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Dressed-band approach to laser-field effects in semiconductors and quantum-confined heterostructures

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A theoretical study of the effects of a laser field on the electronic and optical properties of GaAs-(Ga,Al)As heterostructures is presented by using a Kane model for the GaAs bulk semiconductor and working within an extended dressed-atom approach. 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. This renormalized one-body approach may be used to give a qualitative indication of the laser effects on a variety of optoelectronic phenomena in semiconductor heterostructures for which the effective-mass approximation provides a good physical description. As a test, the exciton Stark shift in quantum wells is calculated and the effects due to the band-structure laser dressing are found to be of the same order of magnitude as those obtained from many-body diagrammatic techniques. We have also analyzed the effects of laser dressing on the shallow-donor peak energies in quantum wells, and found them comparable with those produced by a magnetic field of a few teslas.

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I. INTRODUCTION

Because of the technical and scientific developments achieved in controlling the doping of artificially tailored semiconductor heterostructures, applications to optoelectronic devices are frequent and very successful.[1] The basic understanding of these devices requires a comprehension of their fundamental electronic and optical properties. It is well known that optical and transport properties have a strong relation with the degree of localization of the electronic states in the material. In semiconductor superlattices (SL's), the electronic localization is extremely sensitive to the heterostructure barrier width and height, impurity distribution, effective mass, and action of external fields. Therefore, the possibilities of designing efficient optoelectronic switches and modulators may be greatly improved if we are able to understand the basic physics involved in the external-field–semiconductor interaction. In this respect, a considerable amount of work has been devoted to the study of the interaction of external electric and magnetic fields[2] with SL's, and the physical processes are now well understood. The physical properties of solids may be modified due to interaction with an electromagnetic field, the most studied effect being the energy shift of the electronic states due to the laser-semiconductor interaction, i.e., the optical Stark effect,[3,4] which brings to attention some fundamental aspects of the interaction between light and electrons in semiconductor systems. When light interacts with a semiconductor, a detailed description of the laser-semiconductor interaction requires a many-body treatment, as excitations (real or virtual) such as excitons are created and interact via Coulomb forces.

In the present work we study how a homogeneous and monochromatic laser beam modifies the impurity states of GaAs-(Ga,Al)As semiconductor quantum wells (QW's) under applied magnetic fields perpendicular to the QW interfaces. We also discuss the effects of a laser beam on the exciton states in semiconductor heterostructures. A realistic description of the laser effects on shallow-impurity states in semiconductor heterostructures under magnetic fields would, in principle, require complex calculations involving, for instance, Coulomb interactions between impurities and all virtual excitonic states. Nevertheless, a much simpler situation occurs when the laser is tuned far from any resonances, since the main physics of the laser-semiconductor interaction may be theoretically described by using a nonperturbative one-body approximation. From the experimental point of view, the shifts in the impurity levels induced by the laser light may be used in a possible application to ultrafast optoelectronic devices where no photon absorption occurs in the device. A detector capable of responding to virtual transitions where the number of photons is preserved may be very useful because it is suitable to nondemolition measurements.[5]

Recently, a simple approach in which the effect of the laser-semiconductor interaction is taken into account through the renormalization, or dressing, of the electron/hole effective masses and semiconductor band gap was proposed by Brandi *et al.*,[6,7] by using a simple model semiconductor within a two-parabolic $\mathbf{k}\cdot\mathbf{p}$ band scheme. It was shown that, even far from resonances, laser effects on impurity states in quantum wells under magnetic fields are significant and comparable to those of applied magnetic fields, for intensities adequate to experimental observation. This dressed-band scheme may be very useful to treat situations where the laser is tuned far from any resonances provided the effective-mass approximation constitutes an appropriate physical description, as is the case of (i) evaluation of the optical Stark shifts in excitonic states, (ii) calculation of energy levels of shallow impurities under electric and/or magnetic fields, or (iii) other related phenomena in semiconductor heterostructures under laser fields. Moreover, it was shown that band-dressing effects[6,7] on the exciton optical Stark shift may be quite important and comparable to many-body corrections.[8] Here we consider a more realistic description of the semiconductor system by including spin-orbit coupling within the Kane model[9] in order to discuss the dependence of the laser-dressed energy spectra and renormalized electron/hole effective masses and energy gap on the model band structure. We must mention that our calculations are based on a steady-state model whereas actual experiments dealing with changes in the electronic structure of the semiconductor system are performed using ultrafast laser pulses and intensities of GW/cm^2 (the pulsed-laser regime in which the agreement with steady-state results is expected has been extensively investigated both theoretically and experimentally[4]).

The work is organized as follows. Section II presents the laser-dressed approach for a Kane model semiconductor and details the renormalization both of the semiconductor gap and of the conduction/valence band effective masses. As an application, laser-dressed effects on excitonic states in semiconductor QW's are considered in Sec. III, together with a discussion of the corresponding results within a many-body theoretical approach. Results and discussion in the case of shallow-impurity states in semiconductor QW's under magnetic fields are presented in Sec. IV. Finally, in Sec. V we present our conclusions.

