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Optical absorptions of an exciton in a quantum ring: Effect of the repulsive core ☆

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ABSTRACT

We study the optical absorptions of an exciton in a quantum ring. The quantum ring is described as a circular quantum dot with a repulsive core. The advantage of our methodology is that one can investigate the influence of the repulsive core by varying two parameters in the confinement potential. The linear, third-order nonlinear and total optical absorption coefficients have been examined with the change of the confinement potential. The results show that the optical absorptions are strongly affected by the repulsive core. Moreover, the repulsive core can influence the oscillation in the resonant peak of the absorption coefficients.

1. Introduction

It is now well known that carrier (electrons and holes) confinement into dimensions of a few tens of nanometers provides strong blueshift of the photoluminescence features from that in the original bulk material [1,2]. Various nanometer structures are fabricated endlessly as nanostructure technology develops. They are currently under intense study because of interests in physics [3–6] and in technological applications. Recently, increasing attention has been focused on the study of semiconductor quantum rings (QRs) mainly because of their importance in the electric and optical properties of these low-dimensional confinement systems. Compared with semiconductor quantum dots, QRs belong to another kind of topological structures in which more rich phenomena can be clearly shown. Due to the enhancement of the excitonic binding energy caused by the quantum confinement effect, excitonic spectrum persists even at the room temperatures in QRs. Since QRs are created mainly through producing a lateral confinement restricting the motion of the charge carriers, which are initially confined in a very narrow quantum well, they usually have the shape of flat disks, with transverse dimensions considerably exceeding them thickness. The energy of single-particle excitations across the disk exceeds other characteristic energies in the system, and the exciton in a QR can be considered as a two-dimensional system.

Electron–hole interaction and correlation effects are shown to play an important role in electronic structures and optical properties of both quantum dots and rings [7]. On the other hand, the nonlinear optical properties of quantum dots and rings have attracted an enormous interest in recent years because they have the potential for device applications in far-infrared laser amplifiers, photodetectors, and high-speed electro-optical modulators [1,8,9]. The optical absorption saturation intensity in quantum dots may be controlled by adopting a proper parabolic confinement potential [10]. In the nonlinear optical properties of quantum dots and rings, the analysis of exciton states is inevitable because the confinement of carriers in such structure leads to the enhancement of the oscillator strength of electron–hole excitations. Meanwhile, the dependence of the optical transition energy on the confinement strength (or quantum size) allows the tunability of the resonance frequency. In 1987, Hanamura studied the third-order optical polarizations due to the excitons in semiconductor microcrystallinities, and showed that optical nonlinearity is very large when one considers excitonic effects [11]. Recently, a number of theoretical investigations of excitonic effects in quantum dots have been published [12–16]. The results show that the linear and nonlinear optical properties are greatly enhanced because of the quantum confinement of excitons. Up to now, the study of the effect of the repulsive core on the nonlinear optical properties in QRs, when the electron–hole Coulomb interaction is taken into account, is still rare. In this Letter, we will investigate the evolution of the exciton absorption spectrum as the shape of the confinement potential changes from a circular quantum dot to a QR when a repulsive core

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is introduced into the confinement potential. By using the matrix diagonalization method and the compact density-matrix approach, the linear, third-order nonlinear and total optical absorption coefficients (ACs) are calculated. This investigation allows us to understand the qualitative differences between the absorption spectra of the exciton confined in the potential with and without the repulsive core.

2. Theory

In the effective-mass approximation, the Hamiltonian of an exciton in a two-dimensional QR is given by

$$H = \sum_{i=e,h}\left[\frac{p_i^2}{2m_i} + V_i(r_i)\right] - \frac{e^2}{\epsilon|\vec{r}_e - \vec{r}_h|}, \tag{1}$$

where m_e and m_h are the effective electron and hole masses, $\vec{p}_e$, $\vec{p}_h$, $\vec{r}_e$ and $\vec{r}_h$ denote, respectively, the momenta and positions of the electron and the hole, $V_e(r_e)$ and $V_h(r_h)$ are the confinement potential profiles for the electron and the hole, and ϵ is the dielectric constant of the medium in which the electron and the hole are moving.

To study the effect of a repulsive core in QRs, we assume the confinement potentials of the electron and the hole are given by [17,18]

$$V_e(r) = 0.7\Delta E_g X(r), \tag{2}$$

and

$$V_h(r) = 0.3\Delta E_g X(r), \tag{3}$$

where $\Delta E_g = 1.11$ eV is the band gap difference between GaAs and InAs. According to Ref. [19] we take on the band–offset ratio to be equal to 70/30. Furthermore, we assume that the variation of the effective concentration X of indium in the nanostructure is determined by a smoothly varying function $X(r)$. Here the indium concentration $X(r)$ is given by

$$X(r) = X_0\left\{\exp\left[-(r/R_o)^2\right] - C\exp\left[-(r/R_i)^2\right]\right\}, \tag{4}$$

where r is the distance measured from the centre of the nanostructure, R_o and R_i are the outer and inner radii of the QR, respectively. X_0 describes the maximal concentration of indium in the QR, and parameter $C \in (0,1)$ is responsible for the depletion of the indium concentration near the centre of the QR. Obviously, when $C > 0$, there is a repulsive core in $X(r)$. Hence, the nanostructure, for which $C = 0$, will be referred to as a quantum dot and that with the repulsive core, i.e. $C > 0$, will be called a QR. The shape of the confinement potential for different C values is drawn in Fig. 1.

