Comparative Analysis of Effective Band Gap of Different Material in QW and QD Laser

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Abstract- Quantum well and quantum dot structures are widely used as gain material for semiconductor lasers. In quantum well lasers, low band gap material is sandwiched between larger band-gap materials. Potential well for electrons and holes in a double hetero-structure (DH) depends on the material involved. A quantum dot laser is a semiconductor laser that uses quantum dots as the active laser medium in its light emitting region. Quantum confinement effect takes place if the thickness of the active layer or size of QD particles decreases up to nanometer size; this causes effective Eg to increase. Generally, smaller the size of the crystal, larger the band gap energy; the greater the difference in energy between highest valence band and lowest conduction band, more energy is needed to excite the dot, and the crystal returns to its ground state. Variation of Effective band gap in InAs QW laser is very high as compared to GaAs and InP quantum well lasers. At low d, variation of EgQW in InAs is more than what is there in GaAs and InP lasers. In medium Eg materials, variation of EgQW is very small. Similarly Variation of EgQD in InAs laser is very high as compared to GaAs and InP quantum dot lasers. In GaAs system the higher values of effective band gap are seen in QD laser for the whole range of diameter of the dot taken in our theoretical calculations. Also the range of variations in effective band gap is higher for QD laser. In InAs system, the higher values of effective band gap are seen in QD laser for the whole range of diameter of the dot taken in our theoretical calculations.

Keywords- Quantum well, quantum dot, quantum confinement, Double heterostructure, Energy band gap

I. INTRODUCTON

Quantum well and quantum dot structures are widely used as gain material for semiconductor lasers. In quantum well lasers, low band gap material is sandwiched between larger band-gap materials. Potential well for electrons and holes in a double hetero-structure (DH) depends on the material involved. A quantum dot laser is a semiconductor laser that uses quantum dots as the active laser medium in its light emitting region [1]. Quantum confinement effect takes place if the thickness of the active layer or size of QD particles decreases up to nanometer size; this causes effective E_g to increase. Generally, smaller the size of the crystal, larger the band gap energy; the greater the difference in energy between highest valence band and lowest conduction band, more energy is needed to excite the dot, and the crystal returns to its ground state. In addition to this, the main advantage with quantum dots is the ability to tune the size of the dots for many applications.

In the bulk semiconductor material (several times bigger than 10 nm), charge carriers can have a range of energies. These energies are so close together that they can be described as continuous (Figure 1). There is a certain forbidden range of energies called band gap. Almost all electrons naturally occupy the energy levels below the band gap (valence band) and only very few of them are in the conduction band (above the band gap).

They can jump to the conduction band when they get additional energy from outside (heat, radiation, etc.) and they leave a hole in the valence band. This electron-hole pair is called an exciton which is the true nature of a charged dot and has a lot of properties similar to the hydrogen atom [2]. From Figure 1, it is clear that ΔE_{nano} is greater than ΔE_{bulk}; this is due to the reduction in dimensions of the QD which increases the confinement energy in the dot. Confinement in quantum dots can also arise from electrostatic potentials generated by external electrodes, doping, strain or impurities [3]. The width of the quantum dot band gap depends on its size and chemical composition, making it easy to tune absorption and emission spectra, what is impossible for atoms, but desirable for optical properties [4].

II. EFFECTIVE BAND GAP IN QUANTUM WELL LASER

As the thickness of the active layer is made comparable to de-Broglie wavelength of electron, the energy levels in conduction band and valence band are discretized and effective band gap increases. The expression for E_g in QW laser has been calculated as

$$E_g^{QW}(eV) = E_g(eV) + \frac{\pi^2\hbar^2}{2d^2e}\left(\frac{1}{m_e^*} + \frac{1}{m_h^*}\right)eV \qquad \dots (1)$$

After substituting the values of constants for different semiconductor material like GaAs, InP and InAs in equation 1, we plot a graph between the effective band gap and the thickness of active layer shown by figure 2.

III. EFFECTIVE BAND GAP IN QUANTUM DOT LASER

The dependence of effective band gap on radius of quantum dot is given as

$$E_g^{QD} = E_g(bulk) + \frac{\hbar^2\pi^2}{2d^2}\left(\frac{1}{m_e^*} + \frac{1}{m_h^*}\right) - \frac{1.80e^2}{4\pi\varepsilon\varepsilon_0 r} \qquad \dots (2)$$

The variation of effective band gap E_g^{QD} with radius of the dot has been computed for three QD laser systems, which are reproduced below. The radius of quantum dot has been taken in nm. After substituting the values of constants for different semiconductor material like GaAs, InP and InAs in equation 2, we plot a graph between the effective band gap and the diameter of the dot (d =2r) shown by figure 3.

