Physica B 456 (2015) 129–133

Contents lists available at ScienceDirect

Physica B

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

Size effects in quantum well nanostructures on propagation of light pulse

Ali Golestani [a], H.R. Hamedi [b,*], Ahad Darkhosh [c]

[a] Research Institute for Applied Physics and Astronomy, University of Tabriz, Tabriz, Iran
[b] Institute of Theoretical Physics and Astronomy, Vilnius University, A. Gostauto 12, LT-01108 Vilnius, Lithuania
[c] Physics Department, Ataturk University, Erzurum, Turkey

ARTICLE INFO

Article history:
Received 27 August 2014
Accepted 29 August 2014
Available online 6 September 2014

Keywords:
Light propagation
Width of the wall
Width of the barrier
Quantum well
Dispersion
Absorption

ABSTRACT

In this paper, the effect of dimension on dispersion and absorption properties in an AlGaAs/GaAs quantum well (QW) nanostructure is investigated. We use the conduction-band Hamiltonian to calculate the envelope functions and the eigenenergies. The Schrödinger equation is solved numerically using homemade codes. Then we employ the density matrix formalism to evaluate the behavior of optical susceptibly. The impact of the width of the well and the barrier on the linear optical susceptibility behavior is explored. This investigation can be used for the optimal design of quantum well nanostructures to achieve electromagnetically induced transparency, which is much more practical than atomic structures because of their flexible design and the controllable quantum coherence effects.

1. Introduction

Taking the advantage of electromagnetically induced transparency (EIT) [1,2], the optical response and related absorption of weak laser light can be readily controlled. The EIT phenomenon has been found applications in quantum information science, which form the building blocks of the quantum communication and the quantum computation [3]. EIT has led to many optical phenomena such as Kerr nonlinearity [4–7], gain without inversion [8,9], optical switching [10,11], optical bistability [12–20], four-wave mixing (FWM) [21–26], atom and electron localization [27–33], and so on [34–38].

On the other hand, in the past two decades, many phenomena such as quantum coherence and interference in quantum well and quantum dot structures are considered [39–42]. The semiconductor devices potentially have great advantages such as high electron mobility, high thermal stability, low noise and wide temperature operating range [43]. These structures have tunable of the range of optical wavelengths that can be emitted and absorbed. Semiconductor structures have received considerable attention due to their unique physical properties and their potential applications in optoelectronic devices. In the conduction band of semiconductor quantum wells (QWs), the two-dimensional electron gas behaves atomic like optical responses. Quantum interference and coherence in QWs can generate some interesting phenomena such as strong CPT [44], LWI [45], EIT [46], enhancement of refractive index [47], optical bistability [48–50], Kerr nonlinearity [51,52] and so on [53,54].

In most studies that have been done, the coupling strength of the tunneling, the Fano-type interference, the intensity of the control field and the influence of the frequency detuning of the probe field on light propagation in the quantum well structures are discussed. However, to the best of our knowledge, the impact of dimensional parameters of QW structures are rarely reported, which motivate us for the present study. In this work, we intend to study the physical parameters of an asymmetric AlGaAs/GaAs coupled quantum well on light propagation properties. The physical parameters can influence the band structure of semiconductor structures. Therefore, their effects on the intersubband transition will be noticeable.

2. Model and calculation of electronic structure parameters

In this paper, we have considered an asymmetric coupled quantum well structure according to Fig. 1. Also, the schematic energy-level diagram of AlGaAs/GaAs coupled quantum well structure is shown in Fig. 2. A layer of low bandgap energy (e.g., GaAs) is sandwiched between layers of a compound with larger bandgap energy (e.g., AlGaAs). Ternary compounds are attractive as substrates materials for electronic and optoelectronic applications

* Corresponding author. Tel.: +37067218909.
E-mail addresses: aligolestani.sh@gmail.com (A. Golestani), Hamid.R.Hamedi@gmail.com (H.R. Hamedi).

