Lecture 17: Solid state semiconductor LASERs

Contents

1 Introduction

Light emitting diodes and solid state semiconductor lasers work on the same principle of carrier recombination producing electromagnetic radiation in direct band gap semiconductors. In a LED, the emission process is spontaneous, while in a laser, it is stimulated. LASER is an acronym for **l**ight **e**mission by **s**timulated **e**mission of **r**adiation. There are a large number of laser materials and systems. There are gas based lasers, e.g. He-Ne lasers, and solid state non-semiconducting lasers like ruby lasers. A comprehensive list of commercial laser lines and their emission wavelengths is plotted in figure 1.

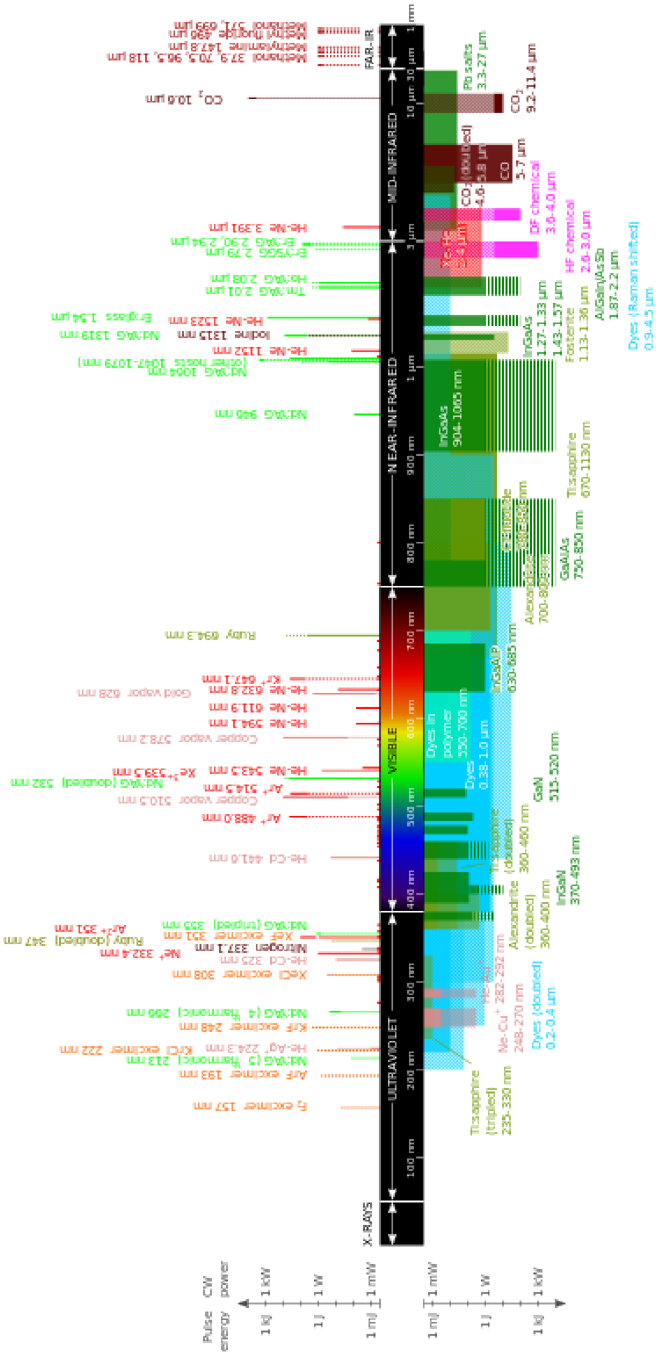

Figure 1: A comprehensive list of commercial laser lines. Refer *http://en.wikipedia.org/wiki/Laser* for a larger picture.

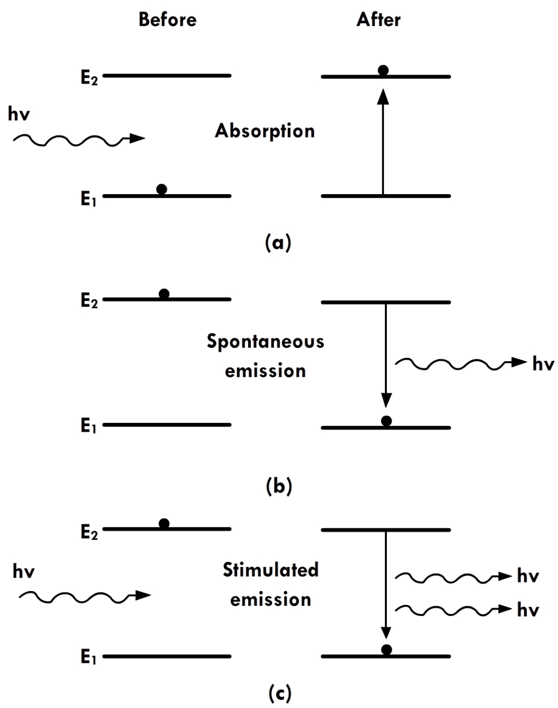

Figure 2: Light (a) absorption, (b) spontaneous, and (c) stimulated emission. Spontaneous emission is used in LEDs while stimulated emission is needed for lasers. In stimulated emission the transition is initiated by incoming radiation and the emitted light is in phase with the incident light. Spontaneous and stimulated emission are competing processes. Adapted from *Physics of semiconductor devices - S.M. Sze.*

Lasers are highly *monochromatic*, i.e. the line width is very small. They are also *spatially and temporally coherent*. The main criterion for laser action is *population inversion* i.e. there must be more number of occupied excited states than ground states. Incident optical radiation causes transition from the excited state to the ground state, leading to stimulated emission. The photon emitted is in phase with the incident radiation. Spontaneous and stimulated emission are competing processes, compared in figure 2.

