CHAPTER 1

Introduction

1. Introduction

Laser diodes, with their extremely small dimensions and a wide range of lasing wavelength, play a vital role in the revolution of optoelectronic and information technology. This chapter gives a short introduction to the laser diode and their applications. A brief history of the development of laser diode, basic principles of laser, and lasing mechanism in semiconductor are included here for the sake of completion and convenience. The evolution of various laser diode structures is described briefly. The chapter also discusses the technological issues related to the fabrication of high-power laser diodes. The thesis deals with the optimization of various processes to address some of these issues. The thesis overview is given in the last part of the chapter.

1.1 Applications of Laser Diode

Revolutionary advancement of information technology in the last decade has converted the world into a global village. Information becomes available - for everyone, always, and everywhere. Computer and communication technologies have entered almost all the aspects of life and hence enormous amount of data are continuously exchanged all over the globe, which requires the data transmission to be as fast as possible. Obviously, the fastest way is to transmit the data in the form of light. Thus, optical data transmission provides the foundation of communication revolution, leading the 21st century to become the century of the photon.

Furthermore, huge volume of data transmission creates another challenge - the storage and retrieval of data when required. Again, light provides the solution. Optical data storage systems have opened the ways of storing and retrieving information with a high density and fast accessibility. Both of these applications, i.e. transmission and storage of data, require light source with special characteristics. The light has to be highly monochromatic at a defined wavelength, intense, and easy to focus, even over long distances. In addition, the source should be small in size, efficient, robust, and economical. At present, a light source that satisfies all of these conditions is the laser diode.

A laser diode, also called semiconductor laser or injection laser, is a tiny, complex structure of semiconductor materials that emits coherent, monochromatic radiation at the cost of electrical energy. Laser diodes are by far the most varied, flexible, cheapest and the most abundant lasers. The use of laser diodes is not only limited to the communication systems. They have been realized over an unparalleled range of emission wavelengths from ultraviolet to far infrared in a variety of material systems, thus expanding their field of applications over a vast area from military to medicine. They are also the key components in many optical and optoelectronic systems due to their small size, possibilities of monolithic integration with circuitry, and the unique ability to modulate the optical output at the speed in the range of gigahertz by a simple direct modulation of the operating current. Thus, the laser diode is an ultimate light source of the communication age.

The development in design and performance of laser diode has also explored new areas of applications for laser diodes and made it almost a household object. Laser diodes are used extensively in CD-DVD drives, HD-DVD, Blu-Ray technology, pointers, barcode readers, spectroscopy and instrumentation. These applications require a few milli-watts of optical power. However, there are other important applications of laser diodes where high optical power, typically from 100 milli-watts to a few kilo-watts, is essential. A primary application among these is the pumping of solid state lasers. Besides this, optical communications, medical diagnosis and surgery, sensing, printing, illuminators, directed-energy weaponry, and industrial applications such as heat-treating, cladding, seam-welding and industrial machining are some of the other significant high-power applications of laser diode. These applications require reliable and efficient high-power continuous-wave (CW) operation of laser diodes. The above scenario gives an impetus for the development and fabrication of high-power laser diode.

In spite of their wide usage, laser diodes are still a subject of dedicated research both from the standpoint of theory and technology. Moreover, 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 paramount 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. RRCAT is planning to start the two activities in the near future. Packaging of laser diode is being carried out at SAMEER, Mumbai. 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.

The present thesis deals with the optimization of various processes for the fabrication of high-power laser diodes. These processes include the epitaxial growth of laser diode structure, post-growth device-processing, facet-coating, packaging and characterizations.

1.2 Brief History of Laser Diode

The word laser is an acronym for Light Amplification by the Stimulated Emission of Radiation. Albert Einstein first suggested the existence of stimulated emission in 1917. However, it took 43 years to put the theory into the practice. In 1960, Theodore Maiman built the first laser using a synthetic ruby, two mirrors, and a flash lamp [1]. This first ruby laser, operated at 694 nm, opened the gateway for a variety of lasers, with various materials and operating wavelengths.

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 [2]. In the same year, three more groups succeeded in making laser diodes within weeks of each other [3,4,5]. 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. These laser diodes could be operated only at cryogenic temperature in pulse mode with a very large amount of current. 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 [6], and Morton Panish and Izuo Hayashi working in the United States [7]. The concept of DH laser diode was proposed earlier by Kroemer [8] and Alferov [9] 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. [10] 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 [11]. 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 [12,13]. 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 reducing the QW layer to a 'layer' of quantum-wires (QWRs)[14,15] or quantum-dots (QDs) [16].

1.3 Background and Prerequisites

A detailed study of semiconductor laser physics is beyond the scope of this work. Instead, the issues related to the fabrication processes of laser diodes are addressed. Also, there exists a wealth of literature covering various types of laser diodes, the physics of their operation, and applications [17,18,19]. Only the most basic concepts of laser action and an overview of the theory of laser diodes are provided here for convenience and completeness.

