Hue University Journal of Science: Natural Science; ISSN 1859–1388

Vol. 127, No. 1A, 2018, P. 119–124; DOI: 10.26459/hueuni-jns.v127i1A.4668

OPTICALLY DETECTED ELECTROPHONON RESONANCE AND LINEWIDTHS IN TRIANGULAR QUANTUM WELLS

Pham Tuan Vinh[1,2], Le Dinh[1*], Luong Van Tung[2]

[1] Physics Department, University of Education, Hue University
[2] Division of Theoretical Physics, Department of Physics, Chemistry & Biology, Dong Thap University

Abstract. In the present paper, we study the linear optical absorption power in triangular quantum wells subjected to a laser field when electrons are scattered with longitudinal optical phonons (LO phonons). The analytic expressions are obtained for optical absorption power via electron-LO phonon scattering. The linear optically detected electron-phonon resonance (ODEPR) effect in a specific GaAs/AlAs quantum well with a triangular potential is investigated. The conditions for the ODEPR are determined on the basis of the energy conservation law. From the curves expressing the dependence of the absorption power on the photon energy, we find the ODEPR-linewidths as the profiles of the curves. The computational results show that the ODEPR-linewidths increase with temperature and decrease with the electric field.

Keywords: absorption power, quantum well, triangular potential, ODEPR-linewidths

1. Introduction

Optically detected electron-phonon resonances (ODEPR) and half linewidths are well-known as an effective tool for investigating the scattering mechanisms of carriers and can be used to study electron-phonon scattering processes. There have been many studies on this phenomenon in low dimensional semiconductors with different types of confined potentials [1–5]. However, these works mostly have dealt with quantum wells with the square shapes. Recent advances in molecular-beam epitaxy have enabled us to fabricate several quantum wells (QW) with non-square shapes, which are more sensitive to external fields compared with the square shape wells [6]. Non-square QW shapes can have potential profiles with steps, triangular, trapezoidal, V-groove, and hyperbolic forms.

It is well known that the quantum confinement of electrons in the triangular quantum well is much stronger than that in the square quantum well with the same width. Therefore, some novel optical properties can be expected in such a quantum system. Motivated by this idea, we consider the linear optically detected electrophonon resonance in a quantum well with

---

** Corresponding: dinhle52@gmail.com*

Submitted: 25–01–2018; Revised: 21–6–2018; Accepted: 20–7–2018

a triangular potential. The dependence of the ODEPR peak linewidths on the electric field and the temperature of the system is clearly displayed.

The paper is organized as follows: the model and theoretical framework are described in section 2; the results and discussions are presented in section 3; and the conclusions are given in section 4.

2. Triangular quantum well model and analytical results

We consider a triangular quantum well structure where electrons move freely in the $(x-y)$ plane and are confined in the *z*-direction with the following potential [7]

$$V(z)=\begin{cases}\infty, & z\le 0,\\ eFz, & z>0,\end{cases} \qquad (0)$$

where *e, F* are the charge of the conduction electron and the electric field amplitude, respectively. Solving the Schrödinger equation in *z*-direction, we obtain the eigenstate and corresponding eigenenergy in the forms [8]

$$\phi_n(z)=C_n Ai\left[M^{1/3}z-\frac{K^2}{M^{-2/3}}\right], \qquad (0)$$

$$E_{n_\alpha}=\left(\frac{\hbar^2}{2m^*}\right)^{1/3}\left[\frac{3\pi eF}{2}\left(n_\alpha-\frac{1}{4}\right)\right]^{2/3}, \quad n_\alpha=1,2,3,.... \qquad (0)$$

where C_n is the normalization constant, Ai is the Airy function, $M=2m^*eF/\hbar^2$, and $K=(2m^*E_{n_\alpha}/\hbar^2)^{1/2}$.

The wave function and energy of the electron in the $(x-y)$ plane are

$$\psi_{\vec{k}_\perp,n}(\vec{r}_\perp,z)=\frac{1}{\sqrt{L_xL_y}}e^{i\vec{k}_\perp\vec{r}_\perp}, \quad E(k_\perp,n)=\frac{\hbar^2k_\perp^2}{2m^*}, \qquad (0)$$

where L_x, L_y are the well widths in the *x,y*-dimensions; $\vec{k}_\perp=\vec{k}_x+\vec{k}_y$; $\vec{r}_\perp=x\vec{i}+y\vec{j}$.

