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Influence of the Electric Field on the Properties of the Bound Magnetopolaron in GaAs Semiconductor Quantum Wells*

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Abstract: The influence of the electric field on the properties of the bound magnetopolaron in an infinite-depth GaAs semiconductor quantum well is investigated using the linear-combination operator and the unitary transformation method. The relationships between the polaron's ground state energy and the Coulomb bound potential, electric field, magnetic field, and well-width are derived and discussed. Our numerical results show that the absolute value of the polaron's ground state energy increases as the electric field and the Coulomb bound potential increase, and decreases as the well-width and the magnetic field strength increase. When the well-width is small, the quantum size effect is significant.

Key words: quantum well; bound magnetopolaron; linear combination operator; ground state energy
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1 Introduction

With the rapid development of magneto-optical techniques, a great deal of interesting phenomena on the magnetopolaron in the semiconductor and crystal materials has been studied experimentally and theoretically. For instance, Wei *et al*.[1] investigated the vibrational magnetic field of the Coulomb impurity bound magnetopolaron in GaAs/Ga_{1-x}AlAs quantum wells using the MacDonald method. The bound magnetic polarons in dilute magnetic semiconductors was investigated by Wolff *et al*.[2] experimentally. Using the Winger-Brillouin perturbation method, Chen *et al*.[3] studied the electron-phonon interaction and the magnetopolaronic impurity transitions in quantum wells. Hai *et al*.[4] studied the polaron-cyclotron-resonance spectrum in GaAs/AlAs quantum wells. Using the degenerate second-order perturbation theory, the polaron's Landau levels were calculated and the resonant region was studied. Yu *et al*.[5] discussed the properties of the bound polaron effect in magnetic fields in terms of the linear combination operator and the unitary transformation method. Kasapoglu *et al*.[6] calculated the effect of crossed electric and magnetic fields on donor impurity binding energy using the appropriate coordinate change method and discussed the dependence of the donor impurity binding energy on the well-width, electric field, magnetic field, impurity position, and the external field orientation.

However, few people have studied the influence of the electric field on the properties of the bound magnetopolaron in quantum wells using the liner-combination operator and the unitary transformation method. Chen *et al*.[7] investigated the influence of the electric field on the properties of the bound polaron in a quantum well in the absence of a magnetic field. In this paper, using the liner-combination operator and the unitary transformation method, we study the influence of the electric field on the properties of the bound magnetopolaron in GaAs semiconductor quantum wells. The dependence of the ground state energy on the well-width, electric field strength, magnetic field strength, and the Coulomb bound potential is derived and calculated numerically. At the same time, the relationship between the vibration frequency of the bound polaron, the magnetic field strength, and the Coulomb bound potential is discussed.

2 Theory

We consider a GaAs polar semiconductor quantum well filled in the range of $|z| \leqslant L$ with an infinite height barrier material occupying the space of $|z| \geqslant L$. An electron is in the quantum well coupled with the impurity in the center well and interacts with the polaron in the semiconductor. An electric field F is applied in the z-direction. Using the Fröhlich Hamiltonian, the system can be expressed as[8]:

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$$H = -\frac{\hbar^2}{2m}\nabla^2 + U(Z) - \frac{e^2}{4\pi k_0 \varepsilon_\infty r} + \sum_K \hbar\omega_L a_K^+ a_K + \sum_K Q_K (a_K + a_{-K}^+) e^{iK\cdot r} + \frac{e^2}{2m}(\boldsymbol{B}\cdot\boldsymbol{L}) + \frac{e^2 A^2}{2m} + |e| FZ \quad (1)$$

