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Magnetoexciton in semiconductor concentric double rings

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ABSTRACT

We investigate theoretically the magnetoexciton states in semiconductor concentric quantum double rings using the multi-band effective mass theory. We find that a perpendicular magnetic field can lead to oscillations in the exciton energy which appear as kinks in the magneto-photoluminescence (PL) spectra as the magnetic field increases. The spatial distribution of the exciton over the rings depends sensitively on the thicknesses of the inner and outer rings. The tunneling coupling between the inner and outer rings and the heavy-hole and light-hole mixing results in different anticrossing behaviors. Exciton can be converted into a spatially separated type-II exciton by tuning the thickness, the inner and/or outer ring radius and the magnetic field. We show that this type I–type II transition is reflected in the oscillator strength of the PL spectrum which will be the experimental signature that will provide us with information about the spatial distribution of the exciton.

1. Introduction

With the rapid progress of fabrication techniques of semiconductor quantum rings using self-assembly techniques, it is possible to make high-quality semiconductor quantum rings using the self-assembly technique [1,2]. Semiconductor quantum rings have attracted intensive interest during the past few years due to its unique topological geometry and energy spectrum. Aharonov–Bohm (AB) oscillations in the PL spectrum of neutral and negative charged excitons in semiconductor quantum ring structures were observed experimentally [3]. Very recently, an interesting lattice-matched GaAs/AlGaAs semiconductor concentric quantum double rings (CQDRs) were fabricated utilizing the droplet epitaxy technique with high uniformity and excellent rotational symmetry, the image of the atomic force microscopy (AFM) clearly demonstrates this concentric structures that can be controlled by tuning the migration of surface adatoms and their crystallization [4]. The carrier dynamics in individual GaAs/AlGaAs concentric quantum double rings was investigated in detail by using the time-resolved photoluminescence (PL) spectrum. The PL spectrum demonstrates that the exciton dynamics in the two rings is completely decoupled due to the weak coupling between the inner and outer rings. This phenomenon is attributed to the exciton center-of-mass localization induced by ring height fluctuations in quantum-wire-like fashion [5].

Recently, there has been considerable theoretical interest in the properties of few electron states [6,7,9] and exciton states [4,8] and the spin–orbit interaction [10–12], impurity effect [13] in the vertically and laterally coupled double rings. The theoretical results based on the single band model gives a good description of the exciton state for small CQDRs since the hole mixing effect is unimportant in such small CQDR [4]. Because the inter-ring tunneling coupling and the size of CQDR can be controlled experimentally, therefore a detailed analysis of the exciton states including the heavy-hole and light-hole mixing is highly desirable for the complete understanding of the optical property of the CQDRs.

In this paper, we investigate theoretically the exciton states in semiconductor concentric double quantum rings using the multi-band effective mass theory. We find that the magnetic field leads to oscillation of the exciton energy and the oscillation strength of the peaks in PL spectrum. It turns out that the spatial distribution of the exciton depends sensitively on the thicknesses of the inner and outer rings. The PL spectrum can provide us with important information on the distribution of the exciton. The inter-rings coupling between the inner and the outer rings and the heavy-hole and light-hole mixing can lead to different anticrossing behaviors in the exciton spectrum. A spatially separated type-II exciton can be found by tuning the thicknesses of the inner and outer rings and the magnetic field. Our theoretical results will be interesting from a fundamental physics point of view and for possible applications where tuning of the exciton properties is desirable.

The present paper is organized as follows. In Section 2 we present our theoretical model. Our numerical results with the corresponding discussions are presented in Section 3. The conclusions are given in Section 4.

2. Theoretical model

We consider CQDRs consisting of the lattice-matched $Al_xGa_{1-x}As$ sandwiched by GaAs material as shown in Fig. 1.

