Study of Multiple Quantum Wire Hg$_{0.8}$Cd$_{0.2}$Te/CdTe Laser

M H Jassam
Iraqi Ministry Education
mohammedhamad424@gmail.com

Abstract. The optoelectronic properties of Hg$_{0.8}$Cd$_{0.2}$Te/CdTe quantum wire laser are investigated, with emphasis on the effect of wire width (W) and barrier width (B) on the optical confinement factor ($\Gamma$), the optical threshold gain ($g_{th}$) and the effect number of well ($N_W$) on the confinement factor have been calculated. The laser operation system has been studied in the two cases; the number of well (2 and 3). It found that in our theoretical study, the values affect the work of a multiple laser system operating a number of well 2 was (W= 65nm, B = 40 nm), the value of optical confinement factor equals ($\Gamma$= 0.055) and the amount of optical threshold gain was ($g_{th}$ = 38 cm$^{-1}$). Further, the suitable values for multi quantum wire system is running a number of well 3 was (W= 42 nm, B = 60 nm), optical confinement factor equal to ($\Gamma$= 0.048) and the threshold gain ($g_{th}$ = 42 cm$^{-1}$). Theoretically, the principle of operation of a laser device depends on the resonator, the effective medium, and the stimulated emission of light radiation which is represented the important process in the work of device. It is found that the effect of optical confinement factor causes an increase in the reflectivity of laser beam in the cavity therefore decrease in the amount of optical threshold gain, noted that the amount of reflection was installed to study the change of other electronic characteristics of the multiple quantum wire.

Keywords: Mercury cadmium telluride, Confinement factor, Optical gain, Wire width, Barrier width.

1. Introduction

HgCdTe is still one of the key component of infrared sensing industry. The market demand as well as other competitive technologies make higher requirements for improving the HgCdTe heterostructure parameters [1]. The specific advantages of HgCdTe are the direct energy gap, ability to obtain both low and high carrier concentrations, high mobility of electrons and low dielectric constant. The extremely small change of lattice constant with quality layered and graded gap structures. HgCdTe can be used for detectors operated at various modes, and can be optimized for operation at the extremely wide range [2]. A number of equations have been developed to summarize the empirically measured relationship. One of these, developed by Hansen et al is given by the expression [3]:

$$E_g = -0.302 + 1.93x - 0.81x^2 + 5.35(1 - 2x)10^{-4} T$$

(1)

The intrinsic carrier concentration is given [4]:

$$n_i(T,x) = (5.585 - 3.82x + (1.753 \times 10^{-3})T - 1.364 \times 10^{-3}T \times x) 10^{14} \times E_g(T,x)^{0.75} \times T^{1.5} \times e^{-\frac{E_g(T,x) \times q}{2kT}}$$

(2)
where \( k \) is Boltzmann's constant, \( q \) is the elementary electric charge, \( T \) is the material temperature, \( x \) is the percentage of cadmium concentration, and \( E_g \) is the bandgap. The refractive index \( \gamma_r \) for material \( Hg_xCd_{1-x}Te \) can be calculated from the following formula [5]:

\[
\gamma_r = 4.427 - 3.617x + 2.055x^2 \quad (3)
\]

In 2012, the semiconductor laser reaches 50 years old. Improvement of the performance such as high speed modulation toward theoretical limit, advanced application of wavelength and polarization and utilization of photonic integration is expected. Exciting challenge will be continued for the next breakthrough in photonic device technology [6]. A heterojunction is a junction formed between two dissimilar semiconductors. For semiconductor – device applications, the difference in energy gap provides another degree of freedom that produces many interesting phenomena. Heterojunctions have been widely used in various device applications [7]. There are two types of heterostructure laser, Single heterojunction (SH) consists of p-type and n-type different semiconductor materials and band gap. In double heterojunction laser, a low band gap material which is sandwiched between two high band gap material [8]. When the photon energy is greater than the bandgap of the semiconductor material, the photon tremendous gets absorbed. This results in the formation of an electron-hole pair, in which an electron in the valence band is promoted to the conduction band [9]. Such a structure called quantum well (QW) laser. Figure 1-a, shows quantum well structure. with one active region which called single quantum well (SQW) laser and those with multiple active region are called multi quantum well (MQW) lasers as shown in Figure 1-b [10]. In recent years, lasers have been fabricated with very thin active layers thickness of around. The occupation states available for confined electrons and holes are no longer continuous but discrete [11].

