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Original Article

Magneto–Thermoelectric Effects in Compositional Superlattice in the Presence of Electromagnetic Wave

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Abstract: This paper surveys the Ettingshausen coefficient (EC) in the compositional semiconductor superlattice (CSSL) under the influence of electromagnetic wave (EMW) by using the quantum kinetic equation for electrons. The analytical expressions of the Ettingshausen coefficient are numerically calculated for the GaAs/AlGaAs compositional semiconductor superlattice. The survey results show that the appearance of EMW changed the EC's value and the EC decreased nonlinearly when the temperature increased. The study of the dependence of EC on the magnetic field discovers that the superlattice period strongly affects the quantum magneto-thermoelectric effect. Accordingly, when the superlattice period is small, the quantum EC resonance peaks appear and when the superlattice period is large, resonance peaks disappear. The quantum theory of the magneto-thermoelectric effect was studied from low temperature to high temperature. The result overcomes the limitations of the Boltzmann kinetic equation which was studied at high temperatures. The results are new and can serve as a basis for further development of the theory of magneto-thermoelectric effects in low-dimensional semiconductor systems.

Keywords: Ettingshausen effect, quantum kinetic equation, compositional semiconductor superlattice, electromagnetic wave

1. Introduction

In recent years, semiconductor materials have been used extensively in electronic devices. This has led to a revolution in science and technology. Therefore, semiconductor materials have attracted much scientists' attention. A recent study of the semiconductor materials is about magneto-thermoelectric effects. The classical theory of Ettingshausen effect in bulk semiconductor was studied in [1] by the

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Boltzmann kinetic equation. When the temperature is bigger than $500^0 K$, the EC decreases. In contrast, when the temperature is smaller than $500^0 K$, the EC's maximum will appear depending on the structure of the material. However, the limitations of Boltzmann kinetic equation is that it has been only studied in the high-temperature domain, so [2] has studied the quantum Ettingshausen effect in the bulk semiconductor by the quantum kinetic equation to overcome this limitation. The results show the dependence of kinetic tensors and the EC on magnetic fields, electric fields, specific parameters in the bulk semiconductor. On the other hand, when the number of free-motion dimensions of the particle decreases, the physical properties of the system change significantly.According to the Hicks and Dresselhaus, [3] predicted that “the thermoelectric figure of merit for two-dimensional QWs and one-dimensional quantum wires should be substantially enhanced relative to the corresponding bulk materials”.The Ettingshausen effect of a two-dimensional electron gas has been theoretically researched within the framework of the Boltzmann kinetic equation for different mechanisms of electronic scattering taking into account phonon-grag contributions [4].In [4] if the magnetic field is parallel to the superlattice axis in the current, the Stark and cyclotron oscillations are independent. By applying to heat flux the situation changes, the above mentioned oscillations couple up and the possibility of Stark-cyclotron resonance appears. The Ettingshausen effect in quantum well with parabolic potential has been studied in [5]. The results showed that the Shubnikov-de Haas oscillations appeared by investigating the EC on magnetic field. The Hall effect in doped semiconductor superlattices under the influence of a laser radiation has been studied in [6]. The Shubnikov-de Haas oscillation has occurred as the dependence of the magnetoresistance on magnetic field was studied. The presence of laser radiation does not affect the value of the Hall coefficient but the phase of oscillation. [7] shows the dependence of the resistor in the compositional superlattice under the influence of electromagnetic waves. The Shubnikov-de Haas oscillations have appeared, however the superlattice structure affects strongly on the magneto resistivity (MR). As the thickness of GaN layers increases or the Al content in AlGaN layers decreases, the Shubnikov-de Haas oscillations become less evident and the MR tends to have the law observed in bulk semiconductors. Recent studies demonstrate that the magneto-thermoelectric effects are interested by many scientists. However, the problem of the Ettingshausen effect in the compositional superlattice in the presence of electromagnetic waves has not been studied yet. Therefore, in this paper, we used the quantum kinetic equation method to calculate the EC in the compositional superlattice under the influence of electromagnetic wave. The quantum theory of the magneto-thermoelectric effect has been studied from low temperature to high temperature. This result overcomes the limitations of the Boltzmann kinetic equation which was studied at high temperatures. We saw some differences between this case and the case of the bulk semiconductors. Numerical calculations are carried out with a specific GaAs/AlGaAs. The final section, then, gives conclusions.

2. Calculation of Ettingshausen coefficient in compositional superlattice in the presence of electromagnetic wave

Because of the accumulation of electrons on one side of the sample, the number of collisions increases and the heating of the material occurs, which called Ettingshausen effect. In this report, we used quantum kinetic equation to obtain the EC in CSSL in the presence of EMW.

