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Control of intersubband transitions in multiple quantum well systems

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HIGHLIGHTS

- Intersubband transitions in a multiple quantum well are studied in the presence of dc–ac fields.
- Band structure is obtained by using the finite difference method.
- Dynamics of system can be perfectly optimized by the selection of field parameters.

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ABSTRACT

The dynamics of intersubband transitions in a multiple quantum well system consisting of GaAs coupled quantum wells separated by an $Al_xGa_{1-x}As$ barrier is studied in the presence of a combined static and a dynamic laser field. The eigenenergies and eigenfunctions of the system under the effect of static field are solved by a time independent Schrodinger equation using a Finite Difference method. Calculations included the effect of the intensity of static field, effect of the number of wells on various intersubband transitions, the energies and wavefunctions of the levels involved. We initiated the study with the periodic structure consisting of a few quantum wells ($N=2$) and studied the bound–bound and bound–continuum transitions in the mini bands formed in the wells. We have analyzed how the features characteristic of long periodic systems are formed as the number of quantum well increases. These are then used to formulate the laser–multiple quantum well interaction using a time dependent Schrodinger equation which is solved with the help of an efficient fourth order Runge Kutta method.

1. Introduction

Semiconductor nanostructure plays an essential role in the modern nanotechnologies. A large number of investigations have been devoted to the field of study of semiconductor heterostructures. A very important manifestation of modern nanotechnology is multiple quantum well (MQW) structures. To modify the properties of quantum wells (QWs), many approaches have been suggested e.g., changing the shape of confining potential, changing the concentration of atoms in barrier, changing the well number, effect of hydrostatic pressure, impurity, well width and applying external electric and magnetic field that affects the energy levels and wavefunctions in low dimensional structures [1–4]. Different geometrical shapes of the quantum well (QW) systems like cylindrical QW wires [5], semiparabolic [6], hyperbolic QW [7], triangular QWs [8,9], delta-doped QW [10], and some others [11] and the effect of number of wells viz. double QW [12,13] and triple QW [14] have also been studied. A very important modification in the structure of a MQW is the reduction in the barrier width which results in the formation of a superlattice (SL).

Superlattices (SLs) are one-dimensional quantum confined structures consisting of two different semiconductor materials interleaved in thin layers by depositing them in alternation. They can be depicted as a periodic alternation of band gap energies of these two semiconductors. The alternation leads the band edges to exhibit a periodic variation with the position along the growth direction and forms a series of barriers perpendicular to the motion of the charge carriers. The difference in the band gaps of materials leads to discontinuities in valence and conduction bands and a set of square potential wells (low band gap semiconductor) separated by potential barriers (high band gap semiconductor) forms. In real life systems we cannot obtain perfect separation of adjacent wells and this results in coupling of their wave functions. In accordance with the Kronig Penney model any level of single energy E_i splits into a series of N levels, where N is the number of wells in the SL. For a N well system with high and thick barriers between the wells, in the first approximation the energy levels coincide with their single well position but they are N-fold degenerate. Tunneling between the wells breaks the degeneracy

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and results in a splitting into N-levels with the wavefunctions common for all the wells. The barrier width in a SL is thin enough for electrons to tunnel through so that the electrons see the alternating layers as a periodic potential in addition to the crystal potential.

Semiconductor SL has been, since their creation in early 1970s [15], a subject of intense study. Special optical and electronic properties of SL have already found their practical applications. The effect of external electric field on dielectric permittivity [16,17], on effective mass of minibands in p–i–n diode structure [18] has been recently reported. SL's have applications in various domains. Ahn et al. recently reported a SL channel consisting of a periodic semiconductor/insulator arrangement providing a creative route for producing more reliable thin film transistor (TFT) which is needed for the realization of acceptable driving transistors for next generation displays [19]. The electrical performance of the TFTs with various channel thicknesses was examined by Ding et al. It is noted that the layer thickness plays a vital role in the electrical performances of TFTs [20]. SLs are also used in laser technology. Spectral characteristics of laser-generated acoustic waves in an InGaN/GaN SL structure are studied at room temperature by Maznev et al. [21]. Optical excitation and detection of terahertz acoustic waves with semiconductor SL has been reported by Huynh et al. [22]. Many applications of SL in optoelectronic devices have already been reported by Ungan et al. and the references therein [23]. Another important applications of crystalline SL are quantum-well infrared photodetectors, lots of information on them can be found in a review paper by Levine and Zeiri [24,25].

