The influence of confined phonons on Ettingshausen effect in Quantum well with parabolic potential in the presence of electromagnetic wave

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Abstract. From Hamiltonian of the confined electron - confined acoustic phonon system, we have successfully built quantum kinetic equation for the distribution function of electrons under the influence of the electromagnetic wave (EMW) in quantum well with parabolic potential (QWPP). We have carefully calculated and obtained analytic expression for Ettingshausen coefficient (EC). The expression shows that EC depends in a complicated way on temperature, magnetic field, characteristic quantities of EMW and m - quantum number which specific the confined phonon. These dependencies are clearly displayed when we apply numberial method for GaAs/GaAsAl quantum well (QW). Especially, if the detention index of the phonon is set to zero, we will achieve results which are suitable for published studies about thermal-electromagnetic effect in the same QW without phonon confinement. Finally, the results we get are new and not found in previous researches.

Keywords: Quantum well, Ettingshausen effect, Quantum kinetic equation.

1 Introduction

The quantization by reducing in size leads to transformation of both wave function and energy spectrum of the electron. So, the low-dimensional semiconductor systems have not only changed physical properties but also appeared new effects. Among them, we have to mention a magneto – thermoelectric effect that called Ettingshausen effect. That is a thermoelectric phenomena that affects the current in conductor in the presence of magnetic field [1]. This effect has studied in various semiconductor structures [2][8], including two-dimensional systems such as QW [3]. However, those studies have only interested in the confinement of the electrons while the phonons are free. Furthermore, several examinations have shown that the confined phonon impact on the feature in the case of quantum effects. How the confined acoustic phonon influence the Ettingshausen effect in QWPP is still a unanswered question.

The starting point is the quantum kinetic equation for electrons [2], in this work, we have considered the presence of EWM. Then, we have calculated and obtained the EC expression in QWPP. In the process of transformation, we always count on the confinement of the acoustic phonon and existence of temperature gradient.

Components of the article are as follows: In section 2, we get the analytic equation of the EC based on computation related to the Hamiltonian of electron. We give the result of numberial calculation and discussion in section 3. Final section contains conclusions.

2 The Ettingshausen constant in the quantum well with parabolic potential under the influence of the confined acoustic phonons

We consider a QWPP: $V_{(z)} = m_e w_z^2 \frac{z^2}{2}$ (w_z is detention frequency characteristic QWPP). There exists an electromagnetic field with $\overrightarrow{B}$ be along the z-axis ($\overrightarrow{B} = (0, 0, B)$) and $\overrightarrow{E}_1$ be along the x-axis ($\overrightarrow{E}_1 = (E_1, 0, 0)$). In this case, movement of electron is limited to Oz. They can only move freely in the xOy plane with cyclotron frequency $w_c = \frac{eB}{m_e}$ and imply velocity $v_d = \frac{E_1}{B}$. Energy of an electron is quantized and receives intermittent values:

$$\varepsilon_{N,n}\left(\overrightarrow{p_y}\right) = \left(N + \frac{1}{2}\right)\hbar w_c + \left(n + \frac{1}{2}\right)\hbar w_z + \frac{m_e v_d^2}{2} - \hbar v_d \overrightarrow{p_y} \tag{2.1}$$

Here: $\overrightarrow{p_y}$ is the wave vector of electron in the y-direction. When QWPP is subjected to a laser radiation $\overrightarrow{E_0}(t) = \overrightarrow{E_0}\sin(\Omega t)$, Hamiltonian of the confined electron - confined acoustic phonon system can be expressed as:

$$\begin{gathered} H = \sum_{N,n,\overrightarrow{p_y}} \varepsilon_{N,n}\left(\overrightarrow{p_y} - \frac{e}{\hbar c}\overrightarrow{A}(t)\right) a^+_{N,n,\overrightarrow{p_y}} a_{N,n,\overrightarrow{p_y}} + \sum_{m,\overrightarrow{q_\perp}} \hbar w_{m,\overrightarrow{q_\perp}} b^+_{m,\overrightarrow{q_\perp}} b_{m,\overrightarrow{q_\perp}} \\ + \sum_{N,n,\overrightarrow{p_y}} \sum_{N',n'} \sum_{m,\overrightarrow{q_\perp}} D_{N,N',n,n',m}\left(\overrightarrow{q_\perp}\right) a^+_{N',n',\overrightarrow{p_y}+\overrightarrow{q_y}} a_{N,n,\overrightarrow{p_y}} \left(b^+_{m,-\overrightarrow{q_\perp}} + b_{m,\overrightarrow{q_\perp}}\right) \end{gathered} \tag{2.2}$$

