OPTICALLY DETECTED ELECTROPHONON RESONANCE IN A SPECIAL ASYMMETRIC HYPERBOLIC-TYPE QUANTUM WELL

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Abstract: In this work, we study the absorption power in the special asymmetric hyperbolic-type (SAsH) quantum well when electrons are scattered with longitudinal optical phonons (LO-phonons). The explicit analytic expression for absorption power (AP) is obtained using the projection operator technique. Conditions for optically detected electrophonon resonance (ODEPR) are obtained based on the energy conservation law. Computational results show that the absorption power as well as the full width at half maximum (FWHM) of the ODEPR peaks increase with temperature and decrease with the characteristic parameters of the quantum well. Moreover, these results also show the agreement with previous studies in both theoretically and experimentally.
Keywords: Electrophonon resonance, Absorption power, the full width at half maximum, Special asymmetric hyperbolic-type.

1 INTRODUCTION

To manufacture optoelectronic and photo-magnetic components that have size few nanometers, scientists have constantly been investigated to the new materials where dynamic effects are considered in the presence of external field to understand transport properties of electron in these models. In addition, at temperature $T >$ 50 K, the electron mobility will be strongly influenced by the scattering process of the electrons with phonons. Bryskin and Firsov [1] predicted that electron-phonon resonance (EPR) appear in nondegenerate semiconductors under the influence of strong external electric field. EPR is a useful tool to determine distances between the lowest subband energy levels as well as effective mass when the processes of electron

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transition are included by absorption and emission of a LO-phonon. Furthermore, ODEPR is also obtained by applying a high-frequency electromagnetic field to detect EPR.

More specifically, the FWHM of resonant peaks is well-known as a good tool for investigating the scattering mechanisms of carriers and can be used to study electrophonon scattering processes. For quasi-two dimensional semiconductor quantum well structures, Lee *et al.* [2] have reported the ODEPR effects for square potential and parabolic potential where the optical conductivity is dependent of the confinement frequency and the width of well. Kang *et al.* [3] have demonstrated that the FWHM in GaN depends on the temperature, the electron density, and electric field due to LO-phonon scattering for the electrons in the triangular potential well. Duan *et al.* [4] showed that the electron–phonon scattering rates due to intrasubband and the intersubband increase with the increase of well width until 110 Å. Besides, when phonon confinement is considered, the obtained results revealed that the FWHMs of the ODEPR peaks in the cases of confined phonons are greater than those in the case of bulk phonons. However, the above mentioned work only focuses on traditional potentials, especially the SAsH potential quantum well, are still restricted.

In this work, we investigate the ODEPR effect due to electron - LO phonon interaction in the SAsH quantum well under the influence of electromagnetic field. First, we obtain the AP expression using the state dependence projection operator technique and consider the ODEPR conditions. Then we use the profile method to consider the dependence of FWHMs on temperature and parameter of the well. Finally, the brief results are presented in the conclusion section.

2 EXPRESSION OF ABSORPTION POWER OF ELECTROMAGNETIC WAVE

We consider the SAsH quantum well in which electrons move freely in the $(x\text{-}y)$ plane and are confined in the z direction with the following potential [7]

$$V(z) = V_0\left(\frac{a}{z} - \frac{z}{a}\right)^2, \tag{1}$$

where V_0 is the confinement potential height and a is the parameter a characterizing the well width. As reported

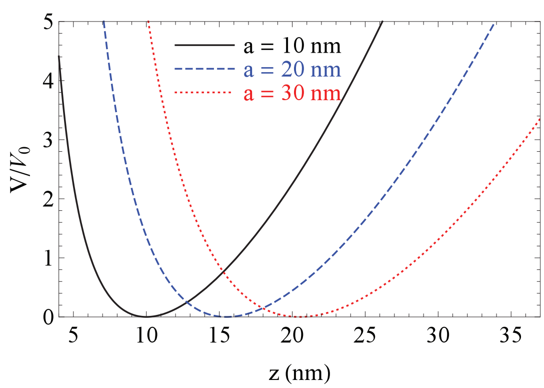

Figure 1: The SAsH quantum well model for different values of a-parameter.

