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The Effects of Electric Field on the Coherence Time of RbCl Quantum Pseudodot Qubit

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Abstract

We academically explore the properties of the coherence time (CT) of an electron powerful coupled to the phonons in a RbCl quantum pseudodot (QPD) qubit with an exterior electric field alongside the ρ_x direction. By employing the Pekar type variational method (PTVM) and the Fermi golden rule, the CT changes with the electric field, the chemical potential of the two-dimensional electron gas (CPTDEG), the zero point of the pseudoharmonic potential (ZPPHP) and the polaron radius is studied. The examined results indicate ① that the CT of RbCl QPD qubit decays with aggrandizing electric field, ② that the CT is a decreasing function of the CPTDEG, the ZPPHP and the polaron radius, ③ that here we can find that we can adjust the CT by changing the external electric field, the CPTDEG, the ZPPHP and the polaron radius.

Keywords RbCl quantum pseudodot · Qubit · Coherence time · Electric field

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1 Introduction

With the development of the quantum information communication in the low-dimensional nanomaterial, crisis-conscious physicists focus on the study of quantum information processing. The executions of quantum computation depends on not only the implementations of the theoretical framework in computation systems, but also the measurements of the experiment phenomena of quantum information [1]. The smallest construction of information content of a message can be measured in terms of the qubits [2]. The two-level system is usually employed as qubit for transmitting information. It is demonstrated that quantum computer with considerable qubits would be realized in solids [3], especially by invoking semiconductor quantum dot (QD).

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Recently, there has been many academic and tentative works on the quantum computer. Moreover, the investigations about quantum coherence properties of the QD qubit have become the main research subjects. For example, Abadillo-Uriel et al. [4] reported the signatures of atomic-scale structure in the energy dispersion and coherence of a Si quantum-dot qubit. Delteil et al. [5] demonstrated realization of a cascaded quantum system: Heralded absorption of a single photon qubit by a single-electron charged QD. Koski et al. [6] experimentally investigated the floquet spectroscopy of a strongly driven QD charge qubit with a microwave resonator. Meanwhile, many theoretical investigators present that the methods of various QD materials are efficient to realizing the transmission of qubits in the quantum information science. Such as parabolic potential, triangular potential, Gaussian potential and so on.

In the recent years, the researchers found that a new confinement potential called pseudoharmonic potential (PHP) is closer to the actual potential of QD. Furthermore, the qubit was built by two-level energy in the special QPD. For example, Khordad and Ghanbari [7] employed the effect of phonons on optical properties of RbCl QPD qubits. Liang and Xiao [8] studied the effect of electric field on RbCl QPD qubit. Chen and Xiao [9] investigated the effect of temperature and electric field on a QPD qubit and the electron's probability density and the oscillating period of an electron in a three-dimensional RbCl QPD. However,the electric field effect on the CT of qubit in the QPD hasn't studied yet.

In this article, the intention of the authors is to dig into the properties of the CT of an electron strongly coupled to phonon in a RbCl QPD qubit with an external electric field. There are three parts in the main body of the article. In the part 2 of this article, the Hamiltonian of the electron and phonon interaction system in QPD with the extra electric field is given. The ground- and first- excited-states (GFES) of the system will be calculated by following the PTVM. Then the superposition state and the CT are investigated by using the Fermi golden rule [10]. Part 3 shows the numerical results and discussion of the relation between the CT and electric field and the QPD's parameters. Finally, in the conclusion, the results indicate that the electric field, the QPD's parameters are important factors to investigate of the CT of the RbCl QPD qubit.

2 Theoretical Model

Considering an electron confined in a RbCl QPD crystal with PHP interacting with the bulk phonons. In the presence of an exterior electric field F along the ρ_x direction. The Hamiltonian of the electron-phonon interaction system is in the following form [11].

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

where

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

where the significances of the physical quantities in Eqs. (1 and 2) are the same with Ref. [11].

And $V(r)$ is the PHP which includes both harmonic QD potential and antidot potential. Besides, V_0 is the CPTDEG and r_0 is the ZPPHP. We carry out the following Lee-Low-Pines [12] transformation to (1)

$$U_2 = \exp\left[\sum_{\mathbf{q}}\left(a_{\mathbf{q}}^{+} f_q - a_{\mathbf{q}} f_q^{*}\right)\right] \tag{3}$$

where $f_q\left(f_q^{*}\right)$ is the variational function.

