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Influence of phonon confinement on the optically detected magneto-phonon resonance line-width in quantum wells

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HIGHLIGHTS

- Absorption power is calculated in square quantum wells taking into account the phonon confinement effect.
- Optically detected magneto-phonon resonance line-width (ODMPRLW) as profiles of curves is determined.
- The ODMPRLW increases with increasing temperature and decreases with increasing well's width.
- The ODMPRLW in the case of confined phonons is greater than it is in the case of bulk phonons.

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ABSTRACT

We investigate the influence of phonon confinement on the optically detected magneto-phonon resonance (ODMPR) effect and ODMPR line-width in quantum wells. The ODMPR conditions as functions of the well's width and the photon energy are also obtained. The shifts of ODMPR peaks caused by the confined phonon are discussed. The numerical result for the GaAs/AlAs quantum well shows that in the two cases of confined and bulk phonons, the line-width (LW) decreases with increasing well's width and increases with increasing temperature. Furthermore, in the small range of the well's width, the influence of phonon confinement plays an important role and cannot be neglected in reaching the ODMPR line-width.

1. Introduction

Magneto-phonon resonance (MPR) effect is known to arise from the resonant coupling between electrons and optical phonons when the separation between two Landau levels approaches the phonon energy, i.e., $P\omega_c = \omega_{op}$ (ω_c, ω_{op} and $P = 1, 2, \ldots$ are the cyclotron frequency, optical phonon frequency, and an index difference between two Landau levels, respectively), and leads to oscillatory behavior in many transport properties [1]. In the presence of an ac electromagnetic field, it has been shown that the influence of this field is to shift the resonant peaks position from $P\omega_c = \omega_{op}$ to $P\omega_c + \omega = \omega_{op}$ [2] with ω being the frequency of the ac electromagnetic field. This is the so-called optically detected MPR (ODMPR). When the confinement of phonon is taken into account, the ODMPR becomes $P\omega_c + \omega = \omega_{conf}$ in which ω_{conf} is the confined phonon frequency which is now quantized into discrete values.

Phonon confinement is an essential part of the description of electron–phonon interactions [3]. It causes the increase of electron–phonon scattering rates [4–6] and significant nonlinearities in the dispersion relations of acoustic-phonon modes, and modifies the phonon density of states [7]. There have been many models dealing theoretically with phonon modes, such as the Huang–Zhu (HZ) model, the slab mode model and the guided mode model [8]. Phonon confinement is shown to be important whenever the transverse dimensions of a quantum well are smaller than the phonon coherence length [3] and should be taken into account in order to obtain realistic estimates for electron–phonon scattering in low-dimensional structures [9–11]. Phonon confinement affects ODMPR mainly through changes in the selection rules for transitions involving subband of electrons, Landau levels, phonon modes and affects the ODMPR line-width (ODMPRLW) through changes in the probability of the electron–phonon scattering. The line-width (LW) is defined by the profile of curves describing the dependence of the absorption power (AP) on

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the photon energy or frequency [12,13]. The LW has been measured in various kinds of semiconductors, such as quantum wells [14–19], quantum wires [20–23], and quantum dots [24–28]. These results show that the absorption LW has a weak dependence on temperature and has a strong dependence on system size. However, in those studies, the absorption LW was investigated based on the interaction of electrons and bulk phonons, the absorption LW in quantum wells (QWs) due to the confined optical phonon–electron interaction is still open for study. Recently, our group has proposed a method, called the profile method, to computationally obtain the LW from graphs of the AP [29], and we used this method to determine the cyclotron resonance LW in cylindrical quantum wires [30] and the influence of phonon confinement on the optically detected electrophonon resonance line-width in GaAs/AlAs quantum wires [31,32].

In the present work, we investigate the ODMPRLW in QWs. The dependence of the ODMPRLW on the well's width and the temperature of system is obtained. The results of the present work are fairly different from the previous theoretical results because the phonon confinement effect is considered. The paper is organized as follows. In Section 2, we introduce several models of the phonon confinement in QWs. Calculation of analytical expression of the AP in QWs is presented in Section 3. The graphic dependence of the AP on the photon energy in the GaAs/AlAs QW is shown in Section 4. From this dependence, we obtain the LW and examine not only the location of resonance peaks, but also the dependence of the LW on temperature and well's width. Finally, remarks and conclusions are shown briefly in Section 5.

2. Confined electron and phonon models

We consider a single quantum well structure where electrons are free to move in the (x, y) plane and a magnetic field B is applied in the z direction. Adopting a single-band spherical effective mass model for electron, the one-electron eigenfunction, ψ, is given by [33]

$$\psi_{N,n,k_y} = \frac{1}{\sqrt{L_y}}\phi_N(x - x_0)\exp(ik_y y)\varphi_n(z), \tag{1}$$

where $N = 0, 1, 2, \ldots$ is the Landau level index; $n = 1, 2, 3, \ldots$ is the electric subband quantum number; ϕ_N is the harmonic oscillator wave function centered at $x_0 = -\lambda^2 k_y$ with $\lambda = (\hbar c/eB)^{1/2}$ being the cyclotron radius; L_y and k_y are specimen dimension and electron wave-vector in y-direction; $\varphi_n(z)$ is the electron wave function in z-direction as determined by the barrier potential $V(z)$.

