SENRA Academic Publishers, Burnaby, British Columbia
Vol. 5, No. 2, pp. 1559-1565, June 2011
Online ISSN: 1920-3853; Print ISSN: 1715-9997

Canadian Journal of pure&applied sciences

MAGNITO-EXCITON IN NARROW-GAP *InSb* CYLINDRICAL LAYER QUANTUM DOT

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ABSTRACT

In frameworks of Kane model we explored the effects of Coulomb electron-hole correlations and magnetic confinement for several cylindrical size combinations in a narrow-gap *InSb* cylindrical layer quantum dot for the heavy hole-electron and light hole-electron. The influence of excitonic effects on the behavior of the energetic spectrum of said system was discussed using a perturbation theory framework. Dependences of the electron-hole energetic spectrum versus the internal radius, external radius, and magnetic field are presented. It was shown that the exciton energy for both type of electrons strongly influenced by changing the geometrical parameters and the value of applied magnetic field. In addition to that it was found that the heavy hole-electron is less sensitive to those parameters comparing with the light hole-electron.

Keywords: Quantum layer, magneto-excitons, narrow-gap, III-V semiconductors.

INTRODUCTION

The Coulomb interaction near the absorption edge leads to considerable changes in the optical properties of matter. The Coulomb interaction leads to the formation of electron-hole pairs which are called excitons. The excitons are to some extent similar to positronium atom in which an electron is bound to a positron through the Coulomb attraction. The electron in an exciton is bound to the hole and the resulted quasi-particle is electrically neutral. An exciton can move like a free atom through the crystal. The existence of excitons yields in intense absorption lines below the energy gap region. As a result of the Coulomb attraction, the photo, due to the exciton transition, has less energy in comparison with the energy gap. Therefore, the phenomenon of photon absorption in a crystal corresponds to direct formation of excitons in the media. The photoluminescence method is one of the interesting methods in studying optical properties of semiconductors. Also, one can use the magneto luminescence to study the optical phenomena in the presence of strong magnetic fields (Knox, 1963; Shields *et al*., 2001). In addition, Wójs and Quinn (2007) and Wójs *et al*. (2000) have studied the spectrum of excitons formed in quantum wells in both singlet and triplet states through considering the Coulomb interaction among the electrons and the holes for $Al_xGa_{1-x}As/GaAs$ samples. Riva *et al*. (2000) have studied the binding energy of trion by considering it as a function of the applied magnetic field. Senger and Bajaj (2003) determined the binding energy of excitons as a function of quantum well width by introducing a function including three variational parameters. The so-called stochastic variational method developed by Shi and Gan (2003) and Wan *et al*. (2001) was used to study the properties of excitons and determine their correlation energy as a function of the quantum well width. Excitons in a quantum wire have also been studied at the absence of magnetic fields (Slachmuylders *et al*., 2007; Sidor *et al*., 2005; Sidor *et al*., 2007). In addition, Charge confinement in InAs/InP self-assembled quantum wires have been investigated theoretically using the adiabatic approach within the effective-mass approximation (Maes *et al*., 2004). On the other hand, concerning the use of the zero-dimensional structures (the quantum dots (QDs)) as an element base for the lasers in the infrared regions of spectrum the necessity of the realization of the narrowband zero-dimensional semiconductor structures arises (Asryan and Suris, 2003, 1996). Recently, Moiseev *et al*. (2007) reported the first results on the growth of *InSb* QDs by liquid-phase epitaxy on *InAs* substrates. They obtained QD arrays with an average height of L = (3.471)10^{-7}cm and an average radius of R = (27.277.5)10^{-7} cm.

