Material type and Dimension Effects of Quantum Box in QD- based waveguides

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***Abstract*—Size and material type of quantum box are important parameters in an optical waveguide consisting of quantum dot structure. It is shown that the type of quantum box structure directly effects maximum gain of the spectrum. That is down using two different core/shell structures of $Al_{0.24}Ga_{0.76}As$/GaAs and $In_{0.47}Ga_{0.53}As$/InP both with the dimensions of 5×5×5nm and 10×10×10nm where it is shown that the gain spectrums differ from each other. Finally we inspect the optical propagation of a quantum box wave guide array and optical energy transfer between adjcent quantum boxes.**

Keywords- Quantum box, waveguide, net gain.

I. INTRODUCTION

The impetus to make high density photonic integrated circuits underlies technological advances in nanometer size optical components [1]. Configuration of Quantum Dot waveguide makes it possible. In a cubic quantum dot core/shell system, the electron-hole energy states is the energy gap difference between the core and shell, which forms a potential well. The wavelengths of photons emitted by exciton recombination is basically determined by the energy band gap of the core compound, which a function of the core diameter. In this paper, we first study quantum box behavior with and without considering optical pumping in different structures, and then optical propagation of a quantum box waveguide array and optical energy transfer is also examined.

II. QUANTUM BOX AND OPTICAL GAIN MODELING

A. Solving schrodinger equation

Fig.1 shows 1D energy diagram of a quantum box. The contribution of each dimension is determined sequentially from the wave equation and summed. For the conduction band (CB), the energy along the z direction is found from equation (1):

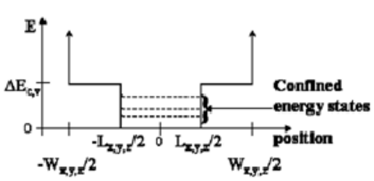


Fig1.Potanciel well energy diagram of core/shell quantum box[3]

$$\left[-\left(\frac{\hbar^2}{2m_{c1,2}}\right)\frac{\partial^2}{\partial z^2}+V_{cz}(z)\right]\phi_{czi}(z)=E_{czi}\phi_{czi}(z) \qquad (1)$$

Because of the symmetry, equation (1) also holds for x and y dimensions also. To solve this equation, we have used the *nextnano map* software. Fig 2 shows the 3-D simulation of wave function.

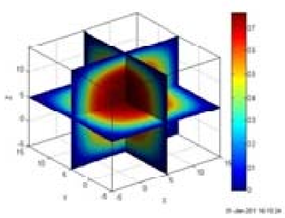


Fig 2.Simulation of wave function by using nextnano software

B. Calculation of net gain without optical pumping

Gain parameter is calculated based on quasi-Fermi level energies: E_{fc} and E_{fv}. With the known material properties, E_{fc} and E_{fv} can be solved directly and then applied to compute the absorption coefficient α(ω) and emission coefficient e(ω) in the quantum box [2]. Finally the net gain can be calculated as in equation (2):

$$G(\omega)=e(\omega)-\alpha(\omega)$$

$$G(\omega)=\frac{\omega}{n_r}\sqrt{\frac{\mu_0}{\varepsilon_0}}\sum_{lmn}\left\langle R_c^2\right\rangle\frac{g_{ch}\left[f_c(E_2)-f_v(E_1)\right]\hbar/\tau_{in}}{\left(E_{ch}-\hbar\omega\right)^2+\left(\hbar/\tau_{in}\right)^2}dE_{ch} \qquad (2)$$

The outcome as a function of photons emitted wavelength is shown in fig 3. For 10×10×10nm and 5×5×5nm $Al_{0.24}Ga_{0.76}As$/GaAs and 10×10×10nm and 5×5×5nm $In_{0.47}Ga_{0.53}As$/InP core/shell QDs.

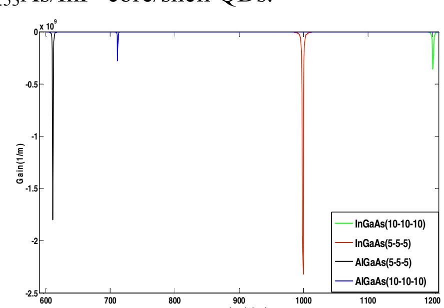
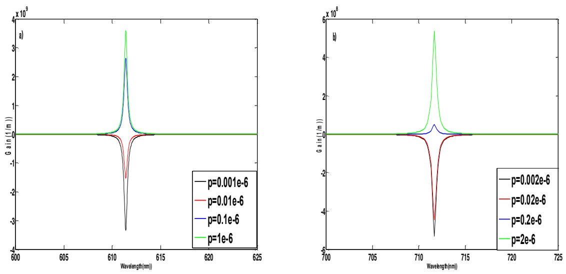


Fig 3. Gain spectra for $In_{0.47}Ga_{0.53}As$/InP and $Al_{0.24}Ga_{0.76}As$/GaAs in 5×5×5nm and 10×10×10nm dimension of quantum box without pumping .

