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THE PARAMETRIC TRANSFORMATION COEFFICIENT OF CONFINED ACOUSTIC AND CONFINED OPTICAL PHONONS IN THE RECTANGULAR QUANTUM WIRE

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Abstract. *The parametric transformation of confined acoustic and confined optical phonons in the rectangular quantum wire is theoretically studied by using a set of quantum kinetic equations for phonons. The analytic expression of parametersq transformation coefficient of confined acoustic and confined optical phonons in the rectangular quantum wire is obtained. The dependence of the parametric transformation coefficient on the temperature T and parameters of the rectangular quantum wire is numerically evaluated, plotted and discussed for a specific quantum wire GaAs/GaAsAl. All the results are compared with those for the unconfined phonons to show the difference.*

I. INTRODUCTION

It is well known that in presence of an external electromagnetic field, an electron gas becomes non-stationary. When the conditions of parametric resonance are satisfied, parametric resonance and tranformation (PRT) of same kinds of excitations such as phonon-phonon, plasmon-plasmon, or of different of excitations, such as plasmon-phonon will arise i.e.., the energy exchange process between these excitations will occur [1-9]. The physical picture can be described as follows: due to the electron-phonon interaction, propagation of an acoutic phonon with a frequency $\omega_{\vec{q}}$ accompanied by a density wave with the same frequency Ω. When an external electromagnetic field with frequency is presented, a charge density waves (CDW) with a combination frequency $\nu_{\vec{q}} \pm l\Omega$ (l =1, 2, 3,..) will appear. If among CDW there exits a certain wave having a frewuency which coincides, or approximately coincides, with the frequency of optical phonon $\nu_{\vec{q}}$, optical phonons will appear. These optical phonons cause a CDW with a combination frequency of $\nu_{\vec{q}} \pm l\Omega$, and when $\nu_{\vec{q}} \pm l\Omega \cong \omega_{\vec{q}}$, a certain CDW causes the acoutic phonons mention above. The PRT can speed up the damping process for one excitation and the amplification process for another excitation. Recently, there have been several studies on parametric excitation in quantum approximation. The parametric interactions and tranformation of unconfined acoustic and unconfined optical phonons has been considered in bulk semiconductors [1-5], for low-dimensional semiconductors (doped superlattices, quantum wells, quantum wire), the dependence of the parametric tranformation coefficient of unconfined acoustic and unconfined opitical phonons on temperature T [9]. In order to improve the PRT theoretics for low-dimensional semiconductors, we, in the paper, examine dependence of the parametric transformation coefficient of confined acoustic and confined optical phonons in the rectangular quantum wire.

II. THE QUANTUM KINECTIC EQUATION FOR PHONONS

We use model for the rectangular quantum wire with electron gas is confined on the 0xy plane and electron is free along the 0z direction. If laser field $\vec{E}(t) = \vec{E}_0 \sin(\Omega t)$ irradiates the sample in direction which are along the 0z axis, the electromagnatic field of laser wave will polarize parallels the z axis and its strength is expressed as a vector potenal $\vec{A}(t) = \frac{c}{\Omega}\vec{E}_0 \cos(\Omega t)$ (c is the light velocity, Ω is EMW frequency, $\vec{E}_0$ is amplitude of the laser field).

The Hamiltonian of the electron-confined acoustic phonon-confined optical phonon system in the rectangular quantum wire can be written as (in this paper $\hbar = 1$):

$$\begin{aligned} H &= \sum_{n,l,k_z} \varepsilon_{n,l}\left(\vec{k}_z - \frac{e}{c}\vec{A}(t)\right) a^+_{n,l,\vec{k}} a_{n,l,k_z} \\ &+ \sum_{m_1,m_2,q_z} \omega_{m_1,m_2,q_z} b^+_{m_1,m_2,q_z} b_{m_1,m_2,q_z} + \sum_{m_1,m_2,q_z} \nu_{m_1,m_2,q_z} c^+_{m_1,m_2,q_z} c_{m_1,m_2,q_z} \\ &+ \sum_{m_1,m_2,q_z} \sum_{n,l,n',l',k_z} C^{m_1,m_2}_{\vec{q}_z} I_{n,l,n',l'} a^+_{n',l',k_z+q_z} a_{n,l,k_z} (b_{m_1,m_2,q_z} + b^+_{m_1,m_2,-q_z}) \\ &+ \sum_{m_1,m_2,q_z} \sum_{n,l,n',l',k_z} D^{m_1,m_2}_{q_z} I_{n,l,n',l'} a^+_{n',l',k_z+q_z} a_{n,l,k_z} (c_{m_1,m_2,q_z} + c^+_{m_1,m_2,-q_z}) \end{aligned} \tag{1}$$

