DETERMINED CONDITIONS OF LASER FIELD ON ACOUSTIC PHONON INCREASING IN SEMICONDUCTOR BLOCK

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Abstract: *In this paper, I have been established the kinetic equation for phonons in semiconductor block under intense laser field. Using this equation, we find expression for the rate coefficient for the case degenerate electron gas. The condition of the acoustic phonon increasing in semiconductor blocks is discussed.*

Keywords: *Acoustic phonon, semiconductor block, laser field.*

1. Introduction

Phonon amplification by absorption of laser field energy is a subject extensively investigated in different structures [1,2,3,4,8]. The main results of these papers are that by absorption of laser field energy, the interaction of the laser field with electron can lead to the excitation of higher harmonics and the amplification of phonon. With the development of modern experimental technology, the fabrications of low-dimensional structures are realizable. Naturally, phonon amplification by absorption of laser radiation in such confined structures should show the characterization of the electron-phonon interaction.

In this paper, we start from Hamiltonian of the electron-phonon system in Semiconductor Block (SB) under intense laser field; we derive a quantum kinetic equation for phonon in SB in the case of multiphoton absorption process. Then, we calculate the phonon excitation rate in the case of the electron gas is degenerative. Finally, we calculate the acoustic phonon excitation rate (APER) in a specific SB to illustrate the mechanism of the phonon amplification.

2. Quantum kinetic equation for phonon in a Semiconductor Block

We use a simple model for a SB, in which an electron gas is confined by SB potential along the z direction and electrons are free on the x-y plane. It is well known that its energy spectrum is quantized into discrete levels in the z direction. A laser field irradiates which is normal to the x-y plane, its polarization is along the x axis, and its strength is expressed as a vector potential $\vec{A}(t)$. The Hamiltonian for the system of the electrons and phonons in the case of the presence of the laser field is written as [8]:

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$$H(t)=\sum_{\vec{p}}\frac{1}{2m}\left(\vec{p}-\frac{e}{c}\vec{A}(t)\right)^2 a^+_{\vec{p}}a_{\vec{p}}+\sum_{\vec{q}}\varepsilon_{\vec{q}}b^+_{\vec{q}}b_{\vec{q}}+\sum_{\vec{p},\vec{q}}C_{\vec{q}}a^+_{\vec{p}+\vec{q}}a_{\vec{p}}(b_{\vec{q}}+b^+_{-\vec{q}}) \quad (1)$$

where $a^+_{\vec{p}}$ and $a_{\vec{p}}$ are the creation and annihilation operators of electron in SB, $b^+_{\vec{q}}$ and $b_{\vec{q}}$ are the creation and annihilation operators of phonon respectively, $\varepsilon_{\vec{q}}=\hbar\omega_{\vec{q}}$ is phonon energy for wave vector $\vec{q}$. $\vec{A}(t)$ is the potential vector, depending on the external field.

$$\vec{A}=\vec{e}_x A_0\cos\Omega t,\ A_0=cE_0/\Omega \quad (2)$$

Under intense laser field, the electron-phonon system is unbalanced, the phonon numbers change over time. The change over time of $N_{\vec{q}}(t)=\left\langle b^+_{\vec{q}}b_{\vec{q}}\right\rangle_t$ is described by the equation:

$$i\hbar\frac{\partial N_{\vec{q}}(t)}{\partial t}=\left\langle b^+_{\vec{q}}b_{\vec{q}},H(t)\right\rangle_t \quad (3)$$

We obtain the quantum kinetic equation for phonons in SB:

$$\frac{\partial N_{\vec{q}}(t)}{\partial t}=\frac{1}{\hbar^2}\sum_{\vec{p}}|C_{\vec{q}}|^2\sum_{s.\ell=-\infty}^{+\infty}J_s\left(\frac{\Lambda}{\hbar\omega}\right)J_\ell\left(\frac{\Lambda}{\hbar\omega}\right)\exp[i(\ell-s)\omega t]$$
$$\times\int_{-\infty}^{t}dt'\Big\{\Big[[N_{\vec{q}}(t')+1]f(\vec{p}+\vec{q})[1-f(\vec{p})]-N_{\vec{q}}(t')f(\vec{p})[1-f(\vec{p}+\vec{q})]\Big]$$
$$\times\exp\left[\frac{i}{\hbar}\left(\varepsilon_{\vec{p}+\vec{q}}-\varepsilon_{\vec{p}}-\varepsilon_{\vec{q}}-\ell\hbar\omega\right)(t'-t)\right] \quad (4)$$
$$+\Big[[N_{\vec{q}}(t')+1]f(\vec{p})[1-f(\vec{p}-\vec{q})]-N_{\vec{q}}(t')f(\vec{p}-\vec{q})[1-f(\vec{p})]\Big]$$
$$\times\exp\left[-\frac{i}{\hbar}\left(\varepsilon_{\vec{p}}-\varepsilon_{\vec{p}-\vec{q}}-\varepsilon_{\vec{q}}-\ell\hbar\omega\right)(t'-t)\right]\Big\}$$

Where $N_{\vec{q}}(t)=<b^+_{\vec{q}}b_{\vec{q}}>_t$, the symbol $<X>_t$ means the usual thermodynamic average of operator X, $J_\ell(z)$ is Bessel function, $f(\vec{p})=<a^+_{\vec{p}}a_{\vec{p}}>_t$, $\Lambda=e\hbar\vec{E}_0\vec{q}/(m\Omega)$.