When a time-dependent external electric field $E(\Omega)=Fe^{i\Omega t}$ with frequency Ω and amplitude F is applied along the *z*-direction, the analytical expression of the linear absorption power due to photon absorption, accompanied by an absorption and/or emission of the phonon is given by [9, 10]

$$P_0(\Omega) = \frac{F^2}{2} \sum_{n_\alpha, n_\beta} \frac{(f_\beta - f_\alpha) B_0(\Omega)}{[\hbar\Omega - (E_{n_\beta} - E_{n_\alpha})]^2 + B_0^2(\Omega)} \delta_{n_\alpha, n_\beta} K_{n_\alpha, n_\beta} L_{n_\beta, n_\alpha} . \qquad (0)$$

In Eq. (5), $E_{\beta\alpha} = E_\beta - E_\alpha = E_{n_\beta} - E_{n_\alpha}$ is the energy separation between the two states, f_α, f_β are the distribution functions of the electron in the initial and final states, respectively, $K_{n_\alpha, n_\beta} = \int_{-\infty}^{-\infty} \phi_{n_\alpha}^*(z) z \phi_{n_\beta}(z) dz$, $L_{n_\beta, n_\alpha} = \int_{-\infty}^{-\infty} \phi_{n_\beta}^*(z) \frac{\partial}{\partial z} \phi_{n_\alpha}(z) dz$, and $B_0(\Omega)$ is the linewidth function and can be expressed as follows [11]

$$\begin{aligned} B_0(\Omega) = {} & \frac{\pi}{(f_\beta - f_\alpha)} \sum_{q,\eta} \left| C_{\beta\eta}(q) \right|^2 \Big\{ [(1+N_q) f_\alpha (1-f_\eta) - N_q f_\eta (1-f_\alpha)] \delta(\hbar\Omega - E_{\eta\alpha} - \hbar\omega_q) \\ & + [N_q f_\alpha (1-f_\eta) - (1+N_q) f_\eta (1-f_\alpha)] \delta(\hbar\Omega - E_{\eta\alpha} + \hbar\omega_q) \Big\} \\ & + \frac{\pi}{(f_\beta - f_\alpha)} \sum_{q,\eta} \left| C_{\alpha\eta}(q) \right|^2 \Big\{ [(1+N_q) f_\eta (1-f_\beta) - N_q f_\beta (1-f_\eta)] \delta(\hbar\Omega - E_{\beta\eta} - \hbar\omega_q) \\ & + [N_q f_\eta (1-f_\beta) - (1+N_q) f_\beta (1-f_\eta)] \delta(\hbar\Omega - E_{\beta\eta} + \hbar\omega_q) \Big\} , \end{aligned} \qquad (0)$$

where $C_{mm'}(q) = V(q) \langle k_{\perp m'}, m' | e^{iq_\perp r_\perp} | k_{\perp m}, m \rangle$ is the matrix elements of the electron-phonon interaction, which depends on the scattering mechanism; $| V_q |^2 = 2\pi e^2 \chi^* \hbar\omega_{L0} / \epsilon_0 V_0 q^2$ is the coupling factor, where ϵ_0 is the permittivity of the free space; $\chi^* = \chi_\infty{}^{-1} - \chi_0{}^{-1}$, where χ_∞ and χ_0 correspond to the static and high-frequency dielectric constant, respectively. The presence of the Dirac-delta function in Eq. (6) exhibits a resonant behavior because of the ODEPR condition: $\hbar\Omega \pm E_{\beta\alpha} \pm \hbar\omega_{LO} = 0$, where ω_{LO} is the longitudinal phonon frequency. These analytical results can be verified by numerical computation and graphical plotting using Mathematica software.

3. Numerical results and discussion

In this section, we use the Mathematica software to numerically calculate the optical absorption power in a $\mathrm{GaAs/Ga_{0.7}Al_{0.3}As}$ quantum well and the profile method [9] to find the linewidths of the resonant peaks. The material parameters are used as follows [10]: $\chi_\infty = 10.89$, $\chi_0 = 13.18$, $m^* = 0.067 m_0$ with m_0 being the mass of the free electron, $E_F = 50$ meV, $\epsilon_0 = 8.85 \times 10^{12}$ F/m, $\hbar\omega_{LO} = 36.25$ meV, $n_\alpha = 1$, and $n_\beta = 2$.

