Optimization of electron Raman scattering in double rectangular quantum wells

A. Keshavarz and N. Zamani

Abstract

In this work, by using the particle swarm optimization the electron Raman scattering for square double quantum wells is optimized. For this purpose, by combining the particle swarm algorithm together with the numerical solution procedures for equations, and also the perturbation theory we find the optimal structure that maximizes the electron Raman scattering. Application of this algorithm to the structure of asymmetric double quantum wells shows that the differential cross section of an electron Raman scattering is $1.30390 \times 10^5 Arb.Units$.

1 Introduction

The possibility of nanofabrication of new electro-optical devices based in low-dimensional systems has led to enormous interest in the investigation of semiconductor nanostructures such as: quantum wells, quantum dots, supperlattices and quantum wires, which are usually made with epitaxially grown materials (for instance $GaAs/AlAs$). In recent years, there has been considerable interest in double quantum well systems; because many new optical devices based on intersubband transitions are being developed. This feature could full the need for efcient sources of coherent mid-infrared radiation for application in several branches of science and technology, such as communications, radar, optical electronics. For example, an intersubband Raman laser can be built with a three-level system[1, 3, 2]. In an asymmetric double quantum well (ASDQW) structure, which consists of two different width wells

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coupled with a thin barrier, the system consists of two GaAs wells separated by AlxGa1-xAs barriers.

Raman scattering experiments are well known to provide a powerful technique for the investigation of direct physical properties of semiconductor nanostructures[8, 7]. The electronic structure of nanostructures and other materials can be studied through the use of Raman scattering processes considering different polarizations of incident and emitted radiation[4, 5]. In all previous work, studies show that the ERS of nanostructure are strongly affected by the material and impurities, geometrical and as well as the external factors such as electric and magnetic elds[6, 9, 10, 11]. Studying in this matter is based on the investigation of the effective parameters in the ERS of those nanostructures. This property can be modified and controlled by tuning the geometrical parameters such as barrier width and the well width which in double quantum well contains ve parameters as shown in Fig.1. In all of the previous works the sensitivity of the ERS for one of these parameters is investigated separately, but the effect of all parameters have not been discussed simultaneously. In the present work, we optimize the ERS with intersubband transitions within the conduction band for ASDQW. For this purpose, we calculate the energy eigenvalues and eigenfunctions of the system and then by using the particle swarm optimization(PSO) method and the variation of different values of the well parameter we obtain the optimum structure for maximized ERS.

2 Theory

The problem of finding the bound states of an electron in the envelope function approximation for a semiconductor ASDQW systems of rectangular form (grown along the z-direction), leads us to solving the Schrödinger equation with constant mass m^* is given by:

$$\left(-\frac{\hbar^2}{2m^*}\frac{d^2}{dx^2} + V(z)\right)\psi(z) = E\psi(z), \tag{1}$$

where the one-dimensional $V(z)$ is potential profile of the ASDQWs and introduced mathematically as:

$$V(z) = \begin{cases} V_0 & z \leq -(L_l + \frac{L_b}{2}), \\ 0 & -(L_l + \frac{L_b}{2}) < z < -(\frac{L_b}{2}), \\ V_0 & -(\frac{L_b}{2}) \leq z \leq (\frac{L_b}{2}), \\ V_1 & (\frac{L_b}{2}) < z < (L_r + \frac{L_b}{2}), \\ V_0 & z \geq (L_r + \frac{L_b}{2}) \end{cases} \tag{2}$$

Fig.1 shows the schematic illustration for this structure where b is the $Al_xGa_{1-x}As$ barrier thickness, L_l and L_r are the left and right $GaAs$ quantum well thickness, respectively. By using the numerical method one can be obtained the energy levels and corresponding wave function for electrons in conduction band of ASDQW.
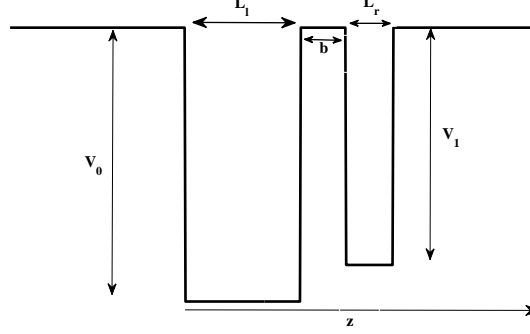

Figure 1: Schematic diagram for an asymmetric double quantum wells.