As is well known, *InSb* is a narrow-gap semiconductor that offers a promising basis for the creation of QD lasers operating in the IR spectral range. In the frames of Kane's model Kazaryan *et al*. (2007) have calculated the interband absorption coefficient in a system of cylindrical QD *InSb* and showed that the absorption threshold is indeed in the infrared region. Note, that geometrical form of the QD defines the symmetry of the one-particle Hamiltonian, which describes the particle behavior in the system under discussion. In terms of simplicity of description for one-particle states in QD's, the most suitable of objects are QD's with a spherical shape (Leonard, 1993; Ferreyra and Proetto, 1999; Phillips *et al*., 1998; Sigrist *et al*., 2004; Vartanian *et al*., 2008). However, such systems have only one geometrical

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parameter – the radius of the QD – which can be used to adjust its energetic spectrum. In this consideration, systems with Cylindrical symmetry is preferred, since for these elements one may manipulate two parameters: the height of the cylinder, and its radius.

One of the first articles, where one and many-electron states in a quantum ring QR were studied, is the work of Chakraborty's and Pietilainen's (Chakraborty and Pietiläinen, 1994). Here, the authors studied the effect of electron-electron interaction on the magnetic moment of electrons in a QR. They have introduced a model, where the electron makes a circular motion in a parabolic confinement simulating a quantum ring, which is subjected to a perpendicular magnetic field (Chakraborty's - Pietilainen's model). Here the electron states in such a ring with and without the Coulomb interaction have been investigated. In addition Barticevic *et al*. (2000) studied the effects of an external electric field on the excitonic and optical spectra of a semiconductor quantum ring threaded by a magnetic flux, a detailed analysis of the ground-state properties of radially polarized excitons and its dependence with magnetic fields applied perpendicular to the ring plane and electric fields parallel to the ring plane were made. The authors found that the electric field breaks the azimuthal symmetry and mixes the eigenfunctions with different angular momentum. Also they found that the low-lying energy levels are almost independent of the magnetic field up to a region in energy where periodic Aharonov-Bohm-type oscillations appear. The effect of magnetic field and geometric confinement on excitons confined to a quantum ring was also studied in Song and Ulloa (2001) they use analytical matrix elements of the Coulomb interaction and diagonalize numerically the effective-mass Hamiltonian of the problem. Also they explored the Coulomb electron-hole correlation and magnetic confinement for several ring width and size combinations.

The Aharanov-Bohm oscillations of exciton Characteristics predicted for one-dimensional rings are found to not be present in these finite-width systems. Subsequently, the properties of excitons in a quantum ring with parabolic confinement in magnetic fields were discussed in Song and Ulloa (1996). The binding energy and electron-hole separation of the exciton are calculated versus the strength of external magnetic fields. They also explored the effects of Coulomb electron-hole correlations and magnetic confinement for several ring width and size combinations in the quantum ring. The linear optical susceptibilities as a function of magnetic fields are also discussed.

It is important to mention, that the realization of layered and ring shape nanostructures, in which radial motion of charge carriers is limited both on inner and on outer borders, has brought a new class of theoretical problems about the physical processes in such systems (Andreev and O'Reilly, 2000).The important feature of theoretical description of layered and ring shape structures is the opportunity of realization of limiting transitions to quantum wells, wires and also to QDs of various geometry. Really, if we fix the thickness of cylindrical nano-layer and increase internal and external radii the system becomes similar to quantum well. On the other hand, if we set the height of cylindrical quantum layer to infinity, and vanishes the internal radius we will get a quantum wire with circular cross section. If we fix the height and vanishes only internal radius we will get a cylindrical QD. Thus, the results received for layered and ring shape systems have general character and for this reason cause essential interest .The authors of Marwan *et al*. (2009), Zoheir *et al*. (2008), Marwan (2010) and Marwan *et al*. (2008) performed a theoretical investigation of electronic states and interband transition in a narrow-gap *InSb* spherical and cylindrical layer quantum dot under the influence of both magnetic and electric field. The authors discussed the transition from the light hole and heavy hole states to the electron state of conduction band in addition to that the interband absorption coefficient, threshold frequencies and the selection rules for different electric field orientation in the presence and absence of magnetic field were calculated.

In the present work, and within the frames of the two-bands of Kane model and parabolic dispersion law, it is interesting to investigate the specifications of the exciton energy spectrum of the heavy hole- electron and light hole-electron pairs in the cylindrical layer quantum dots from *InSb* in the presence of a magnetic field. By writing the Hamiltonian of the exciton in cylindrical coordinates and using an approximate analytical method we obtained the exciton wave function and the corresponding energy as functions of radii and applied magnetic field.

