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Influence of lateral electric field on intraband optical absorption in concentric double quantum rings

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HIGHLIGHTS

- A blueshift in absorption spectrum is obtained by increasing the electric field.
- A change in light polarization creates a redshift in the absorption spectrum.
- The absorption maxima is bigger for y-polarization.
- The absorption maxima changes in a non-monotonic way if the electric field increases.
- Both blueshift and redshift of the spectrum have been obtained with the enlargement of inner ring radius.

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ABSTRACT

The influence of lateral electric field on one-electron states and intraband absorption in two-dimensional concentric double quantum rings is investigated. The confining potential of the rings is modeled as a double harmonic central potential. Using the exact diagonalization technique, we calculate the dependence of the electron energy spectrum as a function of the electric field strength as well as the inner ring radius. Also, different values of confinement strength are considered. Selection rule is obtained for intraband transitions, caused by the direction of incident light polarization. The intraband absorption coefficient is calculated for different values of electric field strength, inner ring radius, confinement strength and incident light polarization direction. The combined influence of electric field strength and change of confining strength show that while the increment of the first one leads only to blueshift of absorption spectrum, the augment of the second one makes the redshift. In addition, both blueshift and redshift of the spectrum have been obtained with the enlargement of inner ring radius. Finally, we show that the absorption spectrum undergoes redshift by changing the polarization of incident light from x- to y-axis.

1. Introduction

Recent advances in nanoscale fabrication processes have made the construction of semiconducting nanoscopic objects with a possible wide range of geometries. Some of the most recent objects are III–V semiconducting torus shaped quantum rings (QRs) [1,2]. Like self-assembled quantum dots (QDs), QRs possess atom-like properties, making them a fair venue for potential device applications in optics, optoelectronics, and quantum computing [3–9]. At the same time QRs are non-simply connected quantum systems – the hole in the middle provides the capability of trapping single magnetic flux and offers the exciting opportunity to observe electronic wave function phases in magneto-optical experiments. Furthermore, QRs can bind only a few electrons and holes, which gives a unique chance to study three-dimensional topological quantum effects, such as magnetization oscillations and persistent current effects [10,13,11,12,14,15].

QRs have already found their applications in optoelectronic devices, like in Ref. [4], where stacked layers of In(Ga)As on GaAs (001) self-assembled QRs have been studied for laser application, with stimulated multimodal emission centered at 930 nm (77 K). Also, it is worth to note the key importance of electric field influence in many cases. For instance, the photoluminescence and excitation of the photoluminescence spectroscopy was performed

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in single InGaAs self-assembled QDs and QRs embedded in a field-effect-structure device [5,6]. Here, the interplay between the exciton radiative recombination and the electronic carrier tunneling has been investigated in the presence of a stationary electric field and compared with a numerical calculation based on the effective mass approximation. The electronic properties of InAs/GaAs QRs and the characteristics of resonant tunnel intraband terahertz detectors with QR-active regions have done in Refs. [7,8], where the electronic states of the QRs have been calculated and measured by the capacitance–voltage technique. Multiple layers of InAs/GaAs QRs have been used as the active region in high-performance photoconductive detectors in the range between 1 and 3 THz [9].

In the past decade, a number of works were devoted to the theoretical investigation of the influence of electric fields on the electronic and optical properties of QR structures [16–28]. For instance, in Ref. [16] the electronic states of a single QR under an applied lateral electric field are theoretically investigated for different values of the outer and inner ring radii ratio using direct matrix diagonalization method. In Ref. [17] a magnetic field perpendicular to the ring plane was used and has been shown that the electric field may suppress the Aharonov–Bohm oscillations of the lower energy levels. The problem of the impurity electron in QRs in the presence of a radially directed strong external electric field has been done in detail in Ref. [18], where both the analytic and numerical approaches to the problem are developed.

The polarization effects of lateral electric fields and eccentricity on electronic and optical properties of QRs are discussed within the effective-mass approximation in [19]. In addition, effects of lateral electric field on the electronic states, interband optical spectra, and Aharonov–Bohm oscillations in single QRs have been investigated in Ref. [20]. The competition between carrier recombination and tunneling in QDs and QRs under the action of electric fields has been studied in Ref. [21]. Also, the effects of lateral electric field on the nonlinear optical rectification of a single QR have been investigated and the results indicate that the increase in electric field yields a redshift in peak positions of nonlinear optical rectification [22].

The simultaneous effects of lateral electric field and hydrostatic pressure on the intraband linear optical absorption coefficient have been investigated in two-dimensional $GaAs/Ga_{1-x}Al_xAs$ single QR [23]. The results indicate that for fixed geometric dimensions, the hydrostatic pressure can lead to both blue- and redshift of the intraband optical absorption spectrum, while only a blueshift is observed as a result of electric field. The combined influences of intense laser field and static lateral electric field on one-electron states and intraband optical absorption have been studied in two-dimensional $GaAs/Ga_{0.7}Al_{0.3}As$ QRs [24]. Here, the calculations have shown that by manipulating the laser field parameter and electric field strength the overlap of the electron wave functions can be altered so that the transition probability will be enhanced or suppressed on demand.

A detailed investigation concerning lateral electric field effect on single electron states in coupled quantum dot-ring (CQDR) structures has been recently performed for cases with and without an on-center hydrogenic donor impurity [25]. This study showed that the influence of lateral electric field on energy levels strongly depends on the electron localization type. The investigations of intraband transitions in CQDR [26] demonstrated that lateral electric field changes energetic shift direction influenced by the variation of barrier thickness of the structure.

To the best of our knowledge, the influence of lateral electric field on physical properties of concentric double quantum ring (CQDR) structures has not been investigated theoretically on a large scale. The one-electron ground state in the presence of lateral electric and magnetic field as well has only been studied in two works [27,28]. The aim of the present work is to study in detail the effect of lateral electric field on electronic states (ground and excited) and intraband optical absorption spectrum in a two-dimensional CQDR. Furthermore, the influence of incident light polarization direction on intraband absorption spectrum would be explored. The paper is organized as follows: in Section 2 we describe the theoretical framework. Section 3 is devoted to the results and discussions, and finally the conclusions are given in Section 4.

2. Theoretical framework

The experimental results show [2] that in double QR structures the radial sizes are around 10 times bigger than vertical sizes, which allows us to consider the two-dimensional model for CDQR structure like it was done in [29–32], and consider a double parabolic central potential for the electron confinement

$$V(x, y) = \frac{m\omega^2}{2}\min[\left(\sqrt{x^2+y^2}-R_1\right)^2, \left(\sqrt{x^2+y^2}-R_2\right)^2], \tag{1}$$

where m is the electron effective mass, ω describes the strength of the confining potential, R_1 and R_2 are the inner and outer ring radii, respectively and $\min[a, b]$ means the minimum between a and b. The width of the rings l is directly related with ω via the expression $l = 2\sqrt{2\hbar/m\omega}$. The confinement is affected by the lateral electric field directed in the x-axis as shown in Fig. 1. Note that in the limit $R_1 \to 0$ the potential is reduced to one of a central QD encircled with QR of a radius R_2 [33,25,26], while in the case of $R_1 = R_2 = R$ the model is reduced to a single ring structure [1,22]. The general form of the potential (1) has been used in Refs. [29–32,34,35].

The Hamiltonian of the system considering the electric field effect can be written as:

$$\hat{H} = -\frac{\hbar^2}{2m}[\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}] + V(x, y) + eFx, \tag{2}$$

where e is the elementary charge and F is the electric field strength. The electron eigenvalues E_N and eigenfunctions $\Psi_N(x, y)$, where N labels the bound electronic state in increasing order of energy, are calculated using the exact diagonalization technique [36,22,24]. The eigenfunctions $\Psi_N(x, y)$ are presented as a linear superposition of the eigenfunctions $\varphi_{n_x,n_y}(x, y)$ of the square with the side L [37]:

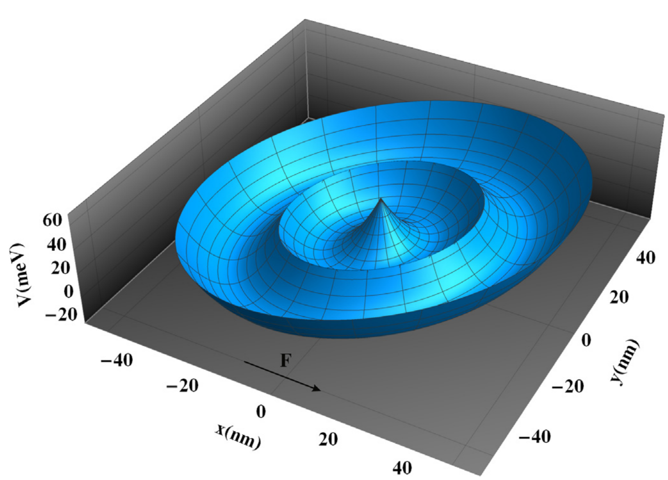

Fig. 1. The confining potential for CDQR structure affected by the radial electric field. The inner and outer ring radii are correspondingly taken as $R_1 = 15$ nm, $R_2 = 40$ nm, confinement strength $\hbar\omega = 20$ meV, and electric field strength F=5 kV/cm. The direction of electric field is taken along the $+x$ axis.