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Combined effects of intense laser field, electric and magnetic fields on the nonlinear optical properties of the step-like quantum well

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HIGHLIGHTS

- Augmentation of laser-field results in red shift in total AC spectra.
- Magnetic field induces a blue-shift in the resonant peak.
- Resonant peak position shifts to red with effect of electric field.
- Resonant peak of total AC shifts to the higher photon energies with increasing well width.

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ABSTRACT

In the present work, the effects of the intense laser field on total optical absorption coefficient (the linear and third-order nonlinear) and total refractive index change for transition between two lower-lying electronic levels in the step-like $GaAs/Ga_{1-x}Al_xAs$ quantum well under external electric and magnetic fields are investigated. The calculations were performed within the compact density-matrix formalism with the use of the effective mass and parabolic band approximations. The obtained results show that both total absorption coefficient and refractive index change are sensitive to the well dimensions and the effects of external fields. By changing the intensities of the electric, magnetic and non-resonant intense laser fields together with the well dimensions, we can obtain the blue or red shift, without the need for the growth of many different samples.

1. Introduction

There is a considerable interest in the optical phenomena based on intersubband transitions in low-dimensional semiconductor quantum systems such as quantum wells, wires and dots. Due to the strong quantum confinement effects, larger values of dipole matrix element and the possibility of achieving the resonance conditions, both the linear and nonlinear optical processes in these structures are investigated [1–24]. Furthermore, it is well known that the nonlinear optical properties of semiconductor quantum well (QW) mainly depend on the asymmetry of the confining potential. Such an asymmetry in potential profile can be obtained, for example either by applying an electric field to a symmetric QW or by compositionally grading the QW. Therefore, several studies were pointed out on the theoretical analysis of linear and third order nonlinear optical absorption in asymmetric QWs, see for example [24–26] and reference therein.

As known, intense laser field (ILF) considerably affects the optical and electronic properties of semiconductors [27–33]. Because when an electronic system is irradiated by ILF, the confinement

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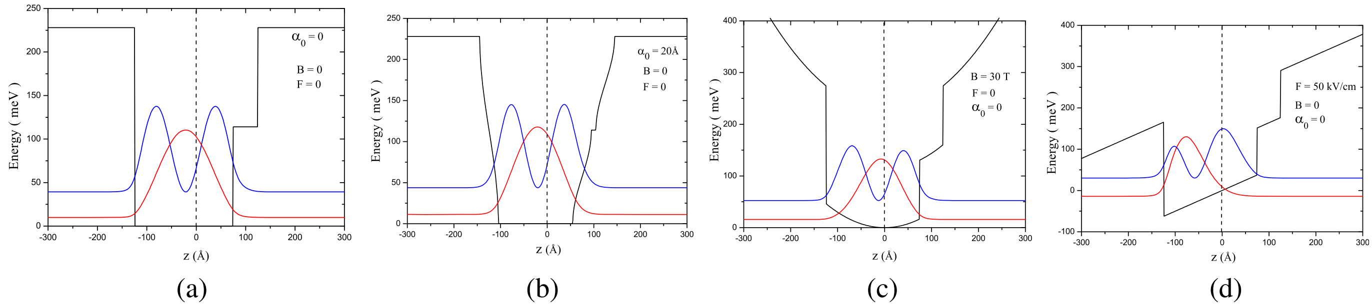

Fig. 1. For $L_w = 250$ Å and $L_b = 50$ Å, the variations of the confinement potential profile, ground and first excited state energies and the squared wave functions for related energy levels for some the electric, magnetic and intense laser field parameters.

potential of the system is dramatically modified, which affects significantly nonlinear optical properties as well as bound state energy levels. So the effects of a high-frequency non-resonant ILF on the confining potential and the corresponding bound state energy levels and also nonlinear optical properties related to the intersubband transitions within the conduction band of the QWs are very important problems. Note that the changes in the bound energy levels as a function, for example, of the intensity of the non-resonant laser radiation can be used to induce the changes in the range of the absorption coefficients, which can be observed as a red and/or blue shift in the main structures of the nonlinear optical properties. These problems have become the focus of interest in recent 20 years [34–41].

