J. At. Mol. Sci.
doi: 10.4208/jams.110611.121411a

Vol. 3, No. 4, pp. 360-366
November 2012

Effect of spin on the ground-state energy of strong-coupled magnetopolaron in triangular quantum well

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Received 6 November 2011; Accepted (in revised version) 14 December 2011
Published Online 18 May 2012

Abstract. The properties of strong-coupled magnetopolaron are studied by using the linear combination operator and unitary transformation methods in triangular quantum well (TQW). Considering the influence of the spin, the ground-state energy of polaron is obtained. The expressions for the ground-state energy as functions of the vibration frequency, the electron areal density and the magnetic field were derived. Numerical calculation on the TlBr TQW, as an example, is performed and the results show that the ground-state energy is composed of three parts. And the ground-state energy of magnetopolaron increase with enlarging the magnetic field and the electron areal density.

PACS: 73.21.La; 71.38.-k

Key words: triangular quantum well, spintronics, ground-state energy, polaron

1 Introduction

The spin effect in semiconductors has attracted great attention in recent years as it plays a key role in the field of semiconductor spintronics[1,2]. The spin effect is a major branch of the spintronics because of its potential impact on the information technology[3-5]. More and more physicists worldwide are paying considerable attention to the research of the local electron in a quantum dot and the supperlattice heterojunction by many theoretical and experimental methods. The induced potential and the self-energy of an interface magnetopolaron were studied by Wei[6] using the Green-function method. Liu and Xiao[7,8] and Li and Xiao[9] investigated the influence of a perpendicular magnetic field on a bound polaron near the interface of a polar-polar semiconductor with Rashba effect

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by using variational method and calculated the influences of spin on the properties of a weak-coupled magnetopolaron in quantum dot by using a linear combination operator and a unitary transformation methods, respectively. Zhang *et al.*[10] researched the properties of the strong-coupling bound polaron in a triangular quantum well induced by the Rashba effect using the Tokuda modified linear-combination operator method and the unitary transformation method.

There has been much work about the influence of the spin on the electron system, the study of the effect of the spin on the magnetopolaron in TQW, however, is quite rare so far. In this paper, we researched the ground-state energy of the polaron considering the effect of the spin in TQW. First, we drew the expression of the ground-state energy by using the linear combination operator and the unitary transformation methods. Then, numerical calculation is performed and the results are presented and discussed. Finally, a brief conclusion is drawn in our investigation.

2 Theory and model

We consider the system that the electrons are much more confined in one direction (taken as the z direction) than that in other two directions, x and y. Therefore, only the electrons moving on the $x-y$ plane need to be considered. In the presence of a magnetic field in the z direction, and we take the magnetic field B as $B=(0,0,B)$. On the basis of the effective mass approximation, the electron-phonons system Hamiltonian can be written as

$$H=H_e+H_{ph}+H_{e-ph}+H_{SO} \tag{1}$$

where H_e is the energy of the electron

$$H_e=\frac{(p+\frac{eA}{c})^2}{2m^*}+U(z) \tag{2a}$$

$$U(z)=\begin{cases} eF_z z, & z\geq 0 \\ \infty, & z<0 \end{cases} \tag{2b}$$

$$F_z=\frac{4\pi n_s}{\varepsilon_0} \tag{2c}$$

where $U(z)$ is the triangular potential; p and m^* stand for the momentum and mass of the electron, respectively. n_s refers to the electron area density and A is vector potential of the magnetic field. The Hamiltonian of the phonons H_{ph} is given by

$$H_{ph}=\sum_w [\hbar\omega_{LO} a_w^+ a_w \tag{3}$$

Here $a_w^+(a_w)$ is the creation (annihilation) operator of the bulk longitudinal-optical (LO) phonons with wave vector w. H_{e-ph} is the Hamiltonian of the electron-phonon interaction

$$H_{e-ph}=\sum_w [a_w V_w \exp(iw\cdot r)+h\cdot c] \tag{4}$$

where $V_w = i(\hbar\omega_{LO}/w)(\hbar/2m^*\omega_{LO})^{1/4}(4\pi\alpha/V)^{1/2}$, $w=(w_\parallel,w_z)$ and $r=(\rho,z)$ refer to the wave vector and the position vector, respectively. V illustrates the volume of TQW. The electron-LO-phonon coupling constant is represented by α. The last term in Eq. (1) is the contribution of the spin energy. It can be expressed as