1.3.1 General Laser Theory

As mentioned earlier, the word laser stands for Light Amplification by the Stimulated Emission of Radiation, which suggests that laser is a special form of light emitted by stimulation, unlike the ordinary light. The electromagnetic radiation interacts with the matter in three different ways that are common to all types of lasers. These are: absorption, spontaneous emission and stimulated emission. These interactions are transitions of the charge carriers in the matter between different energy levels, which are induced by the electromagnetic field, i.e., the photons. The interactions are illustrated in figure 1.1.

For the sake of simplicity, let us consider an atom with only two energy levels; E_0 and E_1, as shown in figure 1.1 [a]. Under normal circumstances the atom will be in the lower level, E_0, as physical systems tend to remain in the lowest possible energy state. If an atom in the lower level is exposed to the radiation with photons of frequency $h\nu = E_1 - E_0$, then there is a high probability that it will absorb a photon and be excited to the upper level, E_1. This process is referred to as absorption, since the energy in terms of photon is absorbed in the material by an atom, raising the atom to a higher energy state (figure 1.1 [b]).

After being excited to the higher energy level, the atom returns to the lower level with emission of a photon of same energy $h\nu = E_1 - E_0$ within a few nanoseconds. In 1917, Einstein showed that this emission can occur in two ways: spontaneous emission - the atom simply falls to the ground state while emitting randomly directed photons (figure 1.1 [c]); and stimulated emission - the photons emitted spontaneously strike other excited atom and induce it to fall to the ground state with the emission of photon (figure 1.1 [d]). The stimulated emission exhibits two very important properties which create the basis for special characteristics of laser. First, the photon produced by stimulated emission has the same energy, and therefore the same frequency as the stimulating photon. Second, the light waves associated with the two photons are in phase and have the same state of 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.

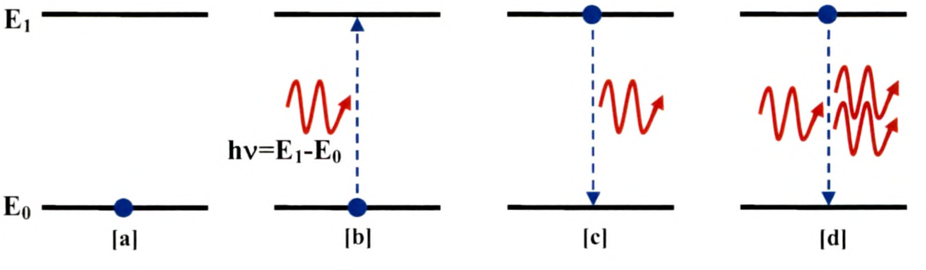

Figure 1.1: Light-matter interactions in simple two energy level system.

The light-matter interactions are governed probabilistically, and it is clear that stimulated emission must be the high-probability light-matter interaction for lasers. However, stimulated emission is not effective under thermodynamic equilibrium, at which the atoms and molecules tend to be at their lowest possible energy levels. The ratio of the number of atoms or molecules in state E_1 to that in state E_0 in thermodynamic equilibrium is given by the Boltzman distribution,

$$\frac{N_2}{N_1} = e^{\frac{-(E_1 - E_0)}{kT}} \tag{1.1}$$

At room temperature, this ratio is quite small for energy difference corresponding to optical wavelengths. This means that in thermodynamic equilibrium, most of the atoms or molecules are in the ground state and the stimulated emission is less probable. However, stimulated emission may dominate if more atoms are in the excited state than in the lower level because in this situation, photons are more likely to stimulate emission than be absorbed. 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. This excitation of the laser medium is called *pumping*, which can be done optically, electrically, or by other excitation methods. Further, these excitation techniques will work only if atoms or molecules have the right energy-level structure. Normally excited states have short lifetimes and release their excess energy by spontaneous emission in nanoseconds. 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.

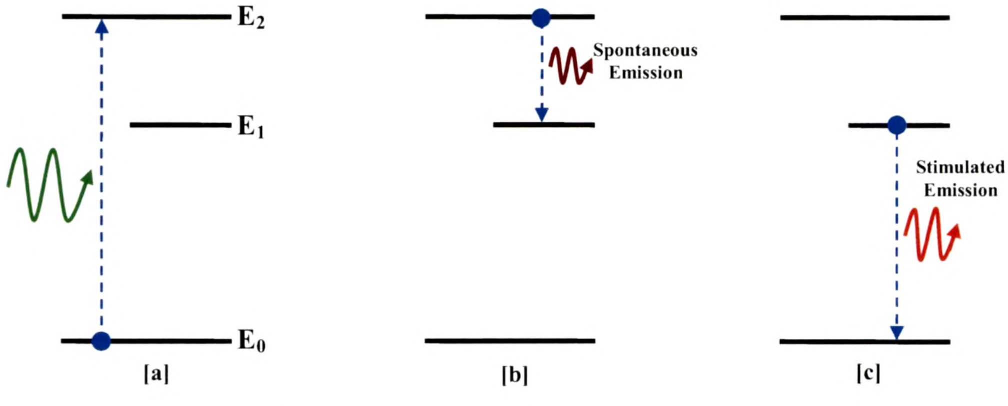

Figure 1.2: Energy levels in three level laser.