We considered a CSSL is subjected to a magnetic field $\vec{B} = (0,0,B)$ and a static electric field $\vec{E}_1 = (E_1,0,0)$. If the specimen is subjected to an intense EMW with the electric field vector $\vec{E} = \left(0, E_0 \sin\Omega t, 0\right)$ (E_0 and Ω are the amplitude and frequency, respectively) so Hamiltonian of the electron-optical phonon in compositional superlatticein the second quantization presentation can be written as:

$$H=\sum_{N,n,\vec{k}_y}\varepsilon_{N,n,\vec{k}_y}\left(\vec{k}_y-\frac{e}{\hbar c}\vec{A}(t)\right)a^+_{N,n,\vec{k}_y}a_{N,n,\vec{k}_y}+\sum_{\vec{q}}\hbar\vec{\omega}_{\vec{q}}b^+_{\vec{q}}b_{\vec{q}}+\sum_{N,N'}\sum_{n,n'}\sum_{\vec{k}_y,\vec{q}}M_{M,n,N',n'}(\vec{q})\times$$
$$+a^+_{M',n',\vec{k}_y+\vec{q}_y}a_{N,n,\vec{k}_y}\left(b^+_{-\vec{q}}+b_{\vec{q}}\right),$$

where $\vec{A}(t)$ is the vector potential of laser field, $k_y\,(k_z)$ is the wave number in the y (z) - direction, $\hbar\omega_{\vec{q}}$ is the energy of an acoustic phonon with the ware vector $\vec{q}=(\vec{q}_\perp,q_z)$, $a^+_{N,n,\vec{k}_y}$ and $a_{N,n,\vec{k}_y}$ (b^+_q and b_q) are the creation and annihilation operators of electron (phonon), respectively.

$$\left|M_{M,n,N',n'}(\vec{q})\right|^2=\left|C_{\vec{q}}\right|^2\left|I_{n,n'}\left(k_z,k_z^{'},q_z\right)\right|^2\left|J_{N,N'}(s)\right|^2,$$

where $C_{\vec{q}}$ is the electron- optical phonon interaction constant. $I_{n,n'}\left(k_z,k_z^{'},q_z\right)$ is the form factor of electron, given by: $I_{n,n'}\left(k_z,k_z^{'},q_z\right)=\left\langle n,k_z\left|e^{\pm iq_z z}\right|n',\mathrm{k}_z^{'}\right\rangle$,

and $\left|J_{N,N'}(s)\right|^2=\left(\dfrac{N_{\min}!}{N_{\max}!}\right)e^{-u}s^{N_{\max}-N_{\min}}\left[L^{N_{\max}-N_{\min}}_{N_{\min}}(s)\right]^2,$

with

$N_{\min}=\min\{N,N'\},$

$N_{\max}=\max\{N,N'\},$

$L^N_M(x)$ is the associated Laguerre polynomials, $s=\dfrac{l_B^2\left(q_x^2+q_y^2\right)}{2}$

$$I_{n,n'}\left(k_z,k_z^{'},q_z\right)=\frac{1}{2}\frac{\sin\left\{\dfrac{\left[q_z\pm\left(k_n^{'}\pm k_n\right)\right]d_I}{2}\right\}}{\dfrac{\left[q_z\pm\left(k_n^{'}\pm k_n\right)\right]d_I}{2}}\exp\left\{\frac{\left[q_z\pm\left(k_n^{'}\pm k_n\right)\right]d_I}{2}\right\},$$

where $k_n=\left(2m_e\varepsilon_{n,k_z}/\hbar^2\right)^{\frac{1}{2}}$, $N,n=0,1,2,3...$, $l_B=\left(\dfrac{\hbar}{m_e\omega_H}\right)^{1/2}$. To simplify the calculation, we will consider only processes at the center and the boundary of the first mini-Brillouin zone, viz., we take $k_z=0$ and $k_z^{'}=\dfrac{\pi}{d}$. Where $d=d_I+d_{II}$ is the superlattice period. The quantum kinetic equation of average number of electron $n_{N,n,\vec{k}_y}=\left\langle a^+_{N,n,\vec{K}_y}a_{N,n,\vec{k}_y}\right\rangle$ is

$$i\hbar\frac{\partial\left\langle a^+_{N,n,\vec{k}_y}a_{N,n,\vec{k}_y}\right\rangle_t}{\partial t}=\left\langle\left[a^+_{N,n,\vec{k}_y}a_{N,n,\vec{k}_y},H\right]\right\rangle_t. \quad (1)$$

