THE CALCULATION OF THE ETTINGSHAUSEN COEFICIENT IN QUANTUM WIRE UNDER THE INFLUENCE OF CONFINED PHONON (FOR ELECTRON – CONFINED OPTICAL PHONON SCATTERING)

Hoang Van Ngoc[1], Nguyen Vu Nhan[2], Tang Thi Dien[3],

Nguyen Thi Nguyet Anh[3], Nguyen Quang Bau[3].

[1]Thu Dau Mot University, [2]Ha Noi Metropolian University, [3]VNU University of Science

Abstract: *In this paper, we have used the method of quantum kinetic equation to calculate the analytic expression for Ettingshausen coefficient (EC) under the influence of confined phonon. We considered a quantum wire in the presence of constant electric field, magnetic field and electromagnetic wave (EMW) with assumption that electron – confined optical phonon (OP) scattering is essential. The EC obtained depends on many quantities in a complicated way such as temperature, magnetic field, frequency or amplitude of EMW and* m_1, m_2*- quantum number which specify confined OP. Numerical results for GaAs/GaAsAl quantum wire (CQW) have displayed clearly the differences in comparison with both cases of bulk semiconductor and unconfined phonon. The result of examining the EC's dependence on magnetic field shows that quantum number* m_1, m_2 *changes resonance condition;*m_1, m_2*not only makes the increase in the number of resonance peak but also changes the position of peaks. When* m_1, m_2 *is set to zero, we get the results that corresponds to unconfined OP.*

Keywords: *Confined optical phonon, Cylindrical Quantum Wire, Ettingshausen Effect, quantum kinetic equation.*

Received 23.12.2020; accepted for publication 25.1.2021

Email: nvnhan@daihocthudo.edu.vn

1. INTRODUCTION

Due to the confinement effect, the movement of electron and phonon is severely limited. This leads to changes in characteristics of quantum effects appeared in low-dimensional semiconductor systems (LDS), in particular one-dimensional systems [2].[3].[6].

The Ettingshausen effect has been studied in semiconductor [4] and quantum wire [2],[6]. Properties of this magneto-thermoelectric effect are different from bulk semiconductor [4] due to the confinement of the electrons. However, the confinement of phonons, in particular OP, has not been interested yet, especially in a cylindrycal quantum wire with an infinite potential.

In this work, we study the influence of confined OP on the EC in CQW The report is structured as follows: in section 2, we report the impact of confined OP on the EC in CQW; section 3 gives the numerial results and discussion for GaAs/GaAsAl QW; conclusions are shown in section 4.

2. CONTENT

2.1. The influence of confined phonons on the Ettingshausen coefficient in a cylindrycal quantum wire with an infinite potential

Consider a cylindrycal quantum wire with an infinite potential $V = \pi R^2 L$subjected is placed in a perpendicular magnetic field$\vec{B}$, a constant - electric field $\overrightarrow{E_1}$and an intense electromagnetic wave $\vec{E} = E_0 \, sin\, \Omega \, t$ Under the influence of the material confinement potential, the motion of carriers is restricted in x, y direction and free in the z one. So, the wave function of an electron and its discrete energy now becomes:

$$\psi_{n,l,\overrightarrow{p_z}} = \frac{1}{\sqrt{V_0}} e^{im\phi} e^{i\vec{p}_z z} \psi_{n,l}(r), \qquad (1)$$

where

$$\psi_{n,l}(r) = \frac{1}{J_{n+1}(B_{n+1})} J_n\left(B_{n,l}, \frac{r}{R}\right).$$

$$\varepsilon_{n,l}(\vec{p}_z) = \left(N + \frac{n}{2} + \frac{l}{2} + \frac{1}{2}\right)\hbar\omega_H + \frac{\hbar^2 \vec{p}_z^2}{2m} - \frac{1}{2m}\left(\frac{eE_1}{\omega_H}\right)^2, \qquad (2)$$

with $\vec{p}_z$ *m,* is the wave vector and the effective mass of an electron, R being the radius of the CQW, *n = 1,2,3,...* and $l = 0, \pm 1, \pm 2$ being the quantum numbers charactering the electron confinement, $\hbar$ is the Planck constant, $\omega_H = \frac{eB}{m}$is the cyclotron frequency.

