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Exciton diamagnetic shift in $GaAs/Ga_{1-x}Al_xAs$ quantum wells under in-plane magnetic fields

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Abstract

Using a variational procedure in the effective-mass and parabolic-band approximations we investigate the effects of in-plane magnetic fields on the exciton states in single $GaAs/Ga_{1-x}Al_xAs$ quantum wells. Exciton properties are analyzed by using a simple hydrogen-like variational envelope wave-function. Present theoretical results are compared with available experimental measurements on the diamagnetic shift of the photoluminescence peak position of $GaAs/Ga_{0.7}Al_{0.3}As$ quantum wells under in-plane magnetic fields [Phys. Rev. B 71 (2005) 045303].

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Low-dimensional heterostructures such as $GaAs/Ga_{1-x}Al_xAs$ superlattices (SLs), quantum wells (QWs), quantum-well wires (QWWs), and quantum dots (QDs) constitute the semiconductor systems that have attracted most attention in the literature. The study of exciton properties in those systems is of great importance due to the fact that the $e-h$ Coulomb interaction may significantly modify the interband optoelectronic properties of these semiconductor heterostructures. Photoluminescence (PL) experiments of modulation-doped GaAs/AlGaAs QWs and heterojunctions [1–6] as well as theoretical calculations [7–10] related to exciton dispersion and associated properties have been recently reported. Here we point out that important modifications in the nature of the electronic subband structure should be observed [1] associated with in-plane $B_\parallel$ applied magnetic fields. This is due to the relationship between the in-plane momentum, perpendicular to the field, and the position of the orbit center on the growth axis. Orlita et al. [2] have studied the properties of spatially direct and indirect excitons in a $GaAs/Ga_{1-x}Al_xAs$ double QW under in-plane magnetic fields. They concluded that the dominating radiative recombination of localized indirect excitons does not allow one to observe the quenching of the spatially indirect exciton luminescence and the quadratic shift of their energy under in-plane magnetic fields [3,4], with the consequence that the possibility of an exciton dispersion engineering [3–5,11] would then be limited in such samples. Combined theoretical and experimental studies for the effect of an in-plane magnetic field on the PL spectrum of modulation-doped heterostructures [6] have suggested that there are remarkable spectral modifications of the PL spectra in both modulation-doped QWs and high-quality heterojunctions due to $B_\parallel$-induced modifications in the direct optical transitions in QWs and effects on the free holes in heterojunctions, respectively.

Here we are concerned with a theoretical study of the in-plane magnetic-field effects on the exciton states in single $GaAs/Ga_{1-x}Al_xAs$ QWs (grown along the z-axis) in order to compare with corresponding exciton diamagnetic shifts measured by Ashkinadze et al. [6]. The present theoretical approach assumes the envelope-function and parabolic-band approximations. We choose the in-plane magnetic

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field in the x-direction, $\vec{\boldsymbol{B}} = B\hat{x}$ (see Fig. 1), and use the Landau gauge $\vec{\boldsymbol{A}}(\vec{\boldsymbol{r}}) = -Bz\hat{y}$. The Hamiltonian for the exciton then takes the following form [7–9]:

$$\hat{H} = \frac{1}{2m_e^*}\left(\hat{\vec{\boldsymbol{p}}}_e + \frac{e}{c}\vec{\boldsymbol{A}}_e\right)^2 + \frac{1}{2m_h^*}\left(\hat{\vec{\boldsymbol{p}}}_h - \frac{e}{c}\vec{\boldsymbol{A}}_h\right)^2 + V_e(z_e) + V_h(z_h) - \frac{e^2}{\varepsilon|\vec{\boldsymbol{r}}_e - \vec{\boldsymbol{r}}_h|}, \quad (1)$$

where $\vec{\boldsymbol{A}}_e = \vec{\boldsymbol{A}}(\vec{\boldsymbol{r}}_e)$, $\vec{\boldsymbol{A}}_h = \vec{\boldsymbol{A}}(\vec{\boldsymbol{r}}_h)$, and $\hat{\vec{\boldsymbol{p}}}_i$, $\vec{\boldsymbol{r}}_i$, m_i^* and V_i, with $i = e, h$, are the momentum operators, electron and hole coordinates, effective masses, and corresponding QW confining potentials (defined as zero in the GaAs material and V_0 elsewhere), respectively, e is the absolute value of the electron charge and ε is the GaAs dielectric constant. For V_0 we have assumed the 60–40% of the band-offset for electrons and holes, respectively.