For simplicity, we limited the problem to case of $l=-1,0,1$. Let assume that $\vec{N}_{\vec{q}}+1\approx\vec{N}_{\vec{q}}$,

$$J_0^2(\alpha q_x) = 1 - \frac{(\alpha q_x)^2}{2}; J_{\pm 1}^2(\alpha q_x) = \frac{(\alpha q_x)^2}{4};\ \alpha = \hbar \upsilon_d,$$

where $\upsilon_d = E_1 / B$ is the drift velocity.

$$\frac{n_{N,n,k_y} - n^0_{N,n,k_y}}{\tau} + (e\vec{E}_1 + \hbar\omega_H[\vec{k}_y, \vec{h}]\frac{\partial \vec{n}_{N,n,\vec{K}_y}}{\hbar \partial \vec{k}_y} = \frac{2\pi}{\hbar}\sum_{N',n',\vec{q}} \left|M_{N,N',n,n'}\right|^2 \bar{N}_{\vec{q}} \left\{\frac{1}{4}\left(\frac{\lambda}{\Omega}\right)^2 \times \right.$$
$$\times\Big[\left(\bar{n}_{N',n',k_y+\vec{q}'_y} - \bar{n}_{N',n',k_y}\right)\delta\left(\varepsilon\left(\vec{k}_y + \vec{q}'_y\right) - \varepsilon\left(\vec{k}_y\right) - \hbar\omega_{\vec{q}} + \hbar\Omega\right) + \left(\bar{n}_{N',n',k_y-\vec{q}'_y} - \bar{n}_{N,n,k_y}\right)\times$$
$$\delta\left(\varepsilon\left(\vec{k}_y - \vec{q}'_y\right) - \varepsilon\left(\vec{k}_y\right) + \hbar\omega_{\vec{q}} + \hbar\Omega\right) + \frac{1}{4}\left(\frac{\lambda}{\Omega}\right)\Big[\left(\bar{n}_{N',n',k_y+\vec{q}'_y} - \bar{n}_{N,n,k_y}\right)\delta\left(\varepsilon\left(\vec{k}_y + \vec{q}'_y\right) - \right. \tag{2}$$
$$-\varepsilon\left(\vec{k}_y\right) - \hbar\omega_{\vec{q}} - \hbar\Omega\Big) + \left(\bar{n}_{N',n',k_y-\vec{q}'_y} - \bar{n}_{N,n,k_y}\right)\delta\left(\varepsilon\left(\vec{k}_y - \vec{q}'_y\right) - \varepsilon\left(\vec{k}_y\right) + \hbar\omega_{\vec{q}} - \hbar\Omega\right)\Big] +$$
$$+\left(1 - \frac{1}{2}\left(\frac{\lambda}{\Omega}\right)^2\right)\Big[\left(\bar{n}_{N',n',k_y-\vec{q}'_y} - \bar{n}_{N,n,k_y}\right)\delta\left(\varepsilon\left(\vec{k}_y - \vec{q}'_y\right) - \varepsilon\left(\vec{k}_y\right) - \hbar\omega_{\vec{q}}\right)\Big]\left(\bar{n}_{N',n',k_y-\vec{q}'_y} - \right.$$
$$\left. -\bar{n}_{N,n,k_y}\right)\delta\left(\varepsilon\left(\vec{k}_y - \vec{q}'_y\right) - \varepsilon\left(\vec{k}_y\right) + \hbar\omega_{\vec{q}}\right),$$

with $\lambda = \frac{eE_0 q_y}{m_e \Omega}$ .The current density $\vec{J}$ and thermal flux density $\vec{q}_e$ given by:

$$\vec{J} = \int_0^\infty \vec{R}(\varepsilon) d\varepsilon = \sigma_{im}\vec{E}_m + \beta_{im}\nabla_m T; \tag{3}$$

$$q_e = \frac{1}{e}\int_{-\infty}^{+\infty} (\varepsilon - \varepsilon_F) R(\varepsilon) = \gamma_{im}\vec{E}_m + \xi_{im}\nabla_m T. \tag{4}$$

