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Temperature and hydrostatic pressure effects on exciton–phonon coupled states in semiconductor quantum dot

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ABSTRACT

We studied theoretically the exciton–phonon coupled states in a cylindrical quantum dot (QD) under hydrostatic pressure and temperature effects. We calculated the exciton binding energy by using a variational approach within the effective-mass approximation. The stress is applied along the QD growth axis and the interactions of charge carriers (electron and hole) with both the confined LO phonon modes and surface phonons (TSO and SSO) are incorporated in our calculation. The effect of these three phonon modes on the exciton binding energy is discussed in the presence of pressure and temperature effects. The numerical computation for $GaAs/Ga_{1-x}Al_xAs$ QD has shown that the exciton binding energy is very significant with increasing pressure and decreasing temperature. Both the exciton binding energy and its polaronic correction increase linearly with increasing stress. We investigated also the effects of the temperature and pressure on the integrated photoluminescence (PL) intensity, and show that at relatively high temperature the phonons have a noticeable effect on it. This physical parameter also shows a great dependence on pressure.

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1. Introduction

Recent advances in experimental techniques such as the molecular beam epitaxy (MBE) and metal-organic chemical-vapor deposition (MOCVD) have made it possible to appear a great interest in semiconductor heterostructures of low dimensionality such as quantum wells (QWs) quantum well wires (QWWs), and quantum dots (QDs). QDs are interesting due to the fact that the motion of the charge carriers are restricted in all three dimensions, which lead to new superior electronic properties and to phenomena with potential optoelectronic device applications [1–4]. A great experimental and theoretical work has also devoted to the qualitative understanding of physical properties of excitons and impurities in QWs, QWWs and QD [5–10].

Excitonic properties in quantum nanostructures have been intensively studied recently because of the high potential for applications and fundamental physics. Among these nanostructures, (QDs) are three-dimensional wells that can trap electrons and holes resulting in quantized energy levels. The density of states is gama function-like, and the wave function of the particles is localized inside the dot. Therefore, excitons play a dominant role for the optical properties and their stability is important for possible devices requiring this characteristic. It is well established that the confinement of excitons in QDs yields an enhanced excitonic effect, which can be exploited in the design of novel optoelectronic devices. The binding energy of exciton increases with the decreasing QD sizes reaching a maximum at some critical size width. This implies the existence of a critical confinement limit where the quantum confinement effect is large. There has been growing interest in the topic regarding the confined exciton states in various nanostructures [11–19]. A reason for this interest is the possible simplification of the intensive computation involved in obtaining exciton binding energies in quantum structures such as QDs systems. Thus, an important binding energy allows exciton states to become stable, and it is favorable for the room temperature operation of devices based on excitons. To improve the physical properties of excitons and impurities in QDs even at room temperature, many works have studied the effect of pressure and temperature for the excitons in nanostructures [20–24]. Raigoza et al. [20] found the effects of hydrostatic pressure on the exciton states in $GaAs/Ga_{1-x}Al_xAs$ semiconductor QWs; a good agreement with available experimental measurements was obtained. Exciton states in QWWs under electric field and hydrostatic pressure were also examined in their work. The pressure effect on the optical transition in QDs was investigated by Duque et al. [21]. Oyoko et al. [22] studied donor impurities in a parallelepiped-shaped GaAs – (GaAl)As QD and they found that the donor binding energy increases with increasing pressure and decreasing QD size. Kasapoglu [23] examined The combined effects of hydrostatic pressure and temperature on donor impurity binding energy in $GaAs/Ga_{0.7}Al_{0.3}As$ double QW. They found that an increment in temperature results in a decrement in donor impurity binding energy while an increment in the pressure for the same temperature enhances the binding energy. More recently, Duque et al. [24] have studied the combined effects of electron–hole correlation, hydrostatic pressure, and temperature on the third harmonic generation in disk-shaped parabolic GaAs QDs are studied under the density matrix formalism and the effective mass approximation. In their calculation the optical phonons are not considered.

One of the most recent interests in the area of QD physics has been to investigate the role of carrier charges interactions not only on the electronic properties, but also on the optical ones. Polaronic properties may influence carrier transportation of semiconductors, and consequently affect the properties of optical-electronic devices. Up to now, most works on polaronic properties have been devoted at zero-temperature limit. It was found that the polaronic properties of layered semiconductors such QWs, QWWs and QDs are obviously different from those of bulk materials. In the last decade, Ban et al. [25] studied the temperature dependence of *N*-dimensional polarons to show their dimensional effect, and it was found that the temperature effect on polarons diminishes with increasing dimensionality. Later, Qin and Gu [26] studied the temperature effect on polaron self-energy for a polar-crystal slab. It is shown that the self-energy is a decreasing function of temperature. Recently, Hua et al. [27] studied the self-energies and effective masses of polarons in a heterostructure. Bouhassoune et al. [28] have presented a study of the exciton binding energy in a cylindrical QWW in the presence of a uniform magnetic field by taking into account the interaction between the electron–hole and the