2 Semiconductor lasers

While there are a number of different laser systems, semiconductor lasers have some unique characteristics.

1. In semiconductors, transitions are between energy bands while in conventional lasers these are usually individual atomic states (either in the gas phase or defect states in the solid phase). Electrons in a band have an energy spread due to thermal fluctuations. This can affect the laser line width. This is similar to the thermal line broadening observed in LEDs.

2. The active region in the laser is narrow, typically less than 1 μm. This can cause a large beam divergence.

3. The spatial and spectral characteristics are influenced by the laser material like band gap and refractive index.

4. The lasing action is controlled by the incident current so modulation by the current is possible. This is also possible because of the short photon lifetimes in the semiconductor material.

3 Stimulated emission

As shown in figure 2, spontaneous and stimulated emission are essentially competing processes. For efficient lasing action, spontaneous emission must be suppressed. Also, when the photon is incident on the semiconductor, absorption is possible instead of stimulated emission. Let ϕ be the incident photon flux, the rate of the three processes (absorption (R_{ab}), spontaneous (R_{sp}) and stimulated emission (R_{st})) can be written as

$$\begin{aligned} R_{ab} &= B_{12}N_1\phi \\ R_{sp} &= A_{21}N_2 \\ R_{st} &= B_{21}N_2\phi \end{aligned} \tag{1}$$

where N_1 and N_2 are the population in the ground state and excited state, see figure 2. The terms B_{12}, A_{21}, and B_{21} are called the **Einstein coefficients** and represent the probability of the three processes. They are material and transition dependent. The rates for absorption and stimulated emission are dependent on the incident photon flux while spontaneous emission is not. For a system in equilibrium, the ratio of the population in the excited and ground state can be approximated by a simple Boltzmann distribution

$$\frac{N_2}{N_1} = \exp(-\frac{\Delta E}{k_B T}) \tag{2}$$

This is true when $\Delta E \gg k_B T$. Since the net optical transition has to be zero

$$\begin{aligned} R_{ab} &= R_{st} + R_{sp} \\ B_{12} N_1 \phi &= A_{21} N_2 + B_{21} N_2 \phi \end{aligned} \tag{3}$$

The Einstein coefficients depend on the material and the energy levels but not on the type of transition. This means that $B_{12} = B_{21}$. Also, for an efficient lasing action the rate of spontaneous emission must be very small. So ignoring R_{sp} equation 3 the difference in stimulated emission and absorption can be written as

$$R_{st} - R_{ab} = (N_2 - N_1) B_{21} \phi \tag{4}$$

Optical gain in a laser is positive only when $N_2 > N_1$, i.e. when population inversion is achieved. Usually, some external means are used for inversion. In a semiconductor laser there are energy bands not individual energy states. So population inversion must lead to an increase in the carrier concentration in the excited state (usually the conduction band). For a *pn* junction, external injection of carriers by applying a forward bias can create population inversion. This is similar to a LED, except that in the laser the spontaneous emission due to carrier recombination has to be suppressed. Population inversion in a semiconductor is shown in figure 3. Along with the population inversion, thermal fluctuations also cause a spread in the electron density of states. The occupation probability of electron and holes in the conduction and valence band is given by the Fermi Dirac distribution.

$$\begin{aligned} f_c(E) &= \frac{1}{1 + \exp\left[\dfrac{(E - E_{Fn})}{k_B T}\right]} \\ f_v(E) &= \frac{1}{1 + \exp\left[\dfrac{(E - E_{Fp})}{k_B T}\right]} \end{aligned} \tag{5}$$

where E_{Fn} and E_{Fp} refers to the highest occupied states in the conduction band and valence band during population inversion. If N_c and N_v refer to the effective density of states at the conduction and valence band edges, then $f_c N_c$ refers to the density of occupied states and $(1 - f_c) N_c$ refers to the density of unoccupied states in the conduction band. A similar expression can be written for the valence band. Then the rates for the three transitions,

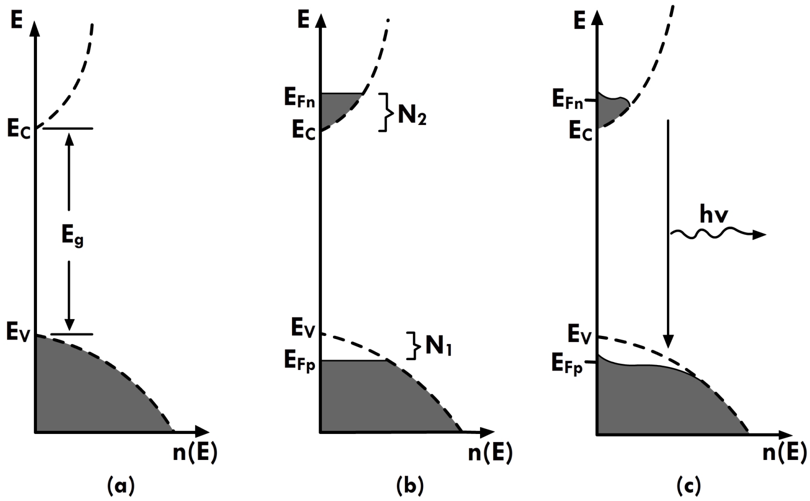

Figure 3: (a) Thermal equilibrium. Majority of the carriers are in the ground state. (b) Population inversion created by an external influence (c) Emission of light when the system goes back to equilibrium. This emission can be stimulated by an incident photon. Adapted from *Physics of semiconductor devices - S.M. Sze.*

absorption, spontaneous emission, and stimulated emission can be written as

$$\begin{aligned} R_{ab} &= B_{12} \int (1 - f_c) f_v N_c N_v N_{ph} dE \\ R_{sp} &= A_{21} \int (1 - f_v) f_c N_c N_v dE \\ R_{st} &= B_{21} \int (1 - f_v) f_c N_c N_v N_{ph} dE \end{aligned} \tag{6}$$

where N_{ph} is the number of photons per unit volume, with energy equal to the band gap, E_g. For lasing action, the spontaneous emission part can be ignored so that the difference between the rate of stimulated emission and absorption is,

$$R_{st} - R_{ab} = B_{21} \int N_{ph} (f_c - f_v) N_c N_v dE \tag{7}$$

For lasing action $f_c > f_v$, which means using equation 5, $E_{fn} > E_{fp}$, which is the condition for population inversion. In a semiconductor, when $E_{fn} = E_{fp}$, then $np = n_i^2$, so population inversion also causes the law of mass action to break down i.e. $np > n_i^2$. Once population inversion is created, for stimulated emission to occur, the incident photon energy must match the emitted photon. Using figure 3, this imposes the condition that the photon energy must be between the band gap and the Fermi level positions in the band i.e. $E_g < h\nu < (E_{fn} - E_{fp})$.

4 Device structure

4.1 Optical cavity

Lasing action is similar to LED emission, but there are some additional device structures that need to be incorporated. The main requirement for an LED is that one side of the device should have transparent conductors and the other side should be reflecting so that the light can be extracted from one side. In lasers, the intensity of the emitted radiation should be high. To build up intensity, optical cavities are used where light is bounced back and forth to develop the high intensity. A schematic of an optical cavity is shown in figure 4. An optical cavity or optical resonator has two reflecting mirrors. One of the mirrors is made totally reflecting, while the other side is partially reflective, so that radiation is emitted from the other side. Typical resonators are called **Fabry Perot resonators**, which consist of smooth parallel walls perpendicular to the junction. The optical resonators are so placed that the distance between them (L) is related to the wavelength of the emitted laser (λ), given by

$$L = m\frac{\lambda}{n_r} \tag{8}$$

m is an integer and n_r is the refractive index of the lasing medium. Typically, L is much larger than λ. The Fabry Perot cavity laser device arrangement is shown in figure 5.

R_1 and R_2 are the reflectivities of the two mirrors. Lasing occurs when the gain due to emission (g) is greater than the loss due to absorption (α). The net gain for this system, as a function of distance within the cavity, is written as

$$\phi(z) = R_1 R_2 \exp[(g - \alpha)z] \tag{9}$$

For the arrangement shown in figure 5 the total path length is $2L$. So the net gain occurs when

