interactions are generally observed in the spectral range covered by laser, between the far infrared and the extreme ultraviolet. The NLO interaction can occur in all types of media including vacuum, in which photon can interact through vacuum polarisation. The nonlinearity, is however, too small to be observed. So, in practical sense, a vacuum can be regarded as linear. The NLO interaction can be used for changing or controlling certain properties of laser radiation such as wavelength, bandwidth, pulse (pump) duration and beam quality as well as high resolution molecular and atomic spectroscopy, material studies, modulation of optical beam, information processing and compensation of distortions caused by imperfect optical materials.

When an electromagnetic wave propagates through a medium, it induces a polarisation p (electric dipole moment per unit volume) in the medium as a result of the motion of the electrons and nuclei in response to the field in the incident light. The induced polarisation oscillates at frequencies determined by combination of the properties of the material and the frequencies and intensities of the incident light waves. The optical properties of the medium and characteristics of the radiation that is transmitted through it, result from interference among the radiation field and induced polarization of the medium.

The present chapter is devoted to the wave interaction in two species ion implanted semi conductor plasma.

In the present work the III-V group (InSb, GaAs) material are taken into consideration due to their favourable semi conductor properties such as band gap, electron mobility etc.

The presence of implanted charged particulates 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 of plasma. Some of these new modes are very similar to those found in negative ion plasma, but with some important differences unique to these medium.

Motivated by the present status and the works of Ghosh et al. (2), in the present paper, we have focused our attention on the study of ion-implantation effects on two species semiconductor plasma. The paper is organized in the following manner. In section 2, we outline the basic equation describing 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 particulates not only causes new mode of propagation but also modifies the existing modes. In section 3, we present numerical calculation of the result obtained and discussion.

Theoretical formulation

The analysis has been carried out using a well known hydrodynamic model of n type semi conductor plasma satisfy the condition $K_a l << 1$ (K_a and l being the acoustic wave no. and electron mean free path respectively).

In order to study the wave –wave interaction arising through four wave mixing phenomena as third order susceptibility χ^3. we use dipole approximation for the idler and signal waves with the help of following equation.

$$\frac{\partial v_0}{\partial t} + w_0 = -\frac{(Zd_e)e}{m} E_0 \qquad (1)$$

$$\frac{\partial v_1}{\partial t} + w_0 + v_0 \frac{\partial}{\partial x} = \frac{-(zde).e}{m} E_1 - \frac{k_\beta T}{m n_0} \frac{\partial n_1}{\partial x} \qquad (2)$$

$$\frac{\partial n_1}{\partial t} + n_0 \frac{\partial v_1}{\partial x} + v_0 \frac{\partial n_1}{\partial x} = 0 \qquad (3)$$

$$\frac{\partial^2 u}{\partial t^2} - \frac{c}{\rho} \frac{\partial^2 u}{\partial x^2} + 2\gamma \frac{\partial u}{\partial t} = \frac{1}{2\rho} \varepsilon(\eta^2 - 1) E_0 \frac{\partial E^*}{\partial X} \qquad (4)$$

$$\frac{\partial E_1}{\partial X} = \frac{-n_1 e(Zde)}{\varepsilon} + \frac{(\eta^2 - 1)}{\varepsilon_1} E_0 \frac{\partial^2 U^*}{\partial X^2} \qquad (5)$$

Equation (1) and (2) describes the electron motion under the influence of the field associated with the pump and EPW (Electron plasma wave), respectively in which m and v represent the effective mass and phenomenological momentum transfer collision frequency of electrons. Conservation of charge is represented by the continuity equation (3) in which n_0 and n_1 are the unperturbed and perturbed electron density, respectively. Equation (4) describes the lattice vibration in an acoustic – optic crystal of material density ρ and elastic constant c, γ and η is respectively the damping constant and refractive index of the medium. The space- charge field E_1 is determined from Poisson's equation (5) in which last term on R.H.S. represents the contribution of acousto-optic polarisation where ε_1 is lattice dielectric constant.

