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Magnetic field effects on the exciton binding energy in a near triangular quantum well

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Abstract : The Binding Energy of an exciton in a Near Triangular Quantum Well (NTQW) composed of $Ga_{1-x}Al_xAs/GaAs/Ga_{1-x}Al_xAs$ with potential profile proportional to $|z|^{2/3}$ is calculated as a function of the quantum wellwidth (L) and barrier height(V_0) with uniform magnetic field applied along growth direction (i.e z-axis). In-plane electron-hole distance $<\rho^2>^{1/2}$, distance of the electron and hole respectively from the well center $<z_e^2>^{1/2}$ and $<z_h^2>^{1/2}$ are also calculated. The results are compared with those of quantum wells with other potential profiles and available experimental data.

Keywords: Quantum well, Exciton, Binding energy, Magnetic field, Barrier height.

Introduction

In recent years, due to significant improvements in micro-fabrication techniques like Molecular Beam Epitaxy and Metal Organic Chemical Vapor Deposition, it is possible to fabricate quantum wells with varied potential profiles. Miniaturization of quantum structures into nano-scale is being applied in the fabrication of nano-scale devices.

Quantum wells with parabolic potential shape (PQW) have been studied quantitatively by several workers. Kyrychenko et al[1] calculated the exciton binding energy in PQW using two different trial wave functions and compared the results with those of rectangular quantum wells (RQW). Tomasz M. Rusin[2] calculated the exciton energy in PQWs using the effective variational Hamiltonian method. They also determined the exciton binding energy in excited quantum well levels. Zang and Rustgi[3] found the effect of magnetic field normal to the plane of the well on the energy levels of a hydrogenic impurity in PQW. Tabata et al.[4] investigated the electronic structure of undoped AlGaAs/GaAs wide PQW as a function of well width, estimating the binding energies of excitons by photoluminescence measurement. The donor binding energy in PQW formed by $GaAs\text{-}Al_xGa_{1-x}As$ is determined by El-Meshad et al.[5] variationally.

The binding energy of the ground state hydrogenic donor in RQW has been calculated by Greene and Bajaj[6]. They have also reported the donor binding energies in RQW with applied magnetic field[7]. Brum and Bastard[8] studied the effect of a constant electric field on the energy position of the ground state exciton in RQW. Elabsy[9] reported the temperature dependence of the binding energy of shallow donors in RQW. Jayakumar et al.[10] determined the effect of non-parabolicity on hydrogenic donor binding energy in RQW without and with an applied magnetic field.

The ground state of a donor and light and heavy hole exciton in triangular quantum wells (TQW) have been calculated by Jiang and Wen[11]. Yu et al.[12] studied the exciton transition energy and oscillator strength under the electric field perpendicular to the heterointerface in TQW by photocurrent spectroscopy.

Vanitha and John Peter[13] reported the effect of applied magnetic field on the ground and excited states binding energy in a corrugated quantum well. Lopes et al.[14] studied the influence of the height and width of the well barrier on the binding energy of exciton in coupled double quantum wells formed by GaAs/AlGaAs. Pavel Redlinski[15] presented the results of numerical calculations of electronic states of an exciton and a trion in quantum well formed by CdTe at magnetic field upto 150T.

Andronikov et al.[16] studied the effect of temperature on excitons and trions in CdTe/CdMgTe quantum well structures and compared the results with the experimental data. The hydrogenic donor binding energy in cylindrical quantum wire with two quantum well formed by GaAs/GaAlAs has been calculated with applied magnetic field by Gonzalez et al.[17]. Arulmozhi[18] studied the effect of temperature on binding energy of hydrogenic donor in PQW. Zhao et al.[19] determined the influence of hydrostatic pressure on the exciton binding energy in quantum well formed by GaAs/AlGaAs and GaN/AlGaN. Raigoza et al.[20] studied the effects of both hydrostatic pressure and electric fields on the exciton energies in single GaAs-(Ga,Al)As quantum wells.

Arulmozhi and Balasubramanian[21] investigated the exciton and hydrogenic donor binding energy in a quantum well with potential profile proportional to $|z|^{2/3}$ (Near Triangular Quantum Well - NTQW) for different well width and barrier height. They have also calculated the binding energy of hydrogenic donor in $/z/^{2/3}$ quantum well as a function of well width and barrier height under an applied magnetic field along the growth direction[22].

The present authors[23] have studied the binding energy of light hole and heavy hole exciton in a surface quantum well (SQW) as a function of the well width including the effect of non-parabolicity. In this paper, a theoretical study is made to calculate the binding energy of light hole and heavy hole exciton in the NTQW formed by GaAlAs/GaAs/GaAlAs for different well width and barrier height with uniform magnetic field applied along growth direction including the effect of nonparabolicity and mass anisotropy. We also calculate the in-plane electron-hole distance and distance of the electron and hole from the well center. The integrated probability of finding the light exciton and heavy hole exciton inside the well is also found in the presence of magnetic field. Finally we compare our results of NTQW with available experimental data and those of quantum wells with other potential profiles.

Theory

The Hamiltonian for exciton in NTQW formed by $Ga_{1-x}Al_xAs/GaAs/Ga_{1-x}Al_xAs$ with an applied magnetic field B along the growth direction is given in the effective mass approximation as,

$$\mathcal{H} = \frac{1}{2m_e^*}\left(p - \frac{eA}{c}\right)^2 - \frac{e^2}{\varepsilon_0 r} + V(z_e) + V(z_h) \qquad (1)$$

where c is the velocity of light, e is the electric charge, ε_0 is the dielectric constant of bulk GaAs and m_e^* is the electron effective mass in GaAs. Using the cylindrical gauge, the vector potential A can be written as

$$A = \frac{1}{2}B \times r \qquad (2)$$

with **B** along the growth axis. We have considered the growth axis of the quantum well structure to be the z-axis. $r = \sqrt{\rho^2 + |z_e - z_h|^2}$, ρ is the distance in x-y plane.

Using the cylindrical co-ordinate system, the Hamiltonian for an exciton can be written as

$$\mathcal{H} = -\left[\frac{1}{\rho}\frac{\partial}{\partial\rho}\rho\frac{\partial}{\partial\rho} + \frac{1}{\rho^2}\frac{\partial^2}{\partial\varphi^2}\right] - \frac{\mu_{hi}^*}{m_e^*}\frac{\partial^2}{\partial z_e^2} - \frac{\mu_{hi}^*}{m_{hi}^*}\frac{\partial^2}{\partial z_h^2} + V(z_e) + V(z_h) - \frac{2}{r} + \gamma L_z + \frac{1}{4}\gamma^2\rho^2 \qquad (3)$$

The effective Rydberg R^* is used as the unit of energy ($R^* = \mu_{hi}^* e^4/2\hbar^2\varepsilon_0^2$) and the effective Bohr radius a^* as the unit of length ($a^* = \hbar^2\varepsilon_0/\mu_{hi}^* e^2$). In equation (3), L_z is the z-component of the angular momentum and γ is the dimensionless measure of the magnetic field, defined as $\gamma = \frac{e\hbar B}{2\mu_{hi}^* c R^*}$. The subscripts h and e stand for the hole and electron respectively. μ_{hi}^* is the reduced effective mass of the heavy hole *(i = h)* or light hole *(i = l)* and the electron. We have considered isotropic masses of light hole exciton and heavy hole exciton as

$$\frac{1}{\mu^*_{hi}} = \frac{1}{m^*_e} + \frac{1}{m^*_{hi}} \qquad (4)$$

The potential profile for the electron and hole in NTQW are given by

$$V(z) = \begin{cases} V_0 \left|\frac{z}{\frac{L}{2}}\right|^{\frac{2}{3}} & |z| < \frac{L}{2} \\ V_0 & |z| > \frac{L}{2} \end{cases} \qquad (5)$$

where V_0 is the barrier height, which depends on the composition x of Al and z = z_e (electron) or z_h (hole). The trial wave function of the exciton in the NTQW is taken to be of the form

$$\Psi = \begin{cases} N\, e^{-\alpha_e^2 z_e^2}\, e^{-\alpha_h^2 z_h^2}\, e^{-ar}\, e^{-\lambda\rho^2} & |z| < \frac{L}{2} \\ N_1\, e^{-\beta_e|z_e|}\, e^{-\beta_h|z_h|}\, e^{-ar}\, e^{-\lambda\rho^2} & |z| > \frac{L}{2} \end{cases} \qquad (6)$$

Here, α_e, α_h, β_e, β_h, a and λ are variational parameters. N is the normalization constant. The continuity conditions at z_e = L/2 and z_h = L/2 relates the normalization constant N and N_1. We have evaluated $\langle\mathcal{H}\rangle$ as a function of the variational parameters using the Hamiltonian in Eq.(3) and the trial wave function in Eq.(6).

The binding energy of exciton is then given by

$$E_B = E_e + E_h + \gamma - \langle\mathcal{H}\rangle_{\min} \qquad (7)$$

where, E_e and E_h are the ground state energies of electron and hole in bare quantum well respectively obtained variationally. $\langle\mathcal{H}\rangle_{\min}$ is the minimized value of $\langle\mathcal{H}\rangle$ with respect to the variational parameters.

The integrated probability of finding an exciton inside the well is obtained as

$$P = \int_0^{2\pi} \int_{-\frac{L}{2}}^{\frac{L}{2}} \int_{-\frac{L}{2}}^{\frac{L}{2}} \int_0^{\infty} \Psi^*\Psi\, \rho\, d\rho\, dz_e\, dz_h\, d\varphi \qquad (8)$$

The in-plane electron-hole distance $<\rho^2>^{1/2}$, distance of the electron and hole respectively from the well center $<z_e^2>^{1/2}$ and $<z_h^2>^{1/2}$ are also calculated.

Results and Discussion

For GaAs, we have taken $m^*_e = 0.0065m_0$, $m^*_{hh} = 0.34m_0$, $m^*_{lh} = 0.094m_0$ and $\varepsilon_0 = 13.2$, where m_0 is the free electron mass. The difference of total bandgap between $Ga_{1-x}Al_xAs$ and GaAs is determined by the equation

$$\Delta E_g = 1.155x + 0.37x^2\ eV \qquad (9)$$

The conduction band and valance band discontinuity is taken to be 65% and 35% of this bandgap difference respectively. We have not considered the effect due to the dielectric constant mismatch, effective mass mismatch and non-parabolicity effect of conduction band for GaAs because these effects are expected to be too small when the exciton binding energy is considered.

Fig.1 shows that the variation of binding energy of heavy hole exciton as a function of well width L for different magnetic field γ applied along the growth direction, for a barrier heights corresponding to the Al composition x = 0.3. For comparison, the variation binding energy of heavy hole exciton with L in the absence of magnetic field[21] is also shown in the figure. When L is reduced, the binding energy increases. If the L is reduced further, they reach a maximum value and then start to decrease rapidly. The peak value of binding energy is observed at L = 25 nm, for all values of γ. The presence of magnetic field leads to more binding. But as the magnetic field increases, the quantity of increase in binding energy decreases. This behavior is the similar to the cases of a hydrogenic donor in potential wells of varied profiles[3, 7, 11, 21] and for the exciton for γ = 0.

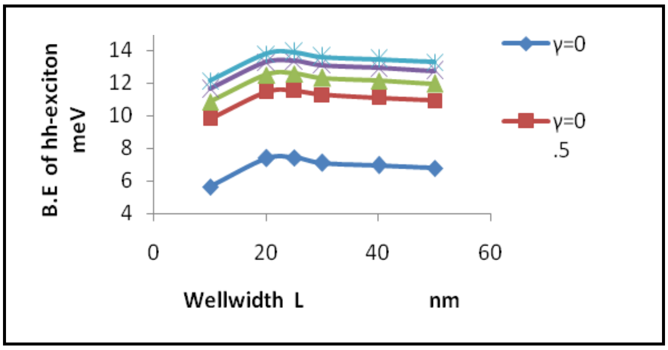

Fig.1. Variation of the binding energy of hh-exciton in $|z|^{2/3}$ quantum well as a function of well width L for different values of the magnetic field parameter γ.

The behavior of binding energy of light hole exciton as a function wellwidth L for different magnetic field parameter **γ** is displayed in Fig. 2.

