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Combined effects of magnetic and electric fields on the interband optical transitions in InAs/InP quantum wire

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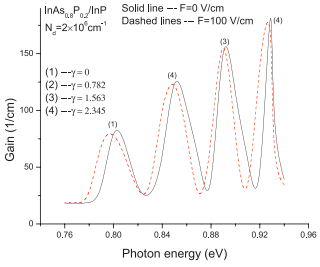
HIGHLIGHTS

- Combined effects of magnetic and electric fields on the confined exciton in an $InAs_{1-x}P_x/InP$ wire are investigated.
- Variational formulism is applied to obtain the exciton binding energy.
- Second order harmonic generation and the optical gain are carried out using compact density method.
- The strain effects are included with the confinement potential in the Hamiltonian.
- Optical properties are more influenced with the effects of geometrical confinement and the external perturbations.

GRAPHICAL ABSTRACT

Variation of gain as a function of photon energy for various values of measure of magnetic field strength in a $InAs_{0.8}P_{0.2}/InP$ quantum well wire is shown for $F=0$ V/cm and $F=100$ V/cm, with the constant electron density. The wire radius is taken as 50 Å.



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ABSTRACT

Combined effects of magnetic and electric fields on the confined exciton in an $InAs_{1-x}P_x/InP$ ($x=0.2$) quantum well wire are investigated taking into account the geometrical confinement effect. Variational formulism, within the frame work of effective mass approximation, is applied to obtain the exciton binding energy. The second order harmonic generation and the optical gain are carried out using compact density method. The strain effects are included with the confinement potential in the Hamiltonian. The energy difference of the ground and the first excited state is found in the presence of magnetic and electric fields taking into the consideration of spatial confinement effect. The result shows that the optical properties are more influenced taking into account the effects of geometrical confinement, magnetic field and electric field. It is shown that the telecommunication wavelength can be achieved with the suitable doping barrier material with the wire material and the external perturbations.

1. Introduction

Among group III–V materials, InAs semiconductor is considered to be a promising candidate for the potential applications of telecommunication wavelength between 1.33 μm and 1.55 μm due to the narrow band gap in the near infrared region. With the help of semiconductor lasers and amplifiers related to the low dimensional semiconductor systems, laser emission can be achieved with the above said ranges of wave length which can be used for long-haul optical transmission and the current technologies need the high power laser diodes. Further, this material is having a property of smaller effective mass and high carrier mobility which

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are essential for the operation of high speed optical devices [1]. The lasing wavelength, between 1.33 μm and 1.55 μm, has been observed using InAs/InP material [2]. Different forms of nanowires with the desired crystalline structures have been achieved nowadays with the help of some sophisticated experimental growth techniques. These nanowires made up of InAs materials can be used for a variety of applications include optical probes, photonic wave guides, fiber optics communication network systems, light emitting diodes, photodetectors, field effect transistors and photovoltaic devices [3,4]. Hence, InAs semiconductor is considered to be a promising material for realizing ultra high-speed optical signal processing devices.

The strain effects due to built-in internal fields result in the modifications of electronic structure of any material and tailor the optical properties of reduced dimensional semiconductors [5]. The lattice mismatch, in the heterostructure materials, induces a spontaneous change in morphology of the materials. The energy band alignments due to the strain effects have been carried out in the lattice matched nanomaterials earlier [6]. The electronic structure of InAs quantum dots embedded in InP material has been investigated using strain dependent eight-band k.p theory in the envelope function approximation taking into account the geometrical confinement [7]. In general, the InAs/InP quantum dot system produces emission wavelength above 1.6 μm at room temperature due to the smaller lattice mismatch between InAs and InP material leading to the shift of emission wavelength beyond 1.6 μm [8,9]. Many works have recently been dealt to fabricate the InAs/InP quantum islands using the Stranski–Krastanov growth mode in order to apply for low threshold micro-lasers emitting at the 1.55 μm optical fiber telecommunication wavelength [10–12]. An intense photoluminescence has been observed from InAsP quantum dots with the wavelength ranging between 1.2 μm and 1.35 μm at the room temperature [13]. Room temperature operating laser, using InAs materials, has been performed earlier [14,15]. Combined effects of magnetic field and electric field induced donor binding energies of a hydrogenic impurity in a corrugated quantum well have been discussed earlier [16].

In the present work, the confined exciton and its binding energy and the optical transition energies are dealt taking the $InAs_{1-x}P_x$/InP ($x=0.2$) quantum well wire as model. Calculations are carried out in the influence of magnetic and electric fields. The geometrical confinement effects and the strain contributions are included in the calculations. Numerical computations are carried out using variational approach within the effective mass approximation. Some optical properties such as second order susceptibility of harmonic generation and the optical gain are carried out using compact density method. The model and theoretical formulism of the well wire system applied in the present paper is briefly explained in Section 2 and the results and discussion are described in Section 3. A brief summary and results are dealt in the last section.

