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Study of electron-related optical responses in the Tietz-Hua quantum well: Role of applied external fields

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ABSTRACT

In the present study, we theoretically reported the effects of applied external fields, such as intense laser field and electric and magnetic fields, on the optical absorption coefficient and refractive index changes in the Tietz-Hua potential quantum well by the compact density-matrix approach. For this, we first calculated the subband energy levels and their corresponding electronic wave functions of the structure by solving the one-dimensional Schrödinger equation within the framework of the effective mass and envelope wave function approximations. Our theoretical results show that the optical absorption coefficient and refractive index changes in the Tietz-Hua potential quantum well are sensitive to the applied external fields. The absorption spectra in the structure can be adjusted depending on the purpose by changing the strength of the applied external fields, and these results can be used to tune and control the electronic and optical properties of the Tietz-Hua potential quantum well.

1. Introduction

One of the most important issues related to low-dimensional systems such as quantum wells (QWs) is the confinement potential profile effects on the electronic and optical properties of these structures. It is well known that these structures play an important role in the development of optoelectronic devices such as semiconductor lasers, electro-optical modulators, semiconductor optical amplifiers, photo-detectors, and tera-hertz devices. The other important issue regarding these structures is the applied external perturbation effects on the nonlinear optical properties of these structures. These external field effects in the abovementioned low-dimensional systems have been theoretically studied intensively by many research groups for different quantum systems [1–8].

The nonlinear optical properties based on intersubband transitions between quantized states within the conduction band in QWs with different confining potential shapes have attracted much interest recently. Among the nonlinear optical properties of these QWs, optical absorption coefficients (ACs), nonlinear optical rectification, electromagnetically induced transparency, refractive index changes (RICs), and second- and third-harmonic generations have been investigated by many authors [9–16]. For example, Fu and Willander [9] carefully analyzed the effect of different doping concentrations on the optical ACs of a semiconductor QW infrared detector. Baskoutas et al. [10] reported the optical ACs in inverse parabolic QWs under an external static electric field. Their numerical results showed that the optical ACs are strongly influenced by the quantum confinement and the external electric field. Zhang et al. [11] calculated the polaron effects on the optical RICs in asymmetrical QWs. Exciton-related nonlinear optical ACs and RICs in symmetric and asymmetric double QWs were studied by Miranda et al. [12]. Niculescu [13] discussed the effect of high-frequency intense laser field (ILF) on the electromagnetically induced transparency in an asymmetric double QW. The nonlinear optical rectification coefficient of asymmetric coupled QWs was intensively studied by Wang et. al [14]. They found that an appropriate choice of the width of the barrier and the right well of the asymmetric coupled QWs can induce a larger nonlinear optical rectification coefficient. Hassanabadi et al. [15] theoretically calculated the electron-related optical responses in different shaped QWs. Orozco et al. [16] theoretically studied the nonlinear optical properties of a GaAs δ-FED structure under hydrostatic pressure. The obtained results indicated that the hydrostatic pressure has a significant impact on the nonlinear optical properties of the GaAs δ-FED structure. Recently, we reported the effects of external fields on the intersubband optical ACs in the Tietz-Hua QW [17]. We also studied the donor impurity binding energy and electron-related optical responses in the Tietz-Hua QW under an

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applied electric field [18]. Although many works have been conducted on the electronic and optical properties of semiconductor QWs, the effects of ILF on the optical ACs and RICs of the Tietz-Hua QW have not been studied thus far. Therefore, we intend to examine this in detail.

The goal of this research is to calculate the combined effects of an applied electromagnetic field and high-frequency ILF on the ACs and RICs in the Tietz-Hua potential QW. The present study is structured as follows: in Section 2, the theoretical model used in calculations and the analytical results are presented, followed by the numerical results and discussion in Section 3. The conclusions are provided in Section 4.

