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Intersubband optical absorption coefficients and refractive index changes in a graded quantum well under intense laser field: Effects of hydrostatic pressure, temperature and electric field

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ABSTRACT

The effects of hydrostatic pressure, temperature, and electric field on the optical absorption coefficients and refractive index changes associated with intersubband transition in a typical $\mathrm{GaAs/Ga_{0.7}Al_{0.3}As}$ graded quantum well under intense laser field have been investigated theoretically. The electron energy eigenvalues and the corresponding eigenfunctions of the graded quantum well are calculated within the effective mass approximation and envelope wave function approach. The analytical expressions of the optical properties are obtained using the compact density-matrix approach and the iterative method. The numerical results show that the linear and nonlinear optical properties depend strongly on the intense laser field and electric field but weakly on the hydrostatic pressure and temperature. Additionally, it has been found that the electronic and optical properties in a $\mathrm{GaAs/Ga_{0.7}Al_{0.3}As}$ graded quantum well under the intense laser field can be tuned by changing these external inputs. Thus, these results give a new degree of freedom in the devices applications.

1. Introduction

In the past years many researches have reported studies on the linear optical properties in low-dimensional semiconductor structures. They included systems having quantum confinement in one, two, and three directions such as quantum wells (QWs) [1–5], quantum well wires (QWWs) [6–8], and quantum dots (QDs) [9–12]. On one hand, due to the strong quantum confinement effect, the nonlinear effects in these semiconductor heterosystems can be significantly enhanced compared to those in bulk materials. On the other hand, these nonlinear optical properties are prospective for photo-electronic device application in far-infrared laser amplifiers [13], far-infrared photodetectors [14,15], high-speed electro-optical modulators [16], and all optical switches [17]. In addition, modern material growth techniques, such as the molecular-beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD), contribute to the accelerated development of research in this area.

A number of experimental and theoretical results on the variation of the linear and nonlinear optical absorption coefficient as well as the relative change of refractive index, associated with intersubband (ISB) optical transitions in semiconductor quantum heterostructures have been published so far. We can mention, for instance, the experimental report for ISB optical transition in a GaAs/AlGaAs QW by West and Eglash [18]. Li and coworkers calculated the polaron effects on the optical absorption and refractive index change in a square QW [19]. The linear and nonlinear ISB optical absorption and refractive index changes in asymmetric double semi-parabolic QWs were theoretically studied by Karimi et al. [20]. Besides, Karabulut and Baskoutas [21] discussed the influences of impurities, applied electric field, and incident optical intensity on the linear and nonlinear optical absorptions in spherical QDs. Baghramyan et al. [22] investigated the effects of the application of hydrostatic pressure and the variation of the aluminum concentration on the linear and nonlinear optical absorption coefficients in GaAs/GaAlAs concentric double quantum rings. The study on the influence of hydrostatic pressure and externally applied electromagnetic fields on the linear and nonlinear optical responses of a hydrogenic impurity confined in a two-dimensional QD was performed by Rezaei and Kish [23].

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The development of high-power tunable laser sources has increased research activities on the interaction of intense laser fields (ILFs) with electrons in the low-dimensional semiconductor systems [24–26]. It is well known that a high-frequency ILF considerably affects the optical and electronic properties of low-dimensional semiconductor quantum systems. It has been reported that the potential of an electronic system irradiated by an ILF is modified, significantly affecting the bound state energy levels; a feature that has been observed in transition energy experiments. Therefore, several studies report investigations on the effect of ILF on low-dimensional semiconductor heterostructures. Within this context, Diniz and Fanyao [27] have calculated the effects of an ILF on the optical properties of semiconductors QWs. By using a non-perturbative theory and a variational approach, they have included the laser effects via laser-dressing QW potentials for both conduction and valence bands. They theoretically predicted a novel approach to build GaAs/AlGaAs lasers by tailoring the semiconductor parameters and external laser field radiation. Lima et al. [28] studied the nonresonant ILF effects on the potential well profile and the corresponding bound states for electrons in a single semiconductor QW. The ILF effects on the density of impurity states of shallow donors in a square, V-shaped, and inverse V-shaped QWs have been investigated by Niculescu et al. [29,30]. Sakiroglu et al. [31] have theoretically calculated the band structure of a semiconductor superlattice under high-frequency ILF. Furthermore, Eseanu et al. [32] studied the combined effects of the hydrostatic pressure and high-frequency ILF on the binding energy of a hydrogenic impurity in square and parabolic QWs.

In this paper, we present a theoretical study of the effects of hydrostatic pressure, temperature, and electric field on the linear and nonlinear optical properties in a $GaAs/Ga_{0.7}Al_{0.3}As$ graded QW under the ILF. This paper is organized as follows: in Section 2, we describe the theoretical framework. Section 3 shows the numerical results and discussions. Finally, the conclusions are given in Section 4.

