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Tilted electric-field and hydrostatic pressure effects on donor impurity states in cylindrical GaAs quantum disks

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Abstract

In this work we are devoted to the study of donor impurity states in a cylindrical GaAs quantum disk under the effects of tilted applied electric field and hydrostatic pressure. A variational procedure has been performed within the effective mass and parabolic-band approximations. For the hydrostatic pressure effects we consider the $\Gamma - X$ mixing via a phenomenological procedure.

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There has been quite a bit of work on the Stark effect in quantum wells [1,2] and quantum wires [3,4] where an electric field is applied along the direction of carrier confinement in the system. In a quantum disk (QD), all the directions are directions of carrier confinement. In quantum wells, the Stark shift depends upon the width of the well [1] while in quantum wires, it depends upon the radius of the wire. Here we investigate how the Stark shift of the first confined electron-level and donor-impurity binding energy in a cylindrical QD of radius R and height L depends upon the dimensions of the disk, tilted applied electric field, and hydrostatic pressure.

The Hamiltonian of a charged particle in a cylindrical QD in the presence of an electric field, applied at an angle α to the axis of the disk, and considering an on-center donor impurity, is given by

$$H = p^2/(2m^*) - qF\rho\cos\varphi\sin\alpha - qFz\cos\alpha - q^2/(\varepsilon r) + V_c(\rho, z), \qquad (1)$$

where p is the carrier momentum, F the applied electric field, m^* and q are the carrier effective mass and charge, respectively, r is the carrier-impurity distance, and $V_c(r)$ is the confining potential, which is defined as zero inside the QD and infinite elsewhere. Following the same reasoning as in Ref. [3], for the Hamiltonian in Eq. (1) without the impurity potential term we take a variational wave function as $\psi(\rho,\varphi,z) = NJ_0(k\rho)\cos(\pi z/L)\exp(\beta\rho\cos\varphi)\exp(\gamma z)$, where $J_0(x)$ is the ordinary Bessel function of order zero. For the complete system under study we use a variational wavefunction as a product between the solution of the non-correlated problem, after minimization process, and a hydrogenic wave function, i.e., $\Psi(\rho,\varphi,z) = M\psi(\rho,\varphi,z)\exp(-\lambda r)$. Here β, γ, and λ are variational parameters and N and M are normalization constants. The hydrostatic pressure effects are incorporated from the dependencies with pressure of the basic input parameters (see Ref. [5] and references therein).

In Fig. 1 we present our theoretical findings for the applied electric field dependence of the first confined electron state (E_0) and donor-impurity binding energy (E_b, defined as the difference of energies between the non-correlated and the correlated problem) in a cylindrical GaAs QD. Different dimensions of the structure, directions