In this work, we have investigated the effect of the non-resonant ILF on the nonlinear optical absorption coefficient and refractive index change of the step-like QW under magnetic and electric fields. The paper is organized as follows: We present the theoretical framework in the Section 2, the numerical results and discussion in Section 3 and also the conclusions in Section 4.

2. Theory

We consider a step like GaAs/$Ga_{1-x}Al_xAs$ QW. The method used in the present calculation is based upon a non-perturbative theory that was developed to describe the atomic behavior under intense high-frequency laser field conditions, and it has already been given elsewhere [39,41,42]. So, we will not enter into details here. Within the framework of an effective mass approximation, the Hamiltonian for the electron in the presence of an intense high-frequency laser field (the laser-field polarization is along the z-direction) in the step-like QW under the magnetic field-**B** which is applied perpendicular to the growth direction i. e. $\mathbf{B} = (B,0,0)$ and the electric field-**F** which is applied parallel to the growth direction $(0,0,F)$, is given by

$$H = \frac{1}{2m^*}\left[\mathbf{p} + \frac{e}{c}\mathbf{A}(\mathbf{r})\right]^2 + V(\alpha_0, z) - \left|e\right|Fz, \quad (1)$$

where m^* is the electron effective mass, e is the elementary electron charge, $\mathbf{p}$ is the momentum, $\mathbf{A}$ is the vector potential and it is written form $\mathbf{A} = (0,-Bz,0)$ to describe the applied magnetic field, $\alpha_0 = eF_0/m^*\varpi^2$ is the laser dressing parameter, F_0 is the field strength, ϖ is the non-resonant frequency of the laser field, and $V(\alpha_0,z)$ is the 'dressed' confinement potential which is given by the following expression (in the absence of the laser field, we have already introduced the functional form of a step-like QW in our previous paper [43];

$$\begin{aligned} V(z,\alpha_0) = {} & V_0\Theta[-\alpha_0 - L_w/2 - z] + V_0\Theta[-\alpha_0 - L_w/2 + z] + \frac{V_0}{2}[1 - \Theta[-z - \alpha_0 - (L_w/2 - L_b)]] \\ & + \frac{V_0}{\pi}\left[(1 - \Theta[-z - \alpha_0 - L_w/2])\Theta[-z + \alpha_0 - L_w/2]\arccos\left[\frac{z + L_w/2}{\alpha_0}\right]\right] \\ & + \frac{V_0}{\pi}\left[(1 - \Theta[z - \alpha_0 - L_w/2])\Theta[z + \alpha_0 - L_w/2]\arccos\left[\frac{L_w/2 - z}{\alpha_0}\right]\right] \\ & - \frac{V_0}{2\pi}\left[(1 - \Theta[-z - \alpha_0 + (L_w/2 + L_b)])\Theta[-z + \alpha_0 + (L_w/2 - L_b)]\arccos\left[\frac{z - (L_w/2 - L_b)}{\alpha_0}\right]\right] \\ & + \frac{V_0}{2\pi}\left[\Theta[z + \alpha_0 - L_w/2](1 - \Theta[z - \alpha_0 - L_w/2])\arccos\left[\frac{(L_w/2 - z)}{\alpha_0}\right]\right]. \end{aligned} \quad (2)$$

where Θ is the step function, L_w is the QW width and L_b is the barrier width. We have chosen as origin the center of well with $L(=L_w + L_b)$ width. The variations of the confinement potential profile, ground and first excited state energies and the squared wave functions corresponding to these energy levels for some the electric, magnetic and intense laser field parameters taken into considerations are given in Fig. 1(a–d). The method used to find the eigenfunctions and eigenvalues of the Hamiltonian given by Eq. (1) is given in the Ref. [43] in detailed. After the energy levels and corresponding wave functions for the Hamiltonian in Eq. (1) are obtained, the linear and nonlinear absorption coefficient (AC) and the refractive index (RI) changes for the intersubband transitions