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Optical properties of impurity-bound polaron in a parabolic quantum dot

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ABSTRACT

The linear and nonlinear optical properties of an electron, which is bounded to a Coulomb impurity in a polar semiconductor quantum dot with parabolic confinement in both two and three dimensions, are studied by using the Landau–Pekar variational method and the compact density-matrix approach. With typical semiconducting GaAs-based materials, the linear, third-order nonlinear, total optical absorption coefficients and refractive indexes have been examined. We find that the all absorption spectra and refractive index changes are strongly affected by the electron–LO–phonon interaction. The results also indicate that the polaron effect increases with decreasing dimensionality of a quantum dot.

1. Introduction

Quantum dots (QDs) exhibit strongly size-dependent electrical and optical properties that might create many opportunities for scientific discovery. On the other hand, QD structures can be realized in different shapes and sizes because of the recent advance in modern micro-fabrication techniques, such as, molecular beam epitaxy and self-assembling. They provides a tremendous design flexibility for their use in semiconductor technology. Recently, intersubband transitions in semiconductor QDs have attracted considerable interest for both fundamental physics study and development of infrared optoelectronic devices. Compared with quantum well structures, the intersubband absorption in QDs has advantages in optical applications due to their sharp delta-like density of states, reduced intersubband relaxation times [1,2]. From the point of view of quantum confinement, engineering the electronic structure of materials by means of shape and size control offers the possibility of tailoring the energy spectrum to produce desirable optical transitions. These features are useful for the development of optoelectronic devices with tunable emission (or transmission) properties and ultra-nar-

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row spectral linewidths. Hence, the linear and nonlinear optical properties of QDs have been investigated both experimentally and theoretically by many authors [3–8].

It is well known that the electron longitudinal–optical (LO) phonon interaction is an important factor influencing the physical properties of polar crystals. The effect of such influence becomes stronger as the dimensionality of the system reduces [9]. In this context, polar semiconductor QD structures have been, in particular, the focus of attention for their potential applications in nano-electronic and optoelectronic devices like single electron transistors, quantum dot lasers, ultra-fast computers and so on. Some experimental and theoretical studies show that electrons confined in QDs are strongly coupled to the LO vibrations of the underlying semiconductor lattice [10–12]. This coupling leads to the formation of the so-called electronic QD polarons, which are the true excitations of a charged dot. Infrared absorption probes directly the polaron levels instead of the purely electronic ones. Interband transitions are also expected to be related to polaron states involving electron states coupled to optical phonons. The Lee-Low-Pines-Huybrechts method has been successfully employed in calculation of the polaronic corrections to the ground- and first-excited slates in QD by Mukhopadhyay and Chatterjee [13]. Recently, Chen et al. investigated the binding energies of the ground and the first-excited states of an electron bound to a Coulomb impurity in a polar semiconductor QD with parabolic confinement in both two and three dimensions [14]. Their results show that the electronic properties of QDs are strongly affected by the electron–LO phonon interaction. However, in these works, the theoretical calculation is limited to the binding energies of the ground and the first-excited states. The ground and the first-excited states of an electron in a QD may be employed as a two-level quantum system (qubit). An electromagnetic pulse can be applied to drive an electron from the ground state to the first-excited state or to a superposition of the ground and the first-excited states. Obviously, electron–phonon interaction will plays an important role in the optical absorptions of the ground and the first-excited states in QDs. However, to our knowledge, there are only few studies on the polaron effects of the linear and nonlinear optical properties of QDs.

If a QD embedded in three-dimensional (3D) material with the motion of the dot electron confined in all the three spatial directions, it will be called a 3D QD. If a QD embedded in a purely two-dimensional (2D) system with the electron's motion confined in two spatial dimensions, it will be called a 2D QD. In reality, however, no systems can be purely 2D, but if the thickness of the system is much smaller than the confinement lengths in the two spatial directions, the corresponding dot may be referred to as a quasi-two-dimensional QD. In the present work, we will devote our calculations to the linear, third-order nonlinear, total optical absorption coefficients (ACs) and refractive index (RI) changes of the Coulomb impurity bound polaron in a QD with parabolic confinement in both two and three dimensions. To the best of our knowledge, this problem has not been studied extensively in the literature.

2. Theory

Consider a Coulomb impurity atom located in an N dimensional parabolic QD with the electron–LO–phonon interaction. The Hamiltonian within the effective-mass approximation can be written as

$$H = \frac{p^2}{2m_e} + \frac{1}{2}m_e\omega_0^2 r^2 - \frac{e^2}{\epsilon_\infty r} + \sum_{\vec{q}} \hbar\omega_{LO} a_{\vec{q}}^{+} a_{\vec{q}} + \sum_{q} (a_q V_q e^{i\vec{q}\cdot\vec{r}} + h.c.), \tag{1}$$

where $\vec{r}$ ($\vec{p}$) is the position vector (the momentum vector) originating from the center of the dot; m_e is the effective mass of an electron; ω_0 is the strength of the confinement, ϵ_∞ is the high-frequency dielectric constant, and $a_{\vec{q}}^{+}$ ($a_{\vec{q}}$) is the creation (annihilation) operator for LO phonons with wave vector $\vec{q}$ and energy $\hbar\omega_{LO}$. The V_q in Eq. (1) is the coefficient of electron–LO–phonon interaction

$$V_q = i\left(\frac{\hbar\omega_{LO}}{q}\right)\left(\frac{4\pi\alpha_{LO}}{V}\right)^{1/2}\left(\frac{\hbar}{2m_e\omega_{LO}}\right)^{1/4}, \tag{2}$$

where V is the crystal volume and α_{LO} the electron–LO–phonon coupling constant given by