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Donor-impurity related photoionization cross section in GaAs/$Ga_{1-x}Al_xAs$ concentric double quantum rings: Effects of geometry and hydrostatic pressure

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ABSTRACT

The donor-impurity related photoionization cross section in GaAs/$Ga_{1-x}Al_xAs$ three-dimensional concentric double quantum rings is investigated. The photoionization cross section dependence on the incident photon energy is studied considering the effects of hydrostatic pressure, variations of aluminum concentration, geometries of the structure, and impurity position. The interpretation of the dipole matrix element, which reflects the photoionization probability, is also given. We have found that these parameters can lead to both redshift and blueshift of the photoionization spectrum and also influence the cross section peak value.

1. Introduction

Ever since the first nanoscale semiconducting single quantum rings (QRs) were fabricated by Lorke et al. [1], these fascinating systems have drawn considerable attention due to the possibility of studying quantum phenomena such as the Aharonov–Bohm effect and persistent currents [2,3]. Recently, by using a droplet epitaxy technique, Mano et al. demonstrated the self-assembled formation of GaAs concentric double quantum ring (CDQR) with high uniformity and excellent rotational symmetry [4]. When compared with single QRs, these new concentric rings represent a new promising route towards quantum interference measurements [5].

QRs have already been used in several optoelectronic applications: stacked layers of In(Ga)As on GaAs(0 0 1) self-assembled QRs have been studied for laser applications with stimulated multimodal emission centered at 930 nm (77 K) [6]; photoluminescence and excitation of the photoluminescence spectroscopy has been performed in single InGaAs self-assembled QRs embedded in a field effect structure device [7]; the electronic properties of InAs/GaAs QRs and the characteristics of resonant tunnel intersubband terahertz detectors with QR-active regions have been studied in Refs. [8,9]. The nonlinear optical properties in GaAs QR-like structures were investigated by Duque et al. [10–12], by Liang et al. [13,14], and by Barseghyan et al. [15].

An understanding of the trap's properties, like donor or acceptor impurities in semiconductor nanostructures, is important because these traps control the electrical and optical properties of the materials and limit the performance of the devices by exchanging carriers with the subbands in the nanostructures. For this reason the investigation of optical processes, such as the photoionization of impurities, is essential for applied reasons. To estimate the photoionization probability it is important to know the cross section of that process [16]. The classical formulation of the photoionization cross section (PCS) for bulk semiconductors was pioneered by Lax [17]. In Ref. [18] the authors examined the photoionization of the trap in AlGaAs/GaAs multiple quantum wells. The photoionization threshold energy, its amplitude, and excitation energy dependence of the PCS were determined.

In the past decade a large amount of theoretical investigations were devoted to the investigation of PCS in zero-dimensional semiconducting nanostructures, such as quantum dots (QDs) and QRs. In Ref. [19] a theoretical research was made on the optical properties of a spherical QD containing one and two electrons for cases with and without a hydrogenic impurity. The PCS has been computed for donor impurities in QDs as a function of dot radii

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and the normalized photon energies. The study shows that the cross section is drastically dependent on the dot size and photon energy. Using a variational approach, Sali et al. [20] calculated the photon energy dependence of the PCS for a hydrogenic donor impurity in an infinite barrier GaAs QD as a function of the sizes of the QD and impurity position. More recently Xie made investigations on PCS in QDs [21] and two-dimensional QRs [22–24]. The effects of external applied electric field and impurity position on the ground and lowest excited states and PCS of a hydrogenic donor in the core–shell QD are studied within the effective mass approximation and taking into account the polarization charges at the nanocrystal boundary [25]. Using a perturbative method, Burileanu investigated the behavior of the binding energy and PCS of a donor impurity in spherical quantum dots under the influence of electric and intense high-frequency laser fields [26]. The results showed that the amplitude of PCS grows with dot radius and the peak of the PCS shows a blueshift with a laser intensity increment. The behavior of the binding energy and PCS of a donor impurity in cylindrical-shape QDs under different hydrostatic pressures and applied electric and magnetic fields directions have been investigated in Ref. [27]. The results showed that the mentioned external influences bring to significant changes in PCS spectrum. The behavior of the binding energy and PCS of a hydrogenic-like donor impurity in a single QR, with Po schl–Teller confinement potential along the axial direction, have been studied in Ref. [28]. The decrease (increase) in the binding energy with electric and magnetic fields and confinement potential parameters (hydrostatic pressure) leads to the redshift (blueshift) of the maximum of the PCS spectrum in the on-center impurity.

In the present paper we are interested in donor-impurity related PCS in GaAs/$Ga_{1-x}Al_xAs$ CDQR, taking into account the effects of geometrical parameters, hydrostatic pressure, aluminum concentration, and impurity position. The paper is organized as follows: in Section 2 we describe the theoretical framework, Section 3 is devoted to the results and discussion, and finally our conclusions are given in Section 4.

2. Theoretical framework

Within Fig. 1 the CDQR under study in the present work is depicted. The impurity position, dimensions of the ring and the propagation direction of the incident light are also shown. The rings are made of GaAs and they are embedded in a $Ga_{1-x}Al_xAs$ matrix.

