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The ground-state transition rate of polaron in quantum rod

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ABSTRACT

The ground-state transition rate of polaron with strong electron-LO-phonon coupling was investigated by employing a Pekar' type variational method in a quantum rod (QR). Quantum transition was occurred in the low dimensional quantum system due to the electron–phonon interaction and the effect of temperature. It was found the polaron can transit from the ground-state to the first-excited state after absorbing a LO-phonon. And the ground-state transition rate of polaron increases with enlarging the transverse and longitudinal confinement lengths of QR and decreases with the increasing of the ground-state energy of polaron. In addition, the ground-state transition rate of polaron is an increasing function of the electron–phonon coupling constant and temperature.

1. Introduction

In the last decade, with the enormous developments in epitaxial technology, such as molecular-beam epitaxy and nanothography, it becomes possible to produce these systems, which are typified by heterointerfaces between the different semiconductors. Consequently optical properties of low-dimensional semiconductor systems have been received considerable research interest both experimentally and theoretically. As we know, in a quantum rod (QR) system, the electron–phonon interactions can be enhanced by the geometric confinement. Many works on the electron–phonon interaction in QR systems have been done. Landau and Pekar [1–4] have researched the physical properties of polarons by the strong-coupling theory. An improved model of electron–phonon interaction for longitudinal-optical phonons in layered semiconductor quantum wells was studied by Wendler and Haupt [5]. Xiao and Ding [6] studied the strong-coupled impurity bound

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polaron properties by using the linear combination operator method in QR. Verzelen et al. [7] investigated the polaron lifetime and energy relaxation in semiconductor quantum dots. The results showed that a harmonicity driven instability of optical phonons in semiconductor quantum dots leads to a decay of polaron states. Li et al. [8] employed Pekar' variational method to study the ground-state lifetime of bound polaron in a parabolic quantum dot. A Landau–Pekar variational theory is employed to obtain the ground and the first excited state binding energies of an electron bound to a coulomb impurity in a polar semiconductor quantum dot with parabolic confinement in both two and three dimensions by Chen and Xiao [9]. Xiao and Zhao [10] have investigated the properties of the quantum rods constituting the bridge between two-dimensional quantum wells, zero-dimensional quantum dots and one-dimensional quantum wires using linear combination operator method. However, the ground-state transition rate of polaron in a quantum rod (QR) system has not been researched in these studies so far.

In the present paper, the ground-state transition rate of polaron with strong electron-LO-phonon coupling was studied by using a variational method of Pekar type in a QR. The relations between the ground-state transition rate of polaron and the transverse and longitudinal confinement lengths of QR, the ground-state energy of polaron, the electron-LO-phonon coupling constant, and the temperature parameter were discussed. It should be noted that as long as the boundary potential of the QR is transformed from the ellipsoidal form into a spherical one, we can conveniently use the Pekar' variational approach in the frame work of the effective-mass approximation to calculate the relevant physical quantities, and do not have to use the real electron boundary condition.

2. Theory

The electron moves in a polar crystal QR with three-dimensional anisotropic harmonic potential. On the basis of the strong-coupled polaron model, the electron–phonon system Hamiltonian in QR reads:

$$H = H_e + H_{ph} + H_{e-ph} \tag{1}$$

$$H_e = \frac{p_{//}^2}{2m^*} + \frac{p_z^2}{2m^*} + V(\rho) + V(z) \tag{2}$$

where $V(\rho) = \frac{1}{2}m^*\omega_{//}^2\rho^2$ and $V(z) = \frac{1}{2}m^*\omega_z^2 z^2$ are the transverse and longitudinal anisotropic harmonic potentials in the radius and the length directions of the QR, respectively. $p = (p_{//}, p_z)$ and m^* denote the momentum and mass of the electron, respectively. The second and third terms in Eq. (1) stand for the local LO-phonon field and the interaction energy of the electron with the LO-phonon. They are given by:

$$H_{ph} = \sum_w \hbar\omega_{LO} a_w^+ a_w \tag{3}$$

$$H_{e-ph} = \sum_w [V_w^* a_w^+ \exp(-iw \cdot r) + h \cdot c] \tag{4}$$

where

$$V_w^* = \frac{i}{\omega}\left(\frac{2\pi e^2 \hbar\omega_{LO}}{\varepsilon V}\right)^{1/2} \tag{5}$$

$$\alpha = \left(\frac{e^2}{2\hbar\omega_{LO}}\right)\left(\frac{2m^*\omega_{LO}}{\hbar}\right)^{1/2}\left(\frac{1}{\varepsilon_\infty} - \frac{1}{\varepsilon_0}\right) \tag{6}$$

Here $a_w^+(a_w)$ indicates the creation (destruction) operator of the bulk LO-phonons field with the wave vector w and $r = \rho, z$ represents the position vector of an electron, respectively. V plots the volume of the QR. The electron-LO-phonon coupling constant is expressed by α. We introduce the coordinate transformation, which changes the ellipsoidal boundary into a spherical one [11]: $x' = x, y' = y,$