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Electromagnetically induced transparency in a multilayered spherical quantum dot with hydrogenic impurity

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ABSTRACT

In this paper the effects of size, hydrostatic pressure and temperature on electromagnetically induced transparency, as well as on absorption and the dispersion properties of multilayered spherical quantum dot with hydrogenic impurity are theoretically investigated. Energy eigenvalues and wavefunctions of quantum systems in three-level and four-level configurations are calculated using the shooting method, while optical properties are obtained using the density matrix formalism and master equations. It is shown that peaks of the optical properties experience a blue-shift with increasing hydrostatic pressure and red-shift with increasing temperature. The changes of optical properties as a consequence of changes in barrier wells widths are non-monotonic, and these changes are discussed in detail.

1. Introduction

In the last decade, there has been tremendous interest in the absorption and dispersion properties of low-dimensional semiconductor heterostructures (quantum wells, quantum wires and quantum dots). Low dimensional semiconductor systems have physical properties that are different from bulk semiconductors. For example, they have discrete energy structure and the absorption spectrum is expected to be a series of discrete lines [1]. The increasing interest in this field is due to technological progress in the field of semiconductor nanotechnology which made it possible to fabricate very small semiconductor heterestructures. Among these, quantum dots (QDs), which are often called artificial atoms due to their mutual similarity in energy level structures [2–5], draw great attention because of their potential applications in optoelectronic and photonic devices [6,7].

Properties of QDs can be changed by making some modifications in their size, shape, and dimensions [8], or by changing the pressure and temperature [9,10], as well as by external electric and magnetic fields [11]. The absorption and the dispersion properties of QDs can also be modified by impurities [10]. The effects of size and dimensions on donor binding energies have been studied theoretically in QDs for geometric forms such as cylindrical, rectangular, spherical and pyramidal ones [12–18].

During the past few years, special attention has been focused on the physical properties of a new kind of quantum dots, called multilayered quantum dots (MSQDs). Technologically, the production of MSQD nanocrystals has become possible by using suitable wet chemical synthesis techniques [19,20]. Studies in this field have firstly been confined to the investigation of electronic properties, i.e. to solving the Schrödinger equation and determining the eigenvalues and eigenfunctions. Aktas and Boz [21] calculated the binding energy of hydrogenic impurity in an MSQD under the effect of the band non-parabolicity by using the fourth-order Runge-Kutta method. Akgül et al. [22] investigated the electronic properties of an MSQD with a parabolic confinement. Mikhail and El Sayed [23] calculated the binding energy of an on-center and an off-center impurity located in an MSQD. Boz et al. discussed the binding energy of an impurity located at the center of MSQD under the influence of an external magnetic field [24]. Electronic and optical properties of an MSQD for cases with and without hydrogenic impurity are investigated in Refs. [25–27], where binding energies, absorption coefficients and oscillator strengths are calculated as a function of the dots' radii and barrier thickness. Linear and nonlinear optical properties of multi-layered spherical nano-

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systems with donor impurity in the center are discussed in Ref. [28]. Karimi et al. [29] investigated the effects of geometrical size, hydrogenic impurity, hydrostatic pressure and temperature on linear and nonlinear optical properties in an MSQD. In this paper [29], a system consisting of two levels which interacts with one laser field is discussed. However, to the best of our knowledge, the absorption and dispersion properties of an MQSD with hydrogenic impurity have not been investigated in multilevel systems in cascade configuration, which interacts with more than one laser field. One of the coherent effects that is a consequence of the interaction between a quantum system with more than one laser field is electromagnetically induced transparency (EIT).

Electromagnetically induced transparency is a quantum interference effect in which reduction of absorption of the resonant laser field occurs in the presence of the second laser field [30–32]. Together with reduction in absorption, EIT leads to modifications in dispersive properties of the medium. The refractive index of the medium is enhanced, and the group velocity of the laser field is reduced. If EIT effect is achieved, the laser field can pass through the media almost unchanged, its group velocity can be reduced to 8 m/s, i.e. it can be hold on in a media for 1 min [33]. All this is of a high interest for applications in the fields of quantum informatics [34,35] and quantum memory [36–38].

The first experiment which demonstrated the EIT effect was conducted on atomic vapors of Strontium atoms [30]. Later, this effect was also realized on other atomic vapors such as Rb, Na, and K. In these experiments, the atoms in atomic vapors can be regarded as quantum systems with three quantum levels in Λ and ladder configurations [39–42], as well as systems with four or more quantum levels in a double Λ [43], ladder [44], Y [45], inverted Y [46,47], W [48], M [49] and other kinds of configurations.