The Ettingshausen coefficient:

$$P = \frac{1}{H}\frac{\sigma_{xx}\gamma_{xy} - \sigma_{xy}\gamma_{xx}}{\sigma_{xx}\left[\beta_{xx}\gamma_{xx} - \sigma_{xx}\left(\xi_{xx} - \kappa_L\right)\right]}, \tag{5}$$

with:

$$\sigma_{im} = a\frac{\tau(\varepsilon_F)}{1 + \omega_H^2\tau^2(\varepsilon_F)}Q + [g_1 + g_2]\frac{e\tau^2\left(C_1 - eE_1\overline{\Delta x}\right)}{m_e\left[1 + \omega_H^2\tau^2\left(C_1 - eE_1\overline{\Delta x}\right)\right]^2}D1_{ij}\delta_{ij}D1_{ij} +$$
$$+ g_3\frac{e\tau^2\left(C_1 - eE_1\overline{\Delta x} - \hbar\Omega\right)}{m_e\left[1 + \omega_H^2\tau^2\left(C_1 - eE_1\overline{\Delta x} - \hbar\Omega\right)\right]^2}D2_{ij}\delta_{ij}D2_{ij} + g_4 D3_{ij}\delta_{ij}D3_{ij}$$
$$\times\frac{e.\tau^2\left(C_1 - eE_1\overline{\Delta x} + \hbar\Omega\right)}{m_e\left[1 + \omega_H^2\tau^2\left(C_1 - eE_1\overline{\Delta x} + \hbar\Omega\right)\right]^2} + [g_5 + g_6]\frac{e\tau^2\left(C_2 - eE_1\overline{\Delta x}\right)}{m_e\left[1 + \omega_H^2\tau^2\left(C_{20} - eE_1\overline{\Delta x}\right)\right]^2} \tag{6}$$
$$\times D4_{ij}\delta_{ij}D4_{ij} + g_7\frac{e\tau^2\left(C_2 - eE_1\overline{\Delta x} - \hbar\Omega\right)}{m_e\left[1 + \omega_H^2\tau^2\left(C_2 - eE_1\overline{\Delta x} - \hbar\Omega\right)\right]^2}D5_{ij}\delta_{ij}D5_{ij}$$
$$+ g_8\frac{e.\tau^2\left(C_2 - eE_1\overline{\Delta x} + \hbar\Omega\right)}{m_e\left[1 + \omega_H^2\tau^2\left(C_2 - eE_1\overline{\Delta x} + \hbar\Omega\right)\right]^2}D6_{ij}\delta_{ij}D6_{ij},$$

$$\beta_{im} == -\left[g_2 + g_1\right]\left(C_1 - eE_1\overline{\Delta x} - \varepsilon_F\right)\frac{e\tau^2\left(C_1 - eE_1\overline{\Delta x}\right)}{m_e\left[1+\omega_H^2\tau^2\left(C_1 - eE_1\overline{\Delta x}\right)\right]^2} D1_{ij}\,\delta_{ij}\,D1_{ij}$$

$$-g_3\left(C_1 - eE_1\overline{\Delta x} - \hbar\Omega - \varepsilon_F\right)\frac{e\tau^2\left(C_1 - eE_1\overline{\Delta x} - \hbar\Omega\right)}{m_eT\left[1+\omega_H^2\tau^2\left(C_1 - eE_1\overline{\Delta x} - \hbar\Omega\right)\right]^2} D2_{ij}\,\delta_{ij}\,D2_{ij}$$

$$-g_4\left(C_1 - eE_1\overline{\Delta x} + \hbar\Omega - \varepsilon_F\right)\frac{e.\tau^2\left(C_1 - eE_1\overline{\Delta x} + \hbar\Omega\right)}{mT\left[1+\omega_H^2\tau^2\left(C_1 - eE_1\overline{\Delta x} + \hbar\Omega\right)\right]^2} D3_{ij}\,\delta_{ij}\,D3_{ij}$$

$$-\left[g_5 + g_6\right]\left(C_2 - eE_1\overline{\Delta x} - \varepsilon_F\right)\frac{e\tau^2\left(C_2 - eE_1\overline{\Delta x}\right)}{m_eT\left[1+\omega_H^2\tau^2\left(C_2 - eE_1\overline{\Delta x}\right)\right]^2} D4_{ij}\,\delta_{ij}\,D4_{ij}$$

$$-g_7\left(C_2 - eE_1\overline{\Delta x} - \hbar\Omega - \varepsilon_F\right)\frac{e\tau^2\left(C_2 - eE_1\overline{\Delta x} - \hbar\Omega\right)}{m_eT\left[1+\omega_H^2\tau^2\left(C_2 - eE_1\overline{\Delta x} - \hbar\Omega\right)\right]^2} D5_{ij}\,\delta_{ij}\,D5_{ij}$$

$$-g_8\left(C_2 - eE_1\overline{\Delta x} + \hbar\Omega - \varepsilon_F\right)\frac{e.\tau^2\left(C_2 - eE_1\overline{\Delta x} + \hbar\Omega\right)}{m_eT\left[1+\omega_H^2\tau^2\left(C_2 - eE_1\overline{\Delta x} + \hbar\Omega\right)\right]^2} D6_{ij}\,\delta_{ij}\,D6_{ij}, \quad (7)$$

