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The ground-state lifetime of polaron in a parabolic quantum dot*

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This paper reports that the ground-state energy of polaron was obtained with strong electron-LO-phonon coupling by using a variational method of the Pekar type in a parabolic quantum dot. Quantum transition is occurred in the quantum system due to the electron–phonon interaction and the influence of temperature. That is the polaron transit from the ground-state to the first-excited state after absorbing a LO-phonon and it causes the change of the polaron lifetime. Numerical calculations are performed and the results illustrate that the ground-state lifetime of the polaron will increase with increasing the ground-state energy of polaron and decrease with increasing the electron-LO-phonon coupling strength, the confinement length of the quantum dot and the temperature.

Keywords: quantum dot, polaron, lifetime
PACC: 7138, 6320

1. Introduction

The rapid advances of nanofabrication technology have made it possible to work with quasi-zero-dimensional quantum dots (QDs) in laboratories. Such systems are of great interest in fundamental studies because of the completely discrete electronic states, as well as in practical applications for microelectronic devices because of their design flexibility. Consequently there has been a large amount of work, both experimental[1−3] and theoretical,[4−9] especially with the development of quantum information and quantum computing in recent years, the most feasible approach is QDs for realizing the quantum computer because of the advantage of being integrated. The two quantum state of electron is employed as a single qubit in a QD[10,11] in practice, the two quantum states of electron interact with its environment (phonon) inevitably which lead to the phenomena of decoherence.[12−14] So the electron–phonon interaction is significant to study the decoherence; meanwhile the electron–phonon interaction is essential to understand the optical absorption spectra in semiconductors, research on the polaron effect has become a main subject in the physics of low-dimensional quantum systems. Especially in a QD system, the electron–phonon interactions are enhanced by the geometric confinement. Therefore, a number of studies have been focused on the polaron decay in QDs recently. Boucaud *et al*[15] studied the polaron decay in InAs/GaAs self-assembled QDs by pump-probe spectroscopy and Zibik *et al*[16] investigated the polaron decay in n-type InAs QDs by using energy dependent, mid-infrared pump-probe spectroscopy. Verzelen *et al*[17] calculated the polaron relaxation time to thermo dynamical equilibrium when its lifetime is limited by the decay of its phonon component due to crystal anharmonicity. in these works, however, the ground-state lifetime of polaron in a parabolic QD has not been investigated so far.

The purpose of the present paper is to explore the ground-state lifetime of polaron in a parabolic QD with strong electron-LO-phonon coupling by using a variational method of Pekar type. The relations between the ground-state lifetime of polaron and the ground-state energy of polaron, the electron-LO-phonon coupling strength, the confinement length of the QD and the temperature are discussed.

2. Theoretical Model

We consider that the system in which the electrons are bounded by the confinement potential in a

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single QD is parabolic.

$$V(r) = \frac{1}{2}m^*\omega_0^2 r^2, \tag{1}$$

where m^* is the band mass of the electron, r is the coordinate of the electron and ω_0 is the confinement strength. The Hamiltonian of the electron–phonon system is given by

$$\begin{aligned} H &= -\frac{\hbar^2}{2m^*}\nabla_r^2 + \frac{1}{2}m^*\omega_0^2 r^2 + \sum_q \hbar\omega_{\rm LO} b_q^+ b_q \\ &\quad + \sum_q (V_q e^{{\rm i}q.r} b_q + {\rm h.c.}), \end{aligned} \tag{2}$$

where $b_q^+(b_q)$ is the creation (annihilation) operator of a bulk LO-phonon with wave vector $q(q = q_{//}, q_\perp)$, and

$$V_q = {\rm i}(\hbar\omega_{\rm LO}/q)(\hbar/2m^*\omega_{\rm LO})^{1/4}(4\pi\alpha/V)^{1/2}, \tag{3}$$

$$\begin{aligned} \alpha &= (e^2/2\hbar\omega_{\rm LO})(2m^*\omega_{\rm LO}/\hbar)^{1/2} \\ &\quad \times(1/\varepsilon_\infty - 1/\varepsilon_0). \end{aligned} \tag{4}$$

The LLP transformation to Eq.(2) is modified as

$$U = \exp\left[\sum_q \left(f_q b_q^+ - f_q^* b_q\right)\right], \tag{5}$$

where f_q will be treated as a variational function. After the above transformation the Hamiltonian becomes

$$H' = U^{-1}HU. \tag{6}$$

Suppose that the Gaussian function approximation is still valid in the ground-state of electron–phonon system according to the variational method of Pekar type. For the ground-state we choose the wave function of the system as

$$|\Psi_0\rangle = \left(\frac{\lambda}{\sqrt{\pi}}\right)^{3/2} \exp(-\lambda^2 r^2/2)\,|0\rangle\,, \tag{7}$$

where λ is a variational parameter and $|0\rangle$ is zero phonon state which satisfies $b_q|0\rangle = 0$. Then the ground-state energy of polaron can be written in the following form

$$\begin{aligned} E_0(\lambda) &= \langle\varphi_{e-p}|\,H'\,|\varphi_{e-p}\rangle \\ &= \frac{3\hbar^2\lambda^2}{4m^*} + \frac{3\hbar^2}{4m^*\lambda^2 l_0^4} \\ &\quad -\sqrt{\frac{2}{\pi}}\alpha\hbar\omega_{\rm LO} r_0\lambda, \end{aligned} \tag{8}$$

where the confinement length of a QD is $l_0 = \left(\frac{\hbar}{m^*\omega_0}\right)^{1/2}$ and the polaron radius is $r_0 = (\hbar/2m^*\omega_{\rm LO})^{1/2}$.

Hence, the ground-state energy of polaron in a parabolic QD can be written as

$$E_0 = \frac{3\hbar^2\lambda_0^2}{4m^*} + \frac{3\hbar^2}{4m^*\lambda_0^2 l_0^4} - \sqrt{\frac{2}{\pi}}\alpha\hbar\omega_{\rm LO} r_0\lambda_0^2. \tag{9}$$

Under the influence of the electron–phonon interaction and the temperature based on the Fermi Golden Rule, the transit rate that the polaron transits from the ground-state to the first-excited state after absorbing a LO-phonon is given by

$$\begin{aligned} T^{-1} &= \frac{\alpha\omega_{\rm LO}}{2\lambda_0}\sqrt{\frac{2m^*\omega_{\rm LO}}{\hbar}}n_q \\ &\quad \times \ln\frac{(\sqrt{\lambda_0^2 + 2m^*\omega_{\rm LO}/\hbar} + \lambda_0)^2}{(\sqrt{\lambda_0^2 - 2m^*\omega_{\rm LO}/\hbar} - \lambda_0)^2}. \end{aligned} \tag{10}$$

According to quantum statistics, we have

$$\bar{n}_q = \left[\exp\left(\frac{\hbar\omega_{\rm LO}}{k_{\rm B}T}\right) - 1\right]^{-1}, \tag{11}$$

where $k_{\rm B}$ is the Boltzmann constant, Eq.(11) should be self- consistent with the n_q of Eq.(10). Meanwhile, we assumed that $\frac{\hbar\omega_{\rm LO}}{k_{\rm B}T} = \gamma$ is the temperature parameter and then the Eq.(11) is converted into $\bar{n}_q = [\exp\gamma - 1]^{-1}$.

3. Results and discussion

The numerical results of the dependence of the ground-state lifetime of polaron on the electron-LO-phonon coupling strength, the confinement length of QD, the ground –state energy of polaron and the temperature in a parabolic QD are presented in Figs.1–4. Choose $\hbar = 2m^* = \omega_{\rm LO} = 1$ polaron units.

Figure 1 presents the ground-state lifetime of polaron as a function of the ground-state of polaron at different temperature parameters. It can be seen that the lifetime of polaron increases with increasing the ground-state energy of polaron. This is because the higher the ground-state energy of polaron, the lower the transition probability per second is, which is a measure of quickness of the polaron scattered from its ground-state into the first-excited state under absorption of a LO-phonon.

