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H. S. Brandi, A. Latgé, and L. E. Oliveira

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Magnetic-field and laser effects on the electronic and donor states in semiconducting quantum dots

H. S. Brandi  
Instituto de Física, Universidade Federal do Rio de Janeiro, Rio de Janeiro-RJ, 21945-970, Brazil

A. Latgé  
Instituto de Física, Universidade Federal Fluminense, Niterói-RJ, 24210-340, Brazil

L. E. Oliveira  
Instituto de Física, Unicamp, CP 6165, Campinas-São Paulo, 13083-970, Brazil

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Light shifts induced in the electronic and shallow on-center donor states in spherical semiconductor quantum dots, including magnetic field effects, are theoretically investigated. The interaction of light with the spherical GaAs–(Ga, Al)As quantum dot is treated within a dressed-band approach in which the Kane band structure scheme is used to model the GaAs bulk semiconductor whereas the dressing by the laser field is treated through the renormalization of the GaAs energy gap and conduction/valence effective masses. This nonperturbative approach is valid far from resonances and has been successfully adopted for other confined semiconductor heterostructures. The discrete nature of the electronic and impurity states, characteristic of quantum dot systems, and the possibility of adding extra confining effects by laser and applied magnetic fields opens up a promising route of applicability and/or manipulation of quantum-dot states in recent quantum-computer proposals. © 2002 American Institute of Physics. [DOI: 10.1063/1.1509110]

I. INTRODUCTION

Different types of quantum-dot (QD) systems have been viewed as promising structures for applications in a large variety of optoelectronic devices mainly due to the discrete nature of the electronic states. More recently, quantum dots have received additional attention due to the possibilities envisaged for their implementation as practical solid-state based quantum computers in which discrete electronic charge or spin states are responsible for encoding quantum information. Some of the proposed schemes are based on transferring information between qubits through electron–electron Coulomb interaction or by optical-cavity modes. In particular, coupled-QD structures were theoretically investigated by Hu and Das Sarma who studied two coupled GaAs QDs in the presence of applied magnetic fields, which corresponds essentially to “a two-dimensional hydrogen-like molecule,” and concluded that the two-dot system provides the necessary two-qubit entanglement required for quantum computers. In addition, Li and Arakawa suggested to build up a single qubit from two coupled QDs, based on the idea that spatial separation of charge states may enhance quantum coherence. In this proposal qubits are selectively addressed by lasers, Coulomb correlation between them are neglected, and the quantum information is stored in electron-hole pair states.

A number of experimental and theoretical investigations have been recently concerned with a quantitative understanding of the laser field-semiconductor interaction, a subject of paramount importance if one is interested in the design of efficient optoelectronic devices. When addressing the interaction of laser light with semiconductor systems, the many-body aspects of the problem must in general be considered, as in semiconductors the photon-generated electron-hole pairs interact through Coulomb forces. Different regimes may be distinguished. It is well known that many-body effects are small corrections to the one-electron approximation, provided the laser is tuned far from any resonances, i.e., exciton and/or impurity states. Moreover, if the laser detuning is large, with the Rabi energy, standard perturbative approaches are adequate to deal with the problem, and one is in the linear regime in the laser-field intensity. On the other hand, when is of the order of the laser-field effects are no longer perturbative, and one must treat the system “laser + electrons” within a nonperturbative approach in the field coupling. In the dressed-band approach, the laser-field effect in the semiconductor electronic states is nonperturbatively taken into account through the renormalization of the semiconductor band gap, and of both the electron and hole effective masses.

Donor states in semiconducting structures have been recently proposed to be used as model qubits in quantum information processors. In particular, Cole et al. have studied quantum-confined donor-electron semiconductor systems (under applied magnetic fields) which may be coherently manipulated by terahertz radiation: 1s and 2p+ donor states may be used as model qubits in quantum computation although the decoherence is increased due to the fact that the bulk 2p+ state is resonant with the continuum states. They also suggested that an excited donor state below the continuum, e.g., the 2p− state, would be more robust to ionization by photons and phonons leading to a favorable situation
concerning the coherence time. As it is well known, low-dimensional heterostructures such as semiconductor QDs are more sensitive to applied fields and therefore exhibit more pronounced confining effects. This makes donor-doped QDs in the presence of laser fields natural candidates to both theoretical and experimental investigations. Here we investigate the confinement effects of both applied magnetic and laser fields on the electronic and on-center donor states in GaAs–Ga$_0.7$Al$_{0.3}$As spherical QDs, and study the conditions in which one may obtain a bound $2p_+$ state in contrast to the resonant one in the study by Cole et al. 

