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Bright-to-dark exciton transition in symmetric coupled quantum wells induced by an in-plane magnetic field

Kai Chang and F. M. Peeters*
Departement Natuurkunde, Universiteit Antwerpen (UIA), Universiteitsplein 1, B-2610 Antwerpen, Belgium
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The energy dispersion of an exciton in a coupled quantum well is modified by an external in-plane magnetic field. We find that the in-plane magnetic field can shift the ground state of the magnetoexciton from a zero in-plane center-of-mass (CM) momentum to a finite CM momentum, and render the ground state of the magnetoexciton stable against radiative recombination due to momentum conservation. At the same time, a spatial separation of the electron and hole is realized. Thus an in-plane magnetic field can be used to tailor the radiative properties of excitons in coupled quantum wells.

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The quasi-two-dimensional (Q2D) magnetoexciton in semiconductor quantum-well structures has been studied extensively over the past decades. Most of these investigations focus on the properties of Q2D magnetoexcitons in the presence of a magnetic field that is applied along the growth direction. In the absence of magnetic fields, the Q2D exciton motion can then be described in terms of uncorrelated relative (RM) and center-of-mass (CM) motions. Such a picture is no longer valid when a magnetic field is applied perpendicular to the growth direction, which induces a coupling between the CM and RM motion.[1] Nevertheless, a partial decoupling of the CM and RM motion is still possible. There exists a constant of motion, the total pseudomomentum, which allows a pseudoseparation of the CM motion.[2] In this case, the dependence of the Hamiltonian on the CM motion can be reduced to a Stark term arising from the electric field induced by the CM motion.[3] Since the total pseudomomentum of the exciton is conserved, the exciton Hamiltonian can be reduced to the internal RM coordinates, which have cylindrical symmetry around the magnetic-field axis. Neglecting the valence-band mixing effect, the heavy-hole exciton ground state has been studied using various methods, such as direct numerical integration,[4] the perturbation approximation,[5] and the variational technique.[6,7] The direct and indirect exciton in coupled symmetric quantum-well (CQW) structures was also investigated extensively in the past few years.[8–10]

The situation is more complicated for a quantum-well exciton in an in-plane magnetic field due to the breaking of the conservation of the total pseudomomentum. Because of the increased complexity, only a very small number of studies on this topic have been done. Fritze *et al.*[11] studied the case of an in-plane magnetoexciton in a very shallow potential that was treated as a perturbation and they observed an interesting crossover from a 3D- to a 2D-like exciton behavior as a function of the strength of the in-plane magnetic field. Xia and Fan[12] included valence-band mixing and studied the electronic structure in semiconductor superlattices under in-plane magnetic fields. They found that the binding energy of the exciton with zero in-plane CM momentum increases with increasing magnetic field. The Γ-X mixing effect on the magnetoexciton in an in-plane magnetic field was also taken into account for the case of a thin AlAs/GaAs quantum well,[13] and it was found that the exciton is spatially separated, which is caused by the competition of the Γ-like and X-like potential profiles. All these studies were focused on the optical properties of excitons with zero momentum. To our knowledge, no theoretical investigation exists of magnetoexcitons in coupled quantum wells in the presence of an in-plane magnetic field. Very recently, it was found experimentally that an in-plane magnetic field changes drastically the photoluminescence (PL) spectra and the kinetics of interwell excitons in GaAs/$Al_xGa_{1-x}As$ coupled quantum wells.[14] In this system, the electrons and holes were already spatially separated by an external electric field and the in-plane magnetic field only influences the energy dispersion.

In the present work, we study the energy dispersion and optical properties of Q2D magnetoexcitons in CQW structures in the presence of an in-plane magnetic field. No perpendicular electric field is present as in Ref. 14. We find that the energy-dispersion curve of the magnetoexciton and the ground-state electron and hole wave functions can be tuned by such an external in-plane magnetic field. The ground state of the magnetoexciton shifts from zero in-plane CM momentum to a finite in-plane momentum when the in-plane magnetic field increases. Consequently, a transition between the momentum direct exciton and the momentum indirect exciton is obtained. As a result of momentum conservation, the in-plane magnetic field will render the ground state of the magnetoexcitons stable against radiative recombination, and leads to the formation of a dark exciton. The latter effect is enhanced by the fact that at the same time a spatial separation of the electron and hole is induced.