Where: $a^+_{N',n',\overrightarrow{p_y}}, a_{N,n,\overrightarrow{p_y}}$ ($b^+_{m,\overrightarrow{q_\perp}}, b_{m,\overrightarrow{q_\perp}}$) are the creation and annihilation operators of electron (phonon)respectively; $\overrightarrow{A}(t)$ is the vector potential of laser field; $\hbar w_{m,\overrightarrow{q_\perp}}$ is the energy of an acoustic phonon with the wave vector $\overrightarrow{q_\perp} = \overrightarrow{q_x} + \overrightarrow{q_y}$; m is the detention index of the phonon. $\left|D_{N,N',n,n',m}\left(\overrightarrow{q_\perp}\right)\right|^2 = \left|C_m\left(\overrightarrow{q_\perp}\right)\right|^2 \left|I^m_{n,n'}\left(\pm\overrightarrow{q_z}\right)\right|^2 \left|J_{N,N'}(u)\right|^2$ with $\left|C_m\left(\overrightarrow{q_\perp}\right)\right|^2 = \frac{\hbar\xi^2\sqrt{q_\perp^2 + q_z^2}}{2\rho v_s V_0}$ is the confined electron - confined acoustic phonon interaction constant (ξ, ρ, v_s are the deformation potential constant, the mass density and the sound velocity respectively);$I^m_{n,n'}\left(\pm\overrightarrow{q_z}\right)$ is the electron form factor; $\left|J_{N,N'}(u)\right|^2 = \frac{N_{\min}!}{N_{\max}!} e^{-u} u^{N_{\max}-N_{\min}} \left[L^{N_{\max}-N_{\min}}_{N\min}(u)\right]^2$ with $L^{N'-N}_N(u)$ is the associated Laguerre polynomial.

The quantum kinetic equation of average number of electron is:

$$i\hbar \frac{\partial f_{N,n,\overrightarrow{p_y}}(t)}{\partial t} = \left\langle \left[a^+_{N,n,\overrightarrow{p_y}} a_{N,n,\overrightarrow{p_y}}, H\right] \right\rangle_t \tag{2.3}$$

with: $f_{N,n,\overrightarrow{p_y}}(t) = a^+_{N,n,\overrightarrow{p_y}} a_{N,n,\overrightarrow{q_y}}$. Using (2.2) for (2.3) then we performed transformations of operator algebra and obtained:

$$\begin{aligned} &\frac{\partial f_{N,n,\overrightarrow{p_y}}}{\partial t} + \left(e\overrightarrow{E_1} + \hbar w_c\left[\overrightarrow{p_y}, \overrightarrow{h}\right]\right) \frac{\partial f_{N,n,\overrightarrow{p_y}}}{\hbar\partial\overrightarrow{p_y}} = \\ &\quad = \frac{2\pi}{\hbar} \sum_{N',n',m,\overrightarrow{q_\perp}} \left|D_{N,N',n,n',m}\left(\overrightarrow{q_\perp}\right)\right|^2 \sum_{l=0} J_l^2\left(\frac{\lambda}{\Omega}\right) * \\ &\quad * \left\{ \left[f_{N',n',\overrightarrow{p_y}+\overrightarrow{q_y}}\left(N_{m,\overrightarrow{q_\perp}} + 1\right) - f_{N,n,\overrightarrow{p_y}} N_{m,\overrightarrow{q_\perp}}\right] * \right. \\ &\quad * \delta\left(\varepsilon_{N',n'}\left(\overrightarrow{p_y} + \overrightarrow{q_y}\right) - \varepsilon_{N,n}\left(\overrightarrow{p_y}\right) - \hbar w_{m,\overrightarrow{q_\perp}} + \hbar\Omega l\right) + \\ &\quad + \left[f_{N',n',\overrightarrow{p_y}-\overrightarrow{q_y}} N_{m,\overrightarrow{q_\perp}} - f_{N,n,\overrightarrow{p_y}}\left(N_{m,\overrightarrow{q_\perp}} + 1\right)\right] * \\ &\quad \left. * \delta\left(\varepsilon_{N',n'}\left(\overrightarrow{p_y} + \overrightarrow{q_y}\right) - \varepsilon_{N,n}\left(\overrightarrow{p_y}\right) - \hbar w_{m,\overrightarrow{q_\perp}} + \hbar\Omega l\right) \right\} \end{aligned} \tag{2.4}$$