Where $\varepsilon_{n,l}\big(\vec{k}_z - \frac{e}{c}\vec{A}(t)\big)$ is energy spectrum of an electron in external electromagnetic filed, $a^+_{n,l,k_z} a_{n,l,k_z}$ is the creation (annihilation) operater of an electron for state $|n,l,k_z\rangle$, $b^+_{m_1,m_2,q_z}, b_{m_1,m_2,q_z}$ ($c^+_{m_1,m_2,q_z}, c_{m_1,m_2,q_z}$) is the creation operator and annihilation operator of an confined acoustic (optical) phonon for state $|m_1,m_2,q_z\rangle$, m_1, m_2 are the index confined. The electron- confined acoustic and optical phonon interaction coefficients take the form [10]:

$$\begin{aligned} \left|C^{m_1,m_2}_{q_z}\right|^2 &= \frac{\xi^2}{2\rho v_s V}\sqrt{q_z^2 + \left(\frac{m_1\pi}{L_x}\right)^2 + \left(\frac{m_1\pi}{L_y}\right)^2}, \\ \left|D^{m_1,m_2}_{q_z}\right|^2 &= \frac{e^2\hbar\omega_0}{2V_0\varepsilon_0}\left(\frac{1}{\chi_\infty} - \frac{1}{\chi_0}\right)\left[q_z^2 + \left(\frac{m_1\pi}{L_x}\right)^2 + \left(\frac{m_2\pi}{L_y}\right)^2\right]^{-1} \end{aligned} \tag{2}$$

Here V, ρ, v_s and ξ are the volume, the density, the acoustic velocity and the deformation potential constant, respectively, ε_0 is the electronic constant, χ_∞, χ_0 are the static and high-frequency dielectric constants, respectively, e is the charge of the electron.

The electronic form factor, $I_{n,l,n',l'}$ is written as [11]:

$$I_{n,l,n',l'} = \frac{32\pi^4(q_xL_xnn')^2\left[1-(-1)^{n+n'}\cos(q_xL_x)\right]}{\left[(q_xL_x)^4-2\pi^2(q_xL_x)^2(n^2+n'^2)+\pi^4(n^2-n'^2)^2\right]^2} \times \frac{32\pi^4(q_yL_yll')^2\left[1-(-1)^{nl+l'}\cos(q_yL_y)\right]}{\left[(q_yL_y)^4-2\pi^2(q_yL_y)^2(l^2+l'^2)+\pi^4(l^2-l'^2)^2\right]^2} \tag{3}$$

Here, n, n' is the position of quantum, l, l' is the radial quantum number, $L_x(L_y)$ is width (length) of the rectangular quantum wire, q_x, q_y is wave vector.

Energy spectrum of electron in the rectangular quantum wire [12]

$$\varepsilon_{n,l}(k_z) = \frac{k_z^2}{2m^*} + \frac{\pi^2}{2m^*}\left(\frac{n^2}{L_x^2}+\frac{l^2}{L_y^2}\right). \tag{4}$$

Here, m^* is the effective mass of the electron.

In order to establish a set of quantum kinetic equations for confined acoustic and confined optical phonons, we use equation of motion of statistical average value for phonons

$$i\frac{\partial}{\partial t}\left\langle b_{m_1,m_2,q_z}\right\rangle_t = \left\langle b_{m_1,m_2,q_z}, H(t)\right\rangle_t; \quad i\frac{\partial}{\partial t}\left\langle c_{m_1,m_2,q_z}\right\rangle_t = \left\langle c_{m_1,m_2,q_z}, H(t)\right\rangle_t. \tag{5}$$

Where $\left\langle X\right\rangle_t$ is means the usual thermodynamic average of operator X.