It is practically impossible to produce population inversion in a two level system. Practical laser systems involve three, four, or more energy levels, depending on how the energy is transferred. The simplest type of energy-level structure is the three-level laser, (like Maiman's ruby laser), which consist of a highly excited level, E_2, a meta stable upper level, E_1, and the ground state, E_0, as shown in figure 1.2.

Although the three-level system works, it is not the ideal one. Most practical lasers involve at least four levels as shown in figure 1.3. In the four level lasers, the excitation energy raises the atom or molecule from the ground state, E_0, to a short-lived highly excited level, E_3. The atom or molecule then drops quickly to a meta-stable upper level, E_2. The laser transition takes the atoms or molecules to a lower state, but not all the way to the ground state in a single step as in the case of three level systems. After they drop to the lower level, E_1, the atoms or molecules eventually lose the rest of their excess energy by spontaneous emission or other processes and drop to the ground state.

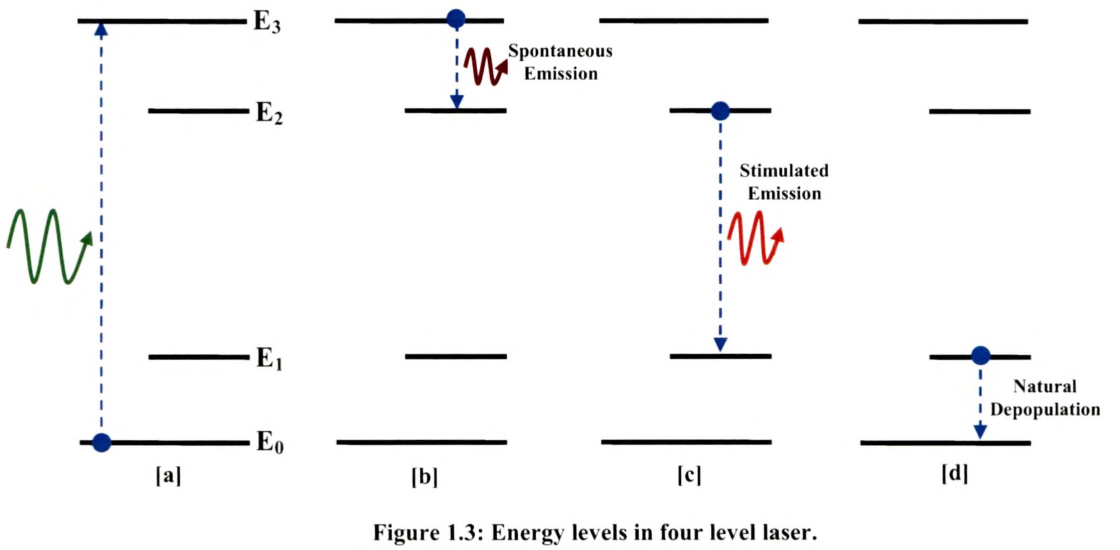

Figure 1.3: Energy levels in four level laser.

Once the stimulated emission starts, it must be sustained in the gain medium which introduces the final requirement for lasing - *the positive optical feedback*. By placing reflective surfaces at the ends of the gain medium, photons will be reflected back and forth along the cavity, forcing the excited atoms to decay via stimulated emission. Since the reflective surfaces are parallel to one another, the positive feedback causes wave amplification along the cavity-length, making the laser beam highly directional. A portion of the propagating wave transmits as the laser beam through one of the reflector at the end of cavity which is kept partially reflective. Thus, any laser system consists of three basics components; gain medium, pumping source and resonator cavity. A simple laser diode configuration is illustrated in figure 1.4.

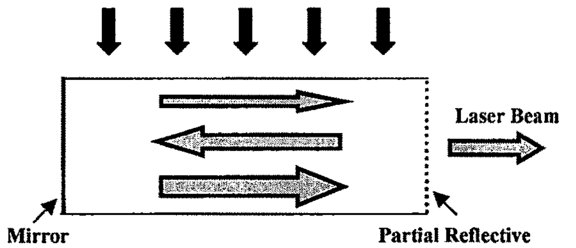

Figure 1.4: Illustration of basic structure of laser system.