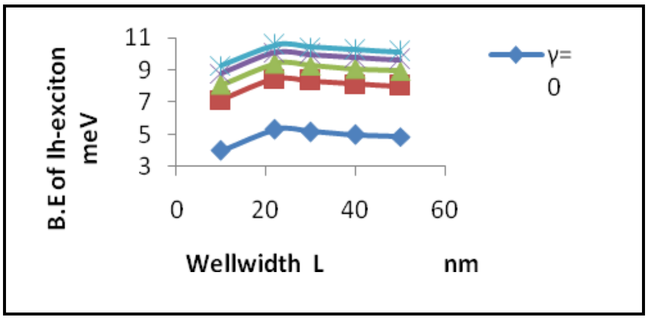

Fig.2. Variation of the binding energy of lh-exciton in $|z|^{2/3}$ quantum well as a function of well width L for different values of the magnetic field parameter γ.

Similar to the case of heavy hole exciton, the binding energy of the light hole exciton also increases and reaches its maximum and then decreases rapidly, when the well width L reduced. The peak value of binding energy is observed at L = 22 nm, for all values of **γ.** It is also noted that the binding energy of heavy hole exciton is more than that of the light hole exciton. This shows that the hh-exciton is more bound than the lh-exciton, which is due to $m_{hh}^* > m_{lh}^*$.

Figures 3 and 4 show the variation of binding energy of hh-exciton and lh-exciton as a function of barrier height V_0 respectively for the well width L = 10 nm, for different magnetic fields. In both cases, the binding energy decreases linearly with $1/\sqrt{V_0}$ for all values of magnetic field parameters.

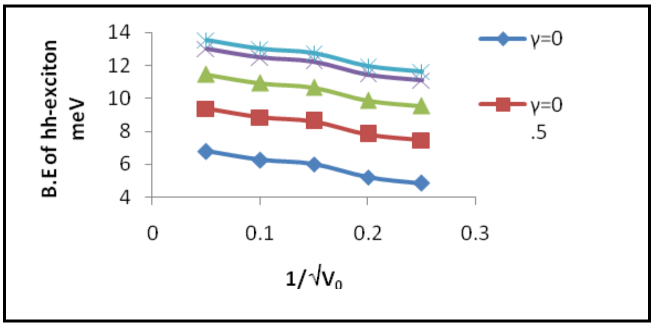

Fig.3. Variation of the binding energy of hh-exciton in $|z|^{2/3}$ quantum well as a function of barrier height V_0 for different values of the magnetic field parameter γ. V_0 is given in effective Rydberg (R*).

As the barrier height increases, the exciton is more and more bound inside the well. The results are qualitatively similar to those corresponding to quantum wells with other shapes.

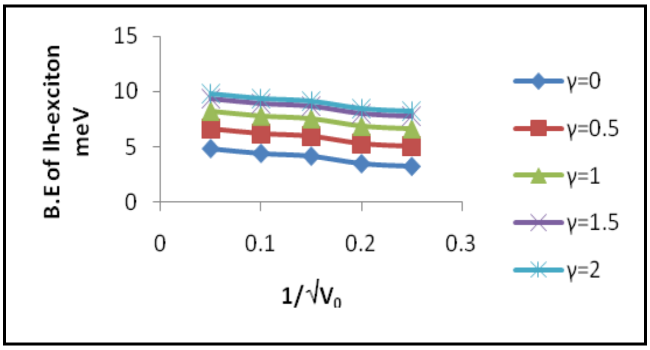

Fig.4. Variation of the binding energy of lh-exciton in $|z|^{2/3}$ quantum well as a function of barrier height V_0 for different values of the magnetic field parameter γ. V_0 is given in effective Rydberg (R*).

It can also be noted here that the binding energy of heavy hole exciton is more than that of the light hole exciton and as the magnetic field increases, the quantity of increase in binding energy decreases.

The variation of in-plane electron-hole distance $<\rho^2>^{1/2}$ as a function of wellwidth for heavy hole and light hole exciton is given in Fig. 5.

