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Optical absorption and refractive index of a donor impurity in a three-dimensional quantum pseudodot

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ABSTRACT

The optical absorption and refractive index of a donor impurity confined by a three-dimensional quantum pseudodot are studied using the matrix diagonalization method within the effective-mass approximation. The great advantage of our methodology is that it enables us to tune confinement strength and regime by varying two parameters in the model potential. Based on the computed energies and wave functions, the linear, third-order nonlinear and total optical absorption coefficients as well as the refractive index changes have been examined. The results are presented as a function of the incident photon energy for the different values of the chemical potential of the electron gas and the zero point of the pseudoharmonic potential. We find that the larger optical nonlinearity will be obtained by varying the zero point of the pseudoharmonic potential compared to the chemical potential of electron gas.

1. Introduction

The study of impurities is one of the main problems in semiconductor low-dimensional systems because the presence of impurities in nanostructures influences greatly the electronic mobility and their optical properties [1]. Hence, the study of the impurity states in low-dimensional semiconductors has been extensively reported in the last few years [2–12]. In the optical transition of quantum confined few-electron systems, the analysis of the donor impurity states is also inevitable because the confinement of quasiparticles in such structure leads to the enhancement of the oscillator strength of electron-impurity excitations. Meanwhile, the dependence of the optical transition energy on the confinement strength allows the tunability of the resonance frequency.

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The linear absorption within the conduction band of a GaAs quantum well has been studied experimentally [13,14]. A very large oscillator strength and a narrow bandwidth were observed. These suggest that intersubband optical transitions in a low-dimensional semiconductor have very large optical nonlinearity. Both linear and nonlinear intersubband optical absorptions can be used for practical applications in photodetectors and high-speed electronic optical devices [15,16]. Of low-dimensional systems, quantum dots (QDs) have attained considerable theoretical and experimental attention due to their potential application in microelectronics and future laser technology [17,18]. Recently, some authors studied the linear [19], and nonlinear optical properties of semiconductor QDs [19–26]. Usually, the harmonic oscillator potential is considered in these studies, since the harmonic oscillator potential is close to the molecular vibrational potential in QDs and this model is easily solved mathematically. However, it is unrealistic in several respects when compared to a real molecular vibrational potential [27]. Some experimental results show that the anharmonic oscillator is great importance in different physical system with many applications in molecular physics [27]. Pseudoharmonic potential is commonly considered as anharmonic oscillator. Therefore, the studies of a quantum pseudodot attracts much attention in the investigation of low-dimensional system recently. Very recently, Rezaei and co-worker studied that the optical absorption coefficients (ACs) and refractive index (RI) changes are associated with intersubband transitions of an electron in a two-dimensional quantum pseudodot [28]. The quantum pseudodot system is a new nanostructure which possesses a finite chemical potential (V_0) and a zero point of the pseudoharmonic potential (r_0) [29]. In addition, the pseudopotential was applied to interpreting some results from experiments with great success [30–32]. In the present work, we will focus on studying the linear and nonlinear optical properties of a donor impurity in a three-dimensional quantum pseudodot. By using the matrix diagonalization method and the compact density-matrix approach, the linear, third-order nonlinear and total optical ACs and RI changes are calculated.

2. Theory

Within the effective-mass approximation, the Hamiltonian of a donor impurity confined by a QD with a three-dimensional pseudoharmonic potential can be written as

$$H = \frac{p^2}{2m_e} + V(r) - \frac{e^2}{\epsilon r}, \tag{1}$$

where $\vec{r}$ ($\vec{p}$) is the position vector (the momentum vector) of the electron originating from the center of the dot, m_e is the effective mass of an electron, e is the electron charge, ϵ is the dielectric constant, and $V(r)$ is the confinement potential that includes both dot and antidot harmonic potentials, as follows [28,29]:

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

where V_0 is the chemical potential of the electron gas and r_0 is the zero point of the pseudoharmonic potential.

To obtain the eigenfunction and eigenenergy associated with the donor impurity in a spherical QD, the Hamiltonian is diagonalized in the Hilbert space spanned by spherical harmonic states

$$\Psi_L = \sum_i c_i \phi_i(\vec{r}), \tag{3}$$

where $\phi_i(\vec{r}) = R_{n_i\ell_i}(r)Y_{\ell_i m_i}(\theta,\varphi)$ is ith spherical harmonic oscillator eigenstate with a frequency ω and an energy $(2n_i + \ell_i + 3/2)\,\hbar\omega$. The principal, orbital, and magnetic quantum numbers of $\phi_i(\vec{r})$ are n_i, ℓ_i, and m_i, respectively. The radial wavefunction $R_{n\ell}(r)$ is given by

$$R_{n\ell}(r) = \frac{\alpha^{3/2}}{\pi^{1/4}}\sqrt{\frac{2^{n+\ell+1}(n-1)!}{(2n+2\ell-1)!!}}(\alpha r)^{\ell} e^{-\alpha^2 r^2/2} L_{n-1}^{\ell+1/2}(\alpha^2 r^2), \tag{4}$$