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Linear and nonlinear optical absorption coefficients and refractive index changes of a spherical quantum dot placed at the center of a cylindrical nano-wire: Effects of hydrostatic pressure and temperature

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ABSTRACT

The combined effects of hydrostatic pressure and temperature on the optical absorption coefficients and refractive index changes of an InAs spherical quantum dot which is located at the center of a GaAs cylindrical nano-wire have been investigated. The wave functions and corresponding eigenvalues are calculated using finite element method in the framework of effective mass approximation. Analytical expressions for the linear and third order nonlinear optical absorption coefficients and refractive index changes are obtained by means of the compact-density matrix formalism. The linear and third order nonlinear absorption coefficient and refractive index changes are presented as a function of the photon energy, dot radius, pressure, temperature, incident photon intensity and relaxation time. It is found from our calculations that the linear and third order nonlinear optical absorption coefficients, refractive index changes and resonance energy are quite sensitive to the dot size, applied hydrostatic pressure and temperature.

1. Introduction

During the past two decades semiconductor quantum dots (QDs) have attracted considerable attentions because of their wide range applications [1–5]. It is to be noted that shallow impurity [6]

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and external factors such as electric field [7], magnetic fields [8], temperature and pressure [9–11] can change the electronic and optical properties of nanostructures [12,13].

One of the most important features of QDs is the intersubband optical transition between the quantized subbands [14]. In optical transition between two subbands, the dipole matrix element is dramatically large and it causes a large change in the dielectric constant of the host material especially when incident photon energy is equal to the intersubband transition energy and which alters the index of refraction and absorption coefficient [15]. Moreover, because of large dipole matrix elements, the large nonlinear optical absorption coefficient (AC) and refractive index (RI) changes are expected [16–18]. The nonlinear optical properties have shown high potential for device applications in far-infrared laser amplifiers, photo-detectors and high speed electro-optical modulators [19–22]. Very fast relaxation time is also the other appealing feature of intersubband transitions in semiconductor quantum dots [23]. The effects of the hydrostatic pressure and temperature on optical properties of nanostructures have also been studied by several authors [24–27]. Their results show that the pressure and temperature play an important role in the optical ACs and RI changes.

Changing the shape, size and confining potential provide great advantages in view of tuning the desired properties [19]. Further, the progresses in fabrication techniques like etching and epitaxial growth have made it possible to produce QDs which are placed in a nano-wire [28,29]. Some researchers also used this structure as a single photon source [30,31] or calculated electronic structure of quantum dots embedded into nanowires [32]. Panev et al. [33] investigated sharp exciton emission from single InAs QDs in GaAs nanowires.

In the previous work [10], one of the authors found the effects of pressure and temperature on the electronic structure of an InAs spherical QD located at the center of a GaAs cylindrical nano-wire. In this work, the optical properties of this geometry have been investigated. The paper is organized as follows: the Hamiltonian, relevant wave functions and energy levels are briefly described in Section 2. The analytical expressions of the optical ACs and RI changes for 1s-2p transition are also presented in this section. Numerical calculations and detailed discussions are given in Section 3. Finally, a brief summary is presented in Section 4.

2. Theory

In the effective mass approximation, the total Hamiltonian for an electron in a spherical quantum dot with radius R_1 located at the center of a cylindrical nano-wire is given by

$$-\frac{\hbar^2}{2}\overrightarrow{\nabla}.\left(\frac{1}{m^*}\overrightarrow{\nabla}\psi\right)+V\psi=E\psi \tag{1}$$

where the ħ is the Planck constant, m^* is the effective mass and E and ψ are the energy eigenvalue and eigenvector, respectively. The inclusion of pressure and temperature effects are made via the variation of the main input parameters, such as energy gap (E_g). The energy gap is proportional to the pressure and temperature according to [34]

$$E_g(P,T)=E_g^{(0)}+\alpha P-\frac{\kappa T^2}{T+c} \tag{2}$$

where $E_g^{(0)}$ is the energy gap at $T = 0$ and $P = 0$, α is the pressure coefficient, and κ and c are the temperature coefficients. The confined potential is related to the energy gap, therefore it depends on the hydrostatic pressure, temperature and vector position and is given as

$$V=\begin{cases}0, & \text{in the well}\\ V_0(P,T)=Q_c(E_g^{GaAs}(P,T)-E_g^{InAs}(P,T)) & \text{in the barrier}\end{cases} \tag{3}$$

In this equation Q_c is the conduction band offset parameter which has a value of 0.6 for such materials [35].

Variations of the electron effective mass according to the Kane model [36] is given in below equation: