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Combined effects of hydrostatic pressure and electric field on the donor binding energy and polarizability in laterally coupled double InAs/GaAs quantum-well wires

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ABSTRACT

This work is concerned with the theoretical study of the combined effects of applied electric field and hydrostatic pressure on the binding energy and impurity polarizability of a donor impurity in laterally coupled double InAs/GaAs quantum-well wires. calculations have been made in the effective mass and parabolic band approximations and using a variational method. The results are reported for different configurations of wire and barriers widths, impurity position, and electric field and hydrostatic pressure strengths. Our results show that for symmetrical structures the binding energy is an even function of the impurity position along the growth direction of the structure. Also, we found that for hydrostatic pressure strength up to 38 kbar, the binding energy increases linearly with hydrostatic pressure, while for larger values of hydrostatic pressure the binding energy has a nonlinear behavior. Finally, we found that the hydrostatic pressure can increase the coupling between the two parallel quantum well wires.

1. Introduction

The field of low dimensional semiconductor heterostructures such us quantum wells (QW), quantum well-wires (QWW), and quantum dots (QD) under the combined effects of hydrostatic pressure and applied electric field has been a topic of great interest in the last decade. Using an applied electric field can cause the lowest energy transitions in a system of coupled QW, QWW, or QD evolves to be associated with spatially direct excitons to spatially indirect excitons or viceversa. Also, hydrostatic pressure can induce resonances between the Γ and X conduction levels and make the photoluminescence peaks of lowest energy are associated with whether direct or indirect excitons in the energy space. These kind of features are an useful tool to determine the parameters of the band structure and to study the electronic and optic properties of the crystal in bulk or semiconductor heterostructures [1–6], and can be used to develop optoelectronic devices.

A calculation of the effective electron barrier potential in quantum-wire superlattices subject to magnetic-field and strain effects was presented by Willatzen and Voon [7] finding that, besides the lateral-confinement contributions to the barrier potential, strong contributions from strain (lattice mismatch) may be present as well. They attributed to the fact that strain values can be several percent in heterostructures while electron deformation potentials are of the order of 10 eV. The detection of quantum confinement in nanowires of InAs-InP with an InAs core with ~25 nm diameter has been reported by Zanolli et al. [8]. They found that under high intensity conditions the emission spectra has two well defined structures (peaks) caused by emission from the ground and excited quantized levels, due to quantum confinement in the plane perpendicular to the nanowire axis. The stress and chemical diffusion effects on electronic behavior in self-assembled InAs/GaAs QD are studied by Zhang and Wang [9], finding that a potential well appears in a QD without a lattice misfit and chemical diffusion, and both stress field and Ga chemical diffusion can induce the formation of a potential barrier, which strongly affects the electronic behavior within the QD. Optical properties of InAs/InP QWW and InAs QD embedded in a lateral in-plane pin or nin device have been studied by Mazur et al. and Reuter et al. [10,11], respectively. In the case of QWW [10] an unusual two-branch switching of the excitonic photoluminescence band maxima is revealed in the temperature dependence; this behavior is interpreted in terms of the thermal activation of excitonic ground states of the confined nanostructures. For the QD system under lateral applied electric field [11], time-resolved measurements show an increase in the radiative lifetime of up to 30% with increasing field. Reuter et al. [11] attribute this to the reduced overlap between the electron and hole wave functions.

Kasapoglu et al., Bilekkaya et al., and Aktas and Boz [12–14] have reported theoretical studies related to donor impurities in single and multiple QW and QWW. These authors have considered the different shapes of the barriers which confine the carriers

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into the different regions of the heterostructure. As a general trend, they have found that the binding energy is highly dependent on external proves such as hydrostatic pressure and applied electric field, and also on the structural characteristics of the quantum system. By applying an electric field in the growth direction of a heterostructure can modify the absorption and photoluminescence spectrum of both donor and acceptor impurities. These effects can be reversed by considering external magnetic fields and/or hydrostatic pressure. In multiple systems of QW, QWW, and QD, the use of appropriate values of external applied electric fields may favor the tunneling processes of carriers between the different regions of the structures by [15,16]. The binding energy of a hydrogenic impurity confined in a cylindrical QD under applied electric field and for several impurity positions was reported by Jiang et al. [17]. They found that: i) for axial-impurity positions, the binding energy has a maximum when the impurity is placed at the center of the structure and that such maximum is shifted when the applied electric field is considered, ii) the binding energy is a decreasing function of the radial-impurity position due to the increasing of the electron-impurity distance associated with the repulsion on the electron wave function in the radial potential barriers, and iii) the binding energy is a decreasing function of the radius and length of the QD.

There have been experimental and theoretical studies to explain the modification in the band structure of bulk and semiconductor heterostructures induced by hydrostatic pressure, which leads to changes in the properties of the elemental excitations. It is well known that, the hydrostatic pressure can modify the parameters of the effective mass such us the bandgaps, the potential barriers, the conduction and valence effective masses, the band-offset, the static dielectric constant, the lattice constant, and even the dimension of the low dimensional systems which are associated with the fractional change in the volume. For example, in the GaAs material the conduction effective mass and the forbidden bandgap are increasing functions of the hydrostatic pressure whereas the static dielectric constant is a decreasing one. All this with the consequent blue and/or red shift in the absorption and photoluminescence spectra. Additionally, with sufficiently high values of hydrostatic pressure can cause a type I heterostructure evolves into a type II one [3,4].