MATERIALS AND METHODS

Electronic states in magnetic field

Consider one-particle states in a cylindrical layer QD with the inner radius R_1, outer radius R_2 and with height L (Fig. 1). Let us determine the energy spectrum and the wave function assuming the existence of the homogeneous magnetic field, directed along OZ-axis, taking into account that the radial motion of an electron is bounded by both the outer and inner radii. The confining potential of the layer is approximated with the infinitely high rectangular walls

$$V_{con}(\rho, z) = \begin{cases} 0, R_1 \le \rho \le R_2, +\frac{L}{2} \le Z \le \frac{L}{2} \\ \infty, \rho < R_1, \rho > R_2, |Z| > \frac{L}{2} \end{cases} \quad (1)$$

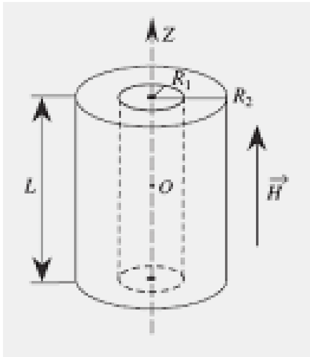


Fig.1. Cylindrical layer quantum dot.

The corresponding Schrödinger equation according to the parabolic dispersion law can be presented in the following form:

$$\frac{1}{2\mu_{lh,hh}}(\vec{p}-\frac{e^{lh,hh}}{c}\vec{A})^2\psi(\rho,\varphi,z)=E_{lh,hh}\psi(\rho,\varphi,z) \quad (2)$$

where $\mu_{lh,hh}$ are the effective mass of both the *lh* and *hh* respectively. The wave function must obey the following boundary condition $\psi(\pm L/2)=\psi(R_1)=\psi(R_2)=0$. We will search the solution of Eq. (2) in the form.

$$\psi(\rho,\varphi,z)=\frac{1}{\sqrt{2\pi}}e^{im\varphi}\sqrt{\frac{2}{L}}\left\{\begin{array}{c}\sin\frac{\pi n}{L}Z\\ \cos\frac{\pi n}{L}Z\end{array}\right\}f(\rho) \quad (3)$$

Substituting Eq. (3) in Eq. (2) we get a new equation for function $f(\rho)$.

$$\frac{η^2}{2\mu}(f^{//}+\frac{1}{\rho}f^{/}-\frac{m^2}{\rho^2}f)+[E_{lh,hh}-E_{n_{lh,hh}}-\frac{\mu\omega_H^2\rho^2}{8}-\frac{η\omega_{H_{lh,hh}}m}{2}]f=0 \quad (4)$$

Where $\omega_{H_{lh,hh}}=eH/\mu_{lh,hh}c$ is the cyclotron frequency and $E_{n_{lh,hh}}=n^2\pi^2η^2/2\mu_{lh,hh}L^2$. The solution of Eq. (4) can be expressed in terms of confluent hypergeometric functions

$$f_{lh,hh}(\rho)=\left\{c_1F\left(-\left(\beta_{lh,hh}-\frac{|m|+1}{2}\right),|m|+1,\frac{\rho^2}{2a^2_{H_{lh,hh}}}\right)+c_2U\left(-\left(\beta_{lh,hh}-\frac{|m|+1}{2}\right),|m|+1,\frac{\rho^2}{2a^2_{H_{lh,hh}}}\right)\right\}e^{\frac{\rho^2}{4a^2_{H_{lh,hh}}}}\rho^{|m|} \quad (5)$$

