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Effect of impurity on the absorption of a parabolic quantum dot with including Rashba spin–orbit interaction

Parinaz Hosseinpour, Ali Soltani-Vala, Jamal Barvestani *

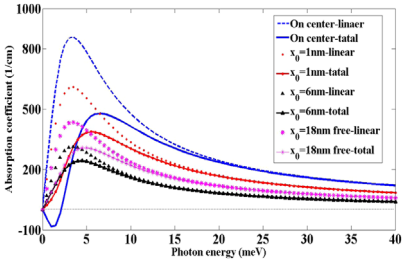
Department of Solid State Physics & Electronics, Faculty of Physics, University of Tabriz, Tabriz, Iran

HIGHLIGHTS

- Calculations of energy states of parabolic disk-like quantum dot.
- The study of the influence of impurity parameters on the absorption coefficients.
- Study of the dependence of the absorption coefficients on the impurity position.
- The absorption coefficient has strong dependency on the impurity parameters.

GRAPHICAL ABSTRACT

Dependence of the linear and total absorption coefficients (ACs) of a doped QD with repulsive impurity on the incident photon energy and different distance of impurity from the dot center (x_0) for the case of X-polarized light.



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ABSTRACT

In this paper, the influence of impurity parameters on the electron energy spectrum and absorption coefficients in a parabolic quantum dot and in the presence of Rashba spin–orbit interaction subjected to a perpendicular magnetic field is studied. The impurity potential is approximated by a Gaussian form. We have shown that in the both cases of a repulsive and attractive Gaussian impurity, the absorption coefficients are strongly affected by the decay length. These coefficients show blue (red) shift as the decay length of repulsive (attractive) impurity is increased. The dependence of the absorption coefficients on the impurity position is also examined for different polarizations. Our results show that the absorption coefficient has local maximum (minimum) for a given value of impurity position for Y-polarized (X-polarized) light.

1. Introduction

Great success in nanofabrication techniques in the past decades [1,2], has now made it possible to manufacture structures with confinement practically in all the 3-directions. These nanostructures are called quantum dots (QDs) and they exhibit interesting electronic behavior owing to the atom-like discrete level energy. Nowadays, more attention has been put on the studies of these systems [3–5] and their electronic and optical properties are essential elements in developing the mesoscopic devices in the future [6]. The spatial confinements and the large dipole matrix elements leading the occurrence of inter levels optical transitions make the quantum dots a better perspective than any low-dimensional structures and eventually a large nonlinearity can be obtained in a quantum dot [7]. This effect can be used for the potential applications for fabricating optical signal processing photoelectric devices [8], high speed electro-optical modulators, far-infrared photodetectors, semiconductor optical amplifiers [9] and optical switching devices [10].

* Corresponding author.
E-mail address: barvestani@tabrizu.ac.ir (J. Barvestani).

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The electron spin is an important parameter and cannot be ignored in the study of electrical and optical properties in any nanostructures. The design of spin-based devices is based on the spin–orbit interactions (SOIs) such as Rashba and Dresselhaus. The Rashba SOI is caused by structural asymmetry [11] and it is significant in low-dimensional systems which is imperative for the potential applications in designing spintronic devices [12] and quantum computing devices [13–15].

On the other hand, one of the most-important properties of a semiconductor QD is that it can be doped with different types and concentrations of impurities to dramatically vary its physical, thermal, electrical and optical properties. Thus, the impurities play a vital role in determining the impurity states in low-dimensional semiconductors and thereby can been exploited to control optoelectronic properties of a wide range of semiconductor devices [16–26]. Generally two models are used for describing of impurity potential in QDs: 1) hydrogenic impurity, 2) Gaussian impurity. Although there are many detailed investigations on the hydrogenic impurity [27–31], studies with Gaussian impurity are much less in numbers [32–35]. Halonen et al. [36] have investigated profound effects of repulsive scattering centers in quantum dots on the energy spectrum of a quantum dot in a magnetic field. Sundqvist et al. have designed an excellent experiment where impurity profiles in low-dimensional structures can be regulated by an external parabolic potential defined by a variety of gate arrangements and found impurity profiles of typical Gaussian shape [37]. Adamowski studied the screening effect of the LO phonons of the D^- center confined by a Gaussian potential [38]. Such a smooth potential offers a reasonable approximation and stands for the finite depth and range of quantum dot confinement potential. It bears a smoothly varying form and therefore is a good approximation of confinement potential in electrostatic quantum dots [39], in which the confinement originates from an inhomogeneous electric field. In self-assembled quantum dots [40] with a composition modulation [41], the confinement potential can also be substituted by the Gaussian potential [42]. Such Gaussian potentials can be assumed to simulate nano-crystals fabricated by means of colloidal chemical synthesis [43]. Halonen et al. have studied the effects of a repulsive scatterer in multi-carrier dots in the presence of magnetic field [44]. However, there have been no reports on the absorption coefficient in a doped parabolic QD with Gaussian impurity potential by including the Rashba SOI under the effect of magnetic field, to the best of our knowledge.

In present report, we have studied that energy levels and optical properties of a doped QD with parabolic confinement potential in the presence of the impurity and Rashba spin–orbit interaction subjected to a perpendicular magnetic field. The form of the impurity potential is assumed to be Gaussian for both cases of repulsive and attractive. We investigate how the absorption coefficients are affected when an impurity center is gradually shifted away from the dot center. The numerical computations are carried out within the framework of single band effective mass approximation and the density matrix formalism.

