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Study of electron-related intersubband optical properties in three coupled quantum wells wires with triangular transversal section

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ABSTRACT

This work concerns theoretical study of confined electrons in a low-dimensional structure consisting of three coupled triangular GaAs/$Al_xGa_{1-x}As$ quantum wires. Calculations have been made in the effective mass and parabolic band approximations. In the calculations a diagonalization method to find the eigenfunctions and eigenvalues of the Hamiltonian was used. A comparative analysis of linear and nonlinear optical absorption coefficients and the relative change in the refractive index was made, which is tied to the intersubband electron transitions.

1. Introduction

Fabrication and practical application of mono-crystal semiconductor heterostructures have intensively developed since the middle of the past century [1]. Low-dimensional configurations on the base of heterostructures like quantum wells (QW), quantum dots (QD), quantum well wires (QWW), etc., became a popular basis for the various kinds of optical and electrical devices [2]. Lately especial attention has been given to the problem of well organized low-dimensional objects, which opens new perspectives for the manipulation of electronic and optical properties of matter and thus the possibility of creating devices on the base of new effects [3]. The new technological methods are developed based on standard technologies for producing semiconductor heterostructures like molecular beam epitaxy (MBE) and metalorganic chemical vapor deposition (MOCVD), allowing to control mutual positions and orientation of nano-size objects within heterostructures; for example, vertically stacked InGaAs/GaAs(001) QWW and QD chains were prepared using MBE method [4] and vertical artificial molecular structures formed by two vertically aligned InAs QDs [5].

Investigation of QD arrays has shown the feasibility of their application, as well as single QDs. In such a system it is very important to control the size of the dots themselves, and their spread, or just the distance between them [3]. Technical

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advance in the production of nano-complexes with a given position led to the boost of experimental [6] and theoretical [7] investigation of such kind of objects.

The 3-fold symmetry in the cross-section of nanostructures is the one of the most popular among the technologists from QWWs with triangular cross-section [8,9] to more elaborated and complex pyramidal structures [10]. Theoretical studies of isolated triangular QWWs were reported [11]. Still with the recent technological advances in ordering, position and number control of the heterojunction-based nanoobjects [3,12], the problem of theoretical study of complex quantum-coupled systems of simple nanoobjects becomes more and more actual.

The task of the present work is to investigate the possible ensemble effect on the intersubband optical properties of the quantum coupled system of three triangular QWWs. We calculated the energy levels and wave functions, as well as the linear and nonlinear parts of the intersubband absorption coefficient and the relative changes in the refractive index. The article is organized as follows: in Section 2 we give some key elements of the theoretical model employed. Section 3 is devoted to the presentation and discussion of the obtained results and finally, Section 4 contains the conclusions of the study.

2. Theoretical framework

The concrete configurations for our investigation are dictated by the task of studying complex quantum-coupled systems of simple nanoobjects. The shape of the elementary nanostructure should be popular enough among the technologists, and the triangular cross-section fits it well as we showed in Introduction, especially if we take into account a widespread class of technologies growing self-organized pyramidal quantum dots. Note that with high enough density of such self-organized objects the coupling effects between them may arise statistically even without further improving of the positioning control. On the other hand our configuration should provide as large as possible natural range of coupling/decoupling degree and the system with parallel edges of the elementary objects can start from the ideal coupling (when the neighboring edges coincide) to give a limit. Also the three configurations below are designed in a way to cover the all range of thinkable spatial configurations of three objects as extreme points, namely 2 against 1, 3 in line with a center and equidistant in 2 dimensions. So, the system under study consists of three QWWs of triangular cross-section (equilateral triangles of side L) oriented in parallel to each other in the z-direction with the corresponding cross-section being in the $x-y$ plane, as depicted in Fig. 1.

Three configurations are investigated: the first one consists of two connected QWWs with one more at the distance of h from them as shown in Fig. 1(a); in the second configuration the QWW cross-sections are positioned along the x-axis (Fig. 1(b)); in the third configuration (Fig. 1(c)) the cross sections are separated by h along the x- and y-axis. In the present work the results are obtained for several values of the L and h parameters.

The system is selected in such a way that when $h = 0$ the system reproduces an isolated QWW with trapezoidal cross-section. So one can observe the decoupling dynamics by varying the h parameter. Note also that in the case of the first configuration the lower coupled QWWs exhibit something like a V-shaped QWW, which has technological implementations [9].

Using the cartesian coordinates and the effective mass and parabolic approximations, the Hamiltonian for the confined electron carrier into the heterostructure described above is given by [13,14]

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

where $m^* = 0.0665\,m_0$ is the electron effective mass (where m_0 is the free electron mass), and $V(x,y)$ is the in-plane triangular confining potential, which is zero inside the QWWs regions and $V_0 = 228$ meV elsewhere.

For the solution of the two-dimensional effective mass equation for the confined motion of the carriers (associated with the in-plane movement of the electrons. Note that here the electron is free to move in the z-direction), is proposed a 2D Fourier expansion in the region corresponding to a rectangle of dimensions $L_x \times L_y$ with rigid barriers, i.e., with infinite confinement potential outside the rectangle (see Fig. 1). The complete set of basis functions consists in products of sine-like functions, which are the eigenstates of the corresponding two-dimensional Schrödinger problem with energies,

$$E_{m,n} = \frac{\hbar^2\pi^2}{2m^*}\left(\frac{m^2}{L_x^2} + \frac{n^2}{L_y^2}\right). \tag{2}$$

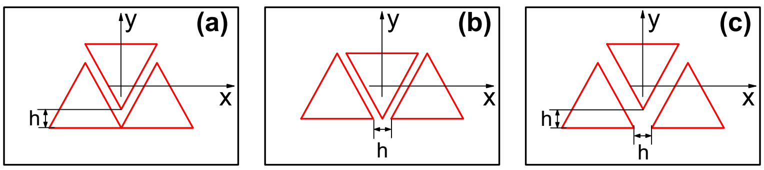

Fig. 1. Schematic representation of three coupled triangular QWWs. Potential inside of triangle is $V = 0$, outside of triangle and inside of rectangle is $V = V_0$. h is the distance parameter. The side of the equilateral triangles is denoted by L. (a) first-, (b) second-, and (c) third-configuration.