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INFLUENCE OF PHONON CONFINEMENT ON OPTICALLY-DETECTED ELECTROPHONON RESONANCE LINEWIDTH IN PARABOLIC QUANTUM WELLS

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Abstract: We investigate the influence of optical phonon confinement described by Huang-Zhu model on the optically-detected electro-phonon resonance (ODEPR) effect and ODEPR linewidth in parabolic quantum wells by using the operator projection. The result for the GaAs/AlAs parabolic quantum well shows that the ODEPR linewidths depend on the well's confinement frequency. Besides, in the two cases of confined and bulk phonons, the linewidth increases with the increase of confinement frequency. Furthermore, in the large range of the confinement frequency, the influence of phonon confinement plays an important role and cannot be neglected in considering the ODEPR linewidth.

Keywords: parabolic quantum well, confined phonon

1 Introduction

Electro-phonon resonance (EPR) effects in a low-dimensional electron gas system have generated considerable interest in recent years [1]. EPR effects can only be observed for the resonant scattering of electrons confined in subband levels by longitudinal optical (LO) phonon whenever the LO phonon energy is equal to the energy separation between two subband levels. The scattering process with LO phonons is dominant in limiting the mobility of electrons in the polar semiconductors for temperature greater than 50 K [2]. EPR was introduced by Bryskin and Firsov [2], who predicted EPR for non-degenerate semiconductors in very strong electric fields. The absorption linewidth is well-known as a good tool for investigating the scattering mechanisms of carriers. Hence, it can be used to probe electron-phonon scattering processes. The absorption LW was investigated based on the interaction of electrons and bulk phonons, but the absorption LW in quantum wells due to confined electrons and confined LO-phonons interaction is still open for study. Phonon confinement is an essential part of the description of electron-phonon interactions [3]. It causes the increase of electron-phonon scattering rates [4] and significant nonlinearities in the dispersion relations of acoustic phonon modes and modifies the phonon density of states [5]. There have been a number of models dealing theoretically with phonon modes, such as the Huang-Zhu model, the slab mode model and guided mode model [6]. The differences among these models are in the way of the lattice dynamics boundary conditions. Phonon confinement is shown to be important whenever the transverse dimensions

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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 [7]. Phonon confinement affects ODEPR mainly through changes in the selection rules for transitions involving subband of electrons, phonon modes. Phonon confinement also affects the ODEPR linewidth through changes in the probability of the electron-phonon scattering. The linewidth is defined as the profile of curves describing the dependence of the absorption power on the phonon energy or frequency [8]. The linewidth has been measured in various kinds of semiconductors, such as quantum wells [9], quantum wires [10], and quantum dots [11]. These results show that the absorption linewidth has a weak dependence on temperature and has a strong dependence on the sample size. However, in these studies, the absorption linewidth was investigated based on the interaction of electrons and bulk phonons. In the case of confined phonon, many works have been reported to clarify the effect of different phonon models on the electron-phonon scattering rates [12], free carrier absorption [13], energy loss rate of hot electrons [14], localized phonon-assisted cyclotron resonance [15], [16], self-energy of confined polaron [17], electron-phonon interaction energies [18], optically-detected electron-phonon resonance [19], optically-detected magneto-phonon resonance [20], and confined optical-phonon-assisted cyclotron resonance in quantum wells via two-photon absorption process [21]. Therefore the absorption linewidth in quantum wells (QWs) due to confined optical phonon-electron interaction has not been fully considered in previously published reports. Recently, our group has proposed a method, called the profile method. This method can be used to computationally obtain the linewidth from graphs of the absorption power [22]. We used this method to determine the cyclotron resonance linewidth in cylindrical quantum wires [23], the influence of phonon confinement on the optically-detected electro-phonon resonance linewidth in GaAs/AlAs quantum wires [24, 25], the influence of phonon confinement on the optically-detected magneto-phonon resonance linewidth in quantum wells [20], and the confined optical-phonon-assisted cyclotron resonance in quantum wells via two-photon absorption process [21].

In the present work, we investigate the influence of phonon confinement described in Huang-Zhu model on the ODEPR effect and ODEPR linewidth in a PQW. The dependence of the ODEPR linewidth on the well's confinement frequency is obtained. The results of the present work are fairly different from the previous theoretical results because Huang-Zhu model of phonon confinement is considered in details. The paper is organized as follows. In Section 2, we introduce Huang-Zhu model of phonon in a PQW. Calculations of analytical expression of the absorption power in PQW due to Huang-Zhu LO phonon modes are presented in Section 3. The graphical dependence of the absorption power on the photon energy in the GsAs/AlAs PQW is shown in Section 4. From this dependence, we obtain the dependence of the linewidth on well's confinement frequency. The results are compared with the corresponding calculations for the bulk phonon model. Finally, remarks and conclusions are shown in Section 5.

2 Huang-Zhu model of phonon confinement

We consider a single parabolic quantum well structure, and the one-electron eigenfunction, $|\alpha\rangle = \Psi_{k_\perp,n}$, is given by [2]

$$\Psi_{k_\perp,n} = \frac{1}{\sqrt{L_x L_y}} exp(i\vec{k}_\perp \vec{r}_\perp)\varphi_n(z), \tag{1}$$

where L_x, L_y are specimen dimension in x,y-direction; $\vec{k}_\perp = (k_x, k_y)$ and $\vec{r}_\perp = (x,y)$ are the wave vector and position vector of a conduction electron in the (x,y) plane, respectively; $\varphi_n(z)$ is the electron wave function in z-direction as determined by the parabolic potential $V(z)$, $V(z) = m^*\omega_z^2 z^2/2$. The energy eigenvalues, $E_{n,\vec{k}_\perp}$, is given by [2]

$$E_{n,\vec{k}_\perp} = \frac{\hbar^2 k_\perp^2}{2m^*} + (n+\frac{1}{2})\hbar\omega_z, \tag{2}$$

where $n = 0,1,2,\cdots$ is the electric subband quantum number; m^* and ω_z are the effective mass of an electron and well's confinement frequency, respectively. In this case $\varphi_n(z)$ is given by [2]

$$\varphi_n(z) = \frac{1}{\sqrt{2^n n!\sqrt{\pi}a_z}} exp(-\frac{z^2}{2a_z^2})H_n(\frac{z}{a_z}), \tag{3}$$

with $a_z = (\hbar/(m^*\omega_z))^{1/2}$, and H_n are nth-degree Hermite polynomials.

The matrix element for electron-confined phonon interaction in a parabolic quantum well in the extreme quantum limits can be written as [26]

$$|\langle i|H_{e-ph}|f\rangle|^2 = \frac{e^2\hbar\omega_{LO}\chi^*}{2\varepsilon_0 V_0}|V_{m\phi}^{HZ}(q_\perp)|^2 |G_{n_i,n_f}^{HZ,m\phi}|^2 \delta_{k_\perp^f, k_\perp^i \pm q_\perp}, \tag{4}$$

where the overlap integral, $G_{n_i,n_f}^{HZ,m\phi}$, is given

$$G_{n_i,n_f}^{HZ,m\phi} = \int_{-\infty}^{\infty} \varphi_{n_f}^*(z) u_{m\phi}^{HZ}(z)\varphi_{n_i}(z)dz, \tag{5}$$

where $\chi^* = (\chi_\infty^{-1} - \chi_0^{-1})$ with χ_∞ and χ_0 are the high and static-frequency dielectric constants, respectively; ε_0 is the vacuum dielectric constants, and $V_0 = SL_z$ is the volume of the system; $u_{m\phi}^{HZ}(z)$ is the parallel component of the displacement vector of the mth phonon mode in the direction of the spatial confinement for the HZ model; ϕ is the even ($-$) and odd ($+$) HZ model mode phonons. In the next section, we will use the HZ model to calculate the optical absorption power in the parabolic quantum well. For the HZ model, $u_{m\phi}^{HZ}(z)$, is given by [27]

$$u_{m+}^{HZ}(z) = sin(\frac{\mu_m \pi z}{L_z}) + \frac{c_m z}{L_z}, \quad m = 3,5,7,\cdots, \tag{6}$$

$$u_{m-}^{HZ}(z) = cos(\frac{\mu_m \pi z}{L_z}) - (-1)^{m/2}, \quad m = 2,4,6,\cdots. \tag{7}$$

3 Analytical results

We utilize Huang-Zhu model for the confined phonon to calculate the absorption power in the above quantum wells, subjected to an electric field with amplitude E_0 and frequency ω. The absorption power is obtained by relating it to the transitions probability of the photon absorption to move to the higher energy levels along with phonon absorption or emission processes as follows [28]

$$P(\omega)=\frac{E_0^2}{2\omega}\sum_{\alpha\beta}(j_k)_{\alpha\beta}(j_\ell)_{\beta\alpha}\frac{(f_\alpha-f_\beta)B_{\alpha\beta}(\omega)}{(\hbar\omega-E_{\alpha\beta})^2+[B_{\alpha\beta}(\omega)]^2}, \quad (8)$$

