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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]

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

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

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

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

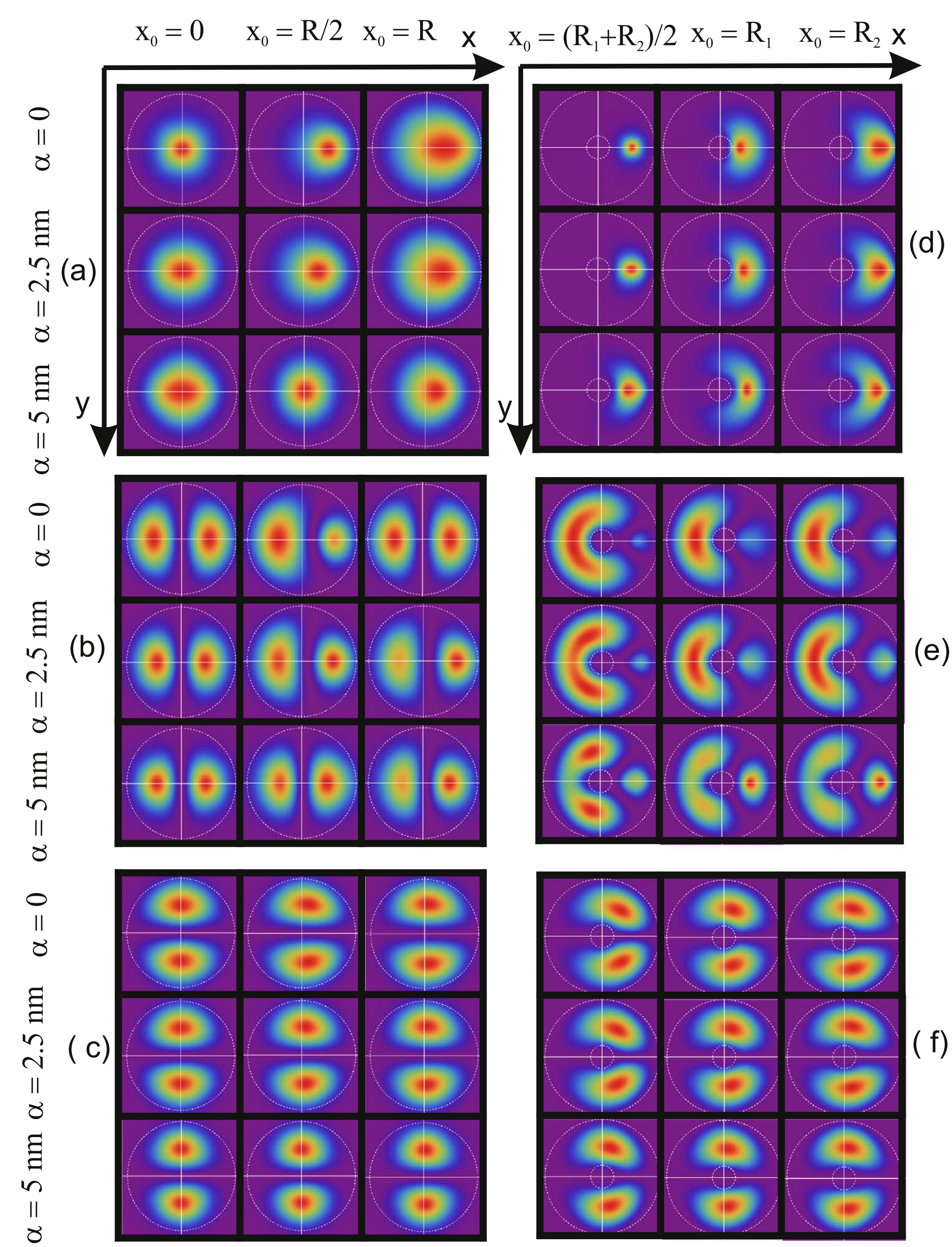

Fig. 1. (Color Online) Electron localization probability in 2D QD structure (left panels) and QR structure (right panels), for different impurity positions. Results are for three values of the laser parameter: $\alpha_0 = 0$; 2.5 nm; 5 nm.

$\Delta_{\pm}^2 = (x - x_0 \pm \alpha_0)^2$ and x_0 is the impurity coordinate. The laser-dressed energies in the presence of hydrogenic donor impurity are obtained from the time-independent Schrödinger equation

$$\left[-\frac{\hbar^2}{2m}\nabla_{\perp}^2 + V_T(x, y)\right]\Phi_d(x, y) = E_d\Phi_d(x, y), \tag{3}$$

where $\nabla_{\perp}^2 = \partial^2/\partial x^2 + \partial^2/\partial y^2$ and $V_T(x, y) = V_d(x, y) + V_c(x, y)$. The laser-dressed energy eigenvalues and eigenfunctions may be calculated using 2D diagonalization technique. The eigenfunctions of the considered system can be presented as a superposition of ones of a two-dimensional rectangle [29,30].

