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Bound polaron in a quantum pseudodot under Rashba effect

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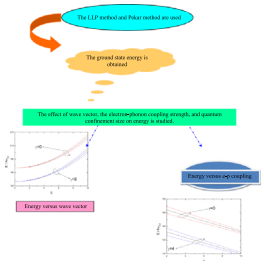
HIGHLIGHTS

- The influence of Rashba effect on bound polaron in a quantum pseudodot is studied.
- We have used the Lee–Low–Pines unitary transformation method and the Pekar type variational procedure.
- The ground state energy is decreased with raising the Coulomb bound potential.
- The ground state energy increases when the wave vector is increasing.
- The ground state energy splits into two branches due to the Rashba effect.

GRAPHICAL ABSTRACT

We have studied the influence of the Rashba effect on bound polaron in a quantum pseudodot. We have used the Lee–Low–Pines unitary transformation method and the Pekar type variational procedure and derive an expression for the bound polaron ground state energy.



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ABSTRACT

In the present work, the influence of Rashba effect on bound polaron in a quantum pseudodot is studied. Using the Lee–Low–Pines unitary transformation method and the Pekar type variational procedure, we have derived an expression for the bound polaron ground state energy. The ground state energy as functions of the wave vector, the electron–phonon coupling strength, and quantum confinement size is obtained by considering different Coulomb bound potentials. It is found that (i) the ground state energy is decreased with raising the Coulomb bound potential, the electron–phonon coupling strength, and quantum confinement size. (ii) The ground state energy increases when the wave vector is increasing. (iii) The ground state energy splits into two branches (spin-up and spin-down) due to the Rashba effect.

1. Introduction

With recent rapid advances of modern technology like molecular beam epitaxy and metal-organic vapor deposition, the investigation of low-dimensional quantum structures has aroused great interest in theory and experiment [1–4]. Examples of low-dimensional quantum structures are quantum wells, quantum wires, quantum dots and quantum pseudodots. It is fully known that some physical properties of the low-dimensional quantum systems such as optical and electron transport characteristics are quite different from those of the bulk material due to the small structures of the systems.

In the past few years, the study of electronic and optical properties of nanostructures under various conditions (magnetic field, electric field, impurity, and electron–phono and interaction) has attracted an increasing interest. Since the electron–phonon interaction is increased by the geometric confinement, much attention has been focused on the polaron effect in nanostructures. There is a large amount of work on polaron effect in nanostructures. For example, Chen and Xiao [5] studied the temperature dependence of the binding energy of an impurity bound magnetopolaron in a GaAs parabolic quantum dot. Cai et al. [6] calculated energy levels and the transition frequency between relevant levels of the strong-coupling polaron in a quantum dot. The transition frequency of the strong-coupling magnetopolaron in quantum

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rods was investigated recently by Xiao and Xiao [7].

It is fully known that the polaron effect plays an important role in the physical properties of low-dimensional semiconductor structures. To study the polaron effect, there are several theoretical methods. In this regard, authors have applied the variational method of the Pekar-type [8,9] and linear combination operator of the Huybrechts [10]. The former has been used for first time by Landau and Pekar to study the properties of the strong-coupling polaron. In the latter, Huybrechts [10] has investigated the properties of the first internal excited state of optical polaron by using linear combination operator method. To obtain more information about polaron effect, the reader can refer to [11–14].

One of the most interesting problems in the condensed matter physics is the study of spin–orbit interaction and its effect on polarons in various nanostructures. A type of spin–orbit interaction prominent in certain quantum well heterostructures is the Rashba interaction [15–17]. This type of spin–orbit interaction is originating from the space inversion asymmetry and it plays a fundamental role in semiconductor spintronics.

In recent years, the Rashba effect in low-dimensional semiconductor structures has attracted great attention. For example, Pietilainen and Chakraborty [18] studied energy levels and magneto-optical transitions in parabolic quantum dots with spin–orbit coupling. Kushwaha [19] investigated the effect of the Rashba-type spin–orbit interaction on the Fock–Darwin energy spectrum in the parabolically confined quantum dots. Chakraborty and Pietilinen [20] investigated the influence of the Bychkov–Rashba interaction on a few interacting electrons confined in a quantum dot. Moreover, significant experimental progresses have been achieved in generating large spin polarizations, in demonstrating the Rashba splitting and also in using the splitting for manipulating the spins. For instance, de Andrada e Silva et al. [21] demonstrated that the Rashba effect is present only in semiconductor heretostructures where there is a lack of inversion symmetry in the growth direction. Koga et al. [22] reported a combined low-temperature scanning tunneling spectroscopy angle-resolved photoemission spectroscopy investigation of the $\sqrt{3}\times\sqrt{3}$ $R30^0$Pb/Ag(1 1 1) surface alloy which provides a giant Rashba-type spin splitting. Nitta et al. [23] proposed a spin-interference device allowing considerable modulation on the electric current. This device is a one-dimensional ring connected with two external leads, made of semiconductor structure in which the Rashba SO interaction is the dominant spin-splitting mechanism. Papadakis et al. [24] studied spin splitting due to Rashba spin–orbit coupling in detail via Shubnikov–de Haas oscillations including also anisotropic properties of the magnetoresistance. For more information, the reader can refer to [25–28].

