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Effect of temperature and electric field on life time and energy states of bound polaron in triangular quantum dot

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ABSTRACT

The ground and first excited state energy of bound polaron in RbCl triangular quantum dot are obtained by employing the linear combination operator and unitary transformation methods. Effects of temperature and electric field, the influence of polaron radius and polar angle on lifetime and energy levels are studied. Numerical results show the decrease of polaron lifetime with increase of temperature and the oscillatory behavior of the lifetime due to the form of triangular potential. These results also show the increase of polaron lifetime with the increase of polaron radius and confinement length. These suggested that to improve the quantum transition in nanostructure, temperature has to be increased, whereas to have a long lifetime of polaron in a considered state, electric field strength, polaron radius and the confinement length have to be well modulated.

1. Introduction

The energy spectrum of an electron moving in a periodical potential of rigid crystal lattice consists of allowed and forbidden bands and is known as the Bloch spectrum. An electron with energy inside an allowed band moves as a free electron but has an effective mass that differs from the electron mass in vacuum. However, a crystal lattice is deformable and displacements of atoms (ions) from their equilibrium positions are described in terms of phonons. Electrons interact with these displacements, and this interaction is known as electron–phonon coupling. Such an electron with the accompanying deformation moves freely across the crystal, but with increased effective mass [1]. Pekar coined for this charge carrier the term polaron. Experimentally, polarons are important to the understanding of a wide variety of materials. The electron mobility in semiconductors can be greatly decreased by the formation of polarons. Organic semiconductors are also sensitive to polaronic effects, which is particularly relevant in the design of organic solar cells that effectively transport charge. Landau [2] and Pekar [3] formed the basis of polaron theory. Fröhlich proposed a model Hamiltonian for this polaron through which its dynamics are treated quantum mechanically (Fröhlich Hamiltonian) [4,5]. This model assumes that electron wave

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function is spread out over many ions which are all somewhat displaced from their equilibrium positions, or the continuum approximation. The strength of the electron–phonon interaction is expressed by a dimensionless coupling constant α introduced by Fröhlich [5]. Since these pioneers works on polaron, it still an active field of research. Wendler [6] has studied a quantum-mechanical theory of the electron-(long-wave optical) phonon interaction in dielectric bilayer systems and in semiconductor superlattices [7]. Devreese and coworkers [8,9] were investigating the polaron complexes related to the excited states of electron-phonon system. In [10] partial summing of infinite range of diagrams for the two-phonon mass operator of polaron described by Fröhlich Hamiltonian is performed using the Feynman–Pines diagram technique. Renormalized spectral parameters of ground and first excited (phonon repeat) polaron state are accurately calculated for a weak electron–phonon coupling at $\boldsymbol{T} = 0\boldsymbol{K}$. It is shown that the stronger electron–phonon interaction shifts the energy of both states into low-energy region of the spectra. The ground state stays stationary and the excited one decays at a bigger coupling constant. Mukhopadhyay et al. [11] investigated the stability of a strong-coupling singlet optical bipolaron for the first time in two- and three-dimensional parabolic quantum dots using the Landau–Pekar variational method. Fai et al. [12] investigated bipolaron states in a quasi-0D quantum dot with a spherical parabolic confinement potential by applying the Feynman variational principle. The bipolaron coupling energy and self-action potential energy are found to increase with an increase in the Frohlich electron–phonon-coupling constant.

