Physica E 63 (2014) 211–214

Contents lists available at ScienceDirect

Physica E

journal homepage: www.elsevier.com/locate/physe

Heavy- and light-hole magneto-excitons bound to donor in quantum ring

W. Gutiérrez*, L.C. Porras, I.D. Mikhailov

Escuela de Física, Universidad Industrial de Santander, A. A. 678, Bucaramanga, Colombia

HIGHLIGHTS

- Analysis of the energy spectrum of magneto-excitons bound to an impurity in nanorings.
- Exciton–donor interaction in nanorings quenching the Aharonov–Bohm oscillations.
- The impurity produces a marked redshift of the lower peaks of the density of states.

ARTICLE INFO

Article history:
Received 26 March 2014
Received in revised form
30 May 2014
Accepted 2 June 2014
Available online 12 June 2014

Keywords:
Nanoring
Aharonov–Bohm oscillations
Magnetoexciton
Donor
Density of states

ABSTRACT

We analyse the alteration of the density of states of the light- and the heavy-hole magnetoexcitons due to the presence of an impurity donor in InAs quantum ring. It is shown that the donor provides a noticeable redshift of the lower peaks of the density of states, corresponding to the vibrational states of the exciton bound to the donor, while the effect on the higher energy levels related to a relative electron–hole rotation is mainly reduced to the splitting of the twofold degenerate states. Energies dependencies on the external magnetic field, applied along the growth direction show that the exciton–donor interaction leads to the flattening of the curves of the Aharonov–Bohm oscillations of the lowest energy levels and to diminishing of their amplitudes. This effect is more pronounced for heavy-hole magneto-exciton.

1. Introduction

Fabrication of nanometer-sized lithography defined semiconductor quantum rings (QR) realized in the last decade has generated interest in the Aharonov–Bohm (AB) effect for excitonic complexes [1]. The possibility to control individual excitations in quantum dot structures is an indispensable prerequisite for the new field of quantum information processing in a semiconductor environment, in which exciton complexes could be implicated as intermediate states. As it was shown in a number of experimental and theoretical studies, a neutral exciton confined in QR [2] exhibits the AB effect resulted from the rotation of carriers at opposite directions by means of the tunneling through barriers of the Coulomb potential that is generated by the external magnetic field. In this work we present a comparative analysis of the AB oscillations of the energy levels of the light- and heavy-hole magneto-excitons, and of changes in these oscillations that produces the presence in QR of a donor impurity. We show that the donor, placed in QR, provides a quenching of the AB oscillations of the lower energy levels of the exciton, similarly to one for the electron in QR with single and coupled donors, revealed previously [3], being this effect more pronounced for the heavy-hole magneto-exciton than for light-hole magneto-exciton.

2. Theory

In order to assess the experimentally relevant domain of parameters we adopt a simple model of a narrow ring, in which its height h and width w are significantly smaller than the centerline's radius R, basing on arguments presented in Ref. [4] in which the dimensions of the ring are associated with the pattern of the carriers pathways which form a narrow region along the rim of the ring-like structure, shown schematically in Fig. 1. In this case, which we call the structural adiabatic limit, 3D wave equations for the exciton can be separated and the analysis of its low-lying states is reduced to solving a simpler problem of 1D rotation of two particles, whose positions are given by polar coordinates of the hole ϑ_h and the electron ϑ_e [4]. By using the

* Corresponding author. Tel.: +57 7 6323095; fax: +57 7 6332477.
E-mail address: willigun@gmail.com (W. Gutiérrez).

