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Effect of magnetic field and the phosphorous alloy content on exciton binding energy in quantum dot

Ada Vinolin[1] and A.John Peter[2]

[1]Department of Physics, Madurai Kamaraj University College, Alagarkoil Road, Madurai-625 002

[2]Department of Physics, Government Arts College, Melur-625 109. Madurai.

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ABSTRACT

The effects of magnetic field on the exciton binding energy and the Phosphorous alloy content in a cylindrical Phosphorous doped GaAs quantum dot are investigated with the geometrical confinement. The various Phosphorous alloy concentration in the $GaAs_{1-x_{oin}}P$ (x_{in} = <0.3) quantum dot has been taken into account. All the computations to get the electronic states are performed using variational procedure within the single band effective mass approximation by the magnetic field strength. The effect of strain due to the spontaneous and piezoelectric polarizations is included.

Introduction

GaAs semiconducting materials are quite interesting due to their potential applications in some device fabrications on opto-electronic devices. The energy levels in these heterostructures not only depend on the composition of the barrier and dot size but also the lattice constants of dot and barrier material. Eventually, this will affect the valence and conduction bands. It is well known that the typical III-V semiconductor such as GaAs experiences a compressive strain whereas AsGaP experiences the tensile strain [1] and this property makes GaAs/AsGaP heterostructure more interesting on the invention of lasers emitting in the infrared red regions. Energies of band-to-band transitions with the quantum-confinement subbands have been investigated from the photoreflection spectra of the strained short-period GaAs/$GaAs_{0.6}P_{0.4}$ superlattice [2].

Theory and Model

Exciton binding energy is calculated in the presence of magnetic field applied in the growth direction of a cylindrical $GaAs_{1-x_{oin}}P/GaAs_{1-x_{out}}P_{x_{out}}$ quantum dot incorporating the effect of piezoelectric field. Various Phosphorus alloy content is included in the Hamiltonian. The cylindrical quantum dot (GaP) is considered with the radius R surrounded with the barrier height H of a larger band gap energy, $GaAs_{1-x}P_x$. The Hamiltonian of a magneto-exciton consists of an electron and a hole along with the Coulomb interaction term between electron-hole pair. This Hamiltonian, within the effective mass-approximation, is expressed as,

$$H_{exc} = \sum_{j=e,h}\left[\frac{1}{2m_j(E)}\left(\vec{p}_j - \frac{q\vec{A}_j}{c}\right)^2 \pm \sigma_z \mu_B g_j(E)B + V(r)\right] - \frac{e^2}{\varepsilon|\bar{r}|} \pm |e|Fz \qquad (1)$$

where $\vec{p}$ is the momentum operator, $\vec{A}$ is the vector potential, q is the charge ($-e$ for electrons and $+e$ for holes), $|\bar{r}| = |\bar{r}_e - \bar{r}_h|$ denotes the relative distance between the electron and the hole, $V(r)$ is the confinement potential of the exciton, F is the effective electric field due to piezoelectric effect and ε is the dielectric constant of material inside the quantum dot, μ_B is the Bohr magneton and σ is the spin taken as $\pm 1/2$ [3]. The z-component of the spin has been taken as $\pm 1/2$ for simplicity for holes.

The Schrödinger equation is solved variationally by finding $\langle H_{exc}\rangle_{\min}$ and the binding energy of the exciton in the quantum dot is given by the difference between the energy with and without Coulomb term. The effects of magnetic field, Phosphorus alloy content and the geometrical effect are included while computing the eigen value energy. Then, the binding energy is by calculated by subtracting its subband energy with the inclusion of magnetic strength. We consider the correlation of the electron-hole relative motion, the trial wave function can be chosen as,

$$\Psi(\bar{r}_e, \bar{r}_h) = \psi_e(\rho_e)\psi_h(\rho_h)\exp(-\gamma\rho^2/4)e^{-\delta\rho^2}e^{-\beta z^2} \qquad (2)$$

where ψ_e and ψ_h are electron and hole wave function in the quantum dot respectively as given in Eq.(2). The above equation describes the correlation of the electron-hole relative motion. δ and β are variational parameters responsible for the in-plane correlation and the correlation of the relative motion in the z-direction respectively. These two variational parameters are the responsible of anisotropy of cylindrical nature of the quantum dots. And hence, it is believed that this type of Gaussian wave function is suitable approximation in a quantum limit region .