Here. $\beta_{lh,hh}=1/η\omega_{H_{lh,hh}}(E_{lh,hh}-E_{n_{lh,hh}})-m/2$ and $a_{H_{lh,hh}}=\sqrt{η/\omega_{H_{lh,hh}}}$ is the magnetic length taking into account that the wave function (5) should vanish at the boundaries ($f(R_1)=f(R_2)=0$). For the determination of the energy spectrum of the system we must have the zero determinant condition

$$\begin{vmatrix}F\left(-\left(\beta_{lh,hh}-\frac{|m|+1}{2}\right),|m|+1,\frac{R_1^2}{2a^2_{H_{lh,hh}}}\right) & U\left(-\left(\beta_{lh,hh}-\frac{|m|+1}{2}\right),|m|+1,\frac{R_1^2}{2a^2_{H_{lh,hh}}}\right)\\ F\left(-\left(\beta_{lh,hh}-\frac{|m|+1}{2}\right),|m|+1,\frac{R_2^2}{2a^2_{H_{lh,hh}}}\right) & U\left(-\left(\beta_{lh,hh}-\frac{|m|+1}{2}\right),|m|+1,\frac{R_2^2}{2a^2_{H_{lh,hh}}}\right)\end{vmatrix}=0 \quad (6)$$

Solving transcendent Eq. (6) numerically we can find our energy spectrum $E_{lh,hh}$.

Excitonic effects

Let us consider the contribution of hole-electron interactions (excitonic effects)on the electronic states using perturbation theory. The authors of (Wang *et al*., 1996) conducted a theoretical examination of the influence of an external magnetic field on the properties of excitons in a potential of finite height. Their theoretical results for the diamagnetic shift are in very good agreement with experimental results. Halonen *et al*. (1992) presented a theoretical investigation of the quantum disk, taking into account the Coulomb interaction between the electron and the hole. They calculated the ground-state energy (as well as the energy of the excited states), the binding energy, and the diamagnetic shift of an exciton in a quantum disk for a hard wall confinement properties of a two-dimensional exciton in a parabolic QD in a magnetic field. Liu *et al*. (2003) studied the optical spectra and exciton states in vertically stacked, self-assembled quantum disks in a vertically applied electric field.

Furthermore, in this work, we assume that the quantization in the direction of the disk axis (OZ) is very strong. Therefore, in this case we will consider motion in OZ direction using the framework of the single-particle model. In other words, we will consider a two-dimensional exciton. In the limit of infinitely high walls, the Hamiltonian of a magneto-exciton takes the following form

$$\hat{H}_{ex}=\hat{H}_e+\hat{H}_h-\frac{e^2}{\varepsilon|\vec{\rho}_e-\vec{\rho}_h|}, \quad (7)$$

where

$$\hat{H}_i=\frac{1}{2\mu^i}(\hat{p}_i-\frac{e^i}{c}A_i)+V(r_i)$$

and

$$\hat{H}_i\psi_i=E_i\psi_i, i=e,h$$

We consider the third term of equation (7) as a small perturbation for the Hamiltonian $\hat{H}_e+\hat{H}_h$. Therefore, the wave function of the magneto-exciton, in a first order approximation, may be presented in the following form

$$\psi^0_{ex}(r_e,r_h)=\psi_e(\rho_e,\varphi_e,z_e)\psi_h(\rho_h,\varphi_h,z_h), \quad (8)$$

The correction for the energy is given by the following expression

$$\Delta E_0 = \int \psi_{ex}^{0*}(r_e, r_h)(-\frac{e^2}{\varepsilon\sqrt{\rho_e^2 - \rho_h^2 - 2\rho_e\rho_h\cos(\varphi_e - \varphi_h)}})\psi_{ex}^0 dV_e dV_h, \quad (9)$$

which can be reduced according to Janssens (2001) to the following form

$$\Delta E_0 = -\frac{8\pi e^2}{\varepsilon}\int_{R_1}^{R_2}\rho_2 d\rho_2 \int_{R_1}^{R_2}\frac{g(\rho_1,\rho_2)}{\rho_1+\rho_2}\times K\left(\frac{4\rho_1\rho_2}{(\rho_1+\rho_2)^2}\right)\rho_1 d\rho_2, \quad (10)$$