II. THEORETICAL FRAMEWORK

The Hamiltonian of a shallow-donor impurity at the center of a GaAs–(Ga, Al)As spherical QD under applied magnetic and laser fields is given by

$$H = \frac{1}{2m^*} (p + eA/c)^2 - \frac{e^2}{\epsilon r} + V(r),$$

with $m^*$ being the laser-dressed renormalized$^{12,13}$ conduction-band effective mass and $\epsilon$ is the dielectric constant (assumed constant throughout the QD heterostructure). $V(r)$ is the QD spherical confinement potential and $A = (B \times r)/2$ is the vector potential associated with the magnetic field $B$. Here we note that the laser is tuned far from any resonances and below the GaAs-energy gap, $\epsilon_g$, so that no real electron excitations to the conduction

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![FIG. 1](image1.png)

![FIG. 2](image2.png)
band occur. Also, the renormalized energy gap and conduction-band effective mass depend on the GaAs Kane-model parameters, on the laser intensity, and on the laser detuning. A standard variational approach is followed in the donor calculation, i.e., a $1s$-like (or $2p_{\pm}$-like) on-center donor trial envelope wave function is taken as the product of the exact solution of the square well QD potential (without the magnetic field effect) and a hydrogenic-like variational $1s$ (or $2p_{\pm}$-) function. The donor binding energy in the presence of an applied magnetic field is given as the ground-state $\epsilon_0 + \gamma$ energy of the QD in the absence of the impurity minus the donor $1s$-like ground-state (or $2p_{\pm}$-like) energy, $\gamma$ being given by $\frac{eB}{2m^*c}R^*$, with $R^* \approx 5.9$ meV the GaAs effective Rydberg.

III. RESULTS AND DISCUSSION

The explicit dependence of the $1s$-like binding energy on the magnetic field intensity and on the QD radius is shown in Figs. 1(a) and 1(b) for GaAs–Ga$_{0.7}$Al$_{0.3}$As spherical QDs. Solid lines in the figures correspond to a laser intensity equal to $5 \times 10^3$ MW/cm$^2$ and a laser detuning $\delta = 75$ meV ($= 0.05\epsilon_g$). For comparison, the results corresponding to the absence of an applied laser (undressed-results) are also shown as dotted lines. For low values of the magnetic field, the $1s$-like donor binding energies exhibit a positive shift (higher values) due to the laser confinement effect whereas as the magnetic field increases the shift changes to the opposite direction. A clear dependence on the dot radius is also noticed. This indicates that both laser and magnetic-field intensities may be properly chosen, together with an appropriate choice of the dot radius, to generate desired results concerning shifts of donor states in GaAs–(Ga,Al)As QDs.

The effects of laser confinement on the $\epsilon_0 + \gamma$ QD ground-state energy, $1s$-like, and $2p_{\pm}$-like on-center energies of GaAs–Ga$_{0.7}$Al$_{0.3}$As spherical QDs are displayed in Fig. 2 as a function of the magnetic field intensity and for a laser detuning $\delta = 75$ meV and intensity $5 \times 10^3$ MW/cm$^2$. For the $R = 200$ and 400 Å QDs, one clearly notices that the dressed $2p_{\pm}$-like states are bound (below the QD ground-state energy) up to a particular critical magnetic field. For the $R = 400$ Å QD, the undressed $2p_{\pm}$-state is also bound up to a lower value of the applied magnetic field, a situation that does not occur for the undressed results corresponding to the $R = 100$ and 200 Å QDs. Figure 3 shows, for $B = 0$ and in the case of undressed QDs, that the $2p_{\pm}$-state becomes bound for $R \geq 250$ Å in the absence of applied magnetic, a result already obtained in a previous work. The crossing regime from bound to unbound $2p_{\pm}$ state depends clearly on the laser intensity, detuning, size of the QD and magnetic field value (cf. Fig. 3). It is clear from the results that the unbound behavior of the binding energies associated to the $2p_{\pm}$-state for small values of the QD radii may be drastically changed by applying a magnetic field. One may understand the $2p_{\pm}$-state unbound behavior as the result of an interplay between the spatial extension of the $2p_{\pm}$-electron radial wave function and the characteristic size of the QD. Figure 3 clearly indicates that the strong confinement effects due to the applied laser play a crucial role on the spatial-electronic wave function distribution, leading to important changes in the bound/unbound regime.

Effects of varying the laser intensity and detuning values on the QD ground state ($\epsilon_0 + \gamma$) and on the $2p_{\pm}$-like ener-
gies are shown in Figs. 4(a) and 4(b), for a particular QD with $R = 200\ \text{Å}$ and $B = 5\ \text{T}$. Of course, the critical laser intensity associated with the crossover from unbound to bound $2p_{1/2}$-like states depends not only on the dot radius but also on the value of the applied magnetic field. In that sense the laser detuning and the intensity of the applied fields, together with the size of the QD radius, may be properly changed to manipulate such transition to obtain a particular favourable situation. This may prove useful in controlling electronic and impurity states in coupled QDs as proposed by Li and Arakawa\textsuperscript{5} and Hu and Das Sarma.\textsuperscript{6} Also, in experiments of the type performed by Cole \textit{et al.},\textsuperscript{7} one could produce robust $2p_{1/2}$-states for terahertz coherent manipulation of qubits.

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\textsuperscript{17} G. Bastard, \textit{Wave Mechanics Applied to Semiconductor Heterostructures} (Les Editions de Physique, Les Ulis, 1988).