$$R_1 R_2 \exp[(g - \alpha)2L] > 1 \tag{10}$$

It is possible to define an threshold gain for lasing as

$$g_{th} = \alpha + \frac{1}{2L}\ln(\frac{1}{R_1 R_2}) \tag{11}$$

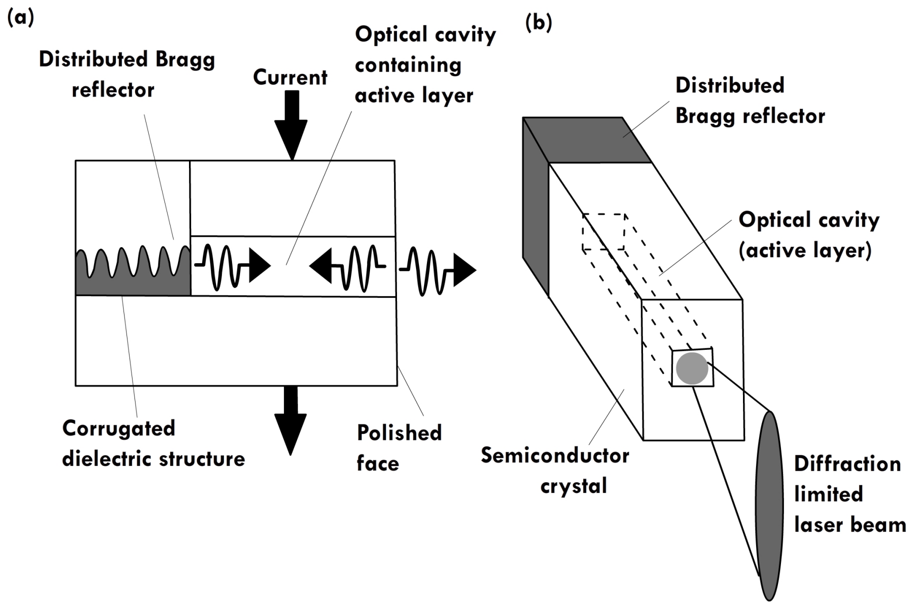

Figure 4: Schematic of the laser optical cavity (a) Side view (b) Front view. The optical cavity is located at the center of the device. Carriers are injected into the center to created population inversion and stimulated emission. The laser light generated is built up in this layer, before it is finally emitted. Adapted from *Principles of electronic materials - S.O. Kasap.*

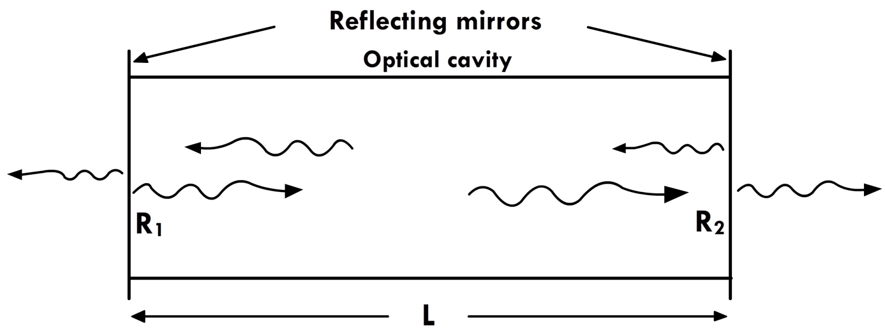

Figure 5: Fabry Perot cavity for lasing action. The two surfaces have reflectivity R_1 and R_2, with transmission coefficient equal to $1 - R$. If $R_1 > R_2$, then light will be emitted from the second surface and vice versa. Adapted from *Physics of semiconductor devices - S.M. Sze.*

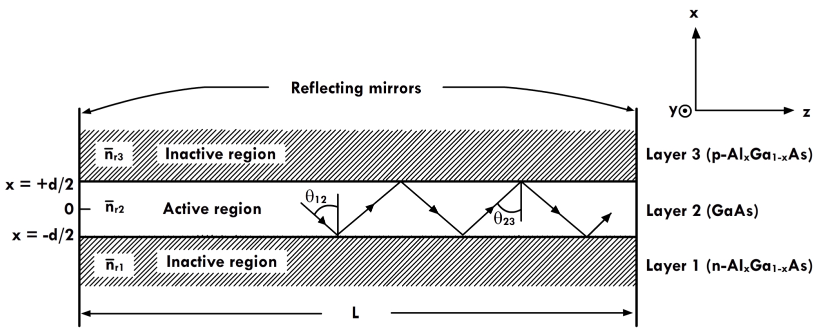

Figure 6: Waveguiding in a heterojunction laser. The beam is confined to the active GaAs region by total internal reflection at the GaAs-AlGaAs layer. This is because the refractive index of the GaAs is higher than AlGaAs. Adapted from *Physics of semiconductor devices - S.M. Sze.*

Higher the values of reflectivity smaller is the threshold gain required for lasing action. Similarly, lower the losses due to absorption, smaller is the threshold gain for lasing.

4.2 Wave guiding

The optical cavity helps in building up the laser intensity but it also important to confine the beam within the lasing medium i.e. the beam must be confined in the direction parallel to the light propagation. This is done by *waveguiding* and it makes use of the concept of *total internal reflection*.
The waveguiding arrangement for a double heterojunction based laser is shown in figure 6. The active region is the GaAs region which is confined between two AlGaAs regions. The higher band gap AlGaAs regions serve to confine the charge carriers within the GaAs region and increase recombination efficiency. This is similar to the band structure in a double heterojunction LED. Also, the refractive indices of the materials are such that the AlGaAs regions also confine the emitted radiation within the active region. Let n_{r1}, n_{r2}, and n_{r3} be the refractive indices of the AlGaAs, GaAs, and AlGas layer respectively, from figure 6. The the condition for total internal reflection in the active region is that

$$n_{r2} \; > \; n_{r1} \;\&\; n_{r3} \tag{12}$$

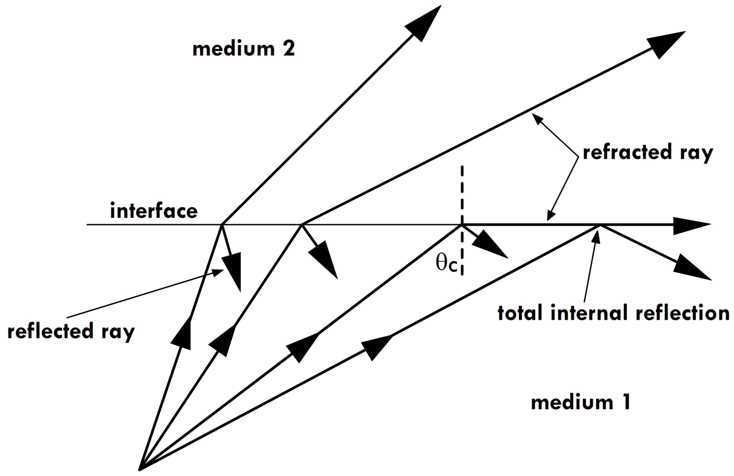

Figure 7: Critical angle for total internal reflection when light passes from a medium with higher refractive index to one with a lower refractive index. At angles above the critical angle, total internal reflection occurs, while refraction occurs for lower angles.

The band gap (E_g) and refractive index (n_r) of AlGaAs (formula $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$) depends on the value of x and is given by

$$\begin{aligned} E_g &= 1.42 + 1.247x \\ n_r &= 3.590 - 0.710x - 0.091x^2 \end{aligned} \tag{13}$$

The AlGaAs performs the dual role of band gap engineering (as in LEDs) and also optical engineering. For a value of $x = 0.3$, E_g is 1.8 eV and n_r is 3.38. This is lower than the refractive index of GaAs, which is 3.59. It is possible to calculate a critical angle for total internal reflection (θ_c), with respect to the normal to the interface, as shown in figure 7. This is given by

$$\theta_c = \sin^{-1}(\frac{n_2}{n_1}) \tag{14}$$

Below θ_c, only partial reflection occurs, while above θ_c there is total internal reflection. For $x = 0.3$, this critical angle is 70.3°. With increasing x, n_2 reduces even further and the value of θ_c reduces. Also, increasing x increases band gap and carrier confinement. Hence, these two effects go together in improving lasing efficiency.

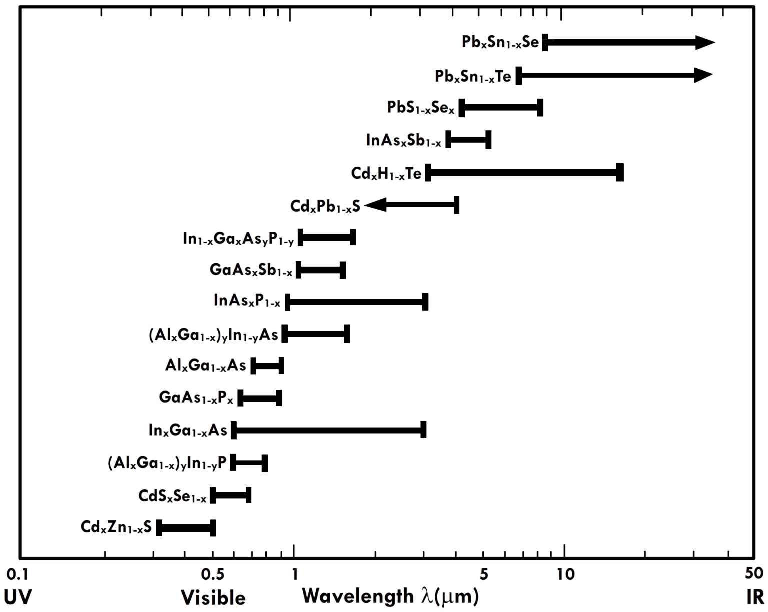

Figure 8: Typical laser materials and their operating wavelengths. The operating wavelength depends on the band gap of the material. Adapted from *Physics of semiconductor devices - S.M. Sze.*

5 Device materials

There are a number of semiconductors that can be used for laser devices. They are summarized in figure 8. The wavelength range depends on the band gap of the active material. Typical laser materials are similar to the ones used for LEDs, i.e. direct band gap semiconductors. GaAs based lasers are used in the near IR region while for larger wavelengths (in the mid IR region) PbX (X is a chalcogenide like S, Se, or Te) lasers are used. For lasers in the visible region, typically CdX (X is a chalcogenide) based lasers are used. Laser devices are single or double heterostructures though homojunction lasers are also possible. Laser structures are compared in figure 9.

Typical doping levels in lasers are much higher than LEDs. One of the materials in the junction is a *degenerate semiconductor* i.e. the doping levels are so high that the dopants form an energy band that merges with the valence or conduction band. This is also seen in the band structures shown in figure 9. The active region is usually lightly doped compared to the other regions of the junction and hence the depletion region lies usually in the active region.

