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Combined effects of intense laser field and applied electric field on exciton states in GaAs quantum wells: Transition from the single to double quantum well

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The effects of intense laser radiation on the exciton states in GaAs-Ga$_{1-x}$Al$_x$As quantum wells are studied with the inclusion of applied dc electric fields oriented along the growth direction of the system. The calculations are made within the effective mass and parabolic band approximations. The intense laser effects have been included along the lines of the Floquet method, modifying the confinement potential associated to the heterostructure. The results for the exciton binding energy, the energy of the exciton-related photoluminescence peak, and the carriers overlap integral are presented for several configurations of the quantum well size, the strength of the applied electric fields, and the incident laser radiation.

1 Introduction

The evolution of the emerging field of nanoelectronics is closely related to the study of the effects of external electromagnetic fields on the optical and transport properties of low-dimensional systems [1]. The electron and hole states in nanostructures are affected by the application of electric and/or magnetic fields, and also by external perturbations like hydrostatic pressure or temperature [2].

Research activities on the interaction of intense laser fields (ILF) with carriers in semiconductor nanostructures were stimulated by the development of high-power tunable laser sources, such as free electron lasers [3]. Interesting physical phenomena have been revealed. For instance, the presence of changes in the electron density of states in quantum wells (QWs) and quantum well wires (QWWs) [4, 5], the measurement of zero-resistance states in two-dimensional electron gases under microwave radiation [6], terahertz resonant absorption in QWs [7], and Floquet-Bloch states in single-walled carbon nanotubes [8], among others.

The influence of an intense high-frequency laser field on the physical properties of bulk semiconductors has received some discussion and analysis in the literature [9–12]. A number of investigations on the effect of laser fields on low dimensional heterostructures have been published. The dressed atom approach was extended by Brandi et al. [13, 14] to treat the influence of the laser field upon a semiconductor system. In the model, the interaction with the laser is taken into account through the renormalization of the semiconductor effective mass. More recently, a theoretical study of the combined effects of intense high frequency laser and static magnetic fields on the binding and transition energies was developed by Niculescu and Burileanu [15] to investigate the ground and some excited states of an on-center hydrogenic donor in a cylindrical GaAs QWW. It was found that the effect of the laser field is more pronounced for s-like states, whereas for 2p-like states the binding energy is weakly dependent on the laser dressing parameter. Using the same scheme, the laser-dressing effects on the electron g-factor in GaAs-Ga$_{1-x}$Al$_x$As QWs and QWWs under applied magnetic fields have also been calculated [16]. The possibility of manipulating and tuning the conduction-electron g-factor in heterostructures by changing the detuning and laser field intensity was discussed in that work.

In addition, the ILF effects on the density of impurity states of shallow donors in a square, V-shaped, and inverse V-shaped QWs have been studied by Niculescu et al. [17, 18]. It was concluded that a proper consideration of the density of impurity states may be relevant in the interpretation of the optical phenomena associated with shallow impurities in QWs; where there is a competition between the effects of an ILF, the applied dc electric field and the quantum confinement. The laser effects have also been included in calculations of a donor-impurity polarizability in a QW under an applied electric field, with the finding of a lack of monotonicity for the polarizability as a function of external perturbations like an applied electric field and the incoming laser radiation [19].

The appearance of an unexpected transition from single to double QW potential induced by ILF was revealed in a theoretical study from Lima et al. [20]. Within the laser-dressed potential model it is found that the formation of a double-well potential for values of the laser frequencies and intensities such that the so-called laser-dressing parameter α_0 is larger than $L/2$, where L is the QW width. This fact is associated with the possibility of generating resonant states into the system's channel, as well as of controlling the population inversion in QW lasers operating in the optical pumping scheme. Finally, the study of ILF effects has been extended to another heterostructures such as QWWs and QDs with several configurations of the quantum confinement, stoichiometry of the well and barrier regions, geometries of the systems, and external perturbations like applied electric and magnetic fields and hydrostatic pressure [21–24].

The knowledge of exciton states is important for the correct understanding of some optical properties in the semiconducting low-dimensional systems. Therefore, the investigation of the excitonic properties in heterostructures under ILF is, arguably, an area of current interest. Accordingly, the present work is concerned with the theoretical study of the effects of ILF on the exciton states in single QWs. The research is extended to include the additional influence of an applied dc electric field oriented along the growth direction. The laser-dressed potential above mentioned, as well as the effect of single-to-double potential well transition are the subject of particular investigation in our case. The paper is organized as follows. In Section 2, we describe the theoretical framework. Section 3 is dedicated to the results and discussion, and finally, our conclusions are given in Section 4.

2 Theoretical framework

Here we are concerned with the effects of ILF on the binding energy of a heavy-hole exciton in a single GaAs-Ga$_{1-x}$Al$_x$As QW grown along the z-axis and in the presence of applied electric field. The envelope-function and parabolic-band approximations are assumed. The choice for the electric field orientation is $\boldsymbol{F} = (0, 0, -F)$. Then, the Hamiltonian for the confined exciton is given by

$$\begin{aligned}\hat{H} = &-\frac{\hbar^2}{2m_e^*}\nabla_e^2 + V_e(z_e) + e\boldsymbol{F}\cdot\boldsymbol{r}_e \\ &-\frac{\hbar^2}{2m_h^*}\nabla_h^2 + V_h(z_h) - e\boldsymbol{F}\cdot\boldsymbol{r}_h - \frac{e^2}{\varepsilon|\boldsymbol{r}_e - \boldsymbol{r}_h|},\end{aligned} \tag{1}$$

where $\boldsymbol{r}_e$ ($\boldsymbol{r}_h$) is the electron (hole) coordinate, m_e^* (m_h^*) is the spherically symmetric electron (hole) effective mass, ε is the static dielectric constant, e is the absolute value of the electron charge, and $V_i(z_i)$ ($i =$ e, h) are the QW confining potential for the electron and hole. The functional form of the potential in the absence of the ILF is given by

$$V_i(z_i) = \begin{cases} 0, & |z_i| \le +L/2, \\ V_i, & +L/2 < |z_i| \le +L_\infty/2, \\ \infty, & |z_i| > +L_\infty/2. \end{cases} \tag{2}$$

The electron and hole effective masses and the static dielectric constant have been considered to have the same value (the one in GaAs) throughout the GaAs-Ga$_{1-x}$Al$_x$As QW.

