Combined effects of hydrostatic pressure and temperature on the binding energy of an exciton in a quantum ring

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Abstract

The effects of a hydrostatic pressure and temperature have been studied theoretically on an exciton confined in $GaAs/Ga_{1-x}Al_xAs$ quantum ring (QR).
The ground state binding energy is calculated as a function of the radius, height of the ring and the barrier height using a variational approach within the effective mass approximation. In the calculations, we considered a finite confinement potential barriers model, and the effects due to the difference effective masses of electron and hole in GaAs and Ga1-xAlxAs are considered. We demonstrated that the binding energy of the exciton is an increasing function of the hydrostatic pressure and strongly influenced by the variation of the radius and height of QR.

Keywords : Exciton, quantum ring, binding energy, hydrostatic pressure, temperature

1. Introduction

Theoretical researches in semiconductor has opened a new dimension of nanostructure research, for instance, by increasing the carrier quantum confinement by going from bulk to quantum well (QW), quantum wire (QWW) and quantum dot (QD) nanostructures, and with the advances in fabrication techniques, have brought to the realization of novel confined structures called quantum rings (QR) and concentric double quantum rings (DQR), which carriers are confined in all spatial dimensions. Semiconductor QR can be fabricated in a variety of sizes and shapes by using different techniques, like Self-assembled growth, Molecular Beam Epitaxy, chemical synthesis, chemical etching and other techniques [1], Recently, T. Mano and al. fabricated the self-assembled formation of concentric double quantum rings formation with high uniformity and rotational symmetry using the droplet epitaxy technique [2]. A theoretical study of the effect geometric confinement in quantum rings, within the effective mass approximation, is presented in Refs. [3].
The studies about the influence of the external perturbations, such as hydrostatic pressure and temperature on the electronic states have proven to be significant in the understanding of some optical properties in QR [4].
In recent years, the exciton problems in quantum nanostructures have been intensively studied due to their possible applications in electronics and optoelectronics. In Ref [5] are studied the Linear and nonlinear optical absorptions of an exciton in a $GaAs/Ga_{1-x}Al_xAs$ quantum ring with parabolic confinement potential. Their found that the intersubband optical absorptions of an exciton in QR are strongly affected by the coulomb interaction, the ring radius, and the incident optical intensity.
In the present work we consider an exciton in a QR $GaAs/Ga_xAl_{1-x}As$ assuming a finite confinement potential under the action of a hydrostatic pressure and temperature, and we present a calculation of the exciton binding energy within the framework of a variation approach in the effective-mass approximation. We have investigated the influence of a hydrostatic pressure and temperature on the binding energy of exciton in QR. Results are calculated for different ring sizes, the difference of the electron and hole effective masses between the QR region and barriers has been considered. The paper is organized as follows; in Section 2 we describe the theoretical framework. Section 3 is dedicated to the discussion of the obtained results, and our conclusions are given in Section 4.

2. BASIC THEORY

Figure 1 shows the schematic plot of the quantum ring structure $GaAs/Ga_{1-x}Al_xAs$. In the following, we choose z-direction of our coordinate system to be perpendicular to the plane of quantum ring. The inner radius and outer radius are R_1, R_2 for the ring respectively. The height of QR is H.

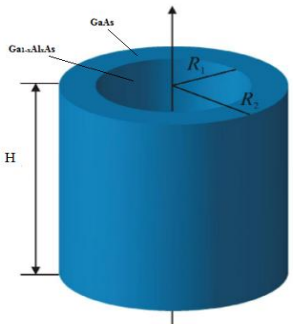

Fig.1 Schematic structure of quantum ring.

The basic Hamiltonian of electron-hole system in DQR can be written within the framework of the effective-mass as follows:

$$H_{ex} = \frac{p_e^2}{2m^*_{e1,2}(P,T)} + V_w^e(r_e,P,T) + \frac{p_h^2}{2m^*_{h1,2}(P,T)} + V_w^h(r_h,P,T) - \frac{e^2}{\epsilon(P,T)|r_e - r_h|} \quad (1)$$

Where $m^*_{e1}(P,T)$ ($m^*_{e2}(P,T)$) and $m^*_h(P,T)$ ($m^*_{h2}(P,T)$) are hydrostatic pressure and temperature dependent the effective masses of the electron and hole in GaAs ($Ga_{1-x}Al_xAs$), respectively, are given by [6]:

$m^*_{e2}(P,T) = (m^*_{e1}(P,T) + 0.0835x)m_0$

Where m_0 is the free electron mass, and x is the mole fraction of Aluminum in the $Ga_{1-x}Al_xAs$ layer.

