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Optical properties of the Tietz-Hua quantum well under the applied external fields

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ABSTRACT

In this study, the effects of the electric and magnetic fields as well as structure parameter-γ on the total absorption coefficient, including linear and third order nonlinear absorption coefficients for the optical transitions between any two subband in the Tietz-Hua quantum well have been investigated. The optical transitions were investigated by using the density matrix formalism and the perturbation expansion method. The Tietz-Hua quantum well becomes narrower (wider) when the γ - structure parameter increases (decreases) and so the energies of the bound states will be functions of this parameter. Therefore, we can provide the red or blue shift in the peak position of the absorption coefficient by changing the strength of the electric and magnetic fields as well as the structure parameters and these results can be used to adjust and control the optical properties of the Tietz-Hua quantum well.

1. Introduction

Investigation of the confinement potential and the applied external field effects on the electronic and optical properties of the low dimensional systems is one of the more important topics of condensed matter physics and these effects have been extensively studied and are still ongoing. Along with recent advances in material growth techniques, semiconductor quantum wells with different geometries have been made possible to grow. In addition to the well-known square [1] and parabolic [2–6] quantum wells, quantum wells such as half parabolic [7], graded [8], V-shaped [9], inverse parabolic, and PoschTeller [10–18] have been manufactured and studied. These structures have fascinated fairly attention because of potential applications in novel semiconductor diode lasers as well as infrared optoelectronic devices based on intersubband transitions. There is a remarkable interest in optical phenomena based on intersubband transitions in low-dimensional semiconductor systems which have different shapes since this case is the reason of the quantum confinement, which allows for bigger values of the dipole matrix elements and the possibility of achieving resonance condition. Linear and nonlinear optical properties in the above mentioned semiconductor heterostructures have been studied intensively by different authors for different quantum systems [17,19–26]. Additionally, interatomic potentials are widely used as the physical basis of molecular mechanics, molecular physics, and materials physics. Lennard-Jones is one of the most widely used interaction potentials [27]. The Morse potential has been applied to studies of molecular vibrations and solids [28], and also can be used to model other interactions such as the interaction between an atom and a surface. The most adequate potential for define the vibration spectrum of diatomic molecules is the Tietz-Hua potential and it is much more realistic than the generalized Morse potential [29,30]. Thus, the use of interaction potential functions of such real systems in the low-dimensional semiconductor systems will be very attractive and interesting.

In this paper, we have studied the combined effects of the electric and magnetic fields, structure parameter-γ and optical intensity-I on the total absorption coefficient, including linear and third order non-linear absorption coefficients for transitions between the ground and first excited level (1-2) and first and second excited level (2-3) of an electron that confined within the GaAs/GaAlAs quantum well with the Tietz-Hua potential which is given the schematic representation in the Fig. 1(a-d). As seen in these figures γ-parameter, the electric and magnetic fields cause more confinement of electron in the Tietz-Hua quantum well.

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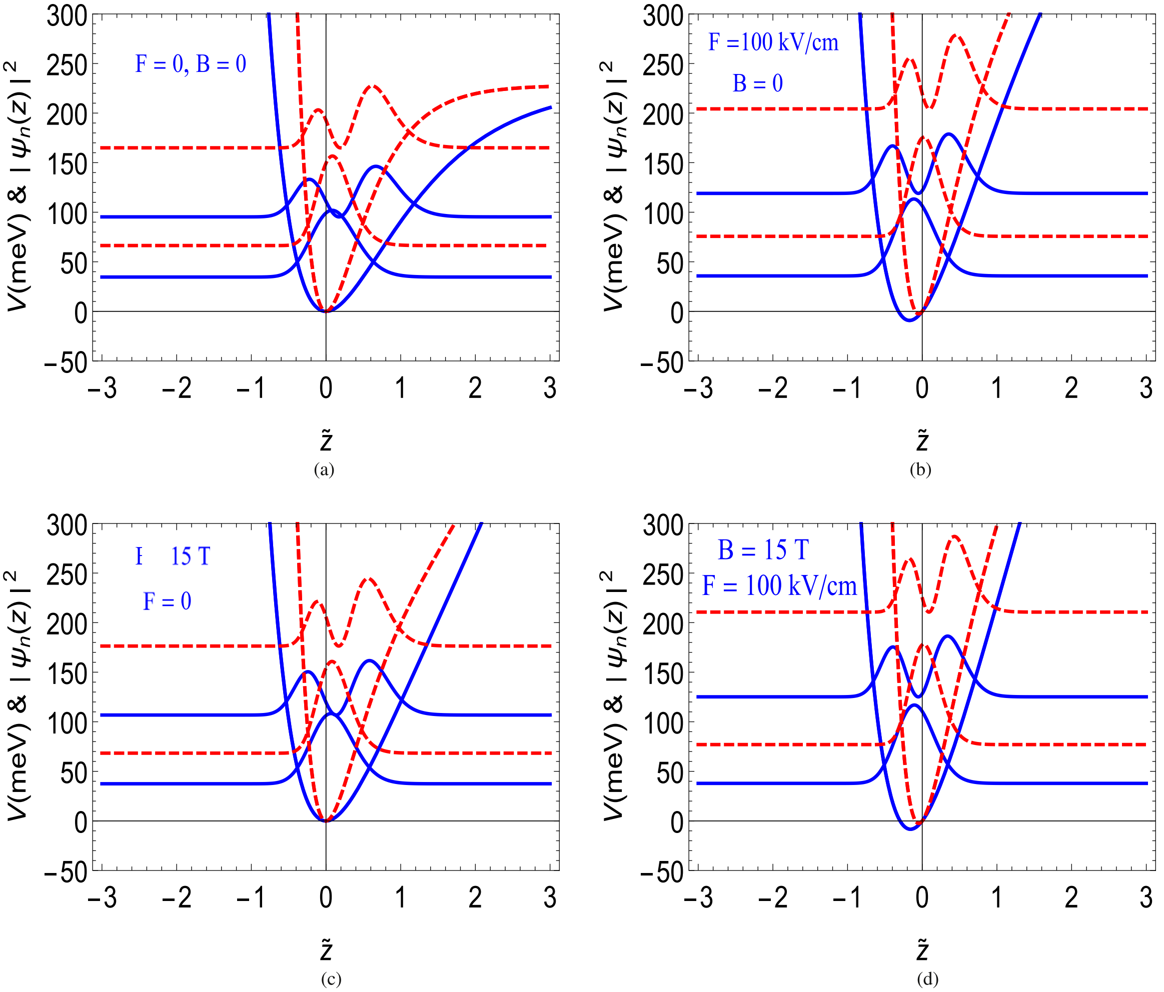