$$\gamma_{im} = \left[g_1 + g_2\right]\left(C_1 - eE_1\overline{\Delta x} - \varepsilon_F\right)\frac{\tau^2\left(C_1 - eE_1\overline{\Delta x}\right)}{m_e\left[1+\omega_H^2\tau^2\left(C_1 - eE_1\overline{\Delta x}\right)\right]^2} D1_{ij}\,\delta_{ij}\,D1_{ij}$$

$$+g_3\left(C_1 - eE_1\overline{\Delta x} - \hbar\Omega - \varepsilon_F\right)\frac{\tau^2\left(C_1 - eE_1\overline{\Delta x} - \hbar\Omega\right)}{m_e\left[1+\omega_H^2\tau^2\left(C_1 - eE_1\overline{\Delta x} - \hbar\Omega\right)\right]^2} D2_{ij}\,\delta_{ij}\,D2_{ij}$$

$$+g_4\left(C_1 - eE_1\overline{\Delta x} + \hbar\Omega - \varepsilon_F\right)\frac{\tau^2\left(C_1 - eE_1\overline{\Delta x} + \hbar\Omega\right)}{m_e\left[1+\omega_H^2\tau^2\left(C_1 - eE_1\overline{\Delta x} + \hbar\Omega\right)\right]^2} D3_{ij}\,\delta_{ij}\,D3_{ij}$$

$$+\left[g_5 + g_6\right]\left(C_2 - eE_1\overline{\Delta x} - \varepsilon_F\right)\frac{\tau^2\left(C_2 - eE_1\overline{\Delta x}\right)}{m_e\left[1+\omega_H^2\tau^2\left(C_2 - eE_1\overline{\Delta x}\right)\right]^2} D4_{ij}\,\delta_{ij}\,D4_{ij}$$

$$+g_7\left(C_2 - eE_1\overline{\Delta x} - \hbar\Omega - \varepsilon_F\right)\frac{\tau^2\left(C_2 - eE_1\overline{\Delta x} - \hbar\Omega\right)}{m_e\left[1+\omega_H^2\tau^2\left(C_2 - eE_1\overline{\Delta x} - \hbar\Omega\right)\right]^2} D5_{ij}\,\delta_{ij}\,D5_{ij}$$

$$+g_8\left(C_2 - eE_1\overline{\Delta x} + \hbar\Omega - \varepsilon_F\right)\frac{\tau^2\left(C_2 - eE_1\overline{\Delta x} + \hbar\Omega\right)}{m_e\left[1+\omega_H^2\tau^2\left(C_2 - eE_1\overline{\Delta x} + \hbar\Omega\right)\right]^2} D6_{ij}\,\delta_{ij}\,D6_{ij}, \quad (8)$$

$$\zeta_{im} = -\left[g_1 + g_2\right]\left(C_1 - eE_1\overline{\Delta x} - \varepsilon_F\right)^2 \frac{\tau^2\left(C_1 - eE_1\overline{\Delta x}\right)}{m_eT\left[1+\omega_H^2\tau^2\left(C_1 - eE_1\overline{\Delta x}\right)\right]^2} D1_{ij}\,\delta_{ij}\,D1_{ij}$$

$$-g_3 \frac{\tau^2\left(C_1 - eE_1\overline{\Delta x} - \hbar\Omega\right)}{m_eT\left[1+\omega_H^2\tau^2\left(C_1 - eE_1\overline{\Delta x} - \hbar\Omega\right)\right]^2}\left(C_1 - eE_1\overline{\Delta x} - \hbar\Omega - \varepsilon_F\right)^2 D2_{ij}\,\delta_{ij}\,D2_{ij}$$

$$-g_4\left(C_1 - eE_1\overline{\Delta x} + \hbar\Omega - \varepsilon_F\right)^2 \frac{\tau^2\left(C_1 - eE_1\overline{\Delta x} + \hbar\Omega\right)}{m_eT\left[1+\omega_H^2\tau^2\left(C_1 - eE_1\overline{\Delta x} + \hbar\Omega\right)\right]^2} D3_{ij}\,\delta_{ij}\,D3_{ij}$$

$$-\left[g_5 + g_6\right]\left(C_2 - eE_1\overline{\Delta x} - \varepsilon_F\right)^2 \frac{\tau^2\left(C_2 - eE_1\overline{\Delta x}\right)}{m_eT\left[1+\omega_H^2\tau^2\left(C_2 - eE_1\overline{\Delta x}\right)\right]^2} D4_{ij}\,\delta_{ij}\,D4_{ij}$$

