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On aspects of electron-LO phonon interaction in magnetized semiconductors in the presence of a hybrid pump field

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Abstract. Most realistic propagation of an intense hybrid pump wave in a magnetized semiconductor plasma has been considered to study some aspects of electron-LO phonon interactions. Hydrodynamic model for one component plasma along with coupled mode theory has been used to study parametric amplification due to polaron mode. Expressions for parametric gain coefficient arising due to parametric instability and threshold field required to incite parametric amplification has been derived. The compound semiconductors of group III-V and II-VI are unique within the universe of simple octet compounds, enable them to dominate higher performance electronics and optoelectronics. Present study aims to compare materials for which favourable magnitudes of parametric gain and threshold value could be obtained with suitable values of external parameters. Numerical estimations were carried out using the data of two different group compound semiconductors namely ZnSe and GaAs. Both the gain coefficients and threshold pump field are found to be strongly dependent on the carrier concentration of the medium. Resonance between plasma frequency and collective excitation frequency affects the process of amplification in both cases. Higher gain is achieved for GaAs which has smaller coupling coefficient as compared to ZnSe. Hybrid pump propagation is found to strengthen the electron-LO phonon coupling.

1. Introduction

In polar materials interaction of electric field takes place with both electrons and optical phonons. Single particle scattering is significant in transport theory. As per the direction of incidence of electromagnetic wave, the collective modes are labelled as longitudinal, transverse, mixed or hybrid, [1]. Present study considers a hybrid pump wave for infinite semiconductor plasma i.e. E_0 must have components that are both parallel and perpendicular to the direction of propagation [2],due to following reasons:-

- So far the response of an electron gas to longitudinal or transverse excitations has been studied by several workers [3-4], but it is not easy to create purely longitudinal or transverse pump.
- When an electromagnetic wave impinges on the surface of crystal at normal incidence, it excites only TO phonons inside the crystal if the provided frequency is matched accurately to that of the phonons. This is so both waves are transverse and consequently they couple together. LO phonons may not be excited in this way, because of the fact that these phonons being longitudinal, do not couple to transverse incident wave. If the incident wave falls obliquely onto the surface, there is a longitudinal electric field at surface which then acts to excite the LO phonons [5].

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Hence in this study, we discuss the physics of interaction of electrons and LO phonons in semiconductor materials, interacting with and through, hybrid pump electromagnetic field. Previously we reported electromagnetic wave - polar semiconductor interaction in III-V polar semiconductor material under hybrid pump field configuration [6].

In the present study we develop a comparative model and to accomplish purpose of study we chose III-V GaAs and II-VI ZnSe direct band gap polar semiconductors.Motive behind choosing these particular semiconductors is the fact that in contrast to pure semiconductors GaAs and ZnSe are direct band gap ionic semiconductors with lower electron masses and higher radiative recombination coefficients which makes them useful for high speed electronics and optoelectronics[7]. As the materials belonging different groups have different magnitudes of physical parameters which may provide a better insight to understand different aspects of electron-LO phonon interactions. Present study probably for the first time establishes a comparative investigation of amplification characteristics of different group polar semiconductors shined by a hybrid pump field.

2. Theoretical formulation

This section deals with the theoretical formulation of the second order nonlinear optical susceptibility $\chi^{(2)}$ for the polaron mode in magnetized doped polar semiconductor plasmas. We consider the propagation of an hybrid pump wave, periodic in both space and time as, $E_0=\left(E_{0x}\hat{x}+E_{0y}\hat{y}\right).\exp\left[i(\mathrm{k}_0\,\hat{x}-\omega_0 t)\right]$, in a homogeneous semiconductor plasma subjected to a magnetic field along z axis i.e. $B_0=B_0\hat{k}$, perpendicular to direction of wave propagation.

In order to develop vital mathematics the basic equations and expressions are adopted from [6] (hereafter referred as paper I) and the procedure adopted from Neogi and Ghosh [8] (here after referred as paper II). We assume that the momentum and energy transfer between the pump, polaron and signal wave satisfy phase matching conditions $k_s=k_0-k_{pl}$ and $\omega_S=\omega_0-\omega_{pl}$.

Propagation of pump wave creates density perturbations in the medium. Using the basic equations of paper I and adopting the procedure of paper II, we get equation for the density perturbation by neglecting the Doppler shift under Rotating Wave Approximation as

$$\frac{\partial^2 n_1}{\partial t^2}+2\Gamma_e\frac{\partial n_1}{\partial t}+\overline{\omega}_p^2 Z n_1-\omega_{p,pl}^2\cdot n_0 A_1\cdot\frac{\partial R}{\partial x}-2\Gamma_{ph}\cdot T=-i(k_0-k_{pl})n_1A_2\overline{E} \tag{1}$$

where, $\overline{E}=(e/m)E_{eff}$ $\quad E_{eff}=-E_{0x}+\upsilon_{0y}B_{0z}$ $\quad \overline{\omega}_p^2=\omega_p^2A_1$

$$\upsilon_{0x}=\overline{E}/2\Gamma_e-i\omega_0\ \ \upsilon_{0y}=\left(-\frac{e}{m}E_{0y}-\omega_c\upsilon_{0x}\right)/2\Gamma_e-i\omega_0$$

The above equation describes coupling between polaron mode and the side band waves in the presence of intense pump. Meaning of all symbols is same as given in paper I. Now we may obtain second-order susceptibility via nonlinear polarization $P_{nl}=\varepsilon_0\chi^{(2)}E_0E_{pl}^*$ as

$$\chi_{eff}=\frac{-iq(k_0-k_{pl})}{M_{pl}}\left\{\frac{\omega_p^2\omega_{p,pl}^2}{\omega_0\omega_1}\right\}Q^*G^* \tag{2}$$

Now by setting P_{nl} equal to zero, one may obtain the effective pump amplitude required to incite the parametric process,

$$E_{th}=\left|\left(m_e\big/e(k_0-k_{pl})A_2\right)\delta_1\delta_2\right|$$

, where $\delta_1=\left(\overline{\omega}_p^2Z-\omega_1^2\right)^{1/2}$ and

$$\delta_2=\left(\overline{\omega}_p^2Z-\omega_{0,pl}^2\right)^{1/2}$$

Now the absorption coefficient can be achieved by using the relation,

$$\alpha_{para} = \frac{k_s}{2\varepsilon_1}\mathrm{Im}(\chi_{eff}^{(2)})\left|E_{eff}\right| = \frac{k_s}{2\varepsilon_1}\left\{\frac{-iq(k_0-k_{pl})}{M_{pl}}\left(\frac{\omega_p^2\omega_{p,pl}^2}{\omega_0\omega_1}\right)\right\}Q^*G^*\left|E_{eff}\right| \quad (3)$$

Where α_{para} is the nonlinear absorption coefficient. Equation (3) is subsequently employed to study the amplification characteristics of the scattered wave in the parametric process. The nonlinear parametric gain of the signal as well as the idler waves can be possible only if α_{para} is negative.

3. Results and discussions

Set of relevant parameters of GaAs is given in paper I and for ZnSe: $\alpha = 0.43$, $\omega_{LO} = 4.814\times10^{13}s^{-1}$ $\varepsilon_s = 9.6$, $\varepsilon_{opt} = 6.3$ and $k_{pl} = 4\times10^5 m^{-1}$. Numerical appreciations of above comparative study are depicted in figures 1-4 in which solid line curve represents GaAs and dotted curves are for ZnSe material. Figure 1 describes the variation of threshold pump field with external magnetic field. Figure depicts that for both the materials, increasing magnitudes of magnetic field reduces the threshold pump field. Pump field required to incite parametric process is slightly lower for GaAs than ZnSe.

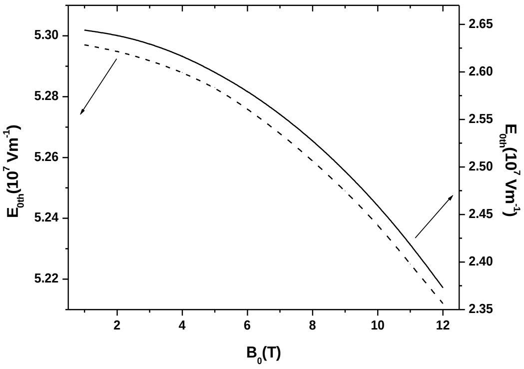

Figure 1. Variation of threshold field E_{th} with magnetic field at $B_0 = 12$ tesla

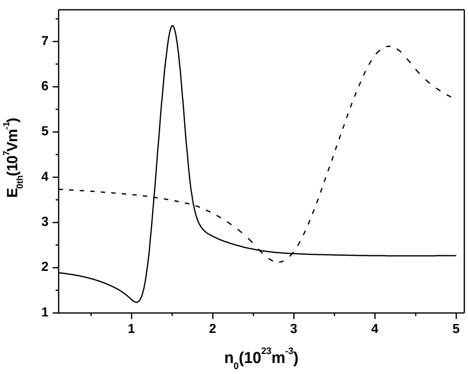

Figure 2. Variation of threshold field E_{th} with carrier concentration at $n_0 = 3\times10^{23}m^{-3}$