where

$$(j_{k_z})_{\alpha\beta}=\frac{ie\hbar}{m^*a_z}\Big(\sqrt{\frac{n_\beta}{2}}\delta_{n_\alpha,n_\beta-1}-\sqrt{\frac{n_\beta+1}{2}}\delta_{n_\alpha,n_\beta+1}\Big)\delta_{k_{\perp\alpha},k_{\perp\beta}}, \quad (9)$$

$$(j_{\ell_z})_{\beta\alpha}=\frac{ie\hbar}{m^*a_z}\Big(\sqrt{\frac{n_\alpha}{2}}\delta_{n_\beta,n_\alpha-1}-\sqrt{\frac{n_\alpha+1}{2}}\delta_{n_\beta,n_\alpha+1}\Big)\delta_{k_{\perp\beta},k_{\perp\alpha}}, \quad (10)$$

f_α and f_β are the Fermi-Dirac distribution function of the electron at states $|\alpha\rangle$ and $|\beta\rangle$,

$$B_0^{\alpha\beta}(\omega)= \quad (11)$$

$$C_0\sum_{n_\eta}\sum_{m,\phi=\pm}\Big\{\frac{2m^*k_{1+}^2|G_{n_\alpha n_\eta}^{HZ,m\phi}|^2}{\hbar^2|k_{1+}|(a_{m\phi}k_{1+}^2+\frac{b_{m\phi}}{L_z^2})}[(1+N_q)f_\beta(1-f_{\eta,k_{1+}})-N_qf_{\eta,k_{1+}}(1-f_\beta)]$$

$$+\frac{2m^*k_{1-}^2|G_{n_\alpha n_\eta}^{HZ,m\phi}|^2}{\hbar^2|k_{1-}|(a_{m\phi}k_{1-}^2+\frac{b_{m\phi}}{L_z^2})}[N_qf_\beta(1-f_{\eta,k_{1-}})-(1+N_q)f_{\eta,k_{1-}}(1-f_\beta)]$$

$$+\frac{2m^*k_{2+}^2|G_{n_\beta n_\eta}^{HZ,m\phi}|^2}{\hbar^2|k_{2+}|(a_{m\phi}k_{2+}^2+\frac{b_{m\phi}}{L_z^2})}[(1+N_q)f_{\eta,k_{2+}}(1-f_\alpha)-N_qf_\alpha(1-f_{\eta,k_{2+}})]$$

$$+\frac{2m^*k_{2-}^2|G_{n_\beta n_\eta}^{HZ,m\phi}|^2}{\hbar^2|k_{2-}|(a_{m\phi}k_{2-}^2+\frac{b_{m\phi}}{L_z^2})}[N_qf_{\eta,k_{2-}}(1-f_\alpha)-(1+N_q)f_\alpha(1-f_{\eta,k_{2-}})]\Big\}, \quad (12)$$

with

$$C_0=\frac{\pi e^2\hbar\omega_{LO}\chi^*}{2\varepsilon_0V_0(f_\alpha-f_\beta)}. \quad (13)$$

N_q is the Planck distribution function for a confined phonon at the state $|q\rangle=|m,q_\perp\rangle$,

$$k_{1\pm} = \{-\frac{2m^*}{\hbar^2}[(n_\eta - n_\beta)\hbar\omega_z + \hbar\omega \pm \hbar\omega_{LO}]\}^{1/2},$$
$$k_{2\pm} = \{\frac{2m^*}{\hbar^2}[(n_\alpha - n_\eta)\hbar\omega_z + \hbar\omega \pm \hbar\omega_{LO}]\}^{1/2}, \quad (14)$$

We can see that these analytical results appear very involved. However, a physical conclusion can be drawn from graphical representations and numerical results, obtained from adequate computational methods.

4 Numerical results and discussion

To clarify the obtained results we numerically evaluate the absorption power, $P(\omega)$, for a specific GaAs/AlAs PQW. The absorption power is considered to be a function of the photon energy. The parameters used in our computational evaluation are as follows [29]: $\chi_\infty = 10.9, \chi_0 = 12.9, m^* = 0.067m_0$ (m_0 being the mass of the free electron), $\hbar\omega_{LO} = 36.25$ meV, $E_0 = 5.0\times 10^6$ V/m. The following conclusions are obtained in the extreme quantum limit and assuming that only the lowest subbands are occupied by the electrons: $n_\alpha = 0$, $n_\beta = 1$ for the confined electron.

Figure 1 shows the dependence of the absorption power on the photon energy for bulk phonons (the solid curve), confined phonons described by the HZ model (the dashed curve). The result is calculated for a parabolic quantum well, at $T = 300$ K and $\omega_z = 0.6\omega_{LO}$. There are three peaks in each curve:

– The first peak (1) corresponds to the value $\hbar\omega = 21.75$ meV, which satisfies the condition $\hbar\omega = E_\beta - E_\alpha$. This condition implies that an electron in the $n_\alpha = 0$ can move to $n_\beta = 1$ by absorbing a photon with energy $\hbar\omega$. This is the condition for intersubband transitions.

