Chapter 1

Introduction

1. Introduction

Since the invention of the GaAs based homojunction semiconductor laser, it has been continuously revolutionized in terms of material system, structure, growth mechanism, efficiency and off course its reliability. This chapter gives a brief introduction about the semiconductor laser and its applications. The contemporary research leading to the device lifetime improvement and the challenges to achieve such reliable operation of the laser diode are also discussed in this chapter. The overview of thesis and its organization are given at the end of the chapter.

1.1 Laser Fundamentals

It is almost difficult to cover a complete study of laser diode physics within the chapter. Hence this part of the chapter includes only the most basic concepts of laser action and an overview of the theory of laser diodes here for convenience and completeness. There are several classical literatures available covering various types of laser diodes, the physics of their operation, and applications [1,2,3].

1.1.1 General Laser Theory

Light Amplification by the Stimulated Emission of Radiation, also known as LASER, is special kind of electromagnetic radiation emitted when atoms make a transition from one quantum state to a lower one. As the name suggest the radiation takes place by stimulation, unlike an ordinary light source. Basically, there are three different processes by which interaction between electromagnetic radiation, i.e. light, and matter takes place namely absorption, spontaneous emission and stimulated emission, shown in Fig. 1.1.

- **Absorption**

As shown in Fig. 1.1 (a), let us consider an atom in its ground state (E_0) and having only one high energy state, excited state (E_1). If an atom is exposed to the electromagnetic radiation having energy $h\nu$ ($h\nu \geq E_1 - E_0$), where h is Plank's constant and ν is the radiation frequency, the atom can absorb an amount of energy and get excited to the higher energy level, E_1, shown in Fig. 1.1 (b). The process is known as absorption.

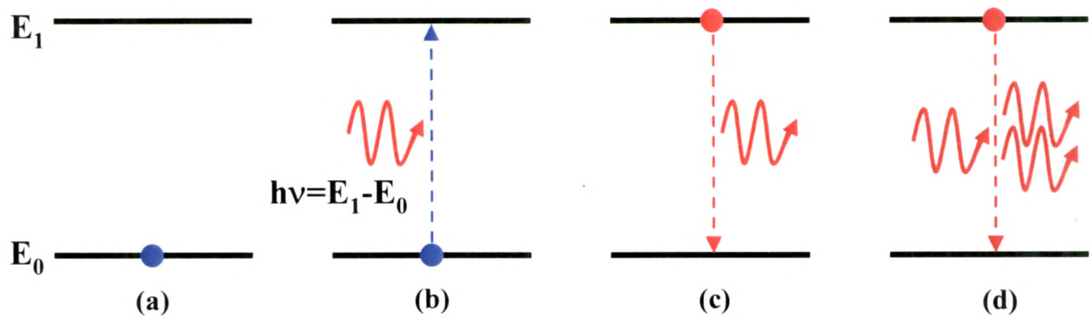

Figure 1.1: Light-matter interactions in simple two energy level system. (a) atom at ground state, (b) absorption of photon having energy $h\nu$, (c) spontaneous emission of photon and (d) stimulated emission of photon.

- **Spontaneous Emission**

After being excited to the higher energy level, the atom returns to the ground state within time interval of the order of 10^{-8} - 10^{-9} s by emitting a photon of energy $h\nu$. The process is known to as spontaneous emission because it is not triggered by any external influence. Fig. 1.1 (c) shows spontaneous emission from the system. In spontaneous emission the atom simply falls to the ground state while emitting randomly directed photons

- **Stimulated Emission**

In 1917, Albert Einstein proposed a theory that emission from excited atom can occur in two ways: spontaneous emission that we have discussed earlier and another one is stimulated emission. Unlike spontaneous emission, the excited atom returns to its ground state by externally triggered or spontaneously emitted photons having energy $h\nu$ and emits the photon, whose energy is also $h\nu$. Hence, in general the phenomenon of photon assisted light emission is known as stimulated emission, shown in Fig. 1.1 (d). The emitted photon is identical to the stimulating photon in all aspects. The light waves associated with these photons have the same direction, energy, phase, and polarization. Thus, in the case of stimulated emission, the wave representing the stimulated photon adds to the incident wave on a constructive basis, thereby increasing its amplitude.

So far we have discussed a system of only one atom to understand absorption and emission process in matter. Now considering the system/material in thermal equilibrium and having large number of atoms at temperature T. Before excitation, number of atoms, say N_0, in its ground state with energy (E_0) and N_1 is in a higher energy state (E_1). Ludwig Boltzmann showed that the number of atoms or molecules in higher energy state, E_1, i.e.

N_1, is represented in terms of the number of atoms in ground state energy, E_0, i.e. N_0, in thermodynamic equilibrium

$$N_1 = N_0 \, e^{\frac{-(E_1 - E_0)}{kT}} \tag{1.1}$$

where k is Boltzmann's constant and kT is the kinetic energy of an atom at temperature T. Hence at the higher temperature atoms will get excited thermally to its higher energy state E_1. In thermodynamic equilibrium, most of the atoms are in the ground state, the net effect will be the absorption of photons, and probability of the stimulated emission is rare. To produce laser light we must have a situation in which stimulated emission dominates. It is only possible if more atoms are in excited state than in the lower or ground state. Such a situation, in which the majority of atoms are excited, is referred to as a *population inversion*; this is a non-equilibrium situation under ordinary conditions.

In order to obtain a population inversion, the material must be excited by an external energy source having energy greater than or equal to the energy level of the atoms or molecules. This excitation of the laser medium is called *pumping*, which can be done optically, electrically, or by other excitation methods. Normally atoms in excited states have a short lifetime ($\sim 10^{-9}$ s) and release their energy by spontaneous emission. Therefore to produce population inversion, longer lived excited states are required, and such states, called meta-stable states, do exist. Meta-stable levels are stable on an atomic time scale and survive for microseconds or even for milliseconds.

1.1.2 Elements of Laser

To achieve lasing, a basic requirement is to realize population inversion by means of *external pumping* in *gain medium.* Once the population inversion is achieved and stimulated emission starts, it must be maintained in the gain medium by means of the *positive optical feedback.* By placing reflective surfaces at the ends of the gain medium parallel to each other, photons will be reflected back and forth along the cavity, forcing the excited atoms to decay via stimulated emission, making the laser beam highly directional. This positive feedback causes wave amplification along the cavity-length. A portion of this propagating wave transmits as a laser from partially reflective mirror.

Thus, any laser system consists of three basics components; gain medium, pumping source and resonator cavity. A simple laser diode configuration is illustrated in Fig. 1.2.