$\frac{e^2}{\epsilon(P,T)|r_e-}$ The Coulomb interaction term between carriers, where $\epsilon(P,$ is hydrostatic pressure and temperature dependent the static dielectric constant. [7]

On the other hand, we have considered heavy-hole, for the effective masses, given by : [8]

$$m^*_{h2}(P,T) = (m^*_{h1}(P,T) + 0.42x)$$

$V_w^e(r_e)$ $\left(V_w^h(r_h)\right)$ In Eq.(1) is corresponding of the electron (hole) confining potential :

$$V_w^i(r_i)\begin{cases} 0; & R_1 < \rho_i < R_2 \;\; ; \; |z_i| \geq \frac{H}{2} \\ V_i(x,P,T); & 0 < \rho_i < R_1 \; ; \; \rho_i > R_2 \;\; \text{(i=e, h)} \\ \infty \;\; ; & |z_i| > \frac{H}{2} \end{cases} \quad (2)$$

The expressions of $V_e(x,P,T)$ and $V_h(x,P,T)$ are given by [7], and we can write: $V_e(x) = 0.6\Delta E_g(x,P,T)$ and $V_h(x) = 0.4\Delta E_g(x,P,T)$, $\Delta E_g(x,P,T)$ is hydrostatic pressure and temperature dependent the band gap difference between well and barrier materials and it is given in [9]:

The Hamiltonian Eq. (4) is written in reduced atomic units, which correspond of energy is the exciton Rydberg $R^*_1(0,0) = \frac{\mu_1(0,0)}{2\epsilon_1^2(0,0}$, and length is the exciton Bohr radius $a^*_1(0,0) = \frac{\epsilon_1(0,0}{\mu_1(0,0}$, to obtain the dimensionless form of the Hamiltonien.

Where $\mu_1(0,0) = \frac{1}{m^*_{e1}(0,0)} + \frac{1}{m^*_{h1}(0,0)}$ is the reduced mass in GaAs DQR region. By using the Hylleraas coordinates coordinates $(\rho_e, \rho_h, \rho_{eh})$ we obtained the Hamiltonian as follows:

$$H_{ex} = -\frac{\mu_1(0,0)}{me_{1,2}(P,T)}\left(\frac{\partial^2}{\partial\rho_e^2} + \frac{1}{\rho_e}\frac{\partial}{\partial\rho_e} + \frac{\rho_{eh}^2+\rho_e^2-\rho_h^2}{\rho_e\rho_{eh}}\frac{\partial^2}{\partial\rho_e\partial\rho_{eh}} + \frac{\partial^2}{\partial z_e^2}\right) - \frac{\mu_1(0,0)}{mh_{1,2}(P,T)}\left(\frac{\partial^2}{\partial\rho_h^2} + \frac{1}{\rho_h}\frac{\partial}{\partial\rho_h} + \frac{\rho_{eh}^2+\rho_h^2-\rho_e^2}{\rho_h\rho_{eh}}\frac{\partial^2}{\partial\rho_h\partial\rho_{eh}} + \frac{\partial^2}{\partial z_h^2}\right) - \frac{\mu_1(0,0)}{\mu_{1,2}(P,T)}\left(\frac{\partial^2}{\partial\rho_{eh}^2} + \frac{1}{\rho_{eh}}\frac{\partial}{\partial\rho_{eh}}\right) - 2\frac{\epsilon_1(0,0)}{\epsilon_1(P,T)\sqrt{\rho_{eh}^2+z_{eh}^2}} + \frac{V_w^e(P,T)}{R_1^*} + \frac{V_w^h(P,T)}{R_1^*} \quad (3)$$

In order to calculate the exciton binding energy, we choose the following trial function of the exciton in the form:

$$\Psi_{ex}^{1s} = N\phi_e(\rho_e,z_e)\phi_h(\rho_h,z_h)\Psi(\rho_{eh},z_{eh}) \quad (4)$$

$\phi_i(\rho_i,z_i)$ (i=e, h), is the ground state eigenfunction of the Hamiltonian without the presence of coulombic interaction, is presented as a linear combination of Bessel functions (radial direction) multiplied by a cosine function (vertical direction) [10]. N is the normalization constant, $\Psi(\rho_{eh},z_{eh})$ is the variational part of the trial wave function :

$$\Psi(\rho_{eh},z_{eh}) = e^{-(at\,\rho_{eh} + al\,(z_e-z_h)^2)} \quad (5)$$

In which a_t and a_l are the variational parameters. The ground state binding energy E_b^{ex} of the exciton can be written as:

$$E_b^{ex} = E_e + E_h - \min\langle\Psi_{ex}^{1s}|H_{ex}|\Psi_{ex}^{1s}\rangle \quad (6)$$

Where E_e (E_h) is the lowest sub bands energy for the electron (hole), without the presence of columbic interaction.