in [8], the quantum well becomes more asymmetric and wider with increasing the a-parameter, as displayed in Fig. 1. Solving Schrödinger equation for electron in z direction, we obtain the eigenstates and corresponding eigenenergies in the following form [7]

$$\phi_n(z) = \mathcal{C}_n z^{\frac{\alpha+1}{2}} e^{-\beta z^2} {}_1F_1\big(-n, \alpha+1, 2\beta z^2\big) \quad (2)$$

$$\varepsilon_n = \frac{2\hbar}{a}\sqrt{\frac{2V_0}{m^*}}\big(n + \frac{1}{2} + \frac{\alpha}{2} - a^2\beta\big), \quad n = 0, 1, 2\cdots, \quad (3)$$

with $\beta = (m^* V_0/2\hbar^2 a^2)^{1/2}$ having the unit of m^{-2}, $\alpha = (16a^4\beta^2 + 1)^{1/2}/2$ is a dimensionless quantity, and ${}_1F_1$ refers to the confluent hypergeometric function. The normalization constants $\mathcal{C}_n$ for the two first states are given as follows: $\mathcal{C}_0 = 2^{\alpha/2+1}\beta^{(\alpha+1)/2}/(\Gamma(\alpha+1))^{1/2}$ and $\mathcal{C}_1 = \mathcal{C}_0(\alpha+1)^{1/2}$.

The overall of electron eigenfunctions and eigenvalues are

$$\langle \mathbf{r}|n\rangle \equiv \langle \mathbf{r}|k_x, k_y, n\rangle = \frac{1}{\sqrt{L_x L_y}} e^{ik_x x} e^{ik_y y}\phi_n(z), \quad (4)$$

$$E_\lambda = E_n(k_x, k_y) = \frac{\hbar^2(k_x^2 + k_y^2)}{2m^*} + \varepsilon_n, \quad (5)$$

where $m^* = m_0(0.067 + 0.083x)$ is the effective mass of a conduction electron with m_0 and x being the mass of a free electron and the alloy concentration, respectively, $\mathbf{r}$ is the position vector of electron, k_x, k_y, L_x and L_y correspond to the electron wave vector and the well's widths in the $(x-y)$ plane, respectively.

Using the projection operator technique [6, 9], we find the analytical expression of the absorption power in SAsH quantum well due to photon absorption with simultaneous absorption and/or emission of phonons is

$$\mathcal{P}_0(\Omega) = A(\Omega, a)\sum_{n_\alpha, n_\beta} \frac{(f_\beta - f_\alpha)B_0(\Omega)}{[\hbar\Omega - (E_{n_\beta} - E_{n_\alpha})]^2 + B_0^2(\Omega)}\delta_{n_\alpha,n_\beta} K_{n_\alpha,n_\beta} L_{n_\beta,n_\alpha}, \quad (6)$$

here, we have denoted $K_{n_\alpha,n_\beta} = \int_{-\infty}^{-\infty}\phi^*_{n_\alpha}(z) z \phi_{n_\beta}(z)dz$, $L_{n_\beta,n_\alpha} = \int_{-\infty}^{-\infty}\phi^*_{n_\beta}(z)\frac{\partial}{\partial z}\phi_{n_\alpha}(z)dz$, $A(\Omega, a)$ is constant, respectively. Quantity $B_0(\Omega)$ is the imaginary part of damping term, which are called the line-width function, will be defined as follows [10]

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

$$+ \quad [N_q f_\eta(1-f_\beta)-(1+N_q)f_\beta(1-f_\eta)]\delta(\hbar\Omega - E_{\beta\eta}+\hbar\omega_q)\big\}, \tag{7}$$

where $E_{\beta\alpha} = E_\beta - E_\alpha = E_{n_\beta} - E_{n_\alpha}$, $C_{mm'}(q) = V(q)\langle k_{\perp m'}, m'|e^{i\vec{q_\perp}\vec{r_\perp}}|k_{\perp m}, m\rangle$ is the matrix elements of electron-phonon interaction which depends on the scattering mechanism.

These above analytical results appear very complex. However, physical conclusions can be drawn from graphical representations and numerical results, obtained from satisfying computational methods in the next section.

3 NUMERICAL RESULTS AND DISCUSSION

We now discuss the ODEPR effect in GaAs/AlGaAs SAsH quantum well through investigating the AP and FWHM, in which we only consider the transition between two first states, i.e., the transition from the $n_\alpha = 0$-state to $n_\beta = 1$ one. We use the following characteristics in our numerical calculations: The electron density $n_e = 3\times10^{16}$ cm^{-3} corresponding to the Fermi energy of $E_F = 83.08$ meV. The other parameters are $E_0 = 4\times10^5$ V/m, and $U_0 = 228$ meV [11].