In which, $N_{m,\overrightarrow{q_\perp}} = b^+_{m,\overrightarrow{q_\perp}} b_{m,\overrightarrow{q_\perp}}$ is the equilibrium distribution function of the phonon; $\lambda = \frac{eE_0\overrightarrow{q_y}}{m_e\Omega}$; $\overrightarrow{h} = \frac{\overrightarrow{H}}{H}$ is unit vector in the direction of magnetic field. The energy of acoustic phonon is small and be ignored. For simplicity, we limit to case of $l = 0, \pm 1$ and get close: $J_0^2\left(\frac{\lambda}{\Omega}\right) = 1 - \frac{1}{2}\left(\frac{\lambda}{\Omega}\right)^2$; $J_{\pm 1}^2 = \frac{1}{4}\left(\frac{\lambda}{\Omega}\right)^2$. We multiply both sides by (2.4) with $\frac{e}{m}\overrightarrow{p_y}\delta\left(\varepsilon - \varepsilon_{N,n}\left(\overrightarrow{p_y}\right)\right)$, then taking sum of N, n, and $\overrightarrow{p_y}$. We get following expression:

$$\frac{\overrightarrow{G}\left(\varepsilon\right)}{\tau\left(\varepsilon\right)} + w_c\left[\overrightarrow{h}, \overrightarrow{G}\left(\varepsilon\right)\right] = \overrightarrow{P}\left(\varepsilon\right) + \overrightarrow{Z}\left(\varepsilon\right) \tag{2.5}$$

In the above expression, we use symbols to replace complex equations. $\left[\overrightarrow{h}, \overrightarrow{G}\left(\varepsilon\right)\right]$ is directional multiplication of $\overrightarrow{h}$ and $\overrightarrow{G}\left(\varepsilon\right)$.

$$\overrightarrow{P}\left(\varepsilon\right) = -\frac{e}{m_e}\sum_{N,n,\overrightarrow{k_y}} \overrightarrow{k_y}\overrightarrow{F}\frac{\partial \overline{f}_{N,n,\overrightarrow{k_y}}}{\partial \overrightarrow{k_y}}\delta\left(\varepsilon - \varepsilon_{N,n}\left(\overrightarrow{k_y}\right)\right) \tag{2.6}$$

and

$$\begin{aligned}\overrightarrow{Z}\left(\varepsilon\right) = \tfrac{4\pi e}{m_e\hbar}\sum_{N',n',m,\overrightarrow{q_\perp}}\sum_{N,n,\overrightarrow{p_y}} \left|D_{N,N',n,n',m}\left(\overrightarrow{q_\perp}\right)\right|^2 N_{m,\overrightarrow{q_\perp}}\overrightarrow{p_y}\left(\overline{f}_{N',n',\overrightarrow{p_y}+\overrightarrow{q_y}} - \overline{f}_{N,n,\overrightarrow{p_y}}\right)\\ *\delta\left(\varepsilon - \varepsilon_{N,n}\left(\overrightarrow{p_y}\right)\right)\left\{\left[1 - \tfrac{1}{2}\left(\tfrac{\lambda}{\Omega}\right)^2\right]\delta\left(\varepsilon_{N',n'}\left(\overrightarrow{p_y} + \overrightarrow{q_y}\right) - \varepsilon_{N,n}\left(\overrightarrow{p_y}\right)\right)\right.\\ +\tfrac{1}{4}\left(\tfrac{\lambda}{\Omega}\right)^2\delta\left(\varepsilon_{N',n'}\left(\overrightarrow{p_y} + \overrightarrow{q_y}\right) - \varepsilon_{N,n}\left(\overrightarrow{p_y}\right) + \hbar\Omega\right)\\ \left. +\tfrac{1}{4}\left(\tfrac{\lambda}{\Omega}\right)^2\delta\left(\varepsilon_{N',n'}\left(\overrightarrow{p_y} + \overrightarrow{q_y}\right) - \varepsilon_{N,n}\left(\overrightarrow{p_y}\right) - \hbar\Omega\right)\right\}\end{aligned} \tag{2.7}$$

with τ is the momentum relaxation time and $\overrightarrow{F} = e\overrightarrow{E_1} - \nabla\varepsilon_F - \frac{\varepsilon-\varepsilon_F}{T}\nabla T$ (ε_F is the fermi energy of electron).

