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Temperature effect of a quantum pseudodot qubit

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ABSTRACT

Considering a variational method of the Pekar type and the quantum statistics theory, the temperature effects on the probability density and the oscillating frequency of an electron-LO-phonon strongly coupling in a RbCl quantum pseudodot (QPD) are investigated. It is discovered that a qubit may be made up of a QPD two-level-system. Furthermore, when an electron locates in the superposition state of the ground and first excited states, the electron's probability density varies periodically with time and oscillates in the RbCl QPD with an independent period. The electron's probability density increases (decreases) with increasing temperature at low (high) temperature. At low (high) temperature, the oscillating frequency decreases (increases) with an increase of the temperature, the chemical potential of the two-dimensional electron gas and the zero point of the pseudoharmonic potential. The oscillating frequency is a decreasing function of the polaron radius.

1. Introduction

In the last few years quantum computing and information science has rapidly developed into an information science field involving the contributions of physicists and computer engineers. The discoveries have not only solved quantum algorithm problems, but also developed quantum error correction and fault-tolerance, and have shown the ultimate feasibility of the experimental realization of quantum computing and information science in quantum systems (especially quantum dot (QD) systems). In the experiments, such as Bianucci et al. [1], an experimental method was employed to obtain the Deutsch–Jozsa algorithm of one qubit in a QD. Shi et al. [2] realized the qubit of a fast hybrid silicon double QD. Kim et al. [3] achieved quantum control and the quantum process tomography of a hybrid qubit in a semiconductor QD. In these reports, the qubit which incorporated two-levels ground and first excited state (GFES) in the QD is the fundamental component in quantum computing and information science. The QD qubit [4–8] is easier to implement than many other qubit designs, and has lots of effects from external environmental factors (temperature, noise, magnetic field, electric field, and so on). However, changing the external environment factors to adjust the qubit in the QD is crucial for achieving quantum computation. Numerous groups throughout the world currently build QD qubits and are considering temperature factors for QD qubits that are much less than those expected based on the theoretical work. For example, Xiao [9] investigated the temperature and electric field effects on the qubit of an asymmetric RbCl QD. Chen and Xiao [10] studied the temperature and magnetic field influences on the qubit of a parabolic QD. Khordad and Ghanbari [11] researched the phonon effect on the optical properties of RbCl QPD qubits. In these researches, the QD qubit is not only at different temperatures and in variant type fields but also is in different potentials. So studying the QD qubit at different temperatures and in variant potentials has been a hot topic in quantum computing and information science. Recently many researchers have studied the variant properties of QPD qubits. A work including one of the authors of this article, Sun et al. [12] has investigated the properties of a QPD qubit. However, the studies of temperature effects on a QPD qubit are very few.

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In this article, the ground and first excited states' eigenenergies and eigenfunctions of the strong electron-LO-phonon coupling in this RbCl QPD are employed. The qubit is built through a two-level in the QPD system. Considering the temperature factor, the electron's probability density is obtained in the QPD oscillating with temperature and time (a few complete periods) when electrons are in the ground and first excited states' superposition state. The effect of the chemical potential of the two-dimensional electron gas, the zero point of the pseudoharmonic potential, the polaron radius and the temperature on the oscillating frequency are discussed. The important findings are useful for qubit building in quantum computing and information science.

2. Theoretical model

2.1. Qubit

The electron moving in a RbCl crystal QPD interacts with bulk longitudinal optical (LO) phonons. The system Hamiltonian of the electron-phonon interaction can be expressed as

$$H = \frac{\mathbf{p}^2}{2m} + V(r) + \sum_{\mathbf{q}} \hbar\omega_{LO} a_{\mathbf{q}}^{\dagger} a_{\mathbf{q}} + \sum_{\mathbf{q}} [V_q a_{\mathbf{q}} \exp(i\mathbf{q}\cdot\mathbf{r}) + h.\,c], \tag{1}$$

where m is the band mass of the electron, $a_{\mathbf{q}}^{\dagger}$ and $a_{\mathbf{q}}$ denote the creation and annihilation operators of the bulk LO phonon, $\mathbf{q}$ is the wave vector, $\mathbf{p}$ and $\mathbf{r}$ are the momentum and the electron position vector.