http://dx.doi.org/10.1016/j.physe.2014.06.001
1386-9477/

exciton effective Bohr radius $a_0^* = \hbar^2\varepsilon/\mu e^2$ as the unit of length, the effective Rydberg $Ry* = e^2/2\varepsilon a_0^*$, as the energy unit and $\gamma = e\hbar B/2\mu c Ry*$, as the unit of the magnetic field strength, being $\mu = m_e^* m_h^*/(m_e^* + m_h^*)$ the reduced mass, the Hamiltonian which describes the electron–hole pair rotation along the QR's centerline can be expressed simultaneously both for the unbound exciton as $\eta = 0$ and for the exciton bound to donor as $\eta = 1$ in the following form [4]:

$$H(\eta) \approx E_0 - \frac{1}{I_h}\frac{\partial^2}{\partial\vartheta_h^2} - \frac{1}{I_e}\frac{\partial^2}{\partial\vartheta_e^2} + \frac{\gamma^2\overline{R}^2}{4}\left(\frac{1}{\mu_h} + \frac{1}{\mu_e}\right) + i\gamma\left(\frac{1}{\mu_h}\frac{\partial}{\partial\vartheta_h} - \frac{1}{\mu_e}\frac{\partial}{\partial\vartheta_e}\right)$$

$$-\eta V_c(\vartheta_e) + \eta V_c(\vartheta_h) - V_c(\vartheta_h - \vartheta_e);$$

$$E_0 = \left[\left(\frac{\pi^2}{h^2} + \frac{\pi^2}{w^2}\right) + \frac{\gamma^2\overline{R}^2}{4}\right]\left(\frac{1}{\mu_h} + \frac{1}{\mu_e}\right) + \Delta;$$

$$\mu_i = m_i^*/\mu; \quad I_i \approx \mu_i\overline{R}^2; \quad i = e, h \tag{1}$$

Within the framework of the adiabatic procedure which we use in order to obtain simplified 1D Hamiltonian (1), the actual momenta of inertia $I_i = \mu_i r^2; \quad i = e, h$, diamagnetic term $\gamma^2 r^2/4$ and the Coulomb potential V_c should be replaced by following approximate expressions $I_i \approx \mu_i\overline{R}^2$, $\gamma^2\overline{R}^2/4$ and $V_c(\vartheta) \approx 2/\sqrt{w^2/4 + \overline{R}^2 \sin^2\vartheta/2}$, respectively, being $\overline{R}^2 \approx R^2 + w^2/12$ [5].

The Hamiltonian (1) is separated completely in the case of the unbound exciton ($\eta = 0$) and partially for the exciton bound to the donor ($\eta = 1$) in the center-of-mass and relative coordinates $\Theta = (I_h\vartheta_h + I_e\vartheta_e)/I; \quad \vartheta = \vartheta_h - \vartheta_e; \quad I = I_h + I_e$. The eigenfunctions $\Phi(\Theta, \vartheta)$ and eigenenergies E of the Hamiltonian (1) then are solutions of the follwing wave equation:

$$-\frac{1}{I_\mu}\frac{\partial^2\Phi}{\partial\vartheta^2} + i\gamma\frac{\partial\Phi}{\partial\vartheta} - \frac{\eta}{I}\frac{\partial^2\Phi}{\partial\Theta^2} + [-V_c(\vartheta) + \eta V_c(\Theta + \vartheta/2) - \eta V_c(\Theta - \vartheta/2)]\Phi$$

$$= (E - E_0)\Phi;$$

$$I_\mu{}^{-1} = I_e{}^{-1} + I_h{}^{-1}; \quad I = I_e + I_h \tag{2}$$

It is seen that for QR without impurity ($\eta = 0$) the variables ϑ and Θ in the Hamiltonian (2) can be separated, the magneto-exciton energy is sum of two terms corresponding to the center-of mass and the relative motions, respectively. The center-of-mass energy is equal to $E_{CM}(M) = M^2/I$, where $M = 0, 1, 2, \ldots$ are values of the dimensionless angular momentum, while the relative motion energy can be found only numerically. In our numerical work we solve the separated part of Eq. (2) by using the Fourier series expansion method. For QR with the impurity Eq. (2) is solved directly by means the method of the double Fourier series expansion.