Using Hamiltonian in Eq.(1) and realizing operator algebraic calculations, we obtain a set of coupled quantum kinetic equations for phonons. The equation for the confined acoustic phonons can be formulated as.

$$\begin{aligned}\frac{\partial}{\partial t}\left\langle b_{m_1,m_2,q_z}\right\rangle_t &+ i\omega_{m_1,m_2,q_z}\left\langle b_{m_1,m_2,q_z}\right\rangle_t = -\frac{1}{\hbar^2}\sum_{n,l,n',l',k_z}\sum_{\nu,\mu=-\infty}^{+\infty} \\ &\times \left|I_{n,l,n',l'}\right|^2 J_\nu\left(\frac{\lambda}{\Omega}\right)J_\mu\left(\frac{\lambda}{\Omega}\right)\left[f_{n',l'}(k_z-q_z)-f_{n,l}(k_z)\right] \\ &\times \int_{-\infty}^{t} dt_1 \exp\left\{\frac{i}{\hbar}\left[\varepsilon_{n,l}(k_z)-\varepsilon_{n',l'}(k_z-q_z)\right](t_1-t)-i\nu\Omega t_1+i\mu\Omega t\right\} \\ &\times \left\{\left|C_{q_z}^{m_1,m_2}\right|^2\left[\langle b_{m_1,m_2,q_z}\rangle_{t_1}+\langle b^+_{m_1,m_2,-q_z}\rangle_{t_1}\right]\right. \\ &+ \left. C_{-\vec{q}}^{m_1,m_2}D_{q_z}^{m_1,m_2}\left[\langle c_{m_1,m_2,-q_z}\rangle_{t_1}+\langle c^+_{m_1,m_2,-q_z}\rangle_{t_1}\right]\right\}\end{aligned} \tag{6}$$

A similar equation for the optical phonons can be obtained in which $\langle c_{m_1,m_2,q_z}\rangle_t$, $\langle b_{m_1,m_2,q_z}\rangle_t$, ν_{m_1,m_2,q_z}, ω_{m_1,m_2,q_z}, $C_{q_z}^{m_1,m_2}$, $D_{q_z}^{m_1,m_2}$ are replaced by $\langle b_{m_1,m_2,q_z}\rangle_t$, $\langle c_{m_1,m_2,q_z}\rangle_t$, ω_{m_1,m_2,q_z}, ν_{m_1,m_2,q_z}, $D_{q_z}^{m_1,m_2}$, $C_{q_z}^{m_1,m_2}$, respectively.

In Eq.(6) $f_{n,l}(\vec{k})$ is the distribution function of electrons in the state $|n,l,\vec{k}\rangle$, $J_\mu(\frac{\lambda}{\Omega})$ is the Bessel function, and $\lambda = \frac{e\vec{E}_0\vec{q}_z}{m\Omega}$.

III. THE PARAMETRIC TRANSFORMATION COEFFICIENT OF ACOUSTIC AND OPTICAL PHONON IN RECTANGULAR QUANTUM WIRE

In order to establish the parametric transformation coefficient of confined acoustic and confined optical phonon, we use standard Fourier transform techniques for statistical average value of phonon operators: $\langle b_{m_1,m_2,q_z}\rangle_t$, $\langle b^+_{m_1,m_2,q_z}\rangle_t$, $\langle c_{m_1,m_2,q_z}\rangle_t$, $\langle c^+_{m_1,m_2,q_z}\rangle_t$. The Fourier transforms take the form:

$$\Psi_{\vec{q}}(\omega) = \int_{-\infty}^{+\infty} \langle \Psi_{\vec{q}}\rangle_t e^{i\omega t} dt; \quad \langle \Psi_{\vec{q}}\rangle_t = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \Psi_{\vec{q}}(\omega) e^{-i\omega t} d\omega.$$

One finds that the final result consists of coupled equations for the Fourier transformations $C_{m_1,m_2,\vec{q}}(\omega)$ and $B_{m_1,m_2,q_z}(\omega)$ of $\langle c_{m_1,m_2,q_z}\rangle_t$ and $\langle b_{m_1,m_2,q_z}\rangle_t$.