IV. EFFECTIVE BAND GAP VERSUS WELL THICKNESS/DIAMETER OF DOT FOR DIFFERENT MATERIAL SYSTEMS

The variation of effective band gap E_g^{QW} th the active layer thickness and variation of effective band gap E_g^{QD} with the diameter of dot has been computed taking the parameters of three different materials having small, medium and large band gaps. Figure 2 shows the variation of effective band gap with active layer thickness in quantum well laser for three different materials GaAs, InP and InAs. Figure 3 shows the variation of effective band gap with diameter of dot in quantum dot laser for three different materials GaAs, InP and InAs.

It is found that changes in E_g^{QW} in small E_g material are very high as compared to large E_g material, which can be clearly seen in Figure 2. Variation of E_g^{QW} in InAs laser is very high as compared to GaAs and InP quantum well lasers. At low energy, variation of E_g^{QW} in InAs is more than that in GaAs and InP active layers. In medium E_g materials, variation of E_g^{QW} is very small. From Figure 3 it is clear that the variation of E_g^{QD} in InAs laser is very high as compared to GaAs and InP quantum dot laser. At low energy, variation of E_g^{QD} in InAs is more than that in GaAs and InP active layers. In medium E_g materials, variation of E_g^{QD} is very small. Thus from Figures 2 and 3, we conclude that the nature of variation in effective band gap is similar in both quantum well and quantum dot lasers. But it is clearly seen from Figures 2 and 3 that the values of effective band gaps are much higher in case of QDs as compared to that of QWs of same thickness. This makes QD laser more suitable for device applications.

V. COMPARATIVE ANALYSIS EFFECTIVE BAND GAP IN QW AND QD LASERS

For GaAs and InAs material systems, effective band gap has been plotted against the well thickness/diameter of the quantum dot and a comparison has been made between the characteristics of QW and QD lasers in relation to the above parameter. Figure 4 shows the comparative behavior of effective band gap for QW and QD lasers in GaAs System. The higher values of effective band gap are seen in QD laser for the whole range of diameter of the dot taken in our theoretical calculations. Also the range of variations in effective band gap is higher for QD laser. Similarly Figure 5 shows the comparative behavior of effective band gap for QW and QD lasers in InAs System. The higher values of effective band gap are seen in QD laser for the whole range of diameter of the dot taken in our theoretical calculations. At lower values of diameter of the dot, relatively very high value of effective band gap is obtained for this system. Also the range of variations in effective band gap is higher for QD laser. It is also seen that the range of variation is larger in case of InAs than that in GaAs.

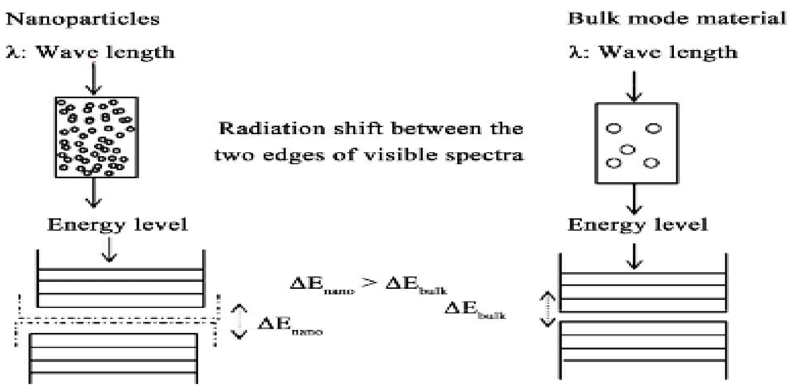

Figure 1: Quantum Confinement is Responsible for the Increase of Energy Difference between Energy States and Bandgap.[2]

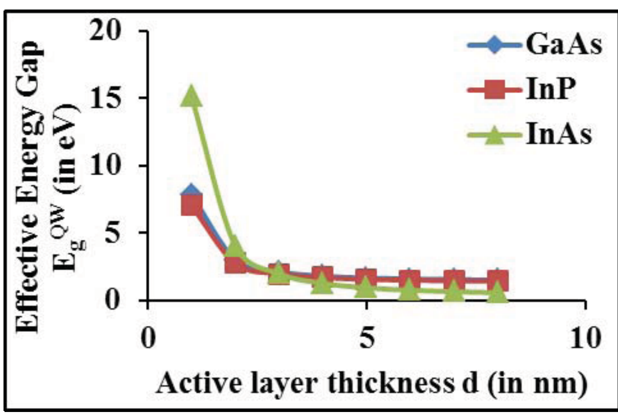

Figure 2: Variation of Effective Band Gap in QW laser System.

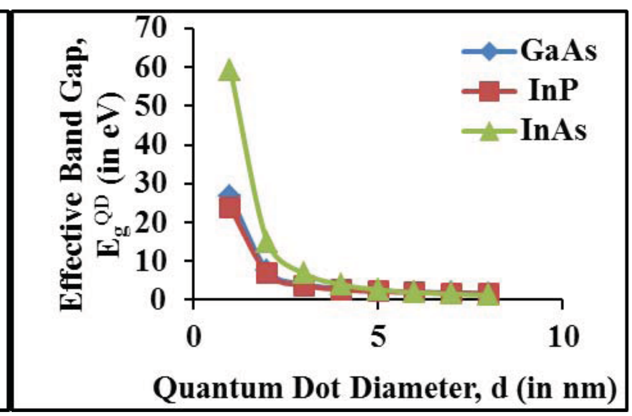

Figure 3: Variation of Effective Band Gap in QD laser System

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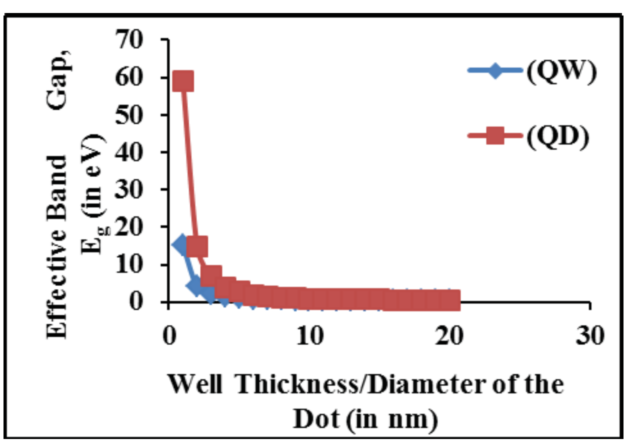

Figure 4: Variation of Effective Band Gap in GaAs Systems.

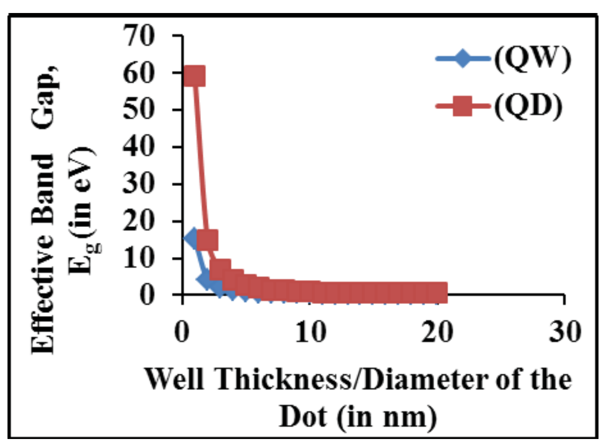

Figure 5: Variation of Effective Band Gap in InAs systems.

VI. RESULTS AND DISCUSSIONS

(i) Decreasing the thickness of the active layer in QW (and size of dot in QD) to nanometer range, quantum confinement effect takes place and effective band gaps increases in both the QW and QD lasers.

(ii) As thickness of active layer in quantum well increases, firstly the effective band gap decreases suddenly and after that it starts decreasing very slowly for all semiconductors and then becomes constant. In case of QDs, a sudden decrement in effective band gap occurs firstly, and after that it decreases slowly with diameter of the dot.

(iii) In both QW and QD lasers, the maximum variation in effective band gap is found in small band gap materials (InAs) as compared to large band gap materials (GaAs and InP).

(iv) Figure 2 shows the variation of effective band gap with active layer thickness in quantum well laser for three different materials GaAs, InP and InAs. It is found that changes in E_g^{QW} in small E_g material are very high as compared to large E_g material, which can be clearly seen in Figure 2. Variation of E_g^{QW} in InAs laser is very high as compared to GaAs and InP quantum well lasers. At low energy, variation of E_g^{QW} in InAs is more than that in GaAs and InP active layers. In medium E_g materials, variation of E_g^{QW} is very small.

(v) Figure 3 shows the variation of effective band gap with diameter of dot in quantum dot laser for three different materials GaAs, InP and InAs. From Figure 3 it is clear that the variation of E_g^{QD} in InAs laser is very high as compared to GaAs and InP quantum dot laser. At low energy, variation of E_g^{QD} in InAs is more than that in GaAs and InP active layers. In medium E_g materials, variation of E_g^{QD} is very small.

(vi) For GaAs and InAs material systems, effective band gap has been plotted against the well thickness/diameter of the quantum dot and a comparison has been made between the characteristics of QW and QD lasers in relation to the above parameter in Figures 4 and 5. The higher values of effective band gap are seen in QD laser for the whole range of diameter of the dot taken in our theoretical calculations. Also the range of variations in effective band gap is higher for QD laser. At lower values of diameter, relatively very high value of effective band gap is obtained for InAs system.

(vii) Good agreement is found between our predictions and experimental results.

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