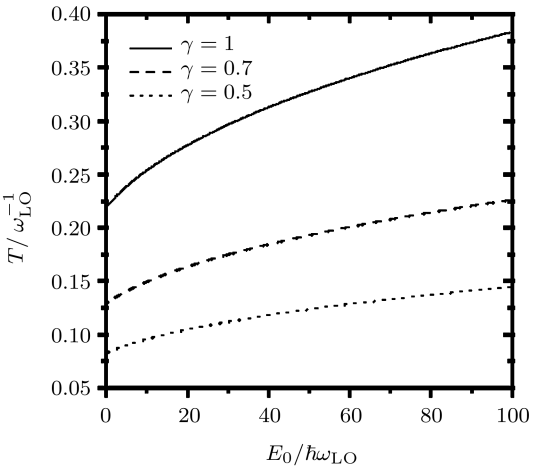


Fig.1. The ground-state lifetime of polaron as a function of the ground-state energy in a parabolic QD.

Figure 2 shows the lifetime of polaron as a function of the confinement length at different electron-LO-phonon coupling strength $\alpha = 5, 6, 7$ and the temperature parameter $\gamma = 1$. From it we can see that the lifetime of polaron decreases with increasing the confinement length. The reason is that with the decrease of confinement length (ω_0 decreasing), i.e. with the increase of r_0, the thermal motion energy of electrons and the interaction between electron and phonons, which take phonon as medium, are reduced because the range of particles motion becomes large. So the ground-state energy of polaron in a parabolic QD decreases. As a result, the transition probability per second becomes fast and it leads to the reduction of lifetime of polaron.

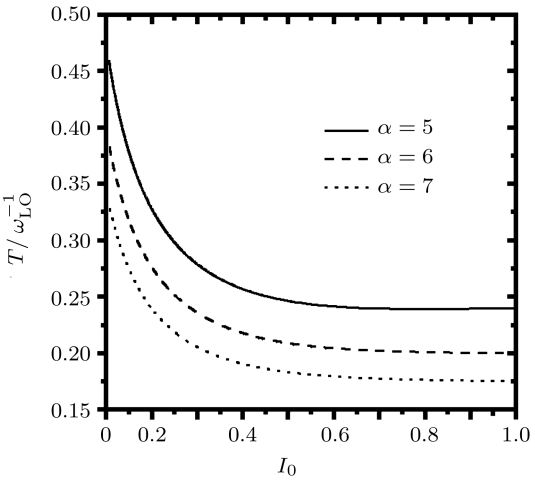


Fig.2. The ground-state lifetime of polaron as a function of the confinement length in a parabolic QD.

Figure 3 illustrates the ground-state lifetime of polaron as a function of the electron-LO-phonon coupling strength at the different confinement length $l_0 = 0.3, 0.4, 0.7$ and the temperature parameter $\gamma = 1$. It shows that the ground-state lifetime of polaron decreases with increasing the electron-LO-phonon coupling strength. This is derived from the contribution for which the electron–phonon interaction to the ground-state energy of polaron is decreased. So with increasing the electron–phonon coupling strength, the ground-state energy of polaron will decrease. And then the transition probability per second becomes large. Consequently, the ground-state lifetime of polaron is reduced with the result.

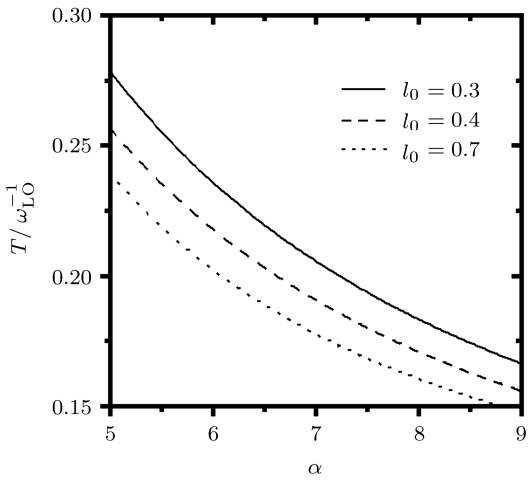


Fig.3. The ground-state lifetime of polaron as a function of the electron-LO-phonon coupling strength in a parabolic QD.

Figures 4(a) and 4(b) plot the ground-state lifetime of polaron as a function of the temperature parameter at different electron-LO-phonon coupling strength and confinement length ,respectively. From them, we can see that with increasing the temperature parameter (the temperature falling) the lifetime of polaron increases rapidly. This is because the lattice thermal vibrations become slowly with falling the temperature. And it makes the numbers of phonon around electron decrease sharply. For this reason, the probability that the electron absorbs a phonon becomes small. Meanwhile, we also see that the influence of temperature to the lifetime of polaron is dominant in a QD. Only on the condition of certain temperature, the influence of coupling strength and the confinement length to the lifetime of polaron is mainly considered.