II. LASER-DRESSED APPROACH FOR A THREE-BAND KANE MODEL SEMICONDUCTOR

A theoretical description of the effects of a laser field on the band structure is performed within the framework of the $\mathbf{k}\cdot\mathbf{p}$ approximation. We adopt the Kane model to describe the set of states formed by the lowest conduction band (Γ_6), the highest light- and heavy-hole valence bands ($\Gamma_8^{lh,hh}$), and the split spin-orbit band (Γ_7), which is split from the other two degenerate valence bands by Δ. In what follows, we use as a basis the states obtained from the diagonalization of the Kane matrix (see the Appendix).[10] The effect of a homogeneous laser field on the band structure may be obtained from the Hamiltonian[6,7]

$$H=H_0+\hbar\omega a^\dagger a+\frac{e}{m_0 c}A_\omega \hat{p}\cdot\hat{\epsilon}(a^\dagger+a), \tag{1}$$

where H_0 is the diagonal matrix obtained from the Kane model, and $a^\dagger$ (a) is the creation (annihilation) photon operator associated with the laser mode of frequency ω and polarization $\hat{\epsilon}$. The vacuum field amplitude in the volume Ω is given by $A_\omega = (2\pi\hbar c^2/\omega\Omega)^{1/2}$, which is related to the classical amplitude of the photon vector potential A_0 by $A_0=2(N_0)^{1/2}A_\omega$ for $N_0\gg 1$, where $N_0\gg 1$ is the average number of photons in the field. Using the states obtained from the diagonalization of the Kane matrix, it is straightforward to extend the dressed-atom approach[11] and diagonalize the Hamiltonian of Eq. (1) within the $|\Gamma_8,N+1\rangle\equiv|\Gamma_8\rangle\otimes|N+1\rangle$ and $|\Gamma_6,N\rangle\equiv|\Gamma_6\rangle\otimes|N\rangle$ manifold, where $|N\rangle$ represents a Fock state with $N\approx N_0$ photons.[11,12] The dressed-band Hamiltonian matrix then becomes

$$H=\begin{pmatrix} E_{\Gamma_6}+\Delta E_{\Gamma_6}+\Delta E'_{\Gamma_6}+N\hbar\omega & \Sigma \\ \Sigma & E_{\Gamma_8}+\Delta E'_{\Gamma_8}+(N+1)\hbar\omega \end{pmatrix}, \tag{2}$$

with

$$\Delta E_{\Gamma_6}\approx\frac{\Lambda_0^2}{3\delta'}\left[1-\frac{m_0}{\mu_{67}}\frac{E_k^0}{\delta'}-\frac{8E_k^0E_p^0}{3}\left(\frac{1}{\epsilon_0^2}+\frac{2}{\epsilon_0'^2}+\frac{2}{\epsilon_0\epsilon_0'}\right)\right], \tag{3}$$

$$\Delta E'_{\Gamma_6}\approx\frac{2}{3}\frac{\Lambda_0^2}{\Lambda_1}\left[1-\frac{m_0}{\mu_{68}}\frac{E_k^0}{\Lambda_1}-\frac{4E_k^0E_p^0}{3}\left(\frac{8}{\epsilon_0^2}+\frac{1}{\epsilon_0'^2}+\frac{2}{\epsilon_0\epsilon_0'}\right)\right], \tag{4}$$

$$\Sigma^2\approx\frac{2\Lambda_0^2}{3}\left[1-\frac{4E_k^0E_p^0}{3}\left(\frac{8}{\epsilon_0^2}+\frac{1}{\epsilon_0'^2}+\frac{2}{\epsilon_0\epsilon_0'}\right)\right], \tag{5}$$

where ϵ_0 is the semiconductor energy gap,[10] $\epsilon_0'=\epsilon_0+\Delta$, δ is the laser detuning given by $\epsilon_0-\hbar\omega$, $\delta'=\delta+\Delta$, and $\Lambda_1=\epsilon_0+\hbar\omega$. The characteristic energy associated with the laser-semiconductor interaction is related to $\Lambda_0=eA_0|p|/2m_0c$. In Eq. (2), ΔE_{Γ_6} is the second-order energy correction due to the laser coupling between the $|\Gamma_6,N\rangle$ and $|\Gamma_7,N+1\rangle$ states (this corresponds to folding back the 3×3 Hamiltonian matrix into a 2×2 matrix; notice that the laser does not couple the $|\Gamma_8,N+1\rangle$ and $|\Gamma_7,N+1\rangle$ states). The Bloch-Siegert contributions[11] are given by $\Delta E'_{\Gamma_6}$ and $\Delta E'_{\Gamma_8}=-\Delta E'_{\Gamma_6}$, respectively, and correspond to the corrections due to the nonresonant coupling between the states $|\Gamma_8,N+1\rangle$ and $|\Gamma_6,N+2\rangle$ and the states $|\Gamma_8,N-1\rangle$ and $|\Gamma_6,N\rangle$, separated by $\pm 2\hbar\omega$. We have defined $E_k^0=\hbar^2k^2/2m_0$ and $E_p^0=p^2/2m_0$ and reduced effective masses $1/\mu_{67(8)}=1/m_{\Gamma_6}-1/m_{\Gamma_{7(8)}}$, where $m_{\Gamma_{6,7,8}}$ are the Kane model bulk semiconductor parameters.[10]

From the diagonalization of the Hamiltonian in Eq. (2), we obtain the eigenvalues λ_+ and λ_- and the associated laser-dressed conduction $(+)$ and valence $(-)$ electronic bands given by

$$\epsilon_+=\lambda_+-N\hbar\omega, \tag{6}$$

$$\epsilon_-=\lambda_--(N+1)\hbar\omega, \tag{7}$$

which results in

$$\epsilon_\pm=\frac{\epsilon_0\pm\hbar\omega}{2}+\frac{\Lambda_0^2}{6\delta'}\pm\frac{1}{2}\sqrt{\frac{8\Lambda_0^2}{3}+\left(\delta+\frac{\Lambda_0^2}{3\delta'}+\frac{4\Lambda_0^2}{3\Lambda_1}\right)^2}+\frac{\hbar^2k^2}{2m_\pm}, \tag{8}$$

and corresponding renormalized effective masses

$$\frac{1}{m_\pm}=\frac{1}{2M}\left[1+\frac{M}{3\mu_{68}}\frac{\Lambda_0^2}{\delta'}\beta_\gamma\pm\frac{M}{\mu_{68}}\Pi\right] \tag{9}$$

with $1/M=1/m_{\Gamma_6}+1/m_{\Gamma_8}$, and

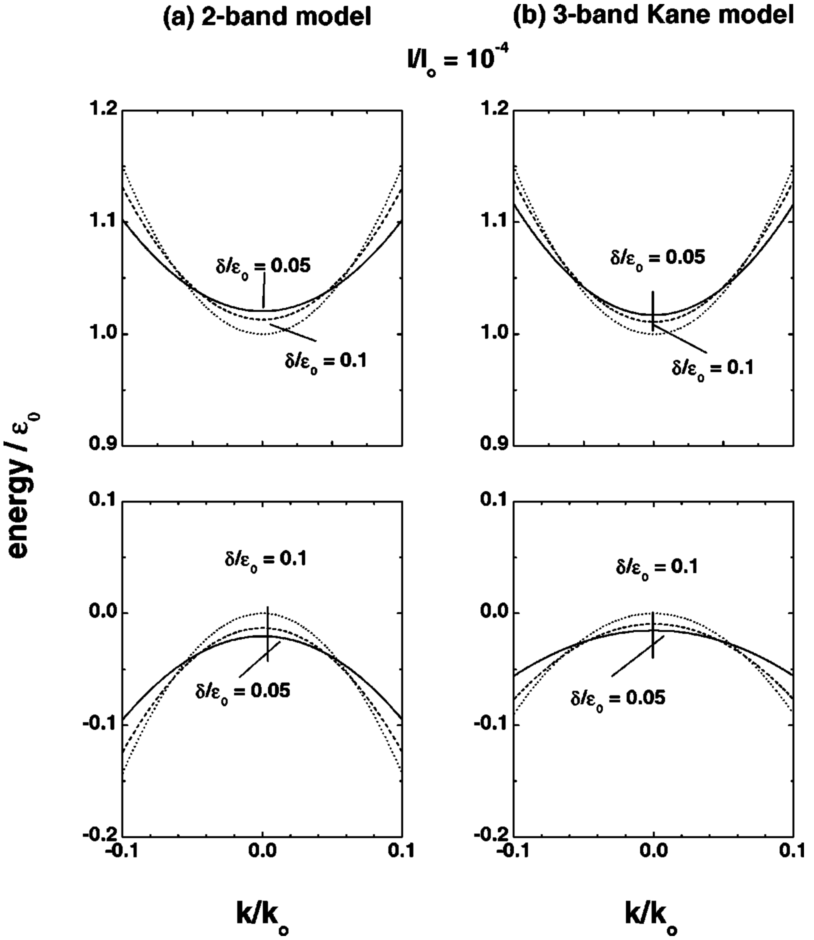


FIG. 1. Laser-dressed GaAs energy dispersion for the (a) two-band and (b) Kane models. All results are presented in reduced units, with energies given in terms of the undressed gap energy $\epsilon_0 = 1.519$ eV and wave vectors in units of the corresponding k_0. Dotted lines display the undressed energy dispersion whereas full and dashed curves are associated with laser detunings $\delta = 0.05\epsilon_0$ and $\delta = 0.1\epsilon_0$, respectively. Results are presented for $I/I_0 = 10^{-4}$, with $I_0 \approx 5 \times 10^4$ GW/cm^2.

$$\Pi=\frac{[1+(\Lambda_0^2/3\delta')\beta_\gamma+(4\Lambda_0^2/3\Lambda_1)\beta_{\gamma'}](\delta+\Lambda_0^2/3\delta'+4\Lambda_0^2/3\Lambda_1)+(4\Lambda_0^2/3)\beta_{\gamma''}}{\sqrt{8\Lambda_0^2/3+(\delta+\Lambda_0^2/3\delta'+4\Lambda_0^2/3\Lambda_1)^2}}, \tag{10}$$

$$\beta_\gamma=-\frac{\mu_{68}}{\mu_{67}}\frac{1}{\delta'}+\frac{8E_p^0}{3}\frac{\mu_{68}}{m_0}\left(\frac{1}{\epsilon_0^2}+\frac{2}{\epsilon_0'^2}+\frac{2}{\epsilon_0\epsilon_0'}\right), \tag{11}$$

$$\beta_{\gamma'}=-\frac{1}{\Lambda_1}+\beta_{\gamma''}, \tag{12}$$

$$\beta_{\gamma''}=-\frac{4E_p^0}{3}\frac{\mu_{68}}{m_0}\left(\frac{8}{\epsilon_0^2}+\frac{1}{\epsilon_0'^2}+\frac{2}{\epsilon_0\epsilon_0'}\right). \tag{13}$$

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 [cf. Eq. (8)],

$$\tilde{\epsilon}_0(k)=\epsilon_0-\delta+\sqrt{\frac{8\Lambda_0^2}{3}+\left(\delta+\frac{\Lambda_0^2}{3\delta'}+\frac{4\Lambda_0^2}{3\Lambda_1}\right)^2}+\frac{\hbar^2k^2}{2\mu} \tag{14}$$

with $1/\mu = 1/m_+ - 1/m_-$. As expected, the zero-field limits for the conduction or valence electronic bands, effective masses, and energy gap are correctly recovered from Eqs. (8), (9), and (14), respectively.