– The second peak (2) corresponds to the value $\hbar\omega = 36.25$ meV, which satisfies the condition $\hbar\omega = \hbar\omega_{LO}$. This condition implies that $n_\alpha = n_\beta$. This is the condition for intrasubband transitions.

– The third peak (3) corresponds to the value $\hbar\omega = 58.00$ meV, which satisfies the condition $\hbar\omega = E_\beta - E_\alpha + \hbar\omega_{LO}$. This condition implies that an electron in the $n_\alpha = 0$ can move to $n_\beta = 1$ by absorbing a photon with energy $\hbar\omega$ along with emitting a phonon with the energy $\hbar\omega_{LO}$. This is the condition for optically-detected electro-phonon resonance.

Figure 3 shows the ODEPR linewidth that increases with the increasing well's confinement frequency for both models of the phonon. This can be explained physically by an increase in the possibility of electron-phonon scattering when the well's confinement frequency increases. Furthermore, the ODEPR linewidth for the confined phonon case varies faster and has a larger value than it does for the bulk phonon case; and the larger range of the confinement frequency is, the more pronounced the difference can be observed. In addition, in the large range of the confinement frequency, the influence of phonon confinement plays an important role and cannot be neglected in reaching the ODEPR linewidths.

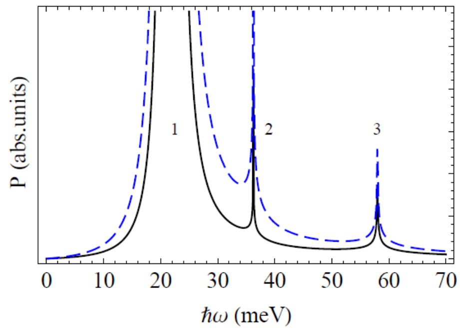

Fig. 1. Dependence of the absorption power in PQW on the photon energy for two different models of phonon at $T = 300$ K and $\omega_z = 0.6\omega_{LO}$: Bulk phonons (the solid curve) and confined phonons (the dashed curve)

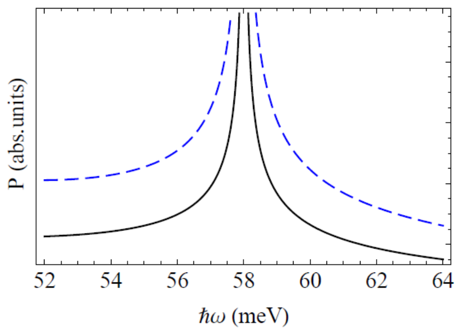

Fig. 2. Dependence of the absorption power in PQW on the photon energy for two different models of phonon at $T = 300$ K and $\omega_z = 0.6\omega_{LO}$ at the third peak in Figure 1: Bulk phonons (the solid curve) and confined phonons (the dashed curve)

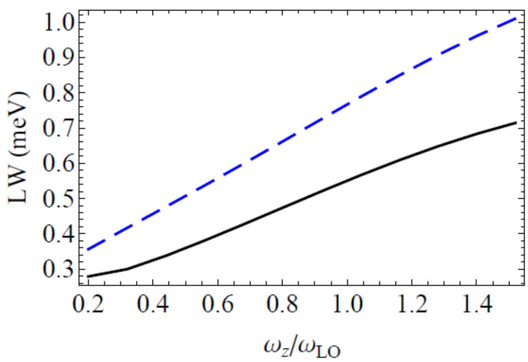

Fig. 3. Dependence of the ODEPR linewidths on the well's confinement frequency for two different models of phonons. The solid and the dashed curves correspond to the case of bulk phonons and confined phonons, respectively. Here, $T = 300$ K

5 Conclusions

We have calculated analytical expressions for the absorption power in the parabolic quantum wells due to confined electrons and confined longitudinal optical phonons interaction. From the graphs of the absorption power, we obtained the optically-detected electro-phonon resonance linewidth as a profile of curves. Computational results show that in the cases of both bulk and confined phonons, the optically-detected electro-phonon resonance linewidth increases with confinement frequency. Furthermore, the optically-detected electro-phonon resonance linewidth for the confined phonon case has a larger value and varies faster than it does for the bulk phonon case when well's confinement frequency increases. In addition, in the large range of the confinement frequency, the influence of phonon confinement plays an important role and cannot be neglected in reaching the optically-detected electro-phonon resonance linewidths. This result is the same as that obtained in a two-dimensional system which was verified by theories and experiments.

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