1.3.2 Diversities of Laser Systems

Table 1.1 illustrates various types of material currently used for lasers and the corresponding wavelengths.

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
Laser Diodes	UV to far-IR
Ti:Sapphire	690 - 960
Alexandrite	720 - 780
Hydgrogen 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

The wavelength of light being emitted depends on the type of lasing material being used. Depending on the application, different types of lasers can be used. Gas lasers are used for high-power industrial applications. Solid state lasers deliver moderate power with excellent beam profiles. Laser diodes are cheap and small laser sources, ideal for applications in consumer products such as CD players or computer peripherals.

1.3.3 Lasing in Semiconductor

The electronic energy levels of gas and solid-state lasers are nearly as sharp as the energy levels of isolated atoms. In semiconductors, these energy levels are broadened into energy bands due to the overlapping of atomic orbitals. Each band consists of a very large number of closely packed energy levels. In an undoped semiconductor with no external excitation at a temperature of T = 0K, the outermost 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.

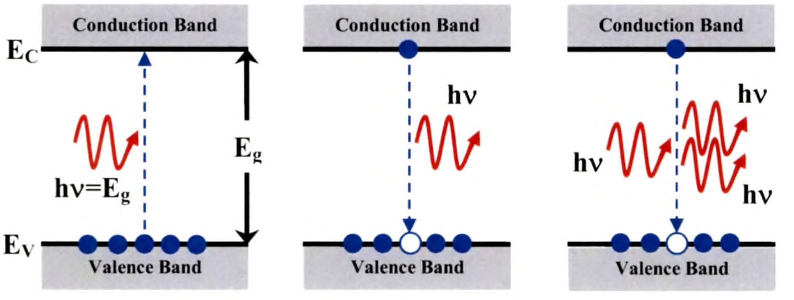

Figure 1.5: [a] Absorption, [b] spontaneous emission and [c] stimulated emission in semiconductors.

Energy transitions between bands are analogous to changes of energy state in an atom. Initially, most or all of the electrons may occupy the lower energy valence band while the conduction band is almost empty. If a photon of energy $h\nu = E_g$ or slightly larger enters the semiconductor, it will excite an electron from the valence band into the conduction band, leaving behind a *hole* in the valence band, as shown in figure 1.5 [a].

However, this excited state is unstable and the electron will eventually recombine with the hole, either spontaneously or by stimulation, thus returning into the ground state. Photon with same energy E_g is emitted when an electron falls from the conduction band to recombine with a hole in the valence band (figure 1.5 [b]).

All three basic elements of a laser, i.e. gain medium, pumping, and resonator cavity apply special mechanism in case of laser diodes.

1.3.3.1 Gain Medium

The optical gain medium is typically semiconductor p-n junction or a layer of a direct bandgap semiconductor material like gallium arsenide (GaAs). The p-n junction is formed by doping the semiconductor with acceptor and donor impurities to make it p-type and n-type, respectively. Light emission is not very efficient in semiconductors such as Si and Ge due to their indirect bandgap [19], which means that the minimum of the conduction band does not have the same value of wave-vector, k, as that with the maximum of the valence band as shown in figure 1.6 [a]. Hence, the recombination of an electron near the bottom of the conduction band with a hole near the top of the valence band requires the exchange of both, the energy in the form of a photon and the momentum in the form of one or more phonons, which makes the transition less probable.

