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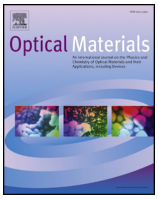

Effects of hydrogenic impurity and external fields on the optical absorption in a ring-shaped elliptical quantum dot

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ABSTRACT

In this work, the effects of the hydrogenic impurity, electric and magnetic fields on the optical absorption of a typical $GaAs/AlGaAs$ ring-shaped elliptical quantum dot are investigated. Energy eigenvalues and wave functions are calculated using the three-dimensional finite element method, and optical absorption is obtained using the density matrix approach. For the impurity located at the center of the quantum dot, results show that the optical absorption increases (decreases) with increasing electric (magnetic) field. Results also indicate that the off-center hydrogenic impurity considerably reduces the optical absorption.

1. Introduction

Recent progress in material growth techniques, such as molecular-beam epitaxy and metal-organic chemical-vapor deposition, made it possible to fabricate various types of nanostructures like quantum wells (QWs), quantum wires (QWRs), quantum dots (QDs) and etc. [1]. Among these low dimensional structures, QDs have attracted much attention due to their potential applications [2–13]. They have unique and tunable electronic and optical properties which make them very useful for the design and fabrication of new optoelectronic devices [1]. Within this context, the ring-shaped QDs are interesting candidates for developing quantum information processing and terahertz device fabrication [14]. Recently, several works have been done to investigate the electronic and optical properties of the ring-shaped quantum dots and more generally QRs [15–23]. The electron states and optical coefficients of a 2D quantum dot-ring in the presence of a donor impurity and electric field have been studied by Duque et al. [14]. Farias et al. investigated the effects of the impurities and magnetic field on the electron energy spectrum of quantum rings [24]. They found that the magnetic field leads to the Aharonov-Bohm (AB) oscillations, which strongly depend on the presence of the static defects. Barseghyan et al. studied the effects of the electric and magnetic fields and hydrostatic pressure effects on the binding energy of a hydrogenic donor impurity in InAs Pöschl-Teller quantum ring using the variational method [25]. Niculescu and Bejan investigated the effects of the magnetic field and off-center impurity on the nonlinear optical properties in a two-dimensional quantum ring [26]. Radu et al. studied the effect of the intense laser field on the electron states and intraband optical absorption coefficients in two-dimensional $GaAs/AlGaAs$ quantum rings [27]. They found that the changes in the polarization of the incident light lead to blueshift or redshift for the optical absorption spectrum. Li et al. studied the magnetic field effect on the donor impurity states in elliptical quantum rings [28]. They found that the energies exhibit AB oscillations which depend on the magnetic field and the eccentricity. The effect of the electron-phonon interaction on the third-harmonic generation in a double ring-shaped quantum dot has been investigated by Khordad [29]. Optical properties of an exciton in a two-dimensional quantum ring subjected to an applied magnetic has been studied by Xie [30].

In this paper, we study the effects of the on-center and off-center hydrogenic impurity, external electric and magnetic fields on the electronic states and optical absorption of a ring-shaped elliptical quantum dot (RSEQD). The paper is organized as follows: We describe the theoretical framework in Section 2. Then, the results are discussed in Section 3, and finally, the conclusions are given in Section 4.

2. Theory

Let us consider an electron bound to a hydrogenic impurity in a $GaAs/AlGaAs$ RSEQD (Fig. 1). Within the framework effective mass approximation, the Hamiltonian of the system in the presence of external electric field F along the x axis and external magnetic field B along the z direction, can be written as

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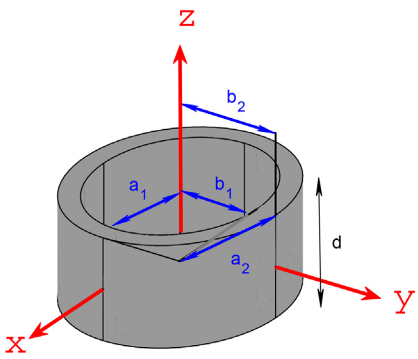

Fig. 1. Schematic diagram of a ring-shaped elliptical quantum dot.

$$H = -\frac{\hbar^2}{2m^*}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right) + eFx - i\frac{eB\hbar}{2m^*}\left(x\frac{\partial}{\partial y} - y\frac{\partial}{\partial x}\right) + \frac{e^2B^2}{8m^*}(x^2 + y^2) - \frac{Ze^2}{4\pi\varepsilon_0\varepsilon_r\sqrt{(x - x_{imp})^2 + y^2 + z^2}} + V_c(x, y, z) \tag{1}$$

where

$$V_c(x, y, z) = \begin{cases} 0 & \frac{x^2}{a_2^2} + \frac{y^2}{b_2^2} < 1 < \frac{x^2}{a_1^2} + \frac{y^2}{b_1^2}, \left|z\right| < \frac{d}{2} \\ V_0 & others \end{cases} \tag{2}$$

is the finite confining potential, $Z = 0$ and $Z = 1$ imply without and with impurity cases, x_{imp} is the impurity position on the x axis, ε_0 is the vacuum dielectric permittivity, ε_r is the relative dielectric permittivity, e is the elementary charge and $\mathbf{A} = \frac{1}{2}B(-\mathbf{y}, \mathbf{x}, 0)$ is the corresponding vector potential of the magnetic field. The electron effective mass is given by

$$m^* = \begin{cases} m^*_{GaAs} & \frac{x^2}{a_2^2} + \frac{y^2}{b_2^2} < 1 < \frac{x^2}{a_1^2} + \frac{y^2}{b_1^2}, \left|z\right| \leq \frac{d}{2} \\ m^*_{AlGaAs} & others \end{cases} \tag{3}$$