Due to the fact that the total in-plane exciton momentum $\hat{\vec{\boldsymbol{P}}}$ (with eigenvalue $\vec{\boldsymbol{P}}$) is an exact integral of motion [7–9] the exciton wave function may be written as

$$\Psi_{exc}(\vec{\boldsymbol{r}}_e, \vec{\boldsymbol{r}}_h) = \frac{\exp((i/\hbar)\vec{\boldsymbol{P}} \cdot \vec{\boldsymbol{R}})}{\sqrt{S}} \Phi(\vec{\boldsymbol{\rho}}, z_e, z_h), \quad (2)$$

where S is the transverse area of the QW, $\vec{\boldsymbol{R}}$ and $\vec{\boldsymbol{\rho}}$ are the in-plane exciton center-of-mass (CM) and relative coordinates, respectively, and $\Phi(\vec{\boldsymbol{\rho}}, z_e, z_h)$ (with exciton energy E_X) is the eigenfunction of the Hamiltonian

$$\hat{H} = \frac{P^2}{2M} + \frac{\hat{p}_\rho^2}{2\mu} + \hat{H}_e + \hat{H}_h - \frac{e^2}{\varepsilon|\vec{\boldsymbol{r}}_e - \vec{\boldsymbol{r}}_h|}, \quad (3)$$

where $P^2 = P_x^2 + P_y^2$, $\hat{\vec{\boldsymbol{p}}}_\rho = \hat{x}\hat{p}_x + \hat{y}\hat{p}_y = -i\hbar(\partial/\partial\vec{\boldsymbol{\rho}})$, $M = m_e^* + m_h^*$ and $\mu = m_e^* m_h^*/M$ are the total and reduced exciton masses, respectively,

$$\hat{H}_\alpha = \frac{\hat{p}_{\alpha z}^2}{2m_\alpha^*} + V_\alpha(z_\alpha) + \frac{1}{2}m_\alpha^*\omega_\alpha^2 z_\alpha^2 \mp \omega_\alpha\left(\frac{m_\alpha^*}{M}P_y \pm \hat{p}_y\right)z_\alpha, \quad (4)$$

where $\omega_\alpha = eB/m_\alpha^* c$ (with $\alpha = e, h$) are the cyclotron frequencies, and the upper (lower) sign refers to e (h).

In order to obtain the ground-state exciton eigenfunction for the $GaAs/Ga_{1-x}Al_xAs$ QW under in-plane magnetic fields, we have taken $K_y = P_y/\hbar = 0$, and restrict ourselves to low-temperatures. Here we have adopted a variational scheme by minimizing the functional [12]

$$E(\Phi) = \frac{\langle\Phi|H|\Phi\rangle}{\langle\Phi|\Phi\rangle} \quad (5)$$

in which the variational wave function is

$$\Phi(\vec{\boldsymbol{\rho}}, z_e, z_h) = f_e(z_e) f_h(z_h) e^{-\lambda r}, \quad (6)$$

where $r = \sqrt{\rho^2 + (z_e - z_h)^2}$, λ is a variational parameter, and $f_e(z_e)$ and $f_h(z_h)$ are the ground-state eigenfunctions [13] of the total Hamiltonian neglecting the Coulomb interaction, i.e., the z-dependent eigenfunctions of the Hamiltonians in Eqs.(4). In what follows, relevant material parameters were taken, at low-temperature, as in Li [14]. Calculations are performed by taking the same GaAs parameters along the heterostructure.

