Journal of Luminescence 139 (2013) 64–68

Contents lists available at SciVerse ScienceDirect

Journal of Luminescence

journal homepage: www.elsevier.com/locate/jlumin

# Optical and electronic properties of a two-dimensional quantum dot with an impurity

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ARTICLE INFO

*Article history:*
Received 21 December 2012
Received in revised form
7 February 2013
Accepted 12 February 2013
Available online 5 March 2013

*Keywords:*
Binding energy
Impurity
Quantum dot
Photoionization cross-section

ABSTRACT

The binding energy and photoionization cross-section (PCS) in a two-dimensional pseudopotential, parabolic potential plus an inverse squared potential, quantum dot (QD) with a donor impurity subjected to a uniform magnetic field directed with respect to the *z*-axis have been investigated within the compact-density matrix formalism. The dependence of these optical properties on the confinement frequency of the parabolic potential, on the magnetic field and on the external field is studied in detail. Moreover, take into account the position-dependent effective mass and dielectric, the dependence of PCS on the dot radius is investigated. The results reveal that the binding energy and the PCS in a two-dimensional pseudopotential QD have been strongly affected by these factors, and the position effect also plays an important role in the PCS of the pseudopotential QD. In addition, the red-shift (blue-shift) of the PCS is found in this system because of the decreasing (increasing) energy difference between the final and initial states.



## 1. Introduction

Great success has been achieved in nanofabrication techniques in the past decades [1–3], especially for the low-semiconductor systems, such as superlattices, quantum well, quantum dots and quantum wires. Nowadays, more and more attention has been put on the studies of those systems, and a great deal of experimentations and theoretical works are performed for the purpose of elucidating the physics of these systems [4–10]. The main reasons are as follows: firstly, the low-dimensional quantum systems can cause more obvious nonlinear optical effects than bulk materials; secondly, the nonlinear optical properties have a wide range of potential applications for high-speed electro-optical modulators, far infrared photodetectors, left-handed materials, semiconductor optical amplifiers and so on [11]. With the advance of the science and technology, much important information has been found with the effect of the external probes [12–15], for instance, the applied electric field, the magnetic field, hydrostatic pressure and temperature and the impurity and so on. Effects of laser radiation on optical properties of disk shaped quantum dot in magnetic field were studied by Prasad and Silotia [16], with the results that the absorption coefficient depends on the optical wave and the strength of the static magnetic field. Philips et al. [17] have reported the photoluminescence study of self-organized InAlAs QDS under pressure. The effect of pressure and temperature on impurity in a spherical GaAs quantum dots has been studied by Perez-Merchancano et al. [18]. Moreover, not only the pressure and temperature effect, but also the exciton effect has important effect on the optical properties, so amount of the previous works have investigated the excitonic transition and other optical properties in low-dimensional systems [19–21]. On the other hand, the pseudopotential also makes significant contributions to the research of the low dimensional systems [22,23]. For example, optical properties of a donor impurity in a two-dimensional quantum pseudodot have been studied by Wenfang Xie [24], and the result shows that the optical properties of a donor impurity in a two-dimensional pseudoharmonic QD are strongly affected by the zero point of the pseudoharmonic potential, the chemical potential of the electron gas and the Coulomb interaction. In addition, the pseudopotential was applied for interpreting some results from experiments with great success. In the present work, we will focus on studying the binding energy and thephotoionization cross-section in a two-dimensional QD with an impurity in the presence of the pseudopotential of a donor impurity in a two-dimensional quantum pseudodot. We present a theoretical investigation of the quantum pseudodot with the effects of the external field, confinement potential and magnetic field.