2. Theory

Here we are concerned with the effects of the electric and magnetic fields and high-frequency ILFs on the electronic states in a QW with the Tietz-Hua potential. An electric field $\mathbf{F} = (0, 0, F)$ (magnetic field-$\mathbf{B} = (B, 0, 0)$) is applied parallel (perpendicular) to the growth direction (z-axis) of the structure. Within the framework of the effective mass and envelope wave-function approximations, the Hamiltonian of the confined electron under these conditions is given as follows:

$$H = -\frac{1}{2m^*}\left(\boldsymbol{P} + \frac{\boldsymbol{e}}{\boldsymbol{c}}\boldsymbol{A}(\boldsymbol{r})\right)^2 + V_{TH}(z) + eFz, \tag{1}$$

where m^* is the conduction band effective mass of the electron inside the QW material, e is the elementary charge, c is the speed of light, $\mathbf{A}(\mathbf{r}) = Bz\hat{y}$ is the corresponding vector potential of the magnetic field, and $V_{TH}(z)$ is the Tietz-Hua potential, which is defined as follows [17,18]:

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

where V_0 is the depth of the confinement potential and γ and κ are the structure parameters. When the κ parameter approaches zero, the Tietz-Hua QW changes into the Morse QW. It should be noted that the results in this study for the Tietz-Hua QW with $\kappa = 0$ are in good agreement with the previous results obtained for the Morse QW [19,20].

To determine the effects of the high-frequency ILF (where the ILF is represented by a monochromatic plane wave, which is polarized linearly in the growth direction), we followed the Floquet method [21]. In the high frequency limit (the zeroth order in $1/\Omega$), electrons are under the effect of the time-averaged potential, and this potential is given as follows [22]:

$$\langle V_{TH}(z, \alpha_0)\rangle = \frac{\Omega}{2\pi}\int_0^{2\pi/\Omega} V(z + \alpha_0 \sin \Omega t dt) \tag{3}$$

where $\alpha_0 = eA_0/m^*\Omega$ is the laser dressing parameter, A_0 is the amplitude of the vector potential, and Ω is the frequency of the applied laser field. It should be noted that the validity of the lowest order approximation is defined as $\hbar\Omega \gg E(\alpha_0)$, which is called the high frequency condition, where $E(\alpha_0)$ is the average excitation energy. Furthermore, there is no limitation on α_0 apart from the high frequency condition. The details for dressed potential in Eq. (3) and the nonperturbative approach based on the Kramers-Henneberger translation transformation developed to describe the atomic behavior in intense high-frequency ILF can be found in Refs. [21–23].

In the high-frequency limit [21,24], the bound energy levels can be obtained from the solutions of the following time-independent one-dimensional Schrödinger equation:

$$\left[-\frac{\hbar^2}{2m^*}\frac{d^2}{dz^2} + \frac{e^2B^2z^2}{2m^*c^2} + \langle V_{TH}(z, \alpha_0)\rangle + eFz\right]\psi(z) = E\psi(z). \tag{4}$$

where E is the electron energy level and $\psi(z)$ is the electron wave function. To find the bound subband (SB) energy levels and their corresponding electronic wave functions in the Tietz-Hua QW under nonresonant monochromatic ILF and electric and magnetic fields, we solved Eq. (4) using the diagonalization method as presented in Refs. [25,26].

To calculate the linear and nonlinear ACs and RICs for the intersubband transitions between quantized states within the same band, we assume that the structure is simultaneously irradiated by non-resonant monochromatic ILF and a light field with frequencies Ω and ω, respectively. By using the compact density-matrix approach and iterative method, the first-order linear and third-order nonlinear ACs and RICs are obtained as follows [27,28]:

$$\beta^{(1)}(\omega) = \omega\sqrt{\frac{\mu}{\varepsilon_r}}\frac{|M_{12}|^2\sigma_v\hbar\Gamma_{10}}{(\Delta E-\hbar\omega)^2 + (\hbar\Gamma_{10})^2}, \tag{5}$$

$$\frac{\Delta n^{(1)}(\omega)}{n_r} = \frac{\sigma_v\ |M_{12}|^2}{2n_r^2\varepsilon_0}\left[\frac{\Delta E-\hbar\omega}{(\Delta E-\hbar\omega)^2 + (\hbar\Gamma_{10})^2}\right], \tag{6}$$

