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Influence of Electric Field on Properties of Strong-coupling Magnetopolaron in Quantum Well

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Abstract The influence of electric field on properties of strong-coupling magnetopolaron in quantum well was investigated using linear-combination operator and unitary transformation method. The ground state energy and vibration frequency of magnetopolaron were obtained. The effects of well-width L, electric field strength F and the cyclotron frequency ω_c of magnetic field on the ground state energy were discussed. The relations of the ground state energy of the magnetopolaron with the coupling constant, the well-width and the electric field strength are derived. Numerical calculations illustrated that the absolute value of the ground state energy of the strong-coupling magnetopolaron will decrease with increasing the well-width and increase with increasing the external electric field strength. The absolute value of the ground state energy of the strong-coupling magnetopolaron will rise with increasing the cyclotron frequency. The smaller well-wider and the larger is the absolute value of the ground state energy of the magnetopolaron, the peculiar quantum size effect is significant.

Key words: linear combination operator; magnetopolaron; quantum-well; electric field
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1 Introduction

With the development of the growth techniques of the semiconductor, the well performance heterostructures, quantum well and superlattice have been prepared, which is the great breach in semiconductor physics and material science. In recent years, many physicists studied the properties of the polaron in the quantum well with various methods. The influence of phonon on the properties of the electron in the microstructure and the properties of the phonon located in the external field have attracted much interest for the physicists.

For the system located in the external field, Larsen[1] calculated the two-dimensional polaron's energy in the magnetic field by using harmonic oscillator operator algebra method. Thinking about the electro-interacts with the bulk LO phonon and the surface optical phonon, Gu *et al*[2]. investigated magnetopolaron cyclotron vibration in the semiconductor quantum well by using the pertubation method. Wei *et al.*[3] investigated vibration magnetic-field of the Coulomb impurity bound magnetopolaron in the GaAs/$Ga_{1-x}Al_xAs$ quantum well by using MacDonald method. Eerdunchaolu *et al*[4]. investigated the electric-magnetic fields and temperature dependence using variational wave-function and harmonic oscillator operator algebra method. Ferreira[5] and Claro *et al.*[7] investigated the electron bulk LO phonon coupling system in the infinite high barrier quantum well which located in the electric-magnetic field paralleling the growth axis. But so far, very few scholars investigated the influence of electric field on properties of strong-coupling magnetopolaron

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in quantum well by using linear combination operator method. Recently, Chen *et al.*[7] investigated the influence of the electric field on the properties of binding polaron in quantum well. In this paper we studied the influence of the electric-field on properties of strong-coupling magnetopolaron in quantum well by using the linear-combination operator and unitary transformation method. The relations of the ground state energy with the well-width, the electric field strength and the cyclotron frequency were obtained.

2 Theory

We consider a quantum well of a polar semiconductor filled on the range of $|z| \leqslant L$ with the infinite high barrier materials filled in the space $|z| \geqslant L$. An electron located in the quantum well and an electric field $\boldsymbol{F}$ and a magnetic field $\boldsymbol{B}$ are applied in the z-direction. The total Hamiltonian for the system can be expressed as

$$H = H_0 + H_{\text{e-ph}} \tag{1}$$

with

$$H_0 = \frac{1}{2m}\left[\left(P_x - \frac{\beta^2}{4}y\right)^2 + \left(P_y + \frac{\beta^2}{4}x\right)^2\right] + \frac{P_z^2}{2m} + \sum_k \hbar\omega_{\text{L}} a_k^+ a_k + |e| Fz + V(z) \tag{2}$$

Using a Frohlich-like Hamiltonian for the electron-LO-phonon interaction

$$H_{\text{e-ph}} = \sum_k (V_k^* a_k^+ \mathrm{e}^{-i\boldsymbol{k}\cdot\boldsymbol{r}} + h\cdot c) \tag{3}$$

For an infinite quantum well we have introduced the confinement potential

$$V(z) = \begin{cases} 0, & -\frac{1}{2}L \leqslant z \leqslant \frac{1}{2}L \\ \infty, & |z| > \frac{1}{2}L \end{cases} \tag{4}$$

The electron band mass is denoted by m and L is the well-width, e is the electron charge, its position $r = (x, y, z)$ and its momentum $\boldsymbol{p} = (p_x, p_y, p_z)$, a_k^+ and a_k are the creation and annihilation operators of the LO phonons with the wave vector $\boldsymbol{k}$.

where
$$V_k = -i\left(\frac{\hbar\omega_{\text{L}}}{k}\right)\left(\frac{\hbar}{2m\omega_{\text{L}}}\right)^{1/4}\left(\frac{4\pi\alpha}{V}\right)^{1/2} \tag{5}$$

$$\alpha = \frac{e^2}{2\hbar\omega_{\text{L}}}\left(\frac{2m\omega_{\text{L}}}{\hbar}\right)^{1/2}\left(\frac{1}{\varepsilon_\infty} - \frac{1}{\varepsilon_0}\right) \tag{6}$$

ω_{L} is the frequency of the LO phonon and α is the Frohlich electron-phonon coupling constant, V is the volume of the crystal.

where
$$\beta^2 = 2eB/c \tag{7a}$$

and
$$\omega_{\text{c}} = \frac{eB}{mc} \tag{7b}$$

We introduce the linear-combination of the creation and annihilation operator b_j^+ and b_j to represent the momentum and position of the electron

$$p_j = \left(\frac{m\hbar\lambda}{2}\right)^{1/2}(b_j + b_j^+) \tag{8a}$$

$$j = x, y$$

$$r_j = i\left(\frac{\hbar}{2m\lambda}\right)^{1/2}(b_j - b_j^+) \tag{8b}$$

and
$$[b_i, b_j^+] = \delta_{ij} \tag{8c}$$

Here λ is vibration frequency of the polaron and is a variational parameter. We substitute Eq. (8) into Eq. (1) and carry out unitary transformation

$$U = \exp\left[\sum_k (a_k^+ f_k - a_k f_k^*)\right] \tag{9}$$

where f_k (f_k^*) is the variational parameter. The transformed Hamiltonian can be rewritten as

$$\begin{aligned} H' = {} & \frac{\hbar\lambda}{4}\sum_j (b_j b_j + b_j^+ b_j^+ + 2b_j^+ b_j + 1) - \\ & \frac{\beta^4\hbar}{64m^2\lambda}[b_x b_x + b_x^+ b_x^+ - 2b_x^+ b_x - 1 + b_y b_y + b_y^+ b_y^+ - \\ & 2b_y^+ b_y - 1] - \frac{\beta^2\hbar i}{8m}[(b_y - b_y^+)(b_x + b_x^+) - \\ & (b_x - b_x^+)(b_y + b_y^+)] + \sum_k \hbar\omega_{\text{L}}(a_k^+ + f_k^*)\cdot \\ & (a_k + f_k) + \sum_k \Big\{ V_k^*(a_k^+ + f_k^*)\cdot \\ & \exp\left[-\sum_j k_j b_j^+\left(\frac{\hbar}{2m\lambda}\right)^{1/2}\right]\exp\left[\sum_j k_j b_j\left(\frac{\hbar}{2m\lambda}\right)^{1/2}\right]\cdot \\ & \exp\left(-\frac{k^2\hbar}{4m\lambda}\right)\exp(ik\cdot z) + h\cdot c\Big\} + \frac{P_z^2}{2m} + |e|Fz \end{aligned} \tag{10}$$

The trial wave function can be written as[8]

$$|\psi\rangle = \varphi_n(z)|0\rangle \tag{11}$$

where $|0\rangle$ is the zero-phonon of the phonon field. $\varphi_n(z)$ is the wave function of the electron moving along with z-direction, and

$$\varphi_n(z) = \begin{cases} N(\gamma)\exp[-\gamma(z/L + 1/2)]\cos(\pi z/L), & |z| \leqslant L/2 \\ 0, & |z| > L/2 \end{cases} \tag{12}$$

where γ is a variational parameter and may be obtained by minimizing the total ground energy. $N(\gamma)$ is a normalization constant which is easily obtained by the relation

$$N(\gamma) = 4\gamma(\gamma^2 + \pi^2)[L\pi^2(1 - e^{-2\gamma})]^{-1} \quad (13)$$

The expectation value of the total Hamiltonian can be obtained as

$$F = \langle \phi | H' | \phi \rangle = \frac{\hbar\lambda}{2} + \sum_k \hbar\omega_L |f_k|^2 + \frac{\beta^4 \hbar}{32m^2\lambda} + \sum_k V_k^* f_k^* \exp\left(-\frac{k^2\hbar}{4m\lambda}\right) \cdot \exp[-ik_z z] + \langle \phi \left| \frac{P_z^2}{2m} \right| \phi \rangle + \langle \phi | eFz | \phi \rangle \quad (14)$$

For $\frac{\partial F}{\partial f_k^*} = 0$, we may get the f_k.