The above equations provide the framework for calculating laser effects on semiconductor systems within the Kane band-structure picture. A comparison between the previously adopted two-band approach[6,7] and the present Kane model for the energy dispersion of GaAs, in the range of small wave vector values, is presented in Figs. 1 and 2. The two-band and Kane results for a fixed laser intensity of $I/I_0 = 10^{-4}$, where[6,7] $I_0 \approx 5 \times 10^7$ MW/cm^2, and different detuning parameters are presented in Fig. 1, whereas Fig. 2 displays the corresponding calculations for a fixed laser detuning $\delta = 0.05\epsilon_0$ and two values of the laser intensity. The laser effect on the band structure may be seen by a comparison with the corresponding results in the absence of the laser displayed by the dotted lines. It is clear that laser effects correspond to a renormalization or dressing both of the semiconductor energy gap and of the conduction/valence effective masses. The dependence of the laser-dressed

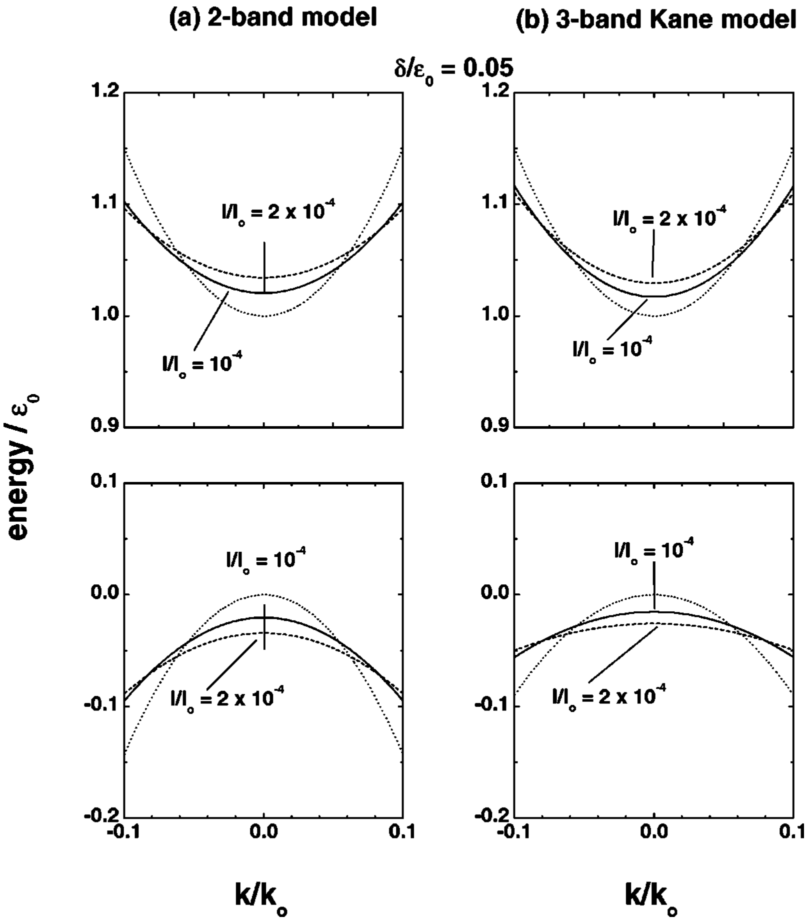


FIG. 2. Same as in Fig. 1, for a laser detuning $\delta/\epsilon_0 = 0.05$, and different laser intensities.

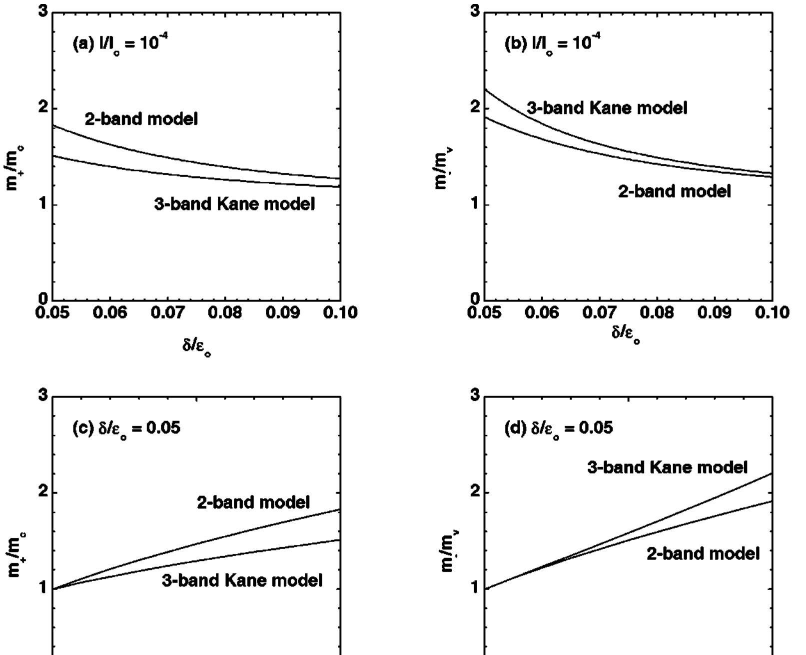


FIG. 3. Laser-dressed effective masses for the conduction (m_+) and valence (m_-) GaAs bands within the two-band and Kane models. Results in (a) and (b) are for a fixed laser intensity $I/I_0 = 10^{-4}$, and variable laser detuning, whereas (c) and (d) display the dependence on the laser intensity for a fixed detuning $\delta/\epsilon_0 = 0.05$.

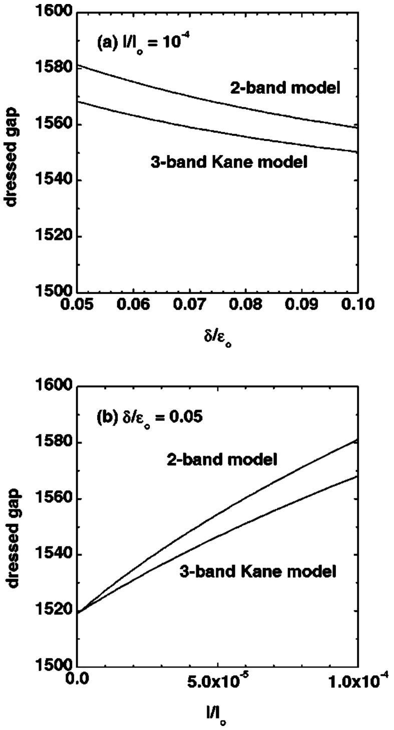


FIG. 4. Laser-dressed GaAs gap (in units of meV) within the two-band and Kane models, as a function of (a) the laser detuning δ for a laser intensity $I/I_0 = 10^{-4}$; (b) the laser intensity for a fixed detuning $\delta/\epsilon_0 = 0.05$.