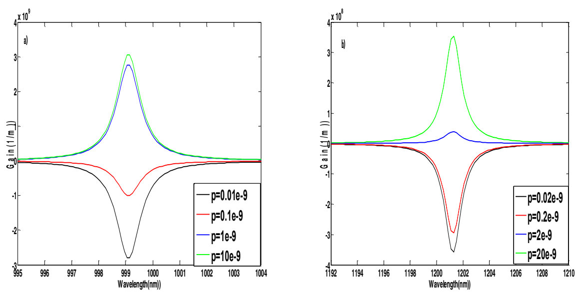
C. Calculate of net gain under optical pumping

Let us consider the effects of optical pumping in net gain [3]. In this case the quantum box is continuously pumped in order to increase the number of free carriers where the values of E_{fc} and E_{fv} will also be changed. We now can calculate again emission, absorption and net gain by using the new values of n and p [3]. Under the normal conditions (i.e. at room temperature), gain spectra is presented for different dimension of $Al_{0.24}Ga_{0.76}As/GaAs$ in Fig. 4. Here the pumping power range for 5×5×5nm is from 1 nW to 1 µW and for 10×10×10nm is 2nW to 2µW. Fig 5 shows gain spectra for different dimension of $In_{0.47}Ga_{0.53}As/InP$. Here the pumping power range for 5×5×5nm is from 10 pW to 10 nW and for 10×10×10nm is 20pW to 20 nW.



(a) (b)

Fig4. Gain spectra of a $Al_{0.24}Ga_{0.76}As/GaAs$ a) 5×5×5nm dimension b) 10×10×10nm dimension under pumping operation



(a) (b)

Fig5. Gain spectra of a $In_{0.47}Ga_{0.53}As/InP$ a) 5×5×5nm dimension b) 10×10×10nm dimension under pumping operation

III. Optical Propagation Modeling in Photonic Waveguide Based on Quantum Box Array

As previously seen, gain spectrum induced by the pump light peaks at the transition energies for first state electron-hole recombination and provides the ideal operating wavelength. The pump and signal lasers function in harmony to propagate electro-magnetic energy through an array of quantum dots, which is show in Fig. 6:

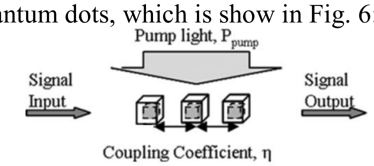


Fig.6.Shematic of array QD waveguide [4]

The signal light enters incident to one end of the waveguide, causing stimulated emission in the nanocrystal adjacent to the edge. With gain accumulated through each quantum dot, signal transmission along the waveguide will be amplified at each stage. The measure of how well the signal is transferred from QD to QD across the device is modeled with an intra-dot coupling coefficient [4]. To find the output intensity of a waveguide, an ABCD matrix approach may be used, that is shown in equation (3):

$$\begin{bmatrix} I_{out,+} \\ I_{out,-} \end{bmatrix} = M_{QD}.\left(M_{prop}.M_{QD}\right)^{N-1}\begin{bmatrix} I_{in,+} \\ I_{in,-} \end{bmatrix} \qquad (3)$$

where, M_{QD} is the matrix of the gain, G, and M_{prop} is the propagation matrix of the coupling efficiency, η. For an array of N QDs, the total intensity M_{total} is computed from the equation (4). Using the Fig.6 and varying the η from 0.1 to 0.9, we get the sketch of I_{out}/I_{in} as a function of the gain, which is demonstrated in Fig. 7.

$$M_{total} = M_{QD}.\left(M_{prop}.M_{QD}\right)^{N-1} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \qquad (4)$$

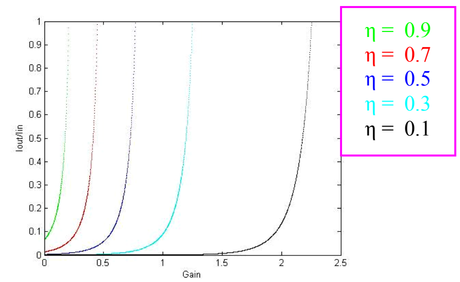


Fig 7.Output versus input intensity as a function of gain.

IV. Conclution

In this paper the effects of material type and size in quantum waveguide with and without optical pumping were considered. For the optical pumping case, the pumping energy was taken to be equal to the separation energy between the first state in the conduction band and the heavy hole first state in the valence band. The signal energy is taken to be equal to the separation between the ground states of conduction and valence bands. The wavelength rang for $Al_{0.24}Ga_{0.76}As/GaAs$ and $In_{0.47}Ga_{0.53}As/InP$ were considered to be 600-700nm and 990-1100nm respectively. Here, we noticed that the absorption rate is more than the emission and the net gain in contrast to the case of no pumping not only was not negative, but also increased considerably.

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