The influence of confined acoustic phonon on the quantum Peltier effect in doped semiconductor superlattice in the presence of electromagnetic wave

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Abstract. Based on the kinetic equation method, the quantum Peltier effect has been theoretically studied under the influence of confined acoustic phonon in doped semiconductor superlattice in the presence of the electromagnetic wave (laser radiation). There were complicated dependences of the analytical expression of the Peltier coefficient (PC) on quantities such as doped concentration of the superlattice, amplitude of the laser radiation, the cyclotron frequency of electrons and temperature of the system. In detailed consideration, the quantum number m was changed in order to characterize the influence of confined acoustic phonon. When setting the m to zero, we obtained the results that corresponded to the case of unconfined phonon. The theoretical results have been numerically evaluated and discussed for the GaAs:Si/GaAS:Be doped semiconductor superlattice (DSS). We found the oscillation of the PC according to enhancement of cyclotron frequency of electrons. Moreover, position of resonant peaks has shifted under the influence of phonon confinement. In the case of low doped concentration (ND), the PC decreased in non-linear way; then it reached a negative constant in high ND value. The non-linear change of the PC also has been detected when investigating its dependence on the laser amplitude. All numerical results have shown that the magnitude of the PC decreased due to the increase of phonon confinement effect. In short, the confinement of acoustic phonon caused the change of the quantum Peltier effect in DSS of GaAs:Si/GaAS:Be in quantitatively as well as qualitatively.

1. Introduction

The Peltier effect was discovered in 1834 by Jean Charles Athanase Peltier when observing the thermo-electric phenomena that occurred at the junction between bismuth and copper. Experiments to confirm this effect were failed until 1838 when Lentz managed to verify. In transitional theory, the Peltier effect was defined as an absorption of the heat of the junction of two conductors and depends on the direction of the electric current, and per unit time [1, 2]. However, this effect is even stronger at the junction between two dissimilar semiconductors. Therefore, scientists have paid much attention for its behaviour in semiconductor systems. At the junction in p-p and n-n structures, the discontinuity in the drift fluxes lead to thermal diffusion fluxes to reduce this discontinuity [3]. In p-n structures, the thermo-electric drift fluxes directed from the interface toward the edge in both layers. Moreover, in the case of strong recombination
in semiconductor system, a p-n junction may be heated or cooled under the influence of the Peltier coefficient and electrical conductivity [4]. In low-dimensional semiconductor system, the linear Peltier response described the initial changes of the entropy at the junctions [5] and the Peltier coefficient oscillated in magnetic field [6]. In doped semiconductor superlattice (DSSL), the quantum Peltier effect and its behaviors can be said be an opened question of interest scientists.

In DSSL, the changes of the quantum effects (QEs) in properties can not be ignored when the phonon confinement is considered in detail. LO-phonon confinement causes the enhancement of the probability of electron scattering and the decrease of the magnitude of the magneto-resistance as well as the Hall coefficient [7]. In GaAs − Al_{0.45}Ga_{0.55}As superlattice, the contributions of confined phonon is controlled through the factor $\Gamma$ and due to the confinement effect, the scattering time decreases when total energy increases [8].

A problem that needs to be solved is how the quantum Peltier effect occurs in DSSL under the influence of confined phonon. In this work, we present the results for this effect within electron-confined acoustic phonon (CAP) scattering. The presence of a laser radiation (LR) and a magnetic field are also taken into account. By using the kinetic quantum equation method [9], we obtain the analytical expressions for the kinetic tensors and the Peltier coefficient (PC). The numerical results for a GaAs:Be/GaAs:Si-doped superlattice are given for clarification of theoretical results.

2. The quantum Peltier effect in DSSL with the confinement of an acoustic phonon

A DSSL is an artificial cyclic structure in which semiconductor layers of the same types but with different doping of nano size are placed in series succession. The width of the layers is narrow enough for the electron to penetrate into adjacent layers. However, in these multi-quantum-well structures, the carrier movement is strictly limited along a defined direction and the size effect causes the changes in quantum properties. As a result, the wave function and energy spectrum of electron are quantized.