3. Phonon excitation rate in a SB

Above results [4] allow one to introduce the kinetic equation for phonon number of the q mode:

$$\frac{\partial N_{\vec{q}}(t)}{\partial t}=\gamma_{\vec{q}}N_{\vec{q}}(t) \quad (5)$$

where $\gamma_{\vec{q}}$ is the parameter that determines the evolution of the phonon number $N_{\vec{q}}(t)$ in time due to the interaction with the electrons. If $\gamma_{\vec{q}}>0$ the phonon population grows with time, whereas for $\gamma_{\vec{q}}<0$ we have damping.

From (6), the phonon excitation rate becomes:

$$\frac{\partial N_{\vec{q}}(t)}{\partial t} = \frac{2\pi}{\hbar}\sum_{\vec{p}} |C_{\vec{q}}|^2 \sum_{\ell=-\infty}^{+\infty} J_\ell^2(\Lambda/\hbar\omega)\left[f(\vec{p}+\vec{q}) - f(\vec{p})\right]\delta(\varepsilon_{\vec{p}+\vec{q}} - \varepsilon_{\vec{p}} - \varepsilon_{\vec{q}} - \ell\hbar\omega) \quad (6)$$

In the strong-field limit, $\Lambda >> \hbar\Omega$ and the argument of the Bessel function in Eq. (6) is larger. For large values of argument, the Bessel function is small except when the order is equal to the argument. The sum over ℓ in Eq. (7) may then be written approximately:

$$\sum_{\ell=-\infty}^{\infty} J_\ell^2\left(\frac{\Lambda}{\hbar\Omega}\right)\delta\left(E - \ell\hbar\Omega\right) = \frac{1}{2}\left[\delta\left(E+\Lambda\right) + \delta\left(E-\Lambda\right)\right] \quad (7)$$

Here $E = \varepsilon_{\vec{p}+\vec{q}} - \varepsilon_{\vec{p}} - \varepsilon_{\vec{q}}$. The first Delta function corresponds to the absorption and the second one corresponds to the emission of $\Lambda/(\hbar\Omega)$ photons. In the strong-field limit only multiphoton processes are significant and the electron-phonon collision takes place with the emission and absorption of $\Lambda/(\hbar\Omega)$ photons. Substituting Eq. (7) into Eq. (6), the phonon excitation rate becomes $\gamma_{\vec{q}} = \gamma_{\vec{q}}^{(+)} + \gamma_{\vec{q}}^{(-)}$, where:

$$\gamma_{\vec{q}}^{(\pm)} = \frac{\pi}{\hbar}\sum_{\vec{p}} \left|C(\vec{q})\right|^2 \left[f(\vec{p}+\vec{q}) - f(\vec{p})\right] \delta\left(\varepsilon_{\vec{p}+\vec{q}} - \varepsilon_{\vec{p}} - \varepsilon_{\vec{q}} \pm \Lambda\right) \quad (8)$$

In the following, we will calculate for the case in which the electron gas is degenerative. In this case, we may simplify the carrier distribution function by using the Boltzmann distribution function:

$$f\left(\vec{p}\right) = \theta\left(\varepsilon_F - \varepsilon_{\vec{p}}\right) = \begin{cases} 0 & \text{khi } \varepsilon_F < \varepsilon_{\vec{p}} \\ 1 & \text{khi } \varepsilon_F > \varepsilon_{\vec{p}} \end{cases}.$$

I calculate the rate of acoustic phonon excitation. For acoustic phonon, we have $\left|C_{\vec{q}}\right|^2 = \frac{\hbar q \xi^2}{\rho v_a V}$ here V, ρ, v_a, and ξ are the volume, the density, the acoustic velocity and the deformation potential constant, respectively.

$$\gamma_{\vec{q}}^{(\pm)} = \frac{\omega_{\vec{q}} m^2 \xi^4}{16\hbar\pi\rho^2 v_a^2 V^2}\left(\pm\frac{eqE_0}{m\Omega} - \varepsilon_{\vec{q}}\right) \quad (9)$$

Analyzing Eq. (10) we can obtain the conditions for the phonon amplification. From the condition $\gamma_{\vec{q}}^{(\pm)} > 0$, we obtain $\left(\pm\frac{eE_o q}{m\Omega} - \varepsilon_q\right) > 0$. The condition which the laser field must satisfy is:

$$\Lambda = \frac{\hbar eqE_0}{m\Omega} > \hbar\omega_{\vec{q}} \quad (10)$$

in which:

$$\varepsilon_F > \frac{m}{2q^2}\left(\omega_o - \vec{q}\vec{v} - \frac{\hbar^2 q^2}{2m}\right)^2; \ \vec{v} = \frac{eE_o}{m\Omega}\vec{e}_x \quad (11)$$

The condition (10) simply means that if the drift velocity of electron $\vec{q}.\vec{E}_0 / m\Omega$ under the intense laser field, excesses the phonon phase-velocity, a deformation potential for multiphonon excitation can be generated in the SB.

In next to the condition (10), in the case of degenerate electron gas must also satisfy the condition (11), so the increase acoustic phonons are more difficult. Note that the condition (11) is not indicated by other authors when studying this effect [6,8].

4. Conclusions

I have analytically investigated the possibility of phonon amplification by absorption of laser field energy in a SB in the case of multiphoton absorption process with non-degenerative electron system. Starting from bulk phonon assumption and Hamiltonian of the electron-phonon system in laser field we have derived a quantum kinetic equation for phonon in SB. However, an analytical solution to the equation can only be obtained within some limitations.

Using these limitations for simplicity, I have obtained expressions of the rate of acoustic phonon excitation in the case of multiphoton absorption process. Finally, the expressions are numerically calculated and plotted for a SB to show the mechanism of the phonon amplification. Similarly to the mechanism pointed out by several authors for deferent models, phonon amplification in a SB can occur under the conditions that the amplitude of the external laser field is higher than some threshold amplitude. This is the Cerenkov’s condition [8].

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