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Spin–orbit effects on the nonlinear optical properties of a quantum dot in simultaneous electric and magnetic fields

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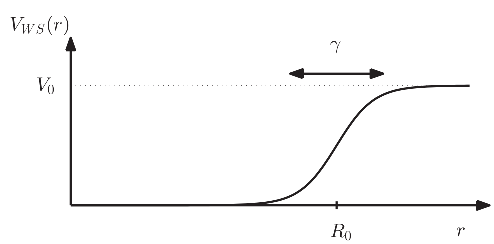
HIGHLIGHTS

- The nonlinear optical coefficients of a quantum dot are studied using a Woods–Saxon potential.
- The Rashba spin–orbit effects on the nonlinear optical properties are investigated.
- The competing effects of spin–orbit, dot size, electric and magnetic fields are given in detail.

GRAPHICAL ABSTRACT



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ABSTRACT

We report on the nonlinear optical properties of a quantum dot including the Rashba spin–orbit interaction (RSOI) with external electric and magnetic fields. The effect of dot size is considered. We do not make any assumptions about the strength of the confinement. We use the numerical diagonalization of the Hamiltonian to determine the electronic structure. The confining potential is taken to be of the Woods–Saxon type. We find the effect of RSOI on nonlinear optical coefficients.

1. Introduction

Increasing perfection in growth techniques allows one to design and investigate high performance, low-dimensional semiconductor structures. This enables one to design and investigate quantum dots (QD) with varying sizes, shapes and the number of electrons. The resulting physics is rich and challenging [1–3].

In recent years, the field of spin physics with the possibility of controlling and manipulating electron spins for low-dimensional semiconducting device applications have received great attention [4–11]. The theoretically interesting spin effect is the study of the spin–orbit interaction (SOI) in low-dimensional structures [12–17]. There are two widely used models for the SOI arising from different physical effects and having different Hamiltonian forms. One is the Dresselhaus [18] spin–orbit interaction (DSOI) caused by bulk inversion asymmetry and the other is the Rashba spin–orbit interaction (RSOI) [19] which arises from the asymmetry of the potential in reduced dimensional structures.

There are a very limited number of investigations of spin–orbit effects on the nonlinear optical properties of quantum dots [20–24]. Hassanabadi et al. have investigated the optical absorption and refractive index changes in a three-electron quantum dot in the presence of the RSOI [20]. They found that a decrease of the quantum dot radius blue shifts and amplifies the refractive index changes. Jha et al. have studied the RSOI effect on the nonlinear optical properties of parabolically confined quantum dot

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in a magnetic field [21]. It is found that the magnetic field red shifts the refractive index changes, whereas the RSOI and confinement blue shift these peaks. Vaseghi et al. have studied the influence of DSOI, electric field and dot size on the refractive index changes [22] and the optical rectification (OR) [23] in a cubic quantum dot. It is found that OR and refractive index changes decrease and occur at lower values of the incident photon energy with SOI. Vaseghi et al. have also studied the effect of RSOI and quantum confinement on the refractive index changes of a spherical quantum dot [24]. They found that the refractive index changes remain constant for different values of RSOI strength. It is also found that the spectrum moves toward higher photon energies as RSOI strength increases.

In the present paper, we have focused on the nonlinear optical properties of a QD by including RSOI with electric and magnetic fields. We make no assumptions on the strength of confinement. Thus, we do not use any perturbational approach. We diagonalize the full Hamiltonian matrix to get the energy spectrum and use the density matrix approach for nonlinear optical coefficients. To the best of our knowledge, the second and the third harmonic generation in this context are not investigated before. We present the theoretical framework in Section 2. The results and discussion are presented in Section 3. A brief summary of our main findings and conclusion are given in Section 4.

2. Theoretical framework

The Hamiltonian of an electron in a two-dimensional QD which is modeled by a Woods–Saxon (WS) potential and subjected to external electric and magnetic fields with RSOI is given by

$$H=\frac{1}{2m^*}(\boldsymbol{p}+e\boldsymbol{A})^2+\frac{\alpha}{\hbar}\boldsymbol{\sigma}\times(\boldsymbol{p}+e\boldsymbol{A})+V_{WS}(r)+eFr\cos\varphi+\frac{g^*e\boldsymbol{B}\hbar}{2m^*}\boldsymbol{\sigma}_z \quad (1)$$

where m^* is the effective mass of the electron, $\boldsymbol{p}$ is the electron momentum operator, e is the electronic charge, $\boldsymbol{\sigma}$ is the Pauli spin-matrix and $\boldsymbol{A}$ is the vector potential. The electric field $\boldsymbol{F}$ is chosen parallel to the x-direction and the magnetic field $\boldsymbol{B}$ is taken to be perpendicular to the xy-plane.