$$\beta^{(3)}(\omega, I) = -2\omega\sqrt{\frac{\mu}{\varepsilon_r}}\left(\frac{I}{\varepsilon_0 n_r c}\right)\frac{|M_{12}|^4\sigma_v\hbar\Gamma_{10}}{[(\Delta E-\hbar\omega)^2 + (\hbar\Gamma_{10})^2]^2}\left[1 - \frac{|M_{22}-M_{11}|^2}{|2M_{10}|^2}\times\frac{(\Delta E-\hbar\omega)^2-(\hbar\Gamma_{10})^2 + 2(\Delta E)(\Delta E-\hbar\omega)}{(\Delta E)^2 + (\hbar\Gamma_{10})^2}\right], \tag{7}$$

$$\frac{\Delta n^{(3)}(\omega, I)}{n_r} = -\frac{\mu c\ |M_{12}|^2}{4n_r^3\varepsilon_0}\frac{\sigma_v I}{[(\Delta E-\hbar\omega)^2 + (\hbar\Gamma_{10})^2]^2}\times\left[4(\Delta E-\hbar\omega)|M_{12}|^2-\frac{(M_{22}-M_{11})^2}{(\Delta E)^2 + (\hbar\Gamma_{10})^2}\{(\Delta E-\hbar\omega)\times[(\Delta E)(\Delta E-\hbar\omega)-(\hbar\Gamma_{10})^2]-(\hbar\Gamma_{10})^2(2(\Delta E)-\hbar\omega)\}\right], \tag{8}$$

where n_r is the refractive index, μ is the magnetic permeability, ε_0 is the dielectric permittivity of the vacuum, σ_v is the electron density, ω is the angular frequency of the incident photon, $I = \frac{2n_r}{\mu c}|E(\omega)|^2$ is the intensity of electromagnetic field, $\Delta E = E_2-E_1$ is the energy difference between the first two energy levels, $\Gamma_{10} = 1/\tau_{10}$ is the relaxation rate, τ_{10} is the relaxation time of the final and initial states, and $M_{ij} = \langle\psi_i(z)ez\psi_j(z)\rangle$ is the dipole moment matrix elements.

The total ACs and RICs can be written as follows:

$$\beta(\omega, I) = \beta^{(1)}(\omega) + \beta^{(3)}(\omega, I) \tag{9}$$

$$\frac{\Delta n(\omega, I)}{n_r} = \frac{\Delta n^{(1)}(\omega)}{n_r} + \frac{\Delta n^{(3)}(\omega, I)}{n_r}. \tag{10}$$

3. Results and discussion

In this section, we theoretically deduce the effects of nonresonant monochromatic ILF and electric and magnetic fields on the ACs and RICs in the Tietz-Hua QW. For this purpose, we first numerically solve the time-independent, one-dimensional Schrödinger equation for the Tietz-Hua potential QW in the presence of applied external fields. Then, we obtain the total ACs and RICs of the Tietz-Hua QW. TO calculate the optical ACs and RICs, we used the values of physical parameters that are suitable for GaAs/$Ga_{1-x}Al_xAs$ materials [17,26]:

$m* = 0.067m_0$ ($m_0 = 9.10956 \times 10 - 31\ kg$), $V_0 = 228\ meV$ (which corresponds to $x = 0.3$ for aluminum concentration), $\kappa = 0.001$, $n_r = 3.2$, $I = 0.05\ MWcm-2$, $\sigma_v = 3.0 \times 1022\ m-3$, $\mu = 4\pi \times 10 - 7\ Hm-1$, and $\tau_{10} = 0.14\ ps$ (where $\tau_{10} = 1/\Gamma_{10}$).

In Fig. 1, we show the variation of the potential profile of the Tietz-Hua QW, the ground and first excited energy states and the probability densities corresponding to these energy states as a function of the position for two different values of (a) ILF and (b) electric and (c) magnetic fields. Fig. 1(a) shows that the depth of the confinement potential reduced with the increase in the ILF intensity. As a result of this effect, the electronic SB energy states shifted to higher energy values. Therefore, the optical properties of the structure based on the intersubband transitions were influenced by the ILF. Fig. 1(b) clearly shows that the effective length of the confinement potential decreased, and the