We examine a DSSL which is placed in a dc electric field $\mathbf{E} = (E, 0, 0)$, in a linearly polarized LR $\mathbf{E}(t) = E_0 \sin (\omega t)$ of classical frequency $\omega$ and in a magnetic field $\mathbf{B} = (0, 0, B)$. The energy spectrum of electron is given by [7, 10, 11]:

$$\varepsilon_{N,n}(\mathbf{k}_y) = \left(N + \frac{1}{2}\right) \hbar \omega_c + \left(n + \frac{1}{2}\right) \hbar \omega_p - \hbar v_d k_y + \frac{1}{2} m_e v_d^2$$

(1)

Here, $N$ and $n$ are the Landau level index and the sub-band index; $\mathbf{k}_y$ is the wave vector of the electron in the y-direction; $\hbar$ is the abridged Planck constant; $\omega_c = \frac{eB}{m_e}$ is the cyclotron frequency ($m_e$ and $e$ are, respectively, the effective mass and the effective charge of the electron, $c$ is the speed of light); $\omega_p = \left(\frac{4\pi e^2 n_D}{\chi_0 m_e}\right)^{1/2}$ is the plasma frequency ($\chi_0$ is the electronic constant and $n_D$ is the doping concentration); $v_d = \frac{E}{B}$ is the drift velocity of electron.

In this work, we assume that the electron-confined acoustic phonon scattering is essential. From the Hamiltonian of the confined electron-CAP system in a DSSL [7], we establish the quantum kinetic equation [9] for average number of electron $n_{N,n,\mathbf{k}_y}(t) = \langle a_{N,n,\mathbf{k}_y}^+ a_{N,n,\mathbf{k}_y} \rangle_t$ of
such a system and obtain the following expression:

\[
\frac{\partial n}{\partial k_y} + (eE + \hbar \omega_c [\vec{k}_y, \vec{\h}(t)]) \frac{\partial n}{\partial k_y} = \frac{2\pi}{\hbar} \sum_{N',N,m,q^z} \left| M_{N,N',n,n'}^{m} (q^z) \right|^2 \sum_{l=0}^{\infty} J_l^2 \left( \frac{\lambda}{\omega} \right) \\
\times \left\{ \left[ n_{N',N',k_y+q_y} (N_mq^z + 1) - n_{N,N,k_y} N_mq^z \right] \delta \left( \omega_{N',n'} (k_y + q_y) - \omega_{N,n} (k_y) - \h_nm_nq^z + \h \omega \right) \\ + \left[ n_{N',n',k_y-k_y} (N_mq^z - N_{n,n}q^z + 1) \right] \delta \left( \omega_{N',n'} (k_y - q_y) - \omega_{N,n} (k_y) - \h_nm_nq^z + \h \omega \right) \right\}.
\]

(2)

Here, \(a_{N,n,\vec{p}_y}^+\) and \(a_{N,n,\vec{p}_y}\) are the creation and annihilation operators of electron, respectively; \(\vec{h}(t) = \vec{B} / B\) is unit vector in the direction of magnetic field; \(m=1,2,3,...\) is the quantum number characterizing the phonon confinement; \(q^z = (\vec{q}_y, \vec{q}_y)\) is the wave vector of CAP in the xOy-plane; \(J_l \left( \frac{\lambda}{\omega} \right)\) is the Bessel function with \(\lambda = eE_0q_y / m_c\omega\); \(N_mq^z\) is the equilibrium distribution function of the phonon; \(\omega_{m,q^z} \approx \omega_m = \h v_nq_y / \d\) is the frequency of CAP \((\d\) is the period of DSSL and \(v_n\) is the sound velocity); \(M_{N,n,N',n'}^{m} (q^z) = D_m (q^z) I_{n,n'}^{m,n'} (q^z, u)\) with \(|D_m (q^z)|^2 = \h B^2q^2 (2\rho\varepsilon_0V_0) / 2\rho\varepsilon_0\varepsilon_0\) is the electron-CAP interaction constant \((q_y = \varepsilon_0 / \d\); \(\xi \) and \(\rho\) are the deformation potential constant, the mass density respectively; \(V_0\) is the normalization volume of the specimen; \(I_{n,n'}^{m,n'} = \frac{1}{\ell_z \sqrt{2^{n+n'}\pi e}} \int_{-\infty}^{\infty} e^{\pm i q_yz} e^{i(z / \ell_z)^2} H_n \left( \frac{\xi}{\ell_z} \right) H_{n'} \left( \frac{\xi}{\ell_z} \right) dz\) is the form factor of electron with \(\ell_z = \sqrt{\h / m_c\omega_p}\) \((\omega_p = \sqrt{4\pi e^2\d / \chi_0 m_c}\) is the plasma frequency, \(\chi_0\) is the electronic constant and \(n_D\) is the doping concentration), \(H_n \left( \frac{\xi}{\ell_z} \right)\) and \(H_{n'} \left( \frac{\xi}{\ell_z} \right)\) are the Hermite polynomial of n-th order and n'-th order, \(|J_{N,N'} (u) |^2 = N! e^{-u} \left[ \frac{L_N - N}{N} \right] (L_N (u)) \right|^2 (L_N \left( u \right) \) is the associated Laguerre polynomial, \(u = \ell z^2q_y^2 / 2\) with \(\ell B = \sqrt{\h / m_c}\omega_c\) [7].