When phonons are confined in CQW, the wave vector and frequency of them are given by [11,12]:

$$\vec{q}=\left(q_{m_1,m_2}\vec{q}_z\right), q_{m_1,m_2}=\frac{x_{m_1,m_2}}{R}, \omega^2_{m_1,m_2,\overrightarrow{q_z}}=\omega_0-\beta^2\left(q^2_{m_1,m_2}+\overrightarrow{q_z}\right) \quad (3)$$

Where β is the velocity parameter, m_1, m_2 = 1,2,3… being the quantum numbers charactering phonon confinement , Also, matrix element for confined electron – confined optical phonon interaction in the CQW now becomes:

$$D^{m_1,m_2}_{n_1,l_1,n_2,l_2}=C_{m_1,m_2,\vec{q}_z}I^{m_1,m_2}_{n_1,l_1,n_2,l_2},$$

where

$$|\,C_{m_1,m_2,\vec{q}_z}\,|^2=\frac{2\pi e^2\hbar\omega_0}{V_0\kappa}\left(\frac{1}{\chi_\infty}-\frac{1}{\chi_0}\right)\frac{1}{q^2_{m_1,m_2}+q_z^2} \quad (4)$$

$$I^{m_1,m_2}_{n_1,l_1,n_2,l_2}=\frac{2}{R^2}\int_0^R J_{|\,n_1-n_2\,|}(q,R)\varphi^*_{n_2,l_2}(r)\varphi_{n_1,l_1}(r)rdr, \quad (5)$$

here, χ_∞andχ_0 are the static and high frequency dielectric constants,κ electric constant.

After using the Hamiltonian of the confined electron-confined optical phonons system in a CQW in the second quantization presentation in E_1,B, E, we obtain the quantum kinetic equation for distribution function of electron, then we calculate the curent density and thermal flux density formula, we obtain the kinetic tensor $\sigma_{ik},\beta_{ik},\gamma_{ik},\zeta_{ik}$. We can have the expression of the EC:

$$P=\frac{1}{H}\frac{\sigma_{xx}\gamma_{xy}-\sigma_{xy}\gamma_{xx}}{\sigma_{xx}[\beta_{xx}\gamma_{xx}-\sigma_{xx}(\xi_{xx}-K_L)]},$$

where:

$$\sigma_{ij}=a\frac{\tau(\varepsilon_F)}{1+\omega_H^2\tau^2(\varepsilon_F)}\sum_{n,l}\left[\delta_{ik}+\omega_H\tau(\varepsilon_F)\varepsilon_{ikj}h_j+\omega_H^2\tau^2(\varepsilon_F)h_ih_k\right]+$$
$$b\sum_{n,l,n',l'}\sum_{m_1,m_2}\left|I^{m_1,m_2}_{n,l,n',l'}\right|^2\{(A_1+A_2)\frac{\tau(\varepsilon_F-\hbar\omega_0)}{1+\omega_H^2\tau(\varepsilon_F-\hbar\omega_0)^2}\left[\delta_{ik}+\omega_H\tau(\varepsilon_F-\hbar\omega_0)\varepsilon_{ikj}h_j+\right.$$
$$\left.+\omega_H^2\tau^2(\varepsilon_F-\hbar\omega_0)h_ih_k\right]+(A_3+A_4)\frac{\tau(\varepsilon_F+\hbar\omega_0)}{1+\omega_H^2\tau(\varepsilon_F+\hbar\omega_0)^2}\left[\delta_{ik}+\omega_H\tau(\varepsilon_F+\hbar\omega_0)\varepsilon_{ikj}h_j+\right.$$
$$\left.+\omega_H^2\tau^2(\varepsilon_F+\hbar\omega_0)^2h_ih_k\right]\}+c\sum_{n,l,n',l'}\sum_{m_1,m_2}\left|I^{m_1,m_2}_{n,l,n',l'}\right|^2\{A_5\frac{\tau(\varepsilon_F-\hbar\omega_0+\hbar\Omega)}{1+\omega_H^2\tau(\varepsilon_F-\hbar\omega_0+\hbar\Omega)^2}\left[\delta_{ik}+\right.$$
$$\left.+\omega_H\tau(\varepsilon_F-\hbar\omega_0+\hbar\Omega)\varepsilon_{ikj}h_j+\omega_H^2\tau^2(\varepsilon_F-\hbar\omega_0+\hbar\Omega)h_ih_k\right]A_6\frac{\tau(\varepsilon_F-\hbar\omega_0-\hbar\Omega)}{1+\omega_H^2\tau(\varepsilon_F-\hbar\omega_0-\hbar\Omega)^2}\left[\delta_{ik}+\right.$$
$$\left.+\omega_H\tau(\varepsilon_F-\hbar\omega_0-\hbar\Omega)\varepsilon_{ikj}h_j+\omega_H^2\tau^2(\varepsilon_F-\hbar\omega_0-\hbar\Omega)^2h_ih_k\right]+$$