In Fig. 1 we present the pictorial view of the "QW model" heterostructure used in the present work. The first electron (E_{e0}) and heavy-hole (E_{h0}) non-correlated confined energies are shown. Fig. 2 presents our results for the in-plane applied magnetic field dependence of the heavy-hole exciton binding energy [Fig. 2(a)] and corresponding diamagnetic shift [Fig. 2(b)] in single $GaAs/Ga_{0.7}Al_{0.3}As$ QWs for different values of the QW width. From Fig. 2(a) it is clear that for small QW widths (100 Å) and for the range of strengths of the magnetic field we have considered, the binding-energy behavior goes essentially as a constant value. This is due to the strong confinement of the electron wave function associated with the effect of the potential barriers. Competing confining effects due to the applied in-plane magnetic field and QW barrier potentials are essentially related to the relationship between the Landau length ($l_B \approx 256/\sqrt{B}$ Å) and size of the QW. One clearly observes the magnetic-field effects for $B \geqslant 10$ T in the case of a width $L = 400$ Å QW [see Fig. 2(a)]. Two regimes on the diamagnetic shift are clearly observed: (i) *quadratic regime* for the large geometrical confinement case ($L = 100$ Å), in the whole range of magnetic-field values considered; (ii) *linear regime*, here essentially observed for $L = 200$ and 400 Åfor $B \geqslant 15$ T. The separation of the two parallel lines corresponds to the difference in energy of the sum of the two z-confined electron and hole states, with confining energies depending on the QW width.

In Fig. 3, present theoretical results for the magnetic-field dependent diamagnetic shift of the PL-peak energy,

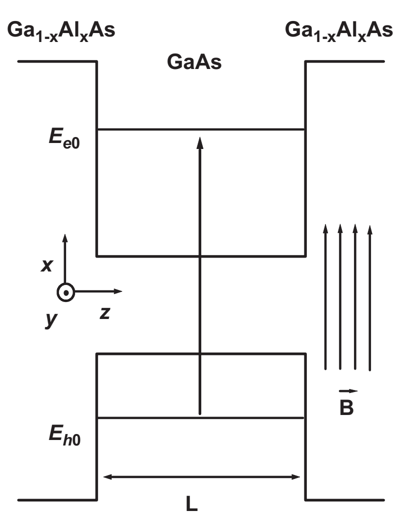

Fig. 1. Pictorial view of the "QW model" heterostructure used in the present work. L corresponds to the QW width.

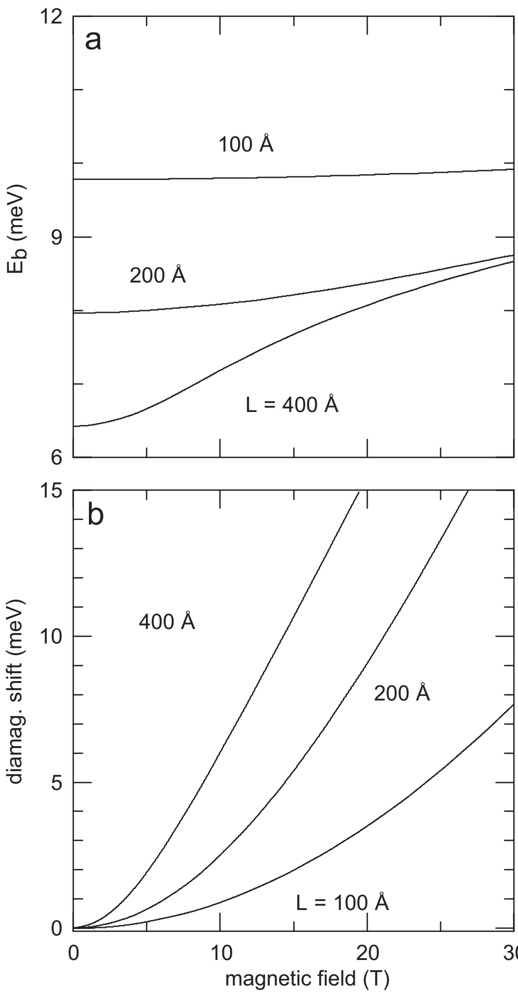

Fig. 2. In-plane applied magnetic field dependence of the heavy-hole exciton binding energy (a) and diamagnetic shift of the PL-peak energy (b) in single $GaAs/Ga_{0.7}Al_{0.3}As$ finite-barrier QWs. Results are shown for different values of the QW width.