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According to the multi-band effective mass theory, the total Hamiltonian of the CQDR structure can be written as

$$H = H_e + H_h + V_{Coul}, \tag{1}$$

where $V_{Coul} = -e^2/4\pi\varepsilon_0\varepsilon|\mathbf{r}_e - \mathbf{r}_h|$ is the Coulomb interaction between the electron and hole, where $\varepsilon(\varepsilon_0)$ is the dielectric constant of the material (vacuum), e the charge of electron. $H_e(H_h)$ is the single electron (hole) Hamiltonian. The electron Hamiltonian reads

$$H_e = \frac{(\mathbf{p}+e\mathbf{A})^2}{2m_e^*} + V_{\parallel}^e(r) + V_{\perp}^e(z) + g_e^*\mu_B B s_z + eEz, \tag{2}$$

where m_e^* is the effective mass of the electron in the unit of electron mass m_0. g_e^* the intrinsic g-factor and $\mathbf{A} = (-y, x, 0)B/2$ the vector potential. The electron is confined perpendicularly and laterally by a square potential well $V_{\perp}^e(z) = \Delta V^e\theta(|z| - W/2)$ and

$$V_{\parallel}^e(r) = \begin{cases} 0 & \text{if } r_1 - d_1/2 < r < r_1 + d_1/2, \\ 0 & \text{if } r_2 - d_2/2 < r < r_2 + d_2/2, \\ \Delta V^e & \text{otherwise.} \end{cases} \tag{3}$$

To solve the single particle problem we consider the CQDR structure embedded in a large hardwall cylinder with radius D and height W. The electron and hole wavefunctions are expanded in a basis consisting of eigenfunctions for the large hardwall cylinder. Considering the rotational symmetry of the Hamiltonian, the electron wavefunction $\Psi_e(r, \phi, z)$ can be expanded as

$$\Psi_e(r, \phi, z) = |n, m, s, \sigma\rangle = \sum_{nms\sigma} a_{nms\sigma}\Phi_{nm}(r, \phi) f_s(z)\chi_\sigma(S_z), \tag{4}$$

where $\Phi_{nm}(r, \phi)$ and $f_s(z)$ are the basis for the in-plane and growth directions, respectively,

$$\Phi_{nm}(r, \phi) = \frac{\sqrt{2}J_{|m|}\left(\frac{\alpha_{n|m|}}{D}r\right)}{dJ_{|m|+1}(\alpha_{n|m|})}\frac{1}{\sqrt{2\pi}}e^{im\phi}, \tag{5}$$

$$f_s(z) = \sqrt{\frac{2}{W}}\sin\left[\frac{s\pi}{W}\left(x + \frac{W}{2}\right)\right]\left(|z| \leqslant \frac{W}{2}\right), \tag{6}$$

where $J_{|m|}$ is the Bessel function of integer order m, $\alpha_{n|m|}$ is the n-th zero point of the m-order cylinder Bessel function, $f_s(z)$ is the eigenstate of the hardwall square potential well with the thickness D along the growth direction. $\chi_\sigma(S_z)$ is the spin component.

The hole state is described by the Luttinger–Kohn Hamiltonian [14]

$$H_h = \frac{\hbar^2}{2m_0}\begin{bmatrix} H_{hh} & R & S & 0 \\ R^* & H_{lh} & 0 & S \\ S^* & 0 & H_{lh} & -R \\ 0 & S^* & -R^* & H_{hh} \end{bmatrix} - 2\kappa^L\mu_B B j_z + V_{\parallel}^h(\rho) + V_{\perp}^h(z) - eEz, \tag{7}$$

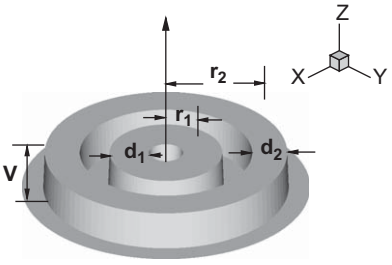

Fig. 1. Schematic diagram of the semiconductor concentric double ring structure. $r_1(d_1)$ and $r_2(d_2)$ denote the radii (widths) of the inner and outer rings, respectively.

