Optics Communications ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Simultaneous effects of hydrostatic pressure and temperature on the nonlinear optical properties in a parabolic quantum well under the intense laser field

F. Ungan [a,*], U. Yesilgul [a], S. Sakiroglu [b], M.E. Mora-Ramos [c], C.A. Duque [d], E. Kasapoglu [a],
Q1 H. Sari [a], I. Sökmen [b]

[a] Department of Physics, Cumhuriyet University, 58140 Sivas, Turkey
[b] Department of Physics, Dokuz Eylül University, 35160 Buca, İzmir, Turkey
[c] Facultad de Ciencias, Universidad Autonoma del Estado de Morelos, Ave. Universidad 1001, CP 62209 Cuernavaca, Morelos, Mexico
[d] Instituto de Fisica, Universidad de Antioquia, AA 1226 Medellin, Colombia

A R T I C L E I N F O

Article history:
Received 11 April 2013
Accepted 3 July 2013

Keywords:
Parabolic quantum well
Intense laser field
Nonlinear optical property
Hydrostatic pressure

A B S T R A C T

In this present study, we have theoretically investigated the effects of hydrostatic pressure and temperature on the nonlinear optical properties in a typical $GaAs/Ga_{0.7}Al_{0.3}As$ parabolic quantum well under the intense laser field. The energy levels and wave functions are calculated using the effective mass approximation and optical properties are obtained using the compact density-matrix approach. The numerical results show that the confinement potential and the energy difference depend strongly on the intense laser field but weakly on the hydrostatic pressure and temperature. Additionally, it has been found that the linear and nonlinear optical properties in a $GaAs/Ga_{0.7}Al_{0.3}As$ parabolic quantum well under the intense laser field can be tuned by changing the hydrostatic pressure and temperature.

1. Introduction

The recent developments of material growth techniques, such as the molecular-beam epitaxy (MBE), metal organic chemical vapor deposition (MOCVD), and electron lithography combined with the use of the modulation-doped technique made it possible the fabrication of the low-dimensional semiconductor structures having quantum confinement in one, two and three directions such as quantum wells (QWs), quantum-well wires (QWWs), and quantum dots (QDs). With these modern growth techniques, QWs can be generated into different forms such as, the parabolic QWs, the graded QWs, and the V-shaped QWs. These semiconductor quantum nanostructures have attracted a great deal of attention because of their unique physical characteristics and potential applications in a variety of electronic and optoelectronic devices.

The advent of high-power, long-wavelength, linearly polarized tunable laser sources has increased research activities on the interaction of intense laser fields (ILF) with electrons in the low-dimensional semiconductor structures [1–3]. As it is known, the effect of a high-frequency ILF also leads to major modifications in the confining potential of these structures. The application of ILF to these structures causes a shift of quantum energy states producing considerable changes in the energy spectrum of the carriers. These effect can be used to control and to modulate the output intensity of devices. For these reasons, the effects of ILF on the confining potential and corresponding bound states play an important role in the optoelectronic device modeling [4–12].

The optical properties of the low-dimensional semiconductor structures are a subject of interest due to possible technological applications in optoelectronic devices associated with these systems. It is also well known that the shape of the confining potential of the QW structures significantly affects the nonlinear optical properties. Therefore, for both fundamental and applied researches, the linear and nonlinear optical properties in these structures under the influence of external perturbations like temperature [13–15], pressure [16–18], electric field [19,20], magnetic field [21] and ILF [22,23] have been studied by many researchers for the past few decades. Zhang and Xie [24] studied the electric field effect on the second-order nonlinear optical properties of parabolic and semi-parabolic QWs. The linear and nonlinear intersubband (ISB) optical absorption in symmetric double semi-parabolic QWs was investigated by Keshavarz and Karami [25]. Karabulut and Baskoutas [26] calculated the effects of impurities, electric field, size and optical intensity on the linear and nonlinear optical absorption coefficients and refractive index changes in spherical QDs. Karimi et al. [27] studied the linear and nonlinear ISB optical absorption and refractive index changes of asymmetric double semi-parabolic QWs. Yakar et al. [28] investigated

Q2 * Corresponding author. Tel.: +90 5055811815.
E-mail address: fungan@cumhuriyet.edu.tr (F. Ungan).

0030-4018/$ - see front matter © 2013 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.optcom.2013.07.006

the linear and nonlinear optical absorption coefficients of a spherical QD with parabolic potential. In our previous studies, we have investigated the effect of ILF [29,30], the electric field [31,32], and hydrostatic pressure [33,34] on the optical properties in a single QW.

This work is concerned with the theoretical study of the effects of hydrostatic pressure and temperature on the linear and nonlinear optical properties in a $GaAs/Ga_{0.7}Al_{0.3}As$ parabolic QW under the ILF. This paper is organized as follows: in the next section, we describe the theoretical framework. The numerical results are presented and discussed in Section 3. Finally, the conclusions are given in Section 4.