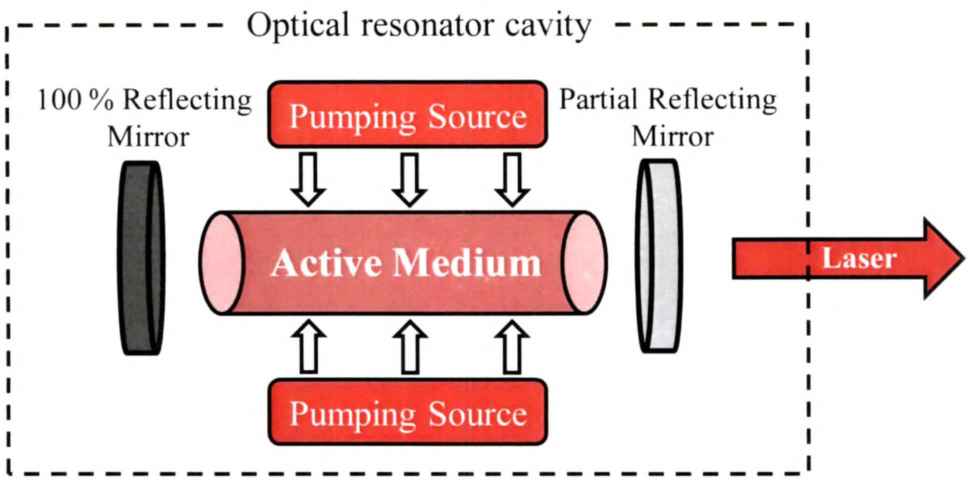

Figure 1.2: Illustration of basic structure of laser system.

Laser gain medium is the essential part of the laser system and used to realize gain and subsequent laser generation. It can be a solid, gas, crystal or semiconductor which can be pumped to the higher energy level. The material should have the suitable energy state, i.e. metastable state, to achieve population inversion. Also the gain medium should be of controlled purity, size and shape. Table 1.1 illustrates various types of material system currently used for lasers and the corresponding wavelengths. The wavelength of light being emitted from the system depends on the type of lasing material being used.

In order to achieve stimulated emission and to excite the atoms, electrons, molecules or ions a suitable **pumping mechanism** is necessary. Otherwise absorption will dominate at the cost of stimulated emission. There are several types of pumping mechanisms available viz. optical, electrical, thermal or chemical techniques, which depends on the type of the laser gain medium utilized.

Finally, **optical resonator** plays a vital role in the generation of the laser, which not only provides gain to the wave generated in the medium but also provides directionality to the out coming laser beam. The optical gain is achieved to overcome losses like absorption, scattering or diffraction, by means of two mirrors, one is 100 % reflective and second one is partially reflective

Table 1.1: Common lasers and their wavelengths.

Laser	Wavelength (nm)
Argon Fluoride	193
Xenon Chloride Excimer	308 and 459
Xenon Fluoride	353 and 459
Helium Cadmium	325 - 442
Rhodamine 6G	450 - 650
Copper Vapor	511 and 578
Argon	457 - 528 (514.5 and 488 most used)
Krypton	337.5 - 99.3 (647.1-676.4 most used)
Ruby	694.3
Semiconductor Laser	UV to far-IR
Ti:Sapphire	690 - 960
Alexandrite	720 - 780
Hydrogen Fluoride	2600 - 3000
Erbium:Glass	1540
Carbon Dioxide	10600
Krypton-Fluoride Excimer	296
Nitrogen	337
Organic dye	300-1000 (tunable)
Helium-Neon	543, 632.8, 1150
Neodymium:YAG	1064

1.1.3 Lasing in Semiconductor

Unlike gas and solid materials, having electronic energy levels which are nearly as sharp as of isolated atoms, in semiconductors the energy levels are broadened into energy bands, consists of a very large number of closely packed energy levels, due to the overlapping of atomic orbitals. In an undoped semiconductor with no external excitation at a temperature of T = 0 K, the uppermost energy band, called the *conduction band*, is completely empty and the energy band below the conduction band, called the *valence band*, is completely filled with electrons. The conduction band and the valance band are separated by a region of forbidden energy, called the *bandgap*. The semiconductor is characterized by its bandgap energy $E_g = E_C - E_V$, which corresponds to the energy difference between the bottom of the conduction band, E_C, and top of the valence band, E_V.

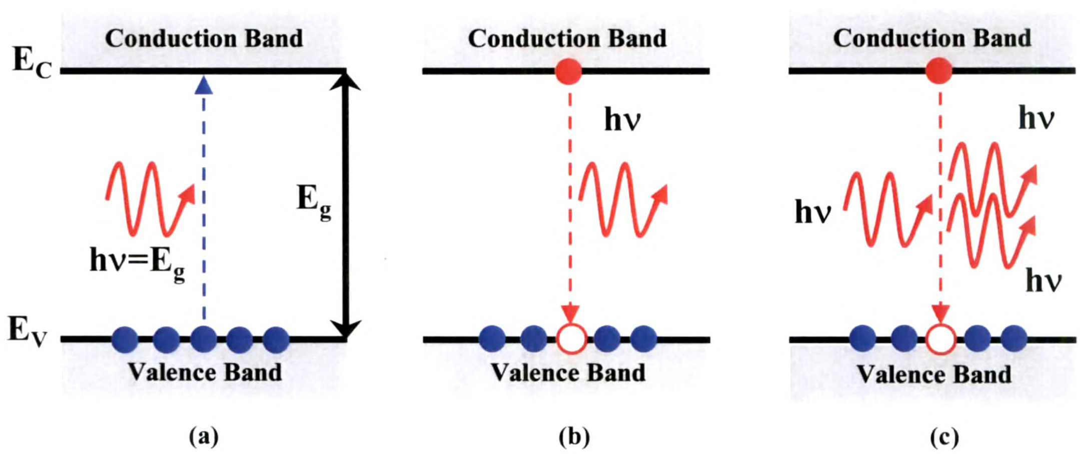

Figure 1.3: Radiative band-to-band transition in semiconductor. (a) Absorption, (b) spontaneous emission and (c) stimulated emission.

Energy transitions between bands are similar to changes of energy state in an atom, shown in Fig. 1.3. Basically, there are two types of carriers contribute to electronic transaction i.e. electrons in the conduction band and holes in the valence band. Initially, most of the electrons may occupy the lower energy and the conduction band is almost empty. If photon having energy $\geq E_g$ interact with semiconductor, it will excite the electron from valance band to the conduction band, leaving behind a hole in a valance band, as shown in Fig. 1.3 (a). However, this excited state is not stable and this excited electron will recombine with hole into the valance band radiatively by emitting a photon, either spontaneously or by stimulation (shown in Fig. 1.3 (b) & (c)), of the energy E_g. All three basic elements of a laser, i.e. gain medium, pumping, and resonator cavity apply special mechanism in case of laser diodes.

