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Effects of indium and nitrogen mole concentrations on the optical properties in a GaInNas/GaAs quantum well under the intense laser field

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The effect of indium and nitrogen mole concentrations on the nonlinear optical properties in a $Ga_{1-x}In_xN_yAs_{1-y}/GaAs$ single quantum well under the intense laser field is theoretically studied within the effective mass approximation and the envelope function approach. The analytical expressions of optical properties are obtained by using the compact density-matrix approach. The numerical results show that the linear, third-order nonlinear and total absorption and refractive index changes depend both on the intense laser field and on the indium and nitrogen concentrations. From the findings of this study, it has been concluded that the linear and nonlinear optical properties in a $Ga_{1-x}In_xN_yAs_{1-y}/GaAs$ single quantum well under the intense laser field can be tuned by changing the indium and nitrogen mole fraction.

1. Introduction

In recent years, group III-N-V alloys, particularly the quaternary material system of $Ga_{1-x}In_xN_yAs_{1-y}$ is being intensively studied for both its particular physical properties [1,2] and its potential for long wavelength optoelectronic device applications [3–5]. The incorporation of small amounts of nitrogen into (In,Ga)As can cause a significant decrease in the band-gap energy and an increase in the electron effective mass [6,7]. This fact enables the usage of these materials for the realization of high-performance laser diodes emitting at the 1.3 and 1.55 μm [8–11], which are important for optical fiber communications systems [12]. These lasers are strongly desired because they can operate in a wide temperature range and have high modulation frequency. By combining GaInNAs with GaAs or other wide gap materials that can be grown on a GaAs substrate, deep quantum wells (QWs) can be fabricated, especially in the conduction band. Since, the electron overflow from the wells to the barrier layers at high temperatures due to the stronger electron confinement can be suppressed, GaInNAs is very attractive to overcome the poor temperature characteristics of conventional GaInPAs/InP laser diodes for optical fiber communication applications [13]. The high-temperature performance of both edge-type and surface-type emitting GaInNAs/GaAs laser diodes are expected to be better than that of GaInAsP devices [4,14–18].

The development of high-power, long-wavelength, linearly polarized laser sources, such as CO_2 and free electron lasers, has increased research activities on the interaction of intense laser fields (ILF) with electrons in semiconductors [19–21]. This has allowed the discovery of interesting physical phenomena. The design of new efficient optoelectronic devices depends on understanding the basic physics involved in this interaction process. For these reasons, the effects of a high-frequency ILF on the confining potential and the corresponding bound state energy levels are very important problems. This problem has been a subject of great interest and an enormous amount of literature has been devoted to this field [22–32]. Brandi et al. [22,23] extended the dressed atom approach to treat the interaction of the laser field with a semiconductor system. In their model, the interaction with the laser is taken into account through the renormalization of the semiconductor effective mass. Fanyao et al. have reported the calculation of the binding energy of an-axial and on-center donor in quantum-well wires (QWWs) and quantum dots (QDs) under the effects of an ILF [24–26]. Niculescu et al. have theoretically investigated the density of impurity states of shallow donors in QWs [27], the energy spectra in finite V-shaped, parabolic and square GaAs/GaAlAs QW under the electric field [28], and polarizabilities of shallow donors in inverse V-shaped QW [29,30]. Eseanu et al. [31] have studied the simultaneous effects of pressure and laser field on donors in GaAs/GaAlAs QWs. Their results show that the effects of the laser field on the electronic

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properties are more pronounced than those of the pressure ones. Lopez et al. [32] have theoretically calculated the ILF effects on the electron g-factor in GaAs/GaAlAs semiconductor QWs under the magnetic fields.

Nonlinear optical properties related to the intersubband transitions in low-dimensional semiconductor systems have attracted considerable attention due to the strong quantum confinement effect, leading to small energy separation between subband levels, large values of dipole transition matrix elements and possibility of achieving resonance conditions. Among the optical properties, especially linear and nonlinear optical processes in these structures are intensely studied due to their potential for device applications in the infrared region of the electromagnetic spectrum [33–35]. The nonlinear optical properties of the low-dimensional systems generally depend on the asymmetry of the confinement potential [36,37]. It is also well known that the shape of the confining potential of the QW structures significantly affects the nonlinear optical properties. The linear and nonlinear optical absorption based on intersubband transitions and the refractive index changes in semiconductor QW structures with different confinement potentials have been studied extensively by many authors [38–46]. As it is known, the effect of a high-frequency ILF also leads to major modifications in the shape of the confining potential of QW structures [29,31,47]. The effects of ILF on the confining potential and corresponding bound states play an important role in the optoelectronic device modeling. Lima et al. [48] have studied the transition from single to double QW potential induced by ILF in a semiconductor QW. Their numerical results show that the rapid approximation of the excited levels for GaAs/GaAlAs QWs with the increase in ILF intensity indicates the possibility of enhancing the population inversion in the optical pumping scheme, which is interesting for the design of powerful QW lasers. Therefore, we think that it is important to investigate the effect of such a field on the nonlinear optical properties.

This work is concerned with the theoretical study of the effects of ILF on the linear and nonlinear optical properties in a $Ga_{1-x}In_xN_yAs_{1-y}$/GaAs QW for different indium (In) and nitrogen (N) concentrations. This paper is organized as follows: in the next section, details of the calculations are presented. The numerical results are presented and discussed in Section 3. Finally, our calculations are given in Section 4.