Here

$g(\rho_1,\rho_2) = \psi_{ex}^{0*}(r_e,r_h)\psi_{ex}^{0}(r_e,r_h)$, and

$K(m) = \int_0^{\pi/2}\frac{d\varphi}{\sqrt{1-m\sin^2\varphi}}$ is a complete elliptic integral of the first kind. Thus, for the energy we have:

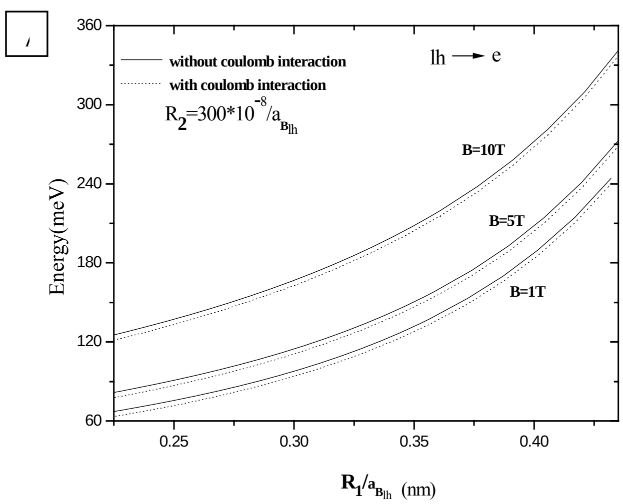
$$E = E_e + E_h + \Delta E_0, \quad (11)$$

DISCUSSION

For the qualitative analysis of the obtained result let us consider *InSb* cylindrical layer for which E_g =0.18 eV, μ_e= 0.015m_e, μ_{lh}= 0.015m_e and μ_{hh}= 0.51m_e (m_e is the mass of free electron). In (Fig. 2A) the dependence of the energy spectrum of the lh-electron transition (solid curve) on the inner radius R1 for fixed value of outer radius $R_2 = 300 * 10^{-8}/a_{B_{lh}}$ and different values of magnetic field (B, 1, 5, 10 T) are presented. As it follows from the figure, the energy levels increase monotonically with increasing R_1. This is connected to the increase of the role of size quantization (layer thicknesses L =R_2-R_1 decrease). This can be explained by the fact that in the parabolic dispersion, the energy depends on the momentum square, as well as on the inverse square of the thickness. In addition, we note that the energy levels depend on the value of the applied magnetic field which can be explained as a result of the dispersion laws.

Also as can be seen in (Fig. 2A) (the dot curve), due to the increase in the energy with increasing R_1 at fixed value of R_2 different behavior takes place for the exciton energy which increase with increasing R_1.This last fact is explained by the more considerable decrease of the absolute value of the Coulomb integral compared with the increase in the energy of the single-particle state (Tadic and Peeters, 2004). In addition, we note that with increasing the magnitude of the magnetic field strength, the energy increase which can be attributed to the well-known fact that the interaction energy for a Coulombic system increases with magnetic field strength (Landau and Lifshitz, 1989).

An opposite picture appears in (Fig. 2B) when we fix the inner radius R_1 ($R_1 = 100 * 10^{-8}/a_{B_{lh}}$) and increase R_2. In this case the layer thickness increases and, correspondingly, the size quantization weakens. This explains the lowering of the energy levels with the increase of R_2. Also we note that the exciton energy



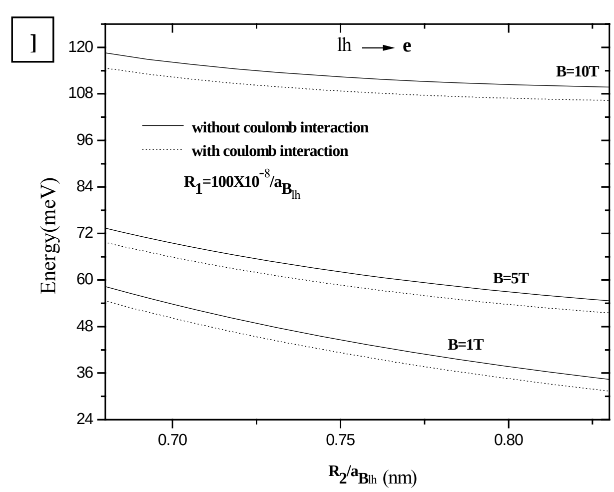


Fig. 2. Dependencies of the energy spectrum for *lh- e* on (A) inner radius R_1 for a fixed value of the outer radius R_2 (B) Outer radius R_2 for a fixed value of R_1 without considering the coulomb interaction (solid curve) and with considering the coulomb interaction (dot curve) for m = 0, n = 1, and different value of magnetic field B.

