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The effect of the Rashba spin-orbit coupling on the ground-state energy of polaron in a parabolic quantum dot

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ABSTRACT

We using a variational method of Pekar type to study the effect of the spin on the ground-state energy of a polaron in a parabolic quantum dot (QD). Under the influences of the Rashba spin-orbit (RSO) coupling and the Zeeman energy level splitting are taken into account, the expression of the ground-state energy of a polaron as functions of the radius of QD, the coupling constant and the magnetic field adjusting length was derived. We found that the ground-state energy and the spin-up (spin-down) ground-state splitting energy decrease with increasing the radius of QD. The absolute ratios of the *Zeeman* energy and RSO coupling energy to the ground-state energy are a decreasing function of the magnetic field adjusting length, respectively. The above results can be attributed to the interesting quantum size confining and spin effects.

1. Introduction

Understanding the influence on the Rashba spin-orbit (RSO) interaction is crucial, since it leads to new interactions (such as the anisotropic exchange) and spin-relaxation. The RSO effect in semiconductors has attracted great attention in recent years as they are the key ingredient in the field of spintronics [1,2]. It created a new research field compared to the traditional spin transport phenomena. The SO interaction induced “spin-splitting”, which is sometimes different with *Zeeman* splitting. The difference between spin-orbit interaction and *Zeeman* is that the former has its influence on the states with different orbital angular momentum and different spin angular momentum, while the latter affects different spin angular momentum. Therefore, *Zeeman* can resolve spin degeneracy in ground state, while spin-orbit interaction cannot resolve spin degeneracy in ground state. Research on the RSO influence has become a main subject in the physics of low-dimensional quantum systems. Especially in a QD system, the low-dimensional material drew physicist great attention because it has theoretical value and leads to the development of high-Tech industry. M.Governale [3] has studied the effects of spin-orbit coupling on the electronic structure of few-electron interaction QDs by means of spin-density functional theory. The effects of the oft-neglected cubic Dresselhaus spin-orbit coupling in GaAs/AlGaAs QDs based on random matrix theory have been studied by Jacob et al. [4]. Eerdunchaolu et al. [5] have researched the influences of Rashba SOI and Polaronic Effects on the ground-state energy of electrons in semiconductor quantum rings by means of the Lee–Low–Pines variational method. Li et al. [6] have calculated the effects of magnetic on the properties of a parabolic QD qubit by using a variational method of Pekar type. Chen et al. [7] have studied the energy levels of an impurity atom and its binding energy in a parabolic QD with electron–phonon interactions by using the second-order Rayleigh–Schrodinger perturbation theory. The effects of the electric field and temperature on RbCl asymmetry QD qubit have been investigated by using a variational method of a Pekar type by Xiao [8]. There has been a large amount of work [9–11] focused on the influence of the electron–phonon interactions on polaron in QDs by employing a Pekar type variationa method. The effective mass of strong-coupled bound polaron in an asymmetric QD induced by the Rashba effect using linear-combination operator and unitary transformation methods have been studied by us [12]. However, the effect of RSO coupling on the ground-state energy of a polaron in a parabolic QD by using the Pekar type variational method has been few investigated so far. In this paper, we have studied the effect of RSO coupling on the ground-state energy of a polaron in a parabolic QD. We organize the paper as follows: we first review the model and method in Section 2, then the results and discussion are shown in Section 3, at last in Section 3, a brief conclusion is presented.

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2. Model and method

We consider the system in which the electron is bounded by the parabolic confinement potential in a QD. On the basis of the strong-coupled polaron model, the Hamiltonian of electron–phonon system in presence of the static uniform magnetic field is along the z direction $\boldsymbol{B} = (0, 0, B)$ and described by a vector potential in the Landau gauge $\boldsymbol{A} = \boldsymbol{B}(-y/2, x/2, 0)$ can be written as follows:

$$H = H_{polaron} + H_{RSO} + H_{Zeeman}. \quad (1)$$

$$H_{polaron} = \frac{(p + eA)^2}{2m^*} + \frac{1}{2}m^*\omega_0^2 r^2 + \sum_q \hbar\omega_{LO} a_q^+ a_q + H_{e-ph}, \quad (2)$$