In Eq. (2), \(\lambda / \omega = eE_0q_y / m_c\omega^2\) is the argument of Bessel function \(J_l\) and depends on amplitude \(E_0\) and frequency \(\omega\) of the LR. We assume that the LR is a high-frequency electromagnetic wave whose amplitude is not too large. According to this assumption, the value of \(\frac{\lambda}{\omega}\) is much smaller than 1. On the other hand, the processes with more than one photon are ignored [7, 9]. Therefore, we take an approximation in LRs intensity and keep only terms with \(l = 0, \pm 1\) for simplicity. The following expression for the individual current density is obtained by solving Eq. (1) in a similar way in Ref. [7]:

\[
\begin{align*}
\vec{R} (\varepsilon, m) &= \tau (\varepsilon) \left[ 1 + \omega_c^2 \tau^2 (\varepsilon) \right]^{-1} \left[ \vec{I} (\varepsilon) + \vec{S} (\varepsilon, m) \right] \\
-\omega_c \tau (\varepsilon) \left[ \vec{h}(t), \vec{I} (\varepsilon) \right] + \left[ \vec{h}(t), \vec{S} (\varepsilon, m) \right] + \omega_c^2 \tau (\varepsilon) \left[ \vec{I} (\varepsilon) \vec{h}(t) + \vec{S} (\varepsilon, m), \vec{h}(t) \right] \vec{h}(t) \end{align*}
\]

(3)
with $\tau (\varepsilon) = \tau (\varepsilon_F) (\varepsilon_F / \varepsilon)^{1/2}$ being the momentum relaxation time in absence of LR, where

$$
\begin{align*}
\bar{\mathbf{F}} (\varepsilon, m) &= \frac{2 e m}{m_e \hbar} \sum_{N, N', n, n'} \frac{M_{N, N', n, n'}^m \bar{n}_{N, n, \mathbf{k}_y} \bar{n}_{N', n', \mathbf{k}_y} (\bar{n}_{N', n', \mathbf{k}_y} + \bar{n}_{N, n, \mathbf{k}_y} - n_{N, n, \mathbf{k}_y})}{m, \bar{q}_{\mathbf{k}_y}} \\
&\times \left\{ \left( 1 - \frac{\lambda^2}{2 \omega^2} \right) \left[ \delta (\varepsilon_{N', n'} (\mathbf{k}_y + \bar{q}_y) - \varepsilon_{N,n} (\mathbf{k}_y) + \hbar \omega_m) \\
+ \delta (\varepsilon_{N', n'} (\mathbf{k}_y + \bar{q}_y) - \varepsilon_{N,n} (\mathbf{k}_y) - \hbar \omega_m) \right] \\
+ \frac{\lambda^2}{4 \omega^2} \left[ \delta (\varepsilon_{N', n'} (\mathbf{k}_y + \bar{q}_y) - \varepsilon_{N,n} (\mathbf{k}_y) + \hbar \omega_m + \hbar \omega) \\
+ \delta (\varepsilon_{N', n'} (\mathbf{k}_y + \bar{q}_y) - \varepsilon_{N,n} (\mathbf{k}_y) - \hbar \omega_m + \hbar \omega) \right] \\
+ \frac{\lambda^2}{4 \omega^2} \left[ \delta (\varepsilon_{N', n'} (\mathbf{k}_y + \bar{q}_y) - \varepsilon_{N,n} (\mathbf{k}_y) + \hbar \omega_m - \hbar \omega) \right] \\
+ \frac{\lambda^2}{4 \omega^2} \left[ \delta (\varepsilon_{N', n'} (\mathbf{k}_y + \bar{q}_y) - \varepsilon_{N,n} (\mathbf{k}_y) - \hbar \omega_m + \hbar \omega) \right]
\right\}
\end{align*}
$$