The Hamiltonian has a cylindrical symmetry which implies that the total orbital angular momentum L is a conserved quantity, i.e., a good quantum number. Hence, the eigenstates of an exciton in a cylindrical symmetry QR can be classified according to the total orbital angular momentum. In order to obtain the eigenenergies and eigenstates, H is diagonalized in model space spanned by translational invariant harmonic product states

$$\Phi_L = \sum_{[K]} \varphi^{\omega}_{n_e\ell_e}(\vec{r}_e)\varphi^{\omega}_{n_h\ell_h}(\vec{r}_h), \tag{5}$$

where $[K]$ denotes the set of quantum numbers $(n_e, \ell_e, n_h, \ell_h)$ in brevity. $\phi_i^{\omega}(\vec{r}) = R_{n_i\ell_i}(r)\exp(-i\ell_i\theta)$ is ith eigen-state of the two-dimensional harmonic oscillator with a frequency ω and an energy $(2n_i + |\ell_i| + 1)\,\hbar\omega$. $R_{n\ell}(r)$ is the radial wave function, given by

$$R_{n_i\ell_i}(r_i) = N_i\exp\left(-r_i^2/(2a^2)\right)r_i^{|\ell|}L_{n_i}^{|\ell|}\left(r_i^2/a_i^2\right), \quad i = e,h, \tag{6}$$

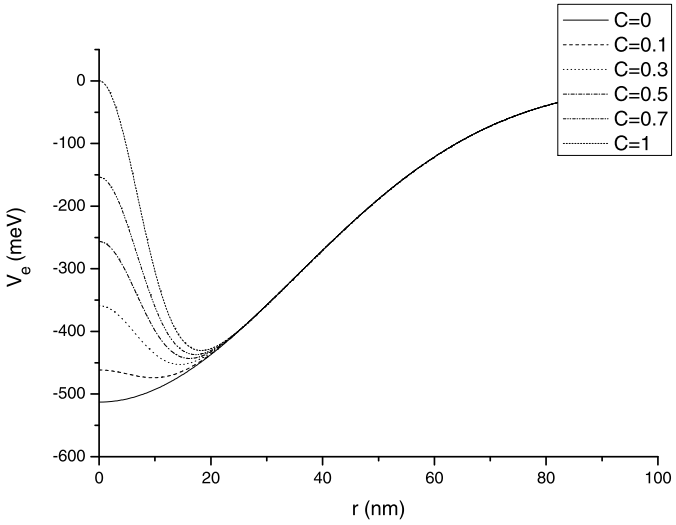

Fig. 1. The potential energy of a QR as a function of the radial distance for different values of the parameter C of the repulsive core.

in which N is the normalization constant, $L_n^{\ell}(x)$ is the associated Laguerre polynomial, $a_i = \sqrt{\hbar/(m_i\omega)}$ and $\hbar$ is the reduced Plank constant. The radial and orbital angular momentum quantum numbers can have the following values

$$n = 1, 2, \ldots, \ell = 0, \pm1, \pm2, \ldots. \tag{7}$$

In our practice calculations, ω serves as a variational parameter to minimize the eigenvalue of the ground state. At the same time, we must take into account the fact that the total angular momentum of an exciton is a good quantum number because of the cylindrical symmetry of the Hamiltonian. The angular momenta of the electron, the hole, and the exciton are denoted by ℓ_e, ℓ_h, and $L = \ell_e + \ell_h$, respectively.

In order to calculate the matrix elements of Hamiltonian, we expand the Coulomb potential in terms of Legendre polynomials as follows:

$$\frac{1}{|\vec{r}_e - \vec{r}_h|} = \sum_{m=0}^{\infty} f_m P_m(\cos\phi), \tag{8}$$

where ϕ is the angle between $\vec{r}_e$ and $\vec{r}_h$ and

$$f_m = \begin{cases} \frac{1}{r_h}\left(\frac{r_e}{r_h}\right)^m, & r_e < r_h, \\ \frac{1}{r_e}\left(\frac{r_h}{r_e}\right)^m, & r_e > r_h. \end{cases} \tag{9}$$

The optical absorption calculation is based on the compact density matrix approach, for which the total AC is given by [15,20]

$$\alpha(\upsilon, I) = \alpha^{(1)}(\upsilon) + \alpha^{(3)}(\upsilon, I), \tag{10}$$

where

$$\alpha^{(1)}(\upsilon) = \upsilon\sqrt{\frac{\mu}{\epsilon_R}}\frac{\sigma_s|M_{fi}|^2\hbar\Gamma_{fi}}{(h\upsilon - \Delta E_{fi})^2 + (\hbar\Gamma_{fi})^2}, \tag{11}$$

and

$$\begin{aligned}\alpha^{(3)}(\upsilon, I) = {} & -\upsilon\sqrt{\frac{\mu}{\epsilon_R}}\left(\frac{I}{2\epsilon_0 n_r c}\right) \\ & \times \frac{\sigma_s|M_{fi}|^2\hbar\Gamma_{fi}}{[(h\upsilon - \Delta E_{fi})^2 + (\hbar\Gamma_{fi})^2]^2}\left\{4|M_{fi}|^2\right. \\ & \left. - \frac{(M_{ff} - M_{ii})^2[3\Delta E_{fi}^2 - 4\Delta E_{fi}h\upsilon + (h^2\upsilon^2 - \hbar^2\Gamma_{fi}^2)]}{\Delta E_{fi}^2 + (\hbar\Gamma_{fi})^2}\right\},\end{aligned} \tag{12}$$