Superlattices and Microstructures 52 (2012) 851–860

Contents lists available at SciVerse ScienceDirect

Superlattices and Microstructures

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

Coulomb bound potential quantum rod qubit

Wei Xiao [a], Jing-Lin Xiao [b,*]

[a] Department of Basic, University of Informational Science and Technology of Beijing, Beijing 100101, China
[b] College of Physics and Electronic Information, Inner Mongolia National University, Tongliao 028043, China

A R T I C L E I N F O

Article history:
Received 21 March 2012
Received in revised form 5 May 2012
Accepted 11 July 2012
Available online 20 July 2012

Keywords:
Quantum rods
Qubit
Coulomb bound potential

A B S T R A C T

We study the eigenenergies and the eigenfunctions of the ground and the first excited states of an electron, which is strongly coupled to LO-phonon in a quantum rod with a hydrogen-like impurity at the center by using the variational method of Pekar type. This quantum rod system may be used as a two-level quantum qubit. When the electron is in the superposition state of the ground and the first-excited states, the probability density of the electron oscillates in the quantum rod. It is found that the probability density and the oscillation period are individually increased and decreased due to the presence of the Coulomb interaction between the electron and the hydrogen-like impurity. The oscillation period is an increasing function of the ellipsoid aspect ratio and the effective confinement lengths of the quantum rod, whereas it is a decreasing one of the electron–phonon coupling strength.

1. Introduction

Quantum computing combines computer science with quantum mechanics, and is a fast growing research field [1]. Consequently, there has been a large amount of experimental work [2–4] on quantum computer (QC). Meanwhile, many investigators studied its properties in many aspects by a variety of theoretical methods [5–8]. In recent years, several schemes, like trapped ions [9], nuclear and electron spins [10–12], quantum optical systems [13], and superconductor Josephson junctions [14,15] have been proposed for realizing quantum computation. In order to show advantage of QC over most classical computer, QC need to be composed of thousands of feasible qubits. Therefore, it

* Corresponding author. Tel.: +86 04758313561.
E-mail address: xiaojlin1939@126.com (J.-L. Xiao).

0749-6036/$ - see front matter Crown Copyright © 2012 Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.spmi.2012.07.010

is clear that QC with a large significant number of qubits would be more realizable in solids [16], especially by invoking semiconductor nanostructures or quantum dots (QDs) [17]. Semiconductor QD was extensively studied because of its novel physical properties and potential applications in opto-electronics [18]. Two-level quantum system can be viewed as a single qubit. For such a single electron QD qubit, Li et al. [19,20] proposed a kind of parameter-phase diagram schemes and defined the parameter region for the use of an InAs/GaAs QD as a two-level quantum system. Li et al. [21] used the variational method of Pekar type [22] to investigate the effect of magnetic field on the properties of parabolic QD qubit. Using linear-combination operator method, vibrational frequency and ground state binding energy of strong-coupling magnetopolaron in a quantum rod (QR) have been studied by us [23]. The properties of QR qubit with Coulomb bound potential, however, have never been investigated yet.

In the present paper, we study the eigenenergies and the eigenfunctions of the ground and the first excited states of an electron, strongly coupled to LO–phonon in a QR with a hydrogen-like impurity at the center. This system may be used as a two-level quantum qubit. We have obtained the probability density of the electron in the QR oscillating with a certain period when electrons are in a superposition state of the ground and first-excited states. The effect of the Coulomb bound potential on the probability density, the ellipsoid aspect ratio, the transverse and longitudinal effective confinement lengths of the QR, the Coulomb bound potential and the electron–phonon coupling strength on the oscillation period are discussed.

2. Theory model

The electron under consideration is moving in a polar crystal QR with three-dimensional anisotropic harmonic potential, and is interacting with bulk LO phonons. The Hamiltonian of the system with a hydrogen-like impurity at the center can be written as:

$$H = \frac{p_{\|}^2}{2m} + \frac{p_z^2}{2m} + \frac{1}{2}m\omega_{\|}^2\rho^2 + \frac{1}{2}m\omega_z^2 z^2 + \sum_{\boldsymbol{q}} \hbar\omega_{LO} a_{\boldsymbol{q}}^{+} a_{\boldsymbol{q}} + \sum_{\boldsymbol{q}} [V_q a_{\boldsymbol{q}} \exp(i\boldsymbol{q}\cdot\boldsymbol{r}) + h\cdot c] - \frac{e^2}{\varepsilon_0 r}, \tag{1}$$

where m is the band mass, $\omega_{\|}$ and ω_z are the measures of the transverse and longitudinal confinement strengths of the three-dimensional anisotropic harmonic potential in the radius and the length directions of the rod, respectively. $a_{\boldsymbol{q}}^{+}(a_{\boldsymbol{q}})$ denotes the creation (annihilation) operator of the bulk LO phonons with wave vector $\boldsymbol{q}(\boldsymbol{q}_{\|}, q_z)$. $\boldsymbol{p}(\boldsymbol{p}_{\|}, p_z)$ and $\boldsymbol{r} = (\boldsymbol{\rho}, z))$ are respectively the momentum and position vectors of the electron. $-\frac{e^2}{\varepsilon_0 r}$ denotes the Coulomb potential between the electron and the hydrogen-like impurity. V_q and α in Eq. (1) are:

$$\begin{aligned} V_q &= i\left(\frac{\hbar\omega_{LO}}{q}\right)\left(\frac{\hbar}{2m\omega_{LO}}\right)^{1/4}\left(\frac{4\pi\alpha}{v}\right)^{1/2}, \\ \alpha &= \left(\frac{e^2}{2\hbar\omega_{LO}}\right)\left(\frac{2m\omega_{LO}}{\hbar}\right)^{1/2}\left(\frac{1}{\varepsilon_\infty} - \frac{1}{\varepsilon_0}\right). \end{aligned} \tag{2}$$

Employing Fourier expansion to the Coulomb bound potential, it can be written as:

$$-\frac{e^2}{\varepsilon_0 r} = -\frac{4\pi e^2}{\varepsilon_0 v}\sum_q \frac{1}{q^2} exp(-i\boldsymbol{q}\cdot\boldsymbol{r})£ \tag{3}$$

where v is the volume of the crystal. q and ε_0 are respectively the wave vector of the phonon and the static dielectric constant. We introduce a coordinate transformation [24], which changes the ellipsoidal boundary into a spherical one: $x' = x, y' = y, z' = z/e'$, where e' is the ellipsoid aspect ratio and (x', y', z') is the transformed coordinate. The electron–phonon system Hamiltonian in the new coordinate is,