Influence of hot carriers on parametrically interacting polaron mode in semiconductors

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Abstract. In the present paper effect of hot carriers due to parametrically interacting electron-longitudinal optical phonons in polar semiconductor is analytically investigated. Presence of hot carriers is found to significantly modify the threshold and amplification characteristics in the presence of external magnetic fields. Expressions for threshold pump field required for the onset of polaron induced parametric interaction and amplification characteristics are explicitly derived. It is found that at moderate magnetic field and high carrier concentrations hot carriers affect threshold and amplification characteristics strongly. Resonance between polaron frequency and plasma frequency is found to be favourable for the minimum threshold field. Presence of hot carriers and magnetic field along with mass modulation effects are found to be additive and resulted into increment in the parametric gain. Typical dependence of parametric gain on magnetic field and carrier concentration could be utilized for the construction of optical switches.

1. Introduction
Parametric interactions offer an efficient way to heat semiconductor plasma, since the incoming photons participating in the process are completely converted into plasmons. The parametric amplification of collective-waves in polar semiconductors such as phonons and polarons at the expense of the pump wave has already aroused much attention for modern optoelectronic device applications [1] e.g. for the generation of tunable laser with high conversion efficiency, photovoltaic effect, far-infrared diagnostic systems and optical parametric amplifiers (OPAs).

Large changes at room temperature and below have been shown to be due to impact ionization of the lattice by hot carriers [2, 3] in polar semiconductors. History of inclusion of carrier heating effects in semiconductor plasmas dates back to 1973 [4]. Recently authors analytically investigated polaron induced parametric interactions in magnetized semiconductors [5] (hereafter referred as paper I). Nonlinear electromagnetic effects connected with free carriers in homogeneous semiconductors result from heating up of the carriers and peculiarities in the dynamics of the carriers in the bands or the dependence of their effective mass $m^*$ on the field. However which of the mechanisms play the dominant role in the processes of Infrared parametric generation is still a question of important. A more fundamental motivation for such studies is that they help in elucidating the interaction of the carriers with the scattering mechanism: the lattice, impurities, and other defects. Therefore in the present paper emphasis will be on the heating of carriers due to Fröhlich interaction and the underlying theory, significant results will be cited. Several factors, including acceptor concentration, carrier density, temperature, magnetic field, mass modulation, all affect hot carrier scattering, with different
mechanisms dominating in various regimes. Here we examine how these external parameters can be used to extract analytically the carrier heating dependence of this interaction in polar semiconductors.

2. Theoretical Formulation

In this section, the parametric amplification of polaron mode arising due to three-wave interaction induced by $\chi^{(1)}$ in polar semiconductor duly irradiated by a relatively high-power laser with photon energy much below the forbidden energy gap of the crystal has been studied. Well-known hydrodynamic model of homogeneous semiconductor plasma, satisfying the condition $kl \ll 1$ ($k$ and $l$ being the wave number and electron mean free path, respectively) has been used. We assume that a spatially uniform $|k_0| = 0$ pump electric field as $E_0 = \hat{\chi}E_0 \exp(-i\omega_0 t)$ irradiates a polar semiconductor medium immersed in a transverse dc-magnetic field $\vec{B}_0 = \hat{\chi}B_0$. Since we are interested in three wave interactions, the phase matching conditions are $\omega_0 \approx \omega_1 + \omega_{pl}$ and $|k_1| = k_{pl}$ (say). Here the parametric interaction of the pump generated a polaron wave at $(\omega_{pl}, k_{pl})$ and scattered side-band wave (SBW) at $(\omega_1, k_1)$ supported by the lattice and electron plasma in the medium, respectively.

2.1. Nonlinearity due to mass modulation

The effective mass is taken to be energy dependent based on Kane’s model [6] as

$$m^* = \frac{2}{k_BT_0} \frac{\varepsilon_p}{k_BT_0}$$

(1)

where, $L = \frac{4\rho^2}{3\hbar^2 k_BT_0}$ and $\langle \varepsilon_p \rangle = \frac{3}{2} k_BT_e$ is the average thermal velocity of an electron (the drift velocity being much smaller than the random velocity), $\varepsilon_p$ is the energy band gap and $\rho \approx 8.5 \times 10^{-8} eV cm$ [7] a matrix element.

2.2. Nonlinearity due to electron collision frequency

When the mobility is high, heating of the carriers occurs in the fields as low as a few volts per centimeter. Particularly in high mobility semiconductors like InSb, it is an established fact that due to high intensity pump (which is one of the pre-requisite conditions for the onset of parametric instability) heating of carrier becomes inevitable. This heating of electrons modifies the electron collision frequency (ECF) through the relation [8]

$$\Gamma_e = \Gamma_{e0} \left( \frac{T_e}{T_0} \right)^{1/2}$$

(2)

where, $T_e$ is the effective temperature of electrons, $T_0$ is the lattice temperature, and $\Gamma_{e0}$ is the ECF when $T_e = T_0$. As a result, the momentum-transfer collision frequency (MTCF), mobility of the carriers and conductivity of the medium become function of the pump amplitude and hence produce refinement effects. The momentum transfer of carriers is assumed to be due to acoustical phonon scattering and the energy transfer due to polar optical phonon (POP) scattering mechanisms in an n-type III-V semiconductor. In steady state, the power absorbed per electron from the pump is just equal to the power lost per electron in the POP scattering. Hence for moderate heating, carrier temperature is-


\[ \frac{T_c}{T_0} = 1 + \frac{e^2 \Gamma_e}{2 m_e} \left( \omega_0^2 + \omega_0^6 \right) \frac{\tau(\omega_0^2 + \omega_0^6)}{(\omega_0^2 - \omega_0^6)^2 + 4 \Gamma_e^2 \omega_0^6} E_0 E_0^* \]  

