Chapter Two *Semiconductor Laser Review*

This chapter reviews the general theory of semiconductor laser. Overview of semiconductor laser operation followed by material used, design structure, characteristics, reliability and its applications are all explained briefly.

2.1 Semiconductor Laser Operation

Basically, a laser diode consists of several semiconductor layers in which part is doped with electron donors to form n-type layer and the other part is doped with electron acceptors to produce p-type layer. A separate undoped active region is formed at the junction, which is sandwiched between the p- and n-type layers. Figure 2.1 shows the schematic structure of laser diode. In practice, the structure may contain additional layers of different composition to improve the operation.

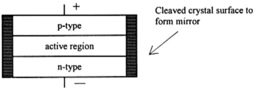

Figure 2.1: Schematic diagram showing essential components of laser diode.

Energy is applied to the laser diode through electrical current injection, plasma excitation or pumping by another laser. In the case of electrical current injection, application of a negative voltage to the n-layer and positive voltage to the p-layer creates an excess of minority carriers on each side of the junction. This process is called forward-biasing the p-n junction, where it lowers potential barriers and causes carrier injection from one side of the junction to the other. Figure 2.2 illustrates the process of electron-hole recombination in a band diagram, which results in a current flow. This recombination releases energy as photons, of which the energy equals to the difference in energy bandgaps between the conduction and valence bands. Two key elements needed to start the lasing operation are population inversion to achieve stimulated emission and optical feedback. Population inversion is achieved by doping heavily both regions of the p-n junction as illustrated in Figure 2.2(a) in equilibrium state energy band diagram. Figure 2.2(b) shows the energy band diagram of the heavily doped junction under forward bias.

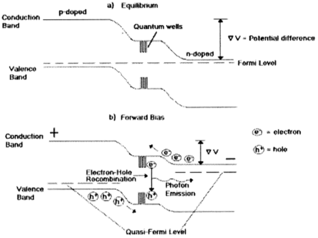

Figure 2.2: Heavily doped p-n junction (a) in equilibrium (b) with forward bias.

Firstly, spontaneous emission is generated by electrons-holes recombination. The emitted photons propagate randomly and stimulate further emissions. After some initial spontaneous emission, stimulated emission will become dominant where it generates more in-phase photons. The photons then amplified by the stimulated emission mostly on the wavelengths where the emission is highest. This amplification compensates for the losses by free-carrier absorption and by the transmission through the mirrors. The lasing oscillation is provided by optical feedback using Fabry-Perot cavity consisting of two reflecting parallel mirrors as shown in Figure 2.1, where the photon is reflected and confined in between. The mirrors can be formed by polishing the two end facets of the laser chip to form smooth reflecting surfaces. Laser oscillation will continues as long as the total power loss does not exceed the power gain by stimulated emission. Once lasing starts, the light in the cavity reflects back and forth, forming a standing wave. Light is coupled out by transmission through one of the mirrors.

2.2 Semiconductor Laser Material

Compound semiconductors, mainly from group III–V elements are well suited for semiconductor laser. The required condition for laser material is that the input energy can be converted into light energy with high efficiency. Figure 2.3 shows the band diagram of GaAs and AlAs.

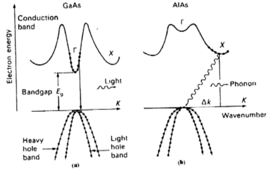

Figure 2.3: Band diagrams of (a) GaAs and (b) AlAs.

As for the case in Figure 2.3(a), the electron from the conduction band makes a transition directly and easily to the valence band with photon emitted. This type of semiconductor is called direct-band gap semiconductor, where the minimum energy in the conduction band and the maximum energy in the valence band occur at the same value of crystal wave vector, κ. On the other hand, in an indirect-band gap semiconductor, this condition does not occur. The electron transition occurs with difficulty and the probability of photon being emitted is much lower as shown in Figure 2.3(b). Si and Ge which are the main materials used in the electronics industry are indirect-band gap semiconductor type, thus not suitable to be used as semiconductor laser material. Si and Ge also have slow response to current modulation due to its long carrier lifetime. In contrast, most of III–V elements are direct-band gap semiconductors with efficient light emission and short carrier lifetime. Moreover, ternary or quaternary materials, which are composed of three or four different chemical alloys from III–V elements as shown in Figure 2.4, have the advantage of having wide range of wavelength operation from visible to far-IR region since the forbidden energy gap of the materials vary with the composition of the alloys.

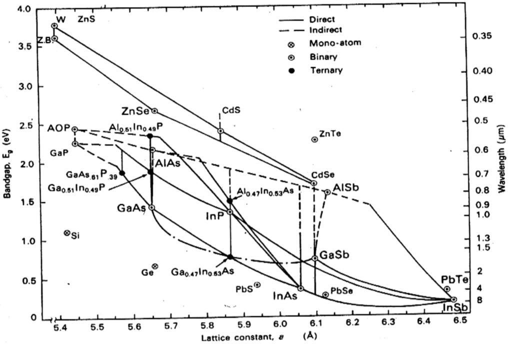

Figure 2.4: Various combinations of compound semiconductors.

Table 2.1: Binary systems showing the respective bandgap, (eV) and lattice constant, (Å).

V / III	P	As	Sb
Al	2.50 eV & 5.451 Å	2.30 eV & 5.661 Å	1.55 eV & 6.135 Å
Ga	2.35 eV & 5.451 Å	1.35 eV & 5.653 Å	0.70 eV & 6.096 Å
In	1.30 eV & 5.869 Å	0.35 eV & 6.058 Å	0.17 eV & 6.479 Å

Binary crystals such as GaAs and InP are now well used as substrates in laser diode fabrication because of controllable and high quality crystal growth. In Table 2.1, III-V binary systems are shown. It is important to match the lattice constant of the binary materials used as the substrates with the ternary system such as AlGaAs or quaternary system such as InGaAsP that are grown on it. The most important semiconductors for optical communications are the group of mixed system based on GaAs or InP, with combination of the neighbouring elements (Al, In, P, As and Sb). This combination will form either ternary or quaternary systems. The various material systems and its respective emission wavelength is shown in Table 2.2.

Table 2.2: Materials for Light Sources.

System	*Compound*			*Emission wavelength (μm)*
	Active layer	*Cladding layer*	*Substrate*	0.5 1 5 10
III–V	AlGaAs	AlGaAs	GaAs	
	GaInAsP	GaInP	GaAs	
	GaInAsP	GaInP	GaAsP	
	GaInAsP	AlGaInP	GaAs	
	AlGaInP	AlGaInP	GaAs	
	GaInAsP	AlGaAs	GaAs	
	GaInAsP	InP	InP	
	AlGaAsSb	AlGaAsSb	GaSb	
	InAsSbP	InAsSbP	InAs	
IV–VI	PbSnSeTe	PbSnSeTe	PbTe	
II–VI	ZnSSe		GaAs	

2.3 Semiconductor Laser Design and Structure

Laser diode has a wide variety of design and structures classifications as shown in Figure 2.5. There are two principal configurations for laser diode basically, that is edge-emitting laser (EELs) with the first reporting in 1962 [4] and surface-emitting lasers (SELs) in 1979 [22] respectively. Recently, SELs have become available for commercial applications with more efficient performances than EELs.

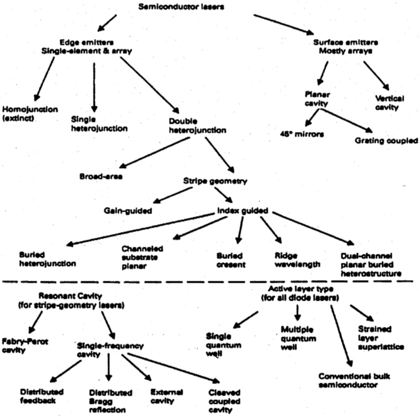

Figure 2.5: Categorization of diode lasers structures. The two classifications at the bottom are not part of the family tree.

2.3.1 *Edge-emitting Lasers (EELs)*

The EELs configuration is based on waveguide structure, as illustrated in Figure 2.6. A slab waveguide is formed by using p-type and n-type semiconductor layers surrounding the active region. There are three major classes of EELs, based on the composition of the semiconductor layers that is Homojunction EELs, Single-Heterostructure EELs and Double-Heterostructure EELs [28]. DFB and DBR lasers that are widely used in optical communication are examples of EELs.

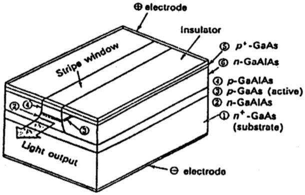

Figure 2.6: Example of edge-emitting lasers.