$$H_{e-ph} = \sum_q [V_q^* a_q^+ \exp(-iqr) + V_q a_q \exp(iqr)] \quad (3)$$

$$H_{RSO} = \alpha_{Rsh}(\sigma \times p)_z \quad (4)$$

$$H_{Zeeman} = g\mu_B B\sigma_z/2 \quad (5)$$

where $H_{polaron}$ shows the Hamiltonian of a polaron, H_{e-ph} indicates the electron–phonon interactions, H_{RSO} shows the Rashba spin-orbit coupling effect and H_{Zeeman} denotes the *Zeeman* energy level. ω_0, m^*, e, r, p, μ_B illustrate the confinement strength of QD, the effective mass of an electron, the electron charge, the radius coordinate of the electron, the momentum and the Bohr magneton, respectively. $a_q^+(a_q)$ shows the creation (annihilation) operator of bulk LO-phonon with the wave vector q. g, α_{Rsh} and σ indicate the Landeg factor, RSO coupling factor and Pauli operator, respectively.

$$V_q^* = \frac{i}{q}\left(\frac{2\pi e^2\hbar\omega_{LO}}{\varepsilon V}\right)^{1/2}, \quad (6)$$

$$\alpha = \left(\frac{e^2}{2\hbar\omega_{LO}}\right)\left(\frac{2m^*\omega_{LO}}{\hbar}\right)^{1/2}\left(\frac{1}{\varepsilon_\infty} - \frac{1}{\varepsilon_0}\right). \quad (7)$$

Where V is the volume of the crystals and α is the electron–LO-phonon coupling constant. And then carry out the unitary transformation

$$U = \exp[\sum_q (a_q^+ f_q - a_q f_q^*)]. \quad (8)$$

where f_q and f_q^* show variational parameters which will subsequently be determined by minimizing the energy. Then [13]

$$\begin{aligned} H' &= U^{-1}HU \\ &= \frac{(p_x - (\hbar/2)(1/R_b^2)y)^2}{2m^*} + \frac{(p_y + (\hbar/2)(1/R_b^2)x)^2}{2m^*} + \frac{p_z^2}{2m^*} \\ &\quad + \frac{1}{2}m^*\omega_0^2 r^2 + \sum_q \hbar\omega_{LO}(a_q^+ + f_q^*)(a_q + f_q) + \sum_q [V_q^*(a_q^+ \\ &\quad + f_q^*)\exp(-iqr) + V_q(a_q + f_q)\exp(iqr)]. \\ &= \frac{p^2}{2m^*} + \frac{\hbar^2}{8m^*}\frac{1}{R_b^4}(x^2 + y^2) + \frac{\hbar}{2m^*}\frac{1}{R_b^2}(p_y x - y p_x) \\ &\quad + \frac{1}{2}m^*\omega_0^2 r^2 + \sum_q \hbar\omega_{LO}(a_q^+ f_q + a_q^+ a_q + a_q f_q^* + |f_q|^2) \\ &\quad + \sum_q \{[V_q^* a_q^+ \exp(-iqr) + V_q^* f_q^* \exp(-iqr)] + V_q a_q \exp \\ &\quad (iqr) + V_q f_q \exp(iqr)\}. \end{aligned} \quad (9)$$

where $R_b = \sqrt{\hbar/eB}$ illustrate the magnetic field adjusting length. Assuming the Gaussian function is still valid in the polaron ground state based on the strong coupling polaron model. We choose the ground-state wave function of the system as $|\psi\rangle = |\varphi_0\rangle|0\rangle_{ph}$. Where

$$|\varphi_0\rangle = \pi^{-\frac{3}{4}}\xi^{\frac{3}{2}}\exp\left[-\frac{\xi^2 r^2}{2}\right], \quad (10)$$

where $|0_{ph}\rangle$ is the zero phonon state, $|\varphi_0\rangle$ indicates the electron wave function. Using the variational method of Pekar type [14,15], the ground-state energy of a polaron can be written as

