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Impurity-related nonlinear optical rectification in double quantum dot under electric field

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ABSTRACT

The characteristics of donor-impurity-related nonlinear optical rectification in asymmetric double quantum dot under electric field are investigated within the compact density-matrix formalism and the effective mass approximation. The results show that: (i) the binding energy of the ground state varies strongly with the impurity position and it is raised or decreased by the applied field, depending on the impurity position; (ii) the optical rectification spectra are rather sensitive to the impurity position and the electric field intensity; (iii) the changes in the impurity position within the double quantum dot and the electric field value may induce red or blue shift of the resonant peaks of the nonlinear optical rectification.

1. Introduction

The low-dimensional quantum systems such as quantum wells (QWLs), quantum wires (QWRs) and quantum dots (QDs) are renowned for displaying enhanced nonlinear optical effects (NLO) than the bulk materials and possess widespread application in various optoelectronic devices. The NLO are due to the extremely large confinement of these systems that leads to small energy separation between the subband levels and large values of electric dipole matrix elements that promote occurrence of resonance conditions. Among the nonlinear optical properties, the second-order nonlinear optical properties such as nonlinear optical rectification (NOR) and second harmonic generation (SHG) play an essential role because they are the simplest and the lowest-order nonlinear effects and their magnitude is usually stronger than those of high-order ones, if the quantum system demonstrates significant asymmetry [1–15].

Impurity plays crucial role in semiconductor devices as it modulates the electronic properties of quantum nanostructures [3,5,9,16–19]. Shallow impurity augments the conductivity of semiconductors by several orders of magnitude. The presence of impurities strongly alters the energy spectrum and optical properties of QD system by virtue of extensive interplay between QD confinement potential and impurity effects. It allows obtaining adjustable optical transitions, an essential ingredient to fabricate optoelectronic devices with tunable emission and ultranarrow spectral linewidths.

The external electric field distorts asymmetrically the confining potential thus modifying the electronic structure and providing a feasible way of tailoring the energy spectrum to attain desirable optical transitions [3,5,8,11,12,15]. Controllable asymmetry of confinement potential turns out to be conducive for generation of NLO properties which usually vanish in a symmetric quantum structure. Thereby, the interplay between impurity and the applied electric field modulates the optical properties of low-dimensional quantum structures and turns out to be useful in view of fundamental physics and device applications like high-speed electro-optical modulators, far IR photodetectors, left-handed materials, semiconductor optical amplifiers etc.

In this work we investigate the effects of a donor impurity on the electronic properties and nonlinear optical rectification in GaAs double quantum dot under electric field. This kind of confining potential has been the subject of some experimental [20–22] and theoretical studies [23–29]. In our previous papers we studied the modulation of the optical properties of these structures by an intense laser field (ILF) [27] or by the combined effects of ILF and a static electric field [28]. In the present work we consider, like Paspalakis et al. [29], a quasi-one-dimensional double quantum dot where the lateral confinement is much stronger than the longitudinal one, so that the assumption that all excitations occur only in the longitudinal direction is justified. Therefore, the system

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is modeled by a quasi one-dimensional Hamiltonian. To calculate the nonlinear optical rectification we use the formulae derived by Paspalakis et al. [29] in the rotating wave approximation and the density matrix formalisms under steady state conditions. To our knowledge, NOR for a quantum double dot system in the presence of 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 describe the theoretical framework. The numerical results and the discussion of the electronic properties and the nonlinear optical rectification spectra are presented in Section 3. A brief summary is given in Section 4.

2. Theory

We assume a hydrogenic donor located at $\vec{r}_{imp} = (x_{imp}, 0, 0)$ in a double quantum dot system under an electric field with magnitude F and directed along the x-direction. In the effective mass approximation, the Schrödinger equation for the confined electron moving along the x axis ($y = z = 0$) is given by:

$$\left(-\frac{\hbar^2}{2m^*}\frac{\partial^2}{\partial x^2} + V(x) \pm eFx - \frac{e^2}{4\pi\varepsilon_0\varepsilon_r\sqrt{(x - x_{imp})^2 + d_{cuttoff}^2}}\right)\Psi(x) = E\Psi(x). \tag{1}$$

Such a one-dimensional treatment of the electrostatic interaction in a quantum dot was already used [6,31,32] for an exciton in semiparabolic QDs or for two electrons interaction in a QD [33]. Similar to the cited papers, in the present work we consider that the one-dimensional double quantum dot is strongly confined in the y and z directions and is confined by the potential $V(x)$ in the x direction. Our 1D quantum dot is actually a small part of a quantum wire separated by two-wall potentials.

In Eq. (1), m^* is the effective mass of the electron, e is the absolute value of the electron charge, ε_0 is the vacuum dielectric permittivity, ε_r is the relative dielectric permittivity of the dot material, x is the electron position. Because the Coulomb potential is singular at the origin we introduce a cut off distance to regularize it. Following Baskoutas et al. [30], we take for $d_{cuttoff}$ a fixed value below which the mean value of the Coulomb potential does not change.