In view of the overwhelming applications of SL we have devoted our work to a theoretical SL or a MQW model and studied the electronic properties of GaAs/AlGaAs MQW under the combined effect of a resonant laser field and a static dc field. GaAs/AlGaAs are good semiconductor structures for realizing MQW intersubband transition and have been studied extensively [26,27]. In this work we have studied how the intersubband transitions of a MQW or SL can be controlled under the effect of a combined dc–ac field. The interaction of the oscillating electric field with intersubband electrons in semi-conductor QWs has led to the prediction of several interesting and potentially useful effects, e.g., enhanced nonlinear-optics [28,29], gain without inversion [30], and electromagnetically induced transparency (EIT) [31]. There have been few experimental and theoretical studies in the field of QW intersubband transitions [32–34]. Several useful devices such as lasers, photo detectors, modulators, optical, and quantum switches are based on intersubband transitions in QWs [35–38,24]. Faisal et al. demonstrated the photoconductive detectors based on intersubband transitions in double-step III nitride QWs [39]. The design of these efficient optoelectronic devices depends on understanding the basic physics involved in this interaction process [40]. The effect of intense high-frequency laser field on the linear and nonlinear intersubband optical absorption coefficients and refractive index changes in a QW under the applied electric field has been reported very recently [41–43]. The various properties of QWs, such as photoionization [44–47], depolarization shift [48,49], optical absorption [50], and free–free transition [51], have also been widely reported.

The work is organized as follows. We have taken a multiple quantum well structure of total length (barrier width + well width) of around 60 nm and a barrier height of 1280 meV and studied the bound–bound and bound–continuum transitions in the mini bands formed in the wells. We focused on the periodic structure consisting of a few quantum wells (N=2) and analyze how the features characteristic of long periodic systems are formed as the number of QWs increases. In the first approximation the energy levels coincide with their single well position and they are n-fold degenerate. The eigenenergies and eigenfunctions of the system under the effect of static field are solved by the time independent Schrodinger equation using the finite difference method. Calculations included the effect of the static field on various intersubband transitions and the energies of the levels. These are then used to formulate the laser–MQW interaction using the time dependent Schrodinger equation which is solved with the help of a fourth order Runge Kutta method.

2. Theory and computation

We study the interaction of the laser field with a multiple quantum well in the presence of external static electric field i.e., a combined dc–ac field ($F+E_f(t)$). The multiple quantum well (MQW) system consists of GaAs coupled QWs separated by the $Al_xGa_{1-x}As$ barrier. For a multiple quantum well structure, assuming that the many body interactions among electrons are negligible, the one electron Hamiltonian can be used to describe the motion of the electrons. Since the perturbing potentials are assumed not to affect the band structures of both the well material and barrier material, the effective-mass approximation can be applied to find the electron energy levels and envelope wave functions.

The potential profile $V(z)$ for the MQW required for the numerical solution is the conduction band edge. The potential $V(z)$ is a periodic function of z with period d

$$V_{SL}(z) = \sum_{l=-\infty}^{+\infty} V(z-ld) \tag{1}$$

in which

$$V(z-ld) = V_b \quad \text{if } |z-ld| \le a/2 \tag{2}$$

$$V(z-ld) = 0 \quad \text{if } |z-ld| > a/2 \tag{3}$$

We have considered a conduction band electron confined in a typical $Al_xGa_{1-x}As$ based MQW grown in the Z-direction subjected to a static electric field 'F' and a periodic perturbation in terms of a spatially homogeneous laser field '$E_f(t)$'. The laser field is characterized by a plane monochromatic electric field of amplitude E_0, angular frequency ω, polarization vector $\hat{\zeta}$ along the Z-direction and is represented in the dipole approximation as

$$E_f(t) = \hat{\zeta} f(t) E_0 \cos(\omega t) \tag{4}$$

$f(t)$ being the Gaussian envelop of the laser field defined by

$$f(t) = \exp(-(t-t_0)/t_p)^2 \tag{5}$$

where t_0 is the centre of the pulse and t_p defines the width of the pulse. The time evolution of the system is determined by solving the time-dependent Schrodinger equation (in atomic units)

$$i\frac{\partial \psi}{\partial t} = H(z,t)\psi(z,t) \tag{6}$$

where

$$H(z,t) = H_0 + ezF + W(z,t) \tag{7}$$

The Hamiltonian of the quantum system is periodic in time with period T such that $H(t+T)=H(t)$, where $\omega T = 2\pi$ and $\hbar = 1$. Here, H_0 is the basis Hamiltonian, 'F' is the static electric field strength, and $W(z,t)$ is the interaction potential energy of the electron with the laser field given by

$$W(z,t) = -\mu(z) \cdot E_f(t) \tag{8}$$

where $\mu(z)$ is the dipole moment of the MQW and $E_f(t)$ is the laser field defined above.