$$-g_7 \frac{\tau^2\left(C_2 - eE_1\overline{\Delta x} - \hbar\Omega\right)}{m_eT\left[1+\omega_H^2\tau^2\left(C_2 - eE_1\overline{\Delta x} - \hbar\Omega\right)\right]^2}\left(C_2 - eE_1\overline{\Delta x} - \hbar\Omega - \varepsilon_F\right)^2 D5_{ij}\,\delta_{ij}\,D5_{ij}$$

$$-g_8\left(C_2 - eE_1\overline{\Delta x} + \hbar\Omega - \varepsilon_F\right)^2 \frac{\tau^2\left(C_2 - eE_1\overline{\Delta x} + \hbar\Omega\right)}{m_eT\left[1+\omega_H^2\tau^2\left(C_2 - eE_1\overline{\Delta x} + \hbar\Omega\right)\right]^2} D6_{ij}\,\delta_{ij}\,D6_{ij}, \quad (9)$$

where δ_{ik} is the Kronecker delta, ε_{ijk} being the antisymmetric Levi–Civita tensor. $\omega_H = \frac{eB}{m_e}$ is the cyclotron frequency in which e is the charge of a conduction electron and m_e is its effective mass. L_y, ε_F and n_0 are normalization length in the y –direction, the Fermi-level and the electron density, respectively. k_B is the Boltzmann constant,

$$Q = \left[\delta_{ij} - \omega_H\tau(\varepsilon_F)\varepsilon_{ijk}h_k + \omega_H^2\tau^2(\varepsilon_F)h_ih_j\right],$$

$$a = -\frac{\hbar\upsilon_d L_y I}{2\pi m_e k_B T}\sum_{N,n} e^{\frac{1}{k_BT}}\left(\varepsilon_F - \varepsilon_{N,n}\right),$$

$$I = \frac{L_x}{2l_B^2}\left(\frac{\hbar\upsilon_d}{k_BT}\right)^{-1}\left[\exp\left(\frac{L_x}{2l_B^2}\frac{\hbar\upsilon_d}{k_BT}\right) + \exp\left(-\frac{L_x}{2l_B^2}\frac{\hbar\upsilon_d}{k_BT}\right)\right] - \left(\frac{\hbar\upsilon_d}{k_BT}\right)^{-2}\left[\exp\left(\frac{L_x}{2l_B^2}\frac{\hbar\upsilon_d}{k_BT}\right) + \exp\left(-\frac{L_x}{2l_B^2}\frac{\hbar\upsilon_d}{k_BT}\right)\right],$$

$$D1_{xy} = \left[\delta_{xy} - \omega_H\tau\left(C_1 - eE_1\overline{\Delta x}\right)\varepsilon_{xyz}h_z + \omega_H^2\tau^2\left(C_1 - eE_1\overline{\Delta x}\right)h_xh_y\right],$$

$$D2_{xy} = \left[\delta_{xy} - \omega_H\tau\left(C_1 - eE_1\overline{\Delta x} - \hbar\Omega\right)\varepsilon_{xyz}h_z + \omega_H^2\tau^2\left(C_1 - eE_1\overline{\Delta x} - \hbar\Omega\right)h_xh_y\right],$$

$$D3_{xy} = \left[\delta_{xy} - \omega_H\tau\left(C_1 - eE_1\overline{\Delta x} + \hbar\Omega\right)\varepsilon_{xyz}h_z + \omega_H^2\tau^2\left(C_1 - eE_1\overline{\Delta x} + \hbar\Omega\right)h_xh_y\right],$$

$$D4_{xy} = \left[\delta_{xy} - \omega_H\tau\left(C_2 - eE_1\overline{\Delta x}\right)\varepsilon_{xyz}h_z + \omega_H^2\tau^2\left(C_2 - eE_1\overline{\Delta x}\right)h_xh_y\right],$$

$$D5_{xy} = \left[\delta_{xy} - \omega_H\tau\left(C_2 - eE_1\overline{\Delta x} - \hbar\Omega\right)\varepsilon_{xyz}h_z + \omega_H^2\tau^2\left(C_2 - eE_1\overline{\Delta x} - \hbar\Omega\right)h_xh_y\right],$$

$$D6_{xy} = \left[\delta_{xy} - \omega_H \tau \left(C_2 - eE_1 \overline{\Delta x} + \hbar\Omega \right) \varepsilon_{xyz} h_z + \omega_H^2 \tau^2 \left(C_2 - eE_1 \overline{\Delta x} + \hbar\Omega \right) h_x h_y \right],$$

$$\overline{\Delta x} = \left(\sqrt{N + \frac{1}{2}} + \sqrt{N + 1 + \frac{1}{2}} \right) \frac{l_B}{2},$$