The mirrors of EELs are usually formed from the natural reflectively of the semiconductor-air interface (~30%) by cleaving the two facets of the laser diode chips. Due to mirror loss, the laser cavity needs to be hundreds of microns long to obtain enough gain for the device to lase. This create heat dissipation problem in EELs since high current densities are produced with broad cavity. Narrow stripe structure has been demonstrated such as buried heterostructure and ridge structure to overcome this problem. As for the EELs laser beam output, the dimension is not well-distributed in both directions. The beam as it leaves the laser diode is small in the vertical direction (perpendicular to the layer structure) and relatively larger in the horizontal direction. As it propagates into the far-field, the situation reverse because of diffraction, producing large beam in the vertical direction and a smaller beam in the horizontal direction, as shown in Figure 2.7.

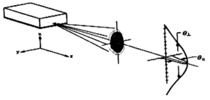

Figure 2.7: The divergence of a laser beam in the vertical and horizontal directions.

2.3.2 *Surface-emitting Lasers (SELs)*

Although the first device was first reported in 1979, it is only in the past few years have seen the high emergence of interest in this novel laser diode configuration. Figure 2.8 shows an example of SELs device. There are two principal SELs design that are Planar-cavity SELs and Vertical-cavity SELs [28] where both can be made as single device or in arrays. Most researches in SELs involved in vertical-cavity because of its simplicity and performance advantages compare to complexity of planar cavity design. Hence, from now onwards, SELs will be refer as Vertical-Cavity Surface-Emitting lasers (VCSELs) in general term.

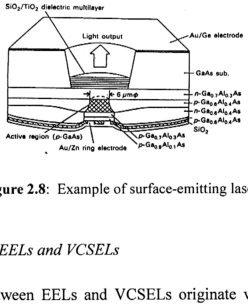

Figure 2.8: Example of surface-emitting lasers.

2.3.3 *Differences between EELs and VCSELs*

Most of the differences between EELs and VCSELs originate with the geometry of devices. Figure 2.9 shows the geometric differences of the wafer level. In VCSELs, the gain region is parallel to the plane of the wafer, resulting in emission perpendicular to the wafer plane. In EELs, the gain region is perpendicular to the plane of the wafer, thus the emission is parallel to the wafer plane. Another consequence of the geometry is the beam shape. VCSELs emit a geometrically symmetric laser output beam, resulting in circular beam with a small divergence and. In contrast, the EELs laser output beam cross section is not symmetric. As a result, the emitted beam is quite astigmatic and has large divergence. Threshold current properties are also consequences of the geometric difference between VCSELs and EELs. The small volume of VCSELs active region produces low threshold current and low threshold current density compare to EELs.

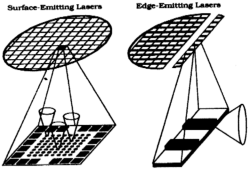

Figure 2.9: Wafer level differences between VCSELs and EELs.

2.4 Semiconductor Laser Characterization

2.4.1 *Light-Current-Voltage (L-I-V) characteristics*

A typical L-I-V characteristic for laser diode is exhibited in Figure 2.10. The L-I curve (red colour) is a measurement of the output power emitted as a function of the device current. From this curve, device parameters such as threshold current, differential quantum efficiency and maximum output power can be obtained.

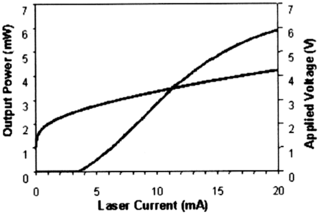

Figure 2.10: Typical L-I-V characteristic of a laser diode.

The V-I curve (blue colour) as shown in Figure 2.10 can give information concerning the device electrical characteristics. The threshold voltage, turn-on voltage and series resistance of a laser diode can be known from this characteristic.

2.4.2 *Operating Mode characteristics*

Longitudinal mode characteristics can be known from the emission spectrum of semiconductor laser. The emission spectrum is determined by the transmission characteristics of the resonance optical cavity of the laser and the gain spectrum profile of the active region. Figure 2.11 shows emission spectrum of VCSELs with single longitudinal mode operation and multi longitudinal mode operation for EELs.

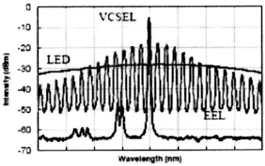

Figure 2.11: Emission spectrum for laser devices such as LED, EELs and VCSELs.