For instance, the equation for $C_{m_1,m_2,q_z}(\omega)$ can be written as:

$$\begin{aligned}(\omega - \omega_{m_1,m_2,q_z})C_{m_1,m_2,q_z}(\omega) = \\ 2\sum_{n,l,n',l'} |I_{n,l,n',l'}|^2 |D^{m_1,m_2}_{q_z}|^2 \nu_{m_1,m_2,q_z} \frac{C_{m_1,m_2,q_z}(\omega)}{\omega + \nu_{m_1,m_2,q_z}} \Pi_0(m_1,m_2,q_z,\omega) \\ + 2\sum_{n,l,n',l'} |I_{n,l,n',l'}|^2 C^{m_1,m_2}_{q_z} D^{m_1,m_2}_{q_z} \nu_{m_1,m_2,q_z} \sum_{s=-\infty}^{\infty} \frac{B_{m_1,m_2,q_z}(\omega - s\Omega)}{\omega - s\Omega + \omega_{m_1,m_2,q_z}} \Pi_s(m_1,m_2,q_z,\omega).\end{aligned} \tag{7}$$

In the similar equation for $B_{m_1,m_2,q_z}(\omega)$, functions such as $C_{m_1,m_2,q_z}(\omega)$, $C_{m_1,m_2,q_z}(\omega - s\Omega)$, $B_{m_1,m_2,q_z}(\omega - s\Omega)$, ν_{m_1,m_2,q_z}, ω_{m_1,m_2,q_z}, $C^{m_1,m_2}_{q_z}$, $D^{m_1,m_2}_{q_z}$ are replaced by $B_{m_1,m_2,q_z}(\omega)$, $B_{m_1,m_2,q_z}(\omega - s\Omega)$,$C_{m_1,m_2,q_z}(\omega - s\Omega)$, ω_{m_1,m_2,q_z}, ν_{m_1,m_2,q_z}, $D^{m_1,m_2}_{q_z}$, $C^{m_1,m_2}_{q_z}$, respectively.

In Eq (7), we have:

$$\Pi_s(m_1,m_2,q_z,\omega) = \sum_{v=-\infty}^{+\infty} J_v\left(\frac{\lambda}{\Omega}\right) J_{v+s}\left(\frac{\lambda}{\Omega}\right) \Gamma_{m_1,m_2,q_z}(\omega + v\Omega), \tag{8}$$

$$\Gamma_{m_1,m_2,q_z} = \sum_{\vec{k}} \frac{f_{n,l}(k_z) - f_{n',l'}(k_z - q_z)}{\varepsilon_{n,l}(k_z) - \varepsilon_{n',l'}(k_z - q_z) - hv\Omega - \hbar\omega - i\hbar\delta}. \tag{9}$$

Where, the quantity δ is infinitesimal and appears due to the assumption of an adiabatic interaction of the electromagnetic wave (EMW).

In Eq (8), the first term on the right-hand side is significant just in case $s = 0$. If not, it will contribute more than second order of electron-phonon interaction constant. Therefore, we have

$$(\omega - \omega_{m_1,m_2,q_z})C_{m_1,m_2,q_z}(\omega) = 2\sum_{n,l,n',l'} |I_{n,l,n',l'}|^2 |D_{q_z}^{m_1,m_2}|^2 \nu_{m_1,m_2,q_z} \frac{C_{m_1,m_2,q_z}(\omega)}{\omega + \nu_{m_1,m_2,q_z}} \Pi_0(m_1, m_2, q_z, \omega)$$
$$+ 2\sum_{n,l,n',l'} |I_{n,l,n',l'}|^2 C_{q_z}^{m_1,m_2} D_{q_z}^{m_1,m_2} \nu_{m_1,m_2,q_z} \sum_{s=-\infty}^{\infty} \frac{B_{m_1,m_2,q_z}(\omega - s\Omega)}{\omega - s\Omega + \omega_{m_1,m_2,q_z}} \Pi_s(m_1, m_2, q_z, \omega). \quad (10)$$

Transforming Eq (10) and using the parametric resonant condition $\omega_{m_1,m_2,q_z} + N\Omega \approx \nu_{m_1,m_2,q_z}$, the parametric transformation coefficient is obtained:

$$\frac{C_{m_1,m_2,q_z}(\nu_0)}{B_{m_1,m_2,q_z}(\omega_{m_1,m_2,q_z})} = \frac{\sum_{n,l,n',l',k_z} |I_{n,l,n',l'}|^2 C_{-q_z}^{m_1,m_2} D_{-q_z}^{m_1,m_2} \Pi_{-1}(m_1, m_2, q_z, \omega_{m_1,m_2,q_z})}{\delta - i\sum_{n,l,n',l'} |I_{n,l,n',l'}|^2 |D_{q_z}^{m_1,m_2}|^2 \mathrm{Im}\Pi_0(m_1, m_2, q_z, \nu_{m_1,m_2,q_z})} \quad (11)$$