The right hand side of equation of motion for acoustic wave equation (4) is an external driving force F_u. Applied by the Electromagnetic field. In order to derive equation (4), consider a differential volume dxdydz inside a plasma fluid subjected to an electric field E. Let the deviation of point x from its equilibrium position be u(x,t) so that the one-dimensional strain is du/dx . We introduce, Phenomenological, a constant $\varepsilon(\eta^2 -1)$ (where η is the refractive index of the medium) that describes the change in the optical dielectric constant induced by the strain through the relation $\delta\varepsilon = -\varepsilon(\eta^2 - 1)(du/dx)$, so that the presence of strain changes the stored electrostatic energy density by $-(1/2)\varepsilon(\eta^2 - 1)(du/dx)E^2$. A change in stored energy that is accompanied by a strain implies the existence of a pressure. This pressure p is found by equation of work p(du/dx) done while straining a unit volume to the change of the energy density that result in $p= -(1/2)\varepsilon(\eta^2 - 1)(du/dx)E^2$. The net electrostriction force in the positive x - direction acting on a unit volume is thus $F_u =(1/2)\varepsilon(\eta^2 - 1)(dE^2/dx)$. Thus, we obtain the required equation (4).

The transport effect arises from the optically generated charge carriers due to which the crystal is exposed to a spatially varying pattern of illumination with photons having sufficient energy. This migration of charge produces a charge separation that then leads to a strong space-charge field. This space- charge can thus be obtained from continuity equation of excited electrons (equation 3) and the Poisson's equation for superposition of Coulomb field arising from the excess charge density n_1 and free (equilibrium) density n_0 (equation 5). In deducing (equation 5), we have included the nonlinear polarisation due to electrostrictive nature of the medium. The electrostatic space-charge field E_1 is thereby generated due to acousto-optic (AO) polarisation induced by the intense pump wave. This polarisation results in the coupling of the space-charge wave with travelling acoustic grating.

$$\frac{\partial^2 n_1}{\partial t^2} + \upsilon \frac{\partial n_{1s}}{\partial t} + \varpi_p{}^2 n_1 - \frac{n_0 (zde) e(\eta^2 - 1)}{m\varepsilon_1} E_0 K_a{}^2 u^* = \frac{\overline{E}\partial n_1}{\partial x} \tag{6}$$

Where $\varpi_p^2 = (\frac{n_0 e^2 z^2 de}{m\varepsilon} + \frac{k_1^2 k_\beta T}{m})$ being the electron –plasma frequency modified by magnetic field, in which $\omega_p^2 = (\frac{n_0 e^2 z_{de}^2}{m\varepsilon})$ is electron plasma frequency, $\overline{E} = \frac{Z_{de} e E_0}{m}$ .We have neglected the Doppler shift under the assumption that ω_0

The above equation describes coupling between acoustic wave (AW) and electron plasma waves (EPW) in the presence of an intense pump. Equation (6) obtains, the slow component ((n_s) associated with AW that produces density perturbation at frequency, and the fast component (n_p) associated with EPW that produces perturbation at frequency $\omega_1 \approx (\omega_0 \pm p\omega_a)$, p being the integer. (Yariv, 1997) [3], one obtains.

$$\frac{\partial^2 n_{1s}}{\partial t^2} + \upsilon \frac{\partial n_{1s}}{\partial t} + \varpi_p^2 n_{1s} = ik\overline{E}n_{1f}^* \qquad (7)$$

$$\frac{\partial^2 n_{1f}}{\partial t^2} + \upsilon \frac{\partial n_{1f}}{\partial t} + \varpi_p^2 n_{1f} - \frac{n_0(zde)e(\eta^2 - 1)E_0 k_a^2 u^*}{m\varepsilon_1} = ik\overline{E}n_{1s}^* \qquad (8)$$

One can easily infer from equations (7) and (8) that the slow and fast components of density perturbation are coupled to each other via pump electric field.