We substitute (2) into the integrals of

$$
\begin{align*}
\bar{Q} (m) &= \frac{1}{e} \int_0^\infty \left( \varepsilon - \varepsilon_F \right) \bar{R} (\varepsilon, m) d\varepsilon = \alpha_{ip} (m) E_p + \sigma_{ip} (m) \nabla T \\
\bar{J} (m) &= \int_0^\infty \bar{R} (\varepsilon, m) d\varepsilon = \gamma_{ip} (m) E_p + \beta_{ip} (m) \nabla T
\end{align*}
$$

for the thermal flux density and

for the total density. After performing analytic calculations, we obtained the expressions for the conductivity tensor $\gamma_{xx}$ and the kinetic tensor $\alpha_{xx}$ as follows:

$$
\begin{align*}
\gamma_{xx} (m) &= A \frac{e \tau (\varepsilon_F)}{1 + \omega_e^2 r^2 (\varepsilon_F)} + \frac{e}{m_e} \left\{ A_1 (m) + A_3 (m) \right\} a_{e_{xx}} (m) \left[ 1 - \omega_e^2 r^2 (\varepsilon_{13}) \right] \\
&\quad + \left\{ A_2 (m) + A_4 (m) \right\} a_{e_{24}} (m) \left[ 1 - \omega_e^2 r^2 (\varepsilon_{24}) \right] \\
&\quad + A_5 (m) a_{e_5} (m) \left[ 1 - \omega_e^2 r^2 (\varepsilon_5) \right] + A_6 (m) a_{e_6} (m) \left[ 1 - \omega_e^2 r^2 (\varepsilon_6) \right] \\
&\quad + A_7 (m) a_{e_7} (m) \left[ 1 - \omega_e^2 r^2 (\varepsilon_7) \right] + A_8 (m) a_{e_8} (m) \left[ 1 - \omega_e^2 r^2 (\varepsilon_8) \right]
\end{align*}
$$