As depicted in figure 2 carrier concentration significantly affects the threshold field magnitude. Initially increasing carrier concentration leads to a reduction in threshold field till a minimum $\left(E_{th} \approx 1.25\times10^7 Vm^{-1}\right)$ is touched at $n_0 \approx 1.2\times10^{23}m^{-3}$ for GaAs. Minima of threshold for ZnSe $\left(E_{th} \approx 2.1\times10^7 Vm^{-1}\right)$ shifts towards higher concentration $\left(n_0 \approx 3\times10^{23}m^{-3}\right)$. It is clear that GaAs requires relatively lower pump field to incite the amplification process than ZnSe at a lower carrier concentration. Minima of both the curve signify the resonance between plasma frequency and collective cyclotron frequency. Further increment in carrier concentration makes $\omega_p^2 > \omega_{0,pl}^2 - \omega_c^2$, hence increments in threshold field is observed.

Absorption coefficient α_{para} is plotted as a function of magnetic field and carrier concentration in figures 3 and 4 respectively, at pump field $E_0 = 5.5\times10^7 Vm^{-1}$. Higher magnetic field proves to be favourable resulting into amplification of the signal wave in both the semiconductors with lower threshold pump field. Highest parametric gain obtained is $\approx 8.7\times10^5 m^{-1}$ for ZnSe and $\approx 1.8\times10^6 m^{-1}$ for GaAs. Figure 4 shows the variation of absorption coefficient with carrier concentration. Initially absorption of the signal wave is depicted in figure for both the materials. It is observed that in both the cases slight increment in carrier concentration leads to amplification of the signal waves. Gain

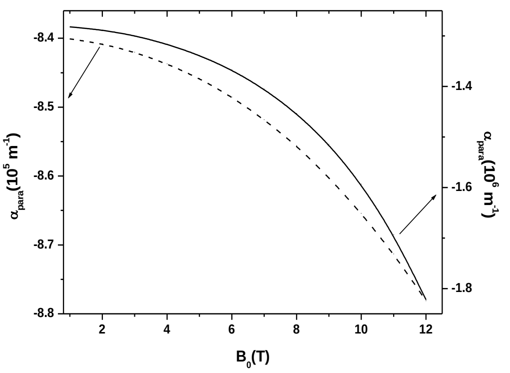

Figure 3. Variation of absorption coefficient with magnetic field at $B_0 = 12$ tesla

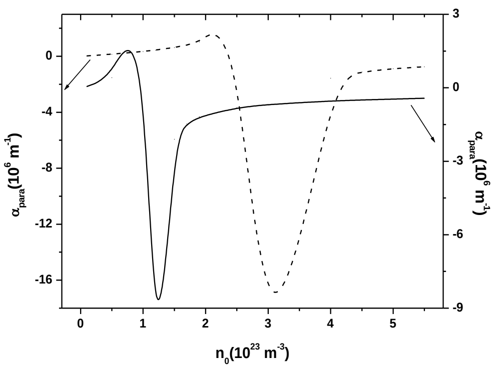

Figure 4. Variation of absorption coefficient with carrier density at $n_0 = 3\times10^{23} m^{-3}$

increases upto $\alpha_{para} \approx 1.7\times10^{7} m^{-1}$ (for ZnSe) and $\alpha_{para} \approx 0.9\times10^{7} m^{-1}$ (for GaAs).Sign reversal of absorption coefficient is due to the reason that initially plasma frequency $\omega_p^2 < \omega_{0,pl}^2 - \omega_c^2$ causing positive values of α i.e. absorption. A slight increment in carrier concentration gives maximum gain due to resonance between plasma frequency and collective normal mode frequency. Further increments in doping concentration reduce parametric gain because $\omega_p^2 > \omega_{0,pl}^2 - \omega_c^2$. This behaviour could be utilised in the optical switching applications. Figure clearly demonstrated the shifting of the maximum gain position towards the higher magnitude of doping concentration for ZnSe as compared to GaAs. Maximum gain is obtained at the concentrations where minimum threshold reported in figure 1 for both semiconductors.

4. Conclusions

This comparative study proves III-V GaAs more suitable material than II-VI ZnSe for commercial optical devices as far as threshold and parametric amplification characteristics are concerned. Effective mass and Fröhlich coupling coefficient are very significant parameters for polar materials. It is found that material with lower effective mass and Fröhlich coupling coefficient (GaAs) is favourable for the design of optical parametric amplifier. Probably hybrid pump propagation strengthens the electron LO phonon coupling. Thus one may conclude that the threshold and amplification characteristics strongly depend on material parameters. It is hoped that result of this paper may be useful in designing optical devices.

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