There has been an intensive research effort on CdTe and heterojunction- based passivation over the last 10 years. CdTe passivation typically results in good interface properties, low fixed charge, and low interface trap densities [12]. The electromagnetic energy moves back and forth between the two components of the resonator and also through the Active Medium. This results in the amplification of the electromagnetic waves through a process known as Stimulated Emission. One of the Resonator components is partially transmitting allowing a part of the electromagnetic oscillating waves to escape in the form of Laser output beam. The basic components are shown in the Figure 2 [13].
Figure 2: Scheme showing basic components of a laser system.

2. Theoretical part

The confinement factor ($\Gamma$) is defined as the ratio of the modal gain to the gain in the active medium at the wavelength of interest [14].

$$\Gamma = \frac{\text{modal gain}}{\text{gain}} = \frac{\int_{-\infty}^{\infty} g(x) |E(x)|^2 \, dx}{\int_{-\infty}^{\infty} |E(x)|^2 \, dx}$$

for a quantum well with width $L_x$, the confinement factor reduces to

$$\Gamma = \frac{\int_{-\frac{L_x}{2}}^{\frac{L_x}{2}} |E(x)|^2 \, dx}{\int_{-\infty}^{\infty} |E(x)|^2 \, dx} \quad (4)$$

The confinement factor, is the fraction of the electromagnetic energy of the guided mode that exists within the active layer, is an important parameter representing the extent to the active layer for a fundamental mode approximately, given [10].

$$D = 2\pi \left( \frac{w}{\lambda} \right) \cdot \left( n_a^2 - n_c^2 \right)^{1/2} \quad (5)$$

$$\Gamma_{QW} = \frac{D^2}{D^2 + 2} \quad \text{for (SQW)}$$

$$\Gamma_{QWR} = \Gamma_{QW} \cdot N_w \cdot F \quad \text{for (MQWR)} \quad (7)$$

$$F = \frac{w}{A} \quad (8)$$

where $n_a$ is the refractive indices of the active layer, $n_c$ is the refractive indices of the cladding layer, $w$ is the wire width, and (D) is the normalized waveguide thickness of the active region. ($\Gamma_{QW}$), ($\Gamma_{QWR}$) is the optical confinement factor of quantum well and quantum wire respectively. $N_w$ is number of well., $F$ is the in plane space filling factor of the active region, $A$ is a period of quantum wire, $F=1$ for QW.
Figure 3. Schematic structure of the Bragg fiber: core radius; \( n \), refractive Index of core; \( B \), barrier and \( w \), well width; \( \Lambda = B+W \), period in the cladding [15].

Figure 4. The distribution of light intensity.

Laser operation begins with spontaneous emission creating a small field with broad bandwidth. We denote the initial complex amplitude at frequency \( \omega \) as \( E^0(\omega) \). During one round trip, the field is exponentially amplified in the active medium, reflected by both mirrors, and it acquires a phase shift due to propagation in air and in the active medium. Mathematically, after one round trip the field component is

\[
E_1(\omega) = R_1R_2E^0(\omega)e^{(g-\alpha)L}e^{-i\delta}
\]  

(9)

here \( \delta = \) is the total phase shift per round trip. For the spontaneous emission seed to be amplified, the gain must be sufficiently high to overcome losses arising from scattering in the active medium as well as mirror reflections. In particular, we require \( |E_1(\omega)| > |E^0(\omega)| \). This condition is achieved when \( R_1R_2 e^{(g-\alpha)L} > 1 \) solving for the gain coefficient yields [16].

\[
g > g_{th} = \alpha - \frac{1}{L} R_1 R_2
\]

(10)

The local gain at threshold can be obtained from the following relation [10].
\[
g_{th} = \frac{1}{\Gamma_{QW}} \left( \alpha_{wC} + \frac{1}{L} \ln \frac{1}{R} \right)
\] (11)

3. Result and discussion

The semiconductor material has a high refractive index value range between 3-4. In order to obtain various parameters for the \( H_{g_{1-x}} Cd_{x} \)Te material by using the following Table 1.

| Constant                  | Values | Unit   |
|---------------------------|--------|--------|
| \text{wave length} \( \lambda \) | 2200   | nm     |
| \text{Energy gap} \( E_g \) for \( x=0.2 \) | 0.1546 | ev     |
| \text{Energy gap} \( E_g \) for \( x=0.6 \) | 0.7120 | ev     |
| \text{Refractive index} \( \gamma_a \) for \( x=0.2 \) | 3.7858 |        |
| \text{Refractive index} \( \gamma_s \) for \( x=0.6 \) | 2.99   |        |
| \text{Cavity Length}     | 2      | mm     |
| \text{Reflectivity}      | 0.3    | \( cm^{-1} \) |

Table 1. properties of \( H_{g_{1-x}} Cd_{x} \)Te fraction.

The band gap energy can be calculated by using equation (1) so that the relationship is plotted between energy gap and Mercury Cadmium Telliride \( H_{g_{1-x}} Cd_{x} \)Te mole fraction. These results drawn as shown in Figure 5 at room temperature 300 k and 85 k.

![Figure 5](image)

Figure 5. Energy gap as a function of Mercury Cadmium Telliride \( H_{g_{1-x}} Cd_{x} \)Te composition.

The refractive index is calculated according to equation (3). It has been found to have a high value of approximation 4. Figure 6 shows the graphical relationship between the refractive index of \( H_{g_{1-x}} Cd_{x} \)Te as a function of mole fraction \( x \). In addition to, through the two Figures 4 and 5 that have been studying the main properties of the material and its effect in this study and the work of the device. The magnitude of resistivity proportional directly with the refractive of index, that means when the refractive of index is high, the resistivity also be high. Although the amount of wavelength
resulting from the operation of the device and determines the range of its work, if it is in the infrared or visible light.

Figure 6. The refractive of index as a function of \( (Hg_{1-x}Cd_xTe) \) fraction.

The parameters affecting the amount of a confinement factor (\( \Gamma \)) are the wire width and barrier width are shown in Figure 7. From equation (5), equation (6), and equation (7), the effect of barrier width on the confinement factor was calculated. For different values of wire width (20, 30, 42, 55, 65, 70, 75) nm, and number of well equal to 2, the confinement factor (\( \Gamma \)) is drawn as a function of barrier width (B). In Figure 7, for wire width less than (\( W = 65 \) nm), the confinement factor (\( \Gamma \)) is increasing slightly with the increase of the barrier width (B). But for wire width of (\( W = 65 \) nm), the confinement factor is approximately constant at (\( \Gamma = 0.055 \)) for the same barrier width range. In addition, when wire width > 65 nm, the confinement factor (\( \Gamma \)) is decreases with the increase of the barrier width (B). We choose wire width 65 nm. At the same time, in Figure 8 we will repeat the calculations by using the same parameters in the program to calculate the confinement factor (\( \Gamma \)) and the value of wire width (20, 30, 42, 55, 65, 70, 75) nm, but using number of well 3. We found that at value less than of (\( W = 42 \) nm), the confinement factor also increasing and at value more than 43 nm the confinement factor decreases but in case (\( W = 42 \) nm) the line is constant, that means the confinement factor is nearly constant equal to (\( \Gamma = 0.048 \)). We choose wire width \( W = 42 \) nm.

Figure 7. The optical confinement factor (\( \Gamma \)) as a function of barrier width (B) for \( Hg_{1-x}Cd_xTe / CdTe \) QWR structure of different wire width (\( W \)), and number of well 2.
Figure 8. The optical confinement factor ($\Gamma$) as a function of barrier width (B) for $Hg_{1-x}Cd_x Te / CdTe$ MQWR structure of different wire width (W), and number of well 3.

From Figure 9, the barrier width (B) was calculated by the graphical relation between the confinement factor of multiple quantum wire with barrier width at the number of well 2, and wire width $W = 65$ nm. We found the point of the intersection with the x-axis, which represents the presentation of the amount of the column-based confinement factor of (0.055), with a determination of the amount of the barrier width equal to $B = 40$ nm. At the same way, we found the barrier width by using the value of confinement factor ($\Gamma = 0.048$), the number of well 3, where drawn line curved to the value of wire width ($W= 42$ nm). We found the magnitude of barrier equal to ($B = 60$ nm).

Figure 9. The optical confinement factor ($\Gamma$) as a function of barrier width (B) for $Hg_{1-x}Cd_x Te / CdTe$. $N_w = 2$, $N_w = 3$.

From Figure 9, we conclude that with increasing the barrier width decreases the confinement factor ($\Gamma$), that means the proportional between them is inverse.

From Figure 10, we observed that the best values for the device's work are to the barrier width between (9-100) nm, where the number of well equal to (2) and the best value when $B= 40$ nm.
Figure 10. The optical confinement factor ($\Gamma$) as a function of wire width (W) for $Hg_{1-x}Cd_xTe/CdTe$ of Barrier (40, 100) nm, and number of well 2.