For an infinite depth quantum well, the confinement potential is:

$$U(Z) = \begin{cases} \infty, & |Z| > \dfrac{d}{2} \\ 0, & |Z| < \dfrac{d}{2} \end{cases} \quad (2)$$

where the spin effect is ignored. k_0 is the permittivity of free space. The electron band mass is denoted by m, ω_L is the frequency of the LO-phonon, and $\boldsymbol{r} = (\rho, Z)$ is the position vector of the electron. The constant magnetic field $\boldsymbol{B}$ is along the z-direction, and $\boldsymbol{L}$ is the angle momentum. We describe the vector potential with $\boldsymbol{A} = (\boldsymbol{B}\times\boldsymbol{r})/2$. Here a_K^+ and a_K are the creation and annihilation operators of the LO phonons with the wave rector $\boldsymbol{K}$.

$$Q_K = \left(\frac{\hbar\omega_L}{K}\right)\times\left(\frac{\hbar}{2m\omega_L}\right)^{1/4}\times\left(\frac{4\pi\alpha}{V}\right)^{1/2} \quad (3a)$$

where V is the volume of the semiconductor and α is a normalization constant of the Fröhlich electron-phonon coupling constant.

$$\alpha = \frac{e^2}{4\pi k_0 \hbar}\times\left(\frac{m}{2\hbar\omega_L}\right)^{1/2}\times\left(\frac{1}{\varepsilon_\infty} - \frac{1}{\varepsilon_0}\right) \quad (3b)$$

where ε_0 and ε_∞, respectively, are the static dielectric constant and high frequency adiabatic constant.

Using the Fourier expansion

$$\frac{1}{r} = \frac{4\pi}{V}\sum_K \frac{1}{K^2}\exp(-i\boldsymbol{K}\cdot\boldsymbol{r}) \quad (4)$$

We carry out two unitary transformations to Eq. (1)

$$U_1 = \exp\left(-i\sum_K \boldsymbol{K}\cdot\rho a_K^+ a_K\right) \quad (5a)$$

$$U_2 = \exp\left[\sum_K (f_K^* a_K^+ - f_K a_K)\right] \quad (5b)$$

where $f_K(f_K^*)$ is the variational parameter.

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 in the x-y plane[9].

$$p_j = \left[\frac{m\hbar\lambda}{2}\right]^{1/2}(b_j + b_j^+) \quad (6a)$$

$$\rho_j = i\left[\frac{\hbar}{2m\lambda}\right]^{1/2}(b_j - b_j^+) \quad (6b)$$

With $j = x, y$; λ is the vibration frequency of the bound magnetopolaron and is also a variational parameter.

The trial wave function can be written as

$$|\Psi\rangle = \Phi(z)|0\rangle \quad (7)$$

where $|0\rangle$ is the zero-plane of the phonon field. $\Phi(z)$ describes the trial wave function of the electron moving along the z-direction in a one-dimensional infinite depth quantum well, and is given by[10]

$$\Phi(z) = \begin{cases} N(\beta)\exp[-\beta(z/L+1/2)]\cos(\pi z/L), & |z| < L/2 \\ 0, & |z| \gg L/2 \end{cases} \quad (8)$$

where β is a variational parameter and may be obtained by minimizing the total ground state energy. $N(\beta)$ is a normalization constant can be obtained by the relation.

$$N^2(\beta) = 4\beta(\beta^2 + \pi^2)[L\pi^2(1 - e^{-2\beta})]^{-1} \quad (9)$$

The expected value of the total Hamiltonian can be obtained as

$$E(\lambda,\beta) = \frac{\hbar\lambda}{2} + \hbar\omega_L\alpha - \beta_0\sqrt{\lambda} + \frac{e^2\boldsymbol{B}^2\hbar}{8m^2\lambda} + \frac{\hbar^2(\pi^2-\beta^2)}{2mL^2} + |e| FL\left(\frac{1}{2\beta} + \frac{\beta}{\beta^2+\pi^2} - \frac{1}{2}\coth\beta\right) \quad (10)$$