2. Theory

Within the framework of effective-mass approximation, the total Hamiltonian for an electron in a parabolic QW, having the z-axis as the growth direction, under the combined effect of hydrostatic pressure and non-resonant ILF (the laser field polarization and the pressure are along the growth direction) may be written as

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

where $P_\perp^2/2m^*(p,T)$ is the kinetic energy operator in the $x-y$ plane, m^* is the effective mass of the electron in the conduction band, p is the hydrostatic pressure in kbar, T is the temperature in Kelvin and $V_b(z,\alpha_0,p,T)$ is the "dressed" confinement potential which is given by

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

Here, $\alpha_0=eF_0/m^*\varpi^2$ is the laser dressing parameter, e is the electron charge, F_0 is the field strength, ϖ is the non-resonant frequency of the laser field, Θ is the step function, L is the QW width, and $V_0(z,p,T)$ is the profile of the conduction band potential. The temperature and pressure dependence of the effective mass of the electron in GaAs is determined from the expression [35–38]

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

where m_0 is the free electron mass. E_p^Γ and Δ_0 are the energies related to the momentum matrix element and the spin–orbit splitting of the valance band, respectively. The values of these parameters are taken as $E_p^\Gamma=7.51$ eV and $\Delta_0=0.341$ eV for GaAs accepted in the literature [36]. $E_g^\Gamma(p,T)$ is the pressure and temperature dependent energy gap (in eV) for the GaAs semiconductor at Γ-point [35]. The expression for $E_g^\Gamma(p,T)$ is

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

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 barrier potential which confines the electron in the parabolic QW in z-direction is given by [39]

$$V(z,p,T)=\begin{cases}V_0(p,T), & z<-Lw(p)/2,\\ \dfrac{4V_0(p,T)}{Lw^2(p)}z^2, & -Lw(p)/2<z<Lw(p)/2,\\ V_0(p,T), & z>Lw(p)/2\end{cases} \tag{5}$$

where

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

where Q_c=0.6 is the conduction band offset parameter [40], 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 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/kbar [41].

In Eq. (5)

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

where $S_{11}=1.16\times10^{-3}$ kbar^{-1} and $S_{12}=-3.7\times10^{-4}$ kbar^{-1} are elastic constants of the GaAs [35–38] and Lw is the original width of the confinement potentials in z-direction.

Our problem is now to use a suitable numerical method to find the solution of both the energy eigenvalues and the eigenfunctions. After the energy levels and corresponding wave functions are obtained, the linear and third-order nonlinear optical absorption coefficient for the ISB transitions between two subbands can be clearly calculated as [42]

$$\beta^{(1)}(\omega)=\omega\sqrt{\frac{\mu}{\varepsilon_R}}\frac{|M_{21}|^2\sigma_V\hbar\Gamma_{12}}{(E_2-E_1-\hbar\omega)^2+(\hbar\Gamma_{12})^2}, \tag{9}$$

$$\begin{aligned}
\beta^{(3)}(\omega)=&-2\omega\sqrt{\frac{\mu}{\varepsilon_R}}\left(\frac{I}{\varepsilon_0 n_r c}\right)\times\frac{|M_{21}|^4\sigma_V\hbar\Gamma_{12}}{[(E_2-E_1-\hbar\omega)^2+(\hbar\Gamma_{12})^2]^2}\\
&\times\left(1-\frac{|M_{22}-M_{11}|^2}{|2M_{21}|^2}\right)\\
&\times\frac{(E_2-E_1-\hbar\omega)^2-(\hbar\Gamma_{12})^2+2(E_2-E_1)(E_2-E_1-\hbar\omega)}{(E_2-E_1)^2+(\hbar\Gamma_{12})^2},
\end{aligned} \tag{10}$$

and the linear and third-order nonlinear refractive index changes can be expressed as [43]

$$\frac{\Delta n^{(1)}}{n_r}=\frac{\sigma_V|M_{21}|^2}{2n_r^2\varepsilon_0}\left[\frac{E_2-E_1-\hbar\omega}{(E_2-E_1-\hbar\omega)^2+(\hbar\Gamma_{12})^2}\right] \tag{11}$$

$$\begin{aligned}
\frac{\Delta n^{(3)}}{n_r}=&-\frac{\mu c|M_{21}|^2}{4n_r^3\varepsilon_0}\frac{\sigma_V I}{[(E_2-E_1-\hbar\omega)^2+(\hbar\Gamma_{12})^2]^2}\\
&\times[4(E_2-E_1-\hbar\omega)|M_{21}|^2\\
&-\frac{(M_{22}-M_{11})^2}{(E_2-E_1)^2+(\hbar\Gamma_{12})^2}\{\{(E_2-E_1-\hbar\omega)\\
&\times[(E_2-E_1)(E_2-E_1-\hbar\omega)-(\hbar\Gamma_{12})^2]-(\hbar\Gamma_{12})^2(2(E_2-E_1)-\hbar\omega)\}],
\end{aligned} \tag{12}$$

where ω is the angular frequency of the incident photon, μ is the permeability of the system, ε_R is the real part of the permittivity, σ_V is the carrier density, E_1 (E_2) is the initial (final) energy state, Γ_{12} is the relaxation rate for states 1 and 2, I is the optical intensity of incident electromagnetic wave (with the angular frequency ω) that excites the structure and leads to the ISB optical transitions, n_r is the refractive index, ε_0 is the permittivity of free space, c is the

Please cite this article as: F. Ungan, et al., Optics Communications (2013), http://dx.doi.org/10.1016/j.optcom.2013.07.006