Figure 1 shows the dependence of the linear absorption power on the photon energy. From the figure, we can see three resonant peaks, the appearance of which can be explained as follows:

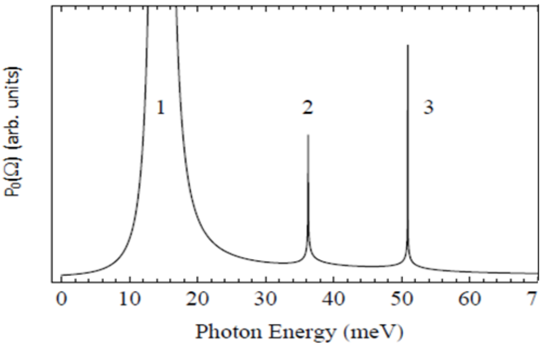

Fig. 1. Dependence of the absorption power on photon energy at $T = 300\,\mathrm{K}$ and $F = 10\times10^5\ \mathrm{V/m}$.

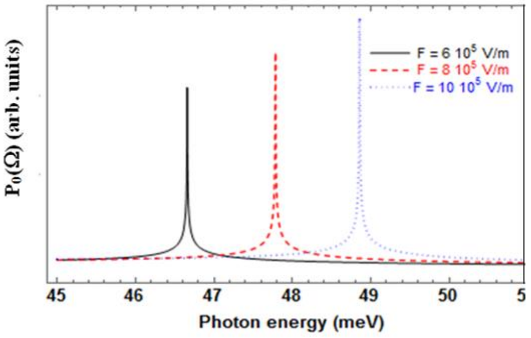

Fig. 2. Dependence of the absorption power on the photon energy for three different values of electric field *F*. The results are calculated at *T* = 300 K.

Peak 1, located at $\hbar\Omega = 14.63\ \mathrm{meV}$, satisfies the condition $\hbar\Omega = E_\beta - E_\alpha = 14.63\mathrm{meV}$. This is the process in which electrons from the state with energy E_α absorb a photon to move to the state with energy E_β without any phonon absorption or emission.

Peak 2, located at the photon energy of $\hbar\Omega = 36.25\ \mathrm{meV}$, satisfies the condition $\hbar\Omega = \hbar\omega_{LO}$. This peak is due to intra-subband transitions.

Peak 3, located at $\hbar\Omega = 50.88\ \mathrm{meV}$, satisfies the condition $\hbar\Omega = \hbar\omega_{LO} + (E_\beta - E_\alpha)$. This is the ODEPR peak, corresponding to the electron in the state with energy E_α, which absorbs one photon to jump to the state with energy E_β . This process is accompanied by an emission of one phonon with energy $\hbar\omega_{LO}$.

Figure 2 describes the dependence of the absorption power on the photon energy with different values of electric field *F* in the case of *T* = 300 K at the ODERP peak. From the figure, we can see that when the electric field increases, the magnitude of the absorption power is enhanced and the resonant peaks shift towards higher photon energies (blue-shift behavior). The main reason for the blue-shift behavior comes from the increase of the energy difference between E_α and E_β. This effect results from the fact that the electric field enforces the confinement of electrons in QW and leads to the increase of energy. The results are in good agreement with the study of Kang and co-workers [8].

Figure 3 describes the dependence of the absorption power on photon energy with different values of temperature at the ODERP peak. From the figure, we can see that the ODMPR-linewidth peaks locate at the same position ◦ω = 50.88 meV, corresponding to the condition of ODMPR and is independent of temperature.

Using the profile method, we obtain the dependence of the ODEPR linewidths on electric field *F* as shown in Fig. 4 and temperature *T* as shown in Fig. 5. It can be seen from Fig. 4 that the ODEPR-linewidths decrease with electric field *F*. This is probably because when the electric field increases, the confinement of the electron decreases, so that the probability of electron-phonon scattering decreases, and therefore do the ODEPR linewidths. Concerning the temperature dependence of linewidths, the ODMPR linewidths increase with temperature because the probability of electron LO-phonon scattering rises (Fig. 5).

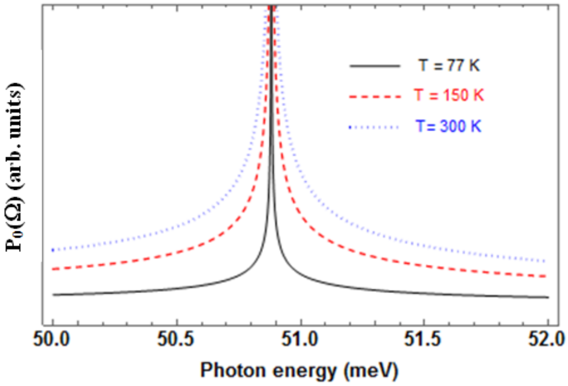

Fig. 3. Dependence of the absorption power on the photon energy for three different values of temperature. The results are calculated at $F = 10 \times 10^5$ V/m.

