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The cyclotron resonance of a polaron in an anisotropic quantum dot

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ABSTRACT

The renormalized cyclotron mass of a strong coupling polaron in a three-dimensional (3D) anisotropic quantum dot is investigated using the Landau-Pekar variational approach in which a 3D anisotropic harmonic potential and electron wave function are included in the Hamiltonian to obtain ground state (GS) and excited-state (ES) energies. The expressions of the GS and ES energies under investigation depict a rich variety of dependent relationship with the variational parameters in three different limiting case based on them. It is demonstrated that the Landau-Pekar variational approach provides a reasonable description of the observed properties, in particular, detailed relations between the cyclotron masses and the magnetic field strength, the confinement lengths in the *xy*-plane and the *z* direction are discussed.

1. Introduction

With the development of nanotechnology in recent years, it is possible to manufacture smaller quantum dots (QDs) in which a few electrons can be confined in all the three dimensions spatially [1,2]. Such QD system exhibits some of most interesting features and attracts many reaserch focuses on the polaronic properties [3–7]. Further, the polaron mass is a very important physical quantity in the process of producing QDs and usually experimentally determined by cyclotron resonance. In particular, the polaron cyclotron mass in quasi-zero dimensions QD is sensitive to the adopted theoretical method and is systemically studied by using second-order perturbation theory [8]. Applying Larsen's perturbation method, Au-Yeung et al. [9] have studied the cyclotron resonance of a three-dimensional bound magnetopolaron. Feng et al. [10] have investigated the polaronic correction to the first excited state energy of an electron in an anisotropic QD using the second-order Rayleigh-Schrodinger perturbation theory. Zhu and Gu [11] have studied the cyclotron resonance of magnetopolarons in a two-dimension parabolic QD using the second-order Rayleigh-Schrodinger perturbation theory. Within the framework of a variational method, Kandemir and Altanhan [12,13] have calculated the polaronic energy levels and the cyclotron mass in a 3D anisotropic QD. However, in above works, the theoretical approach is limited to the weak electron-phonon coupling constant, which is the case for materials such as III-IV compounds. With the rapid development of technology, it is now possible to grow heterostructures based on II-IV compounds by molecular-beam epitaxy in which strong coupling becomes more and more important. Therefore, it has practical significance to research strong coupling polarons. Zhou et al. [14] have researched the cyclotron resonance of strong coupling polaron in disk-shape QD using the variational method of Pekar type. It is generally

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known that the longitudinal confinement strength is greater than the lateral confinement strength in disk-shape QD. To probe the influence of QD's shape on the properties of electron in QD, we generalize the work [14] to include the three kinds of ratios for the longitudinal and lateral confinement strength in the present paper.

The manuscript is organized as follows: in the next section, we shall provide a brief sketch of Landau-Pekar variational theory [15], in particular, we shall provide a few details on obtaining the expressions of GS and ES energies in three limiting cases based on the variation parameters. In Section 3, the numerical results and discussions for the cyclotron mass of a polaron in a 3D anisotropic QD system considering electron-bulk longitudinal-optical (LO) phonon interaction are presented and discussed. Finally, the present work is summarized in Section 4.

2. Theoretical model

We consider an electron, which interacts with bulk longitudinal-optical (LO) phonons and is subjected to a 3D anisotropic harmonic potential. A uniform magnetic field is speculated to be applied along the z direction, under the effective mass approximation, the Hamiltonian of the electron-phonon system is given by

$$H = -\frac{\hbar^2}{2m_b}\nabla^2 + \frac{1}{2}\omega_c L_z + \frac{1}{2}m_b\Omega^2\boldsymbol{\rho}^2 + \frac{1}{2}m_b\omega_z^2 z^2 + \sum_{\boldsymbol{q}}\hbar\omega_{LO}b_{\boldsymbol{q}}^+ b_{\boldsymbol{q}} + \sum_{\boldsymbol{q}}\left(V_q \exp\left(i\boldsymbol{q}_\rho\cdot\rho + i\boldsymbol{q}_z z\right)b_{\boldsymbol{q}} + \mathbf{H.c.}\right) \tag{1}$$

In Eq. (1),$\omega_c = eB/m_b c, \Omega^2 = \omega_\rho^2 + \omega_c^2/4,\ b_{\boldsymbol{q}}^+(b_{\boldsymbol{q}})$ is the creation (annihilation) operator of an optical phonon with a wave vector$\boldsymbol{q}(\boldsymbol{q} = \boldsymbol{q}_\rho, q_z)$.$\omega_\rho$ andω_z are the frequencies of the confining parabolic potential in thexy-plane and the direction z, respectively. V_q is defined as follows:

$$V_q = i(\hbar\omega_{LO}/q)(\hbar/2m_b\omega_{LO})^{1/4}(4\pi\alpha/V)^{1/2}. \tag{2}$$

where α is the electron–phonon coupling constant. By performing the well-known Lee–Low–Pines transformation

$$U = \exp\left[\sum_{\boldsymbol{q}}\left(f_q b_q^+ - f_q^* b_{\boldsymbol{q}}\right)\right], \tag{3}$$

wheref_q is the variational function, we obtain

$$H' = U^{-1}HU. \tag{4}$$

The variational energy is now written as

$$E = \langle\phi|\langle 0|H'|0\rangle|\phi\rangle \tag{5}$$

where $\phi(r)$ is the electronic wave function to be chosen variationally and $|0\rangle$ is the unperturbed zero phonon state.

2.1. The ground state

The electronic wave function is chosen as the following Gaussian type

$$\phi_0 = (\lambda/\pi)^{1/2}(\mu/\pi)^{1/4}\exp\left(-\lambda\rho^2/2\right)\exp\left(-\mu z^2/2\right) \tag{6}$$

whereλ andμ are the variational parameters to be determined.

According to Eq. (6), the energy expectation becomes

$$E_0 = \frac{\hbar^2}{2m_b}\left(\lambda + \frac{\mu}{2}\right) + \frac{1}{2}m_b\Omega^2\frac{1}{\lambda} + \frac{1}{4}m_b\omega_z^2\frac{1}{\mu} - r_0\alpha\hbar\omega_{LO}\frac{I_0(\lambda,\mu)}{\pi} \tag{7}$$

where

$$I_0(\lambda,\mu) = \int_0^\infty\int_{-\infty}^\infty \frac{q_\rho \exp\left(-\frac{q_\rho^2}{2\lambda} - \frac{q_z^2}{2\mu}\right)}{q_\rho^2 + q_z^2} dq_\rho dq_z \tag{8}$$

and$r_0 = [\hbar/2m^*\omega_{LO}]^{1/2}$ is the polaron radius. From Eq. (7), we can see that the energy of GS is parameterized, therefore, the proportional relations for λ andμ will produce different numerical results. We will discuss three possible limiting cases in the following three subsections, i.e. $\lambda = \mu$, $\lambda > \mu$ and $\lambda < \mu$, while the units have been chosen as $\hbar = m_b = \omega_{LO} = 1$ (Feynman units).