3. Results and discussion

The calculations have been performed for $GaAs/Ga_{0.7}Al_{0.3}As$ two-dimensional (2D) QD and QR structures with parameter values $V_0 = 228$ meV and $m = 0.067m_0$, where m_0 is the free-electron mass. A single impurity has been taken into consideration at different positions with respect to the circular quantum structures.

The electron density of probability within the structures is depicted in Fig. 1 as color gradient plots. The images on the left present the calculation results for the first three impurity states in the QD structure, corresponding to panels (a), (b), and (c), respectively (results are for $R = 10$ nm). The right panels (d), (e), and (f) show the density of probability for the first three impurity states in the QR structure (results are for $R_1 = 5$ nm and $R_2 = 25$ nm). In both cases, three impurity positions and three particular values of the laser field parameter have been considered for illustration. From Fig. 1(a) it can be clearly seen that at $\alpha_0 = 0$ the electron cloud corresponding to the *s*-like ground state follows the impurity position. It is rather compressed and centered on the QD for $x_0 = 0$, almost centered on the impurity for $x_0 = R/2$, but off-centered and more spread out within the structure for $x_0 = R$, since the on-border impurity has a weaker effect on the confined electron. The laser field tends to bring the ground state electron cloud toward the center of the dot by enhancing the geometric confinement for relatively low energies. First excited state in Fig. 1 (b) exhibits a *p*-type orbital aligned along the *x*-axis. The impurity position has a weaker effect on the electron cloud than for the ground state that results in a slight dissymmetry of the orbital lobes. Furthermore, the laser field has a smaller effect on the electron cloud location although it tends to compress the orbital inward. Fig. 1(c) presents the density of probability for the second excited state, which is also *p*-like aligned along the *y*-axis. The effect of the impurity position is even less significant in this case. The laser dressing also squeezes in this orbital, thus an increase in energy with α_0 is expected to occur for both excited states.

The density of probability presented in Fig. 1(d) is for the first electron state in QR. It is observed that the electron cloud is no longer ring-shaped as it should be in the absence of the impurity, but tightly centered on the impurity site. Since for inner and outer border impurity positions the electron cloud is a little more spread out in the structure, one may expect that the lowest ground state energy be obtained for $x_0 = (R_1 + R_2)/2$. The laser dressing visibly reduces the electron cloud compression by the impurity, thus an increase of all energies with the laser parameter is predictable. The first excited state is depicted in Fig. 1(e). The *p*-type orbital is oriented along the *x*-axis and slightly blended toward the impurity side, this effect being slightly reduced by the laser field. Again, the strongest effect of the impurity on the electronic cloud is observed for $x_0 = (R_1 + R_2)/2$. Fig. 1(f) presents the *p*-like orbital of the second excited state, which is aligned along the *y*-axis. The impurity induces a strong dissymmetry of the electron cloud, which is only faintly attenuated by the laser dressing effect.

Fig. 2 presents the electron energy levels of the first five bound states induced by the impurity in a 2D QD with $R = 10$ nm as functions of the laser parameter. Three cases have been considered: (a) on-center impurity; (b) half-radius impurity; (c) impurity located at the QD border. As Fig. 2 reveals, the ground state energy in the absence of the laser field increases with the radial impurity position, from −15 meV (for $x_0 = 0$) up to 10 meV (for $x_0 = R$). This is obviously related to the on-center geometric confinement of the electron in the ground state. As the laser parameter increases, the ground state energy augments with a larger shift for the on-center impurity, and a smaller one for the border impurity. In Fig. 2(a) we see that the second energy level is double-degenerated as a result of the concentric symmetrical impurity potential and confinement potential. The degeneracy is removed by the laser field and resulted both energy levels increase with α_0. Fourth and fifth levels are also increased with α_0, by almost the same quantity. In the panels (b) and (c) there is no degeneracy for $\alpha_0 = 0$, which is determined by the off-center impurity positions. These cases have in common the occurrence of an accidental degeneracy [32] by the crossing of the first and second excited levels, at $\alpha_0 = 3$ nm (Fig. 2(b)) and $\alpha_0 = 3.5$ nm (Fig. 2(c)).

Fig. 3 shows the electron energies of the first five impurity states in a QR with $R_1 = 5$ nm and $R_2 = 25$ nm as functions of the laser dressing parameter. In Fig. 3(a) the results are for an impurity located at half distance between inner and outer energy barriers of the ring. The energy of the ground state has relatively low values, due to the good spatial overlapping of the impurity potential and ring-like wave function of the electron in the absence of the impurity. This energy is also very rapidly increasing with the laser parameter, from −18 meV (for $\alpha_0 = 0$) up to −1 meV (for