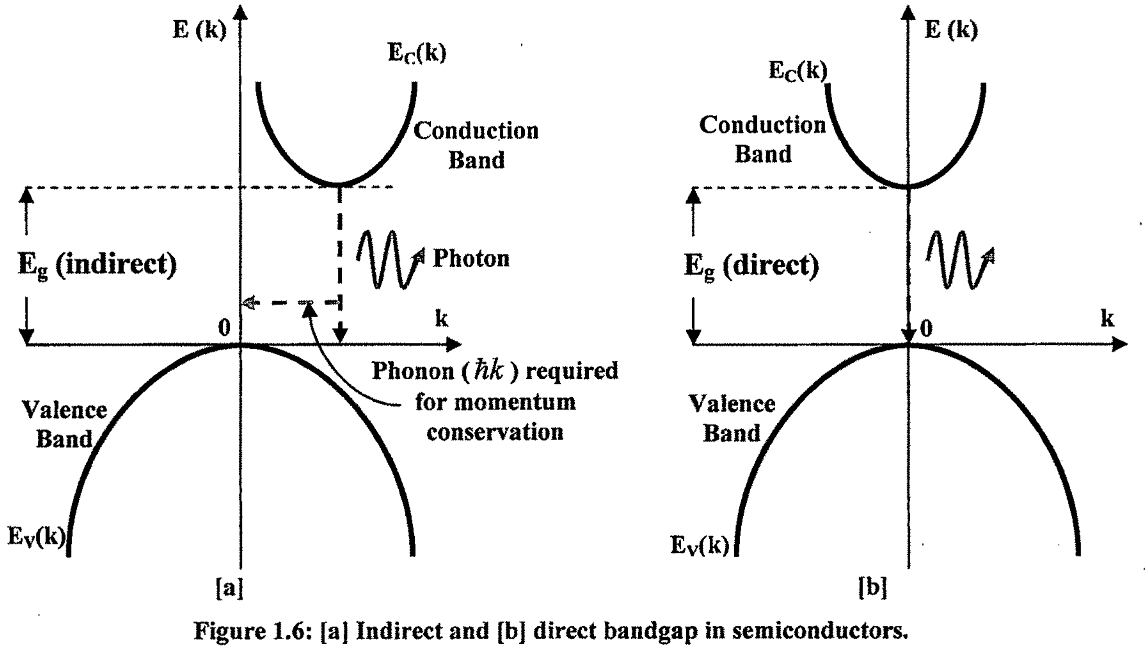

Figure 1.6: [a] Indirect and [b] direct bandgap in semiconductors.

In the case of direct bandgap material, the minimum of the conduction band in E-k diagram corresponds to the maximum of the valence band as shown in figure 1.6 [b]. 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.

Most direct bandgap semiconductors used for laser diodes are compounds formed by the combination of elements from the third and the fifth group of the periodic table, referred to as III-V compounds. Common laser materials are GaAs, AlGaAs, InGaAs, InGaP and InGaAsP depending upon the desired lasing wavelength. More recently, III-nitride and III-V-nitride compounds such as GaN/AlGaN have been used to achieve emission in the blue and ultraviolet regions [20]. 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.

1.3.3.2 Population Inversion

Laser diodes are pumped by electrical energy. Population inversion in a laser diode is achieved by injecting electrical current into the active region from n- and p-doped semiconductor layers using electrical contacts. Laser action arises due to a recombination of charge carriers injected into the semiconductor material. There are two types of charge carriers contributing to the electronic conduction in semiconductors: electrons in the conduction band and holes (electron vacancies) in the valence band.

Population inversion in laser diodes is best understood by considering the earliest type of laser diode based on a simple p-n homojunction, where both the p-type and n-type regions are of same semiconductor material (such as GaAs) and are degenerate, i.e. Fermi level is pushed into the valence band for the p-type material and into the conduction band for the n-type material by heavy doping. Thus both, n-type and p-type regions, contain large concentration of their respective majority charge carriers, i.e electrons and holes. However, at the p-n junction, a depletion region exists due to diffusion and subsequent recombination of electrons and holes from their respective regions. Hence, there are no free carriers in this regions and a barrier is formed which prevents further current flow by diffusion. Thus, under zero bias condition, electron-hole recombination on the average is balanced by the creation of new pairs, and there is no net flow of current carriers in the crystal. The quasi-Fermi levels align across the p-n junction as shown in figure 1.7 [a].

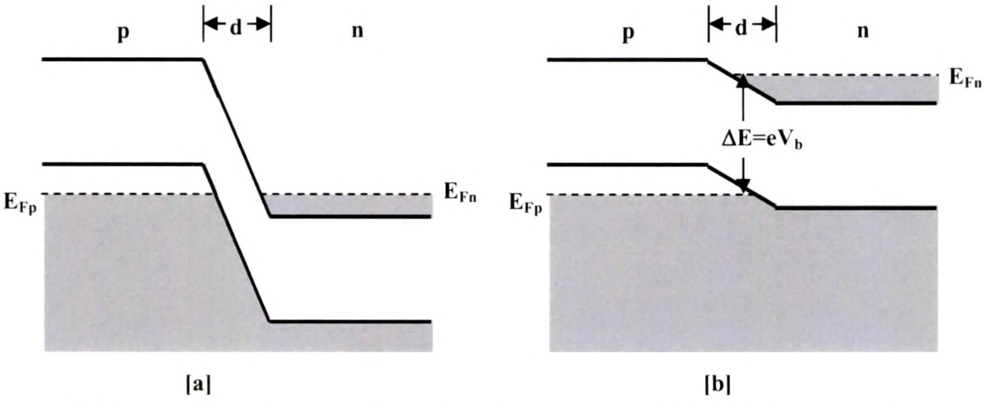

Figure 1.7: Band diagram of p-n junction under [a] zero bias and [b] forward bias conditions.

Under forward bias with voltage V_b, the quasi-Fermi levels become separated by energy $\Delta E = eV_b$ as shown in figure 1.7 [b], and an active region forms at the junction where electrons from the n-type region are injected into the conduction band and holes from the p-type region are injected into the valence band. The overlapping of Fermi levels at the junction causes the electrons and holes are to recombine radiatively as shown in figure 1.8. The corresponding change in energy state results in the population inversion which in presence of an incident photon allows stimulated emission to occur.