http://dx.doi.org/10.1016/j.physb.2014.08.049
0921-4526/

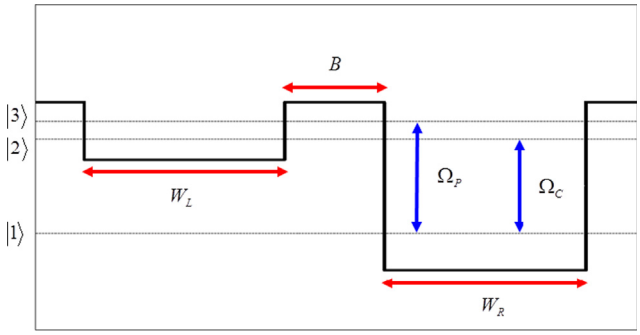

Fig. 1. Schematic of conduction subbands of the asymmetric double quantum well. It consists of two wells which are separated by thin tunneling barrier. W_L and W_R are the width of each wells and B is the width of tunneling barrier.

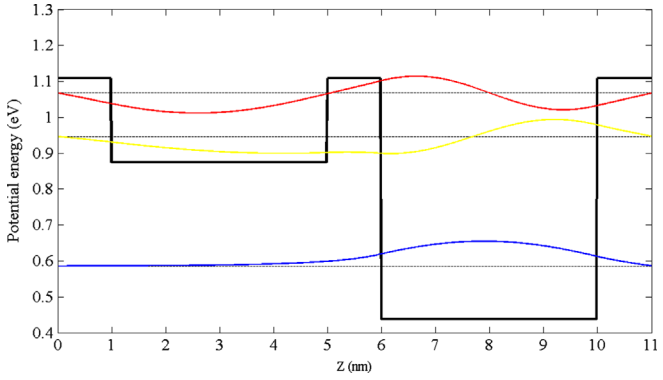

Fig. 2. The schematic energy-level diagram of an AlGaAs/GaAs asymmetric coupled quantum well structure. Related energy level and the corresponding wave functions are shown. The dimensions of quantum well structure are $W_L = W_R = 4$ nm, $B = 1$ nm.

and AlGaAs is the most important III–V semiconductor. We describe the modeling of the $Al_xGa_{1-x}As/GaAs/Al_xGa_{1-x}As$ semiconductor structure. It can be used to engineer the structre with the desired combination of properties. Dependence of bandgap on alloy composition for As-based ternary semiconductors as function of mole percentages is $1.424+1.247x$, $0<x<0.45$ and $1.424+1.087x+0.438x^2$, $x>0.45$ [55].

In order to investigate the optical properties of considered structure, we are going to solve the Schrödinger equation for a conduction-band electronic structure:

$$\frac{\hbar^2}{2m^*}\nabla^2\psi\left(\vec{r}\right)+V(r)\psi\left(\vec{r}\right)=E\psi\left(\vec{r}\right), \tag{1}$$

where $\hbar$ and m^* are the Planck's constant and electron effective mass respectively. E is the energy eigenvalue and $\psi\left(\vec{r}\right)$ is the wavefunction. The Schrödinger equation is being solved numerically using homemade finite difference method (FDM) codes.

We consider the intersubband transition between $|a\rangle$ and $|b\rangle$ states that the Bloch wave functions correspond to these states are:

$$\psi_a\left(\vec{r}\right)=u_c\left(\vec{r}\right)\frac{e^{i\vec{k}\times p}}{\sqrt{A}}\phi_a(z), \tag{2}$$

$$\psi_b\left(\vec{r}\right)=u_{c'}\left(\vec{r}\right)\frac{e^{i\vec{k}'\times p}}{\sqrt{A}}\phi_b(z), \tag{3}$$

where $u\left(\vec{r}\right)$ is the periodic part of the Bloch function and $\phi(z)$ is the periodic functions (describing atomic orbitals) and also $(e^{i\vec{k}\times p}/\sqrt{A})$ a plane wave (describing free electrons). The energy subbands and corresponding wave functions are shown in Fig. 2.