According to the PTVM [13–16], the GFES wavefunctions of the system may be given as

$$|\varphi_0(\lambda_0)\rangle = |0\rangle|0_{ph}\rangle = \pi^{-\frac{3}{4}}\lambda_0^{\frac{3}{2}}\exp\left[-\frac{\lambda_0^2 r^2}{2}\right]|0_{ph}\rangle, \tag{4}$$

$$|\varphi_1(\lambda_1)\rangle = |1\rangle|0_{ph}\rangle = \left(\frac{\pi^3}{4}\right)^{-\frac{1}{4}}\lambda_1^{\frac{5}{2}} r\cos\theta\exp\left(-\frac{\lambda_1^2 r^2}{2}\right)\exp(\pm i\phi)|0_{ph}\rangle, \tag{5}$$

where λ_0 and λ_1 are the variational parameters. Then the energies of GFES can be calculated and written as follows:

$$E_0(\lambda_0) = \frac{3\hbar^2}{4m}\lambda_0^2 + \frac{3V_0}{2\lambda_0^2 r_0^2} + 2V_0\lambda_0^2 r_0^2 - 2V_0 - \frac{\sqrt{2}}{\sqrt{\pi}}\alpha\hbar\omega_{LO}\lambda_0 R_0 - \frac{\sqrt{\pi}e^{*}}{2\lambda_0}F, \tag{6}$$

$$E_1(\lambda_1) = \frac{5\hbar^2}{4m}\lambda_1^2 + \frac{5V_0}{2\lambda_1^2 r_1^2} + \frac{2}{3}V_0\lambda_1^2 r_0^2 - 2V_0 - \frac{3\sqrt{2}}{4\sqrt{\pi}}\alpha\hbar\omega_{LO}\lambda_1 R_0 - \frac{\sqrt{\pi}e^{*}}{2\lambda_1}F, \tag{7}$$

where $R_0 = (\hbar/2m\omega_{LO})^{1/2}$ is the polaron radius. In this two-level quantum system a single qubit can be realized. The superposition state have the following forms:

$$|\psi_{01}\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right). \tag{8}$$

Under the dipole approximation, based on the Fermi golden rule [10], the spontaneous emission rate can be calculated using [17].

$$\tau^{-1} = \frac{e^2(\varDelta E)^3}{\varepsilon_0\hbar^4 C^3}|\langle 0|r|1\rangle|^2 = \frac{e^2(\varDelta E)^3}{\varepsilon_0\hbar^4 C^3}\frac{144\lambda_0^3\lambda_1^5}{\left(\lambda_0^2+\lambda_1^2\right)^5}, \tag{9}$$

where $\varDelta E = E_1 - E_0$ denotes the energy separation between the the GFES and C is the speed of light in vacuum. $\varepsilon(\varepsilon_0)$ is the vacuum dielectric constant and τ is the CT.

3 Numerical Results and Discussion

The effective mass of RbCl, the electron-phonon coupling constant and the energy of bulk phonon are respectively taken as $0.432m_0$, $\alpha = 3.81$, and $\hbar\omega_{LO} = 21.639meV$ [18]. The numerical results are exhibited in Figs. 1, 2 and 3.