conduction- and valence-band effective masses on the laser detuning and intensity is shown in Fig. 3 with results for the two-band and Kane models. In the range of laser detunings and intensities considered, results for both band models are qualitatively the same (differing approximately by 10–20 % at most), the differences increasing for smaller detunings and high laser intensities as one would expect. Figure 4 displays the corresponding behavior of the dressed $k=0$ semiconductor energy gap [cf. Eq. (14)] for both the two-band and Kane models. Again, one sees that results for the two-band and Kane models are qualitatively the same for the laser intensities and detunings considered. In conclusion, results in Figs. 1–4 indicate that laser dressing does not strongly depend on the modeling of the band structure, and therefore the present Kane-model renormalized effective-mass approach, valid within the one-particle picture and for large laser detunings (i.e., for a laser tuned far from any resonances), 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.

III. DRESSED EXCITONS IN SEMICONDUCTOR QUANTUM WELLS

As a simple application of the renormalization scheme, we calculate the optical Stark shift of exciton states in GaAs-(Ga,Al)As QW's. As this is one of the most studied effects originating from the laser-semiconductor interaction, one may compare the results obtained from the present dressed-band approach with previous many-body calculations in order to understand the role of the electron-hole interaction (which is beyond the single-particle approximation) on the exciton shifts.

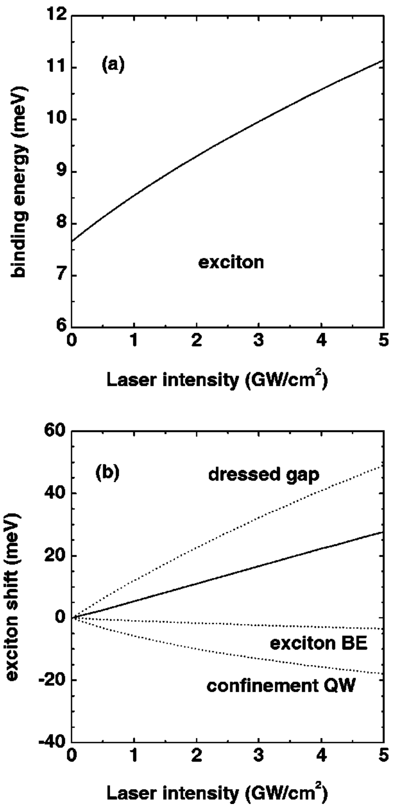


FIG. 5. Laser-intensity dependence (full curves) of the exciton (a) binding energy and (b) optical Stark shift for a 100 Å GaAs-Ga$_{0.7}$Al$_{0.3}$As QW and a laser detuning $\delta/\epsilon_0 = 0.05$. In (b) the dotted curves represent the Kane model contributions to the exciton Stark shift due to the laser-induced changes in the GaAs gap (labeled ''dressed gap''), exciton binding energy (''exciton BE''), and QW confinement of both free electrons and holes (''confinement QW'').

We have first performed calculations for laser-dressed exciton states in a 100 Å GaAs-Ga$_{0.7}$Al$_{0.3}$As QW. The $1s$-like exciton ground state was evaluated within a fractional-dimensional scheme[13] using the three-band Kane renormalized GaAs conduction/valence effective mass and dressed band gap. Results for the laser-intensity dependence of the exciton binding energies and exciton shifts are presented in Fig. 5 for a laser tuned far from exciton resonances, i.e., $\delta = 0.05\epsilon_0$. It is evident from Fig. 5(a) that the laser effect is to significantly enhance the exciton binding energy (notice that the binding energy may increase by $\approx 50\%$ for a laser intensity of 5 GW/cm^2). The blue laser-induced shift in the exciton peak energies is quite remarkable [see Fig. 5(b)], and calculated results qualitatively agree with femtosecond measurements by Mysyrowicz *et al.*[14] Also shown in Fig. 5(b) are the Kane model contributions to the exciton Stark shift due to the laser-induced changes in the GaAs gap, exciton binding energy, and QW confinement of both free electrons and holes. It is apparent from Fig. 5(b) that the exciton blueshift is essentially due to laser-induced changes in the GaAs semiconductor gap. Notice (see Fig. 6) that, in the large detuning limit, perturbation theory (PT) in the laser-dressed

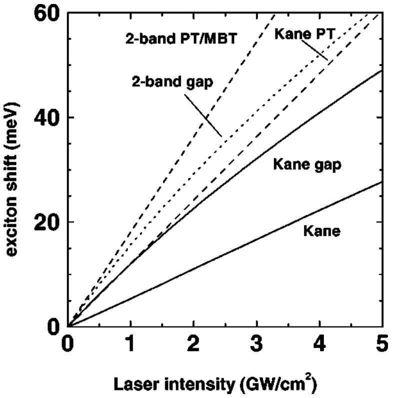


FIG. 6. Same as in Fig. 5(b), with the total optical exciton Stark shift shown as a full curve (labeled ‘‘Kane’’). Also shown are the laser-induced changes in the GaAs gap for a two-band model (dotted curve) together with the perturbative (PT) results (dashed curves) from the two-band and three-band Kane models. As discussed in the text, the two-band PT results in an exciton-shift correction equal to the corresponding diagrammatic expansion within many-body theory (MBT).

three-band Kane gap [see Eq. (14)] results in an exciton blueshift given by $4\Lambda_0^2/3\delta$, in contrast with the two-band model approach,[6,7] which gives a larger detuning PT result of $2\Lambda_0^2/\delta$. This two-band PT result for the contribution of the dressed gap to the exciton shift corresponds to the same exciton blueshift, in the large detuning limit, obtained through a many-body diagrammatic derivation and interpreted by Combescot[3] as coming from *Pauli exclusion between the two e-h pairs forming the biexciton*. We mention therefore that the present Kane results demonstrate that dressed-band effects within a three-band model calculation would change the zeroth-order term of the two-band many-body diagrammatic approach,[3] and suggest that the contribution due to more realistic band-dressing calculations may be as important as many-body corrections.