$+A_7 \frac{\tau(\varepsilon_F+\hbar\omega_0-\hbar\Omega)}{1+\omega_H^2\tau(\varepsilon_F+\hbar\omega_0-\hbar\Omega)^2}\left[\delta_{ik}+\omega_H\tau(\varepsilon_F+\hbar\omega_0-\hbar\Omega)\varepsilon_{ikj}h_j+\omega_H^2\tau^2(\varepsilon_F+\hbar\omega_0-\right.$
$\left.-\hbar\Omega)^2h_ih_k\right]+A_8\frac{\tau(\varepsilon_F+\hbar\omega_0+\hbar\Omega)}{1+\omega_H^2\tau(\varepsilon_F+\hbar\omega_0+\hbar\Omega)^2}\left[\delta_{ik}+\omega_H\tau(\varepsilon_F+\hbar\omega_0+\hbar\Omega)\varepsilon_{ikj}h_j+\omega_H^2\tau^2(\varepsilon_F+\right.$
$\left.+\hbar\omega_0+\hbar\Omega)^2h_ih_k\right]\}$

$\beta_{ij}=b\sum_{n,l,n',l'}\sum_{m_1,m_2}\left|I_{n,l,n',l'}^{m_1,m_2}\right|^2\left\{\frac{\hbar\omega_0}{T}\{(A_1+A_2)\frac{\tau(\varepsilon_F-\hbar\omega_0)}{1+\omega_H^2\tau(\varepsilon_F-\hbar\omega_0)^2}\left[\delta_{ik}+\omega_H\tau(\varepsilon_F-\right.\right.$
$\left.-\hbar\omega_0)\varepsilon_{ikj}h_j+\omega_H^2\tau^2(\varepsilon_F-\hbar\omega_0)h_ih_k\right]-\frac{\hbar\omega_0}{T}(A_3+A_4)\frac{\tau(\varepsilon_F+\hbar\omega_0)}{1+\omega_H^2\tau(\varepsilon_F+\hbar\omega_0)^2}\left[\delta_{ik}+\omega_H\tau(\varepsilon_F+\right.$
$\left.+\hbar\omega_0)\varepsilon_{ikj}h_j+\omega_H^2\tau^2(\varepsilon_F+\hbar\omega_0)^2h_ih_k\right]\}\, c\sum_{n,l,n',l'}\sum_{m_1,m_2}\left|I_{n,l,n',l'}^{m_1,m_2}\right|^2\times$
$\times\left\{\frac{\hbar\omega_0-\hbar\Omega}{T}A_5\frac{\tau(\varepsilon_F-\hbar\omega_0+\hbar\Omega)}{1+\omega_H^2\tau(\varepsilon_F-\hbar\omega_0+\hbar\Omega)^2}\left[\delta_{ik}+\omega_H\tau(\varepsilon_F-\hbar\omega_0+\hbar\Omega)\varepsilon_{ikj}h_j+\omega_H^2\tau^2(\varepsilon_F-\hbar\omega_0+\right.\right.$
$\left.+\hbar\Omega)h_ih_k\right]\frac{\hbar\omega_0+\hbar\Omega}{T}A_6\frac{\tau(\varepsilon_F-\hbar\omega_0-\hbar\Omega)}{1+\omega_H^2\tau(\varepsilon_F-\hbar\omega_0-\hbar\Omega)^2}\left[\delta_{ik}++\omega_H\tau(\varepsilon_F-\hbar\omega_0-\hbar\Omega)\varepsilon_{ikj}h_j+\right.$
$\left.+\omega_H^2\tau^2(\varepsilon_F-\hbar\omega_0-\hbar\Omega)^2h_ih_k\right]-\frac{\hbar\omega_0+\hbar\Omega}{T}A_7\frac{\tau(\varepsilon_F+\hbar\omega_0-\hbar\Omega)}{1+\omega_H^2\tau(\varepsilon_F+\hbar\omega_0-\hbar\Omega)^2}\left[\delta_{ik}+\omega_H\tau(\varepsilon_F+\hbar\omega_0-\right.$
$\left.-\hbar\Omega)\varepsilon_{ikj}h_j+\omega_H^2\tau^2(\varepsilon_F+\hbar\omega_0-\hbar\Omega)^2h_ih_k\right]-\frac{\hbar\omega_0-\hbar\Omega}{T}A_8\frac{\tau(\varepsilon_F+\hbar\omega_0+\hbar\Omega)}{1+\omega_H^2\tau(\varepsilon_F+\hbar\omega_0+\hbar\Omega)^2}\left[\delta_{ik}+\right.$
$\left.+\omega_H\tau(\varepsilon_F+\hbar\omega_0+\hbar\Omega)\varepsilon_{ikj}h_j+\omega_H^2\tau^2(\varepsilon_F+\hbar\omega_0+\hbar\Omega)^2h_ih_k\right]\}$

$$\gamma_{ij}=-\frac{1}{e}\sigma_{ij}\varepsilon_F,\quad \xi_{ij}=\frac{1}{e}\beta_{ij}\varepsilon_F^2,$$

here: $\tau(\varepsilon_F)$ is the momentum relaxation time, δ_{ik} is the Kronecker delta, ε_{ikj} being the antisymmetric Levi- Civita tensor; the Latin symbol i,j,k stand for componments x,y,z of the Cartesian coordinates.

$$a=\frac{e^2\hbar^4LR^2}{8\pi^2m^3}\Delta_{n,l}^{\frac{3}{2}};$$

with

$$\Delta_{n,l}=\frac{2m}{\hbar^2}\left(\varepsilon_F+\frac{1}{2}\left(\frac{eE_1}{\omega_H}\right)^2\right)-\frac{2m\omega_H}{\hbar}\left(N+\frac{n}{2}+\frac{l}{2}+\frac{1}{2}\right);$$

$$x_1=\sqrt{\Delta_{n,l}};\ x_2=-\sqrt{\Delta_{n,l}}$$

$$b=\frac{e^3k_BT\hbar^4L}{48m^3\kappa\pi}\left(\frac{1}{\chi_\infty}-\frac{1}{\chi_0}\right);\ c=\frac{e^5k_B\hbar^4E_0^2}{192m^5\Omega^4\pi\kappa}\left(\frac{1}{\chi_\infty}-\frac{1}{\chi_0}\right)$$

$A_1=-\frac{x_1^2}{\sqrt{\Delta_{11}\Delta_{n,l}}}\left((c_1+d_1)\left(\frac{1}{c_1^2+q_{m_1,m_2}^2}+\frac{1}{d_1^2+q_{m_1,m_2}^2}-\frac{e^2E_0^4}{m^2\Omega^4}\right)\right)-\frac{x_2^2}{\sqrt{\Delta_{12}\Delta_{n,l}}}\left((c_2+\right.$
$\left.+d_2)\left(\frac{1}{c_2^2+q_{m_1,m_2}^2}+\frac{1}{d_2^2+q_{m_1,m_2}^2}-\frac{e^2E_0^4}{m^2\Omega^4}\right)\right)$

$$A_2 = \frac{1}{\sqrt{\Delta_{n',l'}\Delta_{I1}}}\left[y_1(y_1 - C_1)\left(\frac{1}{C_1^2+q_{m_1m_2}^2} - \frac{e^2E_0^4}{2m^2\Omega^4}\right) + y_1(y_1 - D_1)\left(\frac{1}{D_1^2+q_{m_1m_2}^2} - \frac{e^2E_0^4}{2m^2\Omega^4}\right)\right]$$

$$+\frac{1}{\sqrt{\Delta_{n',l'}\Delta_{I2}}}\left[y_2(y_2 - C_2)\left(\frac{1}{C_2^2+q_{m_1m_2}^2} - \frac{e^2E_0^4}{2m^2\Omega^4}\right) + y_2(y_2 - D_2)\left(\frac{1}{D_2^2+q_{m_1m_2}^2} - \frac{e^2E_0^4}{2m^2\Omega^4}\right)\right]$$

If $(c_1, d_1, c_2, d_2, \Delta_{11}, \Delta_{12})$ change to $(m_1, q_1, m_2, q_2, \Delta_{41}, \Delta_{42})$ then A_1becomes A_3 ;

