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Electric field and impurity effect on nonlinear optical rectification of a double cone like quantum dot

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ABSTRACT

In this work, we have investigated the effect of electric field and impurity position on nonlinear optical rectification of a double cone like quantum dot in the effective mass approximation and by using compact density-matrix formalism. We have calculated the energy levels and wave functions using finite element method (FEM) in the presence of impurity and influence of electric field. The results show that: (i) the binding energy changes with the impurity position and it is changed by the applied electric field, (ii) nonlinear optical rectification peak position of this system present the blue or red shift due to the applied electric field and changing the impurity position. (iii) for low electric field, impurity position plays an important role in electronic and optical properties, but for larger electric field, impurity position role becomes non-significant. (iv) the optical rectification changes due to the impurity position and the electric field are considerable.

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1. Introduction

The low-dimensional semiconductor structures physics has become an important part of research, in the past three decades. Low-dimensional structures allow the study of a new optical, mechanical and transport phenomena [1]. Low-dimensional semiconductor structures examples are quantum wells, wires, and dots [2–5]. There are different technological progresses in the semiconductor structures fabrication like chemical lithography, molecular beam epitaxy, and etching [2–4]. Now a day, Quantum dots have become subject of important experimental and theoretical studies. The possibility of obtaining quantum dots with various shapes such as spherical, cylindrical, ellipsoidal, pyramid-like, and cone-like, have been offered by improvements of the semiconductor growth techniques [5–8].

The impurity states have an important role in electronic and optical properties of QDs. So, these states have been extensively investigated in experimental and theoretical procedures [9–11].

It is worth mentioning that the information about electronic and optical properties of nanostructures in the presence of impurity is one of the most important subject in sciences and industries. It is known that investigation of optical properties of QDs has practical usage in novel optoelectronic devices such as QD infrared photo detector, quantum cryptography, and QD lasers [12–18].

Also, the impurity and the applied electric field change the optical properties of low-dimensional quantum structures and it is useful in view of fundamental physics and device applications like semiconductor optical amplifiers, high-speed electro-optical modulators, far IR photodetectors, etc.

Second-order nonlinear optical effects such as nonlinear optical rectification (NOR), second harmonic generation and frequency down conversion in semiconductor nanostructures usually receive more attention due to the fact that the magnitudes of the second-order nonlinear susceptibility are usually larger than those of higher-order ones. Second-order nonlinear optical effects have been observed experimentally [19–25]. Following these experimental observations, many theoretical studies have also been investigated [26–32].

In this work, we have studied the nonlinear optical rectification (NOR) of a GaAs/$Ga_{0.5}$ $In_{0.5}$ As double cone like quantum dot that is grown on a GaAs wet layer under electric field and presence of impurity in realistic case and with finite confining potential. The Impurity-related nonlinear optical rectification in double quantum dot under electric field have been studied by a one dimensional confining potential in Ref. [33] We use the formulae derived by Paspalakis et al. [34] to calculate the nonlinear optical rectification. NOR for a cone like quantum double dot system in the presence of

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an impurity under the influence of an electric field has not been investigated so far.

The outline of the paper is as follows. In Section 2 we present the theoretical framework. The numerical results and the discussion of the electronic properties and the nonlinear optical rectification spectra are presented in Section 3 and a brief summary is given in Section 4.

2. Theory and model

The Hamiltonian of a hydrogenic donor impurity located at the position $\mathbf{r}_0$ in a double quantum dot under x direction electric field, in the effective mass approximation, is given by

$$H = H_0 - eFx - \frac{e^2}{4\pi\varepsilon|\mathbf{r}-\mathbf{r}_0|}, \tag{1}$$

where F is the electric field and

$$H_0 = -\frac{\hbar^2}{2m^*}\nabla^2 + V(x,y,z). \tag{2}$$

In this present work, we have considered a double cone like quantum dot, with finite confining potential. The confining potential $V(x,y,z)$ is given by

$$V(x,y,z) = \begin{cases} 0 & inside \\ V_0 & outside \end{cases}. \tag{3}$$

The boundary surfaces and the shape of system are presented in Fig. 1. The calculation of energy levels and wave functions, analytically, is a nontrivial task because of complicated form of the quantum dot shapes. Therefore, we are interested in using the finite element method (FEM) to find wave functions and energy levels of systems [35].

After obtaining eigenvalues, one can calculate the binding energy (E_b) from the usual relation

$$E_b = (E_0)_{without\ impurity} - (E_0)_{with\ impurity}, \tag{4}$$

where E_0 is, the ground state energy of system.

For a transition between two levels E_i and E_j, the NOR calculated under steady state conditions and in the extended rotating wave approximation in coherent laser-matter interaction of a quantum structure within the compact density-matrix formalism is given by Ref. [34]:

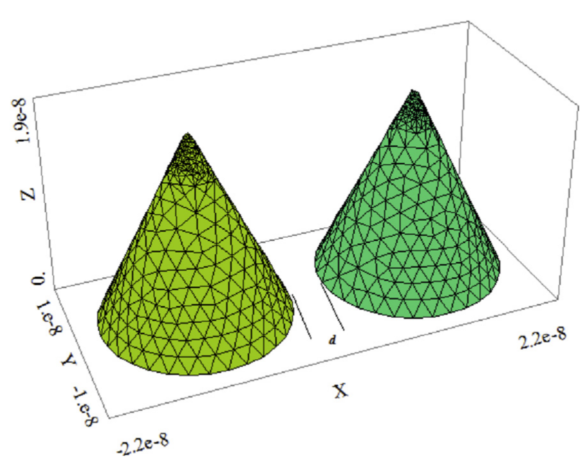

Fig. 1. The boundary surfaces and the shape of a double cone like quantum dot.

$$\chi_0^{ij}(\omega) = \frac{2N\left|\mu_{ij}-\mu_{ii}\right|\mu_{ij}^2 T_1 T_2}{\varepsilon_0\hbar^2}\frac{\left(J_0\left(\frac{|\mu_{jj}-\mu_{ii}|E_0}{\hbar\omega}\right)-J_2\left(\frac{|\mu_{jj}-\mu_{ii}|E_0}{\hbar\omega}\right)\right)^2}{1+T_2^2(\omega-\omega_{ij})^2+\overline{\mu}_{ij}^2E_0^2T_1T_2/\hbar^2}, \tag{5}$$

where $\omega_{ij} = (E_j - E_i)/\hbar$ and

$$\overline{\mu}_{ij}^2 = \mu_{ij}^2\left(J_0\left(\frac{\left|\mu_{jj}-\mu_{ii}\right|E_0}{\hbar\omega}\right)-J_2\left(\frac{\left|\mu_{jj}-\mu_{ii}\right|E_0}{\hbar\omega}\right)\right)^2 \tag{6}$$

In Eq. (5) J_0, J_2 are the ordinary Bessel functions of order 0 and 2, N is the electron density, T_1 is the population decay time and T_2 is the dephasing time. E_0 is the amplitude of the electric field $E(t) = E_0 \cos(\omega t)$ related to the incident intensity I_0 of the probe field by $I_0 = c\varepsilon_0 n_r E_0^2/2$ where n_r is the refractive index and c is the vacuum speed of light. μ_{ij} are the dipole moment matrix elements calculated for a x-polarization of the incident light, $\mu_{ij} = e\psi_i|x|\psi_j$.

3. Results and discussion

In this section, we present the numerical results concerning the effect of the hydrogenic donor impurity on the nonlinear optical rectification of a *GaAs/Ga$_{0.5}$ In$_{0.5}$ As* double cone like quantum dot that is grown on a GaAs wet layer with thickness of *1.6 nm*, radius of cross section of the bottom is *10 nm*, and *20 nm* height, under negative applied electric field in x direction. The parameters are used in our calculations are: $m^*_{GaAs} = 0.067m_0$, $m^*_{GaInAs} = 0.045m_0$ (where m_0 is the mass of a free electron), $N = 3\times10^{22}\ m^{-3}$, the refractive index of the semiconductor $n_r = 3.55$, $T_1 = 10$ *ps* and $T_2 = 5$ *ps* [29]. The electric field direction is in negative of x direction, and impurity is located in x axes.

In Fig. 2 we have presented the first eight energy levels as a function of applied electric field for different d (distance between the edge of two quantum dot on the bottom (see Fig. 1)) without and with presence of impurity in *(0,0,0)*. When $F = 0$, all the electron density probability are in the right and left dot symmetrically, but when F is not zero the states have two different type behavior. The density probability of 1, 3, 4, 5 states are mostly in right (right states) and 2, 6, 7, 8 are in left (left states) until to anticrossing electric field (F_{ac}). The right states energy decrease by increasing F and left states energy increase by increasing F. After F_{ac} all the states except 5 state are right state until forcing electric field (F_f), and after that, also 5 state is right state. F_{ac} and F_f are smaller for larger d because the tilt of energy levels is larger for larger d. In presence of impurity, the behavior of all energy levels is same as without impurity case, but all energy levels are smaller, due to the presences of Coulomb potential.

First eight energy levels as a function of impurity position $(x_0,0,0)$ for different F with $d = 0,4$ *nm* have shown in Fig. 3. One can see from Fig. 3a in the absent of applied electric field there is a symmetry in system around the yz surface. This symmetry is break in presence of F. Also, the minimum of energy levels are according to the maximum of electron density probability position (without impurity) that for $F = 0$ there are two maximum in two left and right dots symmetrically. When impurity position distance from maximum of electron density probability position increases, the energy increases due to the decreasing of Coulomb potential and vice versa. The minimum of energy for right (left) states are in right (left). When F is around the F_{ac}, there are two minimum in energy of some states in right and left because, the impurity position denote the right or left states, when impurity is in right (left) the state is right (left). When $F > F_f$, minimum of all energy is in right.

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