The confinement potential of the double dot structure is:

$$V(x) = \frac{1}{2}m * \frac{\omega_0^2}{D^{2+\delta}}\left|x - \frac{D}{2}\right|^{2+\delta}\left(x + \frac{D}{2}\right)^2. \tag{2}$$

An analogous potential was first proposed by Selstø and Førre [23]. In Eq. (2), ω_0 defines the strength of the potential barrier between the wells and D is the inter-dot distance. The asymmetry of the quantum dot system is described by the parameter δ. The parameters of the quantum dot system (D, ω_0, and δ) are chosen such that the tunneling between the ground states of each dot can be neglected.

Generally, the binding energy is defined as

$$E_B = E_0 - E_C \tag{3}$$

where E_C and E_0 are ground-state energies of equation (1) with and without the Coulomb term, respectively.

For a transition between two levels $E_i = \hbar\omega_i$ and $E_j = \hbar\omega_j$, the NOR calculated within the compact density-matrix formalism under steady state conditions and in the extended rotating wave approximation in coherent laser–matter interaction of asymmetric quantum structures can be written as [29]:

$$\chi_0^{ij}(\omega) = \frac{2N|\mu_{jj} - \mu_{ii}|\mu_{ij}^2 T_1 T_2}{\varepsilon_0\hbar^2}\frac{\left(J_0\left(\frac{|\mu_{jj}-\mu_{ii}|E_0}{\hbar\omega}\right) + J_2\left(\frac{|\mu_{jj}-\mu_{ii}|E_0}{\hbar\omega}\right)\right)^2}{1 + T_2^2(\omega - \omega_{ji})^2 + \bar{\mu}_{ij}^2 E_0^2 T_1 T_2/\hbar^2}, \tag{4}$$

where $\omega_{ji} = \omega_j - \omega_i$ and

$$\bar{\mu}_{ij} = \mu_{ij}\left(J_0\left(\frac{|\mu_{jj} - \mu_{ii}|E_0}{\hbar\omega}\right) + J_2\left(\frac{|\mu_{jj} - \mu_{ii}|E_0}{\hbar\omega}\right)\right). \tag{5}$$

In Eq. (4) 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 $I_0 = \frac{\varepsilon_0 c n_r E_0^2}{2}$, where n_r is the refractive index and c the vacuum speed of light. μ_{ij} are the dipole moment matrix elements calculated for a x-polarization of the incident light, $\mu_{ij} = e\langle\Psi_i|x|\Psi_j\rangle$.

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 asymmetric double dot under applied electric field. The parameters used in our calculations are: $m^* = 0.067m_0$ (where m_0 is the mass of a free electron), $N = 3 \times 10^{22}$ m^{-3}, the refractive index of the semiconductor $n_r = 3.55$, $T_1 = 10$ ps and $T_2 = 5$ ps [29], $\delta = 0.1$, $\hbar\omega_0 = 0.20$ eV and $D = 16$ nm.

We used a discrete variable representation (DVR) technique [34–36] to solve the Schrödinger equation Eq. (1). We tested that our method gives correctly the first ten levels of the hydrogen if the one-dimensional Coulomb potential is attached to a very large square or parabolic well. According to Baskoutas et al. [30], in the electron-ionized-donor-impurity electrostatic interaction we introduce $d_{cuttoff} = R\sqrt{10^{-5}}$ where R is taken as the distance from the origin at which the wavefunctions of the system are zero. For the present QD system in the absence of the impurity $R = 16$ nm.

3.1. Electronic properties

In Fig. 1 we present the confining potential $V(x)$ for some values of the asymmetry parameter δ and of the inter-dot distance D. For $\delta = 0$ the potential is completely symmetric. When δ increases the central potential barrier moves to the left and is weakened as can be seen in Fig. 1a. Thus the left well becomes narrower while the right well is larger. The value of the central barrier is greatly influenced also by the inter-dot distance D: it augments rapidly with increasing D value (see Fig. 1b). For the parameters chosen here the potential is slightly asymmetric and the central barrier height equals 265 meV.

The main characteristics of the electron states in the presence of the impurity have to be presented in order to understand the properties of the nonlinear optical rectification studied in this work. For this reason in Fig. 2 we present the density of probability for the ground state and the lowest excited electron-impurity states in the considered system. The results are for an electric field positive oriented. We performed calculations also for a negative oriented field but, as the differences were negligible due to the slight asymmetry of the confining potential, we do not present those results here.

By observing the graphics of Fig. 2 one may notice several features. The electron density of the ground state (Fig. 2a) has always a sharp maximum placed at the impurity position in the field absence. If the impurity is placed on the right well, raising the