If $(C_1, D_1, C_2, D_2, \Delta_{I1}, \Delta_{I2})$ change to $(M_1, Q_1, M_2, Q_2, \Delta_{IV1}, \Delta_{IV2})$ then A_2becomes A_4 ;

$$A_5 = \frac{x_1^2}{\sqrt{\Delta_{n,l}\Delta_{21}}}(g_1 + h_1) + \frac{x_2^2}{\sqrt{\Delta_{n,l}\Delta_{22}}}(g_2 + h_2) +$$

$$+\frac{1}{\sqrt{\Delta_{n',l'}\Delta_{II1}}}[y_1(y_1 - G_1) + y_1(y_1 - H_1)] + \frac{1}{\sqrt{\Delta_{n',l'}\Delta_{II2}}}[y_2(y_2 - G_2) + y_2(y_2 - H_2)]$$

- $(g_1, h_1, g_2, h_2, G_1, H_1, G_2, H_2, \Delta_{21}, \Delta_{22}, \Delta_{II1}, \Delta_{II2})$

change to $(a_1, b_1, a_2, b_2, A_1, B_1, A_2, B_2, \Delta_{31}, \Delta_{32}, \Delta_{III1}, \Delta_{III2})$ then A_5becomes A_6.

- $(g_1, h_1, g_2, h_2, G_1, H_1, G_2, H_2, \Delta_{21}, \Delta_{22}, \Delta_{II1}, \Delta_{II2}$

change to$(z_1, w_1, z_2, w_2, Z_1, W_1, Z_2, W_2, \Delta_{51}, \Delta_{52}, \Delta_{V1}, \Delta_{V2})$then A_5 becomes A_7.

- $(g_1, h_1, g_2, h_2, G_1, H_1, G_2, H_2, \Delta_{21}, \Delta_{22}, \Delta_{II1}, \Delta_{II2})$

change to $(v_1, t_1, v_2, t_2, V_1, T_1, V_2, T_2, \Delta_{61}, \Delta_{62}, \Delta_{VI1}, \Delta_{VI2})$ then A_5becomes A_8 .

$$\Delta_{11} = x_1^2 - \frac{2m}{\hbar}\left(\left(\frac{n' - n}{2} - \frac{l' - l}{2}\right)\omega_H - \omega_0\right); c_1 = x_1 + \sqrt{\Delta_{11}}; d_1 = x_1 - \sqrt{\Delta_{11}}$$

x_1 change to $x_2$then Δ_{11}, c_1, d_1becomes Δ_{12}, c_2, d_2

$$\Delta_{I1} = y_1^2 + \frac{2m}{\hbar}\left(\left(\frac{n'-n}{2} + \frac{l'-l}{2}\right)\omega_H - \omega_0\right); C_1 = y_1 + \sqrt{\Delta_{I1}}; D_1 = y_1 - \sqrt{\Delta_{I1}}$$

y_1 change to y_2, then Δ_{I1}, C_1, D_1becomes Δ_{I2}, C_2, D_2

$$\Delta_{21} = x_1^2 - \frac{2m}{\hbar}\left(\left(\frac{n' - n}{2} - \frac{l' - l}{2}\right)\omega_H - \omega_0 + \Omega\right); g_1 = x_1 + \sqrt{\Delta_{21}}; h_1 = x_1 - \sqrt{\Delta_{21}}$$

x_1 change to x_2 then Δ_{21}, g_1, h_1becomes Δ_{22}, g_2, h_2;

$$\Delta_{II1} = y_1^2 + \frac{2m}{\hbar}\left(\left(\frac{n'-n}{2} + \frac{l'-l}{2}\right)\omega_H - \omega_0 + \Omega\right); G_1 = y_1 + \sqrt{\Delta_{II1}}; H_1 = y_1 - \sqrt{\Delta_{II1}}$$

$y_1$change to y_2 then Δ_{II1}, G_1, H_1becomes Δ_{II2}, G_2, H_2

$\Delta_{31} = x_1^2 - \frac{2m}{\hbar}\left(\left(\frac{n^{'} - n}{2} - \frac{l^{'} - l}{2}\right)\omega_H - \omega_0 - \Omega\right); a_1 = x_1 + \sqrt{\Delta_{31}}; b_1 = x_1 - \sqrt{\Delta_{31}}$

$x_1$change to x_2 then Δ_{31}, a_1, b_1becomes Δ_{32}, a_2, b_2

$\Delta_{III1} = y_1^2 + \frac{2m}{\hbar}\left(\left(\frac{n' - n}{2} + \frac{l' - l}{2}\right)\omega_H - \omega_0 - \Omega\right); A_1 = y_1 + \sqrt{\Delta_{III1}}; B_1 = y_1 - \sqrt{\Delta_{III1}}$

$y_1$change to y_2 then Δ_{III1}, A_1, B_1 becomes Δ_{III2}, A_2, B_2;

$\Delta_{41} = x_1^2 - \frac{2m}{\hbar}\left(\left(\frac{n^{'} - n}{2} - \frac{l^{'} - l}{2}\right)\omega_H + \omega_0\right); m_1 = x_1 + \sqrt{\Delta_{41}};\ q_1 = x_1 - \sqrt{\Delta_{41}};$

x_1 change to x_2 then Δ_{41}, m_1, q_1 becomes Δ_{42}, m_2, q_2.