During the last decade, there have been intensive investigations of quantum coherence effects in semiconductor nanostructures such as quantum wells – QW and quantum dots – QD [50,51]. One of the advantages of using semiconductor nanostructures instead of atomic vapour systems, are the high values of the dipole moments. Due to larger dipole moment values, lasers with lower intensities can be used in the realization of this effect. However, dephasing rates from the electron-phonon interaction in such media are bigger than those in atomic systems at room temperatures. Therefore, experiments that use semiconductor nanostructures are often used at low temperatures, whereupon the radiation decay part dominates in dephasing rates. Also, one of the most important reasons for using semiconductor nanostructures as media for obtaining EIT effect is their potential use for the realization of quantum computers [52–54].

The main objective of this paper is to investigate the geometric effects, and effects of temperature and pressure on the EIT, absorption and dispersion properties of such systems.

The rest of the paper is organized as follows: In the first part of Sec. 2 the model of the multilayered spherical quantum dot with hydrogenic impurity is described, and in the second part of Sec. 2, master equations for a four-level cascade configuration and the connections between the density matrix elements of this system and the susceptibility seen by the probe field are given. The results and discussion are presented in Sec. 3, and a short conclusion is given in Sec. 4.

2. Theory

2.1. Multilayered spherical quantum dot with hydrogenic impurity

The system under investigation consists of two spherical quantum dots (SQDs), one within the other, separated by a finite potential. The whole system is also isolated with additional potential from the outside. This kind of potential defines the multilayered spherical quantum dot (MSQD) which is given by the following potential:

$$V(r,P,T)=\begin{cases}0, & 0\le r\le R_1(P)\\ V_0(P,T), & R_1(P)<r<R_2(P)\\ 0, & R_2(P)\le r\le R_3(P)\\ V_0(P,T), & R_3(P)<r<\infty\end{cases}, \tag{1}$$

where V_0 (P,T) is the pressure and temperature dependent confinement potential height, and R_1 (P), R_2 (P), and R_3 (P) distances which define the geometry of an MSQD. This kind of quantum dots (QD) can be realized by different kinds of layers of semiconductors, which is shown in Fig. 1. In this paper, *GaAs* and $Ga_{1-x}Al_xAs$ are used.

Let us consider an electron of a hydrogenic impurity confined in the center of this MSQD. The pressure and temperature dependent Hamiltonian of such a system is given by

$$H=-\frac{\hbar^2}{2m^*(r,P,T)}p^2+V(r,P,T)-\frac{1}{4\pi\varepsilon_0}\frac{e^2}{\varepsilon(r,P,T)r}, \tag{2}$$

where m^* (r,P,T), and ε (r,P,T) are the pressure and temperature dependent effective mass of the electron, and the dielectric constant, respectively. These quantities are given by

$$m^*(r,P,T)=\begin{cases}m_w^*(P,T), & 0\le r\le R_1(P)\\ m_b^*(P,T), & R_1(P)<r<R_2(P)\\ m_w^*(P,T), & R_2(P)\le r\le R_3(P)\\ m_b^*(P,T), & R_3(P)<r<\infty\end{cases}, \tag{3}$$

and

$$\varepsilon(r,P,T)=\begin{cases}\varepsilon_w(P,T), & 0\le r\le R_1(P)\\ \varepsilon_b(P,T), & R_1(P)<r<R_2(P)\\ \varepsilon_w(P,T), & R_2(P)\le r\le R_3(P)\\ \varepsilon_b(P,T), & R_3(P)<r<\infty\end{cases}. \tag{4}$$

where subscript w (b) stands for *GaAs* ($Ga_{1-x}Al_xAs$) which in our MSQD represents the quantum well (barrier). The effective mass of the electron (and dielectric constant) in the barrier made from Ga_1 $-xAl_xAs$ can be obtained from the effective mass of the electron (and corresponding dielectric constant) in the well made of *GaAs* by taking into account the mole fraction of aluminum x [55,56]:

$$m_b^*(P,T)=m_w^*(P,T)+0.083x, \tag{5}$$

$$\varepsilon_b(P,T)=\varepsilon_w(P,T)-3.12x. \tag{6}$$

The pressure and temperature dependent static dielectric constant for wells made of *GaAs* is given by Refs. [57–61]

$$\varepsilon_w(P,T)=\begin{cases}12.74\,e^{-1.73\cdot10^{-3}P}e^{9.4\cdot10^{-5}(T-75.6)}, & T<200\\ 13.18\,e^{-1.73\cdot10^{-3}P}e^{20.4\cdot10^{-5}(T-300)}, & T\ge200\end{cases}, \tag{7}$$

and pressure and temperature dependent effective mass for wells made of *GaAs* [57,62,63]

$$m_w^*(P,T)=\frac{m_0}{1+E_P^{\Gamma}\left(\frac{2}{E_g^{\Gamma}(P,T)}+\frac{1}{E_g^{\Gamma}(P,T)+\Delta_0}\right)} \tag{8}$$

where m_0 is the free electron mass, $E_P^{\Gamma}=7.51$ eV is the energy related to the momentum matrix element, E_P^{Γ} (P,T) is the pressure and temperature dependent energy gap for the *GaAs*, and Δ_0