The second term in the Hamiltonian is the RSOI and the α parameter is the strength of the spin–orbit coupling, which is proportional to the symmetry breaking electric field in this structure. We use the symmetric gauge in which the vector potential $\boldsymbol{A}$ has the form $(B/2)(-y,x,0)$. The confining potential is taken to be of the WS form

$$V_{WS}(r)=\frac{V_0}{1+\exp[(R_0-r)/\gamma]}, \quad (2)$$

where R_0 and V_0 define the dot radius and potential depth respectively and γ controls the barrier slope [25]. The last term in the Hamiltonian is the Zeeman splitting due to the magnetic field and g^* is the effective Landé g-factor.

The wave function is written as a superposition of a number of eigenstates of a two-dimensional isotropic harmonic oscillator. The matrix representation of the Hamiltonian is computed in this basis and diagonalized numerically. For brevity, we do not provide the reader with a full set of equations but refer the reader to our recent paper that used the same numerical technique [26].

3. Results and discussion

The parameters used in this calculation are $m^*=0.067m_0$ and $g^*=-0.44$. Like our earlier work [26], the geometrical parameters are set as $V_0=310$ meV, $\alpha=15$ meV–nm [27], $\gamma=30$ Å. We present our results for a narrow ($R_0=100$ and 200 Å) and a wider dot ($R_0=500$ Å).

The optical rectification coefficient $\chi_0^{(2)}$ is presented as a function of the incident photon energies in Fig. 1(a) and (b), for different SOI, magnetic field values and dot sizes. Fig. 1(a) shows clearly that in a dot with radius $R_0=200$ Å the magnetic field and the SOI reduce the peak values of OR coefficient, and this is accompanied with a blue shift. Fig. 1(b) shows that the dot radius increases the OR peak values and there is also a blue shift. The blue shift in both cases is a result of the magnetic field which acts as an additional confining agent. The peak values depend on the dipole matrix elements which give the observed behaviour.

Fig. 2(a) shows $\chi_{2\omega}^{(2)}$ as a function of incoming photon energies. The effect of the magnetic field is similar to the case of OR coefficient because of a similar dependence on the dipole matrix elements. The effect of SOI is quite weak in this case. This may be a result of the dominance of the kinetic energy term for smaller dots. Fig. 2(b) is for a larger dot of radius $R_0=500$ Å. Here, the spin–orbit term is a bit more effective as the effect of the kinetic energy decreases.

The third harmonic generation (THG) susceptibility $\chi_{3\omega}^{(3)}$ is shown in Fig. 3(a) and (b) as a function of the incident photon energies for different dot sizes. The effect of the confinement and

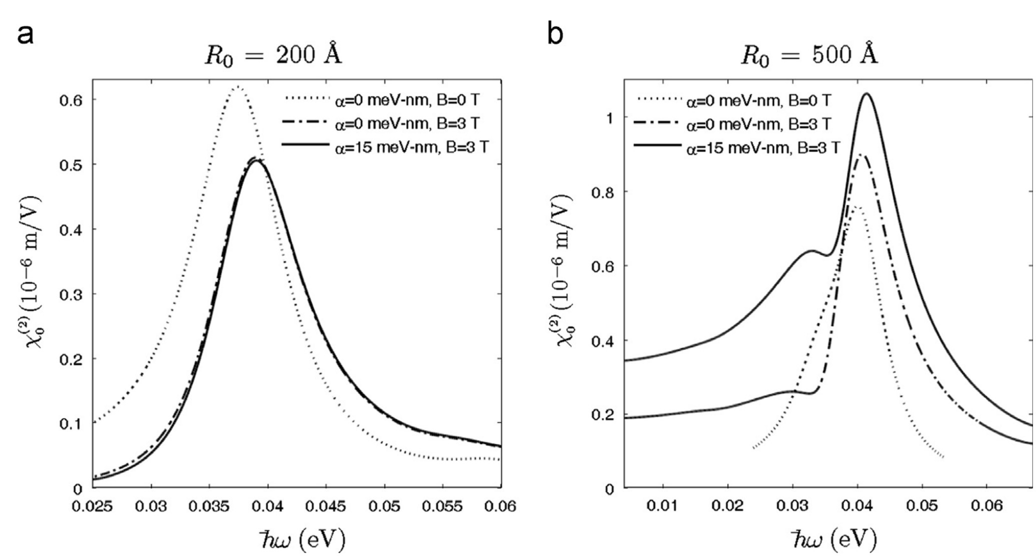

Fig. 1. The resonant $\chi_0^{(2)}$ values in an external electric field of $F=60$ kV/cm for different magnetic fields, α and dot sizes.