We substitute f_k to Eq. (14) and obtain the ground energy of the strong-coupling magnetopolaron in quantum well is

$$F = \frac{\hbar\lambda}{2} + \frac{\beta^4\hbar}{32m^2\lambda} - \frac{2\alpha}{\pi}\int_0^\infty \frac{(\hbar\omega_L)^2\left(\frac{\hbar}{2m\omega}\right)^{1/2}\exp\left[\frac{k^2\hbar}{2m\lambda}\right]}{\hbar\omega_L}dk + \frac{\hbar^2(\pi^2-\gamma^2)}{2mL^2} + |e|FL\left(\frac{1}{2\gamma} + \frac{\gamma}{\gamma^2+\pi^2} - \frac{1}{2}\coth\gamma\right) = \frac{\hbar\lambda}{2} + \frac{\beta^4\hbar}{32m^2\lambda} - \alpha\hbar\sqrt{\frac{\omega_L\lambda}{\pi}} + \frac{\hbar^2(\pi^2-\gamma^2)}{2mL^2} + |e|FL\left(\frac{1}{2\gamma} + \frac{\gamma}{\gamma^2+\pi^2} - \frac{1}{2}\coth\gamma\right) \quad (15)$$

For $\frac{\partial F}{\partial\lambda} = 0$, we may get

$$\lambda^2 - \alpha\sqrt{\frac{\omega_L}{\pi}}\lambda^{3/2} - \frac{\beta^4}{16m^2} = 0 \quad (16)$$

3　Results and Discussion

As shown in the Eq. (15), the ground state energy E_0 of the strong-coupling magnetopolaron in the quantum well is not only related to the electron-LO-phonon coupling-strength α, but also the well-width L, the electric field strength F and the magnetic-field strength B. In order to clarify the influence of the electric-field on properties of strong-coupling magnetopolaron in quantum well, we take RbCl crystal quantum well as an example and perform the numerical calculation. The corresponding parameters for RbCl are $\varepsilon_0 = 12.83$, $\varepsilon_\infty = 10.9$, $\hbar\omega_L = 21.45$ meV, $m = 0.432 m_0$. Where m_0 is the free electron mass, and the electron-phonon coupling constant is $\alpha = 4.2$. The numerical calculation results are shown the figures in Fig. 1~6 and every figure makes the meV as the energy unit.

The Fig. 1 describes the variation of the external electric-field strength versus the variational parameter with the well width $L = 8$ nm and $L = 10$ nm. The figure clearly shows that the external electric-field strength increases with increasing the variational parameter. The well width is more wider and the electric-field is more stronger for a given variational parameter. The Fig. 2 shows the relation of the vibration frequency λ of the strong coupling magneto-polaron in quantum well with the cyclotron frequency ω_c of the magnetic field. We may make out from the figure the vibration frequency λ of the magneto-polaron increases with increasing the cyclotron frequency ω_c of the magnetic-field. From the equation $\omega_c = \frac{eB}{mc}$, we may know that the vibration frequency

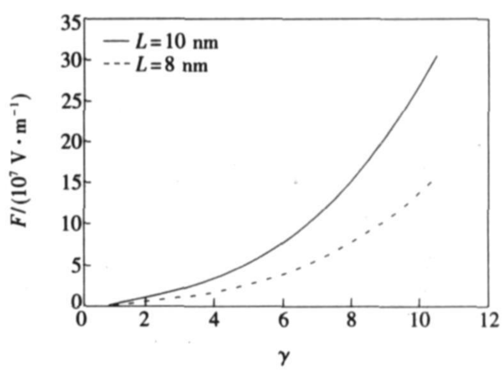

Fig. 1　External electric-field strength F versus the variational parameter for different well width L.