Consider the case of N = 1 and assign

$$\gamma_0 = \sum_{n,l,n',l'} |In, l, n', l'|^2 |D_{q_z}^{m_1,m_2}|^2 \mathrm{Im}\Pi_0(m_1, m_2, q_z, \nu_{m_1,m_2,q_z}). \quad (12)$$

Note that $\delta \ll \gamma_0$, we have

$$K_1 = \frac{\sum_{n,l,n',l',\vec{k}} |I_{n,l,n',l}|^2 C_{-q_z}^{m_1,m_2} D_{q_z}^{m_1,m_2} \Pi_{-1}(m_1, m_2, q_z, \omega_{m_1,m_2,q_z})}{i\gamma_0}. \quad (13)$$

Using Bessel function, Fermi-Dirac distribution function for electron and energy spectrum of electron in Eq. (4), we have:

$$|K_1| = \left|\frac{\Gamma}{2\gamma_0}\right| \quad (14)$$

Where

$$\Gamma = \sum_{n,l,n',l'} |I_{n,l,n',l}|^2 C_{q_z}^{m_1,m_2} D_{q_z}^{m_1,m_2} \frac{\lambda}{\Omega} \mathrm{Re}\Gamma_{m_1,m_2,q_z}(\omega_{m_1,m_2,q_z}) \quad (15)$$

$$\mathrm{Re}\Gamma_{m_1,m_2,q_z}(\nu_{m_1,m_2,q_z}) = \frac{\frac{Lf_0}{2\pi}\sqrt{\frac{2m^*\pi}{\beta}} \exp\Big[-\beta\frac{\pi^2}{2m^*}\Big(\frac{n^2}{L_x^2} + \frac{l^2}{L_y^2}\Big)\Big]}{\frac{\pi^2}{2m^*}\Big(\frac{n'^2-n^2}{L_x^2} + \frac{l'^2-l^2}{L_y^2}\Big) + \frac{q_z^2}{2m^*} + \nu_{m_1,m_2,q_z}} \times\Big\{\exp\Big[-\beta\frac{\pi^2}{2m^*}\Big(\frac{n'^2-n^2}{L_x^2} + \frac{l'^2-l^2}{L_y^2}\Big)\Big] - 1\Big\} \quad (16)$$

$$\mathrm{Im}\Gamma_{m_1,m_2,q_z}(\nu_{m_1,m_2,q_z}) = -\frac{Lm^*f_0}{q_z}\exp\Big\{\beta\Big[-\frac{m^*A^2}{2q_z^2} - \frac{\pi^2}{2m^*}\Big(\frac{n^2}{L_x^2} + \frac{l^2}{L_y^2}\Big) + \frac{\nu_{m_1,m_2,q_z}}{2}\Big]\Big\}\mathrm{sh}\Big[\frac{\beta\nu_{m_1,m_2,q_z}}{2}\Big] \quad (17)$$

$$A = \frac{\pi^2}{2m^*}\Big(\frac{n'^2-n^2}{L_x^2} + \frac{l'^2-l^2}{L_y^2}\Big) + \frac{q_z^2}{2m^*} + \omega_{m_1,m_2,q_z}. \quad (18)$$

In Eqs.(16) and (17), $\beta = 1/(k_B T)$ (k_B is Boltzmann constant), L is depth of the rectangular quantum wire, f_0 is the electron density in rectangular quantum wire.

When the index confined m_1, m_2 to tend to 0, parametric transformation coefficient of confined acoustic and confined optical phonon in rectangular quantum wire be the same as parametric transformation coefficient of unconfined acoustic and unconfined optical phonon[9].

K_1 is analytic expression of parametric transformation coefficient of confined acoustic and confined optical phonon in rectangular quantum wire when the parametric resonant condition $\omega_{m_1,m_2,q_z} + N\Omega \simeq \nu_{m_1,m_2,q_z}$ is satisfied.