2. Theory

The method of approach used in the present study is based on the non-perturbation theory developed to describe the atomic behavior under intense, high-frequency laser field conditions, and it has already been given elsewhere, we will not enter into details here [49,50]. The one-dimensional Schrödinger equation with the "laser-dressed" potential is given by the following expression [49,50]

$$\left[-\frac{\hbar^2}{2m^*}\frac{d^2}{dz^2}+V(\alpha_0,z)\right]\psi(z)=E\psi(z) \tag{1}$$

where $\psi(z)$ is the wave function, m^* is the effective mass and $V(\alpha_0,z)$ is the "laser-dressed" potential for a monochromatic, nonresonant electromagnetic radiation field linearly polarized along the z-axis direction with the angular frequency Ω. This potential is given by [51]

$$\begin{aligned}V(z)=&V_0[\theta(-z-\alpha_0-L/2)+\theta(z-\alpha_0-L/2)]\\&+\frac{V_0}{\pi}\Theta(z+\alpha_0+L/2)\theta(-z+\alpha_0-L/2)\\&\times\arccos\left(\frac{z+L/2}{\alpha_0}\right)+\frac{V_0}{\pi}\Theta(-z+\alpha_0+L/2)\\&\times\theta(z+\alpha_0-L/2)\arccos\left(\frac{L/2-z}{\alpha_0}\right)\end{aligned} \tag{2}$$

where V_0 is the conduction band offset at the interface, $\alpha_0=eF_0/m^*\Omega^2$ (the laser-dressing parameter) and F_0 is the field strength, L is the well width, Θ is the Heaviside unit step function which satisfies $\Theta(z)=1-\theta(-z)$ and θ is the unit step function. We chose the z-axis along the growth direction. The analytical expression for the dressed potential in Eq. (2) is valid for all values of α_0 and all points of z.

Using the envelope wave-function approximation, the energy levels E and the corresponding wave functions $\psi(z)$ in a $Ga_{1-x}In_xN_yAs_{1-y}$/GaAs single QW can be obtained by solving the Eq. (1) [52]. After the energy levels and corresponding wave functions are obtained, the linear and nonlinear refractive index changes and absorption coefficient for the intersubband transitions between two subbands can be easily calculated under the density matrix approach.

Intensity-dependent linear refractive index changes and absorption coefficients are given by Refs. [53–56]:

$$\frac{\Delta n^{(1)}}{n_r}=\frac{\sigma_V|M_{21}|^2}{2n_r^2\varepsilon_0}\left[\frac{E_2-E_1-\hbar\omega}{(E_2-E_1-\hbar\omega)^2+(\hbar\Gamma_{12})^2}\right] \tag{3}$$

$$\beta^{(1)}(\omega)=\omega\sqrt{\frac{\mu}{\varepsilon_R}}\frac{|M_{21}|^2\sigma_V\hbar\Gamma_{12}}{(E_2-E_1-\hbar\omega)^2+(\hbar\Gamma_{12})^2}, \tag{4}$$

On the other hand, the calculation of the nonlinear contributions to these two quantities implies the evaluation of the following expressions:

$$\begin{aligned}\frac{\Delta n^{(3)}}{n_r}=&-\frac{\mu c|M_{21}|^2}{4n_r^3\varepsilon_0}\frac{\sigma_V I}{[(E_2-E_1-\hbar\omega)^2+(\hbar\Gamma_{12})^2]^2}\\&\times[4(E_2-E_1-\hbar\omega)|M_{21}|^2-\frac{(M_{22}-M_{11})^2}{(E_2-E_1)^2+(\hbar\Gamma_{12})^2}\{(E_2-E_1-\hbar\omega)\\&\times[(E_2-E_1)(E_2-E_1-\hbar\omega)-(\hbar\Gamma_{12})^2]-(\hbar\Gamma_{12})^2(2(E_2-E_1)-\hbar\omega)\}]\end{aligned} \tag{5}$$

$$\begin{aligned}\beta^{(3)}(\omega)=&-2\omega\sqrt{\frac{\mu}{\varepsilon_R}}\left(\frac{I}{\varepsilon_0 n_r c}\right)\times\frac{|M_{21}|^4\sigma_V\hbar\Gamma_{12}}{[(E_2-E_1-\hbar\omega)^2+(\hbar\Gamma_{12})^2]^2}\\&\times\left(1-\frac{|M_{22}-M_{11}|^2}{|2M_{21}|^2}\right)\\&\times\frac{(E_2-E_1-\hbar\omega)^2-(\hbar\Gamma_{12})^2+2(E_2-E_1)(E_2-E_1-\hbar\omega)}{(E_2-E_1)^2+(\hbar\Gamma_{12})^2}\end{aligned} \tag{6}$$

where σ_V is the electron density, n_r is the refractive index, ε_0 is the permittivity of free space, μ is the permeability of the system, c is the speed of light in the free space, Γ_{12} is the relaxation rate for states 1 and 2, I is the incident optical intensity of incident electromagnetic wave (with the angular frequency ω) that excites the structure and leads to the intersubband optical transitions, E_1 (E_2) is the initial (final) energy state, ε_R is the real part of the permittivity, and $M_{ij}=|\langle\psi_i|ez|\psi_j\rangle|$ $(i,j=1,2)$ is the dipole matrix element.

The total refractive index change is given by

$$\frac{\Delta n(\omega)}{n_r}=\frac{\Delta n^{(1)}(\omega)}{n_r}+\frac{\Delta n^{(3)}(\omega)}{n_r} \tag{7}$$

and the total absorption coefficient can be written as

$$\beta(\omega,I)=\beta^{(1)}(\omega)+\beta^{(3)}(\omega,I) \tag{8}$$

3. Results and discussion

In this study, we have theoretically investigated the effects of In and N mole concentrations on the nonlinear optical properties in a $Ga_{1-x}In_xN_yAs_{1-y}$/GaAs single QW under the ILF. We consider a QW with a 100 Å thick $Ga_{1-x}In_xN_yAs_{1-y}$ layer sandwiched