The Hamiltonian of the system, considering an electron-impurity Coloumb interaction within the effective mass and parabolic band approximations, is given by [29]

$$\widehat{H} = -\frac{\hbar^2}{2}\left[\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\frac{\rho}{m(x,P)}\frac{\partial}{\partial\rho}\right)+\frac{1}{m(x,P)}\frac{1}{\rho^2}\frac{\partial^2}{\partial\varphi^2}+\frac{1}{m(0,P)}\frac{\partial^2}{\partial z^2}\right] + V_\rho(\rho,x,P)+V_z(z,P)-\frac{e^2}{\varepsilon(P)r}, \tag{1}$$

where $r=\sqrt{\rho^2+\rho_i^2-2\rho\rho_i\cos\varphi+(z-z_i)^2}$ is the distance from the electron to the impurity site [with $(z_i,\boldsymbol{\rho}_i)$ and $(z,\boldsymbol{\rho})$ being the impurity and electron coordinates, respectively]. Here $m(x,P)$ is the aluminum concentration (x), and hydrostatic pressure (P) dependent electron effective mass, which is given by [30,31]

$$m(x,P)=m_0\left[1+\frac{\Pi^2(x)}{3}\left(\frac{2}{E_g^\Gamma(x,P)}+\frac{1}{E_g^\Gamma(x,P)+\Delta_0(x)}\right)+\delta(x)\right]^{-1}. \tag{2}$$

In this expression, m_0 is the free electron mass, $\Pi(x)$ is the interband matrix element, $\Delta_0(x)$ is the valence-band spin–orbit splitting energy, while remote-band effects are taken into account via the $\delta(x)$ parameter. These parameters are given by the following expressions:

$$\begin{aligned}&\Pi^2(x)=a_\Pi+b_\Pi x,\\ &\Delta_0(x)=a_\Delta+b_\Delta x,\\ &\delta(x)=\delta_1+\delta_2 x+\delta_3 x^2.\end{aligned} \tag{3}$$

The energy gap as a function of pressure and aluminum concentration at the i-point ($i=\Gamma,X$) of the conduction band is [30]

$$E_g^i(x,P)=a_i+b_i x+c_i x^2+\alpha_i P. \tag{4}$$

In our calculations we use GaAs hydrostatic pressure dependent static dielectric constant $\varepsilon(P)$, which at $T=4$ K can be expressed by [27,32,33]

$$\varepsilon(P)=\varepsilon_0 e^{\alpha P}. \tag{5}$$

Considering the crossover of the Γ and X conduction band minima caused by the pressure [34,35], the confining potential in the radial direction is defined by the expression

$$V_\rho(\rho,x,P)=\begin{cases}0 & \text{if } \rho_1^{in}\le\rho\le\rho_2^{in} \text{ and } \rho_1^{out}\le\rho\le\rho_2^{out},\\ V_\rho(x,P) & \text{if } 0<\rho<\rho_1^{in},\ \rho_2^{in}<\rho<\rho_1^{out} \text{ and } \rho>\rho_2^{out},\end{cases} \tag{6}$$

where

$$V_\rho(x,P)=r\begin{cases}E_g^\Gamma(x,P)-E_g^\Gamma(0,P) & \text{if } P\le P_1(x),\\ E_g^X(x,P)-E_g^\Gamma(0,P)+S_{\Gamma X}(x,P) & \text{if } P_1(x)<P\le P_2(x).\end{cases} \tag{7}$$

Here, r is the fraction of band gap discontinuity associated with the confinement potential for electrons, $P_1(x)$ is the critical value of the hydrostatic pressure at which the crossover between the Γ and X bands at the $Ga_{1-x}Al_xAs$ barrier occurs, and $P_2(x)$ corresponds to the crossover between the Γ band at the GaAs well and the X band at the $Ga_{1-x}Al_xAs$ barrier:

$$S_{\Gamma X}(x,P)=S_0\frac{P-P_1(x)}{P}x \tag{8}$$

is the $\Gamma-X$ mixing strength coefficient [34], where S_0 is an adjustable parameter to fit the experimental measurements [35].

In z direction we take an infinite confining potential

$$V_z(z,P)=\begin{cases}0 & \text{if } |z|\le H(P)/2,\\ \infty & \text{if } |z|>H(P)/2.\end{cases} \tag{9}$$

Our structure's size dependence on hydrostatic pressure are given by the following relations [27,36]:

$$\begin{aligned}&\rho(P)=\rho(0)[1-2(S_{11}+2S_{12})P]^{1/2},\\ &H(P)=H(0)[1-(S_{11}+2S_{12})P],\end{aligned} \tag{10}$$

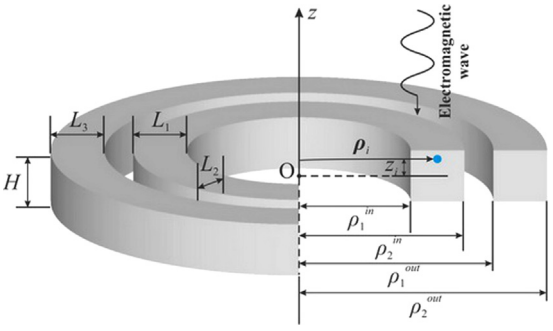

Fig. 1. The concentric double quantum ring heterostructure under study in the present work, where L_1 is the width of the inner ring, L_2 is the width of the coupling barrier, L_3 is the width of the outer ring, ρ_1^{in} and ρ_2^{in} are the inner and outer radii of the inner ring, ρ_1^{out} and ρ_2^{out} are the inner and outer radii of the outer ring, and H is the thickness of rings.