# Laser effects on donor states in low-dimensional semiconductor heterostructures

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A theoretical study of the effects of intense laser fields on the ground-state binding energies of donor impurities in low-dimensional semiconductor heterostructures is performed. The laser-heterostructure interaction is treated within an extended dressed-atom approach, so that, for a laser tuned far below any resonances, the effects of the laser-semiconductor interaction correspond to a renormalization of the semiconductor energy gap and conduction/valence effective masses. Calculations are performed for donors in GaAs-(Ga,Al)As quantum wells, cylindrical quantum-well wires, and spherical quantum dots. The binding energies of donors in low-dimensional systems increase with increasing laser intensity, and for a fixed intensity, the influence of the laser is stronger for small detunings. Results obtained within the extended dressed-atom approach are compared with previous calculations performed by using a simplified high-frequency limit of the Kramers-Henneberger approach.

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The study of the interaction of light with atoms, molecules, and condensed-matter systems is of considerable interest and has been the subject of intense research work.[1–10] The design of new efficient optoelectronic devices depends on deep understanding of the basic physics involved in the interaction process. Special attention has recently been given to the laser interaction with semiconductor heterostructures. Theoretically, the main aspects of the laser-semiconductor interaction may be classified in the following regimes: (a) if the laser is tuned far from any resonances, many-body effects are small corrections to the one-electron approximation; [5] (b) if the laser detuning $\delta$ is much greater than the Rabi energy $\Lambda$, the field-intensity linear regime prevails, and one may resort to the usual perturbative approaches; (c) for $\delta \lesssim \Lambda$, there are situations in which the laser field may not be considered as a perturbation to the electronic system, and the field has to be treated nonperturbatively. Of course, weak resonant excitation can be considered as a perturbation, and this lies in the background of all the absorption and photoconductivity measurements. The correct conditions when resonant excitation cannot be considered as a perturbation should involve decay times.[4] Furthermore, if the laser is on resonance with a characteristic energy of the system, the many-body interaction may also be a source of nonlinear effects, and a realistic theoretical description of problem is quite complicate.

If a many-body treatment is not required, and $\delta \lesssim \Lambda$, there are few theoretical approaches adequate to study the nonperturbative regime in the field intensity. One of these schemes is an extension of the dressed-atom approach,[3,5] which has been recently used to study the effects of the laser field–semiconductor interaction on the electronic, impurity, and optical properties of semiconductor heterostructures, such as quantum wells (QWs) and quantum dots (QDs).[5] In this simple and straightforward scheme, it is possible to incorporate the laser effects through a renormalization of the semiconductor energy gap $\epsilon_g$, and conduction/valence effective masses. For a Kane three-band model semiconductor, one obtains the associated laser-dressed conduction (+) and valence (−) electronic bands, i.e.,

$$\epsilon_{\pm} = \frac{\epsilon_g \pm \hbar\omega}{2} + \frac{\Lambda^2}{6\delta'} \pm \frac{1}{2}\sqrt{\frac{8\Lambda^2}{3} + \left(\delta + \frac{\Lambda^2}{3\delta'} + \frac{4\Lambda^2}{3\Lambda_1}\right)^2} + \frac{\hbar^2 k^2}{2m_{\pm}}, \tag{1}$$

and corresponding renormalized effective masses $m_{\pm}$ (see Brandi *et al.*[5]). In the above expression, $\epsilon_g$ is the semiconductor energy gap, $\delta$ is the laser detuning given by $\epsilon_g - \hbar\omega$, $\delta' = \delta + \Delta$, $\Delta$ is the spin-orbit splitting, and $\Lambda_1 = \epsilon_g + \hbar\omega$.

Note that the $k$-dependent semiconductor energy gap is dressed by laser effects, and is given by the difference between the above renormalized conduction and valence electronic bands

$$\tilde{\epsilon}_o(k) = \epsilon_g - \delta + \sqrt{\frac{8\Lambda^2}{3} + \left(\delta + \frac{\Lambda^2}{3\delta'} + \frac{4\Lambda^2}{3\Lambda_1}\right)^2} + \frac{\hbar^2 k^2}{2\mu}, \tag{2}$$

with $(1/\mu) = (1/m_+) - (1/m_-)$. The above equations provide the framework for calculating laser effects on semiconductor systems within the Kane model renormalized effective-mass approach. This is valid within the one-particle picture and for a laser tuned far from any resonances, and may be used to provide an adequate indication of the laser effects on any semiconductor heterostructure for which the effective-mass approximation is a good physical description.

Here we use the above dressed-band approach[5] to investigate the electronic confinement due both to an intense laser field and to dimensionality effects on the shallow-donor states in GaAs-$Ga_{1-x}Al_xAs$ semiconductor QWs, quantum-well wires (QWWs), and QDs. We comment on a series of

 

previous calculations[6,7] which consider laser effects on donor states through a simplified high-frequency limit of the Kramers-Henneberger[1] approach. In their scheme, they solve the corresponding time-independent Schroedinger equation for the zeroth Floquet component of the wave function, with a zero-photon space-translated version of the laser-dressed potential, which depends on the laser frequency $\omega$ and intensity $I$ through a single parameter $\alpha_0=(e/m^*\omega^2)(8\pi I/c)^{1/2}$. Since, in general, laser-matter interaction depends on both laser frequency and intensity, independently, the use of this approximation deserves special attention.

The high-frequency approximation (HFA) has been introduced in the context of laser-atom/molecule interaction,[2] and it has been argued that it is valid if the laser frequency is much larger than the lowest energy eigenvalue having the same symmetry than the atom ground state. Later, many authors[6,7] have applied a modified form of the HFA to semiconductor heterostructures through an approximation of the exact zero-photon Floquet potential ($n=0$ component) which we name as the modified high-frequency approximation (MHFA). The validity of such approach is still more restrictive concerning the frequency regime. The first general comment on the application of the MHFA to semiconductors is that, in this case, one-electron approximations are only valid if the laser is tuned far from any resonances and no real excitation occurs in the semiconductor.[5] Of course, high-frequency excitations promote electrons to the conduction band, and the Coulomb interaction may play an important role, due to electron-electron, electron-hole, hole-hole interactions, exciton formation, exciton-exciton interaction, etc., which in principle would require a full many-body calculation. If the laser is tuned far from any resonances and the detuning $\delta \ll \epsilon_g$, with the Coulomb-interaction perturbative parameter satisfying $\sqrt{\mathrm{Ry}/\delta} \ll 1$, where Ry is the impurity Rydberg energy, then the Coulomb interaction may be neglected and the one-electron approximation is valid. The conditions under which the many-body effects may be neglected have been extensively discussed by Combescot, [8] and the perturbative parameter comes out essentially from the fact that many-body effects may be taken into account through an expansion in the Coulomb potential. Therefore, if one wants to apply the MHFA to model the laser-semiconductor interaction, it is important to be aware of these restrictions. Notice that one could in principle fix a value for $\omega$ large enough to satisfy the conditions of validity of the MHFA, and then to increase the laser intensity in order to be in the laser nonperturbative limit, i.e., $\delta \lesssim \Lambda$, therefore obtaining large values of $\alpha_0$. However, it is well known that an adequate treatment of high-intensity processes requires a multiphoton description and therefore several components must be taken into account in any realistic description of the Floquet potentials. The above consideration poses a problem in the application of the HFA for very intense laser fields as it only considers the zero-order term of the Floquet potential. For intense laser fields, it is apparent therefore that the HFA may lead to unrealistic or physically incorrect results.

In the present work we compare calculations of the ground-state dressed donor binding energies obtained with the use of the renormalized effective-mass approach [5] and of the MHFA.[6,7] Results are obtained for the binding energies

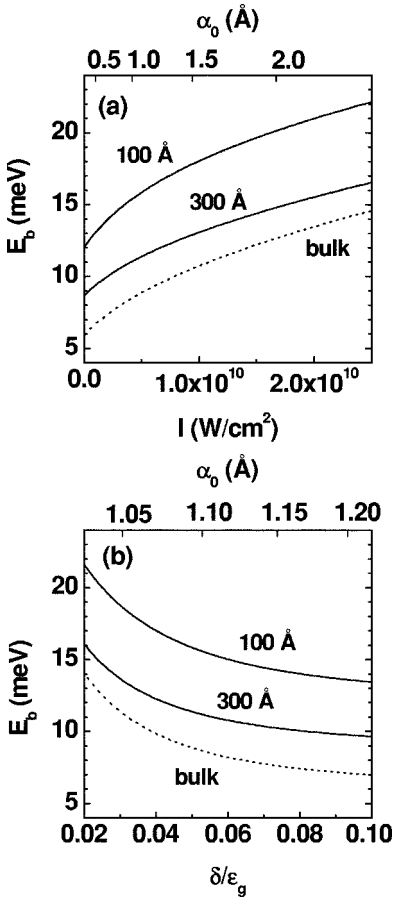


FIG. 1. (a) On-center donor binding energies as functions of the (a) laser intensity for a detuning $\delta=0.05\epsilon_g$ and (b) laser detuning, with a laser intensity $I=0.5\times10^{10}$ W/cm$^2$, for GaAs-$Ga_{0.7}Al_{0.3}As$ QWs with $L=100$ Å and 300 Å widths. Results for bulk GaAs are shown as dotted curves. The upper horizontal axis corresponds to the $\alpha_o$ parameter defined in the text.

of the ground-state 1*s*-like states of donors in GaAs-(Ga,Al)As quantum wells, cylindrical quantum-well wires, and spherical quantum dots. Note that the dressed-band approach has been shown to reproduce with great accuracy the dressed-band energy spectrum obtained from a full Floquet calculation.[9] As an example to show the type of difficulties that may occur with the use of the MHFA, we have assumed typical laser-parameter values used in the experiments of the optical exciton Stark shift in GaAs, to cover both perturbative and nonperturbative laser-field regimes. The range of laser frequencies chosen, $\hbar\omega \lesssim \epsilon_g$, certainly guarantees the applicability of the MHFA large-frequency assumption. In order to compare the present calculations with some results of the MHFA, we note that the impurity Bohr radius is $a_0 \approx 100$ Å and that the effective Rydberg is $1\ \mathrm{Ry}^* \approx 5.9$ meV.

On-center donor binding energies are shown in Fig. 1(a) as functions of the laser intensity for a detuning $\delta=0.05\ \epsilon_g$, whereas Fig. 1(b) shows the on-center donor binding energies as functions of the laser detuning, with a laser intensity $I=0.5\times10^{10}$ W/cm$^2$, for GaAs-$Ga_{0.7}Al_{0.3}As$ QWs with $L=100$ Å and 300 Å widths. Results for bulk GaAs are also presented, as dotted curves. Figure 2(a) shows the donor

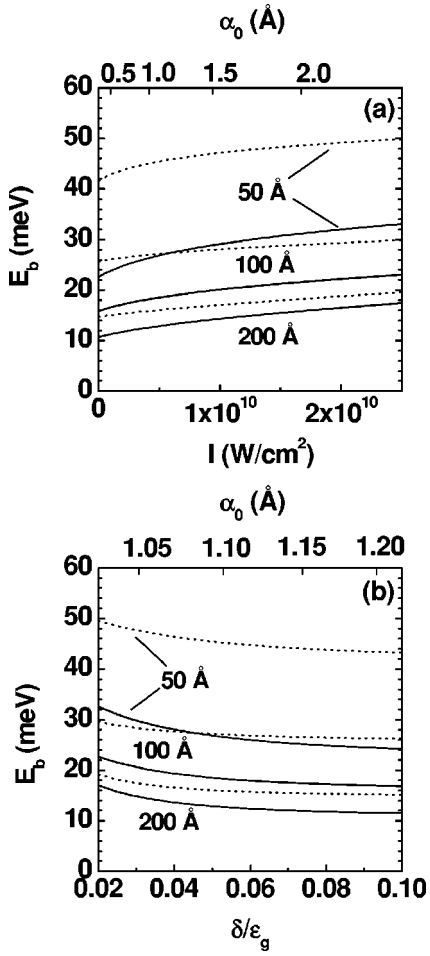


FIG. 2. (a) Donor binding energies as functions of the (a) laser intensity for a detuning $\delta=0.05\epsilon_g$ and (b) laser detuning, with a laser intensity $I=0.5\times10^{10}$ W/cm$^2$, for GaAs-$Ga_{0.7}Al_{0.3}As$ cylindrical QWWs (solid lines, on-axis donors) and spherical QDs (dotted curves, on-center donors) with radii equal to 50 Å, 100 Å, and 200 Å.