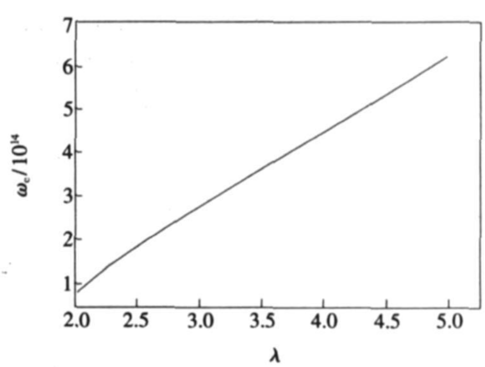

Fig. 2　Cyclotron frequency ω_c versus the vibration frequency λ.

λ of the magnetopolaron increases with increasing the magnetic-field strength B.

The Fig. 3 and Fig. 4 respectively describe the variational of the ground state energy of the strong-coupling magnetopolaron versus the well width with the different variational parameters and the different electric-field strengths. The two figures clearly show the influence of the electric field on the ground state energy of the magnetopolaron in the quantum well. They show that the absolute value of the ground state energy of the magnetopolaron decreases with increasing the well width. This is the peculiar quantum size effect. In Fig. 3 the ground state energy of the magnetopolaron in the quantum well is acted as a function of the electric-field strength for the different variational parameters $\gamma = 4$, $\gamma = 5$, $\gamma = 6$ and the electric-field strength $F = 4 \times 10^6$ V/m. From the Fig. 3, we may know that the change of the ground state energy of the magnetopolaron is more obviously with the change of the well width for the larger variational parameter. In Fig. 4 the ground state energy of the magnetopolaron in the quantum well is acted as a function of the well width for the different electric-field strengths $F = 2 \times 10^6$ V/m, $F = 4 \times 10^6$ V/m, $F = 6 \times 10^6$ V/m and a given variational parameter $\gamma = 4$. We also see that the absolute value of the ground state energy of the magnetopolaron changes obviously with the small electric-field strength. For a constancy well width, the absolute value of the ground state energy of the magnetopolaron becomes larger with a larger electric-field strength. The fourth term and the fifth term in Eq. (15) embody the relation between the ground state energy of the magnetopolaron and the well width. The influence of the fifth term on the ground state energy is larger than the fourth term. The Fig. 3 compared with the Fig. 4, for $\gamma = 4$ and $F = 4 \times 10^6$ V/m, and the change of the curve of the Fig. 4 is obvious. The result is that the influence of the electric field on the ground state energy is larger than the variational parameter.

As shown that the curves of the ground state energy E_0 of the magnetopolaron versus the electric-field strength F for different well width L and different variational parameters γ are given respectively in Fig. 5 and Fig. 6. From the Fig. 6 we easily find that the absolute value of the ground state energy of the magnetopolaron increases monotonically with increasing the electric-field strength. According to the fifth in Eq. (15), the increase of the external electric-field strength will result in the increase of the electric-field energy of the magnetopolaron and cause the total ground state energy to increase. We can see from the Fig. 5 that the ground state energy of the

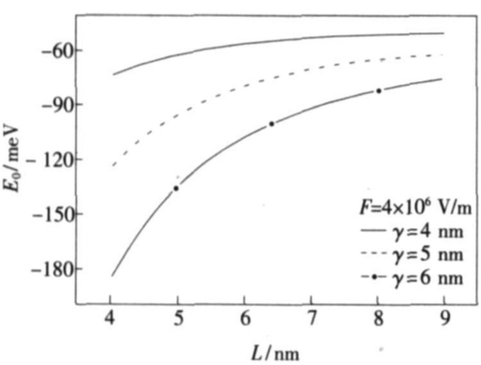

Fig. 3 Ground state energy E_0 of the magnetopolaron versus the well width L for different variational parameter γ.

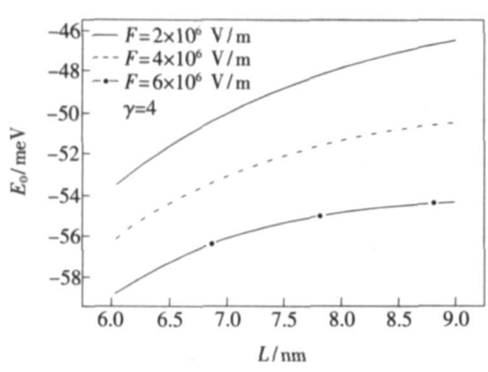

Fig. 4 Ground state energy E_0 of the magnetopolaron versus the well width L for different electric-field strength F.