After the energies and their corresponding wave functions are obtained, can be used to calculate the ERS that the general expression for the ERS differential cross-section is given by[12]

$$\frac{d^2\sigma}{d\omega_s d\Omega} = \frac{V^2\omega_s^2 n(\omega_s)}{8\pi^3 c^4 n(\omega_l)} W(\omega_s, \mathbf{e}_s),\tag{3}$$

where c is the velocity of light in vacuum, $n(\omega)$ is the refractive index as a function of the radiation frequency, $\mathbf{e}_s(\mathbf{e}_l)$ is the polarization vector for the emitted secondary radiation field, ω_s is the secondary radiation frequency, ω_l is the frequency of the incident radiation. $W(\omega_s, \mathbf{e}_s)$ is the transition rate for the secondary radiation and calculated in perturbation theory and substituting in Eq.35 the differential cross-section for a three-level system for ASDQW is expressed in the form of[13]:

$$\left[\frac{d^2\sigma}{d\Omega d\omega_s}\right]_i = \sigma_0 \frac{\omega_s}{\omega_l} |M_0(i)|^2 \frac{E_0^2}{[\hbar\omega_l - \hbar\omega_s + E_1 - E_2]^2 + \Gamma_f^2},\tag{4}$$

where $M_0(i) = E_0 \frac{T_{2,3}(i)T_{3,1}(i)}{\hbar\omega_s + E_2 - E_3 + i\Gamma_a}$, $\sigma_0 = \frac{4e^4 n(\omega_s)\hbar\Gamma_f}{\pi m_0^{*2} c^4 n(\omega_l) E_0^2} |(\mathbf{e}_l \cdot \mathbf{e}_z)(\mathbf{e}_s \cdot \mathbf{e}_z)|^2$ and $E_0 = \frac{\hbar^2}{2m_0^* d_r^2}$. In this paper, a PSO is used to optimize the ASQWs structure in order to maximize the ERS. The PSO is a modern heuristic algorithm based on the social behaviour of bird flocks, colonies of insects, schools of shes, and groups of animals feeding and travelling together. This algorithm

was first introduced by Kennedy and Eberhat[14]which has now been widely used in function optimization applicable in mathematics and physics. The algorithm is started by initializing a population of random solutions called particles and searches for the best position by updating production through the following velocity and position update equations. The velocity and position are updated by the following equations:

$$Vel_j^{t+1} = \omega \times Vel_j^t + c_1 \times rand_1(.)$$
$$\times (Pbest_j - X_j^t) + c_2 \times rand_2(.) \times (Gbest - X_j^t), \quad (5)$$

$$X_j^{t+1} = X_j^t + Vel_j^{t+1}, \quad (6)$$

$$\omega^{t+1} = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{t_{max}} \times t, \quad (7)$$

where $j = 1, 2, ..., N_{Swarm}$ is the index of each particle, N_{Swarm} is the number of the swarms, t is the current iteration number, $rand_1(.)$ and $rand_2(.)$ are random numbers between 0 and 1. Vel_j^t is the current velocity of particle j at iteration t, Vel_j^{t+1} is the modified velocity of particle j at iteration $t + 1$, X_j^t is the current position of particle j at iteration t, $Pbest_j$ is the optimal coordinate value of the jth particle obtained so far and $Gbest$ is the best coordinate value found so far in the whole swarm. Constants c_1 and c_2 are the weighting factors of the stochastic acceleration terms, which pull each particle towards the $Pbest_j$ and $Gbest$. ω is a non-negative constant called inertia weight and used to control the convergence behaviour of the PSO. Here the position of particle involves width of two wells and barrier and height for two wells.

3 Numerical solution and disscussion

Considering ERS of the ASDQW is strongly affected by the geometrical size and any changes in the structure leads to changes in the ERS and the frequency of the secondary radiation. Using the above optimization algorithm, we determine the optimal structure parameters for maximized ERS. In order to use the PSO algorithm, minimum amounts in which there are three energy levels for quantum wells are obtained. The materil parameters used in this paper are as follows: $m_{GaAs}^* = 0.067m_0$, $m^* = 0.067m_0$, $m_{AlGaAs}^* = 0.067m_0$, $m^* = (0.067 + 0.083x)m_0$ where m_0 is the mass of the free electron, incident radiation energy $\hbar\omega_l = 230(meV)$ and the lifetimes of the final and intermediate states are given as $\Gamma_a = \Gamma_f = 3(meV)$, respectively. The rang of particles in the width and height of two wells which are separated by a barrier are given as: $L_l \in [50, 90]A°$, $L_r \in [20, 60]A°$, $b \in [15, 30]A°$, $V_0 \in [300, 400](meV)$ and $V_1 \in [300, 400](meV)$. Results obtained using the PSO algorithm are shown

Table 1: Result of PSO

$L_l(A°)$	$L_r(A°)$	$b(A°)$	$V_0(meV)$	$V_1(meV)$
60	30	15	390	390

in Table.1.