$\Delta_{IV1} = y_1^2 + \frac{2m}{\hbar}\left(\left(\frac{n' - n}{2} + \frac{l' - l}{2}\right)\omega_H + \omega_0\right);\ M_1 = y_1 + \sqrt{\Delta_{IV1}}; Q_1 = y_1 - \sqrt{\Delta_{IV1}}$

y_1 change to y_2, then Δ_{IV1}, M_1, Q_1 becomes Δ_{IV2}, M_2, Q_2.

$\Delta_{51} = x_1^2 - \frac{2m}{\hbar}\left(\left(\frac{n^{'} - n}{2} - \frac{l^{'} - l}{2}\right)\omega_H + \omega_0 - \Omega\right); z_1 = x_1 + \sqrt{\Delta_{51}}; w_1 = x_1 - \sqrt{\Delta_{51}}$

x_1 change to x_2, then Δ_{51}, z_1, w_1 become Δ_{52}, z_2, w_2.

$\Delta_{V1} = y_1^2 + \frac{2m}{\hbar}\left(\left(\frac{n' - n}{2} + \frac{l' - l}{2}\right)\omega_H + \omega_0 - \Omega\right); Z_1 = y_1 + \sqrt{\Delta_{V1}}; W_1 = y_1 - \sqrt{\Delta_{V1}};$

y_1 change to y_2,then Δ_{V1}, Z_1, W_1 becomes Δ_{V2}, Z_2, W_2

$\Delta_{61} = x_1^2 - \frac{2m}{\hbar}\left(\left(\frac{n^{'} - n}{2} - \frac{l^{'} - l}{2}\right)\omega_H + \omega_0 + \Omega\right); v_1 = x_1 + \sqrt{\Delta_{61}}; t_1 = x_1 - \sqrt{\Delta_{61}}$

x_1 change to x_2, then Δ_{61}, v_1, t_1 becomes Δ_{62}, v_2, t_2

$\Delta_{VI1} = y_1^2 + \frac{2m}{\hbar}\left(\left(\frac{n' - n}{2} + \frac{l' - l}{2}\right)\omega_H + \omega_0 + \Omega\right); V_1 = y_1 + \sqrt{\Delta_{VI1}}; T_1 = y_1 - \sqrt{\Delta_{VI1}}$

y_1 change to y_2, then Δ_{VI1}, V_1, T_1 becomes Δ_{VI2}, V_2, T_2,

here: $\kappa, \chi_\infty, \chi_0, \varepsilon_F$ L and k_B are the electric constant, the static dielectric constant, the high frequency dielectric constant, the Fermi level, normalization length and the Boltzmann constant, respectively. From these above expressions, we see that the EC expression in the CQW is more complicated than that in the bulk semiconductor. We also found that the difference in the energy spectrum, the wave function and the presence of electromagnetic waves which lead to this complexity. Moreover ,we see the EC dependent on the frequency

Ω and amplitude $E_0$of the laser radiation, temperature T of system and specially the quantum number m_1, m_2 charactering the phonon confined effect. In the next step, we study quantum wire of GaAs/GaAs:Al to see clearly the dependence mentioned above.

2.2. Numerical results and discussions.

In order to clarify the results that has been obtained, in this section, we numerically calculate the conductive tensors and Ettingshausen coefficient in a Cylindrical Quantum Wire subjected to the uniform crossed magnetic field and electric field in the presence of a strong EMW. For the numerical evaluation, we consider the Cylindrical Quantum Wire of GaAs/Al:GaAs with the parameters [6, 7]: $\varepsilon = \varepsilon_F = 50meV$, $E_d = 13.5eV$, $\rho = 5.32g.cm^{-3}$, $v_s = 5378m.s^{-1}$, $\chi_\infty = 10.9$, $\chi_0 = 12.9$, $\hbar\omega_o = 36.25meV$, $m^* = 0.067m_o$ (m_o is the mass of free electron), $\tau = 10^{-12}s$, $L = 10^{-9}m$.