Thus the presence of the pump field is the fundamental necessity for the parametric interaction to occur By solving equations (7) and (8), we obtain

$$n_{1f} = \frac{n_{1s}^*(\delta_2^2 - i\upsilon\omega_a)}{ik\overline{E}} \qquad (9)$$

and

$$n_{1s} = \frac{-n_0(zde)eE_0E_0^*E_1\varepsilon K_a^2(\eta^2 - 1)A}{2m\varepsilon_1\rho\delta_a^2\overline{E}} \qquad (10)$$

Where, $\delta_2^2 = \omega_a^2 - \omega_p^2$

$\delta_1^2 = \omega_1^2 - \varpi_p^2$ and A = $\left[1 - \frac{(\delta_1^2 + i\upsilon\omega_1)(\delta_2^2 - i\upsilon\omega_a)}{K^2|\overline{E}|^2}\right]^{-1}$

In order to study the role of diffusion on the nonlinearity in the medium, we express the diffusion induced current density at the acoustic frequency by the relation

$$J = -ev_0(Zde)n_{if}^* \qquad (11)$$

Substituting, in the above relation, and computing the time integral of diffusion induced current density yield the diffusion induced polarisation as

$$P = \int J dt = \frac{j}{-i\omega_1} \qquad (12)$$

This leads to the third order nonlinear susceptibility χ^3 in the coupled mode scheme as

$$\chi = \frac{n_0 e^2 v_0 (zde)^2 \; E_0^* \; \varepsilon K_a^2(\eta^2 - 1)(\delta^2 + i\upsilon\omega_a)A}{2i\varepsilon_0 E_0 k\overline{E.m\varepsilon_1\rho\delta_a^2}} \qquad (13)$$

$$E0th_j := \frac{(m)}{(Zde)\cdot e\cdot k1}\cdot\sqrt{-(\delta 1_j)^2(\delta 2_j)^2 + (\delta 1_j)^2\cdot i\cdot va\cdot \omega a - (\delta 2_j)^2\cdot i\cdot va\cdot \omega 1 - va^2\,\omega 1\cdot \omega a} \tag{14}$$

Where $\left(\delta_2^2 + i\upsilon\omega_a\right)$ represents acoustic wave dispersion in the presence of damping. The parameter A represents the dispersion of pump wave due collision and diffusion of charge carriers and $\left[n_0 e^2\left(\eta^2 - 1\right)\right]$ is the acousto-optic coupling parameter in an electrostrictive medium. The above equation infers that the carriers induces third-order nonlinearity in the medium,

Here the damping of AW arises due to its acousto-optic coupling with EPW. To compensate the damping losses of the AW in the diffusive medium, one should apply a pump of certain minimum amplitude called the threshold pump amplitude. The parametric amplification can be achieved at excitation intensity above this threshold pump amplitude under favourable conditions. Threshold pump amplitude E_{0th} may be obtained by setting the lowest order nonlinear susceptibility.

Results and Discussion

We now address a detailed numerical analysis of carrier heating effects on the threshold condition required for the onset of parametric processes and consequently the effective parametric dispersion and amplification in a doped semiconductor at 77K duly irradiated by a nanosecond-pulsed 10.6um CO2 laser. The representative physical constants have been considered as follows: m=0.014m, m_0 being the free electron mass, η =3.9, T=77 k, $\nu_0 = 3.5*10^{11} s^{-1}$, $\omega_a = 2*10^{11} s^{-1}$, $\omega_0 = 1.78*10^{13}$,.

Figure 1: shows the variation of the real part of susceptibility $\left(\chi^3\right)$with wave vector (k) at $E_0 = 2*10^6 V.m^{-1}$and $n_0 = 10^{24} m^{-3}$. In the presence of ion-implantation effect we can see that in case of InSb as we increase a wave number the value decreases from higher negative value to lower negative value linearly and in the case of GaAs the value also changed from higher negative value to lower negative value parabolic. This variation can be studied due to number density. From the figure we can also see that the ion-implantation effect is favourable for enhancing the carrier concentration of both the species.

