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Laser driven impurity states in two-dimensional quantum dots and quantum rings

D. Laroze [a,*], M. Barseghyan [b,c], A. Radu [d], A.A. Kirakosyan [b]

[a] Instituto de Alta Investigación, Universidad de Tarapacá, Casilla 7D, Arica, Chile
[b] Department of Solid State Physics, Yerevan State University, Alex Manoogian 1, 0025 Yerevan, Armenia
[c] National University of Architecture and Construction of Armenia, Teryan 105, 0009 Yerevan, Armenia
[d] Department of Physics, Politehnica University of Bucharest, 313 Splaiul Independentei, Bucharest RO-060042, Romania

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ABSTRACT

The hydrogenic donor impurity states in two-dimensional GaAs/$Ga_{0.7}Al_{0.3}As$ quantum dot and quantum ring have been investigated under the action of intense laser field. A laser dressed effect on both electron confining and electron-impurity Coulomb interaction potentials has been considered. The single electron energy spectrum and wave functions have been found using the effective mass approximation and exact diagonalization technique. The accidental degeneracy of the impurity states have been observed for different positions of the impurity and versus values of the laser field parameter. The obtained theoretical results indicate a novel opportunity to tune the performance of quantum dots and quantum rings and to control their specific properties by means of laser field.

1. Introduction

Progress in semiconductor nanotechnologies has led to developments in the fabrication of various mesoscopic objects, including quantum rings (QRs). The fundamental physical interest attracted by these systems arises from a wide variety of purely quantum-mechanical effects which can be observed in ring-like nanostructures [1,2]. Among them, one best deserving to be mentioned is the Aharonov–Bohm effect arisen from the direct influence of the vector potential on the phase of the electron wave function [3–5]. The tendency toward enlargement of the semiconductor QRs family in the nearest future is quite clear by now. It is quite notable that a lot of studies have been realized to reveal great potentialities of QRs as basis elements for a broad spectrum of applications, starting from terahertz detectors [6], efficient solar cells [7] and memory devices [8], through electrically tunable optical valves and single photon emitters [8], and further to spin qubits for quantum computing [9].

The development of high-power, long-wavelength, linearly polarized laser sources, such as CO_2 and free electron lasers, has enabled to increase research activities on the interaction of intense laser fields (ILFs) with electrons in semiconductors [10–12]. This has initiated the discovery of curious physical phenomena.

On the other hand, the hydrogenic impurity problem in the semiconductor nanostructures is an absolutely helpful task so as to grasp the electronic and optical properties of these structures. It is explained by the vast possibilities of purposeful manipulation of the impurity binding energy by means of external influences, which in turn can be used for controlling means of the electronic and optical properties of functional devices based on such heterostructures [13].

The hydrogenic impurity problem under the action of ILF in semiconductor nanostructures are studied theoretically using two major approaches, based on the effective mass approximation. In the first approach, the variational method for both, laser dressed confining and Coulomb potentials has been realized [14–18]. In the second technique, the Schrödinger equation for laser dressed potential has been solved numerically, and the problem with the Coulomb potential has been solved by variational method [19–23].

It is worth mentioning, that very recently, the hydrogenic impurity states in two-dimensional GaAs/$Ga_{0.7}Al_{0.3}As$ QR under the action of ILF have been investigated [24], where a laser dressed effect has been considered only on electron confining potential.

The aim of this study is to investigate theoretically the hydrogenic donor impurity states in two-dimensional GaAs/$Ga_{0.7}Al_{0.3}As$ quantum dot (QD) and quantum ring under the action of intense laser field considering the laser dressed effect on both Coulomb and confining potentials of the electron. The article is organized as

* Corresponding author at: Instituto de Alta Investigación, Universidad de Tarapacá, Casilla 7D, Arica, Chile.
E-mail addresses: dlarozen@uta.cl (D. Laroze), mbarsegh@ysu.am (M. Barseghyan), radu@physics.pub.ro (A. Radu), kirakosyan@ysu.am (A.A. Kirakosyan).

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follows: in the next section we describe the theoretical model. In Section 3 we present and discuss the numerical results. Finally, the conclusions are presented in Section 4.

2. Theoretical framework

The method of investigation of hydrogenic donor impurity states in quantum dot and ring in the presence of ILF is based on a non-perturbative theory that was developed originally to describe the atomic behavior under intense, high-frequency laser field conditions [25,26]. We suppose the system to be under the action of laser radiation represented by a monochromatic plane wave of frequency ω_0. The laser beam is non-resonant with the semi-conductor structure, and linearly polarized along a radial direction of the QR (chosen along the x-axis). In the high-frequency regime the particle is subjected to the time-averaged potential [27–29]

$$V_d(x, y) = \frac{\omega_0}{2\pi}\int_0^{2\pi/\omega_0} V((x + \alpha_0 \sin(\omega_0 t))\mathbf{i} + y\mathbf{j})dt \quad (1)$$

where $\alpha_0 = eA_0/(m\omega_0)$ denotes the laser field parameter, m is the electron effective mass, $\mathbf{A_0} = A_0\mathbf{i}$ is the vector potential, and $\mathbf{i}$ and $\mathbf{j}$ are the unit vectors along the laser polarization and the y-axis respectively. In the case of finite square lateral confining potential well, from Eq. (1) one may obtain a closed analytical form of $V_d(x, y)$, as is seen in [30]. For the time-averaged laser-dressed hydrogenic donor impurity potential we have used the Ehlotzky [31] approximation

$$V_c(x, y) = -\frac{e^2}{2\varepsilon}\left[\frac{1}{\sqrt{\Delta_+^2 + y^2}} + \frac{1}{\sqrt{\Delta_-^2 + y^2}}\right], \quad (2)$$

where ε is the dielectric constant of the material, which, for simplicity, is taken the same inside and outside the QR. Here

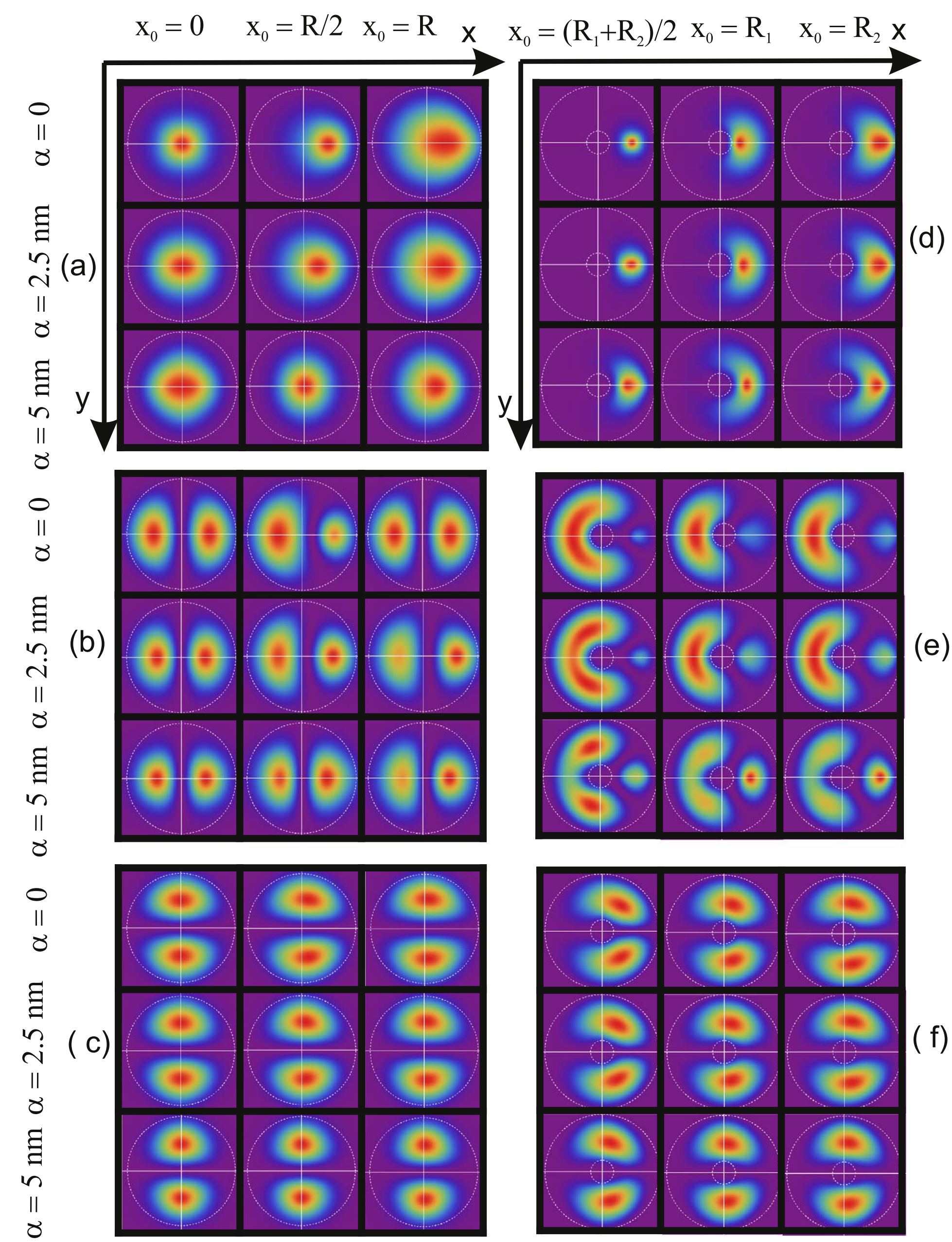

Fig. 1. (Color Online) Electron localization probability in 2D QD structure (left panels) and QR structure (right panels), for different impurity positions. Results are for three values of the laser parameter: $\alpha_0 = 0$; 2.5 nm; 5 nm.