Physica B 457 (2015) 165–171

Contents lists available at ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

The effects of intense laser field and applied electric and magnetic fields on optical properties of an asymmetric quantum well

R.L. Restrepo [a,b,c,*], F. Ungan [a], E. Kasapoglu [a], M.E. Mora-Ramos [d], A.L. Morales [c], C.A. Duque [c]

[a] Department of Physics, Cumhuriyet University, 58140 Sivas, Turkey
[b] Escuela de Ingeniería de Antioquia-EIA, Envigado, Colombia
[c] Grupo de Materia Condensada-UdeA, Instituto de Física, Facultad de Ciencias Exactas y Naturales, Universidad de Antioquia-UdeA, Calle 70 No. 52-21, Medellín, Colombia
[d] Facultad de Ciencias, Universidad Autonóma del Estado de Morelos, Ave. Universidad 1001, CP 62209, Cuernavaca, Morelos, Mexico

ARTICLE INFO

Article history:
Received 20 June 2014
Received in revised form
15 September 2014
Accepted 24 September 2014
Available online 12 October 2014

Keywords:
Asymmetric single quantum well
Nonlinear optical properties
Intense laser field
Electric and magnetic fields

ABSTRACT

This paper presents the results of the theoretical study of the effects of non-resonant intense laser field and electric and magnetic fields on the optical properties (the linear and third-order nonlinear refractive index and absorption coefficients) in an asymmetric quantum well. The electric field and intense laser field are applied along the growth direction of the asymmetric quantum well and the magnetic field is oriented perpendicularly. To calculate the energy and the wave functions of the electron in the asymmetric quantum well, the effective mass approximation and the method of envelope wave function are used. The asymmetric quantum well is constructed by using different aluminium concentrations in both right and left barriers. The confinement in the quantum well is changed drastically by either the effect of electric and magnetic fields or by the application of intense laser field. The optical properties are calculated using the compact density matrix approach. The results show that the effect of the intense laser field competes with the effects of the electric and magnetic fields. Consequently, peak position shifts to lower photon energies due to the effect of the intense laser field and it shifts to higher photon energies by the effects of electric and magnetic fields. In general, it is found that the concentration of aluminum, electric and magnetic fields and intense laser field are external agents that modify the optical responses in the asymmetric quantum well.

1. Introduction

The latest manufacturing and characterization techniques allow the fabrication and study of low-dimensional semiconductor heterostructures with different types of confinement. They exhibit specialized electrical and optical properties which reflect in the increasing use of these systems in optoelectronic devices. In recent years, several researchers have reported the construction of quantum wells (QWs), quantum well wires (QWWs) and quantum dots (QDs) [1–4]. Recent experimental studies of the optical properties of low-dimensional systems under the effects of external agents such as temperature, hydrostatic pressure and electromagnetic fields and stoichiometry have been published [5–7].

Research works on the effects of electric and magnetic fields and other external agents on the electrical and optical properties in QDs, QWWs and QWs have been carried out in recent years. For example, Zhang et al. [8], published in 2010, the theoretical study of the optical absorption coefficients and changes in the refractive index in QDs with parabolic confinement under the application of these external agents. Rezaei et al. [9], presented the effects of electromagnetic fields in such optical properties related to impurities in QWWs with cylindrical profile. In the same way Khordad et al. [10] reported on the effects of an axial magnetic field and the Rasbha spin–orbit interaction on the optical absorption and refractive index changes in a quasi-one-dimensional QWW. These authors have found that such external agents, generally move the resonant peaks of the optical responses into the blueshift. The effects of a magnetic field and the change of aluminum concentration on the impurity binding energy in a rectangular QW plus inverse parabolic potential was described in the work of Kasapoglu et al. [11]. In this same type of heterostructures the combined effects of electromagnetic field and intense laser field modify both the electrical properties and energy levels of impurity, by inducing polarization and asymmetry in the system [12,13]. The effects of aluminum concentration, hydrostatic pressure and applied electromagnetic fields on the optical properties in a GaAs/Ga$_{1-x}$Al$_x$As

---

[*] Corresponding author at: Escuela de Ingeniería de Antioquia-EIA, C. P. 055428, Envigado, Colombia. Tel.: +574 354 90 90; fax: +574 386 11 60.
E-mail address: pfrire@eia.edu.co (R.L. Restrepo).

http://dx.doi.org/10.1016/j.physb.2014.09.041
0921-4526/© 2014 Elsevier B.V. All rights reserved.

QW, were published by Nazari et al. [14]. In this case the optical absorption coefficients and refractive index changes are more sensitive to the size of the heterostructure than to the influence of the external fields. Moreover, Guo and Du [15], together with the application of external electric fields, used a Gaussian potential in an asymmetric quantum well (AQW) configuration. In this case the optical absorption coefficients and refractive index changes exhibit a significant dependence on the Gaussian potential height, the width of the QW and the amplitude of the electric field.

Given the properties of some current laser sources, regarding optical wavelength or light polarization, it is necessary to understand the interaction between these modulated signals with matter. Theoretical research on the effects of an intense laser field–non-resonant–on electrons, holes, impurities or excitons in semiconductor low-dimensional heterostructures have recently occupied the attention of several authors (see [16]). Neto at al. [17] published their study of the effects of intense laser field on the optical properties of a square QW. They found a relationship between the intra-band transitions and the electron-heavy-hole recombination with the blueshift of the optical responses. Combined effects of electromagnetic fields and intense laser field on the nonlinear optical properties in square QWs were introduced by Karabulut [18]. It is found that increasing the amplitude of intense laser field causes more confinement and therefore remarkably modifies the nonlinear optical properties. The study of shallow-impurity-related nonlinear optical absorption and relative refractive index change coefficients in a cylindrical QD with a Woods–Saxon potential is reported in the work of Lu et al. [19]. They focused on the variations of the wavefunctions and impurity binding energies as a result of the change in carrier confinement due to the external agents, and the consequent modifications in the optical response.

Recent articles about the effects of intense laser field (ILF) on the nonlinear optical properties in an AQW are relevant to the objectives of this work [20]. For example, Panda et al. [21] presented a study of this effect on second harmonic generation (SHG) and nonlinear optical rectification (NOR). Therefore, it is found that the relationship between the amplitude of the ILF and the confinement produced a blueshift in such optical responses. Furthermore, Ungan et al. [22] calculated the linear, nonlinear and total coefficients of optical absorption and relative refractive index change associated to the transitions between the first two energy states in the same system. It is shown that, in the case of a graded potential, the effect of an ILF is more relevant, compared to those of temperature and hydrostatic pressure. In the report of Kasapoglu et al. [23] the effects of an electromagnetic field on the optical absorption and relative refractive index coefficients, calculated in the case of an asymmetric, step-like potential are presented. Their results show that the optical responses are more sensitive to the changes in the dimensions of the heterostructures than to the application of external probes to the system.

In this paper, we present the combined effects of non-resonant ILF and applying external electric and magnetic fields on the total refractive index (RI) change and the total optical absorption coefficient (AC) in an AQW calculated as functions of the photon energy. The electric field and ILF are applied in the growth direction of the AQW and the magnetic field perpendicular to these. The effective mass approximation method and the envelope wave function are used to calculate the energy levels and wave functions of this system. The confinement potential is modified by taking different values of the aluminum concentration in the right-side barrier.

The outline of the main physical concepts and theoretical framework appears in Section 2. The discussion of the obtained results is given in Section 3 and finally a summary of the most relevant findings is commented in the conclusions in Section 4.

2. Theoretical framework

Here we consider an asymmetric single GaAs/Ga$_{1-x}$Al$_x$As quantum well (AQW). Within the framework of the effective mass approximation, the Hamiltonian for the electron in the AQW takes into account the effect of a magnetic field (B) oriented perpendicular to the growth direction ($\vec{B} = (B, 0, 0)$), together with that of an electric field (F) applied along the growth direction (z-direction), is given by

$$H = \frac{1}{2m^*}\left[\vec{p} + \frac{e}{c}\vec{A}(\vec{r})\right]^2 + V(z) + eFz \tag{1}$$

where m^* is the electron effective mass, $\vec{p}$ is the momentum operator, e is the absolute value of the elementary charge, c is the speed of light in vacuum, $\vec{A}(\vec{r})$ is the vector potential with a gauge such that $\vec{A} = (0, -Bz, 0)$, and $V(z)$ is the QW confining potential (for which we have the mathematical expressions $V(z) = V_L$ for $z < -L_W/2$, $V(z) = 0$ for $|z| \leq L_W/2$ and $V(z) = V_R$ for $z > L_W/2$).

Looking to include the non-resonant ILF-effects (the polarization of the laser radiation is parallel to the z-direction), we have followed the Floquet method [24]. Consequently, the second term in Eq. (1) must be replaced by $V(z) \to V(z, \alpha_0)$ where

$$\begin{aligned} V(z, \alpha_0) = {} & V_L\Theta\left(-\alpha_0 + \frac{L_w}{2} - z\right) + V_R\Theta\left(z - \alpha_0 - \frac{L_w}{2}\right) \\ & + \frac{V_L}{\pi}\arccos\left(\frac{z - \frac{L_w}{2}}{\alpha_0}\right)\left[1 - \Theta\left(z - \alpha_0 - \frac{L_w}{2}\right)\right]\Theta\left(\alpha_0 - \frac{L_w}{2} + z\right) \\ & + \frac{V_R}{\pi}\arccos\left(\frac{\frac{L_w}{2} - z}{\alpha_0}\right)\left[1 - \Theta\left(z - \alpha_0 - \frac{L_w}{2}\right)\right]\Theta\left(\alpha_0 - \frac{L_w}{2} + z\right), \end{aligned} \tag{2}$$

where $\alpha_0 = eF_0/m^*\varpi^2$ is the laser dressing parameter, F_0 is the laser field strength, ϖ is the non-resonant frequency of the laser field, Θ is the Heaviside step function, and V_L and V_R are the confinement potentials in the left- and right-hand sides, respectively. For the value of the confinement potential barrier height, we use [25]

$$V_0(x) = 0.6(1.155x + 0.37x^2)\ \text{eV}. \tag{3}$$

After the energy levels and the corresponding wave functions for the Hamiltonian in the Eq. (1) are obtained, (for details see Ref. [23]), the RI changes and optical AC, related with the inter-level transition 1 → 2 are given as follows [26,27]:

$$\frac{\Delta n^{(1)}(\omega)}{n_r} = \frac{\sigma_v|M_{21}|^2}{2n_r^2\varepsilon_0}\frac{\Delta E - \hbar\omega}{(\Delta E - \hbar\omega)^2 + (\hbar\Gamma_{12})^2} \tag{4}$$

and

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

The total change of the RI, $\Delta n(\omega, I)/n_r$ can be written as the sum of the linear and nonlinear contributions. On the other hand, the