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Magnetic Field Induced Optical Transition Energy in an InAs/GaAs Quantum Wire

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ABSTRACT

In the present paper, the excitonic transitions are studied in an InAs/GaAs quantum wire with the consideration of geometrical confinement and the applied magnetic field strength. The binding energy of the exciton is found and thereby the interband optical transition energy is investigated using variational formulism within a single band effective mass approximation. The ground state energy of the exciton in the InAs/GaAs quantum wire in the influence of external magnetic field is found by minimizing the expectation value of the taken Hamiltonian with respect to the variational parameters in the trail wave function. The results show that the application of magnetic field and the influence of spatial confinement effect have considerable effects on the exciton binding energies and the optical transition energies and it brings out the quantum size effect. It is hoped that the present investigations would explore for the potential applications in single photon sources, photo-detectors and terahertz detectors.

1. Introduction

Low dimensional semiconductors are paid tremendous attention for their superior behaviour compared to their own counterpart bulk materials. There have been recent developments in the field of nanostructured semiconducting heterostructures especially in quantum wires. Quantum nano-wires exhibit properties which are entirely different from nano-wells and nano-dots, in fact, enhanced physical and chemical properties in quantum wires are obtained than any other quantum well system. The controlled and desired sizes of any low dimensional semiconductor devices are possible with the recent advanced experimental techniques [1-3]. The nano-sized quantum wires and their related materials are given importance for the developments of novel electronic and photonic devices towards the future technologies [4, 5]. One of the semiconductor nano-heterostructure quantum wire systems is InAs/GaAs material which is intensively studied due to the potential applications and they are highly strained materials with the large lattice mismatch of 7% which is helpful for the growth of InAs with GaAs [6]. The electronic and optical properties of dome-shaped InAs/GaAs nano-structured material with a strained potential have been reported [7]. InAs quantum wire is considered to be a good candidate for the emission of lasing wavelengths of lasers and semiconductor optical amplifiers between 1.3 μm and 1.55 μm used for long haul telecommunications [8].

2. Theoretical Formulism

In the present model, an exciton is considered inside the InAs/GaAs quantum well wire. The Hamiltonian of the exciton having a single electron part, the single hole part and the Coulomb interaction term between the electron-hole pair is obtained as

$$H=\sum_{i=e,h}\left[\frac{\left[\vec{p}_i+e\vec{A}(\vec{r}_i)\right]^2}{2m_i^*}+V_i(r_i)\right]-\frac{e^2}{\varepsilon|\bar{r}|} \qquad (1)$$

where m_i^* is the effective mass of electron and hole, e is the absolute value of electron charge, $|\bar{r}|=|\bar{r}_e-\bar{r}_h|$ refers the relative distance between the electron and the hole, V(r) is the potential barrier of the wire and ε is the dielectric constant of material inside the quantum wire. Taking into the consideration of cylindrical quantum wire, the electron (hole) confinement potential $V\left(\rho_j, z_i\right)$ due to the band offset between inner and outer wire structure is obtained as

$$V_{band}\left(\rho_j, z_j\right)=\begin{cases}0 & \rho_j\le R\\ V_0 & otherwise\end{cases} \qquad (2)$$

where $V_0=Q_c\Delta E_g^{\Gamma}(x)$ (3)

is the barrier height and Q_c is the conduction band offset parameter. $\Delta E_g^T(x)$, the band gap difference between quantum well wire and the barrier at Γ-point. The difference in energy band gap is given by

$$\Delta E_g^{\Gamma}(x)=E_g(GaAs)-E_g(InAs) \qquad (4)$$

where Eg(GaAs) and Eg(InAs) are the band gaps of GaAs and InAs respectively.

The exciton ground state eigen energy value and the associated wave functions are the solution of Schrödinger wave equation as,

$$H\Psi(r_e,r_h)=E\Psi(r_e,r_h) \qquad (5)$$

A variational formulism is employed to calculate the eigen function and eigen value of the Hamiltonian and thereby the exciton ground state energy is computed. The trial wave function can be chosen as

$$\Psi_i(\bar{r}_e,\bar{r}_h)=\psi_e(\rho_e,\varphi_e,z_e)\psi_h(\rho_h,\varphi_h,z_h)\exp(-\gamma\rho^2/4)e^{-\alpha\rho^2}e^{-\beta z^2} \qquad (6)$$

where ψ_e and ψ_h are electron and hole wave function in the quantum wire respectively and they have been considered without the interaction term due to electron-hole. γ is the measure of magnetic field strength. The ground state energy of the exciton in the InAs/GaAs quantum wire in the external magnetic field, is obtained by minimizing the expectation value of Hamiltonian with respect to the variational parameters as given

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by Eq. (6). The magnetic field induced optical transition energy associated with the exciton is given by the following equation

$$E_{ph}(B) = E_e + E_h + E_g - E_{exc}(B) \tag{7}$$

where E_e and E_h are the confinement energies of electron and hole respectively. E_g is the band gap energy of InAs material.

3. Results and Discussion

The exciton binding energy and the optical transition energy in the strained InAs/GaAs quantum wire are found in the presence of magnetic field. 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.

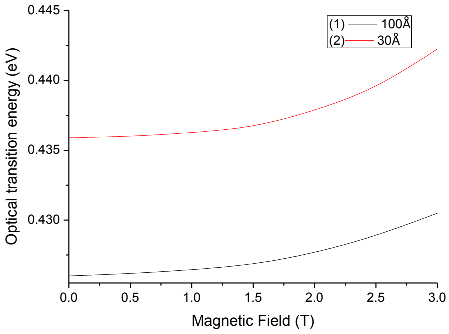

Fig. 1 Optical transition energy as a function of magnetic field strength for two different wire radii in the InAs/GaAs quantum wire

Fig. 1 shows the variation of optical transition energy with the function of magnetic field strength for two different wire radii (30 Å and 100 Å) of InAs/GaAs quantum wire. It is observed that the optical transition energy increases slowly when the radius of wire is decreased. This fact arises due to the confinement of electron-hole with respect to z-plane when the wire radius is decreased. This representation clearly brings out the quantum size effect [9]. Further it is noticed that the optical transition energy increases with the application of magnetic field strength [10].

4. Conclusion

In conclusion, the magnetic field induced binding energy of the exciton has been investigated in the InAs/GaAs quantum well wire using variational formulism and thereby the optical transition energy has been computed for two different wire radii. The change in optical transition energy brings out the possibility of tailoring the wavelength in the presence of applied magnetic field for electro-optical device applications.

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