By solving the equation (2.5), we find out expression of individual current density:

$$\begin{aligned}\vec{G}\left(\varepsilon\right) = \tau\left(\varepsilon\right)\left[1 + w_c^2\tau^2\left(\varepsilon\right)\right]^{-1}\left\{\left[\vec{P}\left(\varepsilon\right) + \vec{Z}\left(\varepsilon\right)\right]\right.\\ \left. -w_c\tau\left(\varepsilon\right)\left(\left[\vec{h}, \vec{P}\left(\varepsilon\right)\right] + \left[\vec{h}, \vec{Z}\left(\varepsilon\right)\right]\right) + w_c^2\tau\left(\varepsilon\right)\left[\vec{P}\left(\varepsilon\right)\vec{h} + \vec{Z}\left(\varepsilon\right)\vec{h}\right]\vec{h}\right\}\end{aligned} \tag{2.8}$$

The total current density $\overrightarrow{J}$ and the thermal flux density $\overrightarrow{Q}$ are given by:

$$\overrightarrow{J} = \int_0^\infty \overrightarrow{G}\left(\varepsilon\right)d\varepsilon \tag{2.9}$$

and

$$\overrightarrow{Q} = \frac{1}{e}\int_0^\infty \left(\varepsilon - \varepsilon_F\right)\overrightarrow{G}\left(\varepsilon\right)d\varepsilon \tag{2.10}$$

In low temperature conditions, the electron gas in QW is completely degenerate. The equilibrium distribution function of electron is of the form: $f^0_{N,n,\overrightarrow{p_y}} = \theta\left(\varepsilon_F - \varepsilon_{N,n,\overrightarrow{p_y}}\right)$. The distribution function of electron is found in linear approximation by E_1:

$$f_{N,n,\overrightarrow{p_y}}\left(\varepsilon\right) = f^0_{N,n,\overrightarrow{p_y}} - \hbar\overrightarrow{p_y}\overrightarrow{\chi}\left(\varepsilon\left(\overrightarrow{p_y}\right)\right)\frac{\partial f^0_{N,n,\overrightarrow{p_y}}}{\partial\varepsilon\left(\overrightarrow{p_y}\right)} \tag{2.11}$$

Here:

$$\overrightarrow{\chi}(\varepsilon)=\frac{\tau(\varepsilon)}{m_e\left[1+w_c^2\tau^2(\varepsilon)\right]}\left\{\overrightarrow{F}(\varepsilon)-w_c\tau(\varepsilon)\left[\overrightarrow{h},\overrightarrow{F}(\varepsilon)\right]+w_c^2\tau^2(\varepsilon)\left(\overrightarrow{h},\left(\overrightarrow{h},\overrightarrow{F}(\varepsilon)\right)\right)\right\} \tag{2.12}$$

From expressions of the total current density and the thermal flux density achieved, comparing it to the writing: $J_i=\sigma_{im}E_{1n}+\beta_{im}\nabla T$ and $Q_i=\mu_{im}E_{1n}+\varphi_{im}\nabla T$, we obtain analytical expression of tensors: $\sigma_{im},\beta_{im},\mu_{im},\varphi_{im}$. Specifically:

$$\begin{aligned}\sigma_{im}&=\zeta\tfrac{e\tau(\varepsilon_F)}{1+w_c^2\tau^2(\varepsilon_F)}\left[\delta_{ij}-w_c\tau(\varepsilon_F)\lambda_{ijk}h_k+w_c^2\tau^2(\varepsilon_F)h_ih_j\right]\\&+(b_1+b_2)\tfrac{e}{m_e}\tfrac{\tau^2(\varepsilon_F)}{[1+w_c^2\tau^2(\varepsilon_F)]^2}\left[\delta_{ij}-w_c\tau(\varepsilon_F)\lambda_{ijk}h_k+w_c^2\tau^2(\varepsilon_F)h_ih_j\right]\\&*\left[\delta_{\ell n}-w_c\tau(\varepsilon_F)\lambda_{\ell mn}h_n+w_c^2\tau^2(\varepsilon_F)h_lh_m\right]\\&+b_3\tfrac{e}{m_e}\tfrac{\tau^2(\varepsilon_F+\hbar\Omega)}{[1+w_c^2\tau^2(\varepsilon_F+\hbar\Omega)]^2}\left[\delta_{ij}-w_c\tau(\varepsilon_F+\hbar\Omega)\lambda_{ijk}h_k+w_c^2\tau^2(\varepsilon_F+\hbar\Omega)h_ih_j\right]\\&*\left[\delta_{\ell n}-w_c\tau(\varepsilon_F+\hbar\Omega)\lambda_{\ell mn}h_n+w_c^2\tau^2(\varepsilon_F+\hbar\Omega)h_lh_m\right]\\&+b_4\tfrac{e}{m_e}\tfrac{\tau^2(\varepsilon_F-\hbar\Omega)}{[1+w_c^2\tau^2(\varepsilon_F-\hbar\Omega)]^2}\left[\delta_{ij}-w_c\tau(\varepsilon_F-\hbar\Omega)\lambda_{ijk}h_k+w_c^2\tau^2(\varepsilon_F-\hbar\Omega)h_ih_j\right]\\&*\left[\delta_{\ell n}-w_c\tau(\varepsilon_F-\hbar\Omega)\lambda_{\ell mn}h_n+w_c^2\tau^2(\varepsilon_F-\hbar\Omega)h_lh_m\right]\end{aligned} \tag{2.13}$$