$$
\begin{align*}
\alpha_{xx} (m) &= \frac{e}{m_e T} \left\{ A_1 (m) + A_3 (m) \right\} (\hbar \omega_m) a_{e_{xx}} (m) \left[ 1 - \omega_e^2 r^2 (\varepsilon_{13}) \right] \\
&\quad + \left\{ A_2 (m) + \kappa_4 (m) \right\} (-\hbar \omega_m) a_{e_{24}} (m) \left[ 1 - \omega_e^2 r^2 (\varepsilon_{24}) \right] \\
&\quad + A_5 (m) (-\hbar \omega_m + \hbar \omega) a_{e_5} (m) \left[ 1 - \omega_e^2 r^2 (\varepsilon_5) \right] \\
&\quad + A_6 (m) (-\hbar \omega_m - \hbar \omega) a_{e_6} (m) \left[ 1 - \omega_e^2 r^2 (\varepsilon_6) \right] \\
&\quad + A_7 (m) (\hbar \omega_m + \hbar \omega) a_{e_7} (m) \left[ 1 - \omega_e^2 r^2 (\varepsilon_7) \right] \\
&\quad + A_8 (m) (\hbar \omega_m - \hbar \omega) a_{e_8} (m) \left[ 1 - \omega_e^2 r^2 (\varepsilon_8) \right]
\end{align*}
$$
in which
\[ A = -e n_0 \hbar k_B T (k_B T m_e)^{-1} I (k_y) \sum_{N,n} \exp \left( \frac{\varepsilon N-n \omega_m}{k_B T} \right); \]
\[ A_1 (m) = B_0 \sum_{N, N', n, n', m} |I_{mn'}^m|^2 \left( \frac{e B}{\hbar} \right) I (k_y) \delta (\Delta - \hbar \omega_m); \]
\[ A_2 (m) = B_0 \sum_{N, N', n, n', m} |I_{mn'}^m|^2 \left( \frac{e B}{\hbar} \right) I (k_y) \delta (\Delta + \hbar \omega_m); \]
\[ A_3 (m) = B_1 \sum_{N, N', n, n', m} |I_{mn'}^m|^2 \left( \frac{e B}{\hbar} \right)^3 I (k_y) \delta (\Delta - \hbar \omega_m); \]
\[ A_4 (m) = B_1 \sum_{N, N', n, n', m} |I_{mn'}^m|^2 \left( \frac{e B}{\hbar} \right)^3 I (k_y) \delta (\Delta + \hbar \omega_m); \]
\[ A_5 (m) = B_2 \sum_{N, N', n, n', m} |I_{mn'}^m|^2 \left( \frac{e B}{\hbar} \right)^3 I (k_y) \delta (\Delta + \hbar \omega_m - \hbar \omega); \]
\[ A_6 (m) = B_2 \sum_{N, N', n, n', m} |I_{mn'}^m|^2 \left( \frac{e B}{\hbar} \right)^3 I (k_y) \delta (\Delta + \hbar \omega_m + \hbar \omega); \]
\[ A_7 (m) = B_2 \sum_{N, N', n, n', m} |I_{mn'}^m|^2 \left( \frac{e B}{\hbar} \right)^3 I (k_y) \delta (\Delta - \hbar \omega_m - \hbar \omega); \]
\[ A_8 (m) = B_2 \sum_{N, N', n, n', m} |I_{mn'}^m|^2 \left( \frac{e B}{\hbar} \right)^3 I (k_y) \delta (\Delta - \hbar \omega_m + \hbar \omega); \]
\[ B_0 = n_0 \varepsilon k_B T (2 e^2 \hbar m_e \nu_0^2 V_0)^{-1}; \quad B_1 = -2^{-1} B_0 (e E_0 / m_e \omega^2)^2; \quad B_2 = -B_1 / 2; \]
\[ I (k_y) = \frac{L_y}{2 \pi^2 \hbar^2 \varepsilon \nu_0^2} (\varepsilon_{N,n} - \varepsilon_F); \quad \varepsilon_{N,n} = \left( N + 1 / 2 \right) \hbar \omega_c + \left( n + 1 / 2 \right) \hbar \omega_p + \frac{m_e}{2} \left( \frac{\ell_B}{\hbar} \right)^2; \]
\[ \Delta = (N' - N) \hbar \omega_c + (n' - n) \hbar \omega_p - e \varepsilon \ell_B \bar{T} = \left( \sqrt{N + \frac{1}{2}} + \sqrt{N + 1 + \frac{1}{2}} \right) \ell_B / 2 \left[ 7 \right]; \]
\[ \varepsilon_{13} = \varepsilon_F + \hbar \omega_m; \quad \varepsilon_{24} = \varepsilon_F - \hbar \omega_m; \quad \varepsilon_5 = \varepsilon_{24} + \hbar \omega; \quad \varepsilon_6 = \varepsilon_{13} - \hbar \omega; \quad \varepsilon_7 = \varepsilon_{13} + \hbar \omega; \]
\[ \varepsilon_8 = \varepsilon_{24} - \hbar \omega; \quad a_{13} (m) = \tau^2 \left( \varepsilon_{13} \right) \left( 1 + \omega_0^2 \tau^2 \left( \varepsilon_{13} \right) \right)^{-2}; \]
\[ a_{24} (m) = \tau^2 \left( \varepsilon_{24} \right) \left( 1 + \omega_0^2 \tau^2 \left( \varepsilon_{24} \right) \right)^{-2}; \quad a_{13} (m) = \tau^2 \left( \varepsilon_i \right) \left( 1 + \omega_0^2 \tau^2 \left( \varepsilon_i \right) \right)^{-2} \quad (i = 5 \pm 8); \]
\[ n_0 \] is the carrier concentration; \( k_B \) is the Boltzmann constant; \( \delta (...) \) is the symbol for the Dirac Delta function.