## 2. Model and calculations

Let us consider a hydrogenic impurity confined by a QD with a two-dimensional pseudoharmonic potential, subjected to a static

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0022-2313/$ - see front matter © 2013 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.jlumin.2013.02.030

magnetic field $B$ along the $z$-direction. Within the effective mass approximation, the Hamiltonian of this system can be written as

$$H=\frac{1}{2m^*}\left[\vec{p}+\frac{e}{c}\vec{A}\right]^2+V(r)-\frac{e^2}{\epsilon r}, \tag{1}$$

where $m^*$ and $e$ are electronic effective mass and charge, respectively. $\epsilon$ is dielectric constant, $\vec{A}=A(A_r=0,A_z=0,A_\varphi=Br/2)$ is the vector potential of static magnetic field. $V(r)$ is pseudopotential which includes parabolic potential and inverse squared potential. It is given as follows [25]:

$$V(r)=\frac{1}{2}m^*\omega_0^2r^2+\frac{\hbar^2}{2m^*}\frac{\beta}{r^2}, \tag{2}$$

where $\omega_0$ denotes the confinement frequency and the dimensionless parameter $\beta$ characterizes the strength of the external field with $\beta\geq 0$ in the present work [11,25].

When without the Coulomb interaction, the Schrodinger equation in plan polar coordinate of this system has the form

$$\left[-\frac{\hbar^2}{2m^*}\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{1}{r^2}\frac{\partial^2}{\partial\varphi^2}\right)+\frac{1}{2}m^*\omega_1^2r^2+\frac{\hbar^2}{2m^*}\frac{\beta}{r^2}+\frac{\omega_c}{2}L_z\right]\psi^0=E^0\psi^0, \tag{3}$$

where $\omega_1=\sqrt{\omega_0^2+\omega_c^2/4}$ is the total confinement frequency in the magnetic field, $\omega_c=eB/m^*c$ is the cyclotron frequency. $L_z$ is the orbital angular momentum along the $z$ direction, $E^0$ and $\psi^0$ are the energy eigenvalue and eigenstate of the QD with a two-dimensional pseudoharmonic potential without the effect of the impurity, respectively. The two-dimensional eigenfunctions and energy spectrum without the Coulomb interaction can be given by the Refs. [11,25]. Taking into account the Coulomb interaction, the trial function of the electron confined in two-dimensional pseudoharmonic QD with a hydrogenic impurity can be obtained with the help of the variational approach, written as

$$\psi(r,\varphi,\alpha)=N\psi^0(r,\varphi)e^{-\alpha r}$$
$$=Ne^{-\alpha r}N_nr^Le^{-r^2/2}\frac{\Gamma(L+n+1)}{n!\Gamma(L+1)}F(-n,L+1;r^2)e^{im\varphi}, \tag{4}$$

where $N$ is the normalization constant, $N_n=\sqrt{n!/\pi\Gamma(L+n+1)}$ and $L=\sqrt{m^2+\beta}$, $n$ and $m$ are main quantum number and magnetic number, respectively. $\alpha$ is the variational parameter. The impurity ground state energy is obtained with respect to the minimum of $\alpha$, as given as follows:

$$E_i=\frac{\langle\psi(r,\varphi,\alpha_{min})|H|\psi(r,\varphi,\alpha_{min})\rangle}{\langle\psi(r,\varphi,\alpha_{min})|\psi(r,\varphi,\alpha_{min})\rangle}, \tag{5}$$

where $\alpha_{min}$ is the value of $\alpha$ corresponding to the minimum of $E_i$. The impurity binding energy is defined as

$$E_b=E^0-E_i. \tag{6}$$

In the dipole approximation, the expression of the photoionization cross-section associated with an impurity, starting from Fermi's golden rule in the well-known dipole approximation, can be obtained by [26,27,29]

$$\sigma(\hbar\omega)=\left(\frac{F_{eff}}{F_0}\right)^2\frac{4\pi^2\alpha_{fs}\hbar\omega}{n_r}\left(\frac{m^*}{m_0}\right)^2\sum_f|\langle\psi_i|\vec{\xi}\cdot\vec{r}|\psi_f\rangle|^2\delta(E_f-E_i-\hbar\omega), \tag{7}$$

with

$$\delta(E_f-E_i-\hbar\omega)=\frac{1}{\pi}\frac{(\hbar\Gamma_f)^2}{(E_f-E_i-\hbar\omega)^2+(\hbar\Gamma_f)^2}, \tag{8}$$