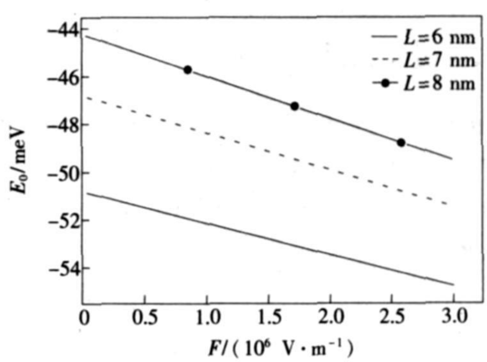

Fig. 5 Ground state energy E_0 of the magnetopolaron versus the electric-field strength F for different well width L.

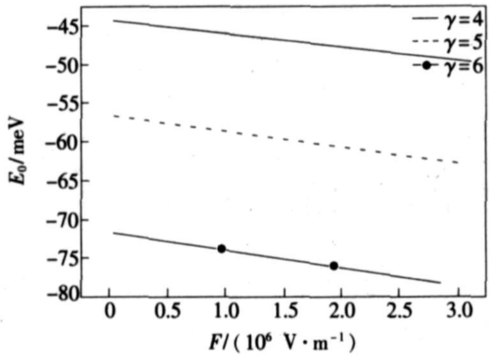

Fig 6 Ground state energy E_0 of the magnetopolaron versus the electric-field strength F for different variational parameter γ.

magnetopolaron decreases with increasing the well-width for a given electric-field strength. We also can see by the diagram that the well-width takes wider and the ground state energy of the magnetopolaron changes more obviously with the electric-field strength varieties. We compare the fourth term with the fifth term in Eq (15), and the fifth term rises the predominant function. The Fig 6 shows that the several lines are almost parallel for the different variational parameter. The ground state energy of the magnetopolaron increases with increasing the variational parameter for a constancy electric-field strength. The Fig 5 and Fig 6 do comparison, and the curve of the Fig 5 changes more obviously. It is to say that the influence of the well-width on the ground state energy of the magnetopolaron is larger and the variational parameter is smaller.

4 Conclusion

We investigated the influence of electric field on properties of strong-coupling magnetopolaron in quantum well by using linear-combination operator and unitary transformation method. We not only obtain the relation about the ground state energy of the strong-coupling manetopolaron in quantum well with the well-width, the electric-field strength and the variational parameter, but also get the relation of the variational parameter with the external electric-field strength and the relation of the cyclotron frequency of the magnetic-field with the vibration frequency. And we carried on the discussion to these relations. Numerical calculations illustrated that the absolute value of the ground energy of the strong-coupling magnetopolaron decreases with rising the well-width and rises with rising the external electric field strength. For a given well-width, the absolute value of the ground state energy of the magnetopolaron increases with increasing the variational parameter. When the well-width is smaller, the variety of the ground state energy of the magnetopolaron is more obvious with the changing of the variational parameter. For the constancy electric-field strength, the absolute value of the ground state energy of the magnetopolaron decreases with increasing the well-width and the ground state energy of the magnetopolaron changes more obviously with the wider well-width.

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电场对量子阱中强耦合磁极化子性质的影响

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摘要: 研究了量子阱中强耦合磁极化子在电场作用下的性质, 采用线性组合算符及幺正变换的方法导出了强耦合磁极化子的振动频率 λ和基态能量 E_0。讨论了强耦合磁极化子的基态能量与阱宽、电场强度、回旋频率之间的关系。通过数值计算, 结果表明: 强耦合磁极化子的基态能量的绝对值随着阱宽的增加而减小, 随着外加电场强度的增加而增加; 磁极化子的基态能量的绝对值随着磁场的回旋频率的增加而增加; 磁场的回旋频率随着磁极化子的振动频率的增加而增加。

关 键 词: 线性组合算符; 磁极化子; 量子阱; 电场
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