3. Results

Our results are applied to the QR of type: GaAs/$Ga_{1-x}Al_xAs$. We have taken x=0.3. The results are displayed in atomic units $a_1^*(0.0) = 8.766$ nm and $R_1^*(0.0) = 6.492$ meV.

In figure 1 we plot the binding energy of exciton confined in QR as a function of H, for fixed $R_1=1a_1^*$ and $R_2=2a_1^*$, for different temperatures T= 0K, 150K and 300K at P=0Kbar. The figure shows that the binding energy of the exciton increases as the height of ring decreases. It is clear that for a given pression the binding energy of the exciton decreases with increasing T which tends to diminish the electron-hole attraction. In figure 2, the binding energy of exciton are plotted as a function of H, for different hydrostatic pressures P=0Kbar and 50kbar. We show that the binding energy increases with applied pressure meaning that the application of the hydrostatic pressure reinforces the interactions between the electron and hole.

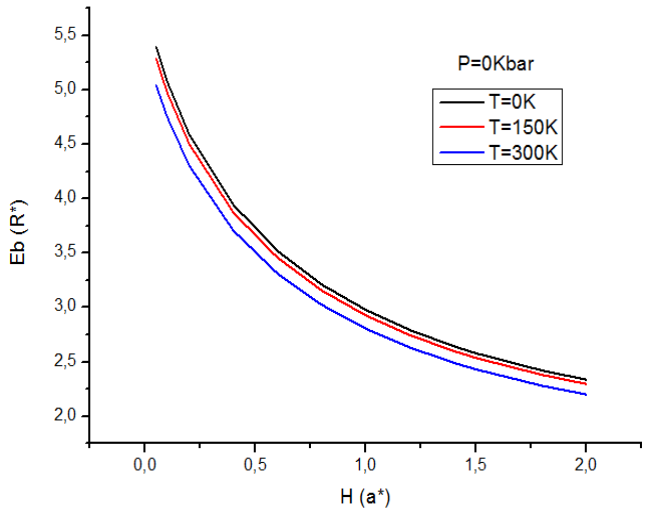

Fig.1 binding energy as a function of the QR height for different temperatures (T=0K,150K and 300K) at P=0Kbar.

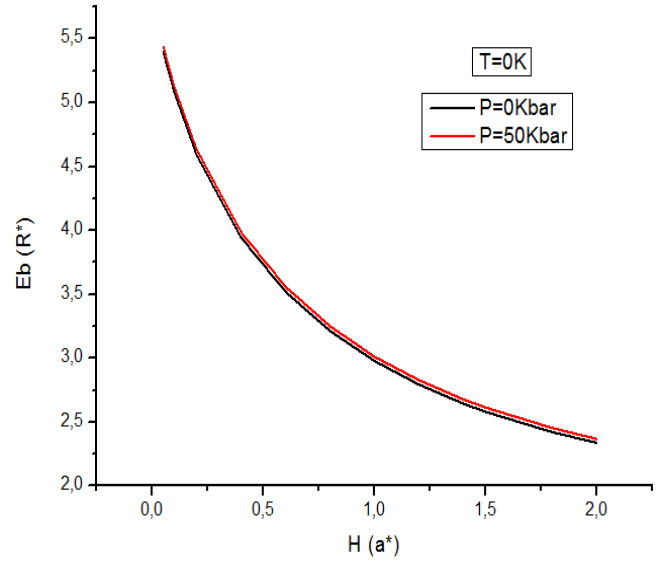

Fig.2 binding energy as a function of the QR height for different hydrostatic pressures (P=0Kbar and 50K) at T=0K.

4. Conclusions

To conclude, we have calculated the ground state binding energy of heavy-hole exciton confined in GaAs/$Ga_{1-x}Al_xAs$ QR as a function of the radius of the ring, the barrier height, following a variational calculation within the effective mass approximation. In this study we demonstrated that the binding energy of exciton is strongly influenced by the variation of the radius and height of QR, and secondly we have investigated The effects of a hydrostatic pressure and temperature, We show that the binding energy increases in the presence of the hydrostatic pressure and decreases with the temperature.

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