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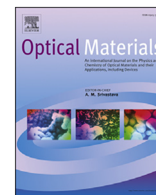

Magnetic field induced optical gain in a dilute nitride quaternary semiconductor quantum dot

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Effects of magnetic field strength on the electronic and optical properties are brought out in a $Ga_{0.661}In_{0.339}N_{0.0554}As_{0.9446}$/GaAs quantum dot for the applications of desired wavelength in opto-electronic devices. The band alignment is obtained using band anticrossing model and the model solid theory. The magnetic field dependent electron-heavy hole transition energies with the dot radius in a GaInNAs/GaAs quantum dot are investigated. The magnetic field induced oscillator strength as a function of dot radius is studied. The resonant peak values of optical absorption coefficients and the changes of refractive index with the application of magnetic field strength in a GaInNAs/GaAs quantum dot are obtained. The magnetic field induced threshold current density and the maximum optical gain are found in a GaInNAs/GaAs quantum dot. The results show that the optimum wavelength for fibre optical communication networks can be obtained with the variation of applied magnetic field strength and the outcomes may be useful for the design of efficient lasers based on the group III-N-V semiconductors.
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1. Introduction

Opto-electronic devices having the light sources operating with the wavelength range 1.3 μm–1.55 μm are required for the telecommunication networks. Laser diodes, having this wavelength range, possess low power consumption, minimum loss and high efficient performance in optical fibre communication. Nitrogen based GaInAs materials are considered to be one of the suitable quaternary semiconductors for long wavelength optical communication. In addition, the wavelength can be extended for suitable purpose with the proper composition of the materials, the reduction of geometrical confinement and the application of external perturbations [1]. GaInNAs can be grown either on GaAs or InP substrate without any strain because of lattice matching and the incorporation of small amount of nitrogen in GaInAs material reduces the band gap energy dramatically as well as the lattice parameter because of the highly nonlinear behaviour of adding nitrogen in the GaInAs [2,3]. The efficient optical lasers with the wavelength range between 1.3 μm and 1.55 μm using quaternary semiconducting materials have been demonstrated earlier [4–7].

The band alignment of the band edges between two materials forming a heterostructure is an important parameter for practical long wavelength applications. The nitrogen level in the system is introduced and the conduction band offset is enhanced with the incorporation of nitrogen in GaInNAs/GaAs material. The formation of isoelectronic impurity level of high electronegativity can be described by the anti-crossing model. It results that the conduction band is reconstructed with the E_+ and E_- subbands which have been observed earlier [8]. There occurs a redshift in the optical absorption with the low nitrogen content displaying a large bowing parameter and this behaviour cannot be observed in any conventional group III-V materials [9]. A large conduction band discontinuity has been shown to occur in GaInNAs/GaAs quaternary heterostructure in order to have a better electron confinement and higher stability at room temperature [10,11]. The interaction between the localized nitrogen states and the extended conduction band states in GaInNAs/GaAs is described by the band anti-crossing model. Hence, it is considered to be a good choice for designing the band structure for the dilute nitride quaternary materials since the shortening the band gap with the non-parabolicity occurs with the addition of small amount of nitrogen creating the localized

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nitrogen states in the conduction band influencing optical gain [12] and, moreover, it is appropriate when the intermixing effects, between nitrogen and arsenic atoms, in GaInNAs/GaAs have been considered [13]. The excitonic properties in a $Ga_{1-x}In_xN_yAs_{1-y}$/GaAs cylindrical quantum dot have been investigated earlier and the optimum condition for the desired band alignment for emitting wavelength 1.55 μm has been found without the application of any external perturbation by Uma et al., [14]. In general, any external perturbation will modify the electronic and optical properties of any semiconductor, in fact, it takes them into optimum efficiency. In the present work too, the same authors have applied the magnetic field in the z-direction of the system and found the improved results.

The application of external perturbations on the GaInNAs/GaAs semiconducting materials is used to tune the band gap for selecting the suitable opto-electronic devices. The tuning of the optical gain by the application of hydrostatic pressure in GaInNAs/GaAs quantum well has been studied theoretically [15]. The application of magnetic field on any low dimensional semiconductor is considered to be one of the best tools to study the band gap process by the variation of emission energy in any optical device. The magnetic field significantly affects the optical and electronic properties of charge carriers in any semiconductors. The effects of magnetic field and the nitrogen and indium compositions on the donor impurity binding energy in a group III-N-V quantum well have been investigated [16]. The effects of magnetic field applied parallel to the plane of a GaInNAs/GaAs quantum well were studied and thereby the photoconductivity has been investigated [17].

In the present work, the magnetic field dependent the excitonic binding energies, oscillator strength and some nonlinear optical properties are obtained in a $Ga_{0.661}In_{0.339}N_{0.0554}As_{0.9446}$/GaAs quantum dot. The band alignment is found using band anticrossing model and the model solid theory. The magnetic field dependent electron-heavy hole transition energies with the dot radius in a GaInNAs/GaAs quantum dot are studied. The resonant peak values of optical absorption coefficients and the changes of refractive index are obtained in the presence of magnetic field strength. The magnetic field induced threshold current density with the dot radius and the maximum optical gain are studied. In Section 2, the present model followed in the calculations is described. The results and discussion are presented in Section 3. And the conclusions are given in Section 4.