The pseudoharmonic potential of the above Eq. (1) is

$$V(r) = V_0\left(\frac{r}{r_0} - \frac{r_0}{r}\right)^2, \tag{2}$$

where V_0 is the chemical potential of the two-dimensional electron gas and r_0 is the zero point of the pseudoharmonic potential. V_q and α in Eq. (1) are

$$V_q = i\left(\frac{\hbar\omega_{LO}}{q}\right)\left(\frac{\hbar}{2m\omega_{LO}}\right)^{\frac{1}{4}}\left(\frac{4\pi\alpha}{V}\right)^{\frac{1}{2}},\ \alpha = \left(\frac{e^2}{2\hbar\omega_{LO}}\right)\left(\frac{2m\omega_{LO}}{\hbar}\right)^{\frac{1}{2}}\left(\frac{1}{\varepsilon_\infty} - \frac{1}{\varepsilon_0}\right). \tag{3}$$

Following a variational method of the Pekar type [13, 14], the trial wavefunction of the strongly-coupled polaron, separated into two parts individually describing the electron and the phonon, is written as

$$\langle\psi| = |\varphi\rangle U|0_{ph}\rangle, \tag{4}$$

where $|0_{ph}\rangle$ is the phonon's vacuum state with $a_{\mathbf{q}}|0_{ph}\rangle = 0$, and $U|0_{ph}\rangle$ represents the coherent state of the phonon. The state $|\varphi\rangle$ depends only on the electron coordinate,

$$U = \exp\left[\sum_{\mathbf{q}} a_{\mathbf{q}}^{\dagger} f_q - a_{\mathbf{q}} f_q^*\right], \tag{5}$$

where $f_q\left(f_q^*\right)$ is the variational function, the trial ground and first excited state wavefunctions [16] of the electron-phonon system take the following forms:

$$|\varphi_0(\lambda_0)\rangle = |0\rangle|0_{ph}\rangle, \tag{6}$$

$$|\varphi_1(\lambda_1)\rangle = |1\rangle|0_{ph}\rangle, \tag{7}$$

where λ_0 and λ_1 are the variational parameters.

By minimizing the expectation value of the Hamiltonian, we then obtain the polaron ground and first excited state energies

$$E_0 = \langle\varphi_0(\lambda_0)|U^{-1}HU|\varphi_0(\lambda_0)\rangle, \tag{8}$$

$$E_1 = \langle\varphi_1(\lambda_1)|U^{-1}HU|\varphi_1(\lambda_1)\rangle. \tag{9}$$

The electron ground and first excited state energies in the QPD can be calculated as

$$E_0(\lambda_0) = \frac{3\hbar^2}{4m}\lambda_0^2 + \frac{3V_0}{2\lambda_0^2 r_0^2} + 2V_0\lambda_0^2 r_0^2 - 2V_0 - \frac{\sqrt{2}}{\sqrt{\pi}}\alpha\hbar\omega_{LO}\lambda_0 R_0, \tag{10}$$

$$E_1(\lambda_1) = \frac{5\hbar^2}{4m}\lambda_1^2 + \frac{5V_0}{2\lambda_1^2 r_0^2} + \frac{2}{3}V_0\lambda_1^2 r_0^2 - 2V_0 - \frac{3\sqrt{2}}{4\sqrt{\pi}}\alpha\hbar\omega_{LO}\lambda_1 R_0, \tag{11}$$

where $R_0 = (\hbar/2m\omega_{LO})^{\frac{1}{2}}$ is the polaron radius. It is known that one can obtain λ_0 and λ_1 with the variational method to get the ground and first excited states energies and wave-functions. Therefore, the two-level system of the single qubit is built up. The superposition state can be written as