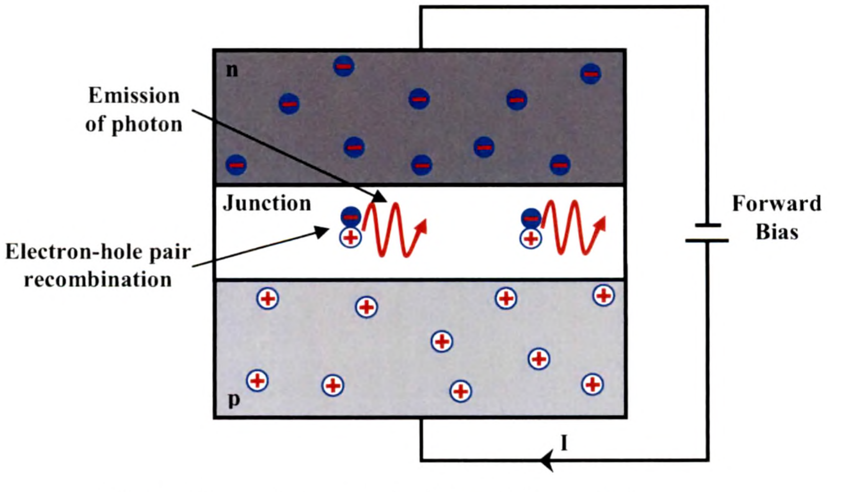

Figure 1.8: p-n junction under forward bias condition.

Thus electromagnetic waves propagating through the material experience gain. For stimulated emission to occur, the externally applied electric field must result in a separation of the quasi-Fermi energies that exceeds the photon energy of the stimulated emission and the bandgap energy of the semiconductor [17].

1.3.3.3 Resonator Cavity

For lasing to take place, the light must remain in the cavity long enough to interact with other electrons. This is achieved by creating a Fabry-Perot cavity with mirrored ends, where the light can reflect back and forth many times before leaving the cavity. The resonator cavity, in the case of laser diodes, is formed by cleaving the semiconductor crystal along one of its crystallographic axes so as to form two perfectly smooth, parallel edges. Due to the large difference of refractive index between the semiconductor materials and air, the cleaved facets of the crystal act like mirrors. The reflectivity of the cleaved facets mainly depends on the refractive index of the semiconductor and is given for the case of normal incidence by [21],

$$R = \frac{(n-1)^2}{(n+1)^2} \qquad (1.2)$$

For example, in case of GaAs with refractive index of about 3.5, the reflectivity is 30% which is sufficient to sustain laser oscillations in the medium. Such laser diodes are referred to as edge-emitting lasers. Photons emitted in precisely the right direction will be reflected several times from each end-facet before they are emitted. 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. More sophisticated coatings can then be applied to these facets to tailor their reflectivities. The lateral confinement is accomplished by gain or index guiding.

1.3.3.4 Condition for Lasing

A quantitative description of the laser process and in particular of the laser threshold can be obtained from calculation of the optical field inside the Fabry-Perot cavity [22]. Figure 1.9 shows such a resonator of length L with a gain medium between two partially reflecting mirrors, which have the reflectance coefficients R_1 and R_2, respectively.

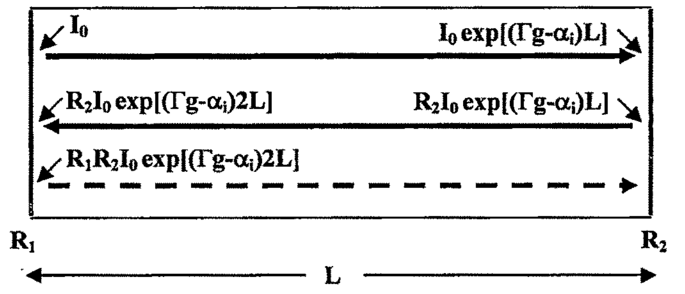

Figure 1.9: Intensity of an optical wave during a roundtrip in a Fabry–Perot resonator with cavity length L and mirror reflectivities R_1 and R_2.

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

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

with I_0 being the initial intensity and α_i the intensity-absorption coefficient, also called internal loss. However, in laser, i.e. active semiconductor material, the optical wave gets amplified. Hence, in this case, an additional exponential term has to be added in equation 1.3 to take account of gain experienced by the optical mode. In an optical waveguide, only a part of the intensity pattern of the optical mode overlaps with the active region, which usually is located in the core of the waveguide. One has to distinguish between the gain of the active material itself, called the material gain g, and the significantly lower gain actually available to the optical mode, called the modal gain g_{modal}. Thus intensity of a planar optical wave in an amplifying medium is given as

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

The relation between modal gain, g_{modal}, and material gain, g, 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.

$$g_{\text{modal}} = \Gamma g \tag{1.5}$$

Thus, we can write equation 1.4 as,

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

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 figure 1.9, the intensity I_{rt} of the optical mode after a roundtrip in the cavity is given by

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

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.

$$I_{rt} = I_0 \tag{1.8}$$

This implies that

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

which gives,

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

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 $\frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right)$, on the other hand.