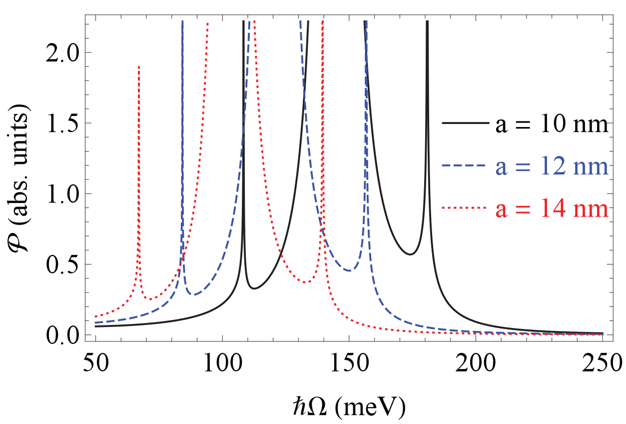

Figure 2: Dependence of the AP on the photon energy for different values of a-parameter. Here $T = 300$ K.

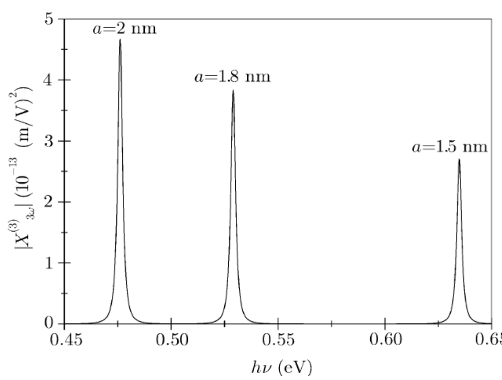

Figure 3: This is figure 4 in Ref. [12].

In figure 2, AP is plotted as functions of photon energy for three different values of a-parameter at $T = 300$ K. The four maxima appeared in each curve which satisfy the ODEPR conditions $\hbar\Omega \pm E_{\beta\alpha} \pm \hbar\omega_{LO} = 0$. From the figure we can see that the resonant peaks give a shift towards the low energy region (red-shift) when the values of a-parameter decrease. These results are well matched with previous work reported for the third-harmonic generation susceptibility, shown by figure 3 in Ref. [12] (corresponding to figure 3). This red-shift of resonant peaks is caused by the reduction of threshold energy with the increase of a-parameter (presented in Ref. [13]). Physically, when the a-parameter is greater, the well-width becomes wider, resulting in the decrease of quantum confinement, leading to the narrower energy separation $\Delta E_{01} = E_1 - E_0$, and so does the threshold energy ΔE.

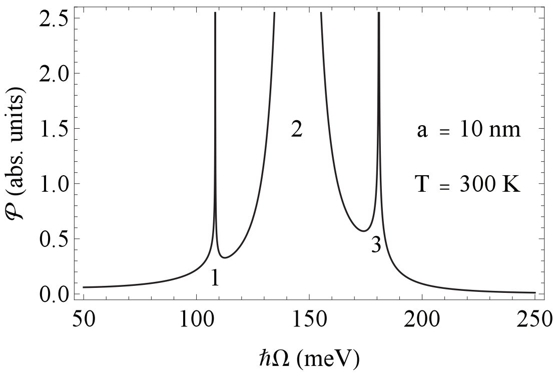

Figure 4: The AP versus photon energy at $a = 10$ nm, and $T = 300$ K.

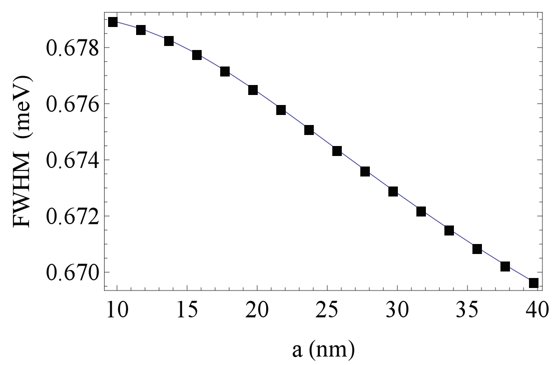

Figure 5: FWHM is a function of a-parameter at $T = 300$ K.

Figure 4 shows the dependence of AP on photon energy in the case of $a = 10$ nm. The three resonant peaks, labeled from "1" to "3" can be explained as follows:

+ Peak 1, located at $\hbar\Omega = 108.32$ meV, satisfies the condition $\hbar\Omega = E_\beta - E_\alpha - \hbar\omega_{LO} = 108.32$ meV. This is the ODEPR peak, corresponding to the electron in the state with energy E_α absorbs one photon to jump to the state with energy E_β. This process accompanies with one phonon absorption with energy $\hbar\omega_{LO}$.