It should be noted that there have been much work about the influence of the Rashba effect on the electron system. However, the study of the effect of the Rashba spin–orbit interaction on the polaron is quite rare so far. Hence, the purpose of the present paper is to investigate the Rashba effect on bound polaron in a quantum pseudodot using Lee–Low–Pines unitary transformation method and the Pekar type variational method. The paper is organized as follows. We first obtain the expression of the ground state energy of the polaron. Then, our numerical results are presented and discussed. Finally, a conclusion is drawn in our investigation.

2. Description of the model

Consider a quantum pseudodot of polar semiconductor in the presence of the Rashba spin–orbit interaction. An electron is bound to a hydrogenic donor-impurity center in the system, and it is interacting with bulk longitudinal optical (LO) phonons. Within the framework of effective mass approximation, the Hamiltonian of the system can be written as

$$H = H_e + H_{LO} + H_{e-LO} + H_R. \tag{1}$$

In Eq. (1) H_e is the Hamiltonian of the bound electron without phonons and is written as

$$H_e = \frac{P^2}{2m^*} + V(\mathbf{r}) - \frac{e^2}{\varepsilon_0 r}, \tag{2}$$

where m^* is the electron band-effective mass, $-e^2/\varepsilon_0 r$ is the Coulomb bound potential and $\mathbf{P}$ is momentum of the electron. $V(\mathbf{r})$ is the pseudoharmonic potential, that includes both harmonic quantum dot potential and antidot potential, and it is written as [29]

$$V(\mathbf{r}) = V_0\left(\frac{r}{r_0} - \frac{r_0}{r}\right)^2, \tag{3}$$

where V_0 is the chemical potential of the two-dimensional electron gas and r_0 is the zero point of the pseudoharmonic potential.

It is worth mentioning that both quantum dot (QD) and quantum pseudodot (QP) are small enough to exhibit quantum mechanical properties. Specifically, their excitons are confined in all two or three spatial dimensions. Electronic characteristics of quantum dot (or quantum pseudodot) are related to its size and shape. For example, the band gap in a quantum dot (or quantum pseudodot) which determines the frequency range of emitted light is inversely related to its size. The frequency of emitted light increases as the size of the quantum dot (or quantum pseudodot) decreases. It should be noted that a quantum pseudodot consists of a quantum dot and a quantum antidot. An electron in a quantum pseudodot including not only harmonic potential but also antidot-potential exhibits some interesting results.

The second and the third terms in Eq. (1) show the LO-phonon field and the interaction energy of the electron–LO phonon. They are given by

$$H_{LO} = \sum_{\mathbf{q}} \hbar\omega_{LO} a_{\mathbf{q}}^{+} a_{\mathbf{q}}, \tag{4}$$

$$H_{e-LO} = \sum_{\mathbf{q}} [V_q a_{\mathbf{q}} e^{i\mathbf{q}\cdot\mathbf{r}} + h.\,c], \tag{5}$$

where $a_{\mathbf{q}}^{+}(a_{\mathbf{q}})$ are the creation (annihilation) operator of the bulk LO phonon with wave vector $\mathbf{q}$ and frequency ω_{LO}. Also, V_q in Eq. (5) is expressed as

$$V_q = i\left(\frac{\hbar\omega_{LO}}{q}\right)\left(\frac{\hbar}{2m\omega_{LO}}\right)^{1/4}\left(\frac{4\pi\alpha}{V}\right)^{1/2}, \tag{6}$$

where V is the volume of the crystal and α is the electron–LO phonon coupling strength and is given by

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

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

The last term in Eq. (1) describes the Rashba spin–orbit interaction and is expressed as [15]

$$H_R = \alpha_R(\sigma_x k_y - \sigma_y k_x), \tag{8}$$

where α_R is the Rashba spin–orbit coupling constant and σ_x, σ_y are the Pauli matrices. Here, we use the notations $\sigma_\pm = \sigma_x \pm i\sigma_y$, $P_\pm = P_x \pm iP_y$ and write Eq. (8) in the following form: