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Donor impurity states and related optical responses in triangular quantum dots under applied electric field

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ABSTRACT

The linear and nonlinear coefficients for the optical absorption and relative refractive index change associated with transitions between donor impurity states in a two-dimensional quantum dot of triangular shape under applied electric field are calculated for y-polarization of the incident light. Both the effective mass and parabolic band approximations have been considered. The results show that the application of a DC electric field strengthens the impurity-related optical absorption response, with particular relevance in the case of the nonlinear contribution to it. However, for a fixed donor atom position inside the triangular quantum dot, the calculations show that the in-plane orientation of the applied field can becomes a critical parameter that may lead to a strong quenching of the interstate light absorption.

1. Introduction

Interest in triangular-shaped quantum nanostructures has grown in recent times. For instance, Khordad et al. reported the intersubband-related optical response of electrons using an infinite-barrier

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model in quantum wires with equilateral triangular cross-section [1–3]. This particular kind of structures saw practical realization several years ago in works like the one by Kim and collaborators [4], who investigated the growth and characterization of triangular-shaped AlGaAs/GaAs and InGaAs/GaAs quantum wire structures. More recently, Xu et al. studied the structure and luminescence of nitride-based heterostructure nanorods with triangular cross-section [5].

On the other hand, quasi-zero-dimensional quantum systems such as quantum dots (QDs) have become the subject of much research due to their current and prospective applications in optics and optoelectronics [6,7]. Reports on experimental obtaining of triangular semiconductor QDs appeared in the works by Kumagai and Tamura [8] and, very recently, in the one by Jo et al. [9].

The mathematical aspects of the exact solution of the non-separable Schrödinger problem in equilateral and isosceles triangles were put forward in the 1980s [10–13], mainly by considering the dynamics of particles completely confined within the triangular regions. Later on, Gangopadhyay and Nag approached the calculation of the energy spectrum of electrons in finite barrier height triangular quantum wires by means of an expansion in terms of the eigenfunctions of the problem with right-angle isosceles triangular shape and infinite barrier height [14]. Meza-Montes and Ulloa determined the electron states in GaAs-based triangular QDs in the presence of magnetic fields by a direct numerical solving that uses finite-element method [15].

The investigation on the linear and nonlinear optical absorption and the relative change of the refractive index in the case of triangular-shaped structures has also appeared in several works throughout these years. One finds, for instance, the report on these particular optical responses by Khordad et al. [1] and the study of impurity-related optical absorption and relative refractive index change in quantum wires of triangular cross-section [16], as well as the electron-related ones in two-dimensional triangular QDs [17] by some of us.

The aim of the present work is to present a study of electron and donor impurity states as well as the impurity-related linear and nonlinear light absorption and the changes in the index of refraction in a two-dimensional triangular quantum dot (2D-TQD) with finite confining barrier height. We shall pay attention to the effect of an external DC electric field, provided the known usefulness of this kind of external probe to help tuning electronic properties in low-dimensional heterosystems. The organization of the work is as follows: The Section 2 contains the details of the used theoretical approach. Section 3 is devoted to the presentation and discussion of the obtained results, whereas the corresponding conclusions appear in the last section.

2. Theoretical framework

The system under study is a two-dimensional triangular QD with finite confining barrier inside which there is placed a donor impurity atom. In addition, we shall consider the influence of an electric field, applied in the xy-plane, on the allowed conduction band and impurity states. These are going to be obtained by working in the effective mass and parabolic approximations to describe the conduction band states, and a diagonalization procedure to deal with the situation of Coulombic coupling and the finite confinement potential. Due to the particular symmetry of the problem, we use the Cartesian coordinate system, so the two-dimensional Hamiltonian is given by:

$$\widehat{H} = -\frac{\hbar^2}{2m^*}\left[\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right] + V(x,y) - \frac{\eta e^2}{\epsilon\sqrt{(x-x_0)^2+(y-y_0)^2}} - e\vec{F}\cdot\vec{\rho}, \qquad (1)$$

where m^* is the electron effective mass and $V(x,y)$, the confining 2D potential which is schematically depicted in Fig. 1. That is, $V = 0$ inside the triangular QD and $V = V_0$ outside, whilst at the sides of the outermost rectangle it becomes infinite. On the other hand, e represents the elementary charge, $\vec{\rho} = (x,y)$, and $\vec{F}$ is the applied electric field. ϵ is the static dielectric constant of the host material and (x_0,y_0) the vector position of the donor center. The parameter η plays the role of a switch for the "connection" of the Coulombic interaction between the conduction band electron and the positively charged ionized impurity atom. $\eta = 0$ implies no impurity effect at all, and $\eta = 1$ corresponds to the situation of electron-impurity coupling.