$$\begin{aligned}\beta_{im}&=-b_3\tfrac{\hbar\Omega}{m_eT}\tfrac{\tau^2(\varepsilon_F+\hbar\Omega)}{[1+w_c^2\tau^2(\varepsilon_F+\hbar\Omega)]^2}\left[\delta_{ij}-w_c\tau(\varepsilon_F+\hbar\Omega)\lambda_{ijk}h_k+w_c^2\tau^2(\varepsilon_F+\hbar\Omega)h_ih_j\right]\\&*\left[\delta_{\ell n}-w_c\tau(\varepsilon_F+\hbar\Omega)\lambda_{\ell mn}h_n+w_c^2\tau^2(\varepsilon_F+\hbar\Omega)h_lh_m\right]\\&+b_4\tfrac{\hbar\Omega}{m_eT}\tfrac{\tau^2(\varepsilon_F-\hbar\Omega)}{[1+w_c^2\tau^2(\varepsilon_F-\hbar\Omega)]^2}\left[\delta_{ij}-w_c\tau(\varepsilon_F-\hbar\Omega)\lambda_{ijk}h_k+w_c^2\tau^2(\varepsilon_F-\hbar\Omega)h_ih_j\right]\\&*\left[\delta_{\ell n}-w_c\tau(\varepsilon_F-\hbar\Omega)\lambda_{\ell mn}h_n+w_c^2\tau^2(\varepsilon_F-\hbar\Omega)h_lh_m\right]\end{aligned} \tag{2.14}$$

$$\begin{aligned}\mu_{im}&=b_3\tfrac{\hbar\Omega}{m_e}\tfrac{\tau^2(\varepsilon_F+\hbar\Omega)}{[1+w_c^2\tau^2(\varepsilon_F+\hbar\Omega)]^2}\left[\delta_{ij}-w_c\tau(\varepsilon_F+\hbar\Omega)\lambda_{ijk}h_k+w_c^2\tau^2(\varepsilon_F+\hbar\Omega)h_ih_j\right]\\&*\left[\delta_{\ell n}-w_c\tau(\varepsilon_F+\hbar\Omega)\lambda_{\ell mn}h_n+w_c^2\tau^2(\varepsilon_F+\hbar\Omega)h_\ell h_m\right]\\&-b_4\tfrac{\hbar\Omega}{m_e}\tfrac{\tau^2(\varepsilon_F-\hbar\Omega)}{[1+w_c^2\tau^2(\varepsilon_F-\hbar\Omega)]^2}\left[\delta_{ij}-w_c\tau(\varepsilon_F-\hbar\Omega)\lambda_{ijk}h_k+w_c^2\tau^2(\varepsilon_F-\hbar\Omega)h_ih_j\right]\\&*\left[\delta_{\ell n}-w_c\tau(\varepsilon_F+\hbar\Omega)\lambda_{\ell mn}h_n+w_c^2\tau^2(\varepsilon_F+\hbar\Omega)h_\ell h_m\right]\end{aligned} \tag{2.15}$$

$$\begin{aligned}\varphi_{im}&=-b_3\tfrac{(\hbar\Omega)^2}{em_eT}\tfrac{\tau^2(\varepsilon_F+\hbar\Omega)}{[1+w_c^2\tau^2(\varepsilon_F+\hbar\Omega)]^2}\left[\delta_{ij}-w_c\tau(\varepsilon_F+\hbar\Omega)\lambda_{ijk}h_k+w_c^2\tau^2(\varepsilon_F+\hbar\Omega)h_ih_j\right]\\&*\left[\delta_{\ell n}-w_c\tau(\varepsilon_F+\hbar\Omega)\lambda_{\ell mn}h_n+w_c^2\tau^2(\varepsilon_F+\hbar\Omega)h_\ell h_m\right]\\&-b_4\tfrac{(\hbar\Omega)^2}{em_eT}\tfrac{\tau^2(\varepsilon_F-\hbar\Omega)}{[1+w_c^2\tau^2(\varepsilon_F-\hbar\Omega)]^2}\left[\delta_{ij}-w_c\tau(\varepsilon_F-\hbar\Omega)\lambda_{ijk}h_k+w_c^2\tau^2(\varepsilon_F-\hbar\Omega)h_ih_j\right]\\&*\left[\delta_{\ell n}-w_c\tau(\varepsilon_F+\hbar\Omega)\lambda_{\ell mn}h_n+w_c^2\tau^2(\varepsilon_F+\hbar\Omega)h_\ell h_m\right]\end{aligned} \tag{2.16}$$