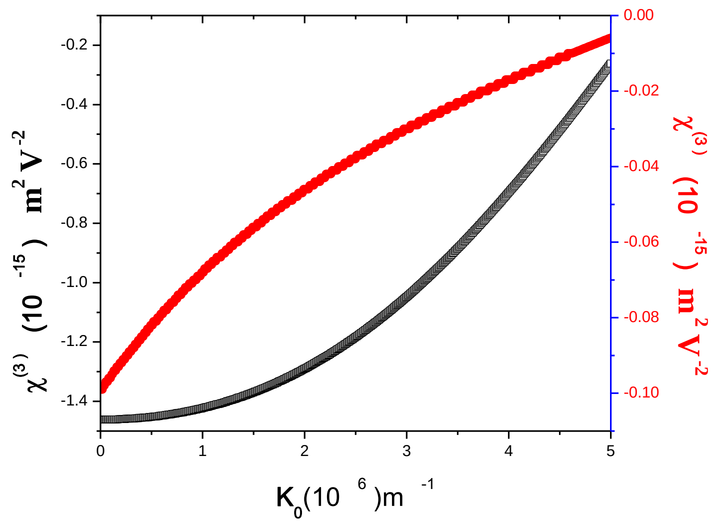

Figure 1: Variation of the real part of susceptibility $\left(\chi^3\right)$ with wave vector (k) at $E_0 = 2*10^6 V.m^{-1}$ and $n_0 = 10^{24} m^{-3}$

Figure 2 shows variation of real part of susceptibility $\left(\chi^{3}\right)$ with number density n_0 at $E_0 = 10^6 V.m^{-1}$ and $K = 10^8 m^{-1}$. The red curve shows the variation of GaAs and black curve shows the variation of InSb. Due to the presence of ion-implantation effect, we can see from the figure that there exists a distinct anomalous dispersion region with positive and negative values. The presence of ion-implantation enhances the carrier density concentration for the case of GaAs ,when modified plasma frequency $\varpi_p^2 \rangle \omega_a$,while in the case of InSb the presence of ion-implantation shows a amplification in negative values/direction, when modified plasma frequency greater then acoustic wave frequency. above this region when $\omega_a \rangle \varpi_p^2$ is gets vanishes. This result can be exploited in the generation of squeezed state and also depicts in the observation of group velocity dispersion in ion-implanted semi conductor plasma.

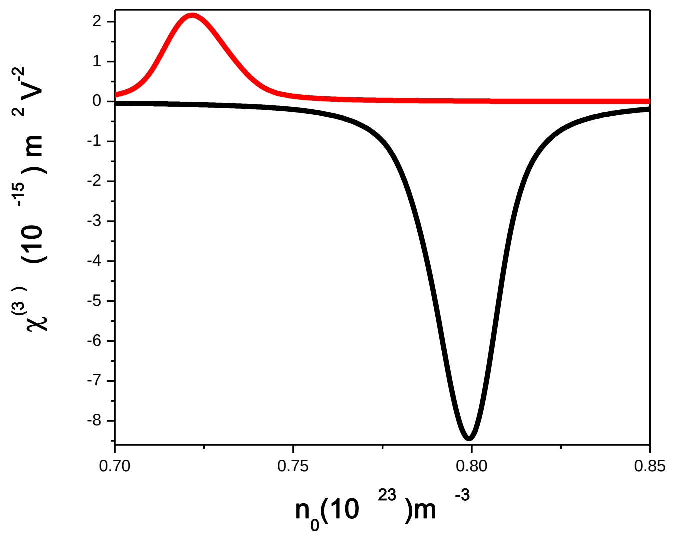

Figure 2: Variation of real part of susceptibility χ^3 with number density n_0 at $E_0 = 10^6 V.m^{-1}$ and $K = 10^8 m^{-1}$

Figure 3, shows the variation of real part of susceptibility χ^3 with Pump electric field $\left(E_0\right)$, considering n-type doping concentration $n_0 = 2*10^{24}$ for two species ion-implanted region.

