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Influence of applied electric fields on the electron-related second and third-order nonlinear optical responses in two dimensional elliptic quantum dots

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ABSTRACT

The coefficients of the second-order nonlinear optical rectification and the generation of second and third harmonics, related to electron energy transitions in a two-dimensional elliptical quantum dot are calculated. The conduction band states are obtained using the finite element method to numerically solve the effective mass Schrödinger differential equation in the parabolic approximation, including the influence of an externally applied static electric field. It comes about that the geometry of the ellipse has a strong influence on the optical response, being the large eccentricity case the more favorable one. Furthermore, it is shown that the application of an electric field is of most importance for achieving well-resolved higher harmonics signals.

1. Introduction

Investigation on the properties of two-dimensional quantum dot (2DQD) nanostructures has attracted some recent interest (for example, see Refs. [1–4]). Those studies have dealt with different

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geometries of the carrier-confining regions. Within that number of works, the one by Rezaei et al. [1] particularly considers the situation of elliptically-shaped 2DQD.

The calculation of confined states in 2D flat elliptic QDs and elliptic quantum wires was performed by van den Broek and Peeters [5]. Tokura et al. [6] calculated the electron states in elliptical QD with three and four electrons. Besides, Ezaki et al. [7,8] investigated the electron structure of few-electron systems in elliptic quantum dots. Zhang et al. [9] considered systems containing coupled elliptical quantum dots and found that the exchange energy between electrons depends on the aspect ratio of interacting dots. Besides, Rezaei et al. [1] studied the nonlinear optical absorption and the refraction index and found that these magnitudes have a strong dependence on ellipticity of the QD.

On the other hand, the analytical solutions of the effective mass equations that describe the confined states in elliptic QD systems are restricted to certain potential energy configurations. Consequently, under circumstances like the presence of externally applied electric fields the option of using straightforward numerical calculations is pretty much suitable. Numerical procedures like finite difference and finite element techniques for solving the differential equations of motion have seen application in recent years [3,10–13].

The calculation of nonlinear optical effects in quantum nanostructures have also been the subject of much research. In particular the second- and third-order responses, in the form of the coefficients of nonlinear optical rectification (NOR) and of second and third harmonics generation (SHG and THG). This is mostly motivated by the appearance of relatively large values of the oscillator strength – with correspondingly high values for the related electric dipole moment off-diagonal matrix elements, together with small relaxation times, associated with energy transitions between the confined states in those systems [14,15]. As a consequence, the nonlinear optical properties would manifest in a more significant way. It s possible to refer, for instance, to the experimental observation of large NOR response in asymmetric quantum wells [16]. Experiments on the SHG, THG, and four wave mixing are also among the reports put forward [17–20], whereas many theoretical studies regarding the NOR, THG and other optical nonlinearities in semiconductor heterostructures have appeared throughout the years [21–29,31,30,32,33,1]. In these works it has been put on relevance the close relation between geometrical asymmetries – reflected in the allowed state wavefunctions – and the nonlinear optical responses. Such asymmetries may appear due to a non-symmetrical design of the system's geometry, the application of electric fields, the variation of the stoichiometry of the well and barrier materials, the insertion of defects, etcetera.

Provided that the analysis of the elliptical shape may lead to a better understanding of the energy states and optical properties of microstructures bearing non-circular geometries (such as, e.g. semiconductor nanoflakes [34]), in this work, we address the problem of investigating the properties of the NOR, SHG and THG coefficients in elliptic 2DQDs under the effects of applied static electric fields. These responses are related with electron transitions between quantized conduction band states. In order to obtain the electronic spectrum the effective mass equation – in the parabolic approximation – is numerically solved with the use of the finite element method (FEM). In Section 2, the theoretical framework is presented, the results are discussed in Section 3 and, finally the conclusions will be presented in Section 4.

2. Theoretical framework

We shall consider an isolated GaAs semiconducting nanosystem (typical length between 1 and 100 nm) whose thickness is small enough to model it as a 2D structure. This can be a realistic description when dealing – for instance – with elliptically shaped independent nanoparticles. If the dots plane is taken as the xy one, the conduction band effective mass Schrödinger equation in the envelope function and effective mass approximations can be written as:

$$\left\{-\frac{\hbar^2}{2m^*}\nabla^2_{xy} + V(x,y) + e\vec{F}\cdot\vec{r}\right\}\Psi(x,y) = E\,\Psi(x,y) \quad (1)$$

where m^* is the electron effective mass, $V(x,y)$ is the confinement potential which is schematically shown in Fig. 1.