Light-induced shifts in the electronic and shallow-donor states in GaAs-(Ga,Al)As quantum dots

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We treat the interaction of light with a spherical GaAs-(Ga,Al)As quantum dot within a dressed-band approach. The Kane band-structure scheme is used to model the GaAs bulk semiconductor and the interaction with the laser field is treated through the renormalization of the semiconductor energy gap and conduction/valence effective masses. This approach, valid far from resonances, is used to investigate the light shifts induced in the electronic and shallow on-center donor states in semiconductor quantum dots, which are shown to be quite considerable. This model calculation may be extended to include magnetic-field effects, and it is suggested that the strong localization of the electronic and impurity states due to the quantum dot and enhanced by laser confinement may prove useful for manipulation of electronic and donor states in some proposed solid-state-based quantum computers.

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In the last few years, a considerable amount of work has been devoted to the study of the interaction of light with condensed-matter systems.[1–7] In particular, the possibilities to design new efficient optoelectronic devices may be greatly improved if we are able to understand the basic physics involved in the laser-field-semiconductor interaction. A peculiarity of the semiconductor system is that the photon-generated electron-hole pairs always interact through Coulomb forces and, therefore, the many-body aspects of the problem must, in general, be considered. From the theoretical point of view, one might identify different regimes and approximations that describe the laser-semiconductor interaction: (a) if the laser is tuned far from any resonances, many-body effects are small corrections to the one-electron approximation;[7] (b) if the laser detuning $\delta \gg \Lambda$, the Rabi energy, the linear (in the field intensity) regime prevails, and usual perturbative approaches are adequate to deal with the problem; (c) on the other hand, in the case where $\delta \lesssim \Lambda$, the external laser field is no longer a perturbation to the electronic system, one must treat the field nonperturbatively and, of course, nonlinear effects are related to the type of nonlinearity of the response for high-field excitation regimes, either due to the many-body interaction or to the nonperturbative field coupling.

Several new proposals are now concerned with solid-state quantum computers due to their great advantage in manipulating a large number of qubits compared to atomic and molecular systems. In particular, Li and Arakawa[2] suggested to built up a single qubit from two-coupled quantum dots (QD's). Hu and Das Sarma[3] theoretically investigated two-coupled GaAs QDs, a ''two-dimensional-hydrogenlike molecule,'' in the presence of an applied magnetic field. They concluded that the two-dot system provides the necessary two-qubit entanglement required for quantum computers. By studying shallow-donor states in semiconductors, in the presence of an external homogeneous magnetic field, Cole *et al.*[4] have demonstrated that a quantum-confined donor electron in a semiconductor may be coherently manipulated by using terahertz radiation, and suggested that $1s$ and $2p_+$ donor states may be used as model qubits in quantum information processors. However, one of the difficulties found lies in the fact that the $2p_+$ state is resonant with the continuum states. Therefore, most electrons promoted to this excited resonant state do not return to the ground state directly and are ionized to the conduction band. This strongly increases the decoherence time. On the other hand, an excited donor state below the continuum (for example, the $2p_-$ state) would be more robust to ionization by photons and phonons leading to a favorable situation concerning the coherence time. One should mention that the behavior of impurity levels in GaAs-(Ga,Al)As quantum wells in the presence of an external magnetic field plus a laser field was recently studied by Brandi *et al.*[7] The effects of the laser field on the electronic impurity and optical properties were incorporated through a renormalization of the semiconductor energy gap and conduction/valence effective masses. The exciton Stark shift in quantum wells and the effects due to the band-structure laser dressing were found to be of the same order of magnitude as those obtained from many-body diagrammatic techniques, and laser effects on the shallow-donor peak energies in quantum wells were comparable to those produced by a magnetic field of a few Teslas. We should point out that the laser-induced shifts on the impurity levels may also be used as a possible application to ultrafast optoelectronic devices, where no photon absorption occurs in the device.[7] It has also been shown that the laser-semiconductor interaction enhances the confinement due to the quantum-well potential, increasing the impurity binding energies. As it is well known, low-dimensional heterostructures such as semiconductor QD's are more sensitive to applied fields and, therefore, exhibit more pronounced confining effects. This makes donor-doped QD's in the presence of laser fields natural candidates to both theoretical and experimental investigations.