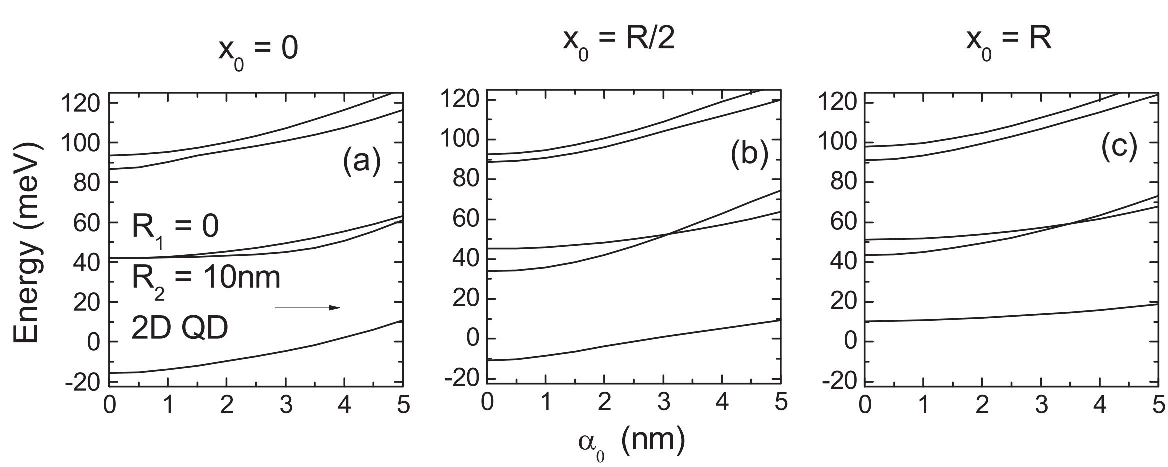

Fig. 2. Electron energy levels of the first five impurity states in a QD, as functions of the laser parameter, for (a) $x_0 = 0$; (b) $x_0 = R/2$; (c) $x_0 = R$.

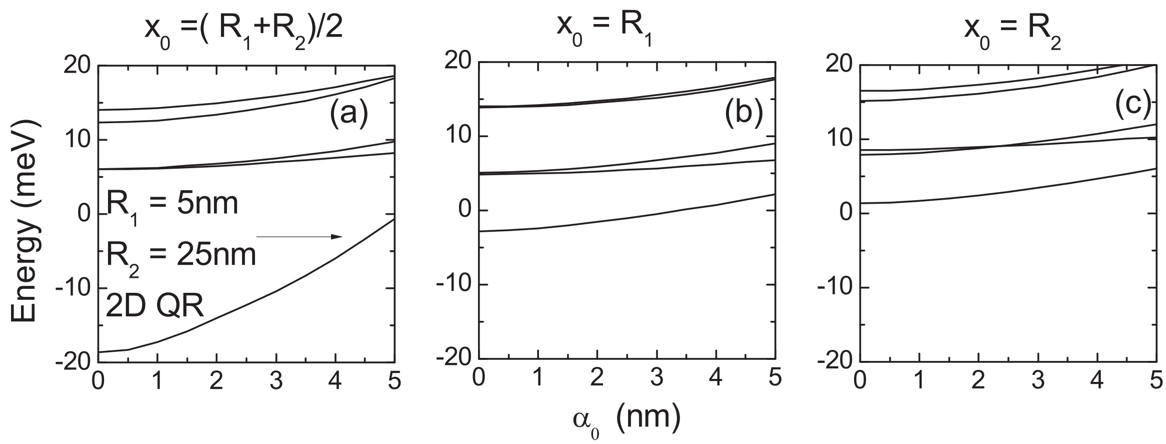

Fig. 3. Electron energy levels of the first five impurity states in a QR, as functions of the laser parameter, for (a) $x_0 = (R_1 + R_2)/2$; (b) $x_0 = R_1$; (c) $x_0 = R_2$.

$\alpha_0 = 5$ nm), as a result of the laser-induced spreading of the wave function. The other four energy levels have an increase of 5 meV, at most. In this case, one may expect a strong dependence on the laser parameter of the intraband optical transitions involving the ground state. The panels (b) and (c) present the energies calculated for impurities located at the inner border of the QR and the outer border, respectively. Similar qualitative dependencies on the laser parameter are observed. Energies in Fig. 3(b) have lower values, since in this case more of the spatial extent of the impurity potential interacts with the electron in the ring. An accidental degeneracy is also observed in Fig. 3(c), as the first and second excited states cross each other over at $\alpha_0 = 2.5$ nm.

4. Conclusions

In this work 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. The laser dressed effect on both electron confining and electron-impurity Coulomb interaction potentials have been considered. We have observed the increasing of the energy levels induced by strengthening of intense laser field. On the other hand, the effective controlling of the electron localization has been achieved by means of intense laser field and hydrogenic donor impurity position. The obtained accidental degeneracy induced by the intense laser field is worth mentioning as well. The calculations showed that the degeneracy of the states can be controlled by changing the sizes of the structures and impurity position. We believe that the effects observed in this work can be used to control physical properties of laser technology devices based on quantum dots and quantum rings.

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