2. Theory and model

The Hamiltonian of the exciton in the model, within the framework of single band effective mass approximation, is given by

$$H_{tot} = H_e + H_h + V_c(\vec{r_e}, \vec{r_h}), \tag{1}$$

where H_e and H_h are the Hamiltonian of the single electron and a hole respectively, V_c is the Coulomb potential between the electron and hole, $\vec{r_e}$ and $\vec{r_e}$ are the relative coordinates of electron and hole. The heterostructure consists of inner $InAs_{0.8}P_{0.2}$ wire material and the outer InP barrier material. The length of the wire is taken as L and the radius as R and the cylindrical coordinates are used in the present paper.

The Hamiltonian of the exciton, in the presence of magnetic and electric fields applied simultaneously in the z-direction, in the $InAs_{1-x}P_x$/InP quantum wire, is given by

$$H_{exc} = \sum_{j=e,h}\left[\frac{1}{2m_j^*(E)}\left(\vec{p}_j - \frac{q\vec{A}_j}{c}\right)^2 + V_j(\vec{r_j}) + \delta E_j(\vec{r_j}) + q_j G z_j\right] - \frac{e^2}{\varepsilon\left|\vec{r_e} - \vec{r_h}\right|} \tag{2}$$

where j=e,h, $m^*_{e(h)}(E)$ is the energy dependent effective mass of electron (hole), $\vec{p}$ is the momentum operator, $\vec{A}$ is the vector potential given by $\vec{A} = \frac{1}{2}\vec{B} \times \vec{r}$, q is the charge ($-e$ for electrons and $+e$ for holes), $\left|\vec{r_e} - \vec{r_h}\right|$ denotes the relative distance between the electron and the hole, $V_j(\vec{r_j})$ is the confinement potential of the electron and hole due to the band offset between the materials, $\delta E_j(\vec{r_j})$ is the strain induced shift to the band offset related to the hydrostatic components on strain tensor, G is the applied electric field in the z-direction, $r = \sqrt{\rho^2 + z^2}$, and ε is the dielectric constant of $InAs_{1-x}P_x$ material. The energy dependent effective mass is used in our calculation since it has a large influence on the electron energy levels in semiconductor quantum wires, especially for thin wires [17]. We follow the procedure for computing the energy dependent effective masses of electron and hole as shown in Ref. [18].

The electron (hole) confinement potential $V(\rho_j)$ related to the band offset in the $InAs_{1-x}P_x$/InP heterostructure is given by

$$V(\rho_j) = \begin{cases} 0 & \rho_j \le R \\ V_0 & \rho_j > R \end{cases} \tag{3}$$

where V_0 is the barrier height of the wire. It depends on the variation of phosphor alloy content in $InAs_{1-x}P_x$/InP and it is expressed as

$$V_0 = Q_c \Delta E_g^{\Gamma} \tag{4}$$

where Q_c is the conduction (valence) band offset parameter and the band offset ratio (ΔE_c: ΔE_v) is taken as 70:30. In general, this larger band offset considerably enhances the high temperature performance of lasing techniques on phosphorus based InAs material [19] which leads to the high power operation in the optical devices albeit large thermal resistance. ΔE_g^{Γ}, denotes the band gap difference between the quantum wire and the barrier at Γ-point and it is given by [20]

$$\Delta E_g^{\Gamma} = \Delta E_g^{\Gamma}(\text{unstrained}) + \delta E_{c(v)} \tag{5}$$

where the unstrained band gap of the wire material is expressed as [21]

$$E^{\Gamma}_{g\text{InAs}_{1-x}\text{P}_x}(x)eV = (1-x)E_{g\text{InAs}} + xE_{g\text{InP}} + x(1-x)b \tag{6}$$

and the calculated values of hydrostatic strain and the conduction (valence) band offsets are followed from Ref. [18].

The polarization, in a self-formed wurzite quantum well wire, possesses both spontaneous and piezoelectric components. The strain induces piezoelectric polarization which results the modification of potentials in the heterostructure. In a wurtzite crystal, the symmetry of the crystal leads to three nonvanishing piezoelectric strain coefficients, e_{31}, e_{33} and e_{15}. The biaxial strain leads to a strong polarization along the z-direction [22]. The total polarization is the combination of spontaneous and piezoelectric polarizations in the absence of external electric field. The built-in electric field is caused by the polarization of the different materials