It is important to point out that the present exciton calculations were performed within the fractional-dimensional space approach[13] which was shown to give results in quite good agreement with accurate variational procedures. On the other hand, recent perturbation-theory calculations within a many-body approach[15] lead to values of the exciton binding energies in semiconductor QW's that agree very well with those calculated using a variational procedure. One may therefore conclude that the present renormalized approach for evaluating the exciton binding energy corresponds essentially to a diagrammatic summation of ladder diagrams associated with laser-dressed *e-h* bubbles (see Fig. 7) built from a renormalized electron and a renormalized hole in the presence of the Coulomb interaction. Alternatively, as this study is a one-body nonperturbative treatment which incorporates the laser field to all orders, one may use a many-body formalism[15] when considering the exciton optical Stark shift, and take into account the effects of the laser-semiconductor interaction, in the large detuning limit, through the renormalization of the effective electron and hole masses and of the semiconductor gap.

In order to probe the laser-dressed semiconductor system, one may consider the excitonic absorption of a test beam of frequency ω_T and electron test probe coupling constant λ_T, which is described in terms of the dressed-exciton Green's function $\tilde{G}(\mathbf{k},\omega_T)$ by

$$A(\omega_T)\propto 4\lambda_T^2\,\mathrm{Im}\sum_{\mathbf{k}}\tilde{G}(\mathbf{k},\omega_T), \tag{15}$$

where $\tilde{G}(\mathbf{k},\omega_T)$ is given by

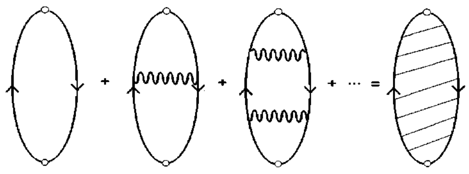
$$\tilde{G}(\mathbf{k},\omega_T)=\tilde{G}_0(\mathbf{k},\omega_T)+\sum_{\mathbf{k}'}\tilde{G}_0(\mathbf{k},\omega_T)V_{k,k'}\tilde{G}_0(\mathbf{k}',\omega_T)+\cdots, \tag{16}$$

$V_{k,k'}$ is the Fourier transform of the one-pair Coulomb potential (e^2/r), and $\tilde{G}_0(\mathbf{k},\omega_T)$ corresponds to the renormalized *e-h* propagator in the absence of Coulomb interactions,

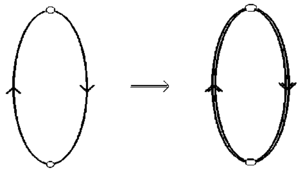
$$\tilde{G}_0(\mathbf{k},\omega)=[\hbar\omega-\tilde{\epsilon}_0(0)-\hbar^2k^2/2\mu]^{-1}, \tag{17}$$

with $\tilde{\epsilon}_0(0)$ and $1/\mu=1/m_+-1/m_-$, being the field renormalized energy gap and dressed-exciton reduced mass, respectively.

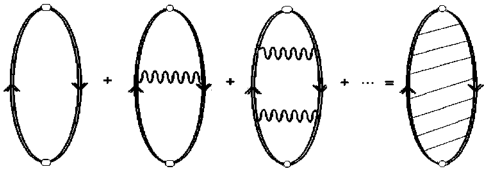
The summation of the renormalized ladder diagrams (see Fig. 7) may be performed exactly,[3] and one obtains for the absorption of a probe beam in the presence of pump photons



(a) bare exciton



(b) laser dressing



(c) dressed exciton

FIG. 7. (a) Coulomb interaction between electron and hole leading to the exciton; (b) Laser-dressed *e-h* bubble built from a renormalized electron and a renormalized hole; (c) Coulomb interaction for a renormalized *e-h* pair leading to the laser-dressed exciton.

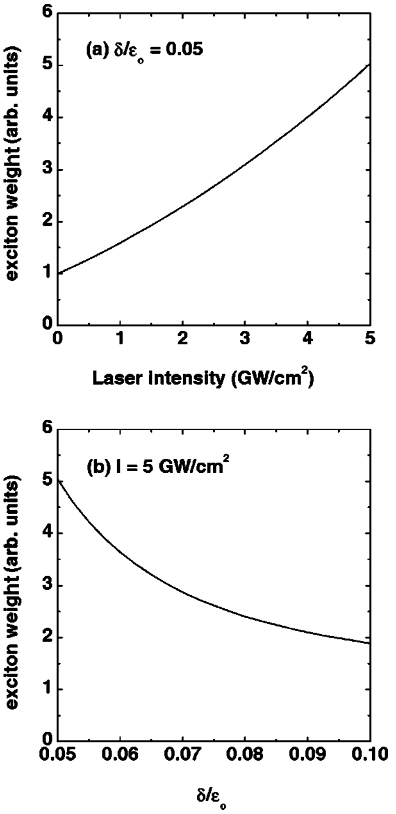


FIG. 8. Laser-dressed weight of the exciton peak as a function of (a) the pump-laser intensity for a fixed detuning $\delta/\epsilon_0=0.05$ and (b) the pump-laser detuning for a fixed laser intensity $I/I_0=10^{-4}$ (or $I=5$ GW/cm^2), for a 100 Å GaAs-Ga$_{0.7}$Al$_{0.3}$As QW.

$$A(\omega_T)\propto 4\pi\lambda_T^2\sum_i |\tilde{\phi}_i^*(\mathbf{r}=\mathbf{0})|^2\delta(\hbar\tilde{\omega}_i-\hbar\omega_T), \qquad (18)$$

where $\hbar\tilde{\omega}_i$ and $\tilde{\phi}_i(\mathbf{r})$ are the dressed-exciton energies and wave functions, respectively, which may be evaluated by using either many-body perturbation theory, or a variational approach, fractional-dimensional scheme, etc. Figure 8 displays the fractional-dimensional[13] theoretical results for the laser-dressed weight of the exciton line in a 100 Å GaAs-Ga$_{0.7}$Al$_{0.3}$As QW. As expected, the exciton weight increases with increased laser intensity, and decreases with increasing laser detuning.

