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Hydrogenic impurity states in a parabolic quantum dot: Hydrostatic pressure and electric field effects

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ABSTRACT

The binding energy of hydrogenic impurity associated with the ground state and some low-lying states in a GaAs spherical parabolic quantum dot with taking into account hydrostatic pressure and electric field are theoretically studied by using the configuration–integration method. The binding energies of these low-lying states of the impurity depend sensitively on the hydrostatic pressure, electric field and the strength of the parabolic confinement. Based on the analysis of these impurity states, we propose a way for preparation of quantum bit (qubit) by using the strong quantum confinement to the impurity in the quantum dot. Also we calculate the wave functions of some low-lying states to discuss the oscillator strength which is related to the electronic dipole-allowed transitions from 0s state to 0p state. The results show that the electronic dipole-allowed transitions mostly happen between the 0s state and 0p state, especially for the quantum confinement large enough.

1. Introduction

The study of semiconductor quantum dots (QDs) holds a great interest in experimental and theoretical subject in recent years [1–24]. The semiconductor structures with quantum confinement

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show interesting physical properties which is not depend only on the strength of the confinement but also on the external electric field. With the development of modern technology, it is now possible to produce QDs by using these techniques such as etching and molecular beam epitaxy [2]. QDs have been fabricated in different shapes, such as disk-like (cylindrical) shape and spherical shape. The new, unusual properties of the low-dimensional nanometer-sized semiconductor (the three dimensional nanoscale confinement of the charge carriers) give rise to a full quantum nature to these structures. Thus increasing attention has been focused on energy quantized states of charge carriers mainly because of their potential applications in the optical devices [2].

The impurities in semiconductors can affect electrical, the optical and transport properties [3–5]. Thus, impurities play an essential role in semiconductor devices. All semiconductor devices factually incorporate dopants as a crucial ingredient for their proper functioning. Thus an understanding of the nature of impurity states in semiconductor structures is one of the crucial problems in semiconductor physics. The study of the behavior of hydrogenic impurity states in semiconductor nanostructures dates back to the early 1980s through the pioneering work of Bastard [6]. In spite of growing interest in the topic of impurity doping in nanocrystallites, most theoretical work carried out on shallow donors in spherical quantum dots employs variational approaches, alternatively, perturbation methods limited to the strong confinement regime and the method of numerical diagonalization [6–10]. Bose and Yuan et al. [7] calculated the binding energy of a shallow hydrogenic impurity in spherical quantum dot with a parabolic potential by using perturbation method, respectively. Li and Xia [8] calculated the electronic states of a hydrogenic donor impurity in low-dimensional semiconductor nanostructures in the framework of effective-mass envelope-function theory by using the plane wave method. Xie and Zhu et al. [9] investigate the binding energy of hydrogenic donor impurity in a parabolic quantum dot and in a rectangle spherical quantum dot using the method of numerical diagonalization, respectively. As far as we known, the electric field will destroy the symmetry of the system. So, a considerable attention of the energy levels of shallow impurities in QDs may be drawn. The energy spectrum of the carriers will make respectable changes because the electric field results in an energy Stark shift of the quantum states. Using the variational approaches [10], Murillo calculated the binding energy of an on-center donor impurity in a spherical GaAs-(Ga,Al)As QD with parabolic confinement as a function of the dot radius and the applied electric field. The quantum size, impurity position and electric field affect on the energy of donor placed anywhere in a GaAs spherical quantum crystallite which embedded in $Ga_{1-x}Al_xAs$ matrix was discussed theoretically by Assaid et al. [11]. It is well known that hydrostatic pressure is a powerful tool to investigate and control the optical properties of low-dimensional semiconductor electronics-related systems. However, most of these studies were concerned with the ground-state electronic properties. Recently, the hydrostatic pressure has been attracted much attention for the impurity state. Within the framework of effective-mass approximation, Xia et al. [12] studied the hydrostatic pressure effects on the donor binding energy of a hydrogenic impurity in InAs/GaAs self-assembled quantum dot (QD) by means of a variational method. Yesilgul et al. [13] investigated effects of an intense laser field and hydrostatic pressure on the intersubband transitions and binding energy of shallow donor impurities in a quantum well. Duque et al. [14] have studied theoretically the hydrostatic pressure effects on optical transitions in InAs/GaAs cylindrical QD. So far, the binding energy of the low-lying states of donor impurity with external electric field in the presence of the hydrostatic pressure was rarely studied. And mostly all of study the binding energy of the ground state about this topic was carried out by the variational approaches [15] or in a two-dimensional QD [16]. It is more interesting for us, recently, the topic for the various confined potential in the QD using potential morphing method (PMM) have been reported by Garoufalis et al. for investigating the lowing-lying state and optical properties [17].

In this work, we will investigate the binding energy of the ground state and some low-lying states of a spherical QD with parabolic confinement in the presence of an external electric field and hydrostatic pressure. The spherical QDs so far are formed from semiconductor nanocrystals embedded in either an insulating or a semiconducting matrix. An attempt is to study the influence of the external electric field, hydrostatic pressure and parabolic confinement strength to the shallow donor impurity using the configuration–integration methods (**CI**) [18]. Our numerical calculations are carried out for one of the typical semiconducting materials, GaAs. We find that the binding energies of these low-lying states of the impurity depend sensitively on the hydrostatic pressure, electric field and