Performing $\partial E/\partial\lambda = 0$ and $\partial E/\partial\beta = 0$, we can get the content equation of the vibration frequency of the magnetopolaron:

$$\hbar\lambda^2 - \beta_0\lambda^{\frac{3}{2}} - \frac{e^2\boldsymbol{B}^2\hbar}{4m^2} = 0 \quad (11)$$

$$F = \frac{-\beta\hbar^2}{meL^3\left[-\dfrac{1}{2\beta^2} + \dfrac{\pi^2-\beta^2}{(\pi^2+\beta^2)^2} + \dfrac{2e^{-2\beta}}{(1-e^{-2\beta})^2}\right]} \quad (12)$$

Substituting Eq. (12) to Eq. (10), we obtain the ground energy of the infinite GaAs semiconductor quantum well in the bound magnetopolaron:

$$E_0 = \frac{1}{2}\hbar\lambda_0 + \hbar\omega_L\alpha - \beta_0\sqrt{\lambda_0} + \frac{e^2B^2\hbar}{8m^2\lambda_0} + |e| FL\left(\frac{1}{2\beta} + \frac{\beta}{\beta^2+\pi^2} - \frac{1}{2}\coth\beta\right) + \frac{(\pi^2-\beta^2)\hbar^2}{2mL^2} \quad (13)$$

3 Results and discussion

In order to study the influence of the electric field on properties of the bound magnetopolaron in the quantum well, we take GaAs as an example material and perform the numerical calculations. The corresponding parameters for GaAs are $\varepsilon_\infty = 10.9$, $m = 0.067m_0$, $\hbar\omega_0 = 36.7$meV, with m_0 the free electron mass, and the electron-phonon coupling constant is $\alpha = 0.067$[11]. The numerical calculation results are shown in Figs. 1～4 and every figure takes meV as the energy unit. As shown in Eq. (13), the vibration frequency λ is not only related to the magnetic field strength B but also to the Coulomb bound potential β_0.

Figure 1 depicts the relational curve of the vibration frequency λ of the bound magnetopolaron in GaAs semiconductor quantum wells to magnetic field B for different Coulomb bound potentials β_0. The figure clearly shows that the vibration frequency increases as the external magnetic field and the Coulomb bound potential increase. Because the electron energy

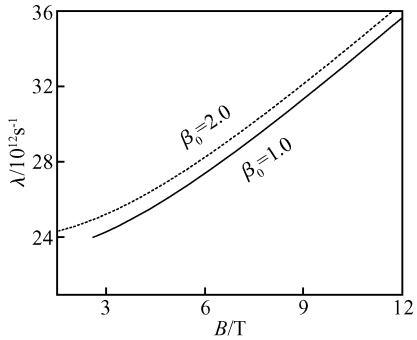

Fig. 1 Relational curves of the vibration frequency λ of the bound magnetopolaron to magnetic field strength B at the different Coulomb bound potentials β_0

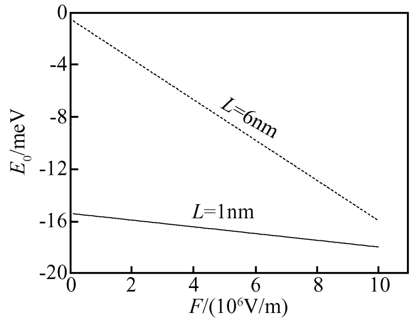

Fig. 3 Relational curves of the ground state energy E_0 of the bound magnetopolaron to the electric field strength F at the different well-widths

will increase as the magnetic field strength B and the Coulomb bound potential increase, the increase of the ground state energy of the magnetopolaron makes the vibration frequency of the magnetopolaron increase. Equation (13) shows that the ground state energy E_0 is not only related to the field strength F, magnetic field strength B, and the Coulomb bound potential β_0, but also to the well-width and the electron-phonon coupling constant α.

Figure 2 shows the relational curves of the ground state energy of the bound magnetopolaron and the magnetic field B for different Coulomb bound potential β_0 with the well width $L = 10$nm and the electric field strength $F = 2 \times 10^6$ V/m. The figure indicates that the absolute value of the ground state energy of the bound magnetopolaron decreases as the external magnetic field strength increases. This is because the increase of the magnetic field B increases the energy of the electron. The total energy is negative and the magnetic field energy is positive, so increasing the magnetic field strength will decrease the absolute value of the total ground state energy. For a constant magnetic field strength B, the absolute value of the ground state energy decreases as the magnetic field strength increases.

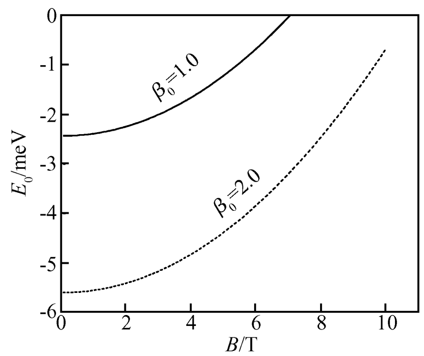

Fig. 2 Relational curves of the ground state energy E_0 of the bound magnetopolaron to magnetic field strength B at the different Coulomb bound potentials β_0

Figure 3 plots the relational curves of the ground state energy E_0 of the bound magnetopoloron to the electric field strength F for different well-widths L with magnetic field strength $B = 5$T, and the Coulomb potential $\beta_0 = 2$. The figure shows that the absolute value of the ground state energy of the magnetopolaron will increase linearly as the electric field strength increases. This occurs because the electric field energy that is obtained by the polaron is larger when the electric field strength is larger, so the total ground state energy will increase. When $L = 1$nm, the variety of the curve is smoother since the influence of the electric field strength on the ground state energy E_0 is minor when the well-width is narrower.

Figure 4 presents the relational curves of the ground state energy E_0 of the bound polaron to the well-width L with different magnetic field strength B for $F = 4 \times 10^6$ V/m and $\beta_0 = 2$. The figure demonstrates that the ground state energy of the weak coupling magnetopolaron increases quickly as the well-width decreases for $L < 2$nm when the peculiar quantum size effect is significant. At the outer region, the ground state energy of the bound magnetopolaron changes slowly as the well-width increases. When the well-width is a large constant, the absolute value of the ground state energy of the bound magnetopolaron decreases as the magnetic field strength increases.

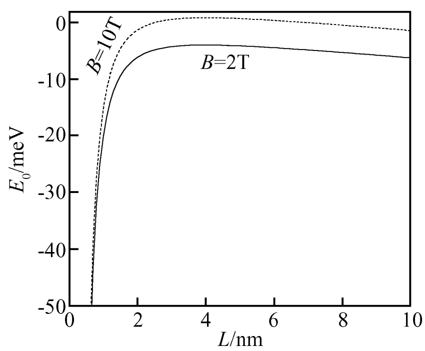

Fig. 4 Relational curves of the ground state energy E_0 of the bound polaron to the well-width L with different magnetic field strengths B

In conclusion, the ground energy of the bound magnetopolaron will increase as the electric field and the Coulomb bound potential increase, and will decrease as the well-width and the magnetic field strength B decrease. When the well-width is small, the quantum size effect is significant.

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电场对半导体 GaAs 量子阱中束缚磁极化子性质的影响

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摘要：研究了在外加电场作用下无限深 GaAs 半导体量子阱中束缚磁极化子的性质，采用线性组合算符及幺正变换方法导出了量子阱中弱耦合束缚磁极化子的基态能量与阱宽、电场强度、磁感应强度、库仑束缚势的变化关系，同时讨论了振动频率和库仑束缚势、外场之间的变化关系. 数值计算结果表明：基态能量的绝对值将随电场强度和库仑束缚势的增加而增加，随磁感应强度和阱宽的增加而减小. 当阱宽较小时，量子尺寸效应较为明显.

关键词：量子阱；束缚磁极化子；线性组合算符；基态能量

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