$$H_{SO} = (\frac{e\hbar}{m_e c}) S \cdot B \tag{5}$$

First, following Huybrechts, we introduce the linear combination of the creation and annihilation operators b^+ and b in the direction of $(x-y)$

$$p_j = (\frac{m^*\hbar\lambda}{2})^{1/2}(b_j - b_j^+) \tag{6a}$$

$$\rho_j = i(\frac{\hbar}{2m^*\lambda})^{1/2}(b_j - b_j^+) \quad (j=x,y) \tag{6b}$$

where λ is the vibrational parameter which describing the vibration frequency of polaron. We substitute Eqs. (6a) and (6b) into Eq. (1) and then carry out the unitary transformation

$$U = \exp[\sum_w (a_w^+ f_w - a_w f_w^*)] \tag{7}$$

where f_w^* and f_w are the variational parameters that will subsequently be chosen by minimizing the energy. For the ground-state of the system, we choose the following variational trial-wave function

$$|\psi\rangle = |\phi(z)\rangle |0\rangle_a |0\rangle_b \tag{8}$$

where $|0\rangle_b$ is the vacuum state of the b operator, $|0\rangle_a$ is the zero phonon state, $|\phi(z)\rangle$ is the wave function of an electron in the z direction. The Fang-Howard variational[10] wave function is given as

$$\phi(z) = \begin{cases} (\frac{d^3}{2})^{1/2} z \exp(-\frac{dz}{2}) & z>0 \\ 0 & z \le 0 \end{cases} \tag{9}$$

It contains one variational parameter d, which can be determined by minimizing the total energy. Then the expected value of the ground-state energy of polaron in TQW can be written as

$$F(\lambda, d, f_w) = \langle\psi|U^{-1} H U|\psi\rangle \tag{10}$$

We can determine parameters f_w, d and λ by minimizing F. The absolute ratio of the spin energy to the ground-state energy, the Landau ground-state energy and the coupled-energy is expressed as p_1, p_2 and p_3, respectively.

3 Results and discussion

To show more clearly the effect of the spin on the ground state energy of polaron, we choose TlBr crystal [11] performing numerical calculations. In this material, we take $\hbar\omega_{LO} = 14.60$ meV, $\alpha = 2.55$, $\varepsilon_\infty = 5.64$, $\varepsilon_0 = 35.10$, $\frac{m^*}{m} = 0.315$, $\omega_{LO} = 2.218\times 10^{13} s^{-1}$. The numerical results are shown in Figs. 1-5.

Fig. 1 plots the ground-state energy E_0, the spin-up splitting energy $E_\uparrow$ and the spin-down splitting energy $E_\downarrow$ as a function of the magnetic field B, at $n_s = 4$. From Fig. 1, it can be found that considering the effect of the spin, the ground-state energy of the polaron splites into three branches. $E_\uparrow(E_\downarrow)$ represents the spin-up (spin-down) splitting energy and E_0 refers to the zero-spin interaction. It is very obvious that the ground-state energy E_0 and the spin-up (spin-down) splitting energy $E_\uparrow(E_\downarrow)$ increase with enhencing the magnetic field B. With the magnetic field B increase, the influence of the spin on the ground-state energy cannot be neglected.

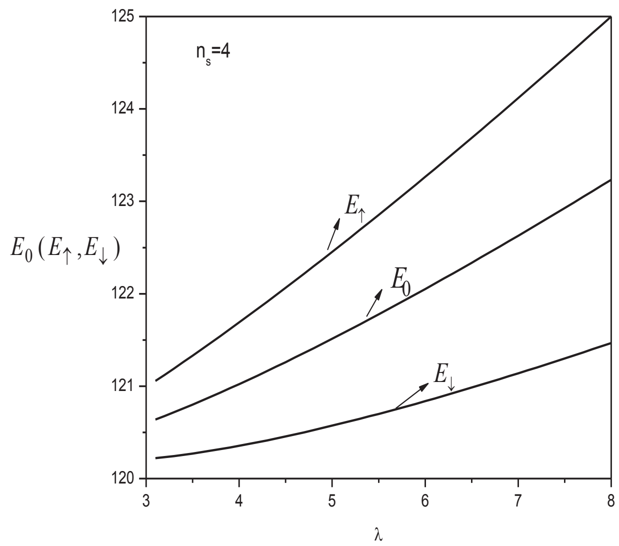

Figure 1: The ground-state energy E_0, the spin-up splitting energy $E_\uparrow$ and the spin-down splitting energy $E_\downarrow$ as a function of the magnetic field B, at $n_s = 4$.