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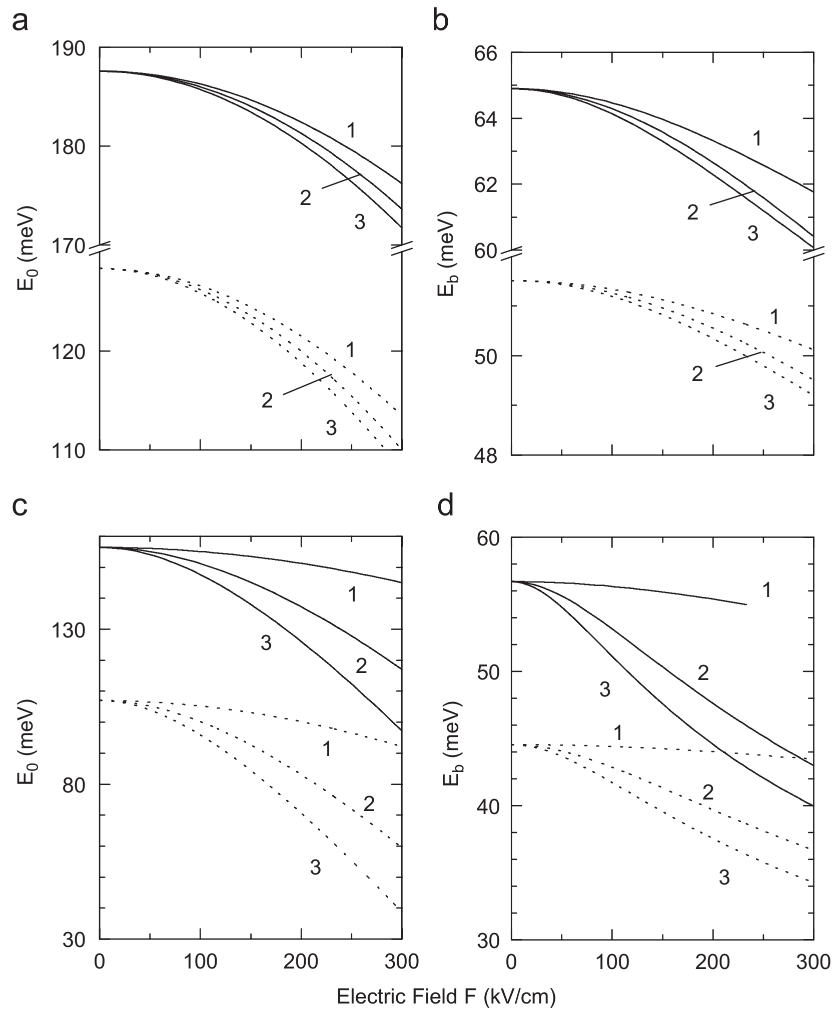

Fig. 1. Applied electric field dependence of the first confined electron state [(a) and (c)] and donor-impurity binding energy [(b) and (d)] in a cylindrical GaAs QD. Different directions of the field have been considered: $\alpha = \pi/2$ (curve 1), $\alpha = \pi/4$ (curve 2), and $\alpha = 0$ (curve 3). In (a) and (b) $L = 100\,\text{Å}$ with $R = 50\,\text{Å}$, whereas in (c) and (d) $L = 150\,\text{Å}$ with $R = 50\,\text{Å}$. Solid lines are for $P = 0$ and dotted lines are for $P = 100\,\text{kbar}$.

of the tilted electric field, and hydrostatic pressure have been considered. From Figs. 1(a) and (c), in which the impurity effects are not considered, it is clear that the electric field diminishes the effective Gap of the heterostructure and for it a red shift must be observed in the optical absorption and photoluminescence processes. This result is contrary to the corresponding one reported by Ham and Spector [6]. The additional red shift behavior with pressure, in (a) and (c), is mainly due to the increasing of the electron effective mass. Variations of the dimensions of the structure with pressure, up to 100 kbar, are responsible of changes in E_0 less than 3%. Comparing lines 1 and 3, we observe that the energy shift is higher when the field is parallel to the axis of the wire. It is due to the higher region in which it is possible to shift the electron cloud. For the binding energy cases, Figs. 1(b) and (d), we observe a red shift with the electric field, associated with the decreasing in the Coulomb interaction. In photoluminescence and absorption processes this phenomena is observed as blue shift modified for the red shift of the effective Gap. The blue shift with pressure, in Figs. 1(b) and (d), is associated with the decreasing of the dielectric constant. In the case of off-axis impurity the break of the axial symmetry is traduced in a diminishing of the binding energy with the electric field and increasing with the hydrostatic pressure. For on axis but off-center impurity, and depending of the impurity position, the applied electric field can increases or decreases the binding energy. In this last case the hydrostatic pressure always increases the binding energy.

Summing up, using the effective mass approximation and a variational procedure we report the effect of tilted applied electric field and hydrostatic pressure on non-correlated electron states and donor impurity binding energy in cylindrical-shape QD. Results show a red shift with the electric field on E_0, contrary to the main conclusion in the work by Ham and Spector [6].

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