

Correlation energies of many-body complexes in biased InAs/GaAs quantum dots

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Abstract

The aim of this work is to analyze theoretically the correlation energies for neutral, positively, negatively charged exciton and bi-exciton. So, we propose a model consistent with experimental observations that is small InAs truncated pyramids with circular base lying on wetting layer, both buried into GaAs matrix.

In a first step and in contrast to other works, we are able to evaluate coulombic interactions between electron and hole, two electrons and two holes by perturbative method at the second order. In a second step, the correlation energies of many-body complexes X , X^- , X^+ and XX are investigated as a function of quantum dots basis radius r_c and the applied electric field.

Our main goal is to provide realistic estimation for the correlation energies of excitons, charged excitons and bi-excitons while retaining at the same time a transparent formalism, which could easily be transposed to structures of actual interest.

The present work provides evidence of the stability of excitons, charged excitons and bi-excitons in InAs/GaAs quantum dots. Calculated correlation energies of many-body complexes are consistent with those reported by recent photoluminescence measurements.

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1. Introduction

Negatively X^- and positively X^+ charged excitons, also called “trions”, have been the subject of

intense studies in the last years, both experimentally and theoretically. The stability of charged excitons in bulk semiconductors was proven theoretically by Lampert [1], but only recently have they been observed in quantum dots (QDs) structures, precisely in isolated InAs quantum dot embedded in a GaAs matrix [2–8]. Quantum dots

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are recently armed at being used for quantum computer [9].

After the initial work charged excitons in bulk semiconductors [1,10] as well as in an exactly two-dimensional configuration [11] were systematically studied theoretically. These studies revealed that, due to the confinement, the two-dimensional charged excitons have correlation energies that are an order of magnitude larger than the charged excitons in the corresponding bulk materials. Apart from these two early studies several works were recently published on charged excitons in the presence of an external electric field [12,13].

In the present paper, we study the neutral ($X = 1e + 1h$), positively ($X^+ = 1e + 2h$), negatively ($X^- = 2e + 1h$) charged exciton and bi-exciton ($XX = 2e + 2h$) correlation energies in semiconductor quantum dots. The paper is organized as follows. In Section 2 we review our theoretical formalism and numerical method to obtain the different correlation energies. In Section 3 we show how excitonic complexes correlation energies are affected by varying the quantum dots basis radius r_c or by applying electric field in the growth direction. The conclusions are given in the last section.

2. Hamiltonian

In this work, we are interested to a numerical study of the correlation energy in a specific shape of the small quantum dot which are small semiconductors structures, where carriers are confined in a box by an external or internal potential in all three spatial dimensions [14,15]. The dots are called quantum when electronic wave functions are coherent over the whole box. Quantum dots for optoelectronics must be able to accommodate at least two types of carriers, electrons and holes. By atomic force microscopy measurements, it was shown that the first dots formed are in the quantum size range (height 3 nm, circular base of radius $r_c = 12$ nm), that the dispersion on their sizes is remarkably low ($\pm 10\%$), and that they are located fairly regularly (interdot distance 60 nm). Upon further growth, density and shapes do not change but sizes

increase up to double values before coalescence occurs. Self-organized growth in strained structures is then shown to be a simple and efficient way of building regular quantum dots [16]. In our calculation, quantum dots are modeled by truncated cones of height h and basis radius r_c as they are presented in Fig. 1. This form of the quantum dot was deduced from the optical study of InAs quantum wells in GaAs [17]. These pyramids have the same height h in the z growth direction and the same radius r_c in ρ direction. The base angle of the truncated cone is close to $\alpha = 30^\circ$.

We have calculated, independently, the electron and heavy hole levels, neglecting light hole effect, excitonic effects and spin-orbit effect. Due to cylindrical symmetry of the situation, the problem is 2D and the quantum dot confinement potential couples the motion along growth direction (z) and radial coordinate ρ .

The Hamiltonian describing a single particle (electron or hole) in the effective mass approximation and with several assumptions, is given by

$$H_0 = T_c + V_{\text{conf}} + V_F, \quad (1)$$

where V_{conf} indicates the quantum dot confinement potential, T_c denotes the kinetic energy operator and V_F is the electrostatic potential including the effects of static electric field applied parallel to the truncated cone axis. z will refer to the cone axis. V_{conf} , T_c and V_F are given, in the cylindrical symmetry, by

$$V_{\text{conf}}(\rho_e, z_e) = V_e \Theta \left[z_e - \left((r_c - \rho) \tan(\alpha) + \frac{Z + d - h}{2} \right) \right]$$

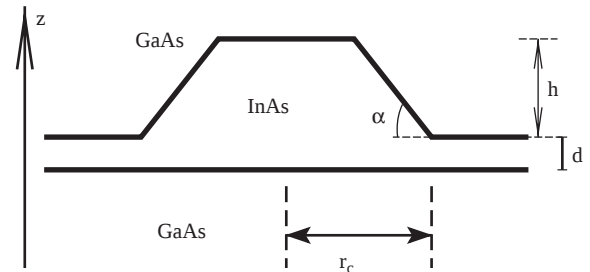


Fig. 1. Morphology of a quantum dot observed in the z growth direction.

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