1.2 Elements of Semiconductor Laser

The basic elements necessary to realize a semiconductor laser are:

- A gain medium that provides optical gain by stimulated emission,
- Fabry-Perot resonator cavity creating optical feedback,
- An optical waveguide confining the photons in the active region of the device, and
- A lateral confinement of current, carriers, and photons

1.2.1 Gain Medium

The gain in laser diodes involves a whole crystal structure rather than excited single atoms, ions, or molecules. Semiconductor lasers can be excited by optical pumping with sufficient energy or by electron beams like gas or solid-state lasers. However, pumping the laser diode by applying an electrical current is the most efficient process compared to the other conventional technologies. Laser diode utilizes the conductivity of doped semiconductor material. The doping, either p-type or n-type, is achieved by introducing respective impurity atoms, acceptor or donor, to the intrinsic semiconductor material. Hence, the gain medium used in semiconductor laser is typically a p-n junction or a direct bandgap semiconductor material viz. gallium arsenide (GaAs).

Figure 1.4 shows energy band structure E(k) for electrons in direct and indirect semiconductor material. In indirect semiconductor like silicon or germanium, minima and maxima of conduction and valance band have different k-values as shown in Fig. 1.4 (a). Therefore, band-to-band recombination can occur not only with photons but also with the contribution of phonons or traps. Furthermore, these transitions are mostly nonradiative and are not suitable for laser activity as the light emission is not very efficient because the spatial density of phonons and traps is very low [3]. The mostly used material in laser diode is direct semiconductor where the maximum of valance band and the minimum of conduction band are at Γ-point ($k = 0$, shown in Fig. 1.4 (b)), i.e. at the center of the Brillouin zone. Direct bandgap structures maximize the tendency of electrons and holes to recombine radiatively and are more efficient for laser diodes and other light emitting devices.

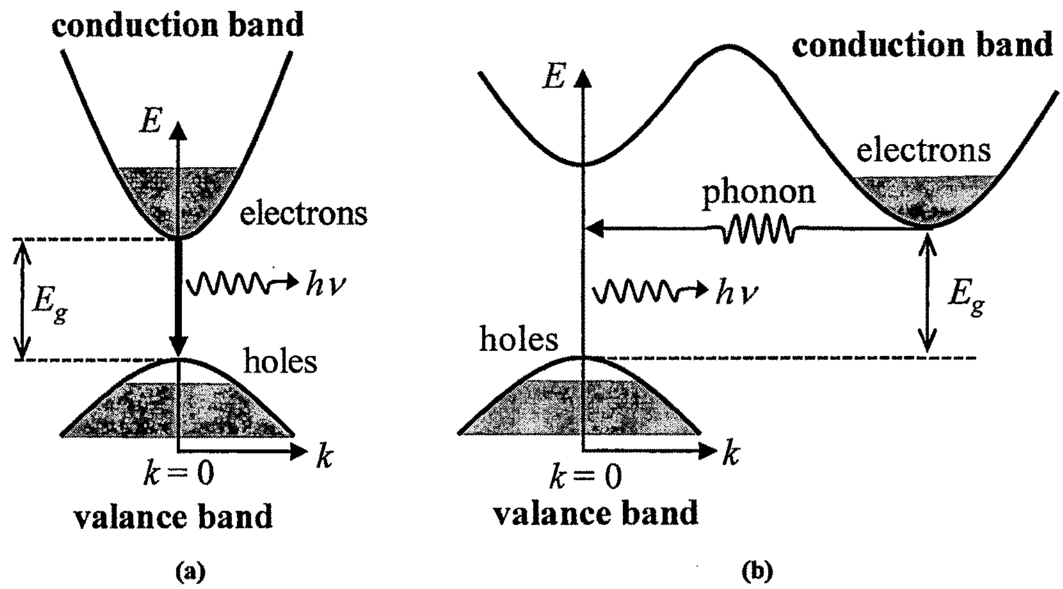

Figure 1.4: (a) Indirect and (b) direct bandgap in semiconductors.

Most direct bandgap semiconductors used for laser diodes are III-V binary or ternary compound material, i.e. combination of elements from the III and V group of periodic table. The attractive feature of these materials is that the binary compounds like GaAs and InAs can be alloyed to form ternary or quaternary compounds. By choosing appropriate compositions, it is possible to tailor the bandgap of the active layer and consequently tune the lasing wavelength. This is one of the key features that make it possible to fabricate laser diodes over a wide range of wavelengths. Gallium arsenide (GaAs), indium phosphide (InP), aluminum gallium arsenide (AlGaAs), indium gallium arsenide (InGaAs), indium gallium phosphide (InGaP) are commonly used direct semiconductor materials according to the desired lasing wavelength. Recently III-V nitride and III-nitride compound such as gallium nitride (GaN) and aluminum gallium nitride (AlGaN) have been used to achieve lasing in ultraviolet and blue regions [4].

1.2.2 Population Inversion

We have already discussed that, laser diodes utilizes the electrical conductivity of semiconductor materials by doping of impurity atoms. The doping, either p-type or n-type, is achieved by introducing respective impurity atoms, i.e. acceptor or donor, to the intrinsic semiconductor material. These atoms create new quantum mechanical states, donor level and accepter level, within the bandgap. Similar to the conventional semiconductor diode, the laser diode consists of both p-doped and n-doped materials. When a forward electrical bias is applied to the device optical gain is generated at the active region viz. p-n junction or undoped direct bandgap semiconductor material. At the active region carriers i.e. electron and hole, will recombine radiatively and generates a photon, shown in Fig. 1.5.

Laser operation requires a process called pumping, which is achieved by means of nonequilibrium carrier distribution in to the semiconductor material. This carrier distribution has to be large enough to enable a population inversion to generate optical gain and is realised using forward biased laser diode. Considering a simple p-n junction laser diode consists of heavily doped, and hence degenerate, p- and n-type material where the Fermi levels are pushed in to the valance band and conduction band, respectively. At the p-n junction, a depletion region exists which prevents majority carrier flow, through diffusion, by forming diffusion potential. Hence, with no forward voltage bias, the quasi-Fermi levels are identical throughout the p-n junction at thermal equilibrium, as shown in Fig. 1.6 (a).