In order to find the eigenfunctions $\Psi(\boldsymbol{r}_e, \boldsymbol{r}_h)$ of the exciton Hamiltonian [Eq. (1)], it must be noticed that the total in-plane exciton momentum $\widehat{\boldsymbol{P}} = (\widehat{P}_x, \widehat{P}_y)$ is an exact integral of motion [25–27] and the exciton envelope wave function may be written as

$$\Psi(\boldsymbol{r}_e, \boldsymbol{r}_h) = \frac{\exp[(i/\hbar)(\boldsymbol{P}\cdot\boldsymbol{R})]}{\sqrt{S}}\phi(\rho, z_e, z_h), \tag{3}$$

where S is the transverse area of the GaAs-Ga$_{1-x}$Al$_x$As QW, $\boldsymbol{R}$ and $\boldsymbol{\rho}$ are the in-plane center of mass and relative exciton coordinates, and $\boldsymbol{P} = (P_x, P_y)$ is the eigenvalue of the operator $\hat{\boldsymbol{P}}$. If $\boldsymbol{P} = 0$ (ground state), $\phi(\rho, z_e, z_h)$ is the eigenfunction of the Hamiltonian

$$\hat{H} = \frac{\widehat{p}_\rho^{\,2}}{2\mu} + \hat{H}_e + \hat{H}_h - \frac{e^2}{\varepsilon[\rho^2 + (z_e - z_h)]^{\frac{1}{2}}}, \tag{4}$$

where $\widehat{\boldsymbol{p}}_\rho = \widehat{x}\,\widehat{p}_x + \widehat{y}\,\widehat{p}_y$, $\mu = m_e^* m_h^*/(m_e^* + m_h^*)$,

$$\hat{H}_e = \frac{\widehat{p}_{z_e}^{\,2}}{2m_e^*} + V_e(z_e) - eFz_e, \tag{5}$$

and

$$\hat{H}_h = \frac{\widehat{p}_{z_h}^{\,2}}{2m_h^*} + V_h(z_h) + eFz_h. \tag{6}$$

The method for the obtention of the electron and hole states is based on the work by Xia and Fan [28]. The z-dependent eigenfunctions of the Hamiltonians in Eqs. (4) and (5) ($f(z_i)$, $i =$ e, h) are written as expansions of the type

$$f(z_i) = \left(\frac{2}{L_\infty}\right)^{\frac{1}{2}} \sum_{m=1}^{\infty} C_m \sin\left(\frac{m\pi z_i}{L_\infty} + \frac{m\pi}{2}\right). \tag{7}$$

Naturally, the number of terms included in the calculation cannot be infinite. It has been shown in this case that the convergence of Eq. (7), for the specific size of the QW considered ($L_\infty = 600$ Å is the width of the well of rigid barriers in this work), is ensured until 10^{-3} meV with the incorporation of 200 terms in the expansion of the $f(z_i)$ wavefunctions.

In order to consider the ILF effects (the polarization of the laser radiation is parallel to the z-direction), the so-called Floquet method is adopted [29]. According to this formalism, the second term at the right hand side in Eqs. (4) and (5) must be replaced by

$$V(z_i) \rightarrow \langle V\rangle(z_i,\, \alpha_{0i}),$$

where for $\alpha_{0i} \leq L/2$

$$\langle V\rangle(z_i,\alpha_{0i}) = \frac{V_i}{\pi} \times \begin{cases} \pi, & -\infty < z_i \leq -L/2-\alpha_{0i}, \\ \arccos\left(\dfrac{L/2+z_i}{\alpha_{0i}}\right), & -L/2-\alpha_{0i} < z_i \leq -L/2+\alpha_{0i}, \\ 0, & -L/2+\alpha_{0i} < z_i \leq +L/2-\alpha_{0i}, \\ \arccos\left(\dfrac{L/2-z_i}{\alpha_{0i}}\right), & +L/2-\alpha_{0i} < z_i \leq +L/2+\alpha_{0i}, \\ \pi, & +L/2+\alpha_{0i} < z_i < +\infty, \end{cases} \tag{8}$$

and for $\alpha_{0i} > L/2$

$$\langle V\rangle(z_i,\alpha_{0i}) = \frac{V_i}{\pi} \times \begin{cases} \pi, & -\infty < z_i \leq -L/2-\alpha_{0i}, \\ \arccos\left(\dfrac{L/2+z_i}{\alpha_{0i}}\right), & -L/2-\alpha_{0i} < z_i \leq +L/2-\alpha_{0i}, \\ \pi + \arcsin\left(\dfrac{z_i-L/2}{\alpha_{0i}}\right) - \arcsin\left(\dfrac{z_i+L/2}{\alpha_{0i}}\right), & +L/2-\alpha_{0i} < z_i \leq -L/2+\alpha_{0i}, \\ \arccos\left(\dfrac{L/2-z_i}{\alpha_{0i}}\right), & -L/2+\alpha_{0i} < z_i \leq +L/2+\alpha_{0i}, \\ \pi, & +L/2+\alpha_{0i} < z_i < +\infty. \end{cases} \tag{9}$$

Here

$$\alpha_{0i} = (eA_0)/(m_i^* c\omega) = (I^{1/2}/\omega^2)(e/m_i^*)(8\pi/c)^{1/2}, \tag{10}$$

is the laser-dressing parameter (from now on ILF-parameter) [30]. In Eq. (10), I and ω are, respectively, the average intensity and the frequency of the laser, c is the velocity of the light, and A_0 is the amplitude of the vector potential associated with the incident radiation.

Under the laser effects the last term of Eq. (4)—the one-center electron–hole Coulomb interaction—must be replaced by a two-center Coulomb interaction as

$$\langle V\rangle_C(z_e, z_h, \alpha_0) = -\frac{e^2}{2\varepsilon\left[\rho^2 + (z_{eh}-\alpha_0)^2\right]^{1/2}} - \frac{e^2}{2\varepsilon\sqrt{\rho^2 + (z_{eh}+\alpha_0)^2}}, \tag{11}$$

where $z_{eh} = z_e - z_h$ and $\alpha_0 = (eA_0)/(\mu c\omega)$. In our calculations we have considered the approximation $\alpha_{0i} = \alpha_0$, $i =$ e, h. This approximation overestimates the ILF on the heavy-hole confinement potential, however, in the case of light-hole excitons it is a very reasonable consideration. Extended details about dressed potential in Eqs. (8), (9), and (11) and the nonperturbative theory developed to describe the atomic behavior in intense high frequency laser field can be found in Refs. [20, 31–35].

The procedure adopted for the variational evaluation of the exciton wavefunction in the GaAs-$Ga_{1-x}Al_xAs$ QW under the ILF effects is the one proposed by Fox et al. [36] and Galbraith and Duggan [37]. The functional

$$E(\lambda) = \langle \phi(\rho,\, z_e,\, z_h)|H|\phi(\rho,\, z_e,\, z_h)\rangle \tag{12}$$

must be minimized with the use of the variational wavefunctions

$$\phi(\rho, z_e, z_h) = Nf(z_e)f(z_h)\exp(-\lambda|\boldsymbol{r}|), \quad (13)$$

with $\boldsymbol{r} = \boldsymbol{r}_e - \boldsymbol{r}_h$. λ is the variational parameter. A second choice for the variational trial function would be

$$\phi(\rho, z_e, z_h) = Nf(z_e)f(z_h)\exp[-\lambda(|\boldsymbol{r}_1| + |\boldsymbol{r}_2|)], \quad (14)$$

where $\boldsymbol{r}_1 = \boldsymbol{r} - (0, 0, \alpha_0)$ and $\boldsymbol{r}_2 = \boldsymbol{r} + (0, 0, \alpha_0)$. Both propositions are going to be used in this work.

The exciton binding energy is obtained from the definition

$$E_b = E_0 - E(\lambda_{min}), \quad (15)$$

where E_0 is the eigenvalue of the Hamiltonian in Eq. (4) without the Coulomb interaction term—the last one at the right hand side—and λ_{min} is the value of the variational parameter in which the energy in Eq. (15) reaches its minimum.

3 Results and discussion The numerical outcome of the study about the intense laser effects on the exciton binding energy is reported for the case of a GaAs-$Ga_{0.7}Al_{0.3}As$ single QW, as a prototypical system. The confining potential configuration chosen is that of a 60% (40%) of the barrier-well band offset for electrons (holes) [$V_e = 0.6(1155x + 370x^2)$ meV and $V_h = 0.4(1155x + 370x^2)$ meV, where x is the aluminum molar fraction in the barrier material]. The parameters used in the calculations are [28]: $\varepsilon = 12.65$, $m_e^* = 0.067\,m_0$, and $m_h^* = 0.34\,m_0$ (where m_0 is the free electron effective mass).

The potential responsible for the confinement of electrons and holes in the system is depicted in Fig. 1. In the column of figures at the left hand side the conduction band profile is presented whilst the corresponding straightened up valence band profiles are shown in the column at the right. The evolution of the QW profile associated with the change in the laser intensity—without applied dc field—can be seen by observing rows one to four in the picture. The transition from a single to a double QW potential is observed in the figures of the fourth road. In the fifth row the deformation of the double QW profile due to the application of a dc electric field is shown as well. In all cases, the curve of the ground state density of probability for confined electron and heavy holes is included.

For zero applied electric field, the binding energy of the heavy-hole exciton in a GaAs-$Ga_{0.7}Al_{0.3}As$ QW is presented in Fig. 2 as a function of the well-width, for several values of the ILF-parameter. In accordance to the use of the two propositions for the exciton trial wavefunction, when the ILF-parameter is zero, the results of both choices are coincident [it must be taken into account that the variational parameter in Eq. (13) must necessarily be twice the one obtained with the use of Eq. (14)]. For finite values of the ILF-parameter it is observed that the values of E_b that come from the two trial functions are almost the same when the QW width is small. A consequence of the use of Eq. (14) is the improvement in the obtained values of E_b. This is explained by the form in which the binding energy is defined in Eq. (15). For this reason, the results reported in the remaining of the article for this energy will be those obtained via Eq. (14).