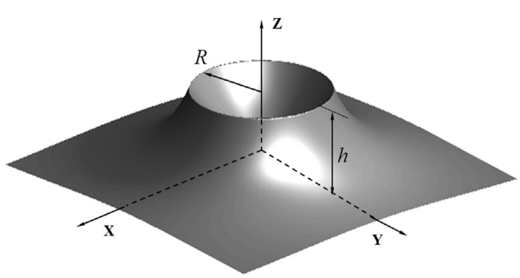

Fig. 1. Scheme of volcano-shaped nanoring.

3. Results and discussions

In order to analyse the effect of the bonding to donor on the magneto-exciton spectral properties in QRs, we have performed numerical calculations for low-lying energy levels as functions of the external magnetic field. The values of the physical parameters pertaining to InAs material used in our calculations are: the effective mass of the electron $m_e* \approx 0.026m_0$, and for light and heavy holes, $m_{HL}* \approx 0.026m_0$ and $m_{HH}* \approx 0.45m_0$, respectively; the dielectric constant, $\varepsilon \approx 13$ and the gap between the valence and conduction bands $\Delta = 0.41$ eV [6]. The values of the effective Bohr radius and the effective Rydberg corresponding to these parameters are $a_0* \approx 26.3$ nm and $Ry* \approx 2.1$ m eV, with $\mu_h \approx 0.5$ for the light hole and $\mu_h \approx 0.026$, for the heavy hole, respectively. Below we present some results of our calculations for the low-lying energies of unbound and bound donor to the excitons confined in InAs QR with centerline radius $R = 40$ nm, height $h = 6$ nm and width $w = 10$ nm.

In Fig. 2 we display the curves of the density of states $\rho(E)$ which we have calculated in our numerical work through the following relation:

$$\rho(E) = \sum_k \frac{1}{\pi}\frac{\Gamma}{(E - E_k)^2 + \Gamma^2} \tag{3}$$

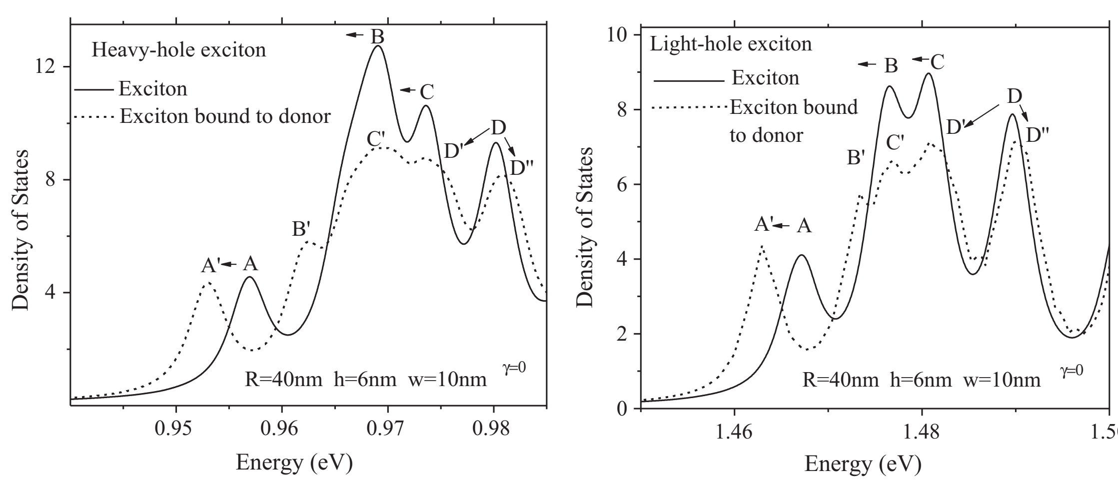

Fig. 2. Density of the excitonic states of the heavy-hole excitons (on the left side) and the light-hole excitons (on the right side) confined in QR with parameters indicated in figure. Solid lines correspond to the free excitons and dashed lines to the excitons bound to the donor. The arrows are guides to the eye in order to follow the redshift of A, B, and C peaks and the splitting of peak D generated by the donor.