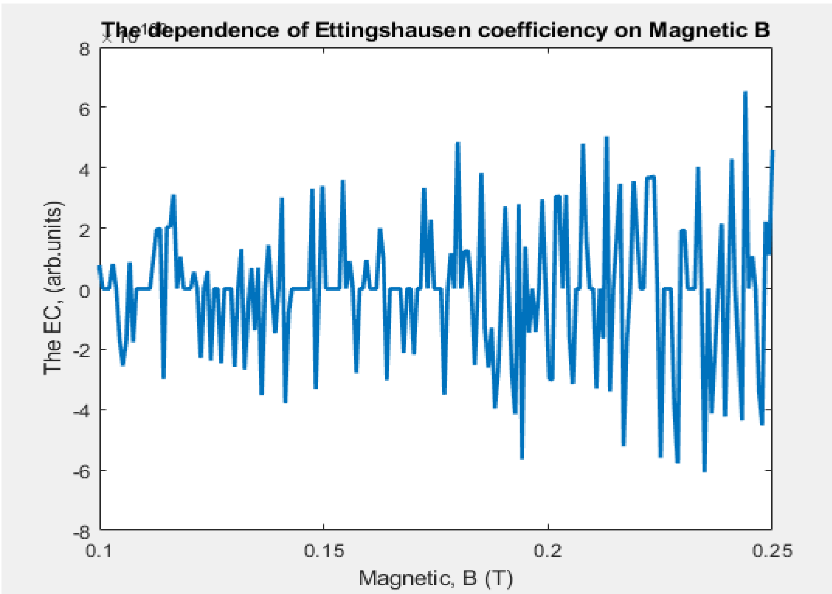

Fig. 1. *The dependence of EC on magnetic field with T=200K* ,$E_0 = 10^5(V.m^{-1})$

Figure 1 shows the dependence of the EC on the magnetic field with the presence of electronmagnetic waves and quantum numbers charactering optical phonon confinement $m_1 = m_2 = 1$, We see that the EC oscillates as the magnetic field increases when OP is confined. Due to the OP confinement, the number of resonance peaks enhance.

Figure 2 shows the dependence of the conductivity tensor σ_{xx} on the Laser frequency at different values of number m,n (characterizing the phonon confinement) . The value of Conductivity tensor σ_{xx} is the same in domain high laser frequency Ω ($\Omega \approx 9 \times 10^{13}$ Hz) with two case: confined and unconfined phonon, and it is very different in the $4.10^{13}Hz$ to $6.10^{13}Hz$ laser frequency domain, when the laser frequency has been valid small, which makes the oscillation of conductivity increase 2.3 times in comparsion with the case of the unconfined phonon. When the quantum number m,n goes to zero , the result it the same as in the case of unconfined phonon.

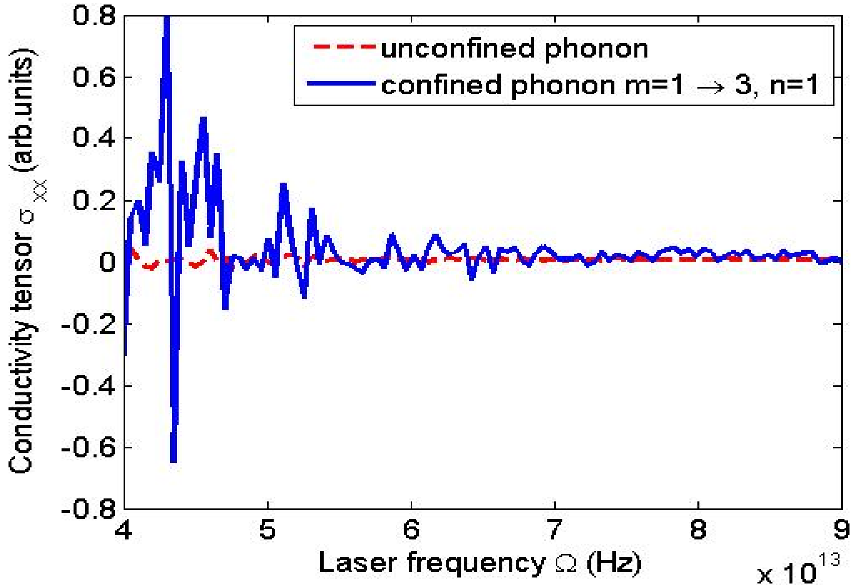

Figure 2. *The dependence of the conductivity tensor σ_{xx} on the Laser frequency*