IV. DRESSED HYDROGENIC STATES IN SEMICONDUCTOR QUANTUM WELLS UNDER APPLIED MAGNETIC FIELDS

As a further application of the present renormalized approach, we investigate the effects of laser dressing on donor states in semiconductor QW's, as impurities play a quite relevant role in a number of properties in semiconductor systems. Here we study the laser effects on the on-center donor-impurity states of a 100 Å GaAs-Ga$_{0.7}$Al$_{0.3}$As QW under the presence of an applied magnetic field perpendicular to the QW interfaces.[2] The importance of the laser dressing on the impurity levels may be inferred via a comparison with the corresponding effects of an externally applied magnetic field. We follow a standard variational scheme within a renormalized laser-dressed effective-mass approach and choose a 1s-like on-center trial envelope wave function as a product of the exact solution of the square well QW potential and a hydrogeniclike variational 1s function.[2] The on-center donor energies may then be obtained as functions of the applied magnetic field, well size, laser intensity, detuning, etc.

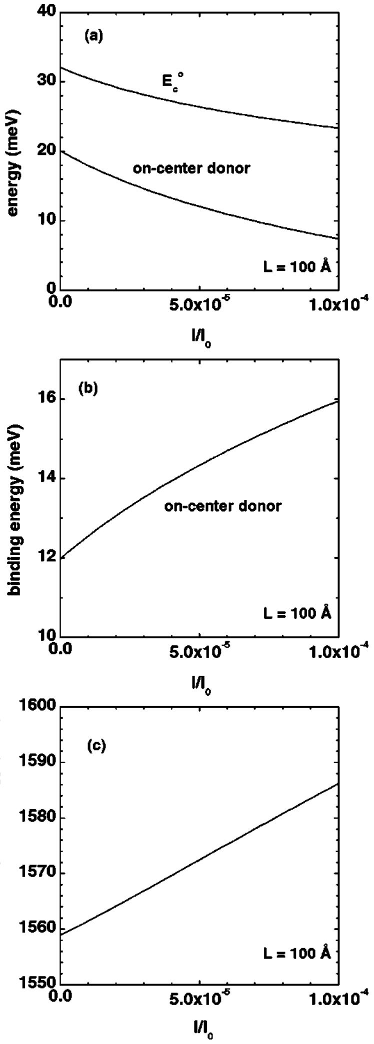


FIG. 9. Laser-intensity dependence of (a) on-center 1s-like donor energies and ground-state energy E_c^0 of the first conduction miniband, (b) on-center 1s-like donor binding energy, and (c) on-center donor peak energy, for a 100 Å GaAs-Ga$_{0.7}$Al$_{0.3}$As QW. Results are shown within the Kane model and for a laser detuning $\delta/\epsilon_0 = 0.05$.

The laser-intensity dependence of dressed-donor ground-state energies and QW first energy level E_c^0 as well as the 1s-like donor binding energy and on-center donor peak energy are shown in Fig. 9 for a 100 Å GaAs-Ga$_{0.7}$Al$_{0.3}$As QW. The theoretical results are obtained within the three-band Kane model and for a laser detuning $\delta=0.05\epsilon_0$. One notices that the laser effect on the dressed-donor binding energies may be significant (≈ 4 meV for $I/I_0=10^{-4}$), with a remarkable blueshift of the donor → valence peak energy, due essentially to the laser-induced changes in the QW effective gap. The corresponding dressed-donor results for the

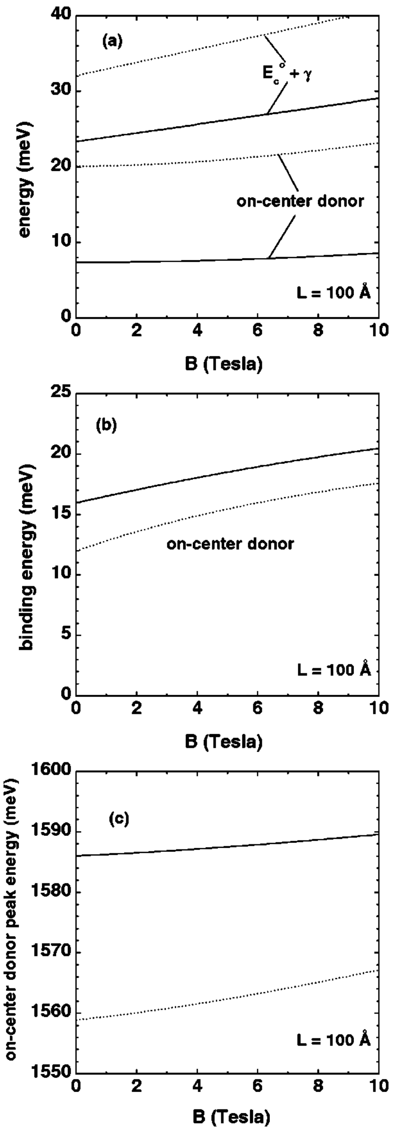


FIG. 10. Same as in Fig. 9 for a laser intensity $I/I_0 = 10^{-4}$ and detuning $\delta/\epsilon_0 = 0.05$ (full curves), with results presented as a function of an applied magnetic field perpendicular to the QW interfaces. Dotted lines are the corresponding results in the absence of laser dressing.

magnetic-field dependence are displayed in Fig. 10 for fixed laser intensity $I/I_0 = 10^{-4}$ and detuning parameter $\delta = 0.05\epsilon_0$, together with the associated results in the absence of laser dressing. One notices that the laser-dressed shift in the donor peak energy is of the same order of magnitude as the QW confined donor binding energy, and much stronger than the corresponding shift induced by the applied magnetic field. The strong blueshift in the donor peak energy could be easily observable, although, to our knowledge, there are no experimental measurements concerning laser effects on shallow-impurity states in doped GaAs-GaAlAs QW's.