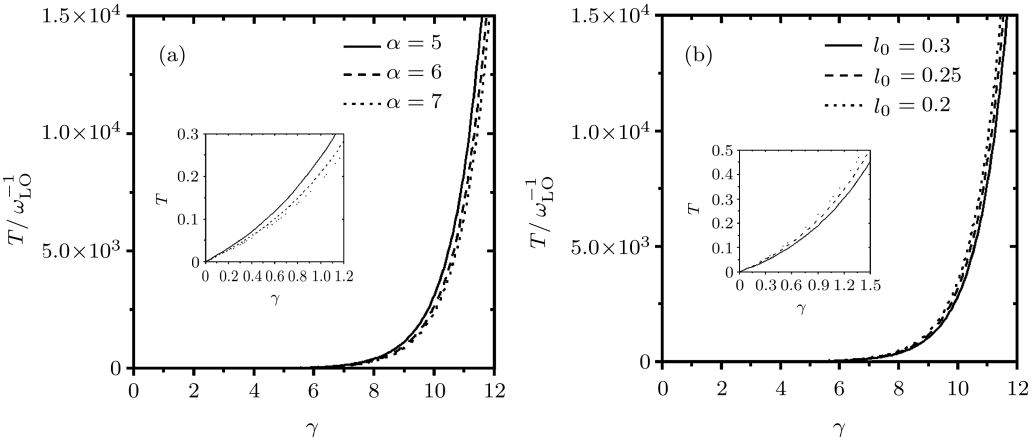


Fig.4. (a) The ground-state lifetime of polaron as a function of the temperature parameter at different coupling strength. (b) The ground-state lifetime of polaron as a function of the temperature parameter at different confinement length.

4. Conclusion

With strong electron-LO-phonon coupling by using a variational method of Pekar type in a QD, the ground-state energy of polaron lifetime was studied. The relations between the ground-state lifetime of polaron and the ground-state energy of polaron, the electron-LO-phonon coupling strength, the confinement length of a QD and the temperature are discussed. The results indicate that the ground-state lifetime of polaron will increase with increasing the ground-state energy of polaron and decrease with increasing the electron-LO-phonon coupling strength, the confinement length of a QD and the temperature.

References

[1] Sikorski C and Merkt U 1989 *Phys. Rev. Lett.* **62** 2164
[2] Lorke A, Kotthaus J P and Ploog K 1990 *Phys. Rev. Lett.* **64** 2559
[3] Demel T, Heitmann D, Gambow P and Ploog K 1990 *Phys. Rev. Lett.* **64** 788
[4] Degani M H and Farias G A 1990 *Phys. Rev.* B **42** 11950
[5] Li S S and Xia J B 2007 *Chin. Phys.* **16** 0001
[6] Li S S and Xia J B 2006 *J. Appl. Phys.* **100** 083714
[7] Li S S and Xia J B 2006 *Chin. Phys. Lett.* **23** 1896
[8] Wang Z W and Xiao J L 2007 *Acta Phys. Sin.* **56** 678 (in Chinese)
[9] Normura S and Kobayashi T 1992 *Phys. Rev.* B **45** 1305
[10] Li S S, Xia J B, Yang F H, Niu Z C, Feng S L and Zheng H Z 2001 *J. Appl. Phys.* **90** 6151
[11] Li S S, Bai F S, Feng S L and Zheng H Z 2001 *Pro. Natl. Acad. Sci. USA* **98** 11847
[12] Denis T and Privman V 2004 *Phys. Rev.* A **69** 062309
[13] Grodecka A and Machnikowski P 2006 *Phys. Rev.* B **73** 125306
[14] Lovrić M, Krojanski H G and Suter D 2007 *Phys. Rev.* A **75** 042305
[15] Boucaud P, Sauvage S, Bras F and Fishman G 2005 *Physica* E **26** 59
[16] Zibik E A, Wilson L R, Green R P, Wells P R, Phillips P J, Carder D A and Cockburn J W 2004 *Physica* E **21** 405
[17] Verzelen O, Ferreira R and Bastard G 2002 *Physica* E **13** 309