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Impurity and exciton effects on the nonlinear optical properties of a disc-like quantum dot under a magnetic field

Liangliang Lu *, Wenfang Xie

Department of Physics, College of Physics and Electronic Engineering, Guangzhou University, Guangzhou 510006, PR China

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ABSTRACT

A detailed investigation of the nonlinear optical properties of the (D^{+},X) complex in a disc-like quantum dot (QD) with the parabolic confinement, under applied magnetic field, has been carried by using the perturbation method and the compact density-matrix approach. The linear and nonlinear optical absorption coefficients between the ground ($L = 0$) and the first excited state ($L = 1$) have been examined based on the computed energies and wave functions. The competition between the confinement and correlation effects on the one hand, and the magnetic field effects on the other hand, is also discussed. The results show that the confinement strength of QDs and the intensity of the illumination have drastic effects on the nonlinear optical properties. In addition, we note that the absorption coefficients of an exciton in QDs depend strongly on the impurity but weakly on the magnetic field. Furthermore, the light and heavy hole excitons should be taken into account when we study the optical properties of an exciton in a disc-like QD.

1. Introduction

The subject of zero-dimensional semiconductor systems has developed at a considerable and at times at an alarming rate over the past decade. The improvement of the devices such as quantum transistors, high-speed memory elements and infrared photodetectors shows that these systems variously labeled as QDs have improved properties as compared to quantum wells and quantum wires [1–4]. Current experiments concerned with QDs focus mainly on studying their optical properties (absorption and emission of light in the visible or far infrared range). Since QDs absorb and emit light in a very narrow spectral range, which is controlled, for instance, by an applied magnetic field, it seems

* Corresponding author. Tel.: +86 13751823828.
E-mail address: lll516946435@126.com (L. Lu).

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that they might very soon find application in the construction of more efficient and more precisely controllable semiconductor lasers. The main features to consider in relation to QDs are geometrical shape, size, and the confining potential. One type of elementary excitations in QDs are excitons which play a central role on semiconductor optical properties [5–15]. Besides, the parabolic confinement is more appropriate when the QDs are fabricated by etching process on a quantum well, by ion implantation or by application of electrostatic gates.

In parallel, impurities in low-dimensional structures are introduced in order to modify the conduction and optical properties. Hence, the understanding of effects of impurities on the properties of QDs is crucial for the evolution of the emerging nanoelectronics, an area that has attracted increasing interest due to the possibilities it opens in applied physics [16–23]. For example, Baskoutas et al. [16] applied the PMM (potential morphing method) to treat the influences of impurities and external field upon a semiconductor system. Ruan and Chang [17] found that the binding of an exciton to an ionized hydrogenic donor is stable with any values of the electron-hole mass ratio in two-dimensional semiconductors. Karabulut et al. [19] investigated the linear and nonlinear optical properties of a hydrogenic impurity in a spherical QD under the influence of electric field and optical intensity. The main conclusions of these works can be summarized as not only the geometry of dot but also the external perturbations can influence the optical properties of a semiconductor greatly.

Furthermore, the linear and nonlinear optical properties (e.g., the optical absorption or refractive index) have much effect on the optical device application in far-infrared laser amplifiers, photodetectors, and high speed electro-opticalmodulators [24]. Hence, for both fundamental and applied researches, the nonlinear optical properties of QDs have attracted much attention in recent years [25–28]. Zhang and Xie [26] brought forward a semiparabolic quantum well instead of symmetried parabolic quantum well to calculate the second-harmonic generation susceptibility tensor under the influence of electric field. Yu et al. [27] investigated the electron-phonon interaction effect on third-harmonic in cylindrical quantum wires by using the compact density-matrix approach and iterative method. In present work, using the perturbation method, we will focus on studying the nonlinear optical properties of the (D^+,X) complex with a hydrogenic donor impurity placed at the center of a semiconductor disc-like QD. From the consideration of device applications, engineering the electric structure of materials by means of external magnetic field and confinement strength, offers the possibility of tailoring the energy spectrum to produce desirable nonlinear optical properties. To the best of our knowledge, the nonlinear optical absorption of the (D^+,X) complex has not been investigated extensively in the literature.

2. Model and theory

In the framework of the effective mass approximation, by considering an exciton and an impurity moving in a disc-like QD with a parabolic confinement, under a magnetic field applied in the z-direction of the QD, we make the generalization that the Hamiltonian in this system is given by

$$H = \frac{1}{2m_e}(\vec{p}_e - e\vec{A}_e)^2 + \frac{1}{2}m_e\omega_0^2\vec{r}_e^2 + \frac{1}{2m_h}(\vec{p}_h - e\vec{A}_h)^2 + \frac{1}{2}m_h\omega_0^2\vec{r}_h^2 - \frac{e^2}{4\pi\epsilon\epsilon_0|\vec{r}_e - \vec{r}_h|} - \frac{e^2}{4\pi\epsilon\epsilon_0|\vec{r}_e|} + \frac{e^2}{4\pi\epsilon\epsilon_0|\vec{r}_h|}, \quad (1)$$

where $m_e(m_h)$ and $r_e(r_h)$ are the effective mass and the position vector of the electron (hole), respectively. ω_0 is used to measure the strength of the confinement, ϵ is the dielectric constant of the medium in which the electron and the hole are moving, and $\vec{A}$ is the vector potential. For a uniform magnetic field, $\vec{A} = \frac{1}{2}\vec{B} \times \vec{r}$.

In the symmetric gauge, the Hamiltonian can be written as

$$H = \frac{\vec{p}_e^2}{2m_e} + \frac{1}{2}m_e\omega_e^2\vec{r}_e^2 - \frac{eB}{2m_e}\widehat{L}_z^e + \frac{\vec{p}_h^2}{2m_h} + \frac{1}{2}m_h\omega_h^2\vec{r}_h^2 + \frac{eB}{2m_h}\widehat{L}_z^h - \frac{e^2}{4\pi\epsilon\epsilon_0|\vec{r}_e - \vec{r}_h|} - \frac{e^2}{4\pi\epsilon\epsilon_0|\vec{r}_e|} + \frac{e^2}{4\pi\epsilon\epsilon_0|\vec{r}_h|}, \quad (2)$$