2.4.3 *Spatial-mode characteristics*

Spatial-mode characteristics of a laser diode are characterised by near-field and far-field as displayed in Figure 2.12. The spatial-intensity distribution of the emitted light near the laser facet is known as *near-field*. Generally, several transverse and lateral modes may appear and the resulting near-field is formed by a superposition of these modes. The angular intensity distribution far from the laser facet is known as *far-field*. It indicates the angular spread of the laser mode and for determining the coupling efficiency between laser diode and an optical fiber. The far-field pattern is obtained by taking the two-dimensional Fourier transform of the near-field.

(a)

(b)

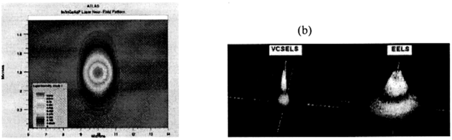

Figure 2.12: Examples of (a) near-field and (b) far-field distributions of laser diode.

2.5 Reliability and Lifetime of Semiconductor Laser

Semiconductor laser are quite sensitive to temperature. Figure 2.13 shows L–I curve at various temperatures. As the operating temperature become higher, the threshold current increases while the output power and efficiency decreases, and decreasing the device performance. As a result, it is important to optimize the laser diode design so that the performance will be reliable at high temperature operations. The operating lifetime of a laser diode is also dependent on its operating temperature. A high quality laser diode operating at 20^{0}C could have a lifetime in excess of 100 000 hours [29]. Device performance can be improved by developing the fabrication technique, device studies, applying heat sinks and analysis of previous failures.

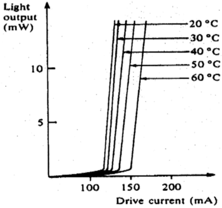

Figure 2.13: L-I curve of laser diode as a function of temperature.

2.6 Semiconductor Laser Applications

Laser diode can be grouped into two wavelength regions that are short-wavelength and long-wavelength. Figure 2.14 illustrates the wavelength range of materials used and their applications. Short-wavelength laser diode has a wide spectrum of wavelength from visible (0.4–0.8) μm to near–IR (0.8–10) μm.

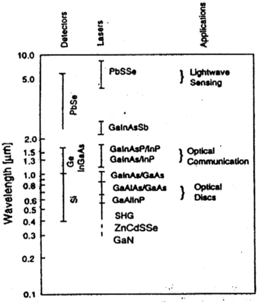

Figure 2.14: Wavelength region and application.

Recent improvements in materials technology have enabled CW operation demonstrated at room temperature using II–VI semiconductors such as ZnSe [30] and ZnCdSe [31]. However both lasers which emit in the green and blue spectrum have many limitations and are not very reliable. Alternatively, CW operation at 417 nm wavelength has been obtained from device based on GaN [32]. These green and blue lasers are now in the market for high-density data storage and lithography applications. Visible laser emitting at 670 nm under the red spectrum was first demonstrated in 1987 [33] and was soon produced commercially in 1990 [34]. The red laser is widely used as laser pointers and bar–code scanners where the red beam produced is visible to human eye. Advances in near-IR laser diode (0.8-1.0) μm are developing into several applications. The first CW operation was achieved in AlGaAS/GaAS system [10]. Laser that emit at 780 nm wavelength is used to read data from optical storage discs such as CD, VCD and optical hardisk. The same wavelength is also applied in laser printers and hard copy machines. High power laser and laser diode arrays above 800 nm are normally used as pump sources for solid-state laser. Most of these high power lasers available commercially operate in the range 790 to 820 nm range. These lasers can be used for other applications in medicine, space communications and military systems. One other expanding application for high power near-IR laser diode is for the pumping of erbium doped fiber amplifiers (EDFA) at 980 nm for long haul optical-fiber communication network.

Semiconductor laser with longer wavelength (>1μm) are used primarily as light source for optical-fiber communications. The only III–IV material system used commercially is InGaAsP, a quaternary compound that can be lattice-matched to InP substrates for laser wavelengths between 1.1 and 1.65 μm. The best reported devices have been developed in 1987 [35]. Research is ongoing on developing new materials such as GaInAsSb system [36] and GaInNAs [37], but none of these systems are commercially available. The search for new materials in the infrared region (2–10 μm) is also being undertaken. Compounds of Pb have been studied, such as PbSnSeTe/PbSeTe [38], showing potential application in optical remote sensing. Nevertheless, the works are still in its early years and working devices have not yet been demonstrated.