In the present work, we study the confinement effects of a laser beam on the electronic and on-center donor states in GaAs-(Ga,Al)As spherical QD's following the same dressed-band approach as in Brandi *et al.*[7] The Hamiltonian of a

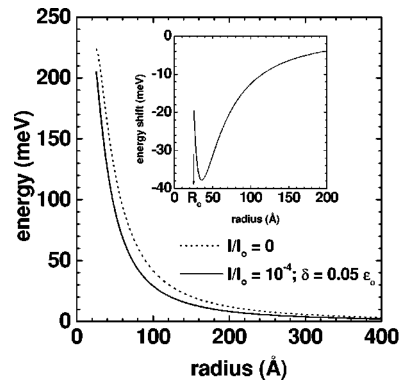

FIG. 1. Dependence of the E_0 ground-state energy of a GaAs-$Ga_{0.7}Al_{0.3}As$ spherical QD on the dot radius. Full (dotted) curves are dressed-laser (undressed) results for a laser detuning $\delta/\epsilon_0=0.05$ and intensity $I/I_0=10^{-4}$. Inset shows the corresponding laser-induced energy shift; R_c is the smallest QD radius for the existence of a bound state.

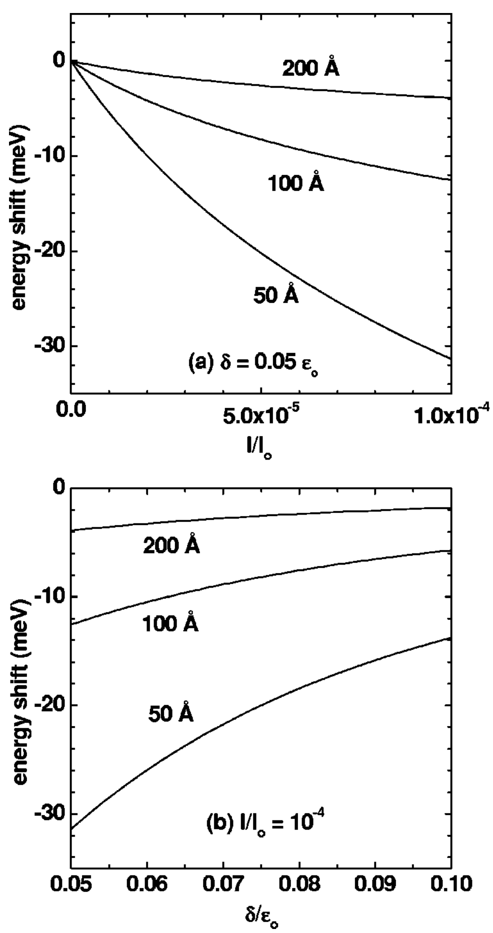

FIG. 2. Laser-induced energy shift of the E_0 ground-state energy of a GaAs-$Ga_{0.7}Al_{0.3}As$ spherical QD, for different dot radii, vs: (a) the laser intensity for fixed detuning $\delta=0.05\epsilon_0$; (b) the laser detuning for fixed intensity $I/I_0=10^{-4}$.

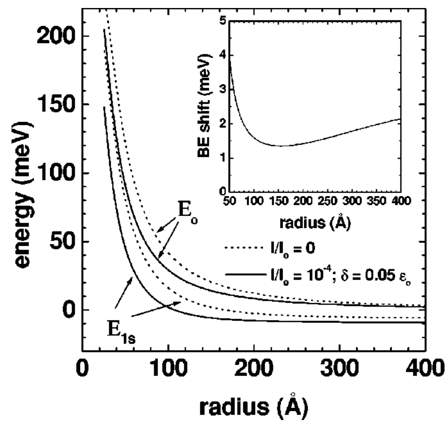

FIG. 3. Dependence of the on-center donor $1s$-like (E_{1s}) and QD (E_0) ground-state energies for a GaAs-$Ga_{0.7}Al_{0.3}As$ spherical QD on the dot radius. Full (dotted) curves are dressed-laser (undressed) results for a laser detuning $\delta=0.05\ \epsilon_0$ and intensity $I/I_0=10^{-4}$. Inset shows the laser-induced shift in the $1s$-like donor binding energy (BE).

shallow-donor impurity at the center of a GaAs-(Ga,Al)As spherical QD under an applied laser field is given by

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

where m^* is the laser dressed, renormalized[7] conduction-band effective mass, ϵ is the dielectric constant that we assume constant throughout the QD heterostructure, and $V(r)$ is the QD spherical confinement potential. We note that the renormalized conduction-band effective mass depends on the GaAs Kane model parameters,[8,9] on the laser intensity, and on the laser detuning[7] $\delta=\epsilon_o-\hbar\omega$, where ϵ_o is the GaAs energy gap[9] and ω is the laser frequency. The laser is tuned far from any resonances and below the gap energy so that no real electron excitations to the conduction band occur.