decrease with increasing R_2 which can be explained as a result of the increase in the absolute value of the Coulomb interaction.

In figure 3 A and B, the dependencies of the energy spectrum for the *hh*-electron on the inner R_1 (fixed R_2) and outer R_2 (fixed R_1) radii and different values of magnetic field (B, 1, 5, 10 T) with coulomb interaction (solid curve) and without coulomb interaction (dot curve) are presented. We see the same behavior as that appears in figure 1(A and B) the only difference is that the coulomb interaction for the *hh*- electron appears to be less sensitive to the change of the geometrical parameters than that in the case of *lh*- electron which can be explained as a result of the difference in masses between the light and heavy holes. Hence, upon the change of layer parameters, the energy level of the heavy hole has less energy shift than once of the light hole. But the electron levels possess the same energy shift, as the light hole.

As can be seen in figure 4 the dependencies of the energy for (A) *lh*- electron (B) *hh*- electron pairs on the value of the applied magnetic field at fixed value of both the inner and outer radii ($R_1$and R_2) without considering the

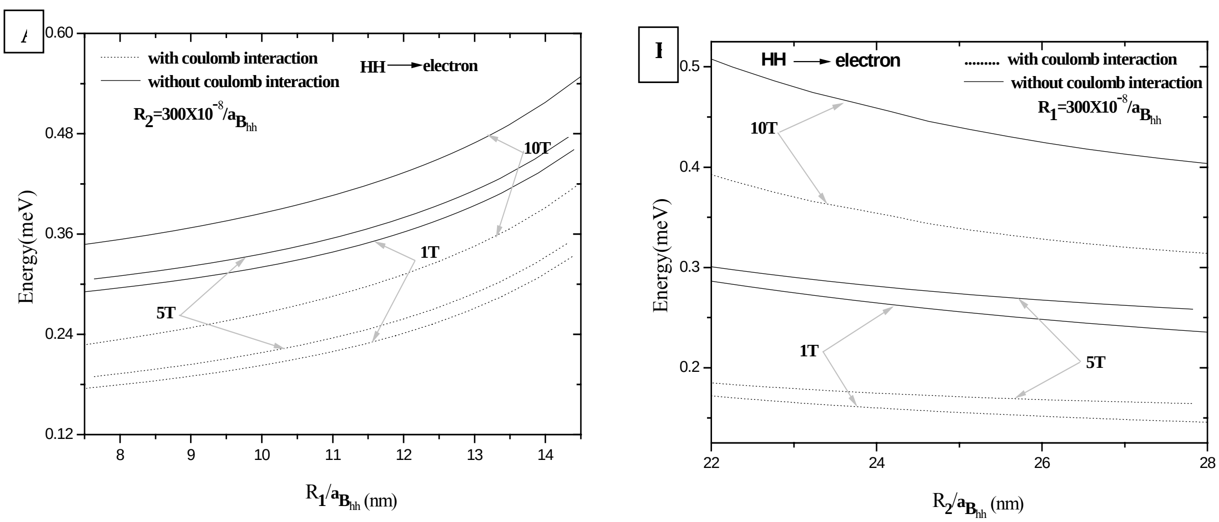


Fig. 3. Dependencies of the energy spectrum for *hh- e* on (A) inner radius R_1 for a fixed value of the outer radius R_2 (B) Outer radius R_2 for a fixed value of R_1 without considering the coulomb interaction (solid curve) and with considering the coulomb interaction (dot curve) for m = 0, n = 1, and different value of magnetic field B.