Therefore, we apply three-dimensional finite element method to obtain the energy eigenvalues and eigenfunctions. In order to calculate the optical absorption coefficient, we assume that the system excited by a circularly polarized electromagnetic field, with frequency ω incident along the z direction given by

$$\mathbf{E}(t) = \frac{E_0(t)}{\sqrt{2}}(\hat{x} + i\hat{y}) \tag{4}$$

where $\hat{x}$ and $\hat{y}$ denote the unit vector in the x and y axis, respectively, and $E_0(t) = \widetilde{E}e^{i\omega t} + \widetilde{E}^* e^{-i\omega t}$. Here, the OAC calculated within the compact density-matrix formalism under steady state conditions [31],

$$\alpha(\omega) = \frac{\omega\sigma_{ij}e^2\mu_{ij}^2 T_2}{\varepsilon_0\hbar c n_r}\frac{\left|J_0^2\left(\frac{\left|\mu_{jj} - \mu_{ii}\right| eE_0}{\hbar\omega}\right) - J_2^2\left(\frac{\left|\mu_{jj} - \mu_{ii}\right| eE_0}{\hbar\omega}\right)\right|}{1 + T_2^2(\omega - \omega_{ji})^2 + \overline{\mu}_{ij}^2 E_0^2 T_1 T_2/\hbar^2} \tag{5}$$

where

$$\overline{\mu}_{ij} = e\mu_{ij}\left(J_0\left(\frac{|\mu_{jj} - \mu_{ii}|eE_0}{\hbar\omega}\right) + J_2\left(\frac{|\mu_{jj} - \mu_{ii}|eE_0}{\hbar\omega}\right)\right) \tag{6}$$

In the above equations, $\omega_{ji} = \omega_j - \omega_i$, μ_{ij} are the electric dipole matrix elements per electronic charge, J_0 and J_2 are the ordinary Bessel function of order 0 and 2, T_1 is the population decay time, T_2 is the dephasing time, σ is the electron density, E_0 is the amplitude of the electric field related to the incident intensity I_0 of the probe field by $I_0 = \frac{\varepsilon_0 n_r c\,|E_0|^2}{2}$ where c is the speed of light in free space and n_r is the refractive index.

3. Results and discussion

The geometrical and structural parameters were chosen in our calculation as follows: $a_1 = 100\,A^0$, $b_1 = 80\,A^0$, $a_2 = 120\,A^0$, $b_2 = 100\,A^0$, $d = 100\,A^0$, $m^*_{GaAs} = 0.067m_0$, $m^*_{AlGaAs} = 0.092m_0$ where m_0 is the free electron mass, $n_r = 3.2$, $\varepsilon_r = 12.58$ is the relative dielectric permittivity of $GaAs$, $I_0 = 0.2\,MW/cm^2$, $T_1 = T_2 = 0.14\,ps$, $\sigma = 3.0 \times 10^{22}\mathrm{m}^{-3}$, $V_0 = 228\,meV$ (corresponding to Al concentration $x = 0.3$) [32].

In Fig. 2, the impact of the hydrogenic impurity on the probability densities of three lowest states are shown. Here, the origin is in the center of each panel, x and y axes are oriented horizontally and vertically, respectively. The ground state ("1s"*state*) is cylindrically symmetric. The higher excited states are called $2p_x$ and $2p_y$ states which aligned along the x-axis and y-axis, respectively. As we expect, this figure shows that the probability density is symmetric with respect to the origin for $Z = 0$ and $(Z = 1, x_{imp} = 0)$ cases. When the impurity position changes from $x = 0$ (origin) to $x = 110A^0$ (ring region), the wave functions are only symmetric across the x axis. The wave function of 1s state more localized around the impurity. $2p_x$ orbital more localized far from the impurity (left side of the ring) and $2p_y$ state slightly

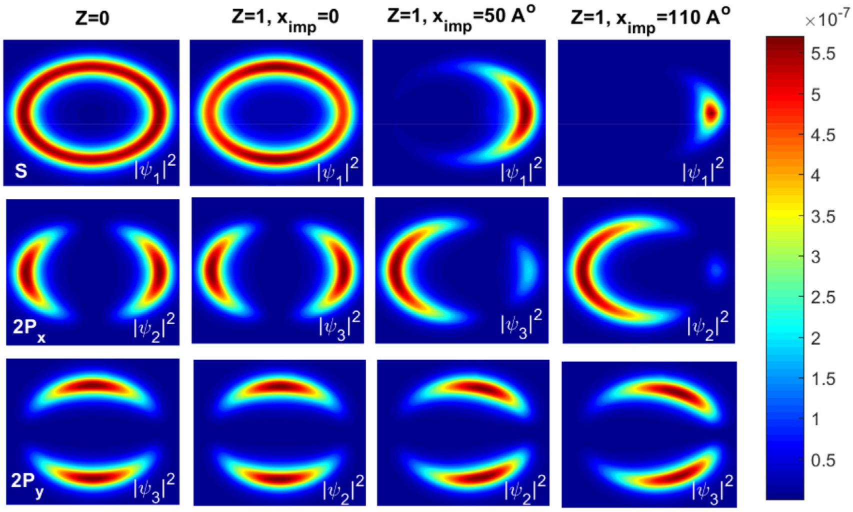

Fig. 2. Contour plot of the probability densities for the three-lowest states in $z = 0$ plane. Results are for several setup of Z and x_{imp}: $Z = 0$ (first column), $Z = 1$, $x_{imp} = 0$ (second column) $Z = 1$, $x_{imp} = 50\,A^0$ (third column) and $Z = 1$, $x_{imp} = 110\,A^0$ (fourth column).