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Absorption coefficient and refractive index changes of a quantum ring in the presence of spin-orbit couplings: Temperature and Zeeman effects

A. Zamani*, T. Azargoshasb, E. Niknam

Young Researchers and Elite Club, Zarghan Branch, Islamic Azad University, Zarghan, Iran

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ABSTRACT

Effects of applied magnetic field, temperature and dimensions on the optical absorption coefficients (AC) and refractive index (RI) changes of a GaAs quantum ring are investigated in the presence of both Rashba and Dresselhaus spin-orbit interactions (SOI). To this end, the finite difference method (FDM) is used in order to numerically calculate the energy eigenvalues and eigenstates of the system while the compact density matrix approach is hired to calculate the optical properties. It is shown that application of magnetic field, temperature as well as the geometrical size in the presence of spin-orbit interactions, alter the electronic structure and consequently influence the linear and third-order nonlinear optical absorption coefficients as well as the refractive index changes of the system. Results show an obvious blue shift in optical curves with enhancing external magnetic field and temperature while the increment of dimensions result in red shift.

1. Introduction

Nowadays, quantum dots (QD) are known as artificial atoms due to their quantum mechanical behavior that is more like atoms than bulk materials with one great advantage in which their electronic and optical properties can be modified via application of external agents as well as the geometrical size. In QDs the charge carrier is captured in all spatial dimensions and the energy levels of the structure become quantized (where all the dimensions are in nanometer scale). However, most of the works have investigated the electronic and optical properties of semiconductor nanostructures neglecting the spin of electron, which is an intrinsic feature of charge carriers and makes the system more sensitive to external factors such as magnetic field due to the spin-orbit interactions (SOI).

The spin-orbit (SO) coupling is defined as the interaction between the spin of electron and a magnetic field created by a Lorentz-transformed electric field. The spin of an electron moving within the electric field, experiences a magnetic field perpendicular to both direction of motion and electric field and is proportional to the local electric field. Such phenomena that comes after coupling between the magnetic field and the spin, leads to a Larmor spin precession. A local electric field in semiconductor crystal is originated either from the hetero-interface, structural inversion asymmetry (SIA), creating the Rashba SO coupling or from the absence of inversion symmetry of the material structure, bulk inversion asymmetry (BIA), leading to the Dresselhaus SOI. From a quantum mechanical point of view, the Rashba coupling makes the spin of electron

* Corresponding author.
E-mail address: alizamanim@zariau.ac.ir (A. Zamani).

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precess around the axis perpendicular to the velocity axis while the Dresselhaus coupling, on the other hand, creates electric fields between atoms that comes from polar bonds caused by the lack of inversion symmetry [1,2,3,4].

Optical properties associated with intersubband transition such as absorption coefficient (AC) and refractive index (RI) changes, beside the electronic structure of QDs, have become one of the leading fields in the study and manufacture of opto-electronic devices based on semiconductor nanostructures. Therefore, lots of discussions and analysis, in both theoretical and applied physics, can be found on linear and nonlinear optical properties of QDs which reveal the remarkable attention has been paid to this subject [5,6,7,8,9,10,11,12]. Zero-dimensional structures (QDs) have large values of dipole transition matrix elements. Resonant absorption spectra occurs when the system is exposed by photons with energies around the intersubband transition energies. Therefore, the optical AC and RI changes of QDs can be manipulated and adjusted by size alteration, application of magnetic field (Zeeman effect that is resulted from interaction of external magnetic field and the spin of electron) as well as the temperature.

While the progress in fabrication of semiconductor nanostructures leads to the opportunity of experimentally produce QDs of various geometrical shapes and sizes, it is important to investigate detailed analysis of such systems, theoretically, in order to use such structures in new generation opto- and nano-electronic devices wisely [13,14,15,16,17,18,19]. Among all shapes of QDs, quantum rings are so fascinating as the magnitude of their dipole moment can be fixed and also in ring geometries the electron wave packets can take two different paths around the ring which leads to interference. On the other hand, in most of the works, the SO interaction in quantum rings dealt with the pure Rashba interaction while the Dresselhaus spin-orbit coupling is usually present and both couplings have similar strength [20,21,22,23,24,25,26,27,28,29]. Therefore, in this article, we intend to consider both Rashba and Dresselhaus SO couplings simultaneously and investigate the AC and RI changes of a GaAs quantum ring under the influence of external magnetic field at finite temperatures. In the following, the effective Hamiltonian of the system and temperature dependency as well as the AC and RI changes will be demonstrated (Section 2) and numerical results will be discussed (Section 3).

2. Model and theory

2.1. Effective Hamiltonian

Now we are going to derive an effective Hamiltonian considering simultaneous Rashba and Dresselhaus SO couplings under the influence of Zeeman effect. The magnetic field is considered along the z-axis. The effective mass approximation is hired in order to obtain the energy eigenvalues and approximate the eigenstates of the system. With these comments in mind, it is appropriate to determine the hamiltonian as [30,31]:

$$H = H_0\mathbf{I}_2 + \frac{1}{2}gB\mu_B\sigma_z + H_R + H_D \tag{1}$$

that $\mathbf{I}_2$ is a 2×2 identity matrix and

$$H_0 = \frac{\mathbf{P}^2}{2m^*} + V_0 \tag{2}$$

where $\mathbf{P} = -i\hbar\overrightarrow{\nabla} + e\mathbf{A}$ ($\mathbf{A}$ is the magnetic vector potential), m^* is the electron effective mass, g represents the Landé factor, μ_B is the Bohr magneton, $\sigma_i \quad (i = x, y, z)$ stands for the ith component of the Pauli matrices vector and V_0 is the confinement potential. H_R and H_D denote the Rashba and Dresselhaus SO coupling terms [30,31], respectively as:

$$H_R = \frac{\alpha}{\hbar}\left(p_y\sigma_x - p_x\sigma_y\right) \tag{3}$$

$$H_D = \beta_b\left[\sigma_x k_x\left(k_y^2 - k_z^2\right) + \sigma_y k_y\left(k_z^2 - k_x^2\right) + \sigma_z k_z\left(k_x^2 - k_y^2\right)\right] \tag{4}$$

Due to the relatively stronger k-dependency of the cubic Dresselhaus term compared with the linear terms, the cubic term can be neglected in comparison to the linear term and by taking into account that for confined electrons $\langle k_z \rangle$ becomes zero but $\langle k_z^2 \rangle$ does not, yields $\beta = -\beta_b\langle k_z^2 \rangle$ and so the Dresselhaus SO interaction is written as [32]:

$$H_D = \frac{\beta}{\hbar}\left(p_x\sigma_x - p_y\sigma_y\right) \tag{5}$$

that α and β are coupling constants.

Since our geometry has axial symmetry, it is more convenient to introduce the model of the half cross-section through the symmetry axis (z-axis) that you can see in Fig. 1.

Considering the symmetric gauge $\mathbf{A} = \frac{Br}{2}\hat{e}_\varphi$, the momentum operator can be written as: