Chapter 5
Semiconductor Laser

5.0 Introduction

Laser is an acronym for light amplification by stimulated emission of radiation. Albert Einstein in 1917 showed that the process of stimulated emission must exist but it was not until 1960 that TH Maiman first achieved laser at optical frequency in solid state ruby. Semiconductor laser is similar to the solid state laser like the ruby laser and helium-neon gas laser. The emitted radiation is highly monochromatic and produces a highly directional beam of light. However, the semiconductor laser differs from other lasers because it is small in 0.1mm long and easily modulated at high frequencies simply by modulating the biasing current. Because of its uniqueness, semiconductor laser is one of the most important light sources for optical-fiber communication. It can be used in many other applications like scientific research, communication, holography, medicine, military, optical video recording, optical reading, high-speed laser printing etc. The analysis of physics of laser is quite difficult and we summarize with the simplified version here. The application of laser although with a slow start in the 1960s but now very often new applications are found such as those mentioned earlier in the text.

5.1 Emission and Absorption of Radiation

As mentioned in earlier Chapter, when an electron in an atom undergoes transition between two energy states or levels, it either absorbs or emits photon. When the electron transits from lower energy level to higher energy level, it absorbs photon. When an electron transits from higher energy level to lower energy level, it releases photon. The frequency $\nu$ of the wave follows equation (5.1).

$$\nu = \frac{\Delta E}{h}$$  (5.1)

$\Delta E$ is the energy difference between two energy levels of a atomic system as shown in Fig. 5.1. From the figure, it shows that the different energy level $\Delta E$ is equal to $E_2 - E_1$. 
One can see that the transition of electron between two energy levels can be in random manner. Spontaneous absorption is shown in Fig. 5.2(a), in which the presence of photon energy ($E_2 - E_1$), the electron is transited to higher energy level. Figure 5.2(b) shows spontaneous emission, which electrons release photon of energy ($E_2 - E_1$).
Stimulated emission is shown in Fig. 5.2(c). With the absorption of photon of having same energy of the band-gap, electron-hole pairs are created. The electrons are considered as stimulated and transited from higher energy layer to lower energy level, which is termed as stimulated emission of radiation. Under normal circumstances, the simulated process is not observed because the probability of spontaneous process occurring is much higher.

The average time for an electron in the excited state is $\tau_{21}$. The probability of a particular electron will undergo spontaneous emission within time interval $dt$ is given by equation (5.2).

$$A_{21}dt = dt/\tau_{21}$$ (5.2)

$A_{21}$ is the spontaneous transition rate. Owing to spontaneous radiation from any atom is emitted randomly, the radiation emitted by large number of atoms will clearly be incoherent. In contrast, the stimulated emission results in coherent radiation. The stimulated photons have identical frequencies, are in phase, have same state of polarization, and travel in the same direction. This means that with stimulated emission the amplitude of an incident wave can grow as it passes through a collection of excited atoms in what is a clear shown an amplification process. As the absorption transition, in common with stimulated emission can only be occurred in the presence of photon of appropriate energy, which is often referred as stimulated absorption.

5.2 Material for Semiconductor Laser

All semiconductor materials for making laser have direct band-gap. This is expected because the momentum is conserved and no phonon is expected. At present the wavelength of laser emission cover the range from 0.3 to 30µm. Gallium arsenide was the first material to emit laser radiation and its related III-V compound alloy are the most extensively studied and developed. The three most important III-V compound alloy systems are $\text{Ga}_x\text{In}_{1-x}\text{As}_{1-y}\text{P}_y$, $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{Sb}_{1-y}$, and $\text{Al}_x\text{Ga}_{1-x}\text{As}_y\text{Sb}_{1-y}$. Figure 5.3 shows the energy band-gap and lattice constant for III-V compound alloy solid alloy system. In order to achieve heterojunction structure with negligible interface trapping, the lattice between two semiconductors must be matched closely. If we use GaAs that has lattice constant 5.6533 Å as the substrate, the ternary compound $\text{Al}_x\text{Ga}_{1-x}\text{As}$ can have lattice mismatch of about 0.1%. Similarly, with InP ($a = 5.8687$ Å) as substrate, the quaternary compound $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ also have nearly perfect lattice match as indicated in Fig. 5.3.
Materials is required to dope in such it becomes a degenerate material. Otherwise, it would not be able to achieve population inversion. The doping is done in such the Fermi level is situated in the conduction band for the \( n \)-type region and Fermi level is situated in the valence for the \( p \)-type region. Figure 5.4 illustrates the position Fermi level for a degenerate GaAs material.

Figure 5.4: The position of Fermi level is in the conduction and valence band of degenerate semiconductor
5.3 Optical Cavity

We have briefly mentioned that the condition necessary to produce laser action is population inversion and the type of semiconductor needed. Photons released by stimulated emission are likely to cause further stimulation as long as there is population inversion. This phenomenon is called \textit{optical gain}. The gain is obtained in a single travel of an optical wave down a laser cavity is small. To increase gain, multiple passes of wave must occur. This can be achieved using mirror placed at either end of the cavity. For semiconductor, the cleaved ends of the crystal forming the device can act as the mirror. For GaAs device, the cleaved end the along (110) plane created two parallel identical mirrors. Sometimes the back mirror is metallized to enhance the reflectivity. The reflectivity $R$ at each end of the mirror follows equation (5.3).

\[
R = \left( \frac{n-1}{n+1} \right)^2
\]  

(5.3)

$n$ is the refractive index of the semiconductor corresponding to the wavelength $\lambda$. It is also noted that the refractive index is depended on the mole fraction of the semiconductor material. For examples, the refractive index of the Al$_x$Ga$_{1-x}$As is 3.2 for mole fraction $x = 0.6$ and 3.4 for mole fraction $x = 0.3$.

The cavity such as Fabry-Perot cavity normally used in semiconductor laser design has an integral number of half-wavelength between two end planes that will reinforce and ensure the coherent light will be reflected back and forth within the cavity. Therefore, for stimulated emission, the length $L$ of the cavity must satisfy the equation (5.4) which defines the length of resonant cavity $L$.

\[
L = \frac{m\lambda}{2n} \text{ or } m\lambda = 2nL
\]

(5.4)

where $m$ is integral, $n$ is the refractive index of semiconductor material, and $L$ is the length of resonant cavity.

Based on equation (5.4) $m\lambda = 2nL$, obviously many wavelength values can satisfy the condition as shown in Fig. 5.5(a). However, only those waves within the spontaneous emission spectrum will be produced as shown in Fig. 5.5(b). In addition, optical losses in the path traveled by wave mean that only the strongest lines will survive, leading to a set of lasting modes as shown Fig. 5.5(c). Thus, the separation $\Delta \lambda$ between the allowed modes in the longitudinal direction is
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difference in the wavelength corresponding to \( m \) and \( m+1 \). Differentiating equation (5.4) with respect to wavelength means that

\[
\Delta \lambda = \frac{\lambda^2 \Delta m}{2nL[1-(\lambda/n)(dn/d\lambda)]}
\]  

(5.5)

Since \( dn/d\lambda \) is very small, therefore, a good approximation of mode spacing of \( \Delta \lambda \) is given by equation (5.6).

\[
|\Delta \lambda| \approx \frac{\lambda^2}{2nL}
\]  

(5.6)

Figure 5.5: (a) resonant mode of laser cavity (b) Spontaneous emission spectrum and (c) optical gain wavelengths

5.4 Population Inversion at Junction

If a \( pn \) junction is formed from degenerate semiconductor material, its energy band diagram under forward bias is shown in Fig. 5.6. If the bias voltage is large enough, electrons and holes are injected across the transition region in considerable concentration. As the electrons or holes injected across the junction, they will diffuse exponentially into the bulk. Thus, there exists a quasi Fermi level at the bulk. The region about the junction is far from being depleted of carriers. This region contains a large concentration of electrons within the conduction band and a large concentration of holes within the valence band. If
these population densities are high enough, a condition of population inversion would be resulted.

![Energy band diagram of a degenerate pn junction](image)

**Figure 5.6:** Energy band diagram of a degenerate pn junction

The closer view of the depletion region of the pn junction, there exists quasi Fermi levels $F_n$ and $F_p$, which are shown in Fig. 5.6. Population inversion can only occur for quasi Fermi level difference ($F_n - F_p$) greater than $(E_C - E_V) = E_G$. Thus, the minimum energy requirement for band-to-band transitions to achieve population inversion of producing photon with energy $h\nu = E_C - E_V$ is

$$(E_n - F_p) > h\nu \quad (5.7)$$

When the quasi level $F_n$ and $F_p$ lie within their respective band, stimulated emission can dominate over a range of transitions, from $h\nu = (F_n - F_p)$ to $h\nu = E_G$.

Figure 5.7 shows the structure of double heterojunction structure laser. It has a larger concentration of hole and electron in the active region of thickness $d$. Indeed, it can be viewed as hole and electron are being trapped. This structure increases the chance radiative recombination that complied with population inversion. This structure has higher refractive index in the active region of thickness $d$ and has a better confinement of light.