In the past few years, the effect polaron in nanostructure have attracted many scientists. Tiotsop et al. [13] investigated the time evolution of the quantum mechanical state of a magnetopolaron using the Pekar type variational method on the electric-LO-phonon. A strong coupling of polaron in triangular RbCl quantum dot with Coulomb impurity was duly derived. Khordad [14,15] have studied the first internal excited state energy and transition frequency of strong-coupling impurity bound polaron in a quantum pseudodot and Gaussian quantum well using the well-known Lee–Low–Pines (LLP) unitary transformation method. Using the same method, the heat capacity of a two electron quantum dot with parabolic confinement in magnetic field in the presence of electron–electron interaction, Dresselhaus spin-orbit interaction has been studied in [16]. The electron–electron interaction has been treated by a model potential which makes the Hamiltonian to be soluble exactly. Xiao et al. [17] have investigated transition frequency of strong-coupling magnetopolaron in quantum rods by using Lee–Low–Pines unitary transformation and linear combination operator methods. Li et al. [18] have obtained the ground state lifetime of bound polaron in a parabolic quantum dot. However, the effect of temperature and electric field on lifetime of polaron in RbCl triangular QD has not yet been investigated.

In this article, by using the linear combination operator and unitary transformation methods, we study the effects of the temperature and electric field strength on the polaron lifetime in RbCl triangular quantum dot. It has the following structure: in Sections 2 and 3, the ground and first excited states energy and the lifetime are derived respectively. In Section 4, we discuss obtained results and finally we end with the conclusion in Section 5.

2. Theory and model

The system consider is which the electrons is much confine in z – direction than in x and y directions under an electric field effect. The electrons are assumed to be moving on the $x-y$ plane. The confining potential is taken as the triangular bound potential form [19]

$$\boldsymbol{V}_{\rho} = \frac{1}{2}\boldsymbol{m}\omega_0^2\boldsymbol{\rho}^2\left(1+\frac{2}{7}\cos 3\boldsymbol{\theta}\right) \tag{2.1}$$

$\boldsymbol{m}$ is the band mass while $\boldsymbol{\omega}_0$ is the magnitude confinement strengths of the potentials in the $x-y$ plane and $\boldsymbol{\theta}$ is the polar angle in the polar coordinate system. The electric field is apply along the x -axis and the Hamiltonian of the electron–phonon interaction system can be written as:

$$\boldsymbol{H} = \frac{p^2}{2\boldsymbol{m}} + \frac{1}{2}\boldsymbol{m}\omega_0^2\boldsymbol{\rho}^2\left(1+\frac{2}{7}\cos 3\boldsymbol{\theta}\right) - e^*x\boldsymbol{F} + \sum_q \hbar\boldsymbol{\omega}_{LO}a_q^+a_q + \sum_q [\boldsymbol{V}_q\boldsymbol{a}_q \exp(iq\cdot r) + h.c.] \tag{2.2}$$

$a_q^+(a_q)$ denotes the creation (annihilation) operator of the bulk LO phonon with wave vector $\boldsymbol{q}$, $\boldsymbol{p} = (\boldsymbol{p}_x,\ \boldsymbol{p}_y\ \boldsymbol{p}_z)$ and $r = (\boldsymbol{\rho},\ z)$ are the momentum and position vectors of the electron and $\boldsymbol{\rho} = (x,\ y)$ is the position vector of the electron in the $x-y$ plane. $\boldsymbol{V}_q$ is the amplitude of electron–phonon interaction and $\boldsymbol{\alpha}$ is the coupling constant define respectively by

$$\boldsymbol{V}_q = i\left(\frac{\hbar\boldsymbol{\omega}_{LO}}{\boldsymbol{q}}\right)\left(\frac{\hbar}{2\boldsymbol{m}\boldsymbol{\omega}_{LO}}\right)^{\frac{1}{4}}\left(\frac{4\pi\boldsymbol{\alpha}}{\boldsymbol{V}}\right)^{\frac{1}{2}} \tag{2.3}$$

and

$$\boldsymbol{\alpha} = \left(\frac{e^2}{2\hbar\boldsymbol{\omega}_{LO}}\right)\left(\frac{2\boldsymbol{m}\boldsymbol{\omega}_{LO}}{\hbar}\right)^{\frac{1}{2}}\left(\frac{1}{\boldsymbol{\varepsilon}_{\infty}} - \frac{1}{\boldsymbol{\varepsilon}_0}\right) \tag{2.4}$$