Fig. 2 shows the ground-state energy E_0, the spin-up and spin-down splitting energies $E_\uparrow$ and $E_\downarrow$ as a function of the vibration frequency λ, at $n_s = 4$. From Fig. 2, it can see that the ground-state energy E_0 splits into three branches. This phenomenon indicates that the contribution of the spin-energy to the ground-state energy cannot be ignored. At the same time, it is easy to find that the ground-state energy E_0 increase with the increasing of the vibration frequency λ. And the changing rules of $E_\uparrow$, $E_\downarrow$, and E_0 are similar.

Fig. 3 illustrates the absolute ratio of the spin-energy to the Landau ground-state energy p_2 and the coupled-energy p_3 as a function of the magnetic field B, at $n_s = 0.5$. From

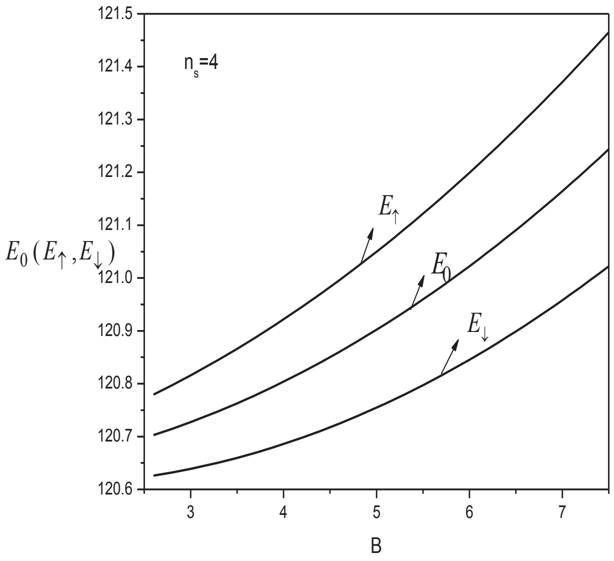

Figure 2: The ground-state energy E_0, the spin-up and spin-down splitting energies $E_\uparrow$ and $E_\downarrow$ as a function of the vibration frequency λ of the polaron, at $n_s = 4$.

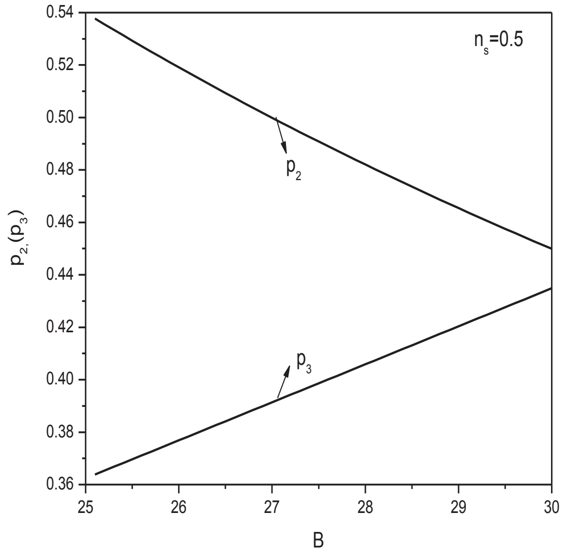

Figure 3: The absolute ratio of the spin-energy to the Landau ground-state energy p_2 and the coupled-energy p_3 as a function of the magnetic field B, at $n_s = 0.5$.

Fig. 3, it can see that p_2 decreases with increasing the magnetic field B. In other words, the spin-energy always is less than the Landau ground-state energy. And the absolute ratio of the spin-energy to the coupled-energy p_3 is a increasing function of the magnetic field B.