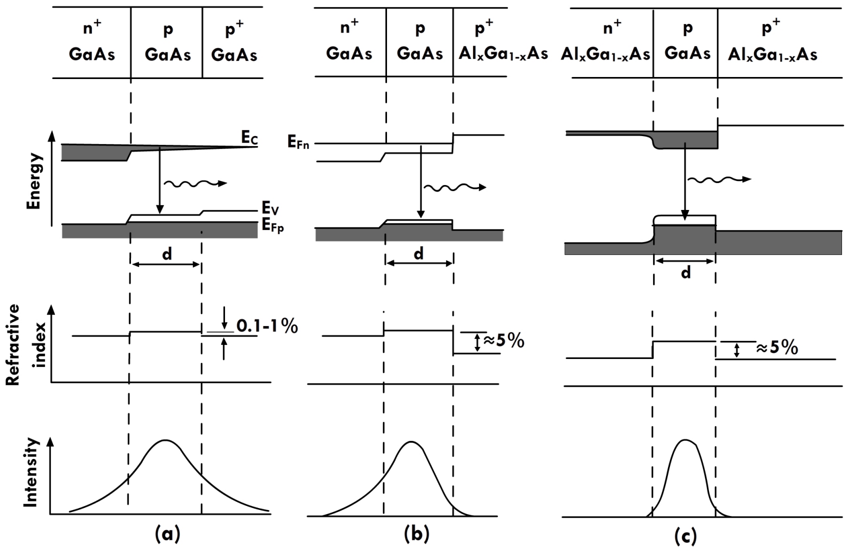

Figure 9: Types of laser structures, (a) homojunctions, (b) single and (c) double heterostructures. The energy band gaps, refractive index, and intensity vs. line width are also plotted. The narrowest line width is obtained for double hetrostructure lasers. Adapted from *Physics of semiconductor devices - S.M. Sze.*

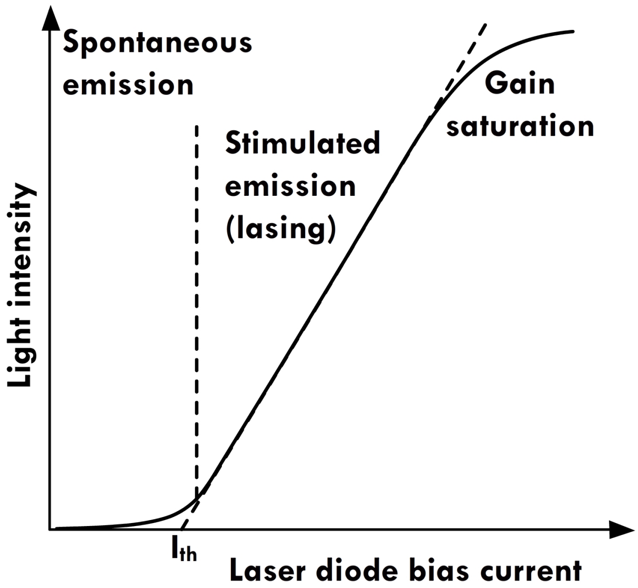

Figure 10: Laser intensity vs. the forward bias current. There is a minimum threshold current for lasing action with the intensity directly proportional to the current. Adapted from *Physics of semiconductor devices - S.M. Sze.*

When a forward bias is applied, carriers are injected into the active region. This achieves population inversion and the recombination leads to emission. The emitted light is reflected by the mirrors at the end of the device and the inactive regions, with their lower refractive index, confine the light within the active region. The light intensity is proportional to the forward bias current, as seen from figure 10. There is a minimum forward bias current, called *threshold current*, I_{th}, above which stimulated emission takes place and here the intensity is directly proportional to the current. At low current, spontaneous emission dominates, while saturation in gain in seen at the other extreme. The threshold current depends on the laser structure, the optical losses due to absorption, the refractive index of the various layers and the device dimensions. Since the active layer is usually less than 1 μm thick, solid state semiconductor devices are highly compact, compared to other types of lasers.

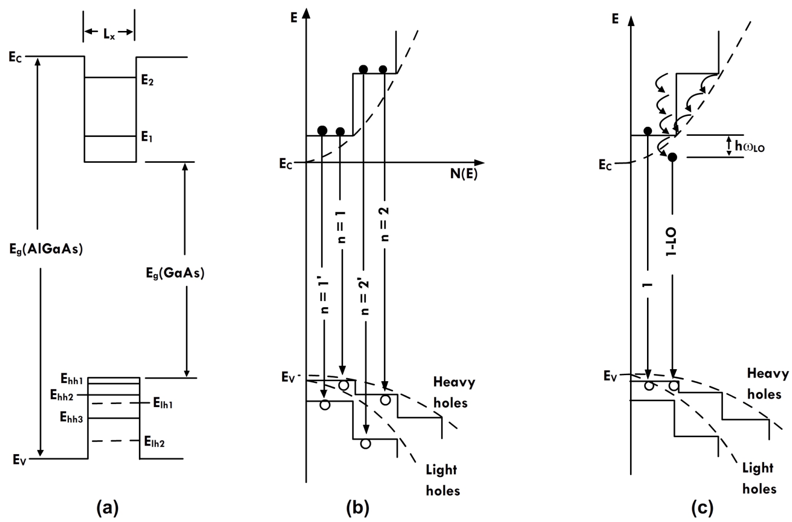

Figure 11: (a) Quantum well laser structure showing discrete energy levels. (b) Excitation of electrons happen to these discrete levels (c) Recombination leads to emission of light. Some of the recombinations are also mediated by the lattice vibrations. Adapted from *Physics of semiconductor devices - S.M. Sze.*

6 Specialty lasers

6.1 Quantum well, wire and dot lasers

The active layer in a heterojunction laser can be made very thin. If the width of the active layer is comparable to the de Broglie wavelength of the electrons (typically around the *nm* range) then *quantum confinement* can be achieved. The energy levels are no longer continuous but are quantized into discrete values. This is shown in figure 11. The spacing between the quantized energy levels depend on the width of the active layer. This also controls the wavelength of the laser radiation. If the *confinement is along only one direction* (thickness) then it is a *quantum well laser*. If there is *confinement along two directions*, then it is a *quantum wire* and for *confinement in all three directions* it is a *quantum dot*. The device structure for the quantum wire and dot laser is shown in figure 12, while the device structure for the quantum well laser is shown in figure 13.

Quantum confinement also changes the density of states function. So, narrower regions of electron energy confinement are possible, and this leads to reduced line widths and sharper peaks. A quantum well structure has a step density of states function, compared to the continuous density of states

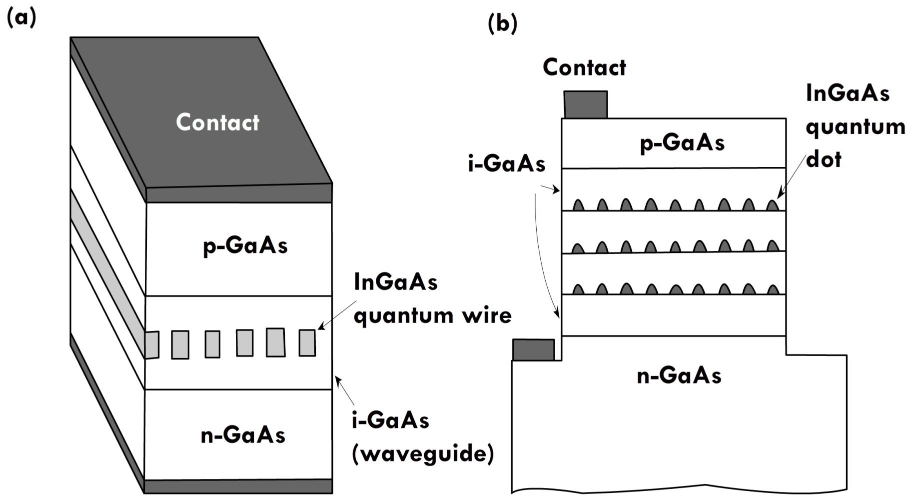

Figure 12: (a) Quantum wire and (b) dot laser. In both cases the active material is InGaAs, confined between GaAs layers. The quantum wire laser has a single layer of the active region, while in the dot laser there are multiple layers of the dots grown on GaAS. Adapted from *Physics of semiconductor devices - S.M. Sze.*

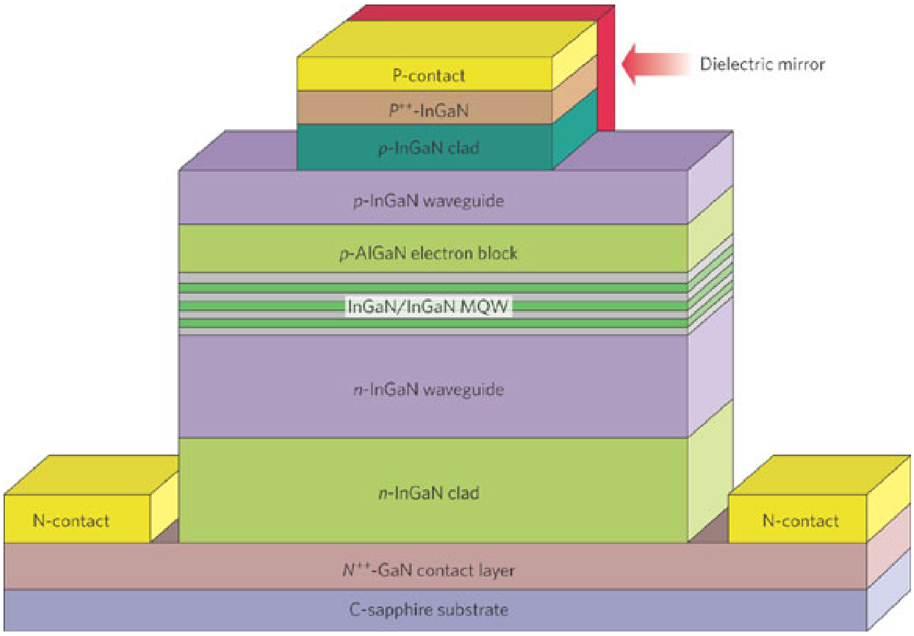

Figure 13: Schematic of a quantum well laser. The active region is a multiple quantum well of InGaN. These are grown on GaN layers on sapphire. Source *Nature Photonics* ***3****, 432 (2009).*

function for three dimensional structure. This is shown in figure 14. With increase in degree of confinement, the peaks are narrower and the gain also increases. Quantum dot and wire structures can be usually made by a self-ordering process. This however limits the range of structures that can be obtained. A general quantum wire or dot structure can also be made by top down fabrication process but the process is complicated and it is very difficult to obtain nm size structures. This can increase overall cost of the device.

6.2 Vertical cavity surface emitting laser

The VCSEL (vertical cavity surface emitting laser) is a type of surface emitting laser, with laser radiation perpendicular to the interface, unlike the other lasers which are edge emitting, with laser radiation parallel to the interface. The structure of the laser is shown in figure 15. The optical cavity is now parallel to the interfaces. It should have high reflectivity since the cavity thickness is smaller than edge emitting lasers. Typically, a multiple quantum well structure is used for the active region. The advantage of the VCSEL is that it can be used to form two dimensional laser arrays and also can be

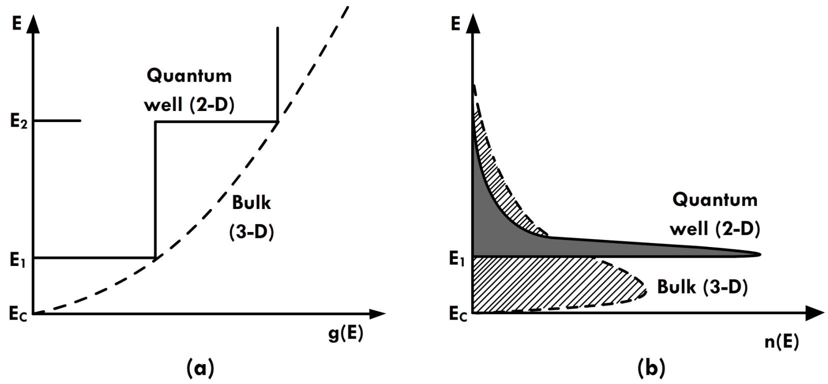

Figure 14: Density of states for (a) quantum well vs. (b) bulk structure. While the bulk has a continuous density of states, the well has discrete energy states. Adapted from *Physics of semiconductor devices - S.M. Sze.*

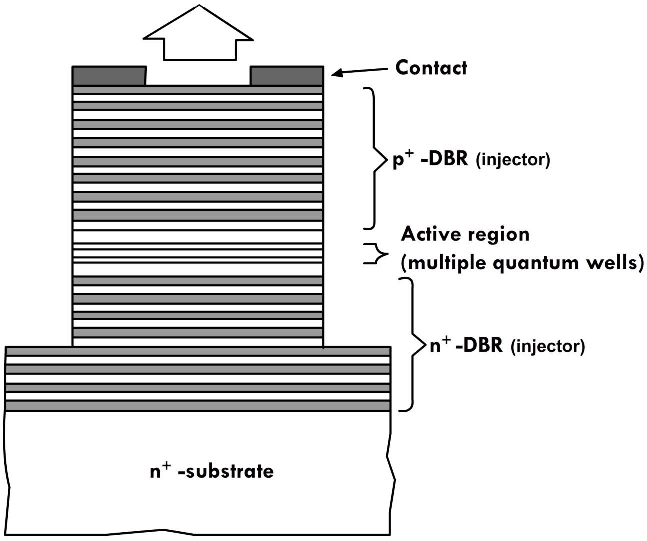

Figure 15: VCSEL device structure. The active region is made of multiple quantum wells and the laser is emitted perpendicular to the surface. There are distributed Bragg reflectors (DBR) that serve as both injectors of the carriers into the active region and also reflected the laser light until a sufficient intensity is built up. Adapted from *Physics of semiconductor devices - S.M. Sze.*

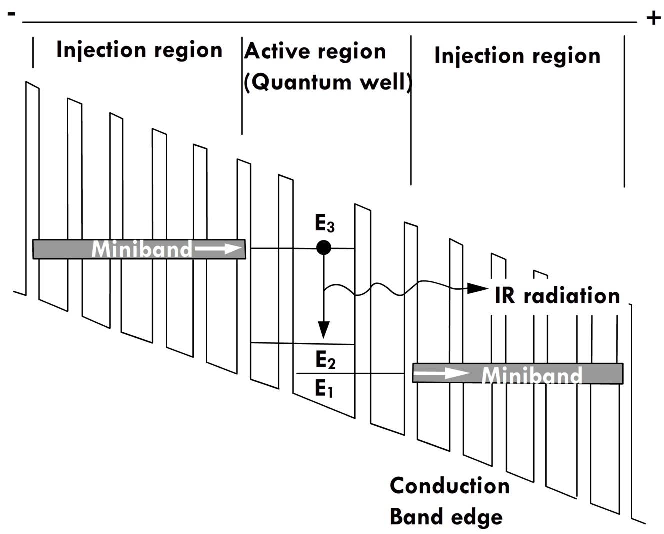

Figure 16: Quantum cascade laser energy band structure. The active region is quantum well with energy gaps of the order of few hundred meVs. These are populated by minibands on either side, while lie in the conduction band. Because of the small energy gap, lasers are produced in the IR region. Adapted from *Physics of semiconductor devices - S.M. Sze.*

integrated in a wafer with other functional devices.

6.3 Quantum cascade laser

In this kind of laser the emission is due to electron emission between sub band energy levels. These are usually created in a quantum well or a super lattice structure (periodic structure of two of more materials with typical thickness of individual layers around a few nm). Since the transition is between sub band structures the energy of the transitions is very small and hence long wavelength lasers (especially in the IR region) can be obtained which cannot be obtained by inter band transitions. The energy band diagram of a quantum cascade laser is shown in figure 16. The wavelength can be tuned by controlling the quantum well thickness without being fixed by the band gap. This is not possible in a conventional quantum well laser which is based on inter band transitions.