1.3.4 Operation of Laser Diode

When the laser diode is forward biased, a net forward current flows through the semiconductor crystal. At low current, laser diodes generate some spontaneous emission by the same processes that drive LEDs and the spectrum is also very broad. However as the current increases, the laser diode passes a threshold, where the population becomes inverted and laser action begins. The light is emitted through the edges of the crystal as shown in figure 1.10.

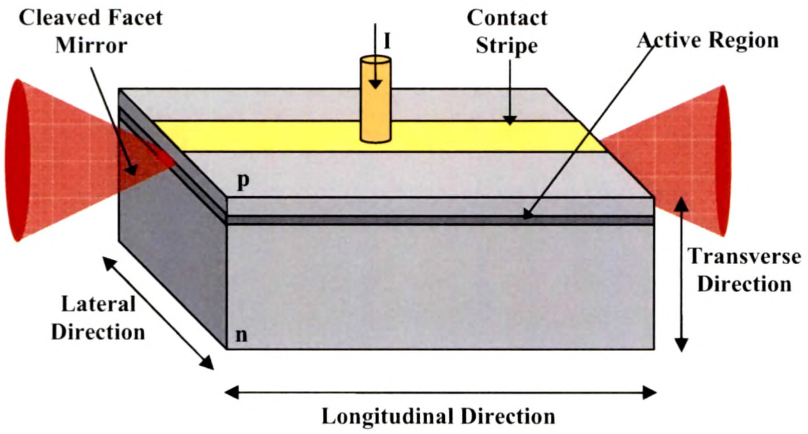

Figure 1.10: Typical edge emitting laser diode.

Once the current has passed the threshold, the light output rises steeply as shown in figure 1.11 [a], showing the presence of stimulated emission. As shown in figure 1.11 [b], the longitudinal modes of the cavity, which provide feedback, also start to dominate and the laser spectrum becomes narrow with typical line width of 1 to 5 nm. Thus, below threshold, spontaneous emission dominates, at the threshold, the semiconductor is optically transparent, i.e., gain equals losses, and above the threshold, stimulated emission dominates, which amplifies the light and the diode gives the laser emission.

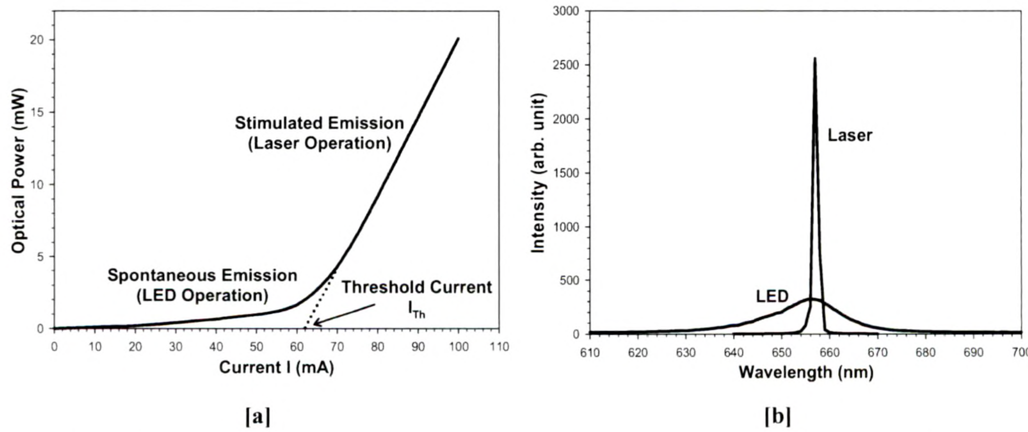

Figure 1.11: [a] Light output as a function of current and [b] laser spectrum of laser diode.

The divergence of edge-emitting laser diode beam is large compared to other lasers since the aperture through which the laser beam is emitted is very small, typically of the order of the optical mode. Moreover, the beam is usually elliptical in cross section. This is because the emission aperture of laser diode is narrow slit, whose long axis lies in the plane parallel to the junction. Diffraction of the beam is therefore stronger in the plane perpendicular to the junction.

1.4 Laser Diode Structures

Laser diode has evolved from simple p-n junction diode structure to very complex structures like vertical external cavity surface emitting laser (VECSEL). Various laser diode structures are described here in brief with their merits and demerits.