Then the optical dipole moment is given by [56]:

$$\vec{\mu}_{ba}=\langle\psi_b|e\vec{r}\,|\psi_a\rangle\approx\left\langle u_c|u_{c'}\right\rangle\left\langle\frac{e^{i\vec{k}'\times p}}{\sqrt{A}}\phi_b(z)|e\vec{r}\,|\frac{e^{i\vec{k}\times p}}{\sqrt{A}}\phi_a(z)\right\rangle$$
$$\approx\delta_{\vec{k},\vec{k}'}\langle\phi_b(z)|ez|\phi_a(z)\rangle\hat{z}, \tag{4}$$

The result of FDM solution will be the wave function and energy eigenvalues which is related to transition frequencies $\omega_{ba}=(E_b-E_a)/\hbar$. By making use of numerical wavefunction, the electronic transition dipole moment can be calculated ($\mu_{ba}=\langle\phi_b(z)|ez|\phi_a(z)\rangle$).

3. The density matrix formalism and the optical susceptibility

In this work, we consider two coherent optical fields that they are applied to our structure. The subbands $|1\rangle$ and $|3\rangle$ are coupled by the weak probe laser field Ω_P (frequency ω_P) and the subbands $|1\rangle$ and $|2\rangle$ are coupled by the strong control laser Ω_C (frequency ω_C). ω_{12}, ω_{13}, and ω_{23} are resonant frequencies which associated with the corresponding optical transitions $|2\rangle\rightarrow|1\rangle$, $|3\rangle\rightarrow|1\rangle$ and $|3\rangle\rightarrow|2\rangle$, respectively. The corresponding Rabi frequency of the probe and control fields are $\Omega_P=(\varepsilon_P\mu_{13}/2\hbar)$ and $\Omega_C=(\varepsilon_C\mu_{12}/2\hbar)$ respectively, where ε_P and ε_C are the amplitudes of probe and control laser field. The intersubband dipole moments of the relevant transitions are defined by $\mu_{ij}(i,j=1-3\ \&\ i\neq j)$ where μ_{ij} denotes the dipole moment for the transition between subbands $|i\rangle$ and $|j\rangle$. Also, γ_2 and γ_3 are the spontaneous decay rates of the excited states $|2\rangle$ and $|3\rangle$ to the ground state $|1\rangle$. The configuration and interaction of these fields with quantum well system is shown in Fig. 1.

The total Hamiltonian for this system includes the free energy and interaction terms are given by:

$$H=H_0+H_1, \tag{5}$$

where

$$H_0=\hbar\omega_1|1\rangle\langle1|+\hbar\omega_2|2\rangle\langle2|+\hbar\omega_3|3\rangle\langle3|, \tag{6}$$

and

$$H_1=-\hbar\Omega_P e^{-i\nu_P t}|3\rangle\langle1|-\hbar\Omega_C e^{-i\nu_C t}|2\rangle\langle1|+C.C.\ . \tag{7}$$

here, H_0 is the free energy term and H_1 denotes interaction Hamiltonian of the system with the probe and control. The interaction of this quantum well medium with the probe and control laser fields will be described by the density matrix equations. The equation of motion for the density matrix is expanded in terms of the eigenstates of the Hamiltonian. The dynamical behavior of the system is obtained by the density matrix formalism,

$$\frac{d\rho}{dt}=-\frac{i}{\hbar}[H,\rho], \tag{8}$$

The density matrix equations of motion in dipole and rotating wave approximations for this system can be written as follows

$$\dot{\rho}_{31}=\left(i\Delta_P-\frac{1}{2}\gamma_3\right)\rho_{31}-i\Omega_C\rho_{32}+i\Omega_P(\rho_{11}-\rho_{33}),$$
$$\dot{\rho}_{21}=-\frac{1}{2}\gamma_2\rho_{12}-i\Omega_P\rho_{23}-i\Omega_C(\rho_{11}-\rho_{22}),$$
$$\dot{\rho}_{23}=-\left[i\Delta_P+\frac{1}{2}(\gamma_2+\gamma_3)\right]\rho_{23}-i\Omega_P\rho_{21}+i\Omega_C\rho_{13},$$
$$\dot{\rho}_{22}=-\gamma_2\rho_{22}+i\Omega_C(\rho_{12}-\rho_{21}),$$
$$\dot{\rho}_{33}=-\gamma_3\rho_{33}+i\Omega_P(\rho_{13}-\rho_{31}),$$
$$\rho_{11}+\rho_{22}+\rho_{33}=1. \tag{9}$$