(a) (b) (c) (d)

Fig. 1. The potential itself and the first two wave functions and their energies are displayed for different electric and magnetic field values as a function of the normalized position ($\tilde{z} = z/a_B$, where $a_B = \varepsilon_0\hbar^2/m^* e^2$ is the effective Bohr radius): (a) $F = 0,\ B = 0$, (b) $F = 100\ kV/cm,\ B = 0$, (c) $F = 0,\ B = 15\ T$ and (d) $F = 100\ kV/cm,\ B = 15\ T$. In all figures, the blue lines (red lines) are for $\gamma = 0.001\ nm^{-1}$ ($\gamma = 0.002\ nm^{-1}$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Theory

In the effective mass approximation, the Hamiltonian of an electron confined in a quantum well with the Tietz-Hua potential under the applied magnetic and electric fields is written by

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

where the magnetic field-B is applied perpendicular to the growth direction i.e. $\overrightarrow{B} = (B, 0, 0)$ and the electric field-F is applied parallel to the growth direction (z-direction), m^* is the effective mass of the electron, e is the elementary charge, $\overrightarrow{p}$ is the momentum, $\overrightarrow{A}(\overrightarrow{r})$ is the vector potential and it is written in the form $\overrightarrow{A} = (0, -Bz, 0)$ to describe the applied magnetic field. $V_{TH}(z)$ is the Tietz-Hua confinement potential and for a constant Al concentration, it is given by

$$V_{TH}(z) = V_0\left(\frac{1 - e^{-\gamma z}}{1 - \kappa e^{-\gamma z}}\right)^2, \tag{2}$$

where, V_0 is depth of the quantum well, γ and κ are the structure parameters that control the well width and the potential depth. When the κ-potential constant approaches to zero, the Tietz-Hua quantum well (THQW) turns into the Morse QW and becomes wider (narrower) for small (large) γ. It should be noted that, the details to find the eigenfunctions and eigenvalues of the Hamiltonian in the Eq. (1) are given in the Ref. [31].

In order to calculate the changes of absorption coefficient (AC) which corresponds to the optical transitions between any two subbands of an electron confined within the QW, we employ the perturbation expansion method and the density matrix method within a two-level system approach. By using these approaches, the linear, third-order nonlinear and total AC related to the intersubband transitions $i \to j$, are given as follows [32–34], respectively

$$\beta^{(1)}(\omega) = \omega\sqrt{\frac{\mu_0}{\varepsilon_r}}\frac{|M_{ij}|^2\sigma_v\hbar\Gamma_{ij}}{(E_{ij} - \hbar\omega)^2 + (\hbar\Gamma_{ij})^2}, \tag{3}$$

$$\beta^{(3)}(\omega) = -2\omega\sqrt{\frac{\mu_0}{\varepsilon_r}}\left(\frac{I}{\varepsilon_0 n_r c}\right)\frac{|M_{ij}|^4\sigma_v\hbar\Gamma_{ij}}{[(E_{ij} - \hbar\omega)^2 + (\hbar\Gamma_{ij})^2]^2} \times\left(1 - \frac{|M_{jj} - M_{ii}|^2}{|2M_{ij}|^2}\frac{(E_{ij} - \hbar\omega)^2 - (\hbar\Gamma_{ij})^2 + 2E_{ij}(E_{ij} - \hbar\omega)}{(E_{ij})^2 + (\hbar\Gamma_{ij})^2}\right), \tag{4}$$

$$\beta(\omega) = \beta^{(1)}(\omega) + \beta^{(3)}(\omega), \tag{5}$$

where, $\varepsilon_r = n_r^2\varepsilon_0$ is the real part of the permittivity, σ_v is the carrier density in the system, μ_0 is the vacuum permeability, $E_{ij} = E_j - E_i$ is the energy difference between any two energy level of the electron in the THQW, $M_{ij} = |\langle\psi_i|ez|\psi_j\rangle|$, $(i, j = 1, 2, 3)$ is the transition element between the eigenstates ψ_i and ψ_j for z polarization of the incident radiation, Γ_{ij} is the relaxation rate which is equals to the inverse relaxation time T_{ij}, c is the speed of the light in free space, and I is the optical intensity of incident photon with the ω -angular frequency that leads to the intersubband optical transitions which is defined as