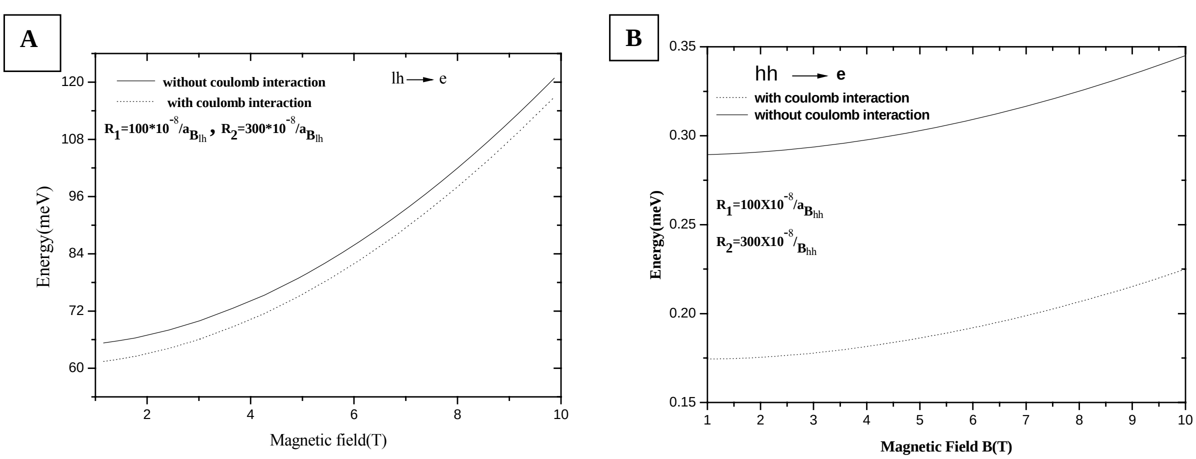


Fig. 4. Dependencies of the energy for (A) *lh- e* (B) *hh-e* pairs on the value of the applied magnetic field at fixed value of both the inner and outer radii (R_1andR_2) without considering the coulomb interaction (Solid curve) and with considering the coulomb interaction (dot curve) for m = 0, n = 1

coulomb interaction (solid curve) and with considering the coulomb interaction (dot curve) .The energy level increase with increasing the applied magnetic field for both cases which attributes to the dispersion law. In addition to that we note that the *hh*- electron is less sensitive to the change of the applied magnetic field than that of the *lh*- electron which can be explained by the fact that the expression for the potential energies in two cases is the same in Hamiltonian, meanwhile the changes in the region of localization of the electron in the case of *hh*-electron are strong and it is clear that with the increase of the magnetic field the region of localization will decrease considering the expression for the energies of the electron in the presence of the magnetic field (Marwan *et al*., 2009).

$$E_{lh,hh}(H) = \frac{1}{2\mu_{lh,hh}}(\vec{p} - \frac{e^{lh,hh}}{c}\vec{A})^2$$

Due to the electron-hole interaction, the total energy increases with increasing the magnetic field (Atayan *et al*., 2008). This can be attributed to the well-known fact that the interaction energy for a Coulombic system increases with magnetic field strength. With an increase in the magnitude of the magnetic field, the system tends to become a one-dimensional one. Therefore, the Coulomb energy increases (Landau and Lifshitz, 1989).

CONCLUSION

In the present work we investigated the effect of changing the geometrical parameters and the magnetic field strength on the exciton energy of the narrow band *InSb* cylindrical quantum layer for the *lh*- electron and *hh*-electron. It is shown that the exciton energy for both type of electron strongly influenced by change those parameters. It should be underlined that the *hh*-electron is less sensitive to the change of geometrical parameters and the magnetic field than those of the *lh*-electron.

ACKNOWLEDGEMENTS

I am grateful to Dr. Areg. Meliksetyan, Faculty of Physics, Yerevan State University and Professor Hayk sarkisyan , Russian-Armenian University for valuable comments and suggestions.

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Received: Nov 19, 2010; Accepted: Jan 26, 2011