V. CONCLUSIONS

We have presented a theoretical approach of the laser-field effects on semiconductor low-dimensional systems by adopting a picture in which the light-matter interaction is taken into account by dressing the semiconductor energy gap and conduction/valence effective masses. Both the two-band and three-band Kane semiconductor models for the electronic band structure are shown to give essentially the same qualitative results for the laser dependence of the dressed semiconductor gap and corresponding effective masses, although an appropriate quantitative comparison with experiment would certainly require a more realistic description of the semiconductor band structure. Furthermore, the present calculations have unambiguously shown that an adequate description of the effects of the laser-semiconductor interaction on the band structure is of considerable importance as a starting point in any more involved many-body approach.

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APPENDIX

By assuming the total angular momentum **J** in the same direction as the wave vector **k**, the Kane eigenvalue problem is reduced to a diagonalization of a Hamiltonian matrix in the basis set of the Γ_6, Γ_7, and Γ_8 edges,[10] which is decoupled in the angular momentum projections $m_J = \pm 1/2$ and 3/2. To second order in k, this procedure leads to a heavy-hole effective mass equal to the bare electron mass m_0, and to a new set of eigenenergies and eigenfunctions, i.e., to parabolic bands written as[10]

$$E_{\Gamma_6} = \frac{\hbar^2 k^2}{2m_{\Gamma_6}}, \tag{A1}$$

$$E_{\Gamma_8} = \frac{\hbar^2 k^2}{2m_{\Gamma_8}^{lh}} - \epsilon_0, \tag{A2}$$

$$E_{\Gamma_7} = \frac{\hbar^2 k^2}{2m_{\Gamma_7^{lh}}} - (\epsilon_0 + \Delta), \tag{A3}$$

with

$$\frac{1}{m_{\Gamma_6}} = \frac{1}{m_0}\left(1 + \frac{4p^2}{3m_0\epsilon_0} + \frac{2p^2}{3m_0(\epsilon_0 + \Delta)}\right), \tag{A4}$$

$$\frac{1}{m_{\Gamma_8^{lh}}} = \frac{1}{m_0}\left(1 - \frac{4p^2}{3m_0\epsilon_0}\right), \tag{A5}$$

$$\frac{1}{m_{\Gamma_7^{lh}}} = \frac{1}{m_0}\left(1 - \frac{2p^2}{3m_0(\epsilon_0 + \Delta)}\right), \tag{A6}$$

where $p = -i\langle s|p_{x(y,z)}|x(y,z)\rangle$ are the matrix elements of the momentum operator with all other interband elements being zero by symmetry, and a new basis set defined by the following normalized wave functions:

$$\Psi_{\Gamma_6}(k)=N_{\Gamma_6}\left(\Psi_{\Gamma_6}(0)-\sqrt{\frac{2}{3}}\frac{\hbar k_z p}{m_0\epsilon_0}\Psi^{lh}_{\Gamma_8}(0)+\frac{1}{\sqrt{3}}\frac{\hbar k_z p}{m_0(\epsilon_0+\Delta)}\Psi^{lh}_{\Gamma_7}(0)\right), \tag{A7}$$

$$\Psi^{lh}_{\Gamma_8}(k)=N^{lh}_{\Gamma_8}\left(\Psi^{lh}_{\Gamma_8}(0)+\sqrt{\frac{2}{3}}\frac{\hbar k_z p}{m_0\epsilon_0}\Psi_{\Gamma_6}(0)\right), \tag{A8}$$

$$\Psi^{lh}_{\Gamma_7}(k)=N^{lh}_{\Gamma_7}\left(\Psi^{lh}_{\Gamma_7}(0)-\frac{1}{\sqrt{3}}\frac{\hbar k_z p}{m_0(\epsilon_0+\Delta)}\Psi_{\Gamma_6}(0)\right), \tag{A9}$$

in which the normalization constants are given by

$$N_{\Gamma_6}^{-2}=1+\frac{\hbar^2 k_z^2 p^2}{m_0^2}\left(\frac{2}{3\epsilon_0^2}+\frac{1}{3(\epsilon_0+\Delta)^2}\right), \tag{A10}$$

$$N^{lh\,-2}_{\Gamma_8}=1+\frac{2}{3}\frac{\hbar^2 k_z^2 p^2}{m_0^2\epsilon_0^2}, \tag{A11}$$

$$N^{lh\,-2}_{\Gamma_7}=1+\frac{1}{3}\frac{\hbar^2 k_z^2 p^2}{m_0^2(\epsilon_0+\Delta)^2}. \tag{A12}$$

Finally, one may use the above electronic states, extend the dressed-atom approach,[11] and diagonalize the Hamiltonian of Eq. (1) within the $|\Gamma_8,N+1\rangle\equiv|\Gamma_8\rangle\otimes|N+1\rangle$ and $|\Gamma_6,N\rangle\equiv|\Gamma_6\rangle\otimes|N\rangle$ manifold, where $|N\rangle$ represents a Fock state with N photons [cf. Eq. (2) for the dressed-band Hamiltonian matrix]. Notice that the influence of the $|\Gamma_7,N+1\rangle$ state was taken into account by considering the second-order energy correction due to the laser coupling between the $|\Gamma_6,N\rangle$ and $|\Gamma_7,N+1\rangle$ states, which corresponds to folding back the 3×3 Hamiltonian matrix into a 2×2 matrix (the laser does not couple the $|\Gamma_8,N+1\rangle$ and $|\Gamma_7,N+1\rangle$ states).

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