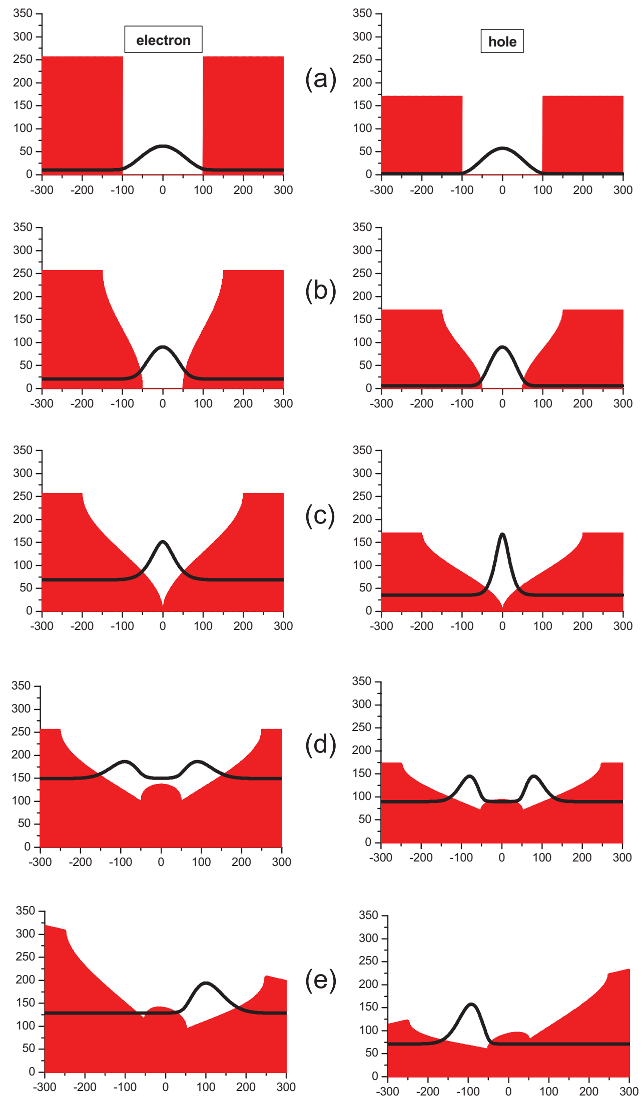

Figure 1 (online color at: www.pss-b.com) Confinement potential and z-dependent amplitude of probability for the first electron (left panel) and hole (right panel) confined states in a GaAs-$Ga_{0.7}Al_{0.3}As$ QW. The results are for $L = 200$ Å, and several values of the ILF-parameter have been considered: $\alpha_0 = 0$ (a), $\alpha_0 = 50$ Å (b), $\alpha_0 = 100$ Å (c), $\alpha_0 = 150$ Å (d, e). In (a–d) the results are for $F = 0$ whereas in (e) the results are for $F = 20$ kV/cm.

From the analysis of Fig. 2 it is observed that:

(i) There is a coincidence of all the curves of the exciton binding energy when the QW width is equals to zero, independently of the value of the ILF-parameter. The corresponding value of E_b is no other than the binding energy of an exciton confined within the infinite barrier QW with a 600 Å width; and is obtained as a consequence of reaching the proper limit for $L \to 0$. We must point out that in the limit $L \to 0$ our results are in perfect accordance with previous works related with excitons in quantum wells with infinite potential barriers [38]. Here, we define the effective Bohr radius (as a unit length) and the effective Rydberg (as the unit energy), respectively, as $a_0 = \varepsilon a_B m_0/\mu$ and $R_0 = R\mu/(m_0\varepsilon^2)$, where $a_B = 0.529177$ Å is the atomic Bohr radius and $R = 13.6058$ eV is the Rydberg energy. In our case, with the numerical values considered in the work, we obtain $a_0 = 119.631$ Å and $R_0 = 4.7559$ meV. Given this, in the limit $L \to 0$, our results correspond to an exciton confined in quantum well of infinite barriers wit a width $L_\infty = 5.0154 a_0$ and a binding energy of 5.69 meV $\approx 1.20 R_0$. In the work by Bastard et al. [38]—Fig. 2—, for a quantum well of width $5.01 a_0$ they report a binding energy of $\approx 1.21 R_0$. The reader is suggested to observe the comparison between the limit of our results obtained here when $L \to 0$ and those of Bastard et al. [38] which are represented by the full dots at the left side of Fig. 2. In addition, for the sake of comparison and validation of the present calculation, in the inset of the figure there are shown our results for $\alpha_0 = 0$ (solid line), the corresponding calculations from Matos-Abiague et al. [39] (full dots), and few experimental data obtained in single QWs [40–42] (full squares). It is readily apparent the accordance of the outcome of the present calculation with the behavior described both in previous theoretical works and experiments, reported in the literature.

(ii) The behavior of the exciton binding energy for $\alpha_0 = 0$ is coincident with that widely discussed in the literature of QW. There is a growth in E_b as a function of L until a maximum is reached, with a subsequent decrease. The initial increase seen for the lower values of the well width is consequence of the confinement of the carriers introduced by the very QW barriers. The augment of the binding energy with L is related with the fact that the there is an augment of the carrier density of probability in the well region (together with the reduction of its value in the barriers). After reaching the maximum, the increment of the QW width is reflected in the fall of the binding energy values given the larger separation of the potential barriers, with the consequent reduction of the carrier confinement. It should be noticed that the monotonic behavior of the exciton binding energy for zero ILF is the same registered for finite values of such parameter. That is, as long as the well width is augmented, there is a growth in the curves until a maximum is reached and then there is a continuous decrease of E_b.

(iii) From the comparison of the curves in Fig. 2 for a fixed value of L, a reduction of E_b as a function of the ILF-parameter can be noticed. Splitting the discussion into two different regimes for the ILF the reason for such a behavior is explained as follows: When $\alpha_0 \leq L/2$, the augment of the ILF-parameter is associated with a decrease of the effective width of the QW [see Fig. 1(a–c)]. As a consequence, there is an augment of the carrier localization within the central region of the heterostructure. But, in accordance with Eq. (11), when there is a growth in the ILF-parameter, a separation of both Coulomb centers with respect to the central region of the structure is gradually induced. As a consequence, a higher localization of the carriers around $z = 0$ and their further separation from the Coulomb centers are responsible for the fall in E_b. It is clearly observed from Fig. 1(c) that—in this regime of the ILF—the height of the potential barriers is partially reduced and that there is a widening of the effective QW, with the consequent drop in the strength of the carrier confinement. In the case of small well width—for instance, around $L = 20$ Å—only a single maximum in the density of probability is reached for both for electrons and holes in the region around $z = 0$. The combination of this situation with the fall of the confinement due to the diminishing height of the potential barriers, as well as the growing separation of the electron and hole Coulomb centers is the reason for which the binding energy is diminished. In the situation of larger values of the L—say 200 Å—the potential profile turns to a double QW configuration, induced by the ILF. The electron and probability densities have their maxima in the regions close to the Coulomb centers.

