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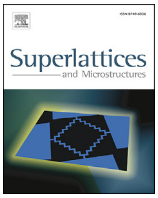

The effect of Rashba spin-orbit interaction on electronic and optical properties of a double ring-shaped quantum dot

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ABSTRACT

In this work, we analytically study the effects of the Rashba spin-orbit interaction (SOI) and magnetic field on energy levels and optical properties of a double ring-shaped quantum dot. For this purpose, we first solve the Schrödinger equation and obtain the energy eigenvalues and the wave functions. Then, we use analytical expressions for optical properties obtained by the compact-density matrix formalism. We calculate the total refractive index change and total absorption in the presence of applied magnetic field and Rashba SOI. It is found that the energy levels strongly depend on the combined effects of the Rashba SOI and the applied magnetic field. The energy levels split into two branches, spin-up and spin-down states, due to the Rashba spin-obit interaction. The peak positions of both optical properties shift towards higher energies with increasing the magnetic field and Rashba parameter.

1. Introduction

The research on quantum dots is a revolutionary fact in the basic sciences such as physics and chemistry [1]. Quantum dots can be prepared using various procedures such as molecular-beam epitaxy, metal-organic chemical vapour deposition and chemical lithography [2–4]. In these structures the electron motion along all directions is quantized and conducting electrons are confined at the semiconductor interface to form zero dimensional systems.

An important and interesting problem of physics science is to study electronic and optical properties of nanostructures. Hitherto, much theoretical potentials such as central and non-central potentials have been extensively employed in the literature. The potentials can provide a useful theoretical foundation for describing a physical system. For example, the Hartmann potential [5] is a type of non-central potential. The spherical harmonic oscillator (SHO) is an interesting and simple potential which applies to various fields of physics [6,7]. We should note that usually SHO model cannot employ for a number of real physical problems. For this reason, many researchers have tried to apply other theoretical models to study of physical problems. Examples of these models are ring-shaped oscillator, ring-shaped non-spherical oscillator, non-spherical oscillator and double ring-shaped oscillator [8–12].

The researches on semiconductor quantum-confined structures have aroused much attention in recent years. One of the major effects remaining to be addressed concerns the effect of the spin-orbit interaction (SOI) on electronic and optical properties of quantum dots. It is noteworthy that the SOI is an important problem for any realistic discussion of the electronic

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and optical properties of quantum dots [13–19]. In addition, SOI plays a very important role in quantum dots due to their potential applications in quantum computer [20,21].

It is worth mentioning that the electron spin plays an important role in spin phenomena such as spintronics, quantum computer and spin relaxation [22,23]. The spin-orbit interaction (also called spin-orbit effect or spin-orbit coupling) is the interaction of an electron's spin with its orbital motion. The SOI can arise in quantum dots by various mechanisms related to electron confinement and symmetry breaking. Two types of SOI in nanostructures are the Rashba and Dresselhaus which arise due to structural inversion symmetry and bulk inversion asymmetry, respectively [24–26]. The strength of these interactions depends on both the characteristics of the material and external electric field.

So far, many works have been done on the influence of Rashba spin-orbit interaction on the electronic and optical properties of nanostructures by researchers during the last decade [27–32]. For example, Shakouri et al. [33] have investigated the simultaneously effects of Rashba and Dresselhaus SOIs and magnetic field on the energy spectra and charge densities in a quasi-one-dimensional quantum rings. Sheng and Zheng [34] have studied the energy levels of two-dimensional ring confining potential in the presence of the Rashba spin-orbit interaction. Chen et al. [35] have studied the effect of SOI in double-ring-shaped oscillator. Recently, we have studied The Rashba and Dresselhaus spin-orbit interactions in a two-dimensional quantum pseudo-dot system [36]. Although many works have been done on the electronic properties of quantum dots under SOI, but effect Rashba SOI on electronic properties of a double ring-shaped quantum dot has not studied so far. For this purpose, we intend to study this problem in detail.

The article is organized as follows: in Section 2, the total Hamiltonian of the system is briefly presented. Analytical expressions for the third-harmonic generation are obtained using the density matrix approach in Section 3. Finally, the results and discussion are presented in Section 4 and conclusions in Section 5.

2. Theory

We consider an electron confined in a double ring-shaped quantum dot. The Hamiltonian of the system under the Rashba SOI and subject to an external magnetic field along the z-direction is given by

$$H = H_0 + H_R + \frac{1}{2} g^* \mu_B B \sigma_z, \tag{1}$$

where H_0 is the electron Hamiltonian as

$$H_0 = \frac{(\boldsymbol{P} + e\boldsymbol{A})^2}{2m^*} + V(r,\theta), \tag{2}$$

And H_R is the Rashba Hamiltonian as

$$H_R = \frac{\alpha_R}{\hbar}[\sigma \times (\boldsymbol{P} + e\boldsymbol{A})] \tag{3}$$

where m^* and g^* are effective mass and Landé factor of the electron, respectively. Also, $\sigma = (\sigma_x, \sigma_y, \sigma_z)$ are the Pauli matrices, α_R is the Rashba parameter (RP) and μ_B is the Bohr magneton. The magnetic field B is parallel to the z-direction and $A = \frac{B}{2}(-y, x, 0)$ is the vector potential induced by the magnetic field which is taken in the symmetric gauge. It is noteworthy that the last term of Eq. (1) is the ordinary Zeeman coupling and $V(r)$ is the confinement potential which is given by Ref. [11].

$$V(r,\theta) = \frac{1}{2} m^* \omega_0^2 r^2 + \frac{\hbar^2}{2m^*}\left(\frac{B}{r^2 \sin^2\theta} + \frac{C}{r^2 \cos^2\theta}\right), \tag{4}$$

where B and C are two potential parameters, m^* is the electron effective mass, ω_0 is the frequency of quantum dot confinement potential and $\hbar$ is the Plank constant. For $C = 0$ and $B = C = 0$ Eq. (4) reduces to ring-shaped oscillator and spherical harmonic oscillator, respectively.

First, we should solve the equation $H_0\psi = E_0\psi$. In cylindrical coordinates, the Schrödinger equation with the potential Eq. (4) is written as

$$\left[-\frac{\hbar^2}{2m^*}\nabla^2 + \frac{1}{2} m^* \omega_0^2 \left(\rho^2 + z^2\right) + \frac{\hbar^2}{2m^*}\left(\frac{B}{\rho^2} + \frac{C}{z^2}\right)\right]\psi(\rho,\phi,z) = E\psi(\rho,\phi,z) \tag{5}$$

Substituting the wave function in the form $\psi(\rho,\phi,z) = R(\rho)F(z)e^{im\phi}$ in Eq. (5), we obtain the following equations