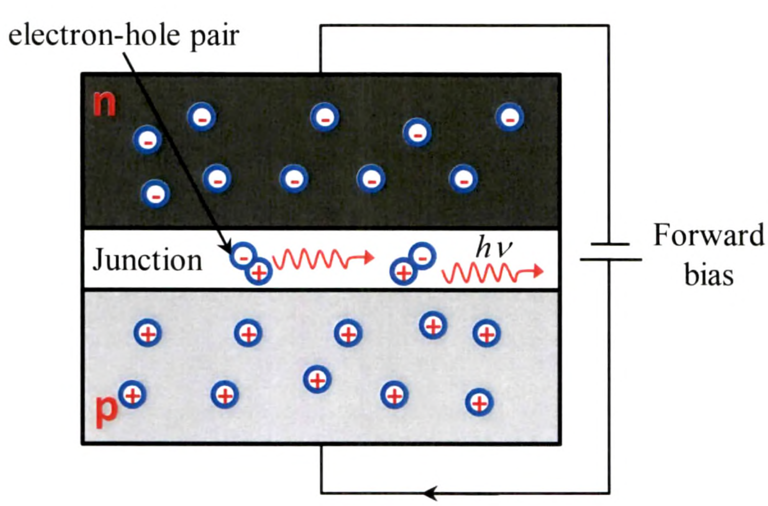

Figure 1.5: p-n junction under forward bias condition.

When the p-n junction is forward biased with a voltage (≈ E_g voltage), the diffusion potential is reduced, and free carriers can flow into p- and n-regions through the junction. Figure 1.6 (b) shows that, under forward bias, sufficient number of electrons and hole are injected into the conduction and valance band, respectively, and can create a population inversion in an active region where carries can recombine radiatively. Thus, while population inversion, photon generated in radiative recombination process either can be reabsorbed or can induce stimulated emission. For stimulated emission to occur, the externally applied field must results in separation of the quasi-Fermi levels such that $(E_{Fc} - E_{Fv}) > h\nu > E_g$ [1].

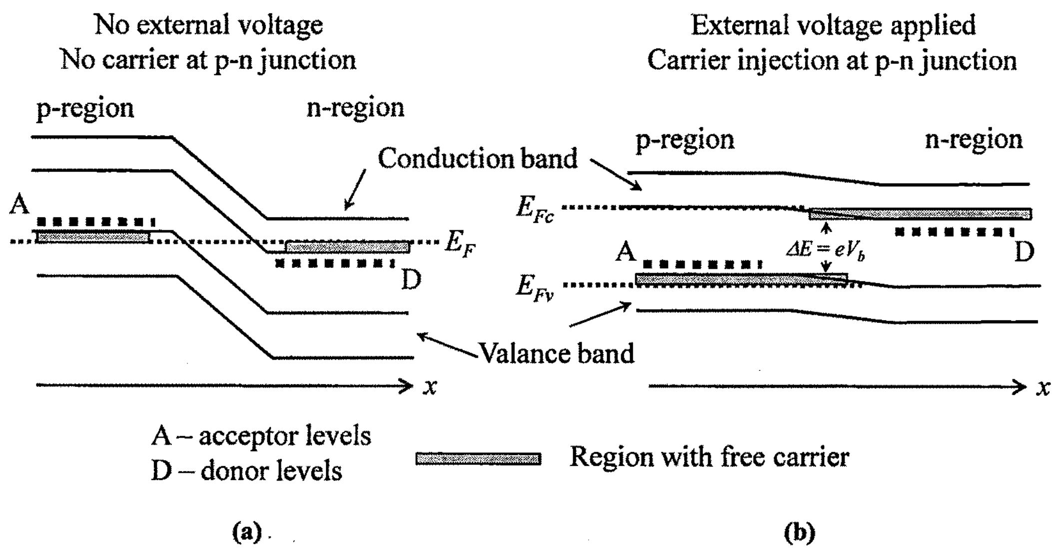

Figure 1.6: Band diagram of p-n junction under (a) zero bias and (b) forward bias conditions.

1.2.3 Resonator Cavity

The resonator cavity is used to provide a positive feedback loop for laser action. Usually, this can be realized by means of Fabry-Perot resonator consists of two parallel plane mirrors. In case of laser diode, usually edge-emitting laser diode, Fabry-Perot resonator cavity is achieved by cleaving the semiconductor crystal perpendicular to the cavity along well define crystal plane, shown in Fig. 1.7.

For GaAs the facets are cleaved at (110) plane and the growth of the active layer is in direction of (100) plane. Since the refractive index of the semiconductor material is very high (e.g. 3.6 for GaAs) in comparison with air, the reflectivity of the cleaved facets is sufficiently high to provide feedback for the laser oscillations. The reflectivity of the cleaved facets depends on the refractive index of the semiconductor. Equation 1.2 gives the reflectivity value for the case of normal incidence by Fresnel reflection [5],

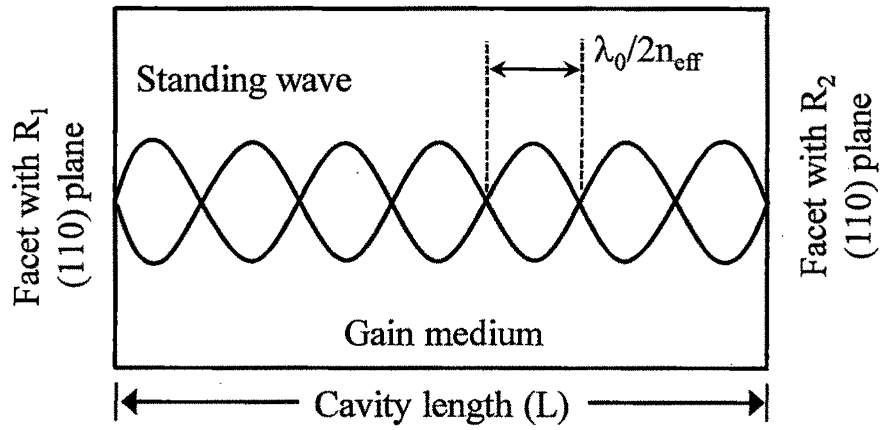

Figure 1.7: Illustration of standing wave in a Fabry-Perot resonator.

$$R = \frac{(n_s - n_a)^2}{(n_s + n_a)^2} \tag{1.2}$$

where, n_s and n_a is refractive index of semiconductor and air, respectively. For GaAs the reflectivity at normal incident is about 32 % at the GaAs/Air interface, which is sufficient to sustain laser oscillations in the medium. Before emission, photons emitted in parallel direction to the cavity length will be reflected severally at the facets. Each time they pass through the cavity, the light is amplified by stimulated emission. Hence, if there is more amplification than loss, the diode begins to lase. Also to enhance the lasing from the device, optical coatings of dielectric with appropriate refractive index can be applied to the facets to modify their reflectivities. Further the lateral confinement of photon is accomplished by gain or index guiding.

1.2.4 Vertical and Lateral Confinement

An epitaxial growth structure of a laser diode determines an optical waveguide and hence vertical optical confinement. An optical waveguide in a laser diode consists of a core film (e.g. quantum well) with high refractive index surrounded by a cladding material, i.e. n- and p-doped shield, with lower refractive index. Figure 1.8 illustrates the basic structure of laser diode consists of a three layer optical waveguide. The number of possible vertical modes and their distributions depends on the core film thickness and the refractive index difference between core and classing layers.