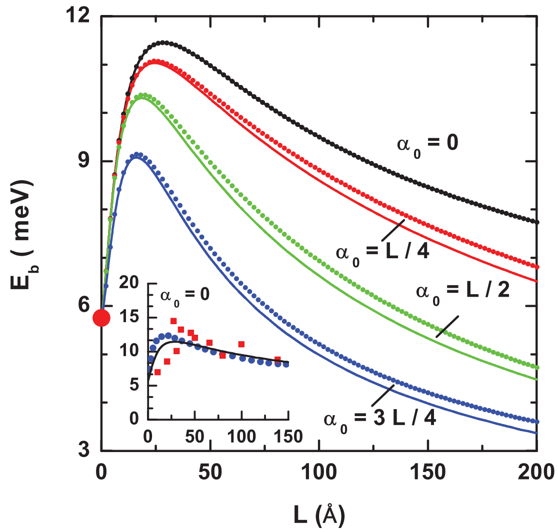

Figure 2 (online color at: www.pss-b.com) Binding energy of heavy-hole exciton in a GaAs-$Ga_{0.7}Al_{0.3}As$ QW as a function of the well-width, for several values of the ILF-parameter with $F = 0$. Lines and dots are obtained by using the trial wave functions in Eqs. (13) and (14), respectively. The full dot at the left vertical-axis corresponds to the exact result for the heavy-hole exciton binding energy in a $L = 600$ Å single QW with infinite potential barrier [38]. In the inset there are shown our results for $\alpha_0 = 0$ (solid line), the corresponding calculations from Matos-Abiague et al. [39] (full dots), and few experimental data in single QWs [40–42] (full squares).

Therefore, there will be a reinforcement of the electrostatic interaction and, as a consequence, an increment in the binding energy. However, this effect is compensated and surpassed by the loss of carrier confinement [see Fig. 1(d)] related to the barrier reduction. Thus, the overall result is the decrease in E_b, as can be observed when the curves for $\alpha_0 = 3L/4$ and $\alpha_0 = L/2$ in Fig. 2 are compared.

At this point it must be clarified that the quality of the trial wavefunctions used in the present work is a restriction to go beyond $3L/4$ in the values of the ILF-parameter considered. Larger values of α_0 would require an improvement in the choice of $\phi(\boldsymbol{r})$, taken into account the loss of spherical symmetry associated with the large separation between the Coulomb centers.

The results obtained for the exciton binding energy of a heavy-hole exciton in a GaAs-$Ga_{0.7}Al_{0.3}As$ QW are shown in Fig. 3, as a function of the ILF-parameter, for several values of the quantum well-width and zero applied electric field. They can be considered as a confirmation of what has been discussed above. For a fixed value of the ILF-parameter the binding energy is a decreasing function of the well width; and for a fixed L the value of this quantity is decreased as long as the ILF is higher.

Unlike the curves with $L = 50$ Å and $L = 100$ Å, in the case of $L = 150$, 200 Å, it is noticed that close to the value $\alpha_0 = 0.6 \times 3L/4$ there is a fall in the rate of decrease in the curves of E_b as a function of the laser parameter. This is exactly the value of α_0 for which—given the particular dimensions of the heterostructure—the laser-induced transition from single isolated well to double isolated well has taken place. The slight shift towards higher binding energy values is due to the strengthening of the electrostatic interaction coming from the appearance of maxima in the electron and hole densities of probability close to the Coulomb centers. The effects on the E_b of the application of a dc electric field are shown in Fig. 4 for several values of the ILF-parameter, and a fixed QW width of 200 Å. When no laser field is present, the binding energy is a decreasing function of the dc field intensity due to the reduction of the Coulombic coupling associated with the enlargement of the field-induced effective separation between electron and hole. The situation in which the localization of the electron is mostly within the region $0 < z < +L/2$, and that of the hole is mostly within the region $-L/2 < z < 0$ is widely known as the spatially-indirect exciton. The decrease of the E_b for $F = 0$ in Fig. 4 as a result of the growth in the ILF-parameter is consistent with the discussion made above for Fig. 3. However, as soon as the electric field is connected, there is a change in this behavior (see for example the binding energy at $F = 30$ kV/cm: an augment in the binding energy with the ILF-parameter is first observed and then a reduction in this quantity, is detected as can be concluded from the comparison of the different curves). As it is observed from Fig. 4 for $\alpha_0 = 50$ Å, there is now a slower fall of the binding energy, and a slightly steeper decrease when $\alpha_0 = 150$ Å. But there is also a rather surprising slight increase of E_b as a function of F when $\alpha_0 = 100$ Å. A closer look is needed in this case.

The carrier confinement is affected by the asymmetry introduced as a consequence of the inclination of the potential barriers due to the dc applied field. In the case of the electron the barrier is lowered at $z = +L/2$ and for the

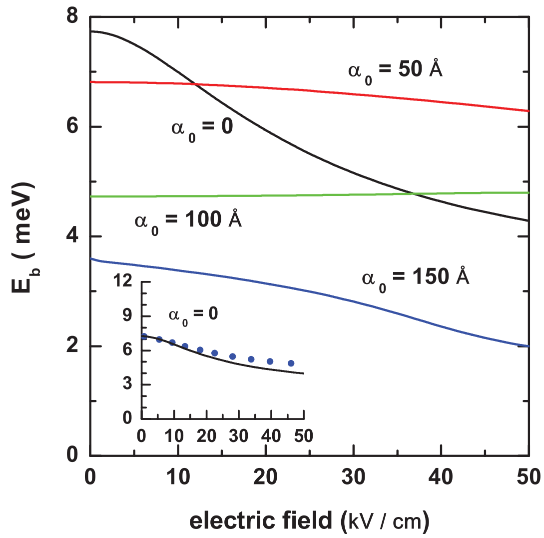

Figure 4 (online color at: www.pss-b.com) Binding energy of heavy-hole exciton in a GaAs-$Ga_{0.7}Al_{0.3}As$ QW as a function of the applied electric field with $L = 200$ Å and several values of the ILF-parameter. For the sake of comparison, in the inset we present results for $\alpha_0 = 0$ (solid line) together with the calculations by Nojima [43] in GaAs-$Ga_{0.75}Al_{0.25}As$ single QWs with $L = 200$ Å (full dots).

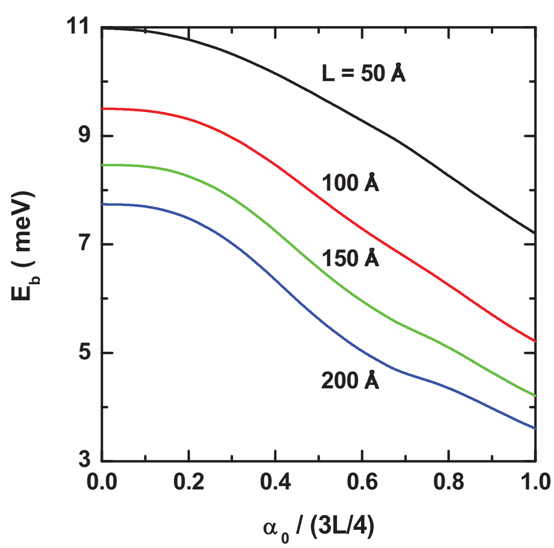

Figure 3 (online color at: www.pss-b.com) Binding energy of heavy-hole exciton in a GaAs-$Ga_{0.7}Al_{0.3}As$ QW as a function of the ILF-parameter, for several values of the quantum well-width with $F = 0$.

hole, it is lowered at $z=-L/2$, as can be seen in Fig. 1(e). This is reflected in a decrease of the carrier localization, and in the fall of E_b. For a fixed value of the laser parameter it is clear that there are two induced Coulomb centers and that the maximum in the density or probability is shifted by the dc field towards the Coulomb center close to $z=\alpha_0$ ($z=-\alpha_0$) in the case of the electron (hole). The fact that the two particles are displaced to the proximity of different Coulomb centers is additionally responsible for the fall in the exciton binding energy. Finally, the two effects—the diminishing in the effective potential barrier responsible for the carrier confinement, and the shifting of the densities of probability of the two carriers with respect to the two Coulomb centers—are additive and the value of the binding energy is brought down by the effect of the applied electric field.

With the intention to compare with previous works, in the inset of Fig. 4 we present our results for $\alpha_0=0$ (solid line) together with the calculation of Nojima [43] in single GaAs-$Ga_{0.75}Al_{0.25}As$ QWs with $L=200$ Å (full dots) under the effects of electric fields. It is possible to see that we are reproducing the same behavior reported by Nojima [43]. The difference observed for electric fields larger than 20 kV/cm can be attributed to the spherical character of the hole effective masses adopted in our model. A more exact calculation should take into account the anisotropy of the heavy-hole effective mass along the parallel and perpendicular directions to the growth direction of the heterostructure.

From the Fig. 4 it is seen that the separation between two distinct regimes of monotonicity of the binding energy is marked at the value $F=12$ kV/cm. When $F\leq 12$ kV/cm, the binding energy is always a decreasing function of the ILF-parameter, whereas for $F>12$ kV/cm the binding energy is an increasing function of the ILF-parameter. A maximum in E_b is reached for specific values of the ILF-parameter depending on the electric field strength. The reason of this behavior is found in the fact that the hole is much more sensitive to the dc field effects than the electron, as can be seen from Fig. 5. There, the densities of probability for electrons and holes are shown for different intensities of the dc field for a fixed QW width and a fixed value of the ILF-parameter.

The particular situation of $\alpha_0=100$ Å with the slight increase of the exciton binding energy is due to the following reason: there are two Coulomb centers exactly located at $\pm L/2$. When the electric field is applied, the hole is displaced towards the Coulomb center at $-L/2$ whilst the position of the electron is kept approximately localized around the middle region of the heterostructure. As a result of this space configuration of the states, the electrostatic interaction of one the particles (the hole) is reinforced. Surely, for high values of the dc electric field—not shown here—there must be a displacement of the electron, approaching the barrier at $z=+L/2$. Therefore, also for $L=100$ Å and in the range of high applied electric fields, E_b must be a decreasing function of the applied dc field.

In the Fig. 6 there are depicted the results for the binding energy of heavy-hole exciton in a GaAs-$Ga_{0.7}Al_{0.3}As$ QW as

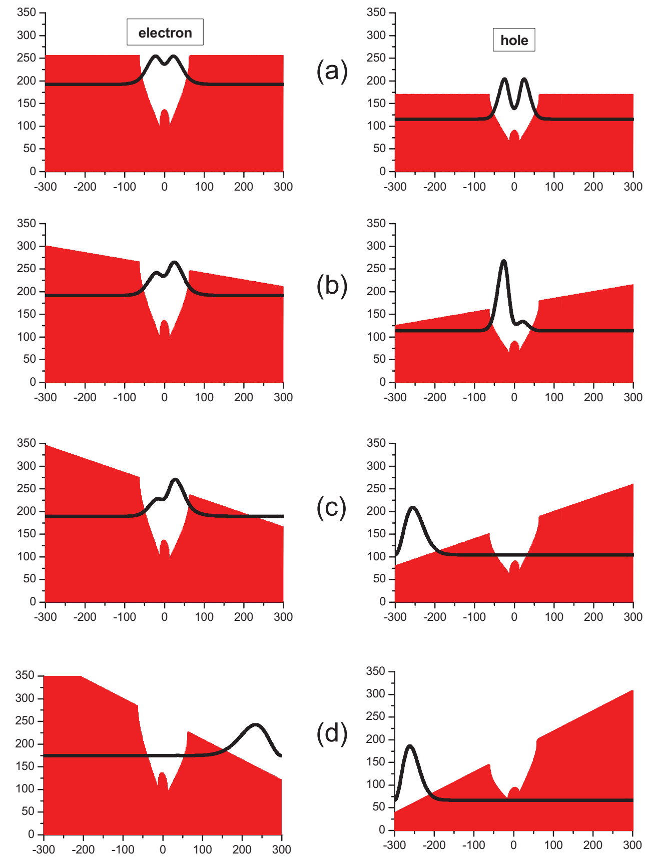

Figure 5 (online color at: www.pss-b.com) Confinement potential and z-dependent amplitude of probability for the first electron (left panel) and hole (right panel) confined states in a GaAs-$Ga_{0.7}Al_{0.3}As$ QW. The results are for $L=50$ Å and $\alpha_0=37.5$ Å, and several values of the applied electric field have been considered: $F=0$ (a), $F=15$ kV/cm (b), $F=30$ kV/cm (c), and $F=45$ kV/cm (d).

a function of the applied electric field for several values of the quantum well-width (L) with $\alpha_0=3L/4$. As it has been already said during the discussion of the Fig. 3 for $F=0$, in the cases of $L=50$, 100 Å, the system is essentially an isolated QW. Whereas, for $L=150$, 200 Å, two maxima in the densities of probability for electrons and holes are detected. This is an indication of a two coupled QW structure. The appearance of a central barrier, due to the laser effect can be seen from Fig. 5. In correspondence, two strongly coupled structures in the density of probability are observed. Because of this coupling the behavior of the system for small dc field is that of a single QW, despite the presence of the barrier at the center. In other words, both structures are part of—essentially—one single slightly perturbed central maximum (around $z=0$) of the probability density.

From the different curves in Fig. 6 it is observed that: (i) If a particular value of the electric field is fixed, the binding energy is a decreasing function of the well width, in coincidence with the results presented in Fig. 2. (ii) For a fixed value of the well width, a reduction in the exciton binding energy as a consequence of the augment of the F is

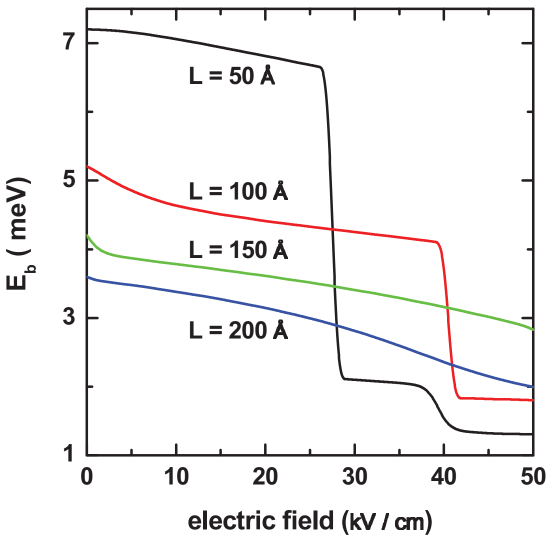

Figure 6 (online color at: www.pss-b.com) Binding energy of heavy-hole exciton in a GaAs-$Ga_{0.7}Al_{0.3}As$ QW as a function of the applied electric field for several values of the quantum well-width (L) with $\alpha_0 = 3L/4$.

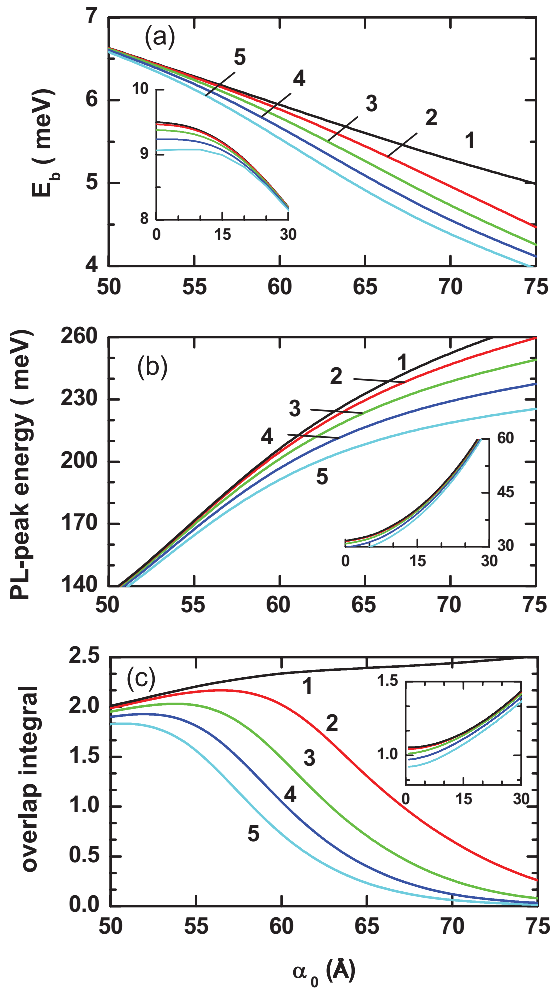

Figure 7 (online color at: www.pss-b.com) Binding energy of heavy-hole exciton (a), PL-peak energy transition (b), and normalized overlap integral (c) in a GaAs-$Ga_{0.7}Al_{0.3}As$ QW as a function of the ILF-parameter for several values of the applied electric field and for $L = 100$ Å. The inset in each figure corresponds to the results for the low regime of the ILF-parameter. Lines 1–5 correspond, respectively, to $F = 0$, 10, 20, 30, and 40 kV/cm.

obtained. Such a decrease is associated with the loss of confinement of the carriers in the QW regions due to the field-induced asymmetry of the potential profile.

The spatially indirect excitons are related to the polarization of the electron-hole system induced by the electric field. For zero field, the configuration of a spatially direct exciton is obtained [see the case of $L = 200$ Å, Fig. 1(d)], with both carriers confined in the laser-induced separated wells. The displacement of both carriers towards opposite well regions is accomplished even for small values—say $F = 1$ kV/cm—of a finite dc electric field. Then, the spatially indirect exciton configuration is achieved, with an appreciable fall in the binding energy. For larger dc fields, the wavefunctions of electrons and holes are even more displaced away. Therefore there will be a further decrease of the binding energy with the applied field.

For the geometries corresponding to $L = 50$, 100 Å, there are significant variations of $E_b(F)$ which can be related with the presence of sudden jumps in the distance between electron and hole. In the case of $L = 50$ Å, if $0 < F < 27$ kV/cm both carriers are confined in the QW region. For $F > 27$ kV/cm, the hole has been thrown towards the infinite potential barrier at the left ($z = -L_\infty/2$), while the position of the electron is kept within the well region. For dc fields above 40 kV/cm, the electron is now pushed close to the infinite barrier at the right hand side ($z = +L_\infty/2$). The consequence of an increase beyond this limit value of the field is that the heavy-hole exciton binding energy will be basically a constant because the charge carriers are separated at a distance of L_∞. There is only one steep fall of E_b in the case of $L = 100$ Å. In the range of $F > 40$ kV/cm, the electron is confined within the well region and the hole is thrown towards the barrier in $L = -L_\infty/2$. These drops in E_b are clearly the result of considering the electric field applied not only on the well region but also on the potential barriers.

The calculations of the binding energy of heavy-hole excitons in a GaAs-$Ga_{0.7}Al_{0.3}As$ QW are presented in Fig. 7, as a function of the ILF-parameter, for several values of the applied electric field and for $L = 100$ Å (a). Also, the variations with α_0 of the exciton-related photoluminescence (PL) peak transition (b), and the normalized overlap integral are depicted with the same set of values for the parameter F. From the Fig. 7(a) is seen that the binding energy is a decreasing function of the ILF-parameter, as has been already discussed. Because the main interest in this work is the laser-induced transition from single to double QW configuration, the results for the low ILF regime are shown in the insets in the figures. From the inset in figure (a) it is observed that the effects of the electric field are practically imperceptible for $\alpha_0 = 30\,\text{Å}$. The effective QW width is changed from $100\,\text{Å}$ at $\alpha_0 = 0$ to $(100 - 2 \times 30)\,\text{Å}$ when $\alpha_0 = 30\,\text{Å}$. Given the strong localization of the carriers within the central region of the heterostructure, the electron–hole system is hardly polarized by the electric field. As a result of this E_b is almost constant. It is observed that there is almost the same value for all the E_b curves when $\alpha_0 = 30\,\text{Å}$. Starting at $\alpha_0 = 50\,\text{Å}$, the effective potential barrier height is decreased due to the maximum at $z = 0$. This should be added to the fact that the effective width of the heterostructure is now equals to $L + 2\alpha_0$. Thus, there is a wider space for the system to be polarized by the dc field, and the binding energy is more sensitive to the field.

The effects of the ILF over the exciton-related PL-peak energy ($= E_{0e} + E_{0h} - E_b$) are found in the Fig. 7(b). The reference for the PL-peak has been chosen to be the value of the GaAs zone center energy gap (1519 meV). It is readily noticed that the PL-peak is an increasing function of the ILF-parameter. When $\alpha_0 < L/2$, the growth of this parameter is responsible of the decrease of the QW effective width, and there is an increase if the carrier confinement with the consequent augment in E_{0e} and in E_{0h}. This is reflected in the increment of the PL-peak. The same effect of localization can be also noticed in the growing form reported for the overlap integral in the Fig. 7(c).

The further increase in α_0 above $L/2$ is related with larger values of the QW effective width. Beyond a certain point, the energies of the electron and hole – referred to the QW bottom—are kept almost constant. But, when $\alpha_0 > L/2$ there is a shift of the well bottom towards higher values of energy due to the maximum at $z = 0$ of the confinement potential. This fact is finally reflected in the augment of the PL-peak. The growth of α_0 is related with a reduction of the negative contribution of E_b to the PL-peak, and that is also why this quantity is increased. In the $\alpha_0 > L/2$ regime, a higher polarization of the system is associated with the augment of the effective width of the QW, with the consequent increase in the polarization of the charge carriers. This is clearly observed in the decreasing form of the overlap integral as a result of the applied dc field. At zero field, the overlap integral is always an increasing function of the ILF-parameter because —for instance, for $\alpha_0 > L/2$—the carrier localization is favored in the case of two coupled QWs. The blueshift observed in our work is in agreement with an analogous behavior in the energy of the resonant peak for interband absorption in square and semiparabolic near-surface QWs under intense laser field reported by Niculescu and Eseanu [34, 35].

The tendency of the PL-peak to diminish as a result of the augment in the applied dc field is due to the carrier loss of confinement given the asymmetry induced in the confining potential. The decreasing behavior of the overlap integral with the electric field is a consequence of the dc-field-induced carrier polarization in the heterostructure. This is closely related with the field-induced spatially indirect excitons in the system.

4 Conclusions The properties of heavy-hole excitons in GaAs-based quantum wells under intense laser and applied dc electric fields are studied for a set of different values of the fields intensities and the well spatial dimensions. Special attention is paid to the laser-field-induced transition from single to double quantum well confining regime. For a fixed geometry of the unperturbed system, the exciton binding energy is a decreasing function of the intense laser field parameter and of the dc electric field. The same behavior is observed in the case of the overlap integral. However, the energy of the exciton-related photo-luminescence peak is an increasing function of the laser field intensity but it is also a decreasing function of the applied dc field strength. It is shown that the changes of the degree of carrier confinement and of the carrier polarization associated to the influence of the laser and the dc fields are the main responsible for the exciton properties mentioned. Up to the authors knowledge, there are no previous reports on exciton properties in double QW induced by intense laser fields. Thus, the results of the present work might be considered as a first approximation to the subject in this kind of systems.

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