From the figure, we can see that the black line indicate InSb and red line indicate GaAs, shows a distinct anomalous behaviour by the virtue of magnitude with E_0. From the figure we can see that, as we increase the electron field amplitude the susceptibility decreases sharply and achieve the minimum value at $E_0 \approx 1.7*10^6 V.m^{-1}$ in the case of GaAs and for the case of InSb it attends minimum value at $E_0 \approx 2*10^6$. When further increase value of E_0 susceptibility increases gradually and get saturates for the high value of E_0. Hence the proper selection of pump amplitude and doping level enable us to enhance significantly for dispersion region in ion-implanted semi conductor plasma. It can also lead to get the opportunity for the observation of group velocity dispersion in ion-implanted semi conductor plasma.

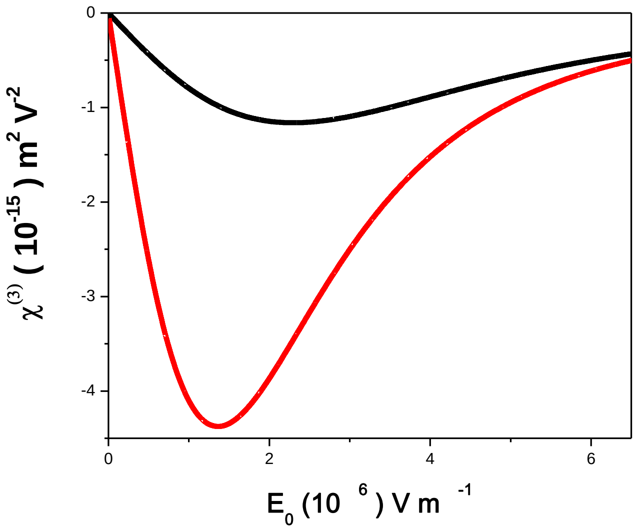

Figure 3: Variation of real part of susceptibility wit (χ^3) with Pump electric field (E_0)

Figure 4 shows variation of threshold pump field E_{0th} with plasma frequency ω_p. When $k = 2*10^8 m^{-1}$. Figure shows the dependence of on carrier concentration via plasma frequency ω_p for ion-implanted effect. Fr E_{0th} on the figure we can see that for both InSb-GaAs. the threshold decrease as increase in plasma frequencies and attend the minimum value at $\omega_p \approx 3.5*10^{13} s^{-1}$.

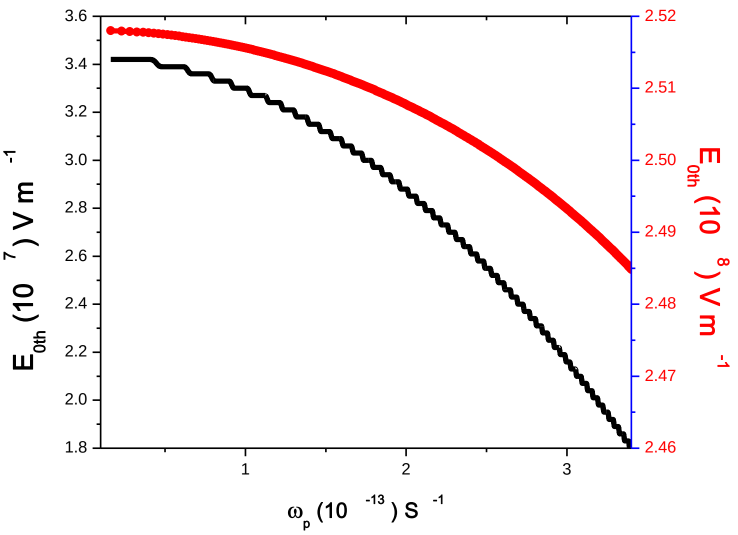

Figure 4: Variation of threshold pump field E_0th with plasma frequency ω_p. When $k = 2*10^8 m^{-1}$

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