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Bound magnetopolaron in delta GaAs quantum dot under Rashba effect

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ABSTRACT

This paper presents the influence of Rashba effect on bound magnetopolaron in delta quantum dot. The unitary transformation method and the variational method of Pekar type have been used to derive the ground and first excited state energy. Due to Rashba effect, the ground and first excited states each split into two energies (spin up and down). Results show that the split up (down) energy of ground and first excited states are increasing (decreasing) function of wave vector; the spin splitting of the ground and first excited states are decreasing function of the delta parameter and the increasing function of Rashba parameter. It has also be seen that the splitting of energies levels occur around the value $q = 0$. The density of probability has its minimum value at the center of the dot while it is maximal at the boundary of the dot. The decoherence has been studied through the Shannon entropy and the results show increase of entropy with time, delta parameter K, and cyclotron frequency ω_c. It also suggests a way to encrypt information and to control decoherence.

1. Introduction

Spintronics studies the intrinsic spin of the electron and its associated magnetic moment, in addition to its fundamental electronic charge in solid state devices. It is the direct application of the Rashba effect. The Rashba effect allows the manipulation of the spin degree of freedom without the aid of the magnetic field. It is a momentum-dependent splitting of spin bands into two-dimensional condensed matter systems similar to the splitting of particles and anti-particles in the Dirac Hamiltonian. The Splitting is the combined effect of atomic spin-orbit coupling and asymmetry of the potential in the direction perpendicular to the two-dimensional plane. It was discovered by Emmanuel Rashba [1].

In recent years, the Rashba effect in low-dimensional semiconductor structures has attracted great attention because of its application in spintronics [2] and topological quantum computation. Sato Masatoshi and Fujimoto Satoshi [3] and Mourik et al. [4] suggested that the Rashba effect can be used to realize a p-wave superconductor. Such a conductor has very special edge-states which are known as Majorana bound states. The non-locality immunizes them to local scattering and henceforth they are predicted to have long coherence times. Decoherence is one of the largest barriers on the way to realize a full scale quantum computer and these immune states are therefore considered good candidates for a quantum bit. Khordad [5] studied the influence of Rashba effect on bound polaron in a quantum pseudodot. Using the Lee-Low-Pines unitary transformation method and the Pekar type variational procedure, he derived an expression for the bound polaron ground state energy as functions of the wave vector, the electron-phonon

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coupling strength, and quantum confinement size obtained with considering different Coulomb bound potentials. Li et al. [6] utilized an exact variational numerical procedure to calculate the ground-state properties of a polaron in the presence of Rashba and linear Dresselhaus spin-orbit coupling. They found that when the linear Dresselhaus spin-orbit coupling approaches the Rashba spin-orbit coupling, the Van Hove singularity in the density of states shifted away from the bottom of the band and finally disappear when the two spin-orbit couplings are tuned to be equal. The effective mass was suppressed; the trend became more significant for low phonon frequency. Huang et al. [7] studied the spin splitting energies of different orbital states of quantum dots with a low-potential barrier. The experimental results showed that the splitting energies are orbital state dependent. The theoretical analysis was done with a generalization of the Fock–Darwin states in the presence of spin–orbit interactions. Kuan et al. [8] solved the Hamiltonian of an electron in a semiconductor double ring subjected to the magnetic flux and Rashba spin-orbit interaction. They found that the Aharonov–Bohm energy spectrum revealed multi-zigzag periodic structures. The investigations of spin-dependent electron dynamics via Rabi oscillations in two-level and three-level systems demonstrated the possibility of manipulating quantum states. Their results showed that the optimal control of photon-assisted inter-ring transitions can be achieved by employing cascade-type and -type transition mechanisms. Under chirped pulse impulsions, a robust and complete transfer of an electron to the final state was shown to coincide with the estimation of the Landau–Zener formula. On the condition of electric-LO phonon strong coupling in a parabolic quantum Li et al. [9] obtained the polaron ground state energy by using the variational method of Pekar, considering the influence of the Rashba spin-orbit interaction. The relations on the polaron ground state energy with the parallel confinement length, the electron-LO phonon coupling constant, and the perpendicular confinement length were derived for a parabolic quantum dot. The heat capacity of a two electron quantum dot with parabolic confinement in magnetic field in the presence of electron-electron interaction and Dresselhaus spin-orbit interaction (DSOI) have been studied by Sanjeev et al. [10]. The electron-electron interaction has been treated by a model potential which makes the Hamiltonian to be exactly soluble. The RSOI has been treated by a unitary transformation and the terms up to second order in DSOI constants were considered.

In quantum mechanics, the delta potential is a potential well described mathematically by the Dirac delta function. Qualitatively, it corresponds to a potential which is zero everywhere, except at a single point where it takes an infinite value. Many studies have been done on polaron in delta dot; for example, Fotue et al. [11] studied the effect of the tunable potential and decoherence of polaron in nanostructures. They arbitrarily chose eight potentials: the elliptical potential, square potential, triangular potential, the quadratic potential, the delta potential, the Gaussian potential, the pseudo-harmonic potential, and Coulombic potential. The bound magnetopolaron in delta quantum dot under Rashba effect and decoherence has not yet been studied, and it is the aim of this research paper. In Section 2, the Hamiltonian of the system and use the Pekar variational method to derive the energies of the ground and first excited states are described. The results are presented and discussed in Section 3 and finally, the conclusion is reached in Section 4.

2. Theoretical model and calculation

In Polar crystal, the electrons are moving and strongly interacting with bulk LO phonons, under the influence of a magnetic field along the $z-$direction with vector potential $A = B(-y/2, x/2, 0)$ in presence of the Rashba spin-orbit interaction. The spatial behavior of the delta potential along the $x-$direction is given by $\delta(ax)$. $\delta(ax)$ has the dimension of a reciprocal length and this attractive potential is written as follow [12].

$$V(x) = -\frac{\hbar^2\kappa}{2ma}\delta(ax) \tag{2.1}$$

where $\delta(ax)$ satisfy $\delta(ax) = \frac{1}{|a|}\delta(x)$; a is an arbitrary quantity with dimensions of a length so that κ is a dimensionless quantity that was used to characterize the strength of the potential.

The Hamiltonian of the electron–phonon interaction system can be written as:

$$\begin{aligned} H &= \frac{1}{2m}\left[\left(p_x - \frac{\beta^2}{4}y\right)^2 + \left(p_y + \frac{\beta^2}{4}x\right)^2\right] - \frac{\hbar^2 K}{2ma}\delta(ax) \\ &+ \sum_q \hbar\omega_{LO} a_q^+ a_q + \sum_q \left[V_q a_q \exp(iq\cdot r) + h.\,c.\right] + H_R \end{aligned} \tag{2.2}$$

The physical quantities in (2.2) were given in [11]. The last term in (2.2) describes Rashba spin-orbit interaction and is expressed as [5,13]

$$H_R = i\frac{\alpha_R}{2\hbar}(P_-^3\sigma_+ - P_+^3\sigma_-) \tag{2.3}$$

where α_R is the Rashba spin-orbit coupling constant $\sigma_\pm = \sigma_x \pm i\sigma_y$ and $P_\pm = P_x \pm iP_y$. σ_x and σ_y are the Pauli matrices. Following the Pekar variational method, the trial function of strong coupling that can be separated into the electron and the phonon part can be