1.4.1 Homojunction Laser Structure

In homojunction laser diodes, pumping is achieved in a p-n junction where both of p and n regions are made of same semiconductor material. As described in section 1.3.3.2, both p and n type semiconductors are in the form of degenerate semiconductors and their Fermi levels remain aligned when no bias is applied. When forward voltage V is applied, Fermi levels in n- and p-type semiconductors get separated by energy, eV. This result in injection of carriers, i.e. electrons from conduction band of n type and holes from valence band of p type materials in to the depletion region and the population inversion is achieved at the junction. Radiative recombination of electrons and holes at the junction produce photons which get amplified by the resonator cavity formed by cleaved mirrors.

These lasers are only of historic importance as they operate only at cryogenic temperatures. This is due to very high threshold current density J_{th} at room temperature which originates from two reasons: (i) there is no cladding layer to prevent the light getting diffused in the diode's p-n side and gets absorbed there, and (ii) the active layer thickness is the thickness of depletion layer at the junction itself, which is relatively large. So, the transparency current density J_0, which is proportional to the volume of active layer, is very high.

1.4.2 Double-Heterojunction Laser structure

To reduce the threshold current density, both the carrier and optical modes need to be confined as closely as possible to the same volume which can be achieved by double-heterojunction (DH) structure. These diodes have surpassed the Homojunction Laser diodes due to a number of advantages. In these devices, a layer of low bandgap material is sandwiched between two high bandgap layers. Each of the junctions between different bandgap materials is called a heterostructure, hence the name *double-heterojunction laser*.

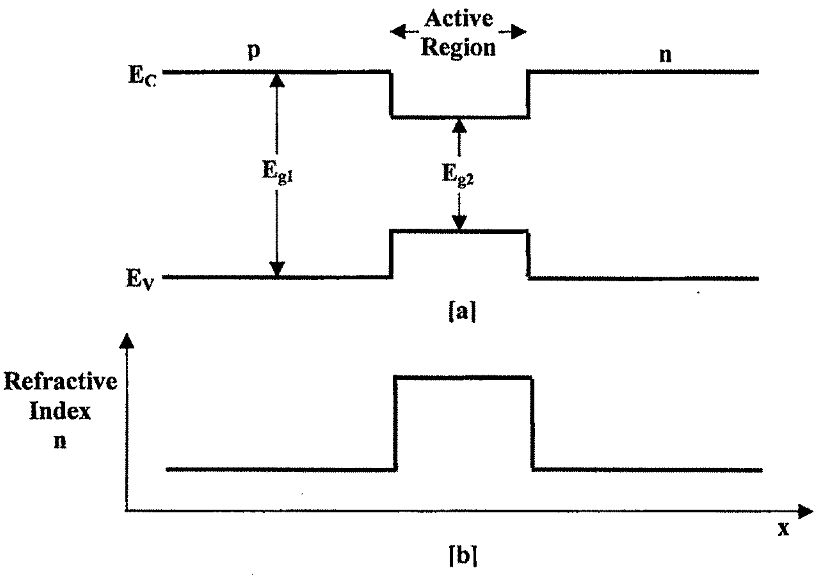

Figure 1.12: [a] Schematic band diagram and [b] refractive index profile for a Double Heterojunction laser structure.

Under forward bias condition electrons can easily fall from n-type material to the active region as they see a potential well but cannot crossover to the p-type material as this time they see a potential barrier, so they are confined in the active region as shown in figure 1.12 [a]. Since the active region has a lower bandgap than the cladding layers, its refractive index will be slightly larger than that of the surrounding layers as shown in figure 1.12 [b]. This useful consequence allows the optical mode confinement along with the carrier confinement in the active region.

With such a diode structure, the threshold current density can be reduced by about two orders of magnitude compared to a homojunction device [23]. Thus CW operation at room temperature is made possible. The reduction of threshold current density is due to the combined effect of three circumstances:

I. The refractive index of active medium is significantly larger than that of cladding regions (p and n sides), thus providing a guiding structure to the radiation. This means that now laser beam is confined in the vicinity of active region (photon confinement).

II. The bandgap of active region, Eg_2, is smaller than that of cladding layer, Eg_1. Energy barriers are therefore formed at two junctions that effectively confine injected holes and electrons within the active region. Thus for a given current density, the concentration of holes and electrons in the active region is increased and so is the gain (carrier confinement).

III. A very important part is that the lasing photon has frequency $\nu = E_{g2}/h$, which cannot be absorbed in the cladding layers as they have larger energy bandgap ($E_{g1}>E_{g2}$).

But in order to have these advantages, one very important requirement is the lattice matching of active layer and cladding layers. If this condition is not fulfilled, the strain produced due to lattice mismatch creates misfit dislocations and consequently lead to the non-radiative recombinations.

1.4.3 QW Laser Diodes

A very interesting and revolutionