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Absorption coefficient and refractive index changes of a lens-shaped quantum dot: Rashba and Dresselhaus spin–orbit interactions under external fields

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ABSTRACT

Tools of mathematical modeling provide a great opportunity in order to investigate semiconductor nanostructures with a conclusive objective of predicting their behavior and understanding of their limits. While most numerical and analytical investigations deal with the pure Rashba interaction, this article will study the absorption coefficient and refractive index changes of a lens-shaped GaAs quantum dot in the presence of simultaneous Rashba and Dresselhaus spin–orbit couplings under the effects of applied electric and magnetic fields. It is shown that applying magnetic field, in the presence of spin–orbit interactions, removes the degeneracy and split the energy levels into two branches and by enhancing the field, absorption coefficient and refractive index changes related to transition between the ground and second excited states (E_{31}) move towards lower photon energies (red shift). It is also revealed that by increasing the applied electric field a blue shift in optical curves can be detected.

1. Introduction

Recently, there has been lots of discussions about the nano-scale structures in pursuance of incorporating the newest ideas and features to produce electronic and opto-electronic devices based on size quantization [1–5]. No degree of freedom for charge carriers in three-dimensional confining potential, restrict the carrier in all spatial dimensions and results in that electrons hold quantized energy levels in which is similar to atoms and differ from the bulk materials (continues energy spectra). Therefore, these structures are known as zero dimensional nanostructures, artificial atoms or quantum dots (QD).

Moreover, contemporary fabrication techniques (such as molecular beam epitaxy (MBE), chemical lithography, etching method, gas epitaxy, Stranski–Krastanov) have made it possible to produce various geometrical shapes and sizes of semiconductor QDs. Several shapes of QD like spherical, pyramidal, ellipsoidal, lens-shaped, cone-like and so on have been investigated extremely both by theorists and experimentalists [6–12]. It is worthy to mention that among all shapes mentioned above, the lens-shaped dots that are generally used for laser applications in order to improve the characteristics of laser diodes, have attracted the most considerable attentions [13,14].

It is clear that, because of the complexity of the equations, most of the theoretical researches neglect the spin of charge carrier. However, in the current work, the spin is considered as it can interact with external fields and the degeneracy of

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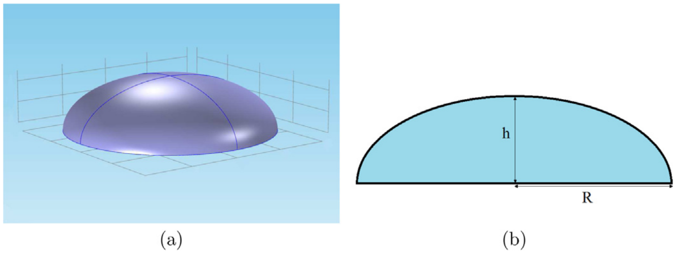

Fig. 1. Schematic view of (a) lens-shaped QDs and (b) the cross-section of the lens-shaped QD through the z-axis.

energy levels can be removed with respect to the spin of electron. As a simple example, Zeeman effect is a spin splitting, which is resulted in the presence of an applied static magnetic field (coupling between the spin of electron and the magnetic field). On the other hand, while an electron also moves (with momentum **P**) along an electric field, its spin experiences an internal magnetic field proportional to the local electric field that leads to splitting degenerate energy levels. Nevertheless, spin degeneracy can also be eliminated in the presence of spin–orbit (SO) interaction in noncentrosymmetric crystals (without applying an external field). Two origins are known for such splitting in a crystal: (I) Bulk inversion asymmetry (BIA), e.g., zinc-blende structure of GaAs; (II) Structural inversion asymmetry, (SIA), e.g., heterointerface of GaAs/AlGaAs.

Absence of the inversion symmetry (creating BIA) engender Dresselhaus spin splitting in bulk and QD semiconductors [15,16]. In return, Rashba term (resulted from the inversion asymmetry of the confining potential) comes after SIA [17,18]. Furthermore, it is worthy to mention that, in zinc blende semiconductors the cubic term of Dresselhaus SO coupling is dominant while in wurtzite structure a linear term exceeds [19,20]. Therefore, the spin properties of semiconductor QDs can be influenced by the fact that, such structures indicate wurtzite crystal structure even though the constituting material has a zinc blende structure in the bulk [19,21]. In the other words, the Dresselhaus SO coupling in QDs is usually approximated by the linear term alone.

Recently, optical properties associated with intersubband transition such as absorption coefficient (AC) and refractive index (RI) changes have become indispensable and one of the most agitating forefront fields in physics of semiconductor nanostructures. In QD structures there will be large values of dipole transition matrix elements [22–25]. Photons with energies equal to intersubband transition energies, lead to resonant absorption spectra (minimum absolute value of RI changes) and due to being sensitive to energy levels, the optical AC and RI changes can be manipulated and altered via spin properties, size effects as well as application of electric and magnetic fields. Therefore, it is possible to find some discussions and analysis on linear and nonlinear optical properties of QDs in the literature, which show the remarkable attention in both theoretical and applied physics on such subject [22–29].

In this regards, in order to utilize low dimensional structures in new generation opto-electronic devices, it is important to study detailed analysis of quantum behaviors going on in these structures. Although it is obvious that the lens-shaped QDs have been studied broadly, the spin of charge carriers has been neglected and also majority of studies on SO coupling in nanostructures are done considering pure Rashba interaction [30–39]. Therefore, in this work, we are going to investigate the simultaneous effects of Rashba and Dresselhaus SO couplings on the optical AC and RI changes in a lens-shaped GaAs QD under the effects of applied electric and magnetic fields. The layout of the rest of this paper is as follows: the effective Rashba and Dresselhaus Hamiltonian as well as analytical expressions for the optical AC and RI changes are briefly presented in Section 2. The results are discussed in Section 3 and finally Section 4 is dedicated to conclusions of this work.

2. Theory

2.1. Schrödinger equation

We are intended to study a GaAs lens-shaped QD in the presence of both Rashba and Dresselhaus SO couplings to investigate the effects of applied magnetic and electric fields on the linear and nonlinear optical properties of such system. A schematic view of the lens-shaped QD is presented in Fig. 1. The electronic structure is studied via single-band model known as effective mass approximation. Generally, in multi-band $k \cdot p$ model, the Hamiltonian H will be a $n \times n$ matrix containing corresponding Schrödinger's partial differential operators (n represents the number of bands included in the analysis). In the current work, by considering the spin of electron, we have 2 S-type conduction bands as a result of the large band-gap of GaAs that ensures band-mixing effects are of minor importance during the study of optical properties. With these comments in mind, the Hamiltonian in the Cartesian coordinate in the effective mass approximation is given by [19,40]:

$$H = \left(\frac{\mathbf{P}^2}{2m^*} + V_0 \right) \mathbf{I}_2 + \frac{1}{2} g B \mu_B \sigma_z - eFx + H_R + H_D \tag{1}$$

In this paper, the electric (F) and magnetic (B) fields are respectively oriented along the x and z axes, $\mathbf{P} = -i\hbar\vec{\nabla} + e\mathbf{A}$ ($\mathbf{A}$ being magnetic vector potential), m^* denote the electron's effective mass, $\mathbf{I}_2$ indicates a 2×2 identity matrix. In the