In addition, from the Fig. 1.9 we can say that this vertical growth structure also provides the carrier and optical confinement. To obtain single-mode operation in both transversal directions, an additional lateral confinement is required. There are three types of lateral-confinement mechanisms are possible: current confinement, optical confinement, and carrier confinement. Further details regarding lateral confinement are discussed in Chapter-3.

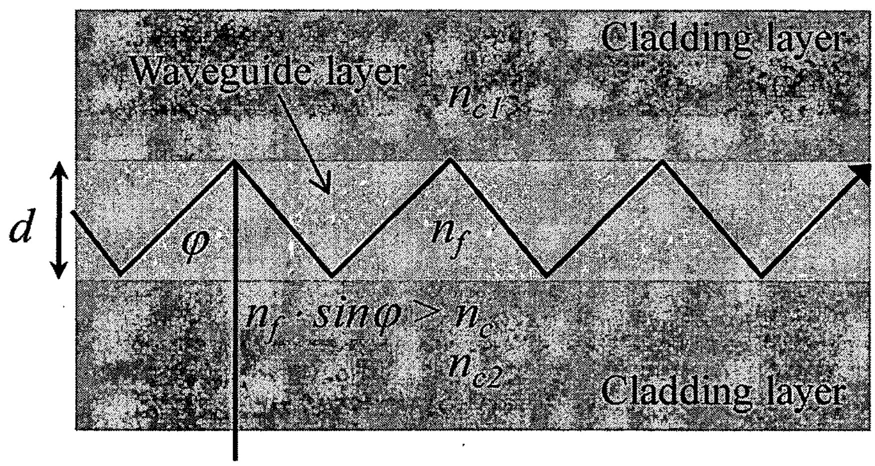

Figure 1.8: Schematic of an optical waveguide for double-heterostructure laser.

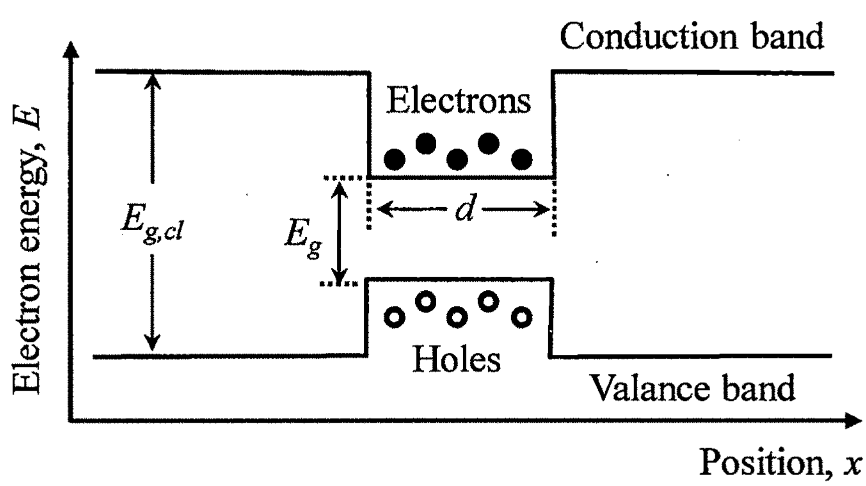

Figure 1.9: Energy band diagram shows vertical confinement of the carrier (electrons and holes) and photon in a double-heterostructure laser.

1.2.5 Condition for Lasing

A mathematical description of the lasing process in the laser diode can be obtained by calculating the optical field density inside the laser diode cavity [6]. As shown in Fig. 1.10, a Fabry-Perot resonator of cavity length, L, and a gain medium between two partial reflecting mirrors, with reflectivity R_1 and R_2.

The intensity, I, of a planar optical wave exponentially decreases while passing through an absorbing material in the z-direction, i.e.

$$I(z) = I_0 e^{(-\alpha_i z)} \tag{1.3}$$

here, I_0 is the initial intensity and α_i is the absorption coefficient, also know to as internal loss.

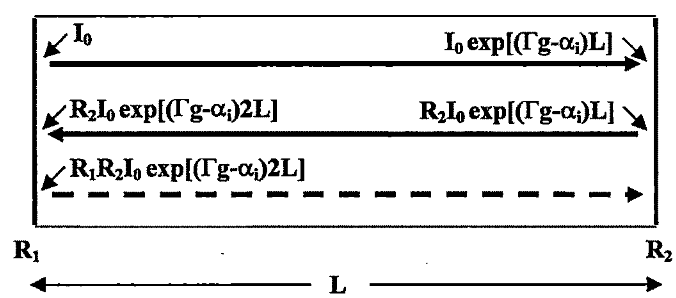

Figure 1.10: Intensity of an optical wave during a roundtrip in a Fabry–Perot resonator with cavity length L and mirror reflectivities R_1 and R_2.

Nevertheless, in laser diode the optical wave gets amplified and hence the optical gain is referred to as $g = (-\alpha)$. In an optical waveguide, the optical gain is classified in to two part because only a part of the intensity of the optical mode overlaps with active region, which is located in the center of the waveguide; one is material gain, g, i.e. the gain of active material itself and second one is the modal gain, g_{modal}, i.e. significantly lower gain of the optical mode. Thus intensity of a planar optical wave in an amplifying medium is given as

$$I(z) = I_0 e^{(g_{modal} z)} e^{(-\alpha_i z)} \tag{1.4}$$

The relation between modal gain and material gain is expressed by defining a confinement factor, Γ, which depends on the overlap of the optical-mode pattern with the gain region of the laser.

$$g_{\text{modal}} = \Gamma g \quad (1.5)$$

so, we can write Eq. 1.4 as,

$$I(z) = I_0 e^{(\Gamma g - \alpha_i)z} \quad (1.6)$$

The intrinsic modal absorption is caused by scattering of the optical mode at defects or rough interfaces and by free-carrier absorption. Although scattering is extremely low for semiconductor lasers with good crystalline quality, free-carrier absorption is inevitable since part of the optical-mode pattern overlaps with the p- and n-doped cladding regions. When the modal gain, g_{modal}, is larger than the modal loss, α_i, the propagating optical mode is amplified.

Moreover, some optical intensity leaves the cavity at these mirrors since the mirrors are partially reflective. As illustrated in Fig. 1.10, the intensity, I_{rt}, of the optical mode after a roundtrip in the cavity is given by

$$I_{rt} = I_0 R_1 R_2 e^{2(\Gamma g - \alpha_i)L} \quad (1.7)$$

Lasing occurs when the gain provided to the optical mode compensates the intrinsic absorption and the mirror losses for a roundtrip. The minimum gain, g, where the device starts lasing operation is called the threshold gain, g_{th}. In this case, the intensity, I_{rt}, after a roundtrip in the cavity again has its initial value, I_0.

$$I_{rt} = I_0 \quad (1.8)$$

This implies that

$$R_1 R_2 e^{2(\Gamma g_{th} - \alpha_i)L} = 1 \quad (1.9)$$

this gives,

$$\Gamma g_{th} = \alpha_i + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right) \quad (1.10)$$

Equation 1.10 illustrates that the gain must compensate for the losses due to internal absorption, α_i, on the one hand, and the light leaving the cavity, also referred to as mirror loss on the other hand.

1.3 Laser Diode Structures

Laser diode has been evolved from a simple p-n junction diode structure to very complex structures like vertical external cavity surface emitting laser (VECSEL) due to the inventions of various growth technologies. The brief description of the various laser diode structures with their merits and demerits are discussed below.

➢ **Homojunction Laser**

- ***Structure:*** a simple p-n junction of heavily doped same p- and n-type semiconductor material.
- Carrier recombination and population inversion takes place in an active region, i.e. a depletion layer formed by p-n junction.
- Optical feedback is realized by means of resonator cavity formed by cleaved mirror facets.
- Since, there is no cladding layer, photon generated inside active region getting absorbed in p- and n- regions.
- Also, the depletion region itself acts as an active layer having relatively higher thickness increases the threshold current density, at which laser begin to lase.
- They can only be operated at cryogenic temperature with very high input current density of the order of 10^3 A/cm^2.

➢ **Heterostructure Laser**

- ***Structure:*** a heterojunction of two unlike semiconductor materials.
- Classified into two: (a) single heterostructure (SH) (b) double heterostructure (DH)
- ***Single heterostructure:*** consists of only one side cladding layer
  - Confines only photon
  - Threshold current is high in comparison with double heterostructure laser.
- ***Double heterostructure:*** consists of two side cladding layer, usually a p-i-n structure i.e. undoped semiconductor (low bandgap, high refractive index) sandwiched between two cladding layers (p- and n-type layer with high bandgap, low refractive index).
  - Confines both photon and carriers

- Carrier confinement can enhance stimulated emission and eventually reduce the threshold current.

➢ **Quantum Well Laser**

- ***Structure:*** similar to DH, quantum well laser consists of an active layer having thickness comparable to the de-Broglie wavelength of the electrons or holes (typically 5 – 10 nm), the motion of the carriers is quantized in two dimensions and the structure is known to as quantum well (QW) structure [2].
- Good carrier confinement due to potential well structure however, reduced active layer thickness exhibits poor optical confinement.
- Low threshold current compared to DH.
- Separate optical confinement is required.
- Wavelength tenability by means of strained QW structure.

➢ **Quantum Dot Laser**

- ***Structure:*** Dimensions of the QW is further reduced in such a way that carriers are confined in all three dimensions.
- Low threshold current
- High temperature stability
- High wavelength tunability

1.4 Brief History of Laser Diode

The word laser is an acronym for Light Amplification by the Stimulated Emission of Radiation. Basically the laser diode has a history as long as that of the laser itself. In 1917 Albert Einstein first suggested the existence of stimulated emission. However, it takes about 43 years to support the theory empirically when Theodore Maiman built the first laser using a synthetic ruby, two mirrors, and a flash lamp [7] in 1960. This first ruby laser, operated at 694 nm, opened the gateway for a variety of lasers, with various materials and operating wavelengths. Few year back in 1962, Robert N. Hall and his team has demonstrated first laser diode at General Electric Research Center, United States [8].

The laser diode has a history essentially as long as that of the laser itself, being first demonstrated in November 1962 by Robert N. Hall and his team at General Electric Research and Development Laboratories in Schenectady, United States [8]. In the same year, three more groups, at IBM T. J. Watson Research Center [9], at MIT Lincoln Laboratory, Texas Instruments, and RCA Laboratories, succeeded in making laser diodes at their respective laboratories [10,11]. Since then, the design of laser diode has undergone an almost continuous evolution. These first generation laser diodes were simple GaAs homojunction p-n diodes with polished sides of the crystal itself forming resonator cavity [8]. These laser diodes are operated with threshold current densities of 1000 A/cm^2 at 77 K temperature in pulse mode. The CW operation at room temperature was made possible only after the demonstration of double-heterostructure (DH) laser diode in which the active layer is sandwiched between two layers of higher bandgap materials. This was demonstrated almost simultaneously by Zhores Alferov of the Soviet Union [12], and Morton Panish and Izuo Hayashi working in the United States [13]. The concept of DH laser diode was proposed earlier by Kroemer [14] and Alferov [15] in 1963, whose importance was recognized by the 2000 Nobel Prize in Physics. The further need and search of better efficiency, reliability and higher power led the laser diode to the design of quantum-well (QW), strained QW, and multiple QW laser diodes.

In 1975, J. P. van der Ziel et al. [16] made the first observation of QW laser operation. However, they were operated at 15 K. The first room-temperature operation of QW injection laser was demonstrated by Dupius et. al. in 1977 [17]. It had a single QW and a threshold current of about 3 kA/cm^2 at 300 K when pulse-operated. Very next year, they demonstrated the first CW operation of single-QW and multiple-QW lasers [18,19]. This started a steady growth in the popularity of QW lasers, which is still continuing. Further improvements in the laser efficiency have also been demonstrated by confining the carrier in two dimensions or three dimensions. This can be realize by reducing the QW layer to a 'layer' of quantum-wires (QWRs) [20,21] or quantum-dots (QDs) [22].

1.5 Application of Laser Diode

Semiconductor lasers, laser diode, due to their small size, robust, high efficiency, and low cost, cover extremely wide range of lasing wavelengths and hence applications from military to medicine and material science to meteorology. They are present in almost all field of our day-to-day life like, data storage, printing, lighting, laser marking, measuring, etc. Laser diodes find wide use in fiber optics communication as a signal source. It is a key component for laser printers, barcode readers, CD, DVD and Blu-ray disc drive. Moreover, the innovative improvement in laser diode fabrication technology and semiconductor material systems has revolutionize the two major systems of the information technology in last decay i.e. optical data transfer and optical data storage. Laser diodes are also used as optical pumping source or an optical amplifier in diode pumped, solid-state laser and fiber laser [23]. On basis of wavelength emitted from the laser diode, they have different application in various fields, as shown in Table 1.2.

Table 1.2: Various laser diodes applications depending on their emission wavelength [24].