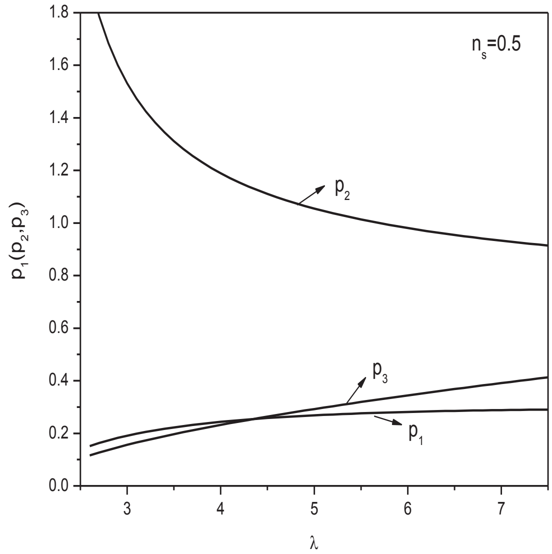

Figure 4: The absolute ratio of the spin-energy to the ground-state energy p_1, the Landau ground-state energy p_2 and the coupled-energy p_3 as a function of the vibration frequency λ.

Fig. 4 expresses the absolute ratio of the spin-energy to the ground-state energy, the Landau ground-state energy and the coupled-energy p_1, p_2 and p_3 as a function of the

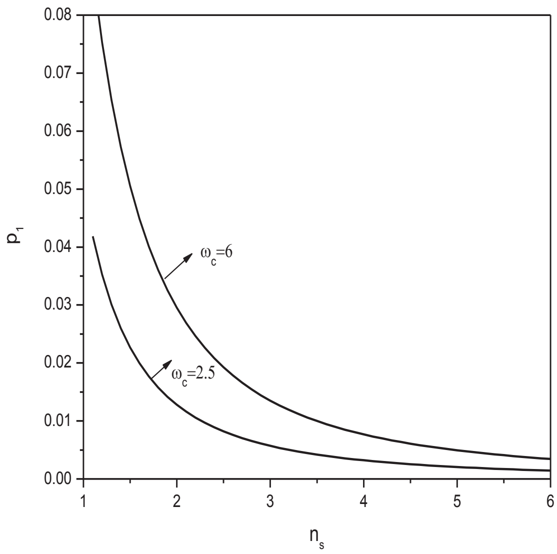

Figure 5: The absolute ratio of the spin-energy to the ground-state energy p_1 as a function of the electron area density n_s, at ω_c=2.5,6.

vibration frequency λ. From Fig. 4, it is very obvious that the absolute ratio of the spin-energy to the ground-state energy p_1 and the coupled-energy p_3 increase with enlarging the vibration frequency λ. This is because that with the increase of the vibration frequency λ, the spin-energy, the ground-state energy and the coupled-energy all increase, but the spin-energy enlarging more rapid than the ground-state energy and the coupled-energy. So p_1 and p_3 increase with the increasing of the vibration frequency.

Fig. 5 shows the absolute ratio of the spin-energy to the ground-state energy p_1 as a function of the electron area density n_s, at $\omega_c = 2.5, 6$. From Fig. 5, it is easy see that p_1 decrease with the increasing of the electron area density. When the electron area density n_s is a fixed value, p_1 increase with increasing the cyclotron resonance frequency ω_c. The effect of the spin on the ground-state energy is very obvious.

4 Conclusion

In summary, the ground-state energy of the magenetopolaron is researched. Considering the influence of the spin, the expression of the ground-state energy is obtained by using the linear combination operator and the unitary transformation methods in a TQW. The results illustrate that when the spin-up splitting energy is considered, the ground-state energy increase with the increasing of the magnetic field B, the change rule of the spin-up and spin-down splitting energy and E_0 is similar; When the spin-down splitting energy is considered, the ground-state energy E_0, the spin-up and spin-down splitting energies $E_\uparrow$ and $E_\downarrow$ decrease with the increasing of the electron areal density n_s. The influence of the spin on the ground-state energy cannot be neglected.

Acknowledgments The authors thank the support from Science and Technology of Bureau Qinhuangdao under Grant No. 201101A025.

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