where $n_r$ is the refractive index of the semiconductor, $\alpha_{fs}=e^2/\hbar c$, the fine structure constant, and $\hbar\omega$ the photon energy, $F_{eff}/F_0$ is the ratio of the effective electric field $F_{eff}$ of the incoming photon and the average field $\xi_0$ in the medium [30], $\vec{\xi}$ is the light wave polarization vectors. The effective field ratio $F_{eff}/F_0$ may be very large for strongly localized states, but for typical shallow donors with wave functions over many lattice sites, it is quite difficult to calculate $F_0$. Therefore the ratio $F_{eff}/F_0$ has generally been treated as an adjustable parameter to fix the absolute values of $\sigma$. It is clear that this factor does not affect the shape of the photoionization cross-section. In this work, the ratio is taken to be approximately equal to unity [28]. $\langle\psi_i|r|\psi_f\rangle$ is the matrix element between the initial and final states of the dipole moment of the impurity. $\Gamma_f$ is the hydrogenic impurity linewidth and taken as $0.1R_y^*$.

## 3. Results and discussions

In this paper, the ground binding energy and PCS in a two-dimensional GaAs QD with an impurity in the presence of the pseudopotential, parabolic potential plus an inverse squared potential, subjected to the uniform magnetic field directed with respect to the $z$-axis have been numerically investigated. The physical parameters for calculations are used as follows [29,31]: $n_r=3.2$, $\Gamma_f=0.1R_y^*$, and $m^*=0.067m_0$, where $m_0$ is the free electronic mass. The results of our calculations are presented in

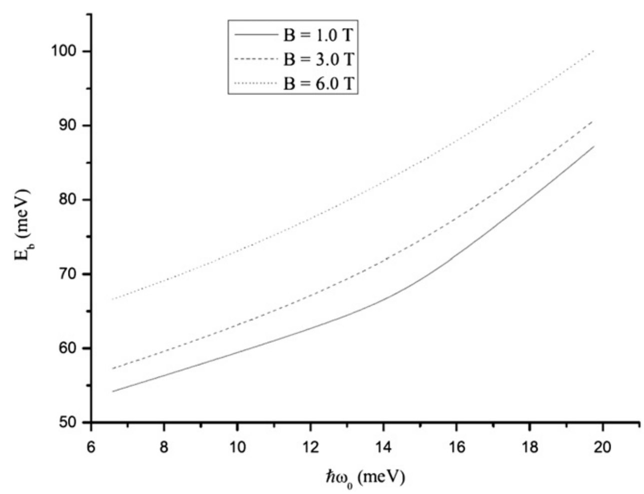


**Fig. 1.** The binding energies as a function of the confinement strength $\hbar\omega_0$ for the three different values of magnetic field $B$ with $\beta=0.5$.

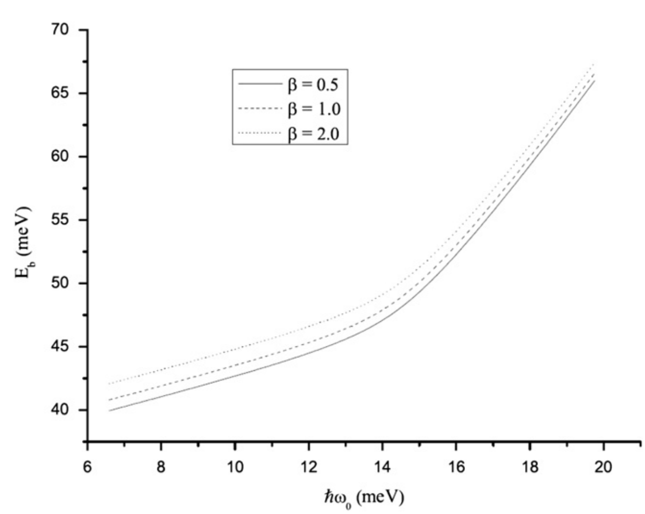


**Fig. 2.** The binding energies as a function of the confinement strength $\hbar\omega_0$ for the three different values of external field $\beta$ with $B=2$ T.