for an $L = 200\,\text{Å}$ $GaAs - Ga_{0.7}Al_{0.3}As$ finite-barrier QW (dotted line), are compared with recent experimental data by Ashkinadze et al. [6]. Theoretical results for an infinite-barrier GaAs QW are also presented and depicted as solid lines, with very good agreement with experimental data. Due to the low magnetic-field regime, here considered, it is clear when comparing the two theoretical results, that the confinement model (finite-barrier or infinite-barrier potentials) introduces important modifications in the diamagnetic shift results. As the experimental measurements are performed at low temperatures (the $T = 4\,K$ GaAs band gap is 1519.4 meV), and the finite-barrier $L = 200\,\text{Å}$ $GaAs/Ga_{0.7}Al_{0.3}As$ QW electron and hole confinement energies are, at zero magnetic field, 10.7 and 2.4 meV, respectively, one finds non-correlated $e-h$ transition energy at 1532.5 meV. As the heavy-hole exciton binding energy, at zero magnetic field, is 8.0 meV [cf. Fig. 2(a)], the resulting *correlated* $e-h$ transition energy (or exciton PL-peak position) would occur at 1524.5 meV, in contrast with the experimental [6] PL-peak position at 1517.1 meV.

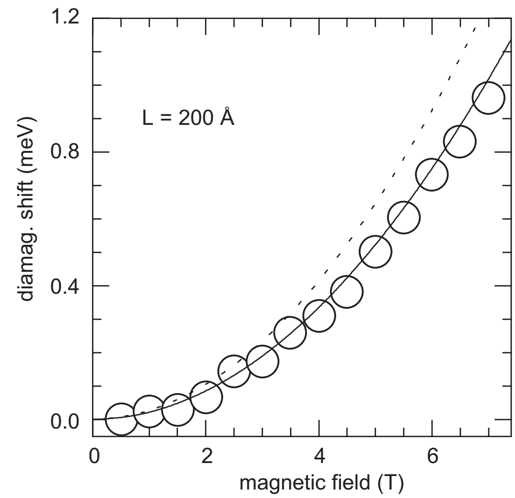

Fig. 3. Diamagnetic shift of the PL peak position for an $L = 200\,\text{Å}$ GaAs/(Ga, Al)As QW calculated as a function of the in-plane applied magnetic field, compared with the experimental measurements (open symbols) by Ashkinadze et al. [6]. The solid line corresponds to calculations in the infinite-barrier QW model whereas the dotted line is for a $GaAs/Ga_{0.7}Al_{0.3}As$ finite-barrier QW model.

To conclude, we have used a variational procedure in the effective-mass and parabolic-band approximations in order to investigate the effects of in-plane magnetic fields on the exciton properties in $GaAs/Ga_{1-x}Al_xAs$ quantum wells. Present theoretical results for infinite-barrier potentials are found in quite good agreement with available experimental measurements [6] on the diamagnetic shift of the photoluminescence peak position of $GaAs/Ga_{0.7}Al_{0.3}As$ quantum wells under in-plane magnetic fields. For finite-barrier $GaAs/Ga_{0.7}Al_{0.3}As$ QWs, however, the agreement between calculated results for the PL peak diamagnetic shift and experiment is only fair, and an understanding of the zero magnetic field PL energy peak position is not clear. This suggests that further theoretical and experimental work are needed in order to achieve an appropriate understanding of the experimental measurements by Ashkinadze et al. [6].

Acknowledgments

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