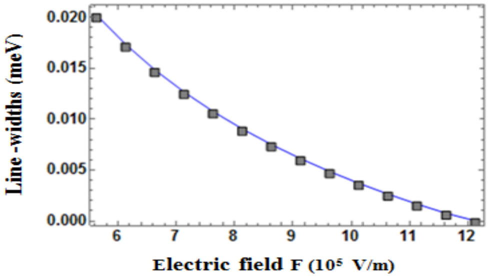

Fig. 4. Dependence of linewidths on electric field F at $T = 300\,\mathrm{K}$

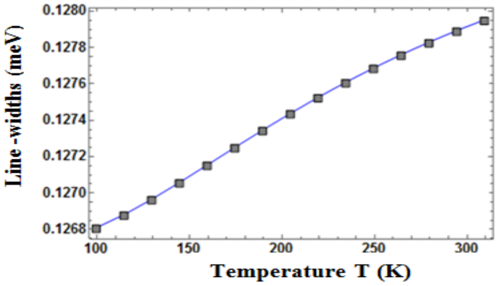

Fig. 5. Dependence of linewidths on temperature T at $F = 10 \times 10^5$ V/m

4. Conclusions

We have theoretically investigated the linear optical absorption power and linewidths due to confined electrons interacting with LO-phonons in a QW with the triangular potential subjected to a laser field. We have found that the absorption power magnitude and linewidths depend significantly on the change of the electric field. The resonant peaks of the absorption power shift towards higher photon energies when the electric field increases, while the linewidths decrease with the electric field. Furthermore, our results also reveal that with the increase of the temperature, the absorption power magnitude and linewidths increase, but the resonant peaks are stable with the variation of temperature.

Acknowledgments: This work is supported by the Ministry of Education and Training under the project coded B2017-DHH-32.

References

1. Sang Chil Lee, *Optically detected magnetophonon resonances in quantum wells*, J. Korean Phys. Soc. 51, (2007), 1979.
2. V.V. Afonin and V.L. Gurevich, *Theory of magnetophonon resonance in quantum wells*, Phys. Rev. B. 62, (2000),15913.
3. D. Schioberg, *The energy eigenvalues of hyperbolical potential functions*, Mol. Phys. 59, (1986), 1123.
4. Shi-Hai Dong, A. Gonzalez-Cisneros, *Energy spectra of the hyperbolic and second Pöschl Teller like potentials solved by new exact quantization rule*, Annals of Physics 323, (2008), 1141.
5. P. Vasilopoulos, P. Warmenbol, F. M. Peeters and J. T. Devreese, *Magnetophonon resonances in quasi-one-dimensional wires*, Phys. Rev. B. 40, (1989), 1810.
6. W. P. Hong and J. Singh, *Study of excitons in an arbitrarily shaped GaAs/Al0.3Ga0.7As single quantum well in the presence of static transverse electric field*, J. Appl. Phys. 61, (1987), 5346.
7. D. H. S. Nam Lyong Kang, S. D. C. Sam Nyung Yi, *Prediction of Intraband Transition Linewidths due to Longitudinal Optical Phonon Scattering in GaN for Electrons in Quantum Wells*, J. Kor. Phys. Soc. 46, (2005), 1040.
8. N. L. Kang, H. M. Lee, S. C. Lee, S. D. Choi, *Theory of intraband transition linewidths due to LO phonon scattering in triangular well based on the many body projection method*, Eur. Phys. J. B 63, (2008), 59.
9. S. Yu, V. Pevzner, K. Kim, M. Stroscio, *Electrophonon resonance in cylindrical quantum wires*, Phys. Rev. B 58, (1998), 3580.
10. V. Zeghbroeck, *Principles of Semiconductor Devices*, Colarado University, 2004.
11. B. D. Hoi, L. T. T. Phuong, T. C. Phong, *Optically detected electrophonon resonance in quantum wells via two-photon absorption processes under the influence of phonon confinement*, Superlattices Microstruct. 100, (2016), 365.