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Electric field and shape effect on the linear and nonlinear optical properties of multi-shell ellipsoidal quantum dots

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ABSTRACT

In the present work, the optical properties of GaAs/$Al_xGa_{1-x}As$/GaAs multi-shell ellipsoidal quantum dot heterostructures with a shallow hydrogenic impurity in the presence of an external electric field have been studied. The results show how the linear and nonlinear optical absorption coefficients and refraction index changes are changed by the variations of the size and shape of the multi-shell structure. Moreover, how the optical properties of this structure are affected by the electric field has also been shown. The physical reasons for the results have been discussed in detail.

1. Introduction

Linear and nonlinear optical absorption coefficients (ACs) and refractive index changes (RICs) are an important source of information about the optical properties of luminescent device, and therefore it has the potential for device research [1–3]. Furthermore, there is no doubt that the zero-dimensional quantum dots (QDs) with well-controlled shape and size have became one of the hottest topics in the area of the condensed matter and materials physics due to their distinctive electronic and optical properties, which shows a potential application in the electronic and optoelectronic devices. Therefore, the optical properties of QDs have attracted the considerable attention in the experimental and theoretical studies in recent years [4–7].

Development in growth technology has resulted in manufacturing of multi-shell quantum dot (MSQDs) structures, and it has attracted more attention than single-layered QDs because of some advantageous properties, such as lower Auger recombination coefficients, higher absorption cross-sections, wider range of absorption and emission spectra, and better photoluminescence properties [8,9], therefore MSODs show better optical performance. In particular, it has a considerable potential application in QD solar cell applications due to its advantageous properties mentioned above [10–12]. Because the shape of QDs lead to the formation of discrete energy levels, the optical properties of semiconductor QDs depend on the shape of QDs. In the theoretical works, it is customary to assume a spherical shape for the MSQDs, and many studies were focused on the optical properties of such structure [4,5]. But from physical point of view the consideration of ellipsoidal shape is actual due to unavoidable small deviations from spherical shape because of deformations during QD growth. Generally speaking, if the MSQD is weakly prolate (oblate), the problem can be solved within the frame work of perturbation theory.

In order to modulate the properties of devices, the effect of electric field on the electronic states in QDs has been studied extensively by many authors in the past few years [13–15]. As we known, the electric field induces both a polarization of the carrier distribution and an energy shift of the quantum state to introduce a considerable change in the energy spectra of

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carriers, and this property is very useful for optoelectronic devices. Because applied electric field has an important influence on the carrier energy and carrier distribution, the optical properties of QDs also depend on the electric field. There are many works about the optical properties of QDs under the influence of electric field [16–18], but for multi-shell ellipsoidal quantum dot (MSEQD) structures it appears insufficient. Actually, the MSEQD is more sensitive to the electric field due to their multi-shell structures, and it is expected that the effect of electric field on the optical properties of MSEQDs will be more pronounced.

In the present paper, the optical properties of GaAs/$Al_xGa_{1-x}As$/GaAs MSEQD heterostructures in the presence of an external electric field have been studied by using a variational approach. As is well known, the existence of impurity which is more close to the actual situation has a strong influence on the electric and optical properties of QDs via changing the quantized energy spectrum and probability density of the charge carriers. Therefore we also consider the effect of an on-center shallow hydrogenic impurity on the optical properties of MSEQDs. In this study, the linear, third-order nonlinear, and total ACs and RICs under the influence of electric field are investigated and discussed. This paper is organized as follows. In Section 2, we present our model and explain the general theory. In Section 3, the numerical results and detailed discussions are given. Finally, the conclusions are presented in Section 4.

2. Theory

2.1. Hamiltonian and wave function

In this study, a GaAs/$Al_xGa_{1-x}As$/GaAs MSEQD structure as seen in Fig. 1 is considered. The core region, barrier region and well region denoted by Ω_1, Ω_2 and Ω_3, respectively. Let us indicate with a and c its semi-axis in the x-y plane and along the z axis, respectively. The equation of the QD surface is

$$\frac{X^2+Y^2}{a^2}+\frac{Z^2}{c^2}=1. \tag{1}$$

In the effective mass approximation, the Hamiltonian of an electron bound to an on-center shallow hydrogenic impurity in the presence of an external electric field along the z-direction is

$$H_0=-\frac{\hbar^2}{2m}\nabla^2+U(r)+V(r)+|e|Fr\cos\theta, \tag{2}$$

with

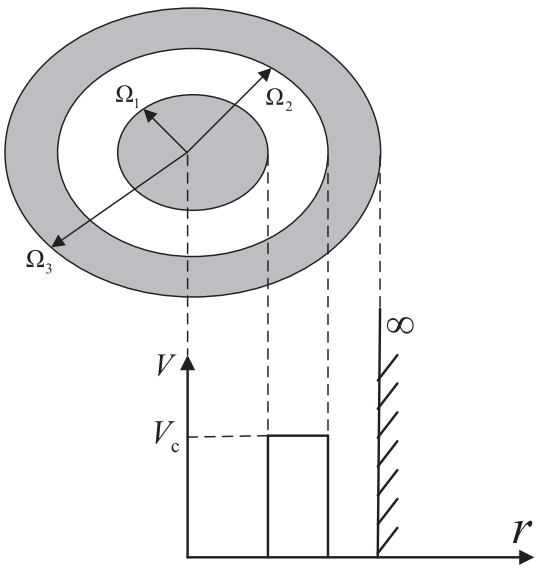

Fig. 1. Schematic diagrams of the MSEQD heterostructure and corresponding confinement potentials.