IV. NUMERICAL RESULTS AND DISCUSSIONS

In order to clarify the mechanism for parametric transformation coefficient of confined acoustic and confined optical phonon in rectangular quantum wire, in this section we perform numerical computations and graph for GaAs/GaAsAl: be quantum wire. The parameters used in the calculation [6,7]: $\xi = 13,5$eV, v_s=5378m/s, χ_∞=10.9, χ_0=12.9, ρ=5.32g/cm^3, m*=0.67×9.1 × 10^{-31}kg, $\hbar\omega_0 = 36.25$eV, E_0=10^6V/m, $q_z = 2 \times 10^5 1/m$, $L = 10^{-7}m$, $f_0 = 10^{23}m^{-1}$, $e = 1.60219 \times 10^{-19}C$, $\hbar = 1.05459 \times 10^{-34}$Js.

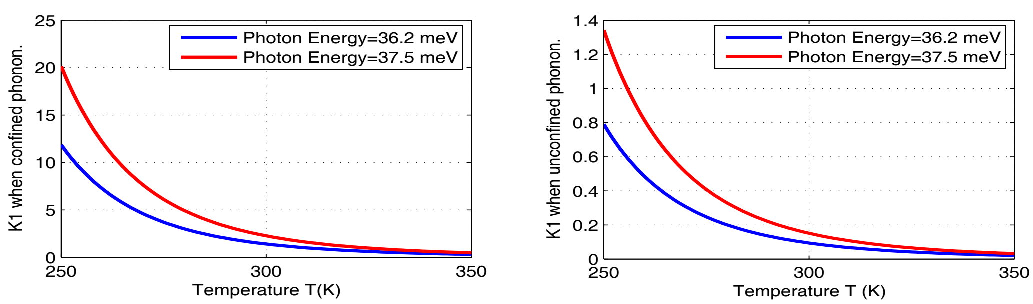

Fig. 1. Dependence of K1 on T when confined phonon (left) and unconfined phonon (right).

Fig 1 shows the parametric transformation coefficient K1 as a function of temperature T. It is seen that the parametric transformation coefficient of acoustic and optical phonons in rectangular quantum wire depends non-linearly on temperature T. The results are compared with those for the unconfined phonons to show the bigger. When the temperature increases 250K : 350K, the parametric transformation coefficient K1 reduced.
Fig 2 shows the parametric transformation coefficient K1 as a function of width L_x of the rectangular quantum wire. It is seen that, when width L_x less than about $20nm$ or width L_x greater than about $70nm$, the parametric transformation coefficient of acoustic and optical phonons in rectangular quantum wire independents on width L_x. When $20nm < L_x < 70nm$, with $L_y = 40nm$, the parametric transformation coefficient of acoustic and optical phonons in rectangular quantum wire is some maximum value. The results are compared with those for the unconfined phonons to show the bigger.

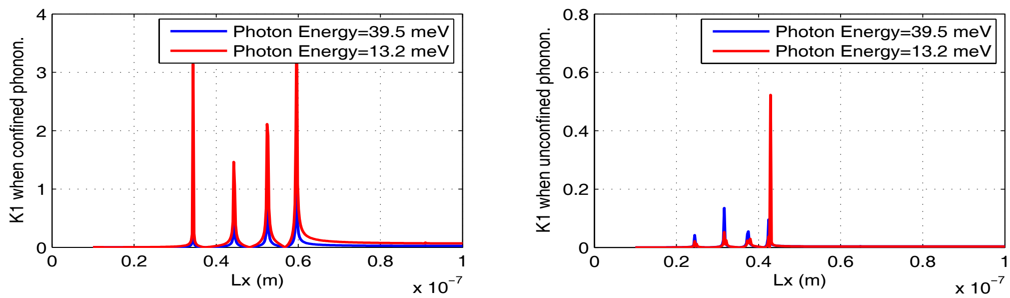

Fig. 2. Dependence of K1 on L_x when confined phonon (left) and unconfined phonon (right).

V. CONCLUSION

In this paper, we obtain analytic expression of the parametric transformation coefficient of acoustic and optical phonons in rectangular quantum wire in presence of an external electromagnetic field K1, Eqs. (14)-(18). It is seen that K1 depends on temperature T and parametric of rectangular quantum wire. Numerical computations and graph are performed for GaAs /GaAsAl be quantum wire. Fig 1 shows the parametric transformation coefficient K1 depends non-linearly on temperature T. Fig 2 shows, when $20nm < L_x < 70nm$, with $L_y = 40nm$, the parametric transformation coefficient of acoustic and optical phonons in rectangular quantum wire is some maximum value. The results are compared with those for the unconfined phonons to show the bigger.

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