Consider a CQW consisting of $Al_xGa_{1-x}As$ and GaAs materials, shown schematically in the inset of Fig. 1. We choose the z axis along the QW growth direction and the x axis parallel to the in-plane magnetic field. The CM and RM in-plane position and momentum operators are denoted by $(\mathbf{R},\mathbf{P})$ and $(\mathbf{r},\mathbf{p})$, respectively. We neglect the valence-band mixing effect, which is allowed due to the strong vertical confinement, and therefore we may limit ourselves to the lowest electron and hole confinement levels.

According to the effective-mass theory, the exciton Hamiltonian in a CQW structure can be written as

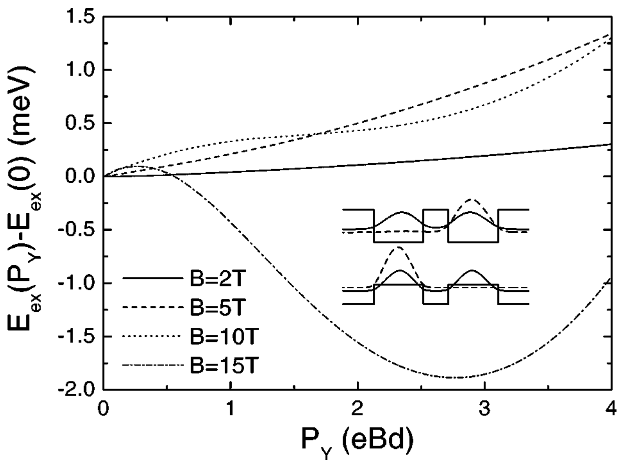

FIG. 1. The energy spectrum of the ground-state exciton in $GaAs/Al_{0.33}Ga_{0.67}As$ CQW. The inset gives the electron and hole band structure schematically and shows the wave functions of electron and hole with $P_Y=0$ (solid lines) and $P_Y=P_Y^{\min}$ (dashed lines) for $B=15$ T. The well width is $W=80$ Å and the thickness of the middle barrier is $d=40$ Å.

$$H_{\rm ex}=\frac{1}{2m_e^*}[\mathbf{p}_e+e\mathbf{A}(\mathbf{r}_e)]^2+\frac{1}{2m_h^*}[\mathbf{p}_h-e\mathbf{A}(\mathbf{r}_h)]^2-\frac{e^2}{\epsilon|\mathbf{r}|}+V_e(z_e)+V_h(z_h), \tag{1}$$

where $\mathbf{r}=\mathbf{r}_e-\mathbf{r}_h=(\rho,z)$ denotes the electron-hole relative coordinates, m_e (m_h) is the effective mass of the electron (hole) in units of the free-electron mass m_0, and ϵ is the dielectric constant. V_e (V_h) is the confining potential of the electron and hole in the CQW,

$$V_i(z_i)=\begin{cases}0 & (d/2+W)>|z|>d/2\\ V_{e,h} & \text{otherwise,}\end{cases} \tag{2}$$

where d is the thickness of the middle barrier and W is the width of the left and the right well.

In a homogeneous magnetic field B, the total in-plane pseudomomentum $\mathbf{\Pi}_{//}=\Sigma_i\mathbf{\Pi}_{i//}$ is an exact integral of motion $[H_{\rm ex},\mathbf{\Pi}_{//}]=0$,[2] where $\mathbf{\Pi}_{i//}=\mathbf{p}_{i//}+e_i\mathbf{A}_{i//}-e_i(\mathbf{B}\times\mathbf{r}_i)_{//}$. Here we work in the Landau gauge $\mathbf{A}_i=(0,Bz_i,0)$, and therefore the total in-plane pseudomomentum becomes $\mathbf{\Pi}_{//}=\Sigma_i\mathbf{\Pi}_{i//}=\hbar\mathbf{K}_{//}$, where the magnetic field points along the x axis.

For a parabolic band, the exciton wave function can be given in the center-of mass coordinates

$$\Psi_{\rm ex}=\Psi(\mathbf{r}_e,\mathbf{r}_h)=\exp(i\mathbf{K}_{//}\cdot\mathbf{R})\varphi(\boldsymbol{\rho},z_e,z_h), \tag{3}$$

which leads to the exciton Hamiltonian for φ in the presence of an in-plane magnetic field,

$$H=\frac{P_Y^2}{2M}+\frac{\mathbf{p}^2}{2\mu}-eB\left(\frac{z_e}{m_e}+\frac{z_h}{m_h}\right)p_y+\left(\frac{m_e}{M}P_Y+eBz_e\right)^2\Big/2m_e+\left(\frac{m_h}{M}P_Y-eBz_h\right)^2\Big/2m_h+\frac{p_{ze}^2}{2m_e}+\frac{p_{zh}^2}{2m_h}+V_e(z_e)+V_h(z_h)-\frac{e^2}{\epsilon|\mathbf{r}|}. \tag{4}$$

