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Linear and nonlinear intersubband optical properties in a triangular quantum ring

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ABSTRACT

Using the effective mass approximation, within the plane wave expansion, the linear and nonlinear coefficients absorption and the refractive index changes relative to the intersubband transitions in the conduction band of an $Al_xGa_{1-x}As$/ $GaAs/Al_xGa_{1-x}As$ triangular quantum ring for an *x*-polarization and an *y*-polarization of the incident light are calculated. It is found that the transition energy between the ground state and the first two excited states and their related optical matrix are strongly influenced by the length of the side of the inner triangle, leading to a red-shift and blue-shift of the resonant peaks of the intersubband optical absorption, for an *x*-polarized light absorption and an *y*-polarized light absorption respectively. Our results are qualitatively similar to those of a triangular quantum wire in the presence of an intense laser field in recent literature.

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1. Introduction

Over the past two decades, the electronic and the optical properties of low dimensional semiconductor structure have attracted considerable interest of the researchers. Among these properties, the linear and nonlinear optical properties have been extensively studied for various quantum dots shape such as sphere [1–9], cylinder [10–14] and box [15–17]. Quantum wires (QWR) with various cross sectional shapes such as elliptic [18,19], circular [20,14], and Vgroove [21,22], have been also widely studied. Recently particular attention has been devoted to the triangular quantum wire (TQWR), for example the electron–phonon interaction in both triangular and parallelogram quantum wires and its effect on the diamagnetic susceptibility was studied by Khordad et al. [23]. Tiutiunnyk et al. showed that the increase of the amplitude of the nonlinear optical absorption resonant peak can be obtained by increasing the size of the TQWR [24]. Khordad et al. calculated the second- and third-harmonic generation (THG) in a GaAs quantum wires with triangular cross-section, they found that a maximum THG is obtained by optimizing the confinement potential [25]. A. Bahramian et al. showed that the electron phonon interaction in a TQWR increases the refractive index change and the absorption coefficients, and their corresponding resonant peaks shift towards higher energy [26]. Barseghyan et al., reported a detailed calculation of the effect of an intense laser field on the linear and nonlinear optical properties of TQWR, they found that the laser field allows an efficient red-shift tuning of the *x*-polarized light absorption at high values of the laser parameter and a blue-shift tuning of the *y*-polarized light absorption for lower values of the laser intensity [27]. Radu et al. studied the effects of the laser dressing field on the intersubband third harmonic generation and quadratic electro-optical process in equilateral TQWR [28]. Niculescu et al. reported a study of the magnetic field effect on the THG in triangular cross section QWR [29]. Martínez-Orozco et al. showed that an efficient tuning of optical coefficients in coupled triangular quantum wires can be achieved by the variation of the inter dot distance and the electric field [30].Very recently, Tiutiunnyk et al. investigated the optical properties in three coupled quantum wells wires with triangular transversal section, they found that both the absorption coefficient and the refractive index changes are redshifted and their magnitudes decrease as the coupling of the system decreases [31].

There are several theoretical works dealing with the calculation of the electronic structure of TQWR, using effective mass approximation. For the finite well potential case, many techniques were used, such as the finite difference method [32], finite element method [27], and the first-principles tight binding method [33]. Another technique in which the eigenfunctions of the rectangular QWR with infinite barrier high potential were used as basis functions has proved to be efficient in the calculation of the electronic properties of triangular quantum wires [24,26,30,31], finally for the case of the infinite well potential, a set of basis as a product of sine like functions were adapted in a manner so that

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the wave functions vanishes at the border of the TQWR [23,25].

Very recently, the electron localization and the optical absorption of triangular (TQR), square and hexagonal quantum rings were theoretically studied [34], on the other hand core shell quantum ring structures with triangular cross section was successfully synthesized [35,36]. According to our knowledge, the linear and nonlinear optical properties in the triangular quantum ring have not been studied until now. For this purpose, we investigate the effect of the well width of an $Al_xGa_{1-x}As$ /GaAs/$Al_xGa_{1-x}As$ triangular quantum ring on the linear and nonlinear optical properties associated with intersubband transitions of electrons in the conduction band. We use the plane wave expansion method including differences between the effective mass in the wells and the barriers regions.

The organization of the paper is as follows: in Section 2 we present the formulation of the plane wave expansion for the triangular quantum ring. Section 3 contains our numerical results and discussions. Our conclusions are presented in Section 4.

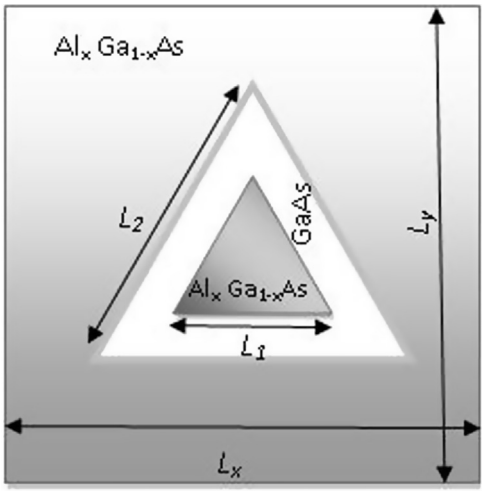

Fig. 1. Schematic diagram of the triangular quantum ring.

