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Effect of position-dependent effective mass on nonlinear optical properties in a quantum well

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ABSTRACT

In this study, the effect of position-dependent effective mass (PDM) on the nonlinear optical properties in a GaAs/AlAs semiconductor quantum well (QW) are intensively studied. Calculations are performed using both the position-dependent effective mass and a constant effective mass within the framework of the compact-density-matrix approach, iterative method, and coordinate transformation method. We have calculated the third-harmonic generation (THG) coefficients, the optical absorption (OA) coefficients and the refractive index changes (RIC) as a function of the incident photon frequency and obtained the energy eigenvalues and eigenfunctions of the system through solving the Schrödinger equation. The results show that spatially varying electron effective mass has a significant impact on the nonlinear optical properties in a quantum well.

1. Introduction

In the past few years, much attentions have been paid to the exact solutions of the Schrödinger equation with position-dependent effective mass [1–3], and many methods aiming at this kind of problem have been proposed such as super symmetric quantum mechanics [4], potential algebras [5], shape invariance [6], path integration [7] and point canonical transformation (PCT) [8]. Among these methods the PCT is a very effective approach to turn mass-dependent Schrödinger equation to the standard Schrödinger equation with constant mass and the effective potentials. The motivation for these studies stems from a wide range of applications for the nonlinear optical properties of low-dimensional semiconductor structures, such as quantum dots, quantum wells, quantum wires and superlattices [9–14]. On account of the enhanced confinement in low-dimensional semiconductor structures, lots of novel nonlinear optical properties appear in these low-dimensional semiconductor structures. These properties are conducive to fabricate new optical devices.

In recent decades, with the rapid progress in semiconductor growth techniques, such as molecular beam epitaxy and metal-organic chemical vapor deposition, which make it possible to fabricate a great deal of low-dimensional semiconductor quantum systems. A number of theoretical and experimental works have been presented in studying nonlinear optical properties for the low dimensional semiconductor nanostructure [15]. For instance, M.J. Karimi investigated the effects of geometrical size, hydrogenic impurity, hydrostatic pressure and temperature on linear and nonlinear optical properties in multilayered spherical quantum dots [16]. Zhang and Guo surveyed the effect of hydrostatic pressure, temperature and magnetic field on the nonlinear optical properties in asymmetrical Gaussian potential quantum wells [17]. These studies show that the external perturbation such as quantum size, magnetic field effect, temperature and hydrostatic pressure

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play important roles in studying the optical properties of semiconductor structures. It is worth mentioning that quantum mechanical systems with a spatially varying effective mass has been the subject of much activity in recent years, for the reason that this system has a strong influence on the optical properties of low dimensional semiconductor nanostructure. Peter and Navaneethakrishnan investigated the ionization energies of a shallow donor in a quantum dot employing a constant effective mass and position-dependent effective mass [18]. Rajashabala and Navaneethakrishnan studied the donor binding energies in quantum well systems within the framework position-dependent effective mass [19].

In this paper, we intend to study the influence of position-dependent effective mass on the THG coefficients, OA coefficients and RIC in a QW. The outline of this paper is as follows. In Section 2, the exact solutions of the system are presented by introducing an electron effective mass model and the analytical expressions of the THG coefficients, OA coefficients and RIC are acquired. In Section 3, the numerical results and discussions are exhibited. In Section 4, a brief conclusion is expressed.

2. Theory

2.1. Energy eigenvalues and eigenfunctions

According to the effective mass approximation, the Hamiltonian of a single electron in a quantum well can be expressed as

$$H = -\frac{\hbar^2}{2m^*}\nabla^2 + V(z). \tag{1}$$

When the compositional variation in a quantum well is a function of location, the kinetic energy and the potential energy function are closely related to position. Under the circumstances, the position-dependent mass Schrödinger equation can be given by [20],

$$\left\{\frac{\mathrm{d}^2}{\mathrm{d}z^2} - \frac{1}{m(z)}\frac{\mathrm{d}m(z)}{\mathrm{d}z}\frac{\mathrm{d}}{\mathrm{d}z} + \frac{2m(z)}{\hbar^2}[E - V(z)]\right\}\psi(z) = 0, \tag{2}$$

in this paper, we adopt the following smooth and suitable effective mass distribution,

$$m(z) = m^* e^{\lambda z}. \tag{3}$$

In above equations, $\hbar$ denotes Planck constant, m^* expresses the effective mass of electron, z represents the growth direction of the quantum well, $V(z)$ is the confining potential, $|\lambda| \propto \frac{1}{L}$ and L means the quantum-well width, respectively. In Fig. 1, we can find that the position-dependent mass is exponentially increasing with respect to the variable z, and the effective mass of electron grows slowly, i.e., becomes steady and uniform when L increases.

Defining $\bar{z} = \frac{2}{\lambda}e^{\frac{\lambda z}{2}}$, $\psi(z) = e^{\frac{\lambda z}{4}}\phi(\bar{z})$, Eq. (2) can be reduced to the form,

$$-\frac{\hbar^2}{2m^*}\frac{\mathrm{d}^2\phi(\bar{z})}{\mathrm{d}\bar{z}^2} + \left[\frac{3\hbar^2}{8m^*\bar{z}^2} + V(\bar{z})\right]\phi(\bar{z}) = E\phi(\bar{z}). \tag{4}$$

When $V(z) = \frac{4B}{\lambda^2}e^{\lambda z} - \frac{3\hbar^2\lambda^2}{32m^*e^{\lambda z}}$ or $V(\bar{z}) = B\bar{z}^2 - \frac{3\hbar^2}{8m^*\bar{z}^2}$, the above equation can be expressed as

$$\left[-\frac{\hbar^2}{2m^*}\frac{\mathrm{d}^2}{\mathrm{d}\bar{z}^2} + B\bar{z}^2\right]\phi(\bar{z}) = E\phi(\bar{z}), \tag{5}$$

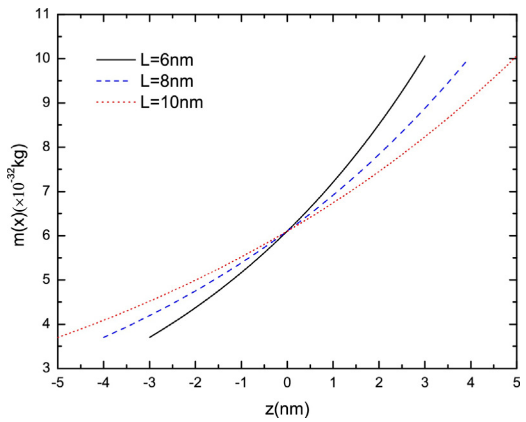

Fig. 1. The mass $m(z)$ as function of z for three different values of L = 6 nm, L = 8 nm, and L = 10 nm.