Capital letters in the above equation are the operators associated with the CM motion, while lower letters denote the operators associated with the RM motion. $M=m_e+m_h$ is the total mass of the exciton, $\mu=m_em_h/M$ is the reduced exciton mass, and m_e (m_h)is the electron (hole) effective mass. If the confinement along the z direction is strong enough, we are allowed to decouple the z motion from the in-plane motion and consequently we use trial wave functions that are products of the electron and hole subband wave functions in the CQW and a Gaussian function that describes the internal RM motion of the exciton in the presence of a magnetic field. $\varphi(\rho,z_e,z_h)=f_e(z_e)f_h(z_h)\exp(-\alpha\rho^2-\beta z^2)$, where α,β are variational parameters that are obtained from the minimization of the exciton energy. $f_e(z_e)$ $[f_h(z_h)]$ can be obtained from Eq. (4) by neglecting the Coulomb interaction. We limit our numerical calculation to the heavy magnetoexciton in $GaAs/Al_{0.33}Ga_{0.67}As$ CQW. The parameters pertaining to GaAs used in our calculations are $m_e=0.067m_0$, $\epsilon_0=12.6$, and $m_h=0.38m_e$. Notice that the variational technique gives an upper bound to the exciton energy. But we expect that this approximation will not influence the physics because we compare the $P_Y=0$ exciton energy with the one for nonzero momentum, for which we used the same type of variational wave function.

The magnetoexciton energy spectrum in the $Al_{0.33}Ga_{0.66}As/GaAs$ CQW is shown in Fig. 1 as a function of the CM momentum P_Y along the y direction. With increasing exciton momentum P_Y, the energy of the magnetoexciton increases quadratically for small P_Y. The energy dispersion changes significantly with increasing magnetic field and exhibits a local minimum at $P_Y\neq 0$ with increasing in-plane magnetic field. This arises from the interplay between the correlation between the CM and RM motion of the magnetoexciton, which is induced by the in-plane magnetic field [Eq. (4)], the tunneling splitting in the CQW, and the Coulomb interaction between the electron and the hole. For small in-plane CM momentum P_Y, the electron and hole localize at the center of each well (see the full curves in the inset of Fig. 1) and they lead to a large binding energy. The binding energy of the exciton decreases with increasing in-plane CM momentum since the in-plane magnetic field results in a spatial separation of the exciton in the z direction (see the dashed curves in the inset of Fig. 1). This interplay shifts the ground state of the exciton from $P_Y=0$ to a state with finite momentum $P_Y^{\min}\cong eBd_{e\text{-}h}$, where $d_{e\text{-}h}$ is the spatial separation between the electron and the hole. Thus the exciton ground state in the CQW becomes optically inactive with increasing in-plane magnetic field because of momentum conservation and the decrease in the overlap between the electron and hole. Notice that the physical mechanism of the spatial separation between the electron and the hole in the CQW is the action of the Lorentz force on the electron and the hole, which are in the opposite direction, and this is quite different from that caused by the electric field.[9]

In Fig. 2, we plot the in-plane CM momentum dependence of the exciton binding energy. From Eq. (4), one sees that the correlation between the CM and RM motion (the fourth and fifth terms) separates spatially the electron and hole when the in-plane CM momentum P_Y increases. Thus

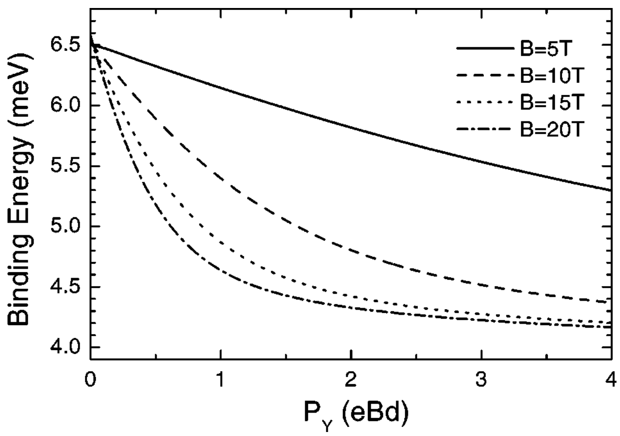

FIG. 2. The binding energy of the ground-state exciton in GaAs/$Al_{0.33}Ga_{0.67}As$ CQW versus the in-plane CM momentum. The well width $W=80$ Å and the thickness of the middle barrier $d=40$ Å.

the exciton binding energy decreases with increasing in-plane CM momentum, and saturates since the electron and hole are pushed against the opposite sides of the CQW, which results in $d_{e\text{-}h}<d+2W$. Therefore, the ground-state exciton in the CQW becomes a spatially separated exciton with finite in-plane CM momentum $P_Y^{\min}$.