$$T_1 = \left(N' - N \right) \hbar\omega_H + \varepsilon_{n', \frac{\pi}{d}} - \varepsilon_{n,0} - \hbar\omega_0 - eE_1 \overline{\Delta x},$$

$$g_1 = \frac{eB\overline{\Delta x}}{M\hbar} e^{\beta(\varepsilon_F - \varepsilon_{N,n})} \left[\frac{(N+M)!}{N!} \right]^2 \delta(T_1), M = |N - N'| = 1,2,3...,$$

$$C_1 = \left(N' - N \right) \hbar\omega_H + \varepsilon_{n', \frac{\pi}{d}} - \varepsilon_{n,0} - \hbar\omega_0,$$

$$C_2 = \left(N' - N \right) \hbar\omega_H + \varepsilon_{n', \frac{\pi}{d}} - \varepsilon_{n,0} + \hbar\omega_0,$$

$$g_2 = -\frac{\theta}{2} \left(\frac{eB\overline{\Delta x}}{\hbar} \right)^2 e^{\beta(\varepsilon_F - \varepsilon_{N,n})} \left[\frac{(N+M)!}{N!} \right]^2 \delta(T_1),$$

$$g_3 = \frac{\theta}{4M} \left(\frac{eB\overline{\Delta x}}{\hbar} \right)^3 e^{\beta(\varepsilon_F - \varepsilon_{N,n})} \left[\frac{(N+M)!}{N!} \right]^2 \delta(T_1 + \hbar\Omega),$$

$$g_4 = \frac{\theta}{4M} \left(\frac{eB\overline{\Delta x}}{\hbar} \right)^3 e^{\beta(\varepsilon_F - \varepsilon_{N,n})} \left[\frac{(N+M)!}{N!} \right]^2 \delta(T_1 - \hbar\Omega),$$

$$T_2 = \left(N' - N \right) \hbar\omega_H + \varepsilon_{n', \frac{\pi}{d}} - \varepsilon_{n,0} - \hbar\omega_0 + eE_1 \overline{\Delta x},$$

$$g_5 = \frac{1}{M} \left(\frac{eB\overline{\Delta x}}{\hbar} \right) e^{\beta(\varepsilon_F - \varepsilon_{N,n})} \left[\frac{(N+M)!}{N!} \right]^2 \delta(T_2),$$

$$g_6 = -\frac{\theta}{2} \left(\frac{eB\overline{\Delta x}}{\hbar} \right)^2 e^{\beta(\varepsilon_F - \varepsilon_{N,n})} \left[\frac{(N+M)!}{N!} \right]^2 \delta(T_2),$$

$$g_7 = \frac{\theta}{4M} \left(\frac{eB\overline{\Delta x}}{\hbar} \right)^3 e^{\beta(\varepsilon_F - \varepsilon_{N,n})} \left[\frac{(N+M)!}{N!} \right]^2 \delta(T_2 + \hbar\Omega),$$

$$g_8 = \frac{\theta}{4M} \left(\frac{eB\overline{\Delta x}}{\hbar} \right)^3 e^{\beta(\varepsilon_F - \varepsilon_{N,n})} \left[\frac{(N+M)!}{N!} \right]^2 \delta(T_2 - \hbar\Omega).$$

Replacing kinetic tensors into Eq (5), we obtained the expression of EC in the CSSL. The results revealed that the EC is not only dependent on the specific characteristics of the CSSL, the EMW (frequency, amplitude) but also on the magnetic field $\vec{B}$, electric field $\vec{E}_1$. The results are completely different from the case in the bulk semiconductors [1]. The analytical expression of the EC in CSSL become more complex than that in quantum well. The presence of the EMW, the structure and the energy spectrum of CSSL caused this result. In the following, we will give a deeper insight to this analytical result by carrying out a numerical evaluation and a graphic consideration.

3. Numerical results and discussion

In this section, we carried out detail numerical calculations of the EC in a specific compostional semiconductor superlatices, in the cases of absence and presence of the electromagnetic wave. For this purpose, we considerGaAs/AlGaAswith the parameters [8, 9]: $\varepsilon_F = 50 meV$, $\chi_\infty = 10{,}9$, $\chi_0 = 12.9$, $\hbar\omega_0 = 36.25 meV$, $m_e = 0.067 \times m_0$ (m_0 is the mass of a free electron), $\tau = 10^{-12}\, s$ and $L_x = L_y = 100 nm$.