This paper is organized as follows: in Section 2, we give the theoretical model that will be used in our calculations of eigenfunctions and eigenenergies of electron states and the optical properties. Section 3 contains numerical results and discussions. Finally, a conclusion is given in Section 4.

2. Model and theory

In single carrier QDs, confinement induced by electrostatic gates can be modeled by a purely harmonic potential. Assuming that the z-extension could be effectively considered zero, the electronic properties in QDs have been successfully described within the model of the one electron in two dimensional harmonic oscillator potential [45,46]. Our Hamiltonian model for Gaussian impurity confined in a two dimensional disk like InAs QD with a parabolic confinement potential in the presence of static external magnetic and Rashba SOI is formulated as follows:

$$H=\frac{1}{2m^*}\left(\mathrm{p}-\frac{e}{c}A\right)+\frac{1}{2}m^*\omega_0^2\left(x^2+y^2\right)+\frac{1}{2}g^*\mu_B B\sigma_z+\frac{\alpha_R}{\hbar}\left[\sigma\times(\mathrm{p}-\frac{e}{c}A)\right]_z+V^{imp}(x,y), \tag{1}$$

where the first term is the kinetic energy (m^* is the effective electron mass), the second term is the parabolic potential confinement ($\hbar\omega_0$ is the strength of confinement potential). With including the spin, two additional terms appear in the Hamiltonian, the first one is Zeeman term ($\frac{1}{2}g^*\mu_B B\sigma_z$) ($g^*$ is the effective g factor of semiconductor and μB is the Bohr magneton) and the other one is the Rashba SOI term where α_R is the Rashba coupling coefficient which can be controlled by varying the gate voltage applied in z-direction. The last term is impurity potential modeled by Gaussian form:

$$V^{imp}(x,y)=V_0 e^{-\frac{[(x-x_0)^2+(y-y_0)^2]}{d^2}}, \tag{2}$$

where V_0 is the potential strength with $V_0>0$ ($V_0<0$) for a repulsive (an attractive) impurity and d is an impurity parameter which can be considered as a measure of the spatial stretch of the impurity domain; a small value of d indicates that the spatial extension of the impurity potential is highly restricted, whereas a large value of d accounts for a spatially diffused one [47]. (x_0, y_0) denotes the position of the impurity center. We have chosen the magnetic field in the z direction, $\vec{B}=B\hat{z}$ and use the symmetric gauge, $\vec{A}=\frac{B}{2}(-y, x, 0)$. With using the annihilation (a) and creation operator ($a^\dagger$), Hamiltonian (1) transform to:

$$\begin{aligned}H=\hbar&\left(1+a_x^\dagger a_x+a_y^\dagger a_y\right)+\frac{\hbar\omega_c}{2}i\left(a_y^\dagger a_x-a_x^\dagger a_y\right)\\&+\frac{\alpha_R}{2\hbar}\left(\frac{\sqrt{2m^*\hbar}}{2}+\frac{eB}{4c}\sqrt{\frac{2\hbar}{m^*\Omega}}\right)\left(a_x\sigma_+ +a_x^\dagger\sigma_- +i\left(a_y^\dagger\sigma_- -a_y\sigma_+\right)\right)\\&+\frac{\alpha_R}{2\hbar}\left(\frac{\sqrt{2m^*\hbar}}{2}-\frac{eB}{4c}\sqrt{\frac{2\hbar}{m^*}}\right)\left(-a_x\sigma_- -a_x^\dagger\sigma_+ +i\left(a_y^\dagger\sigma_+ -a_y\sigma_-\right)\right)\\&+\frac{\hbar}{4}\frac{m^*}{m_e}g^*\omega_c\sigma_z+V^{imp}(x,y),\end{aligned} \tag{3}$$

where ω_c is the cyclotron frequency and $\Omega=\sqrt{\omega_0^2+\frac{\omega_c^2}{4}}$. Physically, the first term of Eq. (3) describes a two-dimensional oscillator with frequency Ω, second term arising from the symmetric gauge couples the two oscillators, while the third and fourth terms, arising from the Rashba SOI couple the electronic spin and subbands. The last term of Eq. (3) is the ordinary Zeeman effect. The matrix elements of V^{imp} in the basis of wave function (a superposition of the harmonic oscillator eigenfunctions) are given by [48]:

$$\left(V^{imp}\right)_{n,m;n'm'}=D_1D_2\sum_{k=0}^{\min(n,n')}\sum_{l=0}^{\min(m,m')}f(k,n,n')\,g(l,m,m'), \tag{4}$$

where

$$f(k,n,n')=2^k k!\,{}^nC_k\;{}^{n'}C_k\left(1-\alpha^{*2}\right)^{\frac{n+n'}{2}-k}H_{n+n'-2k}(\alpha_1\rho_1)$$

and

$$g(l,m,m')=2^l l!\,{}^mC_l\;{}^{m'}C_l\left(1-\alpha^{*2}\right)^{\frac{m+m'}{2}-l}H_{m+m'-2l}(\beta_1\rho_2)$$

$H_n(x)$ stands for the Hermite polynomials of nth order. The various other terms read as follows: $D_1=A\lambda_1\pi^{\frac{1}{2}}/\delta_1$, $D_2=B\lambda_2\pi^{\frac{1}{2}}/\delta_1$, with