Laser wavelength (nm)	Applications
405	Blu-ray disc and HD DVD disc drive
375 - 485	GaN based ultra-violate laser used in biomedical/medical applications
532	Laser pointer,
650	Laser pointer, CD-DVD disc drive
670	Bar code reader, printer
780	Raman spectroscopy
785	CD disc drive
808	Thermal printing
810	Nd:YAG diode pumped solid state laser (DPSSL)
980	Erbium doped fiber amplifier, Yb:YAG DPSSL
1310, 1550	Fiber optic communications
1650 - 3300	Gas sensing (mostly in meteorology)

Besides this, medical diagnosis and surgery, sensing, illuminators, weaponry, and industrial applications such as welding, cutting, heat-treating, cladding, and industrial machining are some of the other significant high-power applications of laser diode. Due to their high-power, small size, high efficiency and advancement in packaging technology, laser diodes are becoming an alternative to flash-lamp pump solid-state laser and carbon dioxide (CO_2) gas lasers.

These applications require reliable and efficient high-power continuous-wave (CW) or pulse mode operation of laser diodes. This application outline gives an impulse for the improvement of high-power laser diode (HPLD) reliability.

Despite their extensive usage, laser diodes are still a subject of dedicated research in a view of technological development, especially in India, because the technology of semiconductor processing is in its infancy in India. The optimization of various processes for the fabrication of high-power laser diode is of principal importance and five national laboratories in India are presently pursuing research in this direction: (1) Raja Ramanna Centre for Advanced Technology (RRCAT), Indore; (2) Tata Institute of Fundamental Research (TIFR), Mumbai; (3) Solid State Physics Laboratory (SSPL), New Delhi; (4) Central Electronics Engineering Research Institute (CEERI)-Pilani, Rajasthan and (5) Society for Applied Microwave Electronics Engineering and Research (SAMEER), Mumbai. Facet coating of laser diodes is being carried out at SSPL and CEERI only, whereas for bonding purposes some efforts have been put by TIFR and SSPL. Packaging of laser diode is being carried out at SAMEER, Mumbai. Fabrication and processing of laser diode is also being carried out at RRCAT. They have also started optimising facet coating and packaging of the laser diode. Recently, the unbounded diode laser of 450 mW/facet continuous wave (CW) power from single diode element of 980 nm wavelength with slope efficiency 0.82 W/A has already been reported at Semiconductor Laser Section (SCLS), RRCAT [25]. However, the high-power laser diode is still at a laboratory level and so far no industrial or manufacturing unit has entered this field of technology in India as per the best of our knowledge.

1.6 Motivation

Laser diodes are basically consists of a gain section between two mirror facets of a semiconductor crystal. Due to their high output power, small size and high efficiency laser diodes have potential to replace other laser viz. gas laser or solid-state laser, in various scientific and industrial applications. However, the reliability and lifetime of the laser diodes are still the crucial matter of concern and require significant development in laser diode fabrication technology. The major issue concerning with high-power laser diode is the device degradation. Basically, there are three main degradation modes namely rapid, gradual and sudden failure [26], affecting reliable performance of the laser diode. In case of high-power laser the most common degradation mode is sudden failure, also known to as catastrophic optical damage (COD) or catastrophic optical mirror damage (COMD).

In last decade, several studied have been performed to improve COMD level in various laser diode structures and its material systems such as AlGaAs, InGaAs, InGaP and InGaAsP. The increasing demand and importance of extracting more output power from the high-power laser diode has not only promoted the need to improve laser diode characteristics, but also encouraged the study to understand the causes behind the various failure modes. It has been revealed that during COMD dark line defects (DLDs) develop from the output facet into the lasers as dislocations and dislocation networks [27,28].This characterizes COD as a general mechanism related to high-power densities. Recent developments to overcome COMD include facet passivation [29] to reduce surface recombination velocity and hence facet degradation, variations in laser diode structures viz. quantum well intermixing [30] and low optical confinement structures [31] are introduced to decrease absorption at the facet, and non-injecting mirror [32,33] and non-absorbing mirror approach [34,35] to reduce current density and optical density in the vicinity of the laser facets.

Today's laser diodes are most efficient devices that convert electrical power into the optical. However, while operating in high-power mode part of the electrical power remains in the device and converted into the heat causes poor device performance. Therefore, to achieve high-power operation packaging of the device is the most vital part to attain. The present thesis deals with the optimization of various processes for the fabrication of high-power laser diodes to improve its lifetime and reliability. These processes include the epitaxial growth of laser diode structure, post-growth device-processing, facet coating, packaging and characterizations.

1.7 Thesis Overview

The present thesis deals with the post-growth processing and various fabrication processes for HPLD. These processes include laser diode processing, facet coating, and packaging. Each of these processes plays a vital role in determining the overall performance of the laser diode and need to be optimized very carefully, as various laser diodes characteristic parameters viz. electrical, optical, spectral, and device life-time, depend on it. The thesis includes the development and optimization of these processes for HPLDs to improve its performance and hence it reliability. The thesis also consists of various laser diode characterization techniques to characterize laser diode at different stages of optimization. The fabrication and automation of these characterization facilities are also discussed in the thesis.

The post growth processing has been optimized for InGaAs/GaAs double QW HPLD, fabricated at semiconductor laser section (SCLS), Raja Ramanna Center for Advance Technology (RRCAT), Indore (M.P), using metal organic vapor phase epitaxy (MOVPE) technique. The epitaxially grown wafer was processed to make laser diode bars using mesa-stripe geometry. Photolithography and lift-off processes are employed to form top metal contact stripe on the wafer. The contact stripe geometry of the laser diode defines the threshold current and external efficiency of the device and hence the optimization if this process is very crucial for HPLD. Moreover, mechanical lapping and polishing has been done to thin down the substrate up to 150 μm thickness, which reduces the device's electrical and thermal resistance and hence increase the efficiency. The metal contact deposition is also a very important process as it contributes to the series resistance of the devices. This process is optimized to minimize the series resistance.

The next step after optimizing the device processing is to passivate facets of cleaved laser bars by means of coating the facets with dielectric materials such as aluminum oxide (Al_2O_3), silicon dioxide (SiO_2), zirconium oxide (ZrO_2), titanium dioxide (TiO_2), or magnesium fluoride (MgF_2). The face-passivation to the laser diode reduces the surface recombination velocity and hence the degradation of the facets. Eventually, it increases the optical output power level at COMD (P_{COMD}). The cleaved bare facet, without facet coating, laser gives optical output from both the facets. In most of the applications optical power from only one of the two facets is useful. So we have designed and optimized single layer anti-reflection (AR) and quarter-wave optical thick (QWOT) multilayer high-reflection (HR) coatings on the front-and on the back-facets of the laser diode, respectively. The AR-HR films are deposited using electron beam evaporation technique. A special jig is designed and fabricated to hold the laser diode bar in the vacuum chamber during the facet coating. The AR-HR coatings are optimized for various laser diode structures such as,

- 808 nm multimode commercial laser diode [36];
- 980 nm, InGaAs/GaAs double QW laser diode grown by MOVPE [25,37,38];

We have also designed and installed in-situ reflectivity measurement system for precise control and monitoring of thin film reflectivity of AR and HR film during facet coating. To verify the empirical reflectivity data, measured in-situ, we have developed a numerical simulation based on the characteristic matrix solution [39]. The optical output power is enhanced from the front facet by a significant amount [36, 38] as a result of AR-HR facet coating. The optimized facet coating have also been tested for laser-induced-damage thresholds (LIDT) measurements and proved to be a suitable facet coating for HPLD [40].