The ground state energy of the exciton in the $GaAs_{1-x_{oin}}P/GaAs_{1-x_{out}}P_{x_{out}}$ quantum dot in the external magnetic field, E_{exc}, is obtained by minimizing the expectation value of H_{exc} with respect to the variational parameters using Eq. (19). The ground state energy of the exciton in the $GaAs_{1-x_{oin}}P/GaAs_{1-x_{out}}P_{x_{out}}$ quantum dot is calculated by using the following equation

Tele:

E-mail addresses: a.john.peter@gmail.com

$$E_{exc} = \min_{\gamma,\delta,\beta} \frac{\langle \psi_e | H_{exc} | \psi_h \rangle}{\langle \psi_e | \psi_h \rangle} \qquad (3)$$

The exciton binding energy in the presence of magnetic field is given by

$$E_B(B) = E_e + E_h + \gamma - E_{exc}(B) \qquad (4)$$

We define $\gamma = \frac{\eta\omega_c}{2Ry^*}$ where R_y^* is the effective Rydberg energy and ω_c is the cyclotron frequency.

Results and discussion

We have carried out the calculation to find out the exciton binding energy with the effects of magnetic field and the geometrical confinement in a Phosphrous based group III-V quantum dot. The atomic units have been followed in the determination of electronic charges and the wave functions in which the electronic charge and the Planck's constant have been assumed as unity. All our calculations of exciton binding energy have been carried with the heavy hole mass as the heavy excitons are more common in experimental results.

We present the variation of exciton binding energy as a function of dot radius for three different concentration of Phosphorus content in a $GaAs_{1-x_{oin}}P/GaAs_{1-x_{out}}P_{x_{out}}$ quantum dot in the absence of magnetic field strength. In all the cases, the exciton binding energy increases with a decrease of dot radius, reaching a maximum value and then decreases when the dot radius is still decreased. The Coulomb interaction between the electron and hole is increased which ultimately causes the decrease in binding energy when the dot radius decreases. The binding energy decreases further as the dot radius approaches zero since the confinement becomes negligibly small, and in the finite barrier problem the tunneling becomes huge. Also, the contribution of confinement is dominant for smaller dot radii making the electron unbound and ultimately tunnels through the barrier. It is agreeable with the other investigator [2]. Moreover, we find that the exciton binding energy increases with the Phosphorous alloy content for all the dot radii. It is because the barrier height increases when the Phosphorous concentration is increased in the $GaAs_{1-x_{oin}}P/GaAs_{1-x_{out}}P_{x_{out}}$ quantum dot.

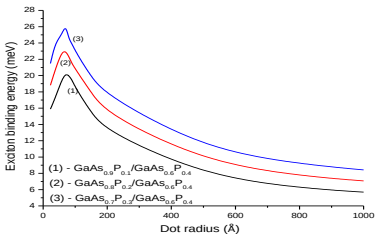

Fig.1 Variation of exciton binding energy as a function of dot radius for three different concentration of Phosphorus content in a $GaAs_{1-x_{oin}}P/GaAs_{1-x_{out}}P_{x_{out}}$ quantum dot in the absence of magnetic field strength

Fig.2 displays the variation of exciton binding energy as a function of dot radius of the $GaAs_{0.9}P_{0.1}/GaAs_{0.6}P_{0.4_{out}}$ quantum dot for different magnetic field strength as well as various Phosphorous alloy content. It is observed that the exciton binding energy increases with the magnetic field and increase in the Phosphorous concentration. Former effect is due to the confinement and latter is due to the increase in barrier height with the Phosphorous alloy content. Moreover, we notice that a linear variation of exciton binding energy is observed with the magnetic field strength.

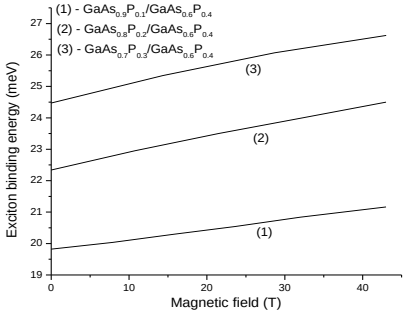

Fig.2 Variation of shift in exciton binding energy as a function of magnetic field strength for three different Phosphorus content of 80 Å, $GaAs_{1-x_{oin}}P/GaAs_{1-x_{out}}P_{x_{out}}$ quantum dot.

Conclusion

To summarize, the magnet-exciton binding energy has been computed as a function of geometrical confinement of a Phosphorous based GaAs quantum dot. We hope that the present results will motivate to invent a high performance in long wavelength semiconductor laser.

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