3. CONCLUSION

By using quantum kinetic equation method, we have found out the analytic expressions for the conductivity tensors and the EC in CQW of GaAs/GaAsAl under the influence of confined OP. Due to significant contribution of the confined OP, theoretical results are different from the previous researches for Ettingshausen effect in CQW [2]. The more confinement effect of OP, the more resonance peaks of the EC appear. In other hand, We see that the EC oscillates as the magnetic field increases when OP is confined. Due to the OP confinement, the number of resonance peaks enhance. When we set quantum number *m and n* specific the OP confinement to zero, the results we get are fit to the case of unconfined OP. So far, the results obtained contribute to the theory of quantum effect in low - dimensional systems.

Acknowledgment

This work was completed with financial support from Thu Dau Mot University, Thu Dau Mot city, Viet Nam.

REFERENCES

1. D.T Hang, D.T. Ha, D.T.T. Thanh, N.Q. Bau (2016.), "The Ettringshausen coefficient in quantum wells under the influence of laser radiation in the case of the electron-optical phonon interaction", *PSP*, 8 (3): pp. 79-81.
2. N.Q . Bau, D.M. Quang, T.T. Hung (2019), "Magneto - thermoelectric Effect in Cylindrical Quantum Wire under the Influence of Electromagnetic Wave for Electron-optical Phonon Scattering", *VNU, journal of science: Mathematics - Physics*,lol. 35(4): pp. 116-123.
3. P.N. Thang, D.T. Long, N.Q. Bau, L.T. Hung (2019),"Influence of Confined Phonon on the Hall Coefficient in a Cylindrical Quantum Wire with an Infinite Potential (for Electron-acoustic Optical Phonon Scattering)", *VNU, journal of science: Mathematics - Physics,* vol. 35(3): pp. 46-51.
4. B.V Paranjape, J.S Levinger (1960), "Theory of the Ettringshausen effect in semiconductor", *Phys.ReV,* vol. 120(2): pp. 437-441.
5. N. T. L. Quynh, C. T. V. Ba, N. Q. Bau (2019), "The Caculation of the Ettingshausen Coefficient in Quantum Wells under the Influence of Confined Phonons (for Electron-confined Optical Phonon Scattering)", *VNUjournal of science: Mathematics - Physics,*vol. 35(2): pp. 67-73.
6. C. T. V. Ba, T. T. Hung, D. M. Quang, N. Q. Bau, (2017) "Calculation of the Ettingshausen Coefficient in a Rectangular Quantum Wire with an Infinite Potential in the Presence of an Electromagnetic Wave (the Electron-Optical Phonon Interaction)", *VNU journal of science: Mathematics - Physics*, vol. 33(4): pp. 17-23.

TÍNH HỆ SỐ ETTINGSHAUSEN TRONG DÂY LƯỢNG TỬ DƯỚI ẢNH HƯỞNG CỦA PHONON GIAM CẦM (CƠ CHẾ TÁN XẠ ĐIỆN TỬ-PHONON QUANG GIAM CẦM)

Tóm tắt: *Áp dụng phương pháp phương trình động học lượng tử để tính biểu thức giải tích hệ số Ettingshausen (EC) dưới ảnh hưởng của phonon giam cầm. Bài toán được nghiên cứu trong dây lượng tử với sự có mặt của điện trường, từ trường và sóng điện từ không đổi (EMW) với giả thiết tán xạ điện tử- phonon quang (OP) được coi là trội. EC thu được phụ thuộc phức tạp vào nhiều tham số đặc trưng như nhiệt độ, từ trường, tần số hoặc biên độ của EMW và số lượng tử* m_1, m_2 *đặc trưng cho sự giam cầm của OP. Kết quả tính số cho dây lượng tử GaAs/GaAsAl (CQW) cho thấy sự khác biệt so với cả hai trường hợp bán dẫn khối và dây lượng tử với phonon không bị giam cầm. Kết quả khảo sát sự phụ thuộc của EC vào từ trường đã chỉ ra số lượng tử* m_1, m_2*thay đổi điều kiện cộng hưởng, không chỉ làm tăng số lượng đỉnh cộng hưởng mà còn thay đổi vị trí của nó. Khi* m_1, m_2 *tiến tới 0, kết quả tương ứng với các kết quả trong trường hợp OP không giam cầm.*

Từ khóa: *Phonon quang giam cầm, dây lượng tử hình trụ, hiệu ứng Ettingshausen, phương trình động học lượng tử.*