2. Theory and model

The Hamiltonian of the bound magneto-exciton, within the framework of single band effective mass approximation in a strained GaInNAs/GaAs quantum dot, is given by

$$H_{exc}(B) = \frac{\left[\vec{p}_e + e\vec{A}\left(\vec{r}_e\right)\right]^2}{2m_e^*} + \frac{\left[\vec{p}_h - e\vec{A}\left(\vec{r}_h\right)\right]^2}{2m_h^*} + V_j\left(\rho_j, z_j\right) - \frac{e^2}{\varepsilon|r_e - r_h|} \quad (1)$$

where j refers electron, hole, m_e^* is the effective mass of an electron and m_h^* denotes the effective mass of heavy hole. $\vec{r}_e$ and $\vec{r}_h$ refer their co-ordinate position and p is its respective momentum. $\vec{A} = \frac{1}{2}\vec{B} \times \vec{r}$ is the vector potential of the magnetic field $\vec{B}$ and e is the electron charge. $V_j(\rho_j, z_j)$ is the strained induced confined potential for the electron (hole). ε is the effective mean relative dielectric constant of the embedded material between the electron and hole.

The electron (hole) confinement potential, $V_j(\rho_j, z_j)$, due to the band offset in the GaInNAs/GaAs quantum dot structure is considered as the addition of radial and axial confinements, taking into consideration of z-dependent asymmetric confinement, it is given by

$$V_j\left(\rho_j, z_j\right) = \begin{cases} V_j\left(\rho_j\right) & |z_j| \le L/2 \\ V_{e(h)} & |z_j| > L/2 \end{cases} \quad (2)$$

and

$$V_j\left(\rho_j\right) = \begin{cases} 0 & \rho_j \le R \\ V_{1j} & \rho_j > R \end{cases} \quad (3)$$

where R is the radius and L is the height of the cylindrical quantum dot. We have taken V_{1j} as 100 Å. $V_{e(h)}$ are the conduction (valence) band offsets with

$$V_{e(h)} = Q_c \Delta E_g \quad (4)$$

where Q_c is the conduction band offset parameter and the ΔE_g is the band gap energy between the inner and outer barrier materials. The conduction band offset is considered as 80% of the total discontinuity between the band gap of inner and outer materials [18].

The band gap energy is given by Ref. [19],

$$\begin{aligned} E_{g(Ga_{1-x}In_xN_yAs_{1-y})} = {} & (1-x)(1-y)E_{g(GaAs)} + x(1-y)E_{g(InAs)} \\ & + y(1-x)E_{g(GaN)} + xyE_{g(InN)} \\ & + x(x-1)yC_{In-Ga}(InGaN) \\ & + (1-y)C_{In-Ga}(InGaAs) \\ & + y(y-1)xC_{As-N}(InNAs) \\ & + (1-x)C_{As-N}(GaNAs) \end{aligned} \quad (5)$$

where x is the concentration of indium and y is the concentration of nitrogen. $C_{X-Y}(XYZ)$ is the bowing parameter of XYZ. The values are taken from Ref. [18]. With the proper concentration, y = 0.0554% and x = 0.339% in $Ga_{1-x}In_xN_yAs_{1-y}$/GaAs, the inner band gap of the taken system becomes 1.247 eV and it has been reduced significantly compared with outer material, GaAs. Thus, the lattice matched inner and outer materials can be applied for the suitable design of optoelectronic devices. They are related by the following expression as shown in Ref.14 by

$$y = \frac{0.405}{2.463 + 0.0466x} \quad (6)$$

The relationship between the compositions of nitrogen and indium is taken into account the lattice matched to quaternary alloys. The lattice parameter of $Ga_{1-x}In_xN_yAs_{1-y}$ alloy is expressed, from the well-known Vegard's law, as

$$\begin{aligned} a_{Ga_{1-x}In_xN_yAs_{1-y}} = {} & (1-x)(1-y)a_{GaAs} + x(1-y)a_{InAs} \\ & + y(1-x)a_{GaN} + xya_{InN} \end{aligned} \quad (7)$$

where a_{GaAs}, a_{InAs}, a_{GaN} and a_{InN} are the lattice constants of GaAs, InAs, GaN and InN materials respectively. The requirement for $Ga_{1-x}In_xN_yAs_{1-y}$ lattice-matched to GaAs brings out the ratio between nitrogen and indium alloy composition (y/x) is 0.1634. The obtained lattice parameter for this quaternary material is 5.728 Å which is closer to the lattice parameter of GaAs when x = 1/18.05 and y = 1/2.949.

The band lineups of the heterostructure material are computed using the model solid theory. The deformation potential theory is

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