Superlattices and Microstructures 90 (2016) 20–29

Contents lists available at ScienceDirect

Superlattices and Microstructures

journal homepage: www.elsevier.com/locate/superlattices

Bound magneto-polaron in triangular quantum dot qubit under an electric field

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ARTICLE INFO

Article history:
Received 23 July 2015
Received in revised form 27 November 2015
Accepted 30 November 2015
Available online 8 December 2015

Keywords:
Polaron
Quantum dot
Electromagnetic field
Pekar type variational method

ABSTRACT

In this paper, we examine the time evolution of the quantum mechanical state of a magnetopolaron using the Pekar type variational method on the electric-LO-phonon strong coupling in a triangular quantum dot with Coulomb impurity. We obtain the Eigen energies and the Eigen functions of the ground state and the first excited state, respectively. This system in a quantum dot is treated as a two-level quantum system qubit and numerical calculations are done. The Shannon entropy and the expressions relating the period of oscillation and the electron-LO-phonon coupling strength, the Coulomb binding parameter and the polar angle are derived.

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1. Introduction

With the exponential advancement of nanotechnology during these last years, the study of quantum computing and quantum information processing has generated widespread interest. The two-level system is usually employed as the elementary unit for storing information. Quantum computation will be based on the laws of quantum mechanics. Several schemes have been proposed for realizing quantum computers in recent years [1–8]. For quantum computers to have an edge over classical computers, they will need to carry thousands of qubits. Consequently, quantum computers with large numbers of qubits will be most feasible as solid-state systems. Self-assembled quantum dots (QDs) have attracted substantial attention due to their perfect crystal structures. Therefore, it is one of the most popular solid-state quantum information research fields that qubits can be realized by solid-state devices. Many schemes with widely varying content have been proposed for carrying out research on quantum dots [1,2,9,10]. Ezaki et al. [11] investigated the electronic structures in a triangular bound potential quantum dot. Jia-kui Sun et *al.* [12] and Zhi-Xin Li [13] respectively studied the decoherence and the effect of temperature on a polaron in a triangular quantum dot.

However, self-assembled quantum dots (QDs) have also attracted substantial attention due to their perfect crystal structures [14–17]. One of the major concerns in QDs is the impurity states, which have attracted extensive attention in recent

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http://dx.doi.org/10.1016/j.spmi.2015.11.036
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years [18–22]. More recently, the related problem of an optical polaron bound to a Coulomb impurity in a QD has also been considered in the presence of a magnetic field [23,24]. Imperfections being a rule rather than an exception, such an impurity-bound polaron problem [25,26] is obviously more realistic and is therefore of much practical importance.

After the pioneering work on information theory by Shannon [27] many studies have been carried out on the question of how information storage, processing and transmission tasks can be performed with macroscopic decohered resources [28,29]. However, the two level system and the influence of the Shannon entropy on the coherence of the polaron in a triangular quantum dot with a Coulomb impurity have not been taken into account in preceding works.

In the present work, we obtain the Eigen energies of the ground state and the first-excited state, the Eigen functions of the ground state and the first-excited state by using variational method of Pekar type on the condition of electric-LO phonon strong coupling in a triangular quantum dot. This system in a quantum dot may be employed as a two-level quantum system-qubit [30–33]. We obtain the probability density of the polaron which oscillates with a given period when it is in a superposition of the ground and first excited states. The expressions relating the period of oscillation and the transition frequency of the polaron to the cyclotron frequency, electric field density parameter and Coulomb potential are derived. The phonon spontaneous emission causes the decoherence of the qubit. The Shannon entropy is derived and used to discuss the decoherence of the system.

This paper has the following structure: In section 2, we describe the Hamiltonian of the system and use the Pekar variational method to derive the ground and first excited state energies. We also derive the probability density and the Shannon entropy. In section 3, we present and discuss the results and then, we end with the conclusion in section 4.

2. Theoretical model and calculation

We consider a system in which the electrons is much more confined in the $z-$ direction than in the x and y directions. The electrons are assumed to be moving on the $x-y-$ plane. The confining potential is taken as a triangular bound potential with the form [34]

$$V_{\rho\vartheta} = \frac{1}{2}m\omega_0^2\rho^2\left(1+\frac{2}{7}\cos 3\,\vartheta\right) \tag{2.1}$$

The electrons are moving in this polar crystal and interacting with bulk LO phonons under the influence of an electric and a magnetic field. The electric field F is along the $x-$ direction while the magnetic field is along the $z-$ direction with vector potential $A = B(-y/2, x/2, 0)$. The Hamiltonian of the electron–phonon interaction system can be written as:

$$H = \frac{1}{2m}\left(p_x - \frac{\gamma^2}{4}y\right)^2 + \frac{1}{2m}\left(p_y + \frac{\gamma^2}{4}x\right)^2 - e^*xF + \sum_q \hbar\omega_{LO}a_q^+a_q + \frac{1}{2}m\omega_0^2\rho^2\left(1+\frac{2}{7}\cos 3\,\vartheta\right) + \sum_q\left[V_q a_q \exp(iqr) + h.c.\right] - \frac{\beta}{r} \tag{2.2}$$

where $\gamma^2 = (2e/c)B$ and m is the band mass while ω_0 is the magnitude confinement strength of the potentials in the $x-y-$ plane and ϑ is the polar angle in the polar coordinate system. $a_q^+(a_q)$ denotes the creation (annihilation) operator of the bulk LO phonon with wave vector q. $p = (p_x, p_y, p_z)$ and $r = (\rho,z)$ are the momentum and position vectors of the electron and $\rho = (x,y)$ is the position vector of the electron in the $x-y-$ plane. V_q and α in (2.2) are respectively the amplitude of the electron-phonon interaction and the Fröhlich coupling constant defined as

$$V_q = i\left(\frac{\hbar\omega_{LO}}{q}\right)\left(\frac{\hbar}{2m\omega_{LO}}\right)^{1/4}\left(\frac{4\pi\alpha}{V}\right)^{1/2} \tag{2.3}$$

where

$$\alpha = \left(\frac{e^2}{2\hbar\omega_{LO}}\right)\left(\frac{2m\omega_{LO}}{\hbar}\right)^{1/2}\left(\frac{1}{\varepsilon_\infty}-\frac{1}{\varepsilon_0}\right) \tag{2.4}$$

The last expression of the Hamiltonian (2.2) is the Coulomb impurity potential [35]between the electron and the hydrogen-like impurity. The Fourier transform of this expression is written as follows

$$-\frac{\beta}{r} = -\sum_q \frac{4\pi\,\beta}{V}\frac{1}{q^2}\exp(-iq.r) \tag{2.5}$$

here, $\beta = e^2/\varepsilon_\infty$ is the strength of the Coulombic impurity potential.

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