Where: δ_{ij} is the Kronecker delta; λ_{ijk} is the antisymmetric Levi - Civita tensor.

$$b_1=\sum_{N,N'}\sum_{n,n',m}\kappa\left(\tfrac{B_1}{\gamma}\right)^2\left|J_{N,N'}(u_1)\right|^2;\ b_2=\sum_{N,N'}\sum_{n,n',m}\kappa\tfrac{\vartheta}{2}\left(\tfrac{B_1}{\gamma}\right)^4\left|J_{N,N'}(u_1)\right|^2$$

$$b_3=\sum_{N,N'}\sum_{n,n',m}\kappa\tfrac{\vartheta}{4}\left(\tfrac{B_1-\hbar\Omega}{\gamma}\right)^4\left|J_{N,N'}(u_2)\right|^2;\ b_4=\sum_{N,N'}\sum_{n,n',m}\kappa\tfrac{\vartheta}{4}\left(\tfrac{B_1+\hbar\Omega}{\gamma}\right)^4\left|J_{N,N'}(u_3)\right|^2$$

$$\zeta=\tfrac{eL_y}{2\pi m_e\gamma}(\varepsilon_{N,n}-\varepsilon_F);\ \vartheta=\tfrac{e^2E_0^2}{m_e^2\Omega^4};\ \gamma=\hbar v_d;\ \kappa=\tfrac{2AeL_y}{m_e\hbar^2\beta v_sV_0\gamma^3}\left|I_{n,n'}^m\right|^2(\varepsilon_{N,n}-\varepsilon_F)$$

$$\varepsilon_{N,n}=\left(N+\tfrac{1}{2}\right)\hbar w_c+\left(n+\tfrac{1}{2}\right)\hbar w_z+\tfrac{m_ev_d^2}{2};\ u_1=\tfrac{a_c^2B_1^2}{\gamma^2};\ u_2=\tfrac{a_c^2(B_1-\hbar\Omega)^2}{\gamma^2}$$

$$u_3=\tfrac{a_c^2(B_1+\hbar\Omega)^2}{\gamma^2};\ A=\tfrac{\hbar\xi^2}{2\rho v_s};\ \beta=\tfrac{1}{k_BT};\ B_1=(N'-N)\hbar w_c+(n'-n)\hbar w_z$$

The expression of the EC is given by:

$$EC=\frac{1}{H}\frac{\sigma_{xx}\mu_{xy}-\sigma_{xy}\mu_{xx}}{\sigma_{xx}\left[\beta_{xx}\mu_{xx}-\sigma_{xx}(\varphi_{xx}-K_L)\right]} \tag{2.17}$$

Above expressions show that the EC depends in a complicated way on characteristic quantities of EMW (the amplitude E_0 and the frequency Ω), the temperature, the magnetic field, and especially the m-quantum number being specific to the confined phonon. These dependencies will be clarified in section 3 when we study QWPP of GaAs/GaAsAl.

3 Numberial results and discussions

To get influence of the confined acoustic phonon on the EC in QWPP in the presence of EMW in detail, we consider the QWPP of GaAs/GaAsAl with the parameters: $m_e = 0.067m_0$ (m_0 is the mass of a free electron), $\xi = 13.5eV$, $\rho = 5.32gcm^{-1}$, $v_s = 5378ms^{-1}$, $\varepsilon_F = 50eV$, $\tau(\varepsilon_F) = 10^{-12}s$ and $L_y = 2nm$ [3].

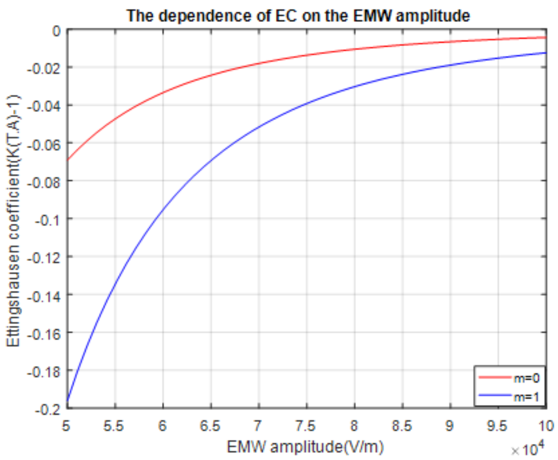

Figure 1

Fig.1 describes the dependence of EC on EMW amplitude in two cases: with and without confinement of acoustic phonon at $T = 10K$. The graph indicates that: the EC depends clearly on the EMW in low amplitude domain. The EC rises fast and linearly to reach the horizontal line in both cases to be considered in higher amplitude region. We realize that in the high EMW amplitude condition, the EC is almost unchanged when the EMW amplitude increases.

Besides, the EC has negative values when the phonon is free and even confined. These results are suitable for research about Ettingshausen effect in the same QWPP but not interested in the confined acoustic phonon [3].

Fig.2 describes the dependence of EC on the EMW frequency with $\Omega = 0 \div 10^{14}\,(Hz)$. This figure is investigated in the same conditions as above. As can be seen from the graph, the EC oscillates when the EMW frequency is less than $10^{14}\,(Hz)$. In this frequency range, both EC peak and EC peak position tend to downward. When the EMW frequency increases from 10^{14} to $1,8.10^{14}$ (Hz), the EC has the same value in both cases and be unchanged. If the frequency of the EMW continues to rise, the EC begins to decrease fast and reaches smaller values than the peak in small frequency region.

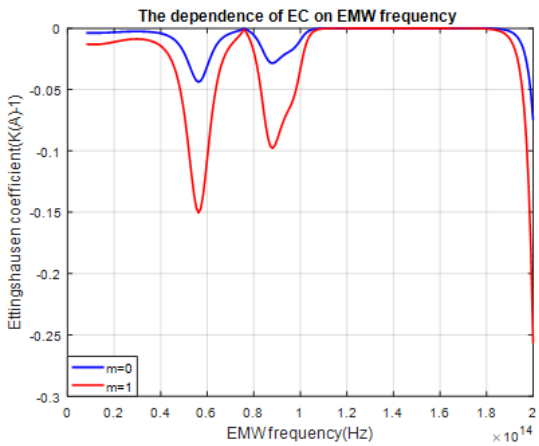

Figure 2

Meanwhile, the EC always increases when the EMW frequency increases in the same frequency domain as in electron - optical phonon interaction. Moreover, in the case of electron - acoustic phonon scattering, the EC has negative values. This result is completely opposite to case of electron - optical phonon scattering - the EC has positive values [4]. Thus, the scattering mechanism not only affects the value but also the variation of the EC under influence of EMW frequency change.

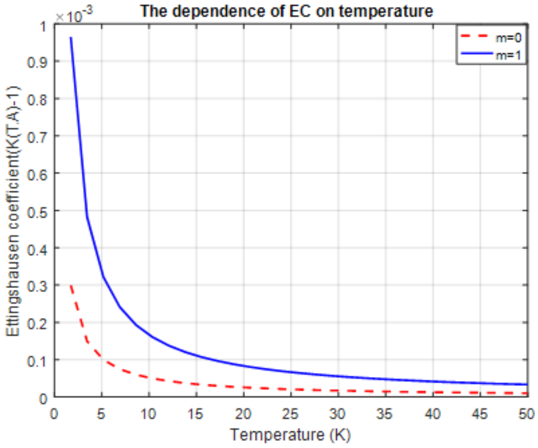

Figure 3

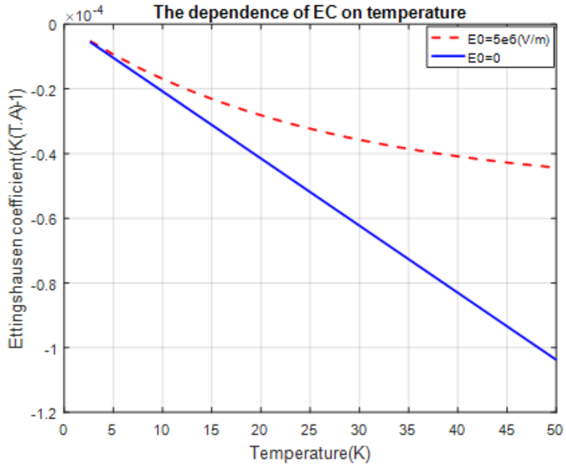

Figure 4

Both graphs were set in conditions of $B = 5T$ and $\Omega = 10^{10}Hz$. Fig.3 indicates that the EC decreases as the temperature increases. The value of the EC decreases very fast in small temperature domain (under 20K). When the temperature increases from 20 to 50 (K), the dependence of the EC in QWPP on the temperature is nearly linear. In both cases - with and without the confinement of phonon - the EC has negative values.

The presence of the electromagnetic field also influences on the EC. It is displayed clearly in the Fig.4. In the temperature domain investigated, the EC has greater values within the presence of the electromagnetic field and the confinement of acoustic phonon. However, the influence of electromagnetic field is weak and almost only causes change in the magnitude of the EC while temperature increases. Those are similar to the results obtained in the same QWPP in the case of unconfined acoustic phonon [3].

In the Fig.5, we can see oscillations of the EC when the magnetic field changes. The EC fluctuates strongly in region of magnetic field between 12(T) and 20(T). Both blue line (with the confinement of phonons) and red line (without the confinement of phonons) oscillate and reaches resonant point. It can be clearly seen that peaks of the blue line are taller than peaks of the red line at the same magnetic field point.

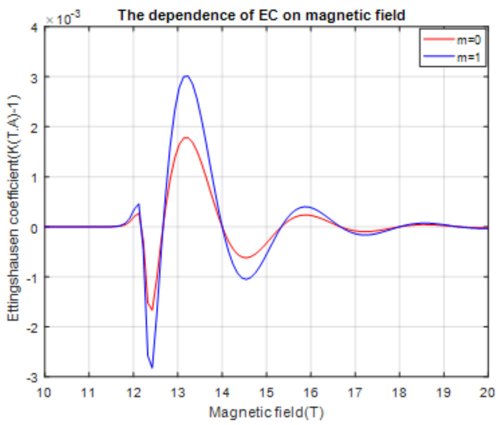

Figure 5

In both cases, the EC curve for the change of magnetic field has the same number of resonance peaks but the magnitude is different. It can be explained as follows: when acoustic phonons are confined, their wave vector are quantized. Both phonon's energy and interaction constant depend on quantum number m. Though, energy of confined acoustic phonon is considered small and ignored in computing. So, the resonance condition is not affected by m. The quantum number m only impacts to the electron form factor. That means the confinement of acoustic phonon don't affect the EC's changing law under increasing of magnetic field.

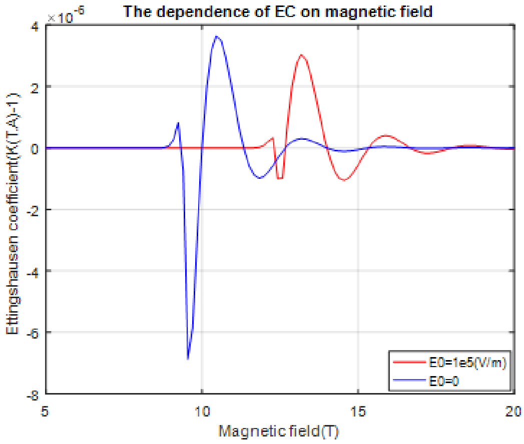

Figure 6

According to the magnetic field, existence of EMW also governs the EC's law of change. It is displayed in figure 6. E_0 appears in the argument of the Bessel function and not related to the resonance condition. So, E_0 exists or not leading to unchanged number of peaks. In comparison to the case of $E_0 = 10^5 V m^{-1}$(the red line), peaks of the blue line ($E_0 = 0$) sideways to the left and be taller. This is different from the case of unconfined acoustic phonon. Without confinement of phonon, the EC reaches the resonant points at the same magnetic field points and be sorter if E_0 is set to zero [3].

4 Conclusions

By using the quantum kinetic equation for electron with the presence of invariable electromagnetic field and EMW, in this paper, we have calculated the analytic expression of the EC, graphed the theoretical results for GaAs/GaAsAl QWPP and compared to the case of unconfined phonon. The achievements get show that the formula of EC depends on many factor, especially the quantum index m specific the confinement of phonon. All of numberial results indicate that the quantum number m have impacted to values of the EC. The EC values are greater when we carry out the survey within confined acoustic phonon. If m goes to zero, the results obtained come back to the case of unconfined phonon. Finally, we can assert that the confinement of acoustic phonon creates surprising changes of the EC in the QWPP. When quantities which the EC depends on are set to limited, we find out relevance to the previous researches published.

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