In the donor calculation, we follow the standard variational approach[10] and choose a $1s$-like (or $2p$-like) on-center donor trial envelope wave function as a product of the exact solution of the square-well QD potential and a $\Gamma(\mathbf{r},\lambda)$ hydrogeniclike variational $1s$ (or $2p$) function, i.e.,

$$\Psi(\mathbf{r},\lambda)=\begin{cases}\dfrac{\sin(k_1 r)}{k_1 r}\Gamma(\mathbf{r},\lambda), & \text{if } r\leqslant R\\[2ex] \dfrac{\sin(k_1 R)}{k_1 r}e^{k_2(R-r)}\Gamma(\mathbf{r},\lambda), & \text{if } r\geqslant R,\end{cases} \tag{2}$$

where R denotes the QD radius, λ is a variational parameter, and $k_{1,2}$ are defined[10] in terms of the QD barrier potential and ground-state energy. The donor binding energy is given as the ground-state energy E_0 of the QD in the absence of the impurity, minus the donor $1s$-like ground-state (or $2p$-like) energy.

The effect of the laser confinement on the E_0 ground-state energy of a GaAs-$Ga_{0.7}Al_{0.3}As$ spherical QD is clearly seen in Figs. 1 and 2 as functions of the relevant parameters of the problem (laser intensities are given in units[7] of $I_o\approx 5$

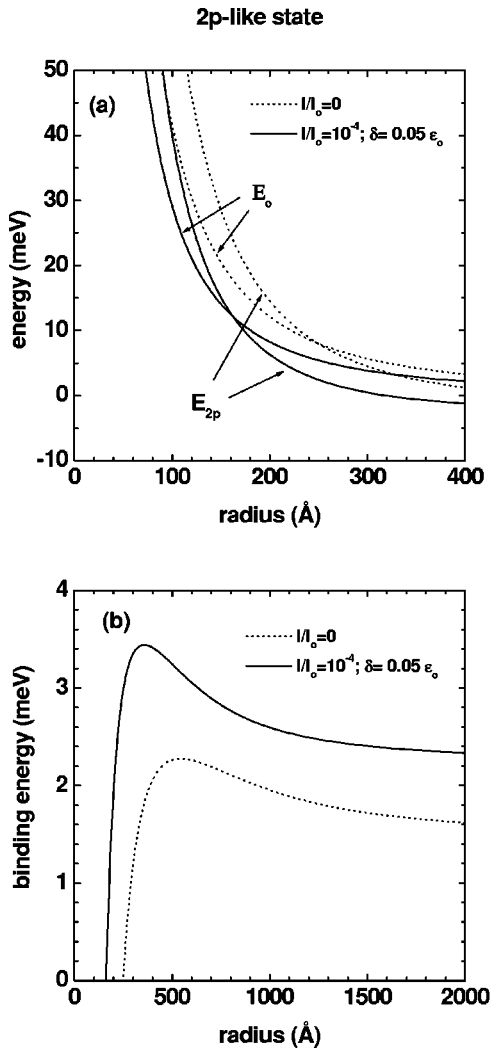

FIG. 4. (a) Dependence of the on-center donor $2p$-like (E_{2p}) and QD (E_0) ground-state energies for a GaAs-$Ga_{0.7}Al_{0.3}$As spherical QD on the dot radius; (b) Laser effects on the $2p$-like donor binding energy. Full (dotted) curves are dressed-laser (undressed) results for a laser detuning $\delta=0.05\epsilon_0$ and intensity $I/I_0=10^{-4}$.

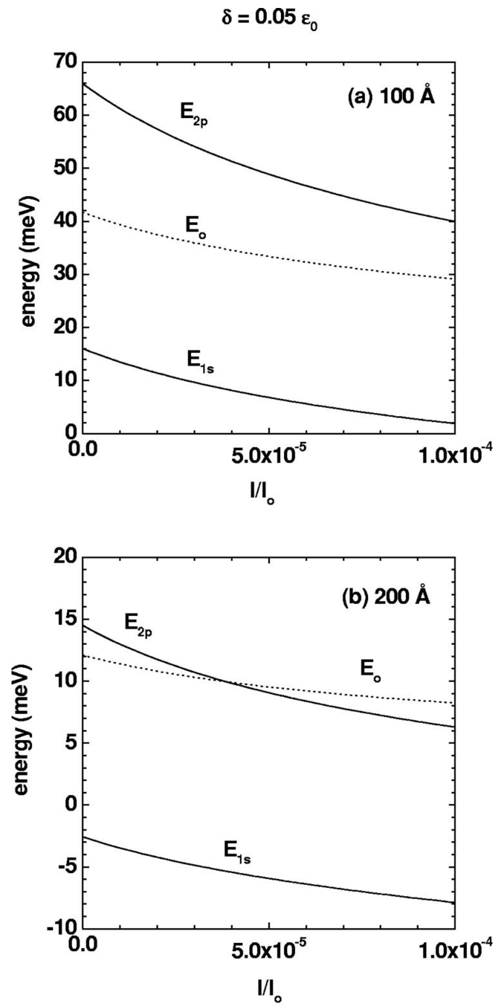

FIG. 5. Dependence of the on-center donor $1s$-like (E_{1s}), $2p$-like (E_{2p}), and QD ground-state (E_0) energies, for $R=100$ Å (a) and $R=200$ Å (b) GaAs-$Ga_{0.7}Al_{0.3}$As spherical QD's, on the laser intensity for fixed detuning $\delta=0.05\epsilon_0$.

$\times 10^7$ MW/cm^2). In particular, the inset in Fig. 1 shows that the shift on the QD ground-state energy may be quite significant. Of course, as one would expect, this depends on the laser intensity, detuning and size of the QD: notice in Fig. 2 that laser effects increase for increasing intensities (for a fixed detuning) and decrease for increasing detuning (for a fixed laser intensity), being more pronounced for small-radii QD's. Figure 3 shows that the laser-induced confinement produces a similar effect for the $1s$-like on-center donor state. The inset in Fig. 3 displays the shift in the donor binding energies due to the confinement effect of the laser that could be experimentally detected. To our knowledge, however, no experimental measurements concerning laser effects on donor states in doped GaAs-(Ga,Al)As QD's have been reported in the literature.

Laser effects on the E_0 QD ground-state energy and $2p$-like on-center energies are displayed in Fig. 4(a), for a laser detuning $\delta/\epsilon_0=0.05$ and intensity $I/I_0=10^{-4}$. For the dot radius $R\gtrsim 160$ Å one notices that the dressed $2p$-like state becomes bound (below the QD ground-state energy), a situation that only occurs for $R\gtrsim 250$ Å in the absence of the laser. The unbound behavior of the binding energies associated to the $2p$-state for small values of the QD radii is basically related to an interplay between the spatial extension of the $2p$-like electron radial wave functions and the characteristic sizes of the quantum dots. Effects of the laser on the $2p$-like binding energies are also shown in Fig. 4(b), where it is clear the role of the laser in enhancing the donor-state confinement. A similar behavior is also displayed in Fig. 5 for the eletronic and donor $1s$- and $2p$-like states as a function of the laser-field intensity, for two particular QD radii. For an $R=100$ Å QD [cf. Fig. 5(a)], the $2p$-like state is unbound, whereas Fig. 5(b), for an $R=200$ Å QD, indicates that a QD radius-dependent critical intensity determines the existence of a crossover from unbound to bound $2p$-like states. It is important to mention that this could be useful in experiments such as the one performed by Cole *et al.*,[4] in order to produce robust states for terahertz coherent manipulation of qubits. In addition, this behavior may also be useful in controlling electronic states in coupled QD's as proposed by Li and Arakawa[2] and Hu and Das Sarma.[3]

Summing up, we have presented a theoretical approach of the laser-field effects in semiconductor GaAs-(Ga,Al)As QD's by adopting a picture in which the light-matter interaction is taken into account by a convenient dressed-band[7] approach. This scheme, valid far from resonances, may be readily extended to include magnetic-field effects and indicates that the light shifts induced in the electronic and shallow on-center donor states in semiconductor QD's may be quite considerable. Moreover, the strong localization of the electronic and donor states due to the QD and enhanced by laser confinement may result useful for manipulation of electronic and donor states in some proposed solid-state-based quantum computers.

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