The homojunction structure such as GaAs that has its energy band diagram shown in Fig. 5.6 has lesser concentration of hole and electron. Thus, it requires higher current density to achieve population inversion. Moreover, due to such characteristic, the refractive index in the depletion is low. The result is less confinement of laser produced. Consequently, the density of light is lower. The refractive index of the homojunction changes about 0.1 to 1% in the depletion
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region, whereas for double-heterojunction, the change is about 5.0%. Thus, it has better wave confinement because the wave confinement factor $\Gamma$ is higher that follows equation (5.8).

$$\Gamma \equiv 1 - \exp(-C\Delta n)$$  \hspace{1cm} (5.8)

d is the thickness of the active layer, C is the constant, and $\Delta n$ is the change in refractive index. It is clearly shown the larger change of refractive index $\Delta n$ and d have higher confinement factor $\Gamma$.

Figure 5.7: A double-heterojunction laser. The refractive index of the d region has higher value than its corresponding homojunction laser and the confinement of light is of higher density.
5.5 Basic Structure of Semiconductor Laser

Figure 5.8 shows three laser structures. The first structure is a basic $pn$ junction laser called a homojunction laser shown in Fig. 5.8(a) because it has the same semiconductor material such as GaAs. A pair of parallel plane or facets are cleaved or polished perpendicular to the <110> axis. Under appropriate biasing condition, laser light will be emitted from these planes (only the front emission is shown). The two remain sides of the diode are roughened to eliminate lasing in the direction other than the main ones. This structure is called *Fabry-Perot cavity* with typical length cavity $L$ of about 300µm. This type of cavity is extensively used in modern semiconductor laser.

![Figure 5.8: Semiconductor laser structure in Fabry-Perot cavity configuration (a) Homojunction laser, (b) double-heterojunction laser(DH), and (c) stripe-geometry double-heterojunction laser](image.png)
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Figure 5.8(b) shows the double heterojunction structure laser, which has a thin layer of semiconductor such as GaAs sandwiched between layers of a different semiconductor such as Al$_x$Ga$_{1-x}$As. The homojunction and double heterojunction lasers are broad-area laser because the entire area along the junction plane can emit radiation. Figure 5.8(c) shows the double-heterojunction laser with strip geometry. The strip width $S$ is typically 5-30µm. The advantages of the strip geometry are reduced operating current, elimination of multiple-emission area along the junction, and improved reliability that is result of removing most of the junction perimeter.

5.6 Threshold Current Density

One of the important parameters for lasing is the threshold current density $J_{th}$. The current density must attain the minimum value before lasing occurs. Figure 5.9 shows the threshold current density of the homojunction and double heterojunction structure lasers. As temperature increases, the threshold current increases but it is much slower for double heterojunction structure laser. Similar observation is noticed for heterojunction-structure laser, the threshold current density is lower than the homojunction-structure laser type. Because of low threshold current density value for double heterojunction DH laser at 300K, DH laser can continuously operate at room temperature. This characteristic has led to the increased use of semiconductor laser, especially in optical-fiber communication systems.

![Threshold current density versus temperature for homojunction and heterojunction structure laser](image)

**Figure 5.9:** Threshold current density versus temperature for homojunction and heterojunction structure laser

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In a semiconductor laser, the gain $g$, the incremental optical energy flux per unit length depends on the current density. The gain $g$ can be expressed as a function of a nominal current density $J_{\text{nom}}$, which is defined for quantum efficiency (i.e. the number of carriers generated per photon) as the current density required to uniformly excite 1µm thick of an active layer. The actual current density is given by

$$J(A/cm^2) = \frac{J_{\text{nom}}d}{\eta}$$

(5.9)

d is the thickness of active layer in µm. Figure 5.10 shows the calculated gain for the typical GaAs DH laser. The gain increases linearly with $J_{\text{nom}}$ for $50 \leq g \leq 400 \text{cm}^{-1}$. The relationship follows equation (5.10).

$$g = \left(\frac{g_0}{J_0}\right)(J_{\text{nom}} - J_0)$$

(5.10)

g_0/J_0 = 5 \times 10^2 \text{cm-µm/A} \text{ and } J_0 = 4.5 \times 10^3 \text{A/cm-µm}.

![Figure 5.10: Variation of gain coefficient versus nominal current density. Dash line represents a linear dependence](image)

5.6.1 Temperature Effect of Threshold Current

The temperature dependence of output power of laser versus its current for continuous wave stripe geometry $\text{Al}_x\text{Ga}_{1-x}\text{As-GaAs}$ double heterojunction laser is shown in Fig. 5.11.
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Figure 5.11: Temperature dependence of output power versus current of a continuous wave Al$_{x}$Ga$_{1-x}$As-GaAs DH laser

Figure 5.12 shows the threshold current $I_{th}$ versus the temperature for an continuous wave Al$_{x}$Ga$_{1-x}$As-GaAs DH laser.

The threshold current increases with temperature based on equation (5.11), which is

$$I_{th} \sim \exp\left(\frac{T}{T_0}\right)$$

(5.11)

where $T$ is the temperature in $^0$C and $T_0$ is equal to $110^0$C for laser.
5.6.2 Modulation Frequency and Longitudinal Modes

For optical fiber communications, the optical source must be able to be modulated at high frequencies. Unlike LED, whose output power decreases with increasing modulation bandwidth, the output power of typical GaAs or InGaAsP remains constant well into GHz range. For GaInAs-AlGaAs DH laser at the current above the threshold value, many emission lines exist that are approximately evenly spaced with a separation of $\Delta \lambda$ of approximately a few $\AA$ following equation (5.5). Owing to longitudinal modes, the stripe geometry laser is not spectrally pure light source because there is a number of light traveling in optical fiber causing pulse spread.

5.7 Quantum-Well Laser

The structure of quantum-well QW laser shown in Fig. 5.13 is similar to the DH laser except the thickness of the active layer in a QW laser is very small typically about 10-20nm sandwiched between two large band-gap AlGaAs. It can emit laser with 900nm wavelength. The length $L_y$ is comparable to de Broglie wavelength and the carriers are confined in a finite potential well in y-direction. The energies of electron and hole are separated into confinement components in the y-direction and two unconfined in the x- and z direction. According Schrödinger's wave equation with the boundary conditions applied to the quantum well, the energy confinement component is defined as

$$E(n, k_x, k_y) = E_n + \frac{\hbar^2}{2m^*_n} (k_x^2 + k_y^2)$$

(5.12)

where $E_n$ is $n^{th}$ eigenvalue of the confined particle, $m^*_n$ is the effective mass, and $k_x$ and $k_y$ are the wave number in the x- and y-direction respectively. Figure 5.13(a) shows the energy level of quantum well. The value of $E_n$ are shown as $E_1$, $E_2$, $E_3$ for electrons, $E_{hh1}$, $E_{hh2}$, $E_{hh3}$ for heavy hole, and $E_{lh1}$, $E_{lh2}$ for light holes. The usual parabolic forms for the conduction and valence band density of states have been replaced by a ‘staircase’ representation of discrete levels as shown in Fig. 5.13(b). Each level corresponding to a constant density of states per unit area given by equation (5.13).

$$\frac{dN}{dE} = \frac{m^*}{\pi \hbar^2}$$

(5.13)
Since the density of state is stair case form and constant rather than continuous type for the case of conventional type of 3-dimensional semiconductor. This group of electron of nearly same energy can combine with a group of hole of near same energy. For an example, the level E$_1$ in conduction band combines with the level E$_{hh1}$ in the valence band. This makes QW laser much better performance like reduction in threshold current, high output power, and high speed as compared with conventional DH laser. QW laser makes from GaAs/AlGaAs material has threshold current density as low as 65A/cm$^2$ and sub-milliampere threshold current. The laser operates at emission wavelength around 0.9µm.

For long wavelength operation, GaInAs/GaInAsP multiple-quantum-well MQW laser with wavelength 1.3µm and 1.5µm regions have been developed. Figure 5.14(a) shows a schematic diagram of separate-confinement-heterostructure SCH MQW laser where four QWs of GaInAs with GaInAsP barrier layers are sandwiched between the InP cladding layers to form a waveguide with step index change. These alloy compositions are chosen so that they are lattice matched with the InP substrate. The active region is composed of four 8nm thick, undoped GaInAs QWs with E$_G$ = 0.75eV separated by 30nm thick undoped GaInAsP layers with E$_G$ = 0.95eV. Figure 5.13(b) shows the corresponding energy band diagram of the active region. The $n$- and $p$-cladding InP layers are doped with sulfur (10$^{18}$ cm$^{-3}$) and zinc (10$^{17}$ cm$^{-3}$) respectively.
A graded-index SCH (GRIN-SCH) shown in Fig. 5.14(c), in which a GRIN of waveguide is accomplished by several small stepwise increases of band-gap energies of multiple cladding layers. The CRIN-SCH structure confines both the carriers and the optical field more effectively than the SCH structure and consequently leads to an even lower-threshold current density. With MQW structure, a variety of advanced lasers and photonic integrated circuits becomes possible for future system applications.

**Figure 5.14:** GaInAs/GaInAsP multiple-quantum well laser structure

### Exercises

5.2. Describe the conditions needed to design semiconductor laser in terms of type and semiconductor and doping concentration requirement.
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5.3. Calculate the reflectivity of GaAs semiconductor that has refractive index 3.6.

5.3. Calculate the mode spacing for a typical GaAs laser with wavelength 940nm and \( L = 300\mu m \).

5.4. A typical AlGaAs laser diode has a cavity length of 300\( \mu m \) and frequency of 800nm. How many wavelength will fit into it cavity?

5.5. Calculate the temperature at which the room temperature value of the threshold current doubles for the semiconductor.