On the other hand, Figure 11 we observed that the best values for the device's work are to the barrier width between (1-130) nm, where the number of wells equal to 3 and the best value when B=60 nm.

Figure 11. The optical confinement factor ($\Gamma$) as a function of wire width (W) for $Hg_{1-x}Cd_xTe/CdTe$ of Barrier width (60, 130) nm, and number of well 3.

We noticed the less value of the confinement factor through the theoretical schemes values of it in the two cases number of well 2, and 3, for barrier width 1 nm. This is all clear in Figure 12.
Figure 12. The optical confinement factor ($\Gamma$) as function of wire width (W) for the two cases number of well 2 and 3 $Hg_{1-x}Cd_x Te/CdTe$ in, $B=1$ nm.

Also it studied another property of the main properties of quantum wire in the Nano scale. The optical threshold gain ($g_{th}$) can be calculated by equation. 7 and equation. 11. Figure's 13 and 14 have explained the relation between the threshold gain and the optical confinement factor. As the increase in the wire width caused an increase in the confinement factor and the increase in the confinement factor caused a decrease in the threshold gain, the proportionality is inverse according to Figures 13 and 14. When the barrier width is 60 nm, the amount of threshold gain for a system that has a number of well (2) is equal to ($g_{th} = 38 \text{ cm}^{-1}$). While when the system includes a number of well (3), threshold gain is equal to ($g_{th} = 42 \text{ cm}^{-1}$).

Figure 13. The threshold gain $g_{th}$ as a function of the optical confinement factor ($\Gamma$) for number of well 2.
The threshold gain $g_{th}$ as a function of the optical confinement factor ($\Gamma$) for number of well 3.

The increasing of the wire width causes the increase of the optical confinement factor, and the decrease of the threshold gain. As well as an increase in the reflection is done this is because the reverse proportion between threshold gain and reflectivity that explained in Figure 15. So the proportional between the reflectivity and the optical confinement factor is directly.

References

[1] Madejczyk, A P, Piotrowski A, Klos K, Gawron W, Rogalski A, Rutkowski J and Mroz W (2009) Surface Smoothness Improvement of HgCdTe Layers Grown By MOCVD Bulletin of the polish Academy of sciences technical sciences Vol. 57 No. 2.

[2] Băjenescu T M I (2018) Infrared detectors.

[3] Anne M Itsuno Ph.D. thesis (2012) Bandgap-Engineered HgCdTe Infrared Detector Structures for Reduced Cooling Requirements University of Michigan.

[4] Pierre-Yves Emelie Ph.D. thesis (2009) HgCdTe Auger-Suppressed Infrared Detectors Under Non-Equilibrium Operation The University of Michigan.

[5] Wedian Kadhoum Abad Al-zubad y thesis (2016) Theoretical Comparison between HgCdTe
and AlGaAs Heterostructure Quantum Well Laser Systems University of Baghdad.

[6] Katsuyama T (2009) Development of Semiconductor laser for optical communication SEI. Technical Review Num. 69 pp.13-20.

[7] Sze S M and Kwok K Ng (2007 ) Physics Of Semiconductor Devices 3rd edition John Wiley & Sons Inc.

[8] Hill J (2005) Laser Diode Technology and Application Portland State University Physics 464.

[9] Perera D, Pattison J and Wijewarnasuriya P (2013) Minimizing Reflectivity by Etching Microstructures in Mercury Cadmium Telluride (HgCdTe) Sensors and Electron Devices Directorate ARL delphi MD 20783-1197.

[10] Pospiech M and Sha Liu (2004) Laser Diodes an Introduction University Of Hannover Germany 1-25.

[11] Connelly M J ( 2006) Semiconductor Optical Amplifiers World Scientific Publishing Co. Pte. Ltd London.

[12] Jing Zhang Ph.D. thesis (2015) A Fundamental Study of Interface Effects in HgCdTe Materials and Devices University of Western Australia p-22.

[13] Dr Asloob A Mudassar (2015) Laser Physics First edition. Pteas pages 1-22.

[14] Van B, and Zeghbroeck (2011) Principles of Semiconductor Devices Ch.4 (p-n) Junction p (1-17).

[15] Sakai J I and Jan (2007) Optical Power Confinement Factor a Bragg Fiber Formulation and general properties Japan Vol.24 No.1 E. Opt. Am. B 9-19.

[16] Dr. Miro Erkintalo (2017) Physics 325- Optics and Laser Physics New Zealand The University of Auckland.