The analytical expressions for the PC can be written:
\[ PC = \alpha_{xx} (m) \gamma_{xx}^{-1} (m) \quad (10) \]

According to Eq.(10), \( m \) - specific CAP parameter- affects the PC in the complicated way and directs the theoretical calculation outcomes. We obtain results corresponding to unconfined AP case as \( m \) is set to zero. The PC also depends on the amplitude and the frequency of the LR and the doping concentration of the DSSL. Lastly, the obtained results holds true for all temperatures.

3. Numerical Results and Discussion
Temperature can be considered to be a rather important condition that influences on the behavior of quantum effects in low-dimensional semiconductor systems. In this section, we present the numerical results of investigating the PC as a function of quantities including the cyclotron frequency, the laser amplitude and the doping concentration of DSSL under the low
temperature condition (T = 5 K). In addition, the results obtained by using the quantum kinetic equation method are not only valid for low temperature conditions but also for all temperature range. Therefore, the classical limitation which the kinetic Boltzmann equation method cannot solve is overtaken.

To evaluate the influence of CAP on the quantum Peltier effect, we consider a GaAs:Si/GaAs:Be-doped semiconductor superlattices with used parameters: $\xi = 13.5$ eV; $\tau(\varepsilon_F) = 10^{-12}$ s; $\varepsilon_F = 50$ meV; $L = 2.5$ nm; $m_e = 0.067m_0$ ($m_0 = 9.1094.10^{-31}$ kg is the mass of a free electron); $\rho = 5.32$ $g.cm^{-3}$; $v_s = 5330$ $m.s^{-1}$. Frequency of the LR to be used is $\omega = 2.89.10^{12}$ Hz.
Figure 1 shows the influence of the cyclotron frequency on the PC. The values of doping concentration and laser amplitude used in this case are $n_D = 3.10^{23} \text{ m}^{-3}$ and $E_0 = 4.10^5 \text{ Vm}^{-1}$, respectively. An oscillation of the PC with increasing cyclotron frequency (CF) was observed in both cases (with and without a CAP). When the CF was increased, the oscillation amplitudes of the PC grew. Because the CF is determined by an expression: $\omega_c = \frac{eB}{mc}$, so the rising the magnetic field causes the rise of CF. The PC is determined through conductivity tensor $\gamma_{xx}$ and kinetic tensor $\alpha_{xx}$ according to the Eq. (10). Meanwhile, an experimental observation for the low-dimensional GaAs/AlGaAs structure indicated that the magnetic oscillations of the conductivity tensor occurred and the novel high-B characteristics in wires are caused by the combination of confinement and phase coherence in the confined direction [13]. Besides, the kinetic tensor $\alpha_{xx}$ also oscillates when the magnetic field increases [16]. The origin of these Shubnikov-de Hass (SdH) oscillations is the Landau quantization with increasing magnetic field [13]. Therefore, the observed oscillations of the PC is consistent. The oscillations of PC according to the cyclotron frequency was also presented in theoretical research on Peltier effect in two-dimensional quantum point contacts [6]. Moreover, the inter-subband magnetophonon resonance condition (MRC) [14]: $(N' - N) \hbar\omega_c = (n' - n) \hbar\omega_p + eE\ell \pm \hbar v_s \frac{m^*}{m} \mp \hbar\omega$ determines the position of the peaks. The quantum number $m$ is set to zero in unconfined phonon case and receives values greater than zero in the case of confined phonon. As a results, the confinement of an AP which characterized by $m$ not only impacted the the values of PC, but also shifted the resonant peaks (when compared with the case of unconfined AP).

A nonlinear dependence of the PC on the characteristic quantity of the LR being the amplitude is displayed in Fig. 2, with high doping concentration $n_D = 3.10^{23} \text{ m}^{-3}$ and cyclotron frequency $\omega_c = 8, 15.10^{12} \text{ Hz}$. Due to the influence of CAP, the PC is much smaller. However, the phonon confinement does not cause any change in the role of dependence of the PC on the laser amplitude.