As the PSO algorithm is a random statistical algorithm, the typical convergence plots of PSO for nding optimal absorption for 50 iterations is shown in Fig.2. In this figure shows that by using the PSO algorithm after 20 iteration optical rectification coefficient has a constant value which is equal to $1.30390 \times 10^5 Arb.Units$.
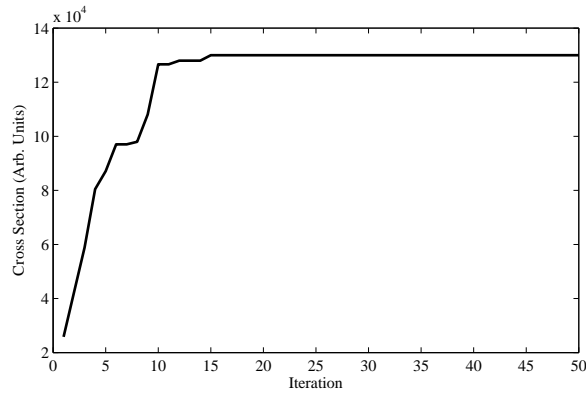

Figure 2: Convergence plot of PSO for nding optimal ERS.

The optimum structure of double quantum wells depicts in Fig.3. includes the wave functions of ASDQWs. Seen that optimum structure is asymmetric and using the numerical solutions.

Fig.4 display the ERS as a function of secondary radiation photon energy $\hbar\omega_s$ for our optimal structure. This indicates that resonant peak at photon energy value of $125.498\,(meV)$ as expected corresponding to the is $\hbar\omega_s = E3 - E2$ and non-resonant peak at photon energy value of $125.473\,(meV)$ as expected corresponding to the is $\hbar\omega_s = \hbar\omega_l + E3 - E2$. From this figure we see that resonant and non-resonant are overlapping and the magnitude of the non-resonant peak is $1.30390 \times 10^5 Arb.Units$. We should note that the resonant peak does not depend on incoming radiation and the non-resonant peak depends on it.
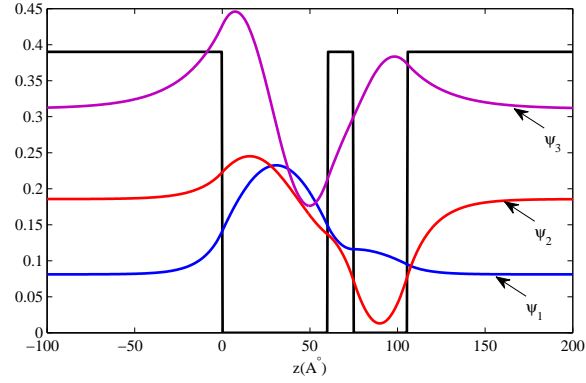
Figure 3: Schematic diagram for an asymmetric double quantum well for optimal parameters with wave function.
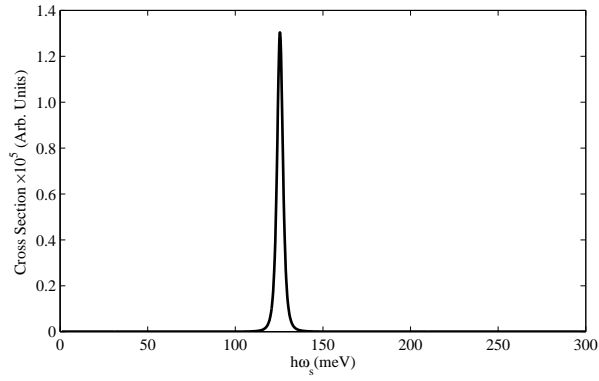

Figure 4: Schematic diagram for an asymmetric double quantum well for optimal parameters with wave function.

4 Conclusion

The ERS of quantum wells which depend on the energy eigenstate and their corresponding eigenfunctions associate with the potential shape and geometrical features are calculated numerical by solving the equation. The calculations mainly focus we to find the optimum parameters to maximize the ERS. For this purpose we used the particle swarm optimization and introduce the geometrical set of parameters.

Acknowledgements

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