The HPLDs characterization facility viz. L-I-V characteristics, spectral response, junction temperature measurement [41], life-time [42], and thin film characterization viz. transmission and reflection spectral measurements have been automated using Laboratory Virtual Instrument Engineering Workbench (LabVIEW).

Finally, the laser diode packaging has been optimized to mount the device on proper packages, according to its utilization. The packaging of the HPLDs is the most essential process for device production. It provides not only the mechanical support but also the electrical and thermal conduction to the device that makes it suitable for all applications. The leading factor in the laser diode packaging is die-and wire-bonding. The process to solder the laser chip or bar to the appropriate substrate by means of the any solder material viz. indium (*In*), gold tin (*AuSn*), known as die-bonding; while the further electrical interconnections of the laser chip/bar to the contact lead of the package by means of gold wire or ribbon is known as wire-bonding. Laser diode die-bonding is an essential part of the packaging which makes the device handy for further application. We have optimized the HPLD die-bonding process with two different types of solder material/s, namely, *In* preform (soft solder) and eutectic *AuSn* (hard solder) preform, using an indigenously developed setup [43].

Thermal management is an important factor for HPLDs packaging because the spectral response and lifetime are very sensitive to the device operating temperature. The chip material, the bonding medium and mount may have different coefficient of thermal expansion (CTE). As a result, significant stresses are produced on the bonded laser diode structure. These stresses may induce chip cracking and joint fracture thereby causing the device failure. Hence, the packaging substrate material selected for the laser diode should have high thermal conductivity and the coefficient of thermal expansion (CTE) should be matched with the device's substrate material i.e. GaAs, in our case. We have used gold plated Copper (*Cu*) and KOVAR (Ni:Co:Fe::29:17:54 wt%), as packaged substrate to optimize the bonding process. Once the laser diode chip is attached on the package, the next step in the packaging is assembly interconnection. The most common method for electrical interconnections is wire-bonding. Thin metal wire, usually gold, was used to connect device and contact lead. Wire bonded laser diode assemblies are then tested and characterized for high-power CW operation and life-time measurements.

The improved device performance has successfully been demonstrated after applying various optimized post growth process to the HPLDs. Single laser diode element with effective packaging gave an output power of ~ 670 mW/facet at ~ 2 A under CW operation with the dynamic series resistance of ~ 200 mΩ. Subsequently, the developed semi-packaged, non hermetic, laser diode was used for the characterization of electronic transitions of InAsP/InP quantum well in photoluminescence (PL) spectroscopy.

1.8 Thesis Organization

The thesis entitled "Reliability and Life-Time Improvement of High-Power Laser Diodes" has been organized in total six chapters, as follow:

Chapter 2: Following to the introductory chapter-1, the chapter includes primary characteristics of the laser diode, i.e. L-I and I-V characteristic, spectral response, lifetime measurement, and the optimization of its characterization processes. The development and upgradation of these characterization facilities and online data acquisition by means of LabVIEW (ver. 8.2) is also discussed in this chapter. The successful extraction of various laser parameters [Threshold current (I_{th}), Optical power (P_{out}), Turn-on voltage (V_0), Dynamic series resistance (R_s), Slope efficiency (η_{slope}), Differential efficiency (η_d), Junction temperature (T_j), and device Life-time (τ)] using an automated data acquisition system is described in this chapter.

Chapter 3: The chapter describes the study of growth and processing of HPLDs. It discusses laser structure design and growth techniques used for the fabrication of quantum well (QW) laser, in brief. The optimization of post-growth processes to fabricate the laser diode out of grown wafers is discussed in detail in this chapter. The laser diode processing to develop desired laser geometry (i.e. mesa-stripe in our case), comprise of: photolithography and lift-off process to make stripes, metal-semiconductor contact layer deposition, rapid thermal annealing (RTA), mechanical lapping and polishing, chemical etching, and scribing.

Chapter 4: This chapter deals with AR and HR coating of the front and back facets of the HPLD, respectively. Various dielectric oxide materials like aluminum oxide (Al_2O_3), titanium dioxide (TiO_2), silicon dioxide (SiO_2), zirconium oxide (ZrO_2), and magnesium fluoride (MgF_2), and their combinations are used to achieve the desired reflectivity, on respective facets, to optimize the facet coating process. Thin film deposition and its optical characterization, i.e. reflectivity measurement, are also discussed in brief, including in-situ reflectivity measurement, i.e. online reflectivity measurement and optimization while material is being deposited for the desired laser wavelength. The numerical simulation was done to calculate thin film reflectivity for particular wavelength using LabVIEW (ver. 8.2). The thickness of the film was estimated by means of matching the empirical reflectivity data to the simulated one. The effect of facet coating on laser diode performance is studied by measuring various laser parameters like, threshold current, optical power, and device-efficiency.

Chapter 5: This chapter describes optimization of bonding and packaging process for the HPLD. After being fabricated, the laser diode has to be bonded on some packages, to get properly utilized, by means of solder materials. Laser diode packaging process consists of die-bonding and of wire-bonding of the device. The laser diode chip/bar, generally known as die in technical terminology, is attached to the package by means of any solder material, the process is known as die-bonding. Parameters like bonding-temperature and curing-time are optimized for indium preform and gold-tin eutectic solder preform. Consecutively, the wire-bonding parameters viz. bonding-time, temperature, ultrasonic power, bonding-force, etc., have been optimized to provide external connection to the laser diode with package. The effect of bonding on various characteristic parameters of the laser diode is studied in this chapter, in detail.

Chapter 6: This final chapter contains miscellaneous topics related to the studies on damage testing of facet coated materials, device life-time measurement, and application of the packaged device. In case of HPLD, the main factor which limits the high-power operation is facet-degradation. To overcome this limitation, we have already optimized the facet coating; however, to improve the quality of the facet coating further, we have measured the damage threshold of these optical coatings using high-power solid state Nd:YAG laser operated under pulse mode and continuous wave (CW) operation. The effect of packaging on the reliability and performance of laser diode by measuring the device life-time is also discussed in this chapter. Finally, we have demonstrated the device application in photoluminescence spectroscopy of InAsP/InP quantum well samples.

* * *