For an infinite barrier square well $V(z) = 0$ for $|z| < L_z/2$ and $V(z) = \infty$ for $|z| > L_z/2$, the corresponding energy eigenvalues, E_{Nn}, is given by [34]

$$E_{Nn} = (N + 1/2)\hbar\omega_c + n^2\epsilon_0, \tag{2}$$

where $\omega_c = eB/m_e$ is the cyclotron frequency and $\epsilon_0 = \hbar^2\pi^2/(2m_e L_z^2)$ is the energy of the lowest electric subband, L_z denoting the width of the well. In this case $\varphi_n(z)$, for a well centered at $z=0$, is given by [33]

$$\varphi_n(z) = \sqrt{\frac{2}{L_z}}\sin\left(\frac{n\pi z}{L_z} + \frac{n\pi}{2}\right). \tag{3}$$

The matrix element for confined electron-confined phonon interaction in QW in the extreme quantum limits can be written as [35]

$$|\langle i|H_{e-ph}|f\rangle|^2 = |C_{i,f}(\vec{q})|^2 = |C_m(q_\perp)|^2 |J_{NN'}(q_\perp)|^2 |G^{m\alpha}_{nn'}|^2 \delta_{k'_y, k_y+q_y}, \tag{4}$$

where

$$|C_m(q_\perp)|^2 = \frac{2\pi e^2\hbar\omega_{m,q_\perp}}{\varepsilon_0\Omega}\left(\frac{1}{\chi_\infty} - \frac{1}{\chi_0}\right)\frac{1}{q_\perp^2 + q_m^2} \tag{5}$$

where χ_0, χ_∞, ε_0 and Ω are, respectively, the static, high-frequency, vacuum dielectric constants and the normalization volume of specimen, respectively; $q_\perp$ is a two dimensional vector in the (x,y) plane of phonon; $q_m = m\pi/L_z$. The term $G^{m\alpha}_{nn'}$ is given by

$$G^{m\alpha}_{nn'} = \int_{-L_z/2}^{L_z/2} \varphi^*_{n'}(z) u_{m\alpha}(z)\varphi_n(z)\, dz, \tag{6}$$

where α distinguishes the even $(-)$ and odd $(+)$ confined phonon mode, $u_{m\alpha}(z)$ being the parallel component of the displacement vector of m-th phonon mode in the direction of spatial confinement. It is different for different models and has been calculated for some confined models such as the HZ model, slab mode model, and guided mode model [8,34]. In the next section, we will use the HZ model to calculate the optical absorption power in quantum wells because among these models, the HZ model has received wide acceptance and best describes the electron–phonon interaction in quasi-two-dimensional systems [33,36,37]. For example, calculations of electron intra- and inter-subband scattering rates in GaAs quantum wells due to confined LO phonons using the HZ model [11,38,39] have been found to be in good agreement with experimental results [40,41]. For this model [8,34]

$$u_{m+}(z) = \sin\left(\frac{\mu_m \pi z}{L_z}\right) + \frac{C_m z}{L_z}, \quad m = 3, 5, 7, \ldots \tag{7}$$

$$u_{m-}(z) = \cos\left(\frac{m\pi z}{L_z}\right) - (-1)^{m/2}, \quad m = 2, 4, 6, \ldots \tag{8}$$

The overlap integral (6) can be evaluated for intra-subband transition $(1 \to 1)$, and is obtained for the HZ model as

$$G^{m-}_{11} = \tfrac{3}{2}\delta_{m,2} - (-1)^{m/2}(1 - \delta_{m,2}), \quad m = 2, 4, 6, \ldots \tag{9}$$

$$G^{m+}_{11} = 0, x \quad m = 3, 5, 7, \ldots \tag{10}$$

Also [33],

$$|J_{NN'}(u)|^2 = \frac{n_2!}{n_1!} e^{-u} u^{n_1-n_2} [L^{n_1-n_2}_{n_2}(u)]^2, \tag{11}$$

where $u = \lambda^2 q_\perp^2/2$; $\lambda = \sqrt{\hbar/(m_e\omega_c)}$; $\omega_c = eB/m_e$; $n_1 = \max\{N, N'\}$; $n_2 = \min\{N, N'\}$; $L^{n_1-n_2}_{n_2}$ is the Laguerre polynomial.

3. Absorption power in quantum wells

In this section, we utilize the HZ model for confined phonons to calculate the AP in above mentioned quantum wells, subjected to an ac electromagnetic field (electromagnetic wave) with amplitude E_0 and frequency ω. The AP can be obtained by relating it to the transition probability of the photon absorption to move to the higher energy levels along with phonon absorbing or emitting processes as follows [42]:

$$P(\omega) = \frac{E_0^2}{2\hbar\omega}\sum_\alpha \frac{|j^+_\alpha|^2 (f_\alpha - f_{\alpha+1})B(\omega)}{(\omega - \omega_c)^2 + [B(\omega)]^2}, \tag{12}$$

where $|j^+_\alpha|^2 = |\langle\alpha + 1|j^+|\alpha\rangle|^2 = (N + 1)(2e^2\hbar\omega_c)/m_e$; f_α is the Fermi–Dirac distribution function of the electron at the state $|\alpha\rangle = |N, n, k_y\rangle$. The term $B(\omega)$ takes the form [42]

$$B(\omega) = \frac{\pi}{\hbar}\sum_{m,q_\perp} |C_m(q_\perp)|^2 \delta_{k_y, k'_y+q_y}[(1 + N_q)X_1 + N_q X_2], \tag{13}$$