The influences of the doping concentration ($n_D$) on the PC in a DSSL are shown in Fig. 3 with laser amplitude $E_0 = 4.10^5 \text{ Vm}^{-1}$. According to the Fig.3(a), when the cyclotron frequency $\omega_c = 8, 15.10^{12} \text{ Hz}$, the PC takes on negative values throughout the doping concentration range of interest. However, due to the influence of the CAP, value of the PC varies significantly from the case of unconfined acoustic phonon. In both cases (with and without phonon confinement), the PC depends on the doping concentration in a nonlinear way. One of the reasons leading to the stabilization of the PC in a DSSL with high doping concentration might be the saturation of
the current flows through the p-n junction at the very high doping concentration. Experimental results on the influence of doping concentration on GaAs/AlGaAs RTD have proven that charge density in device increases as number of electron increases with increased doping concentration; and after very high concentration, the peak current in device goes to saturation [15]. Thus, the obtained results are completely reasonable. Besides, Fig.3(b) indicates that the stabilization of the PC expands towards the lower doping concentration as the cyclotron frequency decreases in the case of CAP.

4. Conclusions

In this work, we present the analytic expression of the PC obtained by using the quantum kinetic equation method and graph the theoretical results for GaAs:Si/GaAs:Be-doped semiconductor superlattices. The analytic results show that the formula of PC depends on many quantities, especially the quantum number m characterizing the phonon confinement. When m is set to zero, we obtain the results corresponding to the unconfined phonon case. All numerical results investigated under the low temperature condition indicate that the influence of CAP on the quantum Peltier effect in DSSL cannot be ignored. Under the influence of CAP, the PC changes in magnitude in comparison with unconfined phonon case. Oscillations occur in the dependence of the PC on the cyclotron frequency. Besides, the PC are relatively stable at a high doping concentration. Our obtained results are consistent with some experimental data including the results of experimental survey for the quantum effects in various structures such as RTD and low-dimensional semiconductor system of GaAs. Finally, the results presented in this paper will help to complete the theory of the thermo-magnetoelectric effects, in general, and the Peltier effect, in particular, in low-dimensional semiconductor systems.

References

[1] Ioffe A F, Stil’bans L S, Jordanishvili E K, Stavitskaya T S, and Gelbtuch A 1959 Physic Today 12 5
[2] Samoilovich A G and Korenblit L L 1953 Uspekhi Fiz. Nauk 49 243
[3] Gurevich Y G and Logvinov G N 2005 Semicond. Sci. Technol. 20 57
[4] Gurevich Y G and Velázquez-Pérez J E 2014 Peltier Effect in Semiconductors (New York: John Wiley and Sons).
[5] Mierzejewski M, Crivelli D, and Prelovsek P 2014 Phys. Rev. B 90 075124
[6] Bogachek E N, Scherbakov A G and Landman U 1998 Solid State Communications 108 851
[7] Bau N Q, and Long D T 2016 J. Sci: Adv. Mater. Dev. 1 209
[8] Abouelaoualim D 2006 Pramana J. Phys. 66 455
[9] Epshtein E M 1976 Sov. Tech. Phys. Lett. 2 234
[10] Friedman L 1985 Phys. Rev. B 32, 955
[11] Charbonneau M, Van Vliet K M and Vasilopoulos P 1982 J. Math. Phys. 23 318
[12] Hashimzade F M, Hasanov K A, Mehdiyev B H, and Cakmak S 2010 Phys. Scr. 81 015701
[13] Mani R G, Von Klitzing K, Vasiliadou E, Grambow P, and Ploog K 1994 Surf. Sci. 305 654
[14] Shmelev G M, Tsurlan G I, and Shon N H 1982 Phys. Semicond. 15 156
[15] Singh M M, Siddiqui M J, Khan A B, and Anjum S G, Annual IEEE India Confer. (INDICON) (New Delhi, India, 2015), p.1
[16] Bau N Q, Quynh N T L, Ba C T V and Hung L T 2020 J. Korean Phys. Soc. 77 1