(3)

where \( \tau^{-1} = \left( \frac{2 \kappa B \Theta_D}{m_e \pi} \right)^{1/2} e^{E_p x_0} \) \( K_0 \left( \frac{x_0}{2} \right) \frac{x_0^{1/2} \exp \left( \frac{x_0}{2} \right)}{\exp(x_0) - 1} \)

2.3. Threshold and amplification characteristics

Using basic equations from paper I [5] second-order nonlinear susceptibility \( \chi^{(2)} \) can be derived as

\[ \chi^{(2)} = -\frac{i k e (N M)^{0.5}}{m_e e_0 \omega_{pl}} \left( \frac{\omega_0 \Omega_p^2}{\omega_0^2 - \omega_e^2} \right) \frac{Q A_T}{F_1} G^* \]  

(4)

Here we have neglected the Doppler shift under the assumption \( \omega_0 >> \Gamma_e \theta_0 \) and

\[ G = \left[ \delta_2^2 - 2 i \Gamma_p \omega_{pl} - \frac{k^2 A_p^2 |E|^2}{\delta_1^2 - 2 i \Gamma_1 \omega_1} \right]^{-1}, \delta_1 = A_1 \omega_p - \omega_1^2, \delta_2 = A_1 \omega_p - \omega_2^2, E = \frac{e}{m_e} E_{eff}, \omega_p = \sqrt{n_0 e^2 m_e} \]

\[ \omega_{cp} = \left( \frac{-e}{m_e} + \frac{q}{M} \right) B_0, A_1 = \frac{\omega_0^2}{\omega_1^2 - \Omega_p^2 - \omega_e^2}, A_2 = \frac{\omega_0^2}{\omega_1^2 - \Omega_p^2 - \omega_e^2}, Q = X_1 + Y_1, X_1 = \frac{4 \Gamma_p^2}{2 \Gamma_p^2 + \omega_e^2} \]

\[ Y_1 = \frac{\omega_{cp}^2}{4 \Gamma_p^2 - \omega_e^2}, T = \frac{n_0 e^2}{m_e} + \frac{N e}{m_e} \frac{n_0 e^2}{m_e} - N \omega_e^2, F_1 = \omega_0^2 - \omega_{pl}^2 - 2i \Gamma_p \omega_{pl} \]

\[ \overline{\omega}_p^2 = \left[ \omega_p^2 + k \left( \frac{k T_e}{m_e} \right)^{1/2} \frac{4 \Gamma_p^2}{2 \Gamma_p^2 + \omega_e^2} \right] \]

It is clear that \( \chi^{(2)} \) is influenced by the wave vector \( k \), carrier concentration \( n_0 \), and by the transverse dc magnetic field through \( \omega_e \).

Threshold pump amplitude for the onset of parametric amplification may be obtained as

\[ E_{\text{th}} \text{para} = \frac{m_e}{e k A_1} \left( 1 - \frac{\omega_0^2}{\omega_e^2} \right) \delta_1 \delta_2 \]  

(5)

The parametric amplification can be achieved at excitation intensity above this threshold value under favourable conditions and nonlinear absorption coefficient is given by

\[ \alpha_{\text{para}} = \frac{k}{2 e_1} \left( \chi^{(2)} \right) E_0 \]  

(6)

The nonlinear parametric gain of the signal as well as the idler waves can be possible only if \( \alpha_{\text{para}} \) obtained from equation (6) is negative.

3. Results and discussions

Numerical estimations were carried out by using the relevant parameters chosen for InSb medium are listed in [9]. Figure 1 depicts the variation of threshold pump electric field \( [E_{\text{th}}] \text{para} \) (with or without CH effects) with carrier density. The threshold pump electric field achieves its minimum value carrier density when dependent modified plasma frequency becomes smaller and smaller and finally resulting into \( A_1 \omega_p^2 \sim \omega_{pl}^2 \) in \( \delta_1 \) term. This figure clearly illustrates that the polaron frequency plays an important role in the appreciable reduction of threshold pump electric field. CH effects tend to shift minimum threshold pump electric field towards the smaller concentration of the carriers.
Figure 1. Variation of threshold pump field as a function of carrier density. [Curve (a) with CH effects and Curve (b) without CH effects].

Figure 2. Variation of absorption coefficient as a function of wave vector with and without magnetic field.

Figure 2 represents the variation of absorption coefficient with wave vector. It is inferred from figure 2 that at 
\[ k \approx \left[ \frac{\alpha_{pl}^2 - 2i\Gamma_{pl}^{\omega \omega pl}}{\alpha_{pl}^2 - 2i\Gamma_{pl}^{\omega \omega pl}} \right]^{0.5} \] the absorption coefficient \( \alpha_{para} \) decreases suddenly and achieves its minimum. Above or below this resonance condition \( \alpha_{para} \) is nearly independent of wave vector. Presence of magnetic field significantly increases the parametric gain by a factor of \( \approx 10^2 \) in comparison with that in the absence of magnetic field. It is found that presence of magnetic field is favourable for polaron induced parametric gain in heavily doped semiconductor. It is also noticed that the nonlinearity due to mass modulation and electron collision frequency modifies threshold and amplification characteristics strongly. CH effects are found to lower the threshold pump field and effectively raise the parametric gain.

Acknowledgement
One of the authors (S. Ghosh) is thankful to MPCST, Bhopal for financial assistance.

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