Figure 3 shows the in-plane CM momentum $P_Y^{\min}$ corresponding to the minimum of the magnetoexciton energy as a function of the in-plane magnetic field. There is a sudden transition at B_c from $P_Y=0$ to $P_Y\neq 0$ with increasing in-plane magnetic field since the exciton energies with finite in-plane CM momentum at B_c are lower than that with zero in-plane momentum. The minimum shifts rapidly to the state with finite in-plane CM momentum when the in-plane magnetic field approaches the critical magnetic field B_c. When the magnetic field is larger than the critical magnetic field B_c, the in-plane CM momentum $P_Y^{\min}$ saturates to a finite value, which equals $eBd_{e\text{-}h}$. Recent experiments on symmetric CQW (Ref. 14) showed that the PL intensity exhibits a jump after the excitation is switched off, which was induced by the kinetics of the occupation in the optically active zone. This jump disappears at high in-plane magnetic field (≈ 8 T) for a GaAs/$Al_{0.33}Ga_{0.67}As$ CQW ($W=80$ Å,$d=40$ Å) under an electric field since the in-plane magnetic field shifts the exciton ground state from $P_Y=0$ to $P_Y\neq 0$ and therefore changes the occupation in the optically active zone and the exciton kinetics.[15] In our calculation, we find that the transition takes place at $B_c\approx 10$ T for the same structure in the absence of an external electric field. The latter will decrease this critical field.

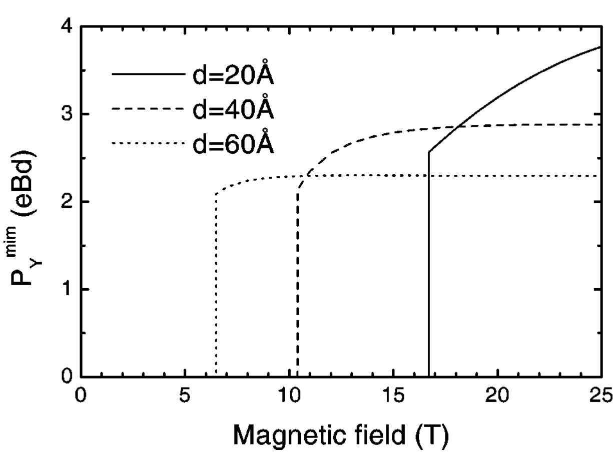

FIG. 3. The position of the minimum of the in-plane CM momentum of the ground-state exciton in GaAs/$Al_{0.33}Ga_{0.67}As$ CQW versus the in-plane magnetic field. The well width is $W=80$ Å .

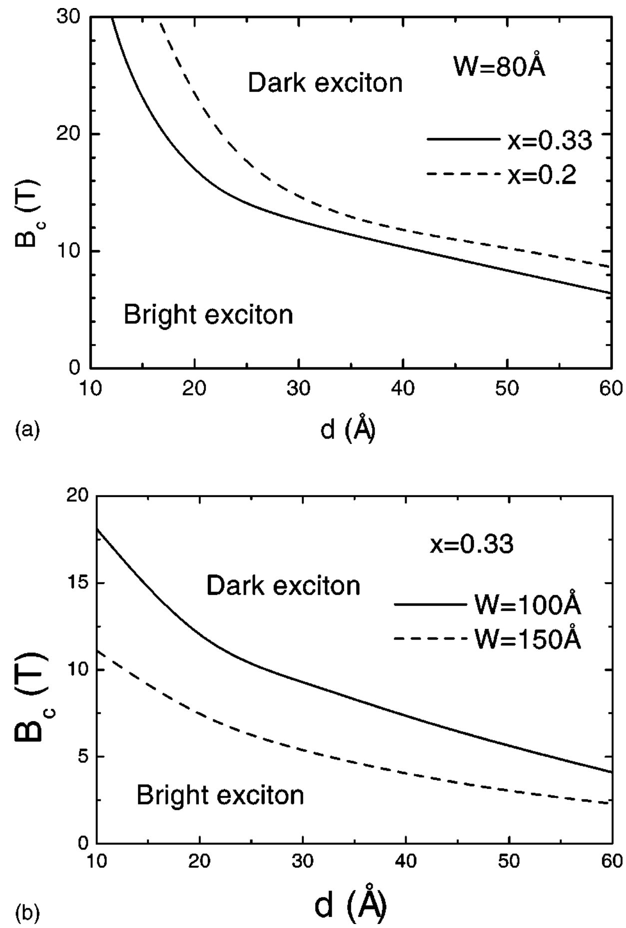

FIG. 4. The phase diagram of Q2D magnetoexcitons for different composition x of the barrier (a) and different well width W (b).