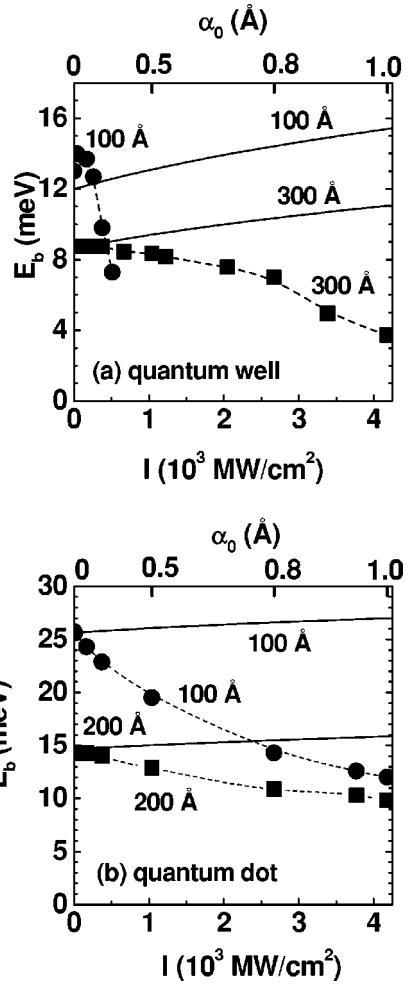


FIG. 3. On-center donor binding energies as functions of the laser intensity for a laser detuning $\delta=0.05\epsilon_g$, for GaAs -$Ga_{0.7}Al_{0.3}As$ (a) QWs with length equal to 100 Å and 300 Å, and (b) spherical QDs with radii equal to 100 Å and 200 Å. Full curves are results of the present work whereas full symbols and dashed curves are associated to the MHFA calculations (Ref. 6).

binding energies as functions of the laser intensity for a detuning $\delta=0.05\epsilon_g$ and Fig. 2(b) as a function of the laser detuning, with a fixed laser intensity $I=0.5\times10^{10}$ W/cm$^2$, for GaAs-$Ga_{0.7}Al_{0.3}As$ QWWs (solid lines: on-axis donors) and QDs (dotted curves: on-center donors) with radii equal to 50 Å, 100 Å, and 200 Å. Results of Figs. 1(b) and 2(b) are a demonstration of the well-known fact that, for a fixed intensity, the influence of the laser is stronger for small detunings. Finally, the effect of the dimensionality on the electronic confinement is evident from the results displayed in Figs. 1 and 2: the lowest the dimensionality the largest the binding energy, for a given laser intensity. To illustrate the significant difference between the present results with the corresponding calculations by using the MHFA,[6,7] Fig. 3 compares our calculations for GaAs-$Ga_{0.7}Al_{0.3}As$ QWs and QDs with those using the MHFA, from Fanyao *et al.*[6] One notices that the results obtained in the two schemes are strikingly different. The present dressed-band calculations indicate that the binding energy of an impurity in low-dimensional systems increases with increasing laser intensity, in contrast with the MHFA results.

We must comment on the quite high values of $\alpha_0$ assumed in several MHFA works.[6,7] We note that if we consider a $CO_2$ laser, $\omega\sim2\times10^{14}$ seg$^{-1}\sim0.13$eV, for $I\sim10^9$ W/cm$^2$, one has $\alpha_0\sim60$ Å. In these conditions, due to the very large detuning, the change in the semiconductor electronic structure is negligible and a calculation within the renormalized effective-mass approximation would result in essentially no impurity dressing. On the other hand, real excitations from the impurity levels to the conduction band occur and one-electron schemes may not be adequate to properly describe the laser-semiconductor interaction. In particular, the HFA-type of approach, which takes into account only the $n=0$ component of the Floquet potential, cannot account for photon excitations, and is not able to realistically describe these excitation processes.[9] Of course it would be interesting if one could compare the results of both the HFA and dressed-band schemes with experimental data. Unfortunately, we are not aware of the existence in the literature of measurements related to energy shifts of impurity states for the studied laser-frequency regime. One should note, however, that the

dressed-band approach has been used to treat exciton optical Stark shifts in GaAs quantum wells and the general trend of the calculated shifts is in fair agreement with available experimental data.[10]

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