The figure 1 shows that the dependence of EC in CSSL on magnetic field with different values of the layer GaAs's thickness. The results show that Shubnikov-de Haas oscillations no longer appear like the electron–acoustic phonon interaction in quantum well [5] because of the remarkable contribution of the confined potential of CSSL and the electron-phonon interaction in CSSL. The graph shows that the resonance peaks have appeared. However, the number of resonance peaks mainly depends on the thickness of the layer GaAs. In particular, the number of resonance peaks increases when the thickness d_I or d_{II} reduces. That means the smaller the superlattice period is, the stronger the confined electron is and the quantum effect by reducing size becomes more apparent. When the superlattice period is very large, the quantum size effect is small so the resonance peaks gradually disappear.

The figure 2 shows the dependence of EC on temperature with $T = 200 \div 300 K$. It can be clearly seen that the EC decreases nonlinear with increasing temperature. The outcomes show that the EC decreases sharply in the range $200K \div 230K$ and the same in the range $> 230K$. This result is the same with the empirical results for the EC in p-type germanium with resistivities $30\ ohm - cm$ studied in [10]. Comparing to EC in the quantum well [11], the EC in CSSL is larger than that in the quantum well. This result is due to the difference in energy spectrum and the wave function of the material. On the other hand, the presence of EMW makes increases the intensity of the EC in comparison to the case the absence of EMW.

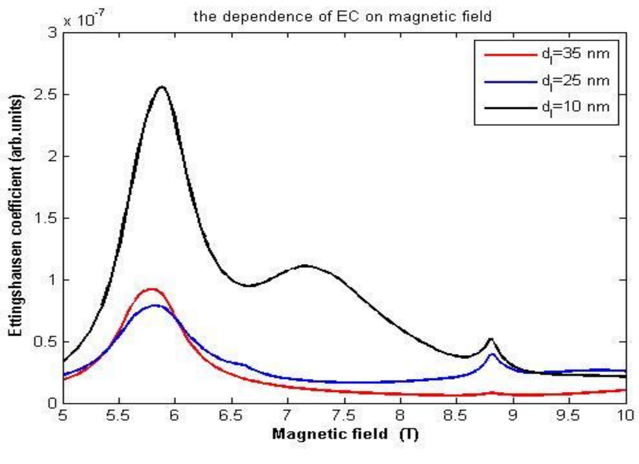

Figure 1. The dependence of EC on magnetic field.

$$E_1 = 10^5 \frac{V}{m}; E_0 = 5.10^4 \frac{V}{m};\ T = 300K; \Omega = 10^{13}\, Hz$$

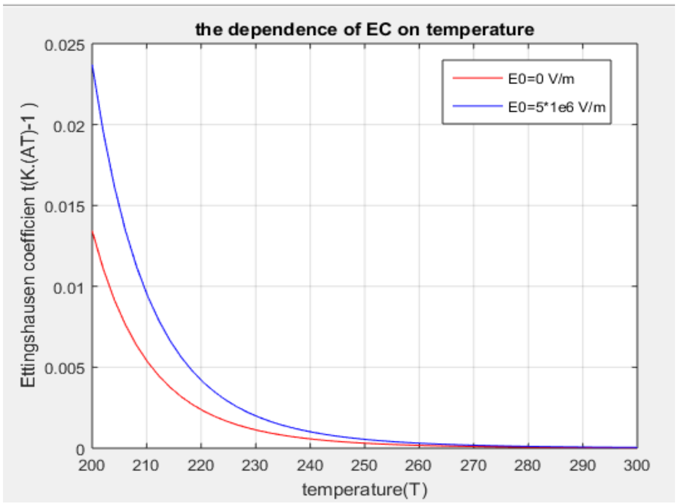

Figure 2. The dependence of EC on temperature.

$$E_1 = 10^5 \frac{V}{m}; E_0 = 5.10^4 \frac{V}{m}; d_I = 15nm; d_{II} = 10nm; B = 0,5T; \Omega = 10^{13}\ Hz$$

4. Conclusion

In this report, we analytically investigated EC in the compositional semiconductor superlattice in the presence of the EMW. The electron-phonon interaction is taken into account at high temperatures. Basing on our new analytical expression of the EC in the compositional semiconductor superlatice under the electron-optical phonon scattering mechanism, we realized that the EC depends on some elements such as: amplitude and frequency of laser radiation, magnetic field and temperature.

Considering the dependence of EC on the magnetic field fields with different values of the layer GaAs's thickness, we found that the resonance peaks have appeared and the number of resonance peaks mainly depends on the superlattice period. On the other hand, in the case of high temperatures, we found that the EC decreases as the temperature increases, which is consistent with the previous experiments. However, the value of EC in CSSL is much bigger in quantum well. These are the latest results that we have already obtained.

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