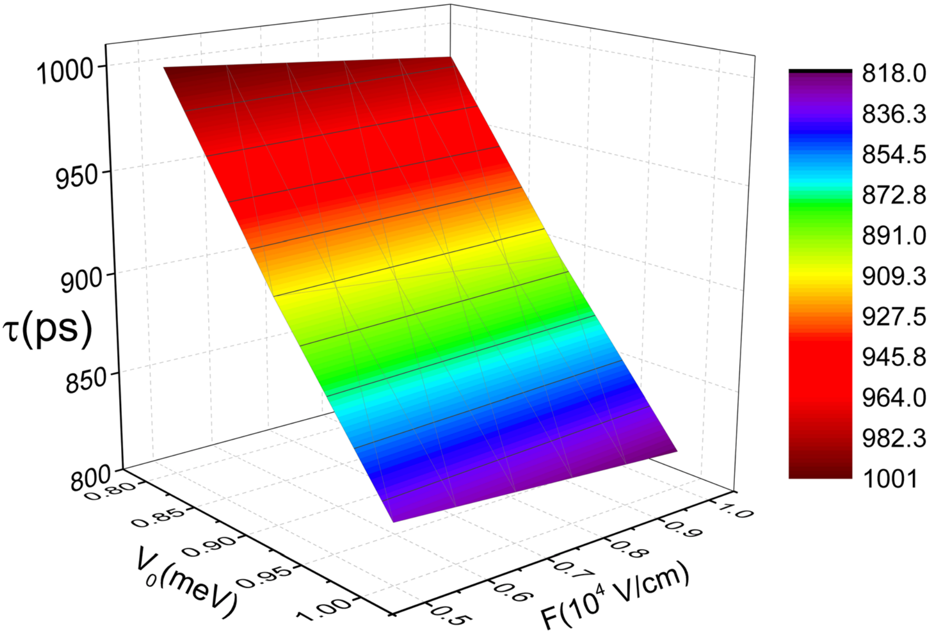

Fig. 1 The CT τ versus the CPTDEG V_0 and the electric field F

Figure 1 depicts the CT τ of QPD qubit varying with the electric field F and the CPTDEG V_0 for $R_0 = 1.0nm$ and $r_0 = 0.2nm$. It is seen from Fig.1 that the CT raises with decaying electric field F. This is because that the CT τ above is dependent not only on the energy separation ΔE