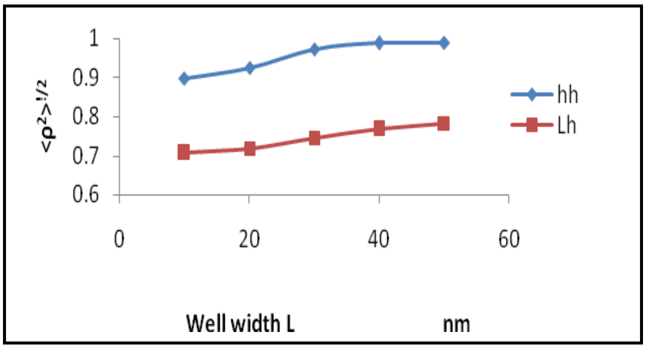

Fig.5. Variation of $<\rho^2>^{1/2}$ with the well width L for hh-exciton and lh-exciton

The values of $<\rho^2>^{1/2}$ are nearly independent of magnetic field and less dependent on L. This is expected because magnetic field is applied along z-axis and $<\rho^2>^{1/2}$ is calculated along the xy plane.

Figures 6 and 7 show the variation of $<z_e^2>^{1/2}$ and $<z_h^2>^{1/2}$ of hh-exciton and lh-exciton as a function of well width L. Both values of $<z_e^2>^{1/2}$ and $<z_h^2>^{1/2}$ for a hh-exciton increase with wellwidth and reaches a constant value (0.6 for $<z_e^2>^{1/2}$ and 0.4 for $<z_h^2>^{1/2}$) at exactly the same wellwidth at which the binding energy attains the peak value.

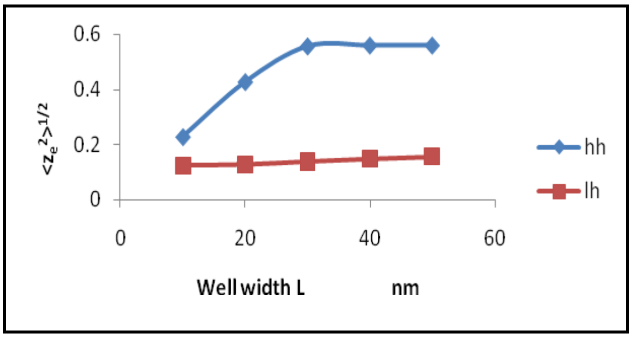

Fig.6. Variation of $<z_e^2>^{1/2}$ with the well width L for hh-exciton and lh-exciton

For the case of lh exciton, these values are nearly independent of the wellwidth.

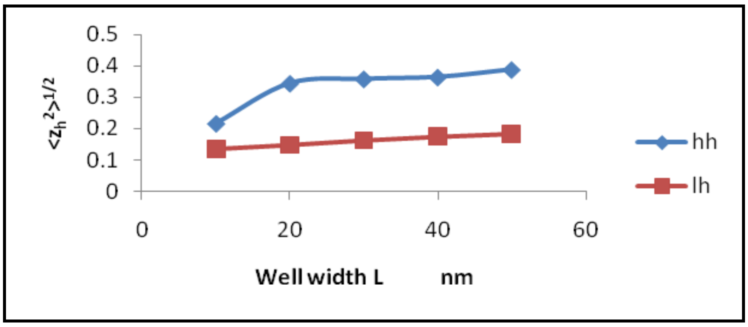

Fig.7. Variation of $<z_h^2>^{1/2}$ with the well width L for hh-exciton and lh-exciton

Conclusions

Binding energy of hh-exciton and lh-exciton in the presence of magnetic field in a Near Triangular Quantum Well (NTQW) are calculated variationally. A turnover occurs at a critical well width (25 nm for hh-exciton and 22 nm for lh-exciton), same for all values of magnetic field parameter **γ**. Applied magnetic field leads to more binding and the increased binding decreases as the magnetic field increases. Also the exciton binding energy decreases almost linearly with $1/\sqrt{V_0}$. $<\rho^2>^{1/2}$, is less dependent on magnetic field and wellwidth. $<z_e^2>^{1/2}$ and $<z_h^2>^{1/2}$ increases till the critical wellwidth and remains constant thereafter for hh-exciton and less dependent on wellwidth for lh-exciton.

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