In Figs. 4(a) and 4(b), we show the phase diagram of the Q2D magnetoexciton for different barrier heights, i.e., different alloy composition and different quantum-well widths, respectively. The critical magnetic field B_c decreases with increasing barrier thickness d and well width W. Spatially separated and momentum indirect excitons exist above each curve, and the excitons experience a transition from the spatially separated and momentum indirect state to the spatial and momentum direct exciton with decreasing parameters B_c and d or W. Notice that the critical magnetic field B_c is very high for small barrier thickness but it decreases rapidly with increasing d, and for the same barrier thickness d, the critical magnetic field B_c increases with decreasing composition x [Fig. 4(a)] and well width W [Fig. 4(b)]. This behavior can be explained as follows. The minimum of the Q2D magnetoexciton spectrum [see Fig. 1(d)] is approximately equal to $E_{\mathrm{min}}=e^2B^2d_{e\text{-}h}^2/2M$. The critical magnetic field B_c is obtained from the competition of the exciton energies between zero in-plane CM momentum and finite in-plane CM momentum. The spatial separation $d_{e\text{-}h}$ can be enhanced by increasing the barrier thickness d or the barrier height (i.e., the composition x) or the well width for the same magnetic field, and therefore the critical magnetic field B_c decreases for a fixed value of the minimum $E_{\mathrm{min}}=e^2B^2d_{e\text{-}h}^2/2M$.

In conclusion, we investigated Q2D magnetoexcitons in CQW under an in-plane magnetic field and found a transition from the optical active exciton state to a dark exciton state with increasing in-plane magnetic field. In-plane magnetic fields can modify the exciton dispersion as a function of the in-plane CM momentum by the coupling between the CM and RM motions and shift the ground state of the magnetoexciton from zero in-plane momentum to a state with finite in-plane momentum. Then the ground state of the magnetoexciton will be a dark exciton with a long lifetime.

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*Electronic address: Francois.peeters@ua.ac.be.

[1] L. P. Gor'kov and I. E. Dzyaloshinskii, Zh. Éksp. Teor. Fiz. **53**, 717 (1967) [Sov. Phys. JETP **26**, 449 (1968)].

[2] B. R. Johnson, J. O. Hirschfelder, and Kuo-Ho Yang, Rev. Mod. Phys. **55**, 109 (1983).

[3] W. E. Lamb, Phys. Rev. **85**, 259 (1952).

[4] G. Duggan, Phys. Rev. B **37**, 2759 (1988).

[5] K. J. Nash, M. S. Skolnick, P. A. Claxton, and J. S. Roberts, Phys. Rev. B **39**, 10 943 (1989).

[6] R. L. Greene and K. K. Bajaj, Phys. Rev. B **31**, 6498 (1985).

[7] G. Bastard, E. E. Mendez, L. L. Chang, and L. Esaki, Phys. Rev. B **26**, 1974 (1982).

[8] I. Galbraith and G. Duggan, Phys. Rev. B **40**, 5515 (1989); G. W. Bryant, *ibid.* **46**, 1893 (1992); **47**, 1683 (1992).

[9] F. M. Peeters and J. E. Golub, Phys. Rev. B **43**, 5159 (1991).

[10] A. B. Dzyubenko and A. L. Yablonskii, Phys. Rev. B **53**, 16 355 (1996).

[11] M. Fritze, I. E. Perakis, A. Getter, W. Knox, K. W. Goossen, J. E. Cunningham, and S. A. Jackson, Phys. Rev. Lett. **76**, 106 (1996).

[12] J. B. Xia and W. J. Fan, Phys. Rev. B **40**, 8508 (1989).

[13] C. P. Chang, Solid State Commun. **114**, 627 (2000).

[14] L. V. Butov, A. V. Mintsev, Yu. E. Lozovik, K. L. Campman, and A. C. Gossard, Phys. Rev. B **62**, 1548 (2000); A. Parlangeli, P. C. M. Christianen, J. C. Maan, I. V. Tokatly, C. B. Soerensen, and P. E. Lindelof, Phys. Status Solidi A **178**, 45 (2000).

[15] L. V. Butov, A. Imamoglu, S. V. Mintsev, K. L. Campman, and A. C. Gossard, Phys. Rev. B **59**, 1625 (1999).