2. Theory

In the effective-mass approximation, the Hamiltonian of an electron confined in the graded QW, having the z-axis as the growth direction, under the combined effects of hydrostatic pressure, temperature, applied electric field in the z-direction, and non-resonant ILF (the laser field polarization is along the growth direction) can be written as [32]

$$H=\frac{P_{\perp}^2}{2m^*(p,T)}+\frac{P_z^2}{2m^*(p,T)}+V_b(z,\alpha_0,p,T)+eFz \tag{1}$$

where $P_{\perp}^2/2m^*(p,T)$ is the kinetic energy operator in the $x-y$ plane, $P_z^2/2m^*(p,T)$ is the kinetic energy operator in the z-direction, m^* is the electron effective mass, p is the hydrostatic pressure in kbar, T is the temperature in Kelvin, e is the electron charge, F is the external applied electric field, $\alpha_0=eF_0/m^*\varpi^2$ is the laser dressing parameter, F_0 is the field strength of the incident radiation, ϖ is the non-resonant frequency of the laser field, and $V_b(z,\alpha_0,p,T)$ is the "dressed" confinement potential which is given by the following expression:

$$\begin{aligned}V_b(z,\alpha_0,p,T)=&\frac{V_0(z,p,T)}{\pi}\left(\arccos\left[\frac{L(p)/2+z}{\alpha_0}\right]\Theta[\alpha_0-z-L(p)/2]\right.\\&\left.+\arccos\left[\frac{L(p)/2-z}{\alpha_0}\right]\Theta[\alpha_0+z-L(p)/2]\right)\\&-\frac{V_0(z,p,T)}{\pi}\left(\frac{\sqrt{-(-L(p)/2-z)^2+\alpha_0^2}}{2L(p)}\right.\\&\left.+\left(\frac{1}{4}+\frac{z}{2L(p)}\right)\arccos\left[\frac{L(p)/2+z}{\alpha_0}\right]\Theta[\alpha_0-z-L(p)/2]\right)\\&-\frac{V_0(z,p,T)}{\pi}\left(\frac{\sqrt{-(L(p)/2-z)^2+\alpha_0^2}}{2L(p)}\right.\\&\left.+\left(\frac{1}{4}+\frac{z}{2L(p)}\right)\arccos\left[\frac{L(p)/2-z}{\alpha_0}\right]\Theta[\alpha_0+z-L(p)/2]\right)\\&+\frac{V_0(z,p,T)}{2L(p)}z+\frac{V_0(z,p,T)}{4},\end{aligned} \tag{2}$$

where $V_0(z,p,T)$ is the confinement potential at zero-ILF effects, Θ is the Heaviside step function, and $L(p)$ is the QW width. The pressure and temperature-dependent effective mass for the electron is obtained by [33–36]

$$m^*(p,T)=\frac{m_0}{1+E_p^{\Gamma}\left[\frac{2}{E_g^{\Gamma}(p,T)}+\frac{1}{E_g^{\Gamma}(p,T)+\Delta_0}\right]}, \tag{3}$$

where m_0 is the free electron mass, $E_p^{\Gamma}=7.51$ eV is the energy related to the momentum matrix element, $\Delta_0=0.341$ eV is the spin–orbit splitting of the valence band. $E_g^{\Gamma}(p,T)$ is the pressure and temperature dependent energy gap for the GaAs semiconductor at the Γ-point, given by [33]

$$E_g^{\Gamma}(p,T)=E_g^{\Gamma}(0,T)+bp+cp^2, \tag{4}$$

where $E_g^{\Gamma}(0,T)=[1.519-(5.405\times10^{-4}T^2)/(T+204)]$ eV, $b=1.26\times10^{-2}$ eV/kbar and $c=-3.77\times10^{-5}$ eV/kbar^2.

The confinement potential is given by

$$V(z,p,T)=\begin{cases}V_0(p,T), & z<-L(p)/2,\\ \frac{V_0(p,T)}{2L(p)}(z+\frac{L(p)}{2}), & -L(p)/2\le z\le L(p)/2,\\ V_0(p,T), & z>L(p)/2\end{cases} \tag{5}$$

and the barrier height is given by [37]

$$V_0(p,T)=Q_c\Delta E_g^{\Gamma}(x,p,T), \tag{6}$$

where Q_c=0.6 is the conduction band offset parameter, x is the mole fraction of aluminum in $Ga_{1-x}Al_xAs$, and $\Delta E_g^{\Gamma}(x,p,T)$ is the band gap difference between QW and the barrier matrix at the Γ-point as a function of p and T, which is given by

$$\Delta E_g^{\Gamma}(x,p,T)=\Delta E_g^{\Gamma}(x)+pD(x)+G(x)T, \tag{7}$$

where $\Delta E_g^{\Gamma}(x)=(1.155x+0.37x^2)$ eV is the variation of the energy gap difference, $D(x)=[-(1.3\times10^{-3})x]$ eV/kbar, and $G(x)=[-(1.15\times10^{-4})x]$ eV/K [38].

In Eq. (5), the QW width is a function of the hydrostatic pressure, given by

$$L(p)=L[1-(S_{11}+2S_{12})p], \tag{8}$$

where $S_{11}=1.16\times10^{-3}$ kbar^{-1} and $S_{12}=-3.7\times10^{-4}$ kbar^{-1} are the elastic constants of the GaAs [33–36] and L is the original width of the QW in z-direction.

After the energies and their corresponding wave functions are obtained, the first-order linear absorption coefficient $\beta^{(1)}(\omega)$ and third-order nonlinear absorption coefficient $\beta^{(3)}(\omega,I)$ for the ISB transitions between two subbands can be calculated as [39–41]

$$\beta^{(1)}(\omega)=\omega\sqrt{\frac{\mu}{\varepsilon_R}}\frac{|M_{21}|^2\sigma_V\hbar\Gamma_{12}}{(\Delta E-\hbar\omega)^2+(\hbar\Gamma_{12})^2}, \tag{9}$$

$$\beta^{(3)}(\omega,I)=-2\omega\sqrt{\frac{\mu}{\varepsilon_R}}\left(\frac{I}{\varepsilon_0 n_r c}\right)\times\frac{|M_{21}|^4\sigma_V\hbar\Gamma_{12}}{[(\Delta E-\hbar\omega)^2+(\hbar\Gamma_{12})^2]^2} \tag{10}$$