where in the axial approximation,

$$H_{hh} = (\gamma_1^L + \gamma_2^L)(k_x^2 + k_y^2) + (\gamma_1^L - 2\gamma_2^L)k_z^2, H_{lh} = (\gamma_1^L - \gamma_2^L)(k_x^2 + k_y^2) + (\gamma_1^L + 2\gamma_2^L)k_z^2,$$

$$R = 2\sqrt{3}\gamma_3^L ik_- k_z,$$

$$S = \sqrt{3}\gamma^L k_-^2,$$

where $\mathbf{k} = -i\nabla - e\mathbf{A}/\hbar$, $k_\pm = k_x \pm ik_y$, γ_1^L, γ_2^L and γ_3^L are Luttinger parameters, and $\gamma^L = (\gamma_2^L + \gamma_3^L)/2$, and j is the spin of hole. The total angular momentum along the z axis $F_z = L_z + J_z$ (L is the orbital angular momentum) is a constant of motion, and the hole is also confined perpendicularly and laterally by a square potential well with different barrier height ΔV^h, therefore the eigenstates of H_h can be obtained through the basis set expansion

$$\Psi_h^{nF_z}(r, \phi, z) = \sum_{nj_z s\sigma} b_{nF_z\sigma}\Phi_{n,F_z-j_z}(r, \phi) f_s(z)|3/2, j_z\rangle, \tag{8}$$

where $\Phi_{n,F_z-j_z}(r, \phi)$ and f_s are also the basis for the in-plane and growth directions, respectively.

The exciton state $|\Psi_{ex}\rangle$ can be obtained by expanding $|\Psi_{ex}\rangle$ in the basis set constructed by the direct product of the eigenstates of the electron and the hole $|\Psi_e\rangle \otimes |\Psi_h\rangle$ as

$$\Psi_{ex}(\mathbf{r}_e, \mathbf{r}_h) = \sum_{ij} c_{ij}|\Psi_e^i\rangle \otimes |\Psi_h^j\rangle. \tag{9}$$

The Coulomb interaction can be calculated numerically in the basis set. The exciton states can be obtained by diagonalizing the matrix of exciton Hamiltonian.

The relevant material parameters used in our calculation are $m_e^* = 0.067m_0$, $g_e^* = -0.44$, $\gamma_1^L = 6.98$, $\gamma_2^L = 2.06$, $\gamma_3^L = 2.93$, $\kappa^L = 1.20$, the band gap for GaAs $E_g = 1.56$ eV. The band offsets of the electron and the hole are $\Delta V^e = 262$ meV and $\Delta V^h = 195$ meV [4], respectively. In our calculation, all physical quantities are dimensionless, e.g., the length unit $R = 100$ Å is the effective Bohr radius and the energy is in the unit of $E_0 = \hbar^2/2m_e^*R^2$. The unit of magnetic field is defined as $B_0 = \hbar/eR^2$. The magnetic flux is in the unit of $\Phi_0 = B_0\pi r_2^2$.

3. Numerical results and discussions

To understand the electron and hole states in CQDRs, we first plot the energies of the electron states as a function of the magnetic field for different inter-ring couplings in Fig. 2. For the weak inter-ring coupling we find that the energy levels belonging to the inner and outer rings cross each other with increasing the magnetic field (see Fig. 2(a)). But these levels exhibit an anticrossing behavior for the strong inter-ring coupling (see Fig. 2(b)). The splitting of energy levels is caused by the Zeeman effect.

The hole states are more complicated due to the heavy-hole and light-hole mixing. For weak inter-ring coupling and hole mixing case, the hole levels behave similar as the electron energy levels (see Fig. 3(a)). Strong inter-ring coupling would also result in the anticrossing between the hole levels. Since the hole states are more localized than the electron states in CQDR, the inter-ring coupling for the hole states is weaker than that between the electron states, therefore the anticrossing behavior in the hole spectrum is much weaker as compared to those found in the electron spectrum (see Figs. 2(b) and 3(b)). The hole spectrum becomes more complicated for weak inter-ring coupling and strong hole mixing case (see Fig. 3(c)). Note that the hole mixing can be controlled by varying the thickness of the CQDR which determines the energy difference between the heavy hole and the light hole states. The anticrossing behavior can also be induced by