$$\begin{aligned} E_0(\xi) &= \langle\psi|H'|\psi\rangle \\ &= \frac{3}{4}\frac{\hbar^2}{m^*}\xi^2 + \frac{3}{4}\frac{\hbar^2}{\xi^2 R_0^4} - \sqrt{\frac{2}{\pi}}\alpha\hbar\omega_{Lo}r_0\xi + \frac{\hbar^2}{2m^*}\frac{1}{8R_b^4\xi^2}, \end{aligned} \quad (11)$$

here $R_0 = \sqrt{\hbar/m^*\omega_0}$ illustrate the radius of QD. Throughout this study, the length and energy are taken in units of the polaron radius $r_0 = (\hbar/2m^*\omega_{Lo})^{1/2}$ and the phonon energy constant $\Omega^* = \hbar\omega_{LO}$. Under taking into account the RSO coupling and the *Zeeman* energy level splitting, the ground-state energy of a polaron can be expressed as

$$\begin{aligned} E_0^{\downarrow\uparrow}(\xi_0) &= \langle\psi|H'|\psi\rangle \\ &= \frac{3}{4}\frac{\hbar^2}{m^*}\xi_0^2 + \frac{3}{4}\frac{\hbar^2}{\xi_0^2 R_0^4} - \sqrt{\frac{2}{\pi}}\alpha\xi_0\hbar\omega_{Lo}r_0 + \frac{\hbar^2}{2m^*}\frac{1}{8R_b^4\xi_0^2} \\ &\quad \pm \alpha_{Rsh}\left(\hbar^2\xi_0^2 + \frac{\hbar^2}{4R_b^2\xi_0^2}\right)^{1/2} \pm \frac{g\hbar^2}{4m^* R_b^2}. \end{aligned} \quad (12)$$

in Eq. (12), the variational parameter ξ_0 has been determined by $\partial E_0^{\downarrow\uparrow}/\partial\xi = 0$. The absolute ratios of the *Zeeman* energy and the RSO coupling energy to the ground-state energy of a polaron are written as P_1 and P_2, respectively.

3. Results and discussion

In order to show more clearly the influence of RSO coupling on the ground-state energy of the polaron in a parabolic QD, the numerical calculation is performed and the results are shown in Figs. 1–4.

Fig. 1 illustrates the ground-state energy E_0, spin-up (spin-down) ground-state splitting energy $E_0^{\uparrow}$ ($E_0^{\downarrow}$) as a function of the radius of QD R_0 for the coupling constant $\alpha = 6$, the magnetic field adjusting length $R_b = 0.03r_0$, the Rashba constant $\alpha_{Rsh} = 2 \times 10^{-13}ev$ and the Lande factor $g = 0.5$. From Fig. 1, it can

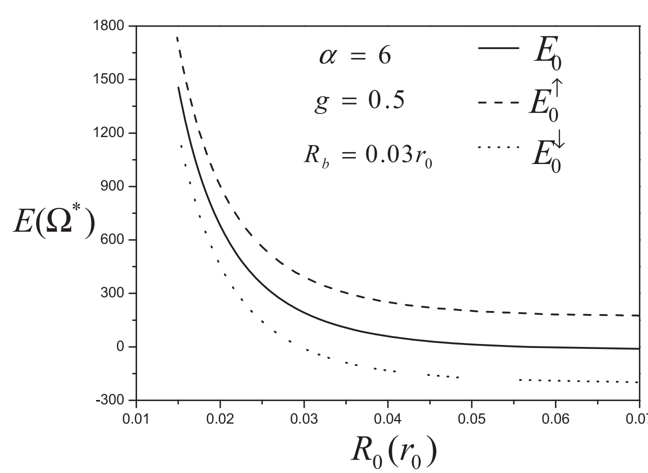

Fig. 1. The ground-state energy E_0 and the spin-up (spin-down) splitting energy $E_0^{\uparrow}(E_0^{\downarrow})$ as a function of the radius of QD R_0, for $\alpha = 6$, $R_b = 0.03r_0$, $g = 0.5$ and $\alpha_{Rsh} = 2 \times 10^{-13}ev$.