Stimulated by previous works, here we are concerned with the combined effects of hydrostatic pressure and applied electric field on the binding energy of a donor impurity in a two coupled InAs/GaAs QWW. calculations are made in the effective mass and parabolic band approximations and using a variational method to obtain the energy and the wave function for the ground state of the correlated system. The paper is organized as follows: Section 2 describes the theoretical framework, Section 3 is devoted to results and discussion and finally the conclusions are reported in Section 4.

2. Theoretical framework

In Fig. 1 we show a pictorial view of the heterostructure under study in the present work, which is conformed by two InAs QWW, laterally coupled by a GaAs central barrier. The dimensions of the transversal cross-section of the wires and of the central barrier are defined. The potential barrier confinement, which depends on the (x, y)-coordinates is shown with different colors of gray. The applied electric field, parallel to the growth direction of the heterostructure ($\vec{F} = -F\hat{x}$), is also depicted. In the effective mass and parabolic band approximations the Hamiltonian for a donor impurity in the InAs/GaAs double QWW under the combined effects of hydrostatic pressure (P) and applied electric field is

$$H = -\frac{\hbar^2}{2m_e^*}\nabla^2 - eFx + V(x, y, P) - \frac{e^2}{\varepsilon r}, \quad (1)$$

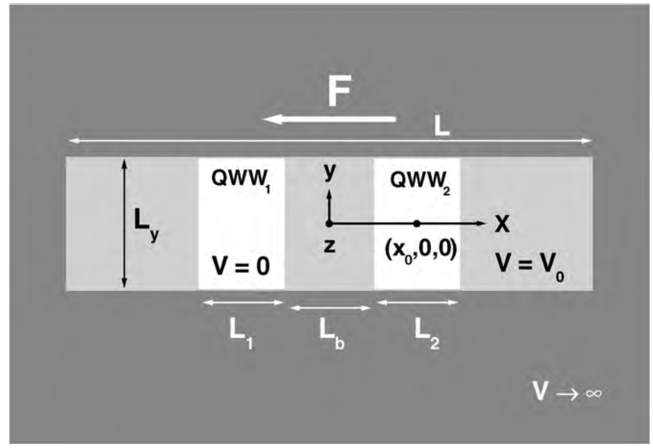

Fig. 1. Pictorial view of the rectangular-transversal section InAs/GaAs double QWW discussed in this work. The transversal dimensions of the wires and the central coupling barrier are shown. Also, the directions of the applied electric field and the confinement potentials, for each region of the space, are defined.

where m_e^* (= 0.04 m_0, where m_0 is the free electron mass) [5,6,18] is the conduction band effective mass, ε (= 14.6) [5,6,18] is the InAs static dielectric constant and $r = \sqrt{(x-x_0)^2 + y^2 + z^2}$ is the electron-impurity distance [$(x_0, 0, 0)$ and (x, y, z) are the impurity- and electron-position, respectively]. Here e is the absolute value of the electron charge and $V(x, y, P)$ is the hydrostatic pressure dependent confinement potential which, in our case, can be separated in the form $V(x, y, P) = V_1(x, P) + V_2(y)$, where

$$V_1(x,P) = \begin{cases} & -L/2 < x \le -L_b/2 - L_1, \\ V_0(P), & |x| \le L_b/2, \\ & L_b/2 + L_2 \le x < L/2, \\ 0, & -L_b/2 - L_1 < x < -L_b/2, \\ & L_b/2 < x < L_b/2 + L_2, \\ \infty, & |x| \ge L/2, \end{cases} \quad (2)$$

and

$$V_2(y) = \begin{cases} 0, & |y| < L_y/2, \\ \infty, & |y| \ge L_y/2. \end{cases} \quad (3)$$

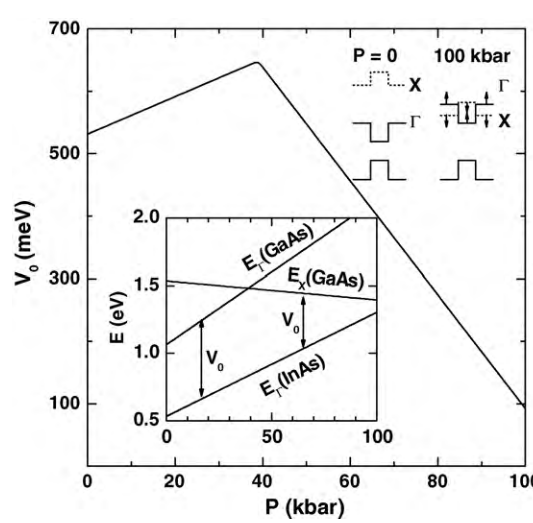

Fig. 2. Dependence with the hydrostatic pressure of the confinement potential $V_0(P)$ in the coordinate $\hat{x}$.