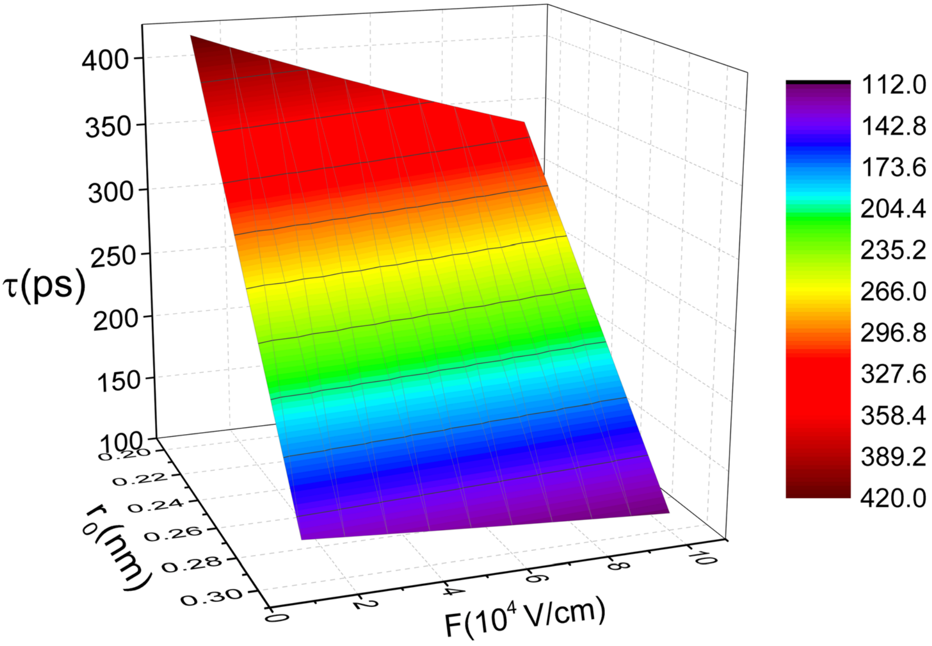

Fig. 2 The CT τ versus the electric field F and the ZPPHP r_0

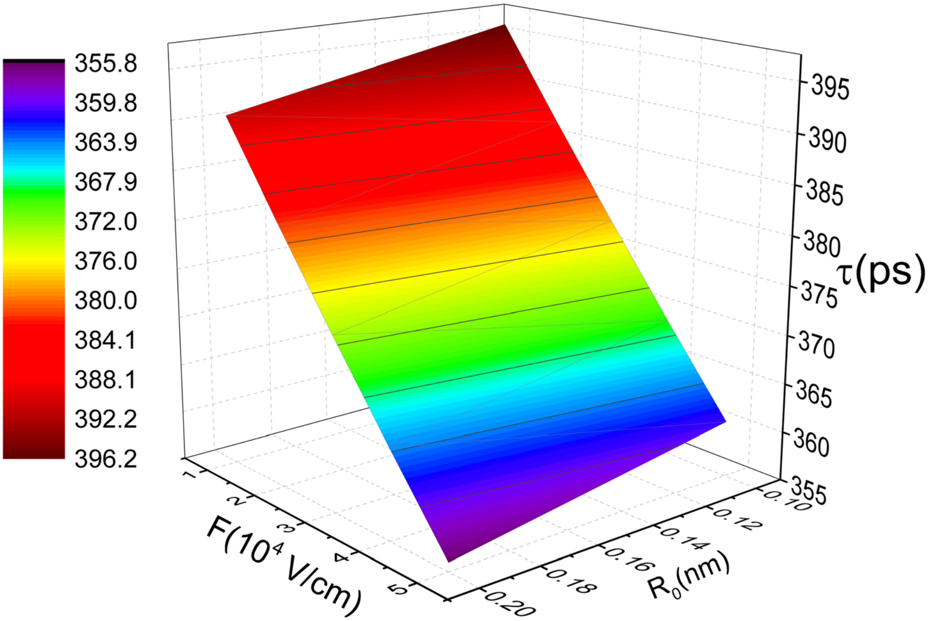

Fig. 3 The CT τ versus the electric field F and the polaron radius R_0

between the GFES, but also on the variational parameters λ_0 and λ_1, besides, the CT τ is a decreasing function of the ΔE. The GFES' energy levels are decreasing functions of the electric field, and the electric field's influences on the first-excited state is weaker than that on the ground state. So the ΔE enhances with raising the electric field. So the CT decays. As it can also be seen from Fig.1 that the CT of QPD qubit enhances with decaying CPTDEG. The physical origin is that the energy separation enhances with raising the CPTDEG. So the CT decreases.

The CT τ as the functions of the electric field F and the ZPPHP r_0, with $R_0 = 1.0nm$ and $V_0 = 1.0meV$ is shown in Fig. 2. From Fig. 2, we can clearly see that in the presence of the influence of the ZPPHP r_0, whereas without the influences of the CPTDEG V_0 and the polaron radiusR_0, the CT τ will decrease with increasing electric field F. The results and the reason are in harmony with the Fig. 1 without considerations of the polaron radius and the ZPPHP, whereas only consideration of the CPTDEG. It is also noted that with the decay of the ZPPHP, the CT aggrandize. Because the ZPPHP is weaker in the first-excited state than that in the ground state and the energy separation lifts with raising the ZPPHP. Hence the CT decays.

To make the relationships between the CT τ and the electric field F and the polaron radius R_0 more clearly, we have depicted Fig. 3, which presents the CT τ as the function of F and R_0 with $r_0 = 0.1nm$ and $V_0 = 1.0meV$. It is observed from the Fig. 3 that the CT is an decreasing functions of the polaron radius and the electric field. This is due to the GFES' energy levels are decreasing functions of the polaron radius, and the polaron radius' influences on the first-excited state is weaker than that on the ground state. So the ΔE enhances with raising the electric field. So the CT decays with increasing the polaron radius. The reason that the CT will decrease with increasing electric field is similar to the cases of the Fig. 1 without considerations of the polaron radius and the ZPPHP, whereas only consideration of the CPTDEG, and the Fig. 2 without considerations of the polaron radius and the CPTDEG, whereas only consideration of the ZPPHP.

The magnitude of the CT obtained in the present paper is 100–400-1000 ps, which is in agreement with Refs. [19, 20] and [21, 22], which were obtained respectively by experiments and theory. The coherence of qubit is crucial to the investigations of quantum computation, where the CT is one of the physical quantities representing the properties of coherence. Here we can find that we can adjust the CT by changing the electric field, the CPTDEG, the ZPPHP and the polaron radius.

4 Conclusions

In conclusion, we theoretically discuss the effects of the extra electric field, the CPTDEG, the ZPPHP and the polaron radius on the CT of the polaron in a RbCl QPD qubit by using the PTVM and the Fermi golden ruled. The results indicate that the electric field, the CPTDEG, the ZPPHP and the polaron radius are important factors to investigate of the CT of the RbCl QPD qubit.

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