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Tunability of the optical absorption and refractive index changes in step-like and parabolic quantum wells under external electric field

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ABSTRACT

In this paper, the effects of an external electric field on the energy transitions and optical absorption lineshape in step and parabolic GaAs quantum wells are theoretically investigated. The energy separations between the three lowest energy levels E_1, E_2 and E_3 and their corresponding wavefunctions are calculated by solving the Schrödinger equation. Our theoretical findings show that the intersubband transitions and the optical absorption in the step-like quantum well can be tuned and controlled by an applied electric field (F). Especially the optical absorption coefficient $\alpha_{12}(\omega)$ presents a blue shift by increasing the intensity of F. Contrary to the case of step-like quantum well, the energy transition and the optical absorption coefficient $\alpha_{12}(\omega)$ are less sensitive to the applied electric field F in the case of parabolic quantum well. In the latter case $\alpha_{12}(\omega)$ presents a small red-shift variation. The obtained behavior in the optical absorption coefficient and refractive index changes can be used to design and fabricate new optical devices such as optical modulators.

1. Introduction

Recently, the studies of electronic transitions of electrons in the conduction band of quantum well heterostructures have been largely considered in fundamental physics due to the wide range of technological applications in optoelectronics domain [1–6]. The optical absorption coefficient (OAC) and the refractive index changes have a strong dependence on the shape of the quantum well semiconductors. The improvement of modern growth methods used in fabrication of semiconductors has demonstrated that it's possible to design devices structures accommodated to special applications. By changing the shape of semiconductor quantum well, the energy separation between different levels, the wavefunctions and the confining potential change, and so do the rest of physical properties depending on them. Among these properties, we can cite the linear and nonlinear optical absorption coefficients and refractive index changes which are in the core of the present study. Due to the various applications in industry, single and double quantum wells with different shapes have been intensively studied under different parameters, such as the applied electric field, magnetic field, hydrostatic pressure and insertion of some impurities. The application of an external electric field can provide a useful tool to adjust and modulate the electronic properties as well as the optical absorption in semiconductor quantum wells and low-dimensional systems [7–15]. The application of an external electric field importantly disturbs the electronic and optical properties of semiconductor quantum wells due to

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principally to the changes in energy separation between different levels. The sole properties of the intersubband transitions in semiconductor quantum wells which are the large amplitudes of dipole moments and wavelength transitions make them strongly used in the novel technological applications. During the last years many devices have been designed and fabricated to replace the conventional detectors [16–22]. Various devices based on the intersubband transition phenomenon for example infrared lasers [23,24], all optical switches [25] and far infrared photodetectors [26–30] have been designed and fabricated. The nonlinear optical properties in the quantum wells and wires are much important compared to the bulk materials owing to the presence of a large confinement behavior. Through the optical properties of semiconductor quantum wells, the linear and nonlinear optical absorption coefficients and refractive index changes have pointed a great attention for theoretical and experimental research [31–34]. These properties depend strongly on the asymmetry and on the profile of the confinement potential. The asymmetry of any quantum systems can be obtained by different geometrical shapes, like square quantum well, parabolic quantum well or step-quantum well. Theoretical and experimental results show that the electronic and optical properties depend on the asymmetry of the confining potential. In addition, an introduction of external electric field within the growth direction of the heterostructure produces a polarization of the electrons and consequently disturbs the energy levels which may be used to adjust and control the output power of optoelectronic devices. Therefore, many authors studied the optical absorption coefficient and the refractive index changes under external perturbations such as intense laser field, electromagnetic fields and inserted doped layers [35–44]. Wang et al. [39] calculated the optical absorption coefficient and refractive index changes in semi-parabolic quantum well. In their study, they showed that the parabolic confinement frequency has a strong impact on the optical absorption lineshape. Yildirim and Tomak [40] investigated the influence of an applied electric field on the intersubband transition in Si-delta doped GaAs. Their findings show that the nonlinear optical absorption becomes asymmetric by increasing the intensity of the optical field. Magdaleno et al [43] studied the effect of an applied electric field on the optical absorption in asymmetric double delta doped GaAs quantum well. They demonstrated that the electronic states depend on the asymmetry of double delta quantum well system and the applied electric field. Sari et al. [45] investigated the effects of magnetic and electric fields on the optical absorption coefficients and refractive index changes. Despite the large findings of the cited papers which are considerable, they have not elaborated the impact of the electric field on the electronic transition in the step and parabolic GaAs quantum well. In this work, we investigated the effect of the shape and applied electric field on the optical absorption coefficient and refractive index changes relatively to the transition between the ground state E_1 and the first excited E_2. In our simulation we develop a comparative study between the parabolic and the step quantum well under the action of an external electric field. The rest of the paper is organized as follows: in section II, we describe our theoretical model and we outline the method of resolution. In section III, we give our discussions and interpretations of the obtained numerical results. Finally, in section IV, we give our conclusions.

2. Theory

Within the effective mass approximation and the envelope-function theory, the energy levels and their corresponding wavefunctions can be derived by solving the one-dimensional Schrödinger equation which can be written as following [46]:

$$-\frac{\hbar^2}{2m^*}\frac{d^2\Psi(z)}{dz^2}+V(z)\Psi(z)=E\Psi(z) \tag{1}$$

m^* denotes the effective mass of electron. E and $\Psi(z)$ represent the energy level and the wavefunction respectively. In this work, we solve the Schrödinger equation using the finite difference method. Consequently, the Eq. (1) will be transformed to linear equation and the energy levels and their wavefunctions represent the eigenvalues and eigenvectors of a tridiagonal matrix. The confinement potential $V(z)$ which represents the discontinuity in the conduction band between $Al_xGa_{(1\text{-}x)}As$ and GaAs along the growth axis takes the following forms for the step and parabolic quantum wells [47]:

$$V^{step\ QW}=\begin{cases} V_1\ ; & 0\le z\le L_{b1}\\ V_2\ ; & L_{b1}\le z\le L_{b1}+L_{b2}\\ 0\ ; & L_{b1}+L_{b2}\le z\le L_{b1}+L_{b2}+L_w\\ V_1\ ; & L_{b1}+L_{b2}+L_w\le z\le L_{b1}+L_{b2}+L_w+L_{b3}\end{cases} \tag{2}$$

$$V^{parabolic\ QW}=\begin{cases} V_1\ ; & 0\le z\le L_{b1}\\ 4V_1\left(\frac{z}{L_w}\right)^2\ ; & L_{b1}\le z\le L_{b1}+L_w\\ V_1\ ; & L_{b1}+L_w\le z\le L_{b1}+L_w+L_{b3}\end{cases} \tag{3}$$

In this paper, the discontinuity in the conduction band and the effective mass of electron in each layer are determined by the following analytical expressions [48,49];

$$V(Al_xGa_{(1-x)}As/GaAs)=0.6(E_{gap}^{Al_xGa_{(1-x)}As}-E_{gap}^{GaAs}) \tag{4}$$