+ Peak 2, located at $\hbar\Omega = 144.58$ meV, satisfies the condition $\hbar\Omega = E_\beta - E_\alpha = 144.58$ meV. This is the process in which electrons from the state α absorbs a photon to move to the state β without any phonon absorption or emission.

+ Peak 3, located at $\hbar\Omega = 180.82$ meV, satisfies the condition $\hbar\Omega = E_\beta - E_\alpha + \hbar\omega_{LO} = 180.82$ meV. This is the ODEPR peak, corresponding to the electron in the state with energy E_α absorbs one photon to jump to the state with energy E_β. This process accompanies with an emission one phonon with energy $\hbar\omega_{LO}$.

In the following, we use peak 1 to examine the FWHM of ODEPR peak using the profile method. From figure 5, we observe that FWHM reduces with increasing a-parameter. As mentioned above, when the a-parameter increases, the well-width becomes wider, leading to the reduction of quantum confinement and, therefore, bringing down the electron–phonon interaction, and so does the FWHM. This result agrees qualitatively with that in the previous works [13, 14], in which the FWHM is reported to decrease with increasing well-width.

Figure 6 shows the dependence of the AP on the photon energy for three different values of temperature T at $a = 10$ nm. From the figure, we can see that the temperature does not affect the position of the ODEPR resonant peaks but changes the peak intensities. The higher temperature is, the greater resonant peak intensities are. This can be explained as follows: The AP magnitude mainly depends on temperature due to the temperature dependence of phonon populations, N_0. Its position is decided through the selection rules as indicated by the delta functions in Eq. (7). As the increase of temperature, the phonon populations increase, which in turn leads to the increase in AP magnitude. Whereas, since the temperature independence of the delta functions, the absorbed photon energies are maintained with the change of the temperature. This behavior is consistent with that shown in previous works [6, 9].

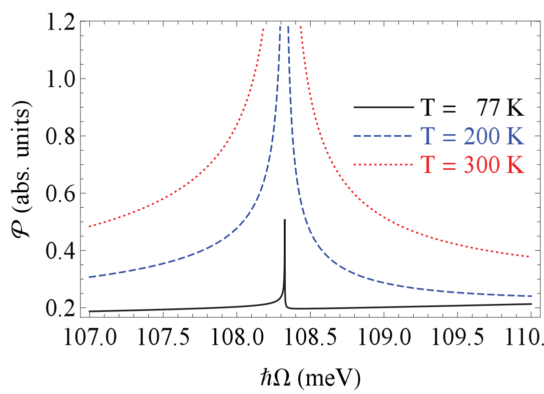

Figure 6: Dependence of the AP on the photon energy for different values of T at $a = 10$ nm.

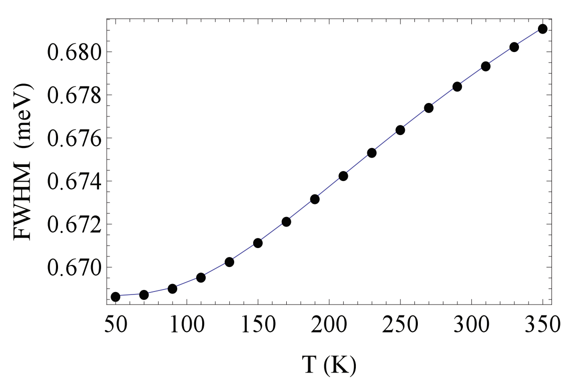

Figure 7: FWHM versus T at $a = 10$ nm.

Finally, we found that the FWHM of ODEPR increases with the increase of the temperature, shown in figure 7. Physically, this means that FWHM is proportional to the possibility of the electron–LO phonon scattering, which increases as the temperature increases. The result is consistent with that shown in previous work for electro-phonon resonance line-width [15, 16].

4 CONCLUSIONS

In this paper, we have theoretically investigated the absorption power and FWHM due to confined electrons interacting with LO-phonons in a SAsH quantum well, subjected to a electromagnetic field. We have demonstrated that with the increase of the temperature, the AP and FWHM of the ODEPR increase but resonant peaks are unchanged with the change of temperature. Moreover, our results also reveal that AP and FWHM strongly depend on the characteristic parameters of confined potential shapes. The resonant peaks of AP shift towards photon lower energies as a-parameter increases. In addition, FWHM decreases with the a-parameter. These results would be opened up the way to orientate the experimental investigation in the future and could be important for device applications.

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