2. Theory

We consider a triangular quantum ring resulting from a concentric equilateral triangular quantum wires ($Al_xGa_{1-x}As$/GaAs) surrounded by a two dimensional hard-wall potential of $Al_xGa_{1-x}As$ energy gap materials, L_x, and L_y are the dimensions of the unit cell size see Fig. 1.

We use the effective-mass approximation by expanding the wave function in a plane wave basis [37,38], the origin of coordinates was taken at the centre of the QWR. The Schrödinger equation can be written as:

$$\left[-\frac{\hbar^2}{2}\left(\frac{\partial}{\partial x}\frac{1}{m_e^*(x,y)}\frac{\partial}{\partial x}+\frac{\partial}{\partial y}\frac{1}{m_e^*(x,y)}\frac{\partial}{\partial y}\right)+V(x,y)\right]\Psi_n(x,y)=E_n\Psi_n(x,y) \tag{1}$$

Where $m_e^*(x,y)=\begin{cases}\text{in side the well of the quantum ring}\\ m_b^* \text{ outside the quantum ring}\end{cases}$

And $V(x,y)=\begin{cases}0 \text{ in side the well of the quantum ring}\\ V_0 \text{ outside the quantum ring}\end{cases}$

The wave functions are expanded in a plane wave basis:

$$\Psi(x,y)=\frac{1}{\sqrt{L_xL_y}}\sum C_{n_xn_y}\, exp\ i(n_xk_xx+n_yk_yy) \tag{2}$$

With $k_x=\frac{2\pi}{L_x}$ $k_y=\frac{2\pi}{L_y}$

Substituting Eq. (2) into (1), then we obtains the following secular matrix equation

$$\left[\frac{\hbar^2}{2}\left[\frac{1}{m_b^*}\delta_{n_xn_x'}\delta_{n_yn_y'}+\left(\frac{1}{m_w^*}-\frac{1}{m_b^*}\right)\left(Cf_{out}-Cf_{in}\right)\left(n_xk_xn_x'k_x+n_yk_yn_y'k_y\right)\right]+V_0\right.$$
$$\left.\delta_{n_xn_x'}\delta_{n_yn_y'}+V_0\left(Cf_{out}-Cf_{in}\right)-E\delta_{n_xn_x'}\delta_{n_yn_y'}\right]C_{n_xn_y}=0 \tag{3}$$

With, Cf_{in} and Cf_{out} are the two dimensional Fourier coefficients for the inner and the outer triangle shape respectively, $Cf_{in}=f(L=L_1)$, $Cf_{out}=f(L=L_2)$,and the $f(L)$elements can be evaluated analytically:

$$f(L)=\begin{cases}\frac{\sqrt{3}L}{4}\text{if}n_x=n_x'\text{and}n_y=n_y'\\ \frac{2\sqrt{3}}{k_x^2}\left[1-\cos\left(\frac{k_xL}{2}\right)\right]\text{if}n_x\neq n_x'\text{and}n_y=n_y'\\ 4\frac{\sqrt{3}}{k_y^2}\sin\left(\frac{k_yL\sqrt{3}}{4}\right)e^{ik_y\frac{\sqrt{3}L}{4}}\frac{L}{ak_y}\text{if}n_x=n_x'\text{and}n_y\neq n_y'\\ -e^{ik_y\frac{\sqrt{3}L}{4}}\left[\frac{2i}{k_xk_y}\sin\left(\frac{k_yL}{2}\right)+\frac{2i\sin\left(k_x\frac{L}{2}\right)}{\left(k_y-\sqrt{3}k_x\right)k_y}\right]\\ \text{if}n_x\neq n_x'\text{and}n_y\neq n_y'\end{cases} \tag{4}$$

$n_x\in\{-m_x\ldots.m_x\}$, $n_y\in\{-m_y\ldots.m_y\}$, N_x and is the plane wave number, then the total number of plane waves is

$N_{xy}=(2m_x+1).(2m_y+1)$

Shen and Xia [39] established a convergence criterion of the plane wave method, in which they suggested the plane wave number $N_x=15$ for circular quantum wires, and the dimension of the unit cell size satisfies the following relation:

$L_x=L_y\geq L_2+2.5a^*$; $a^*=\frac{\hbar^2\varepsilon_r}{m_w^*e^2}$ (where a^* is the effective Bohr radius of the wells material)

Note the case of $L_1=0$ correspond to a quantum wire with equilateral triangle cross section

Once the energy levels and their corresponding eigenfunctions are obtained, the dipole moment transition matrix element can be easily evaluated in the momentum space, using the Fourier series properties, instead of the hard numerical integration in the real space [40]

$$M_{fi}=\psi_f|e\alpha|\psi_i=\sum_{n_xn_y}\sum_{n_x'n_y'}C_{n_xn_y}^i\,C_{n_xn_y}^f\,W_\alpha \tag{5}$$

where

$$W_\alpha=\begin{cases}0 n_\alpha=n_\alpha'\\ \frac{L_x(-1)^{n_\alpha-n_\alpha'}}{2\pi(n_\alpha-n_\alpha')}n_\alpha\neq n_\alpha'\end{cases}$$

($\alpha=x$ or y for x-polarization or y-polarization respectively)

Derived from the density matrix approach and perturbation expansion method [1,27] the total absorption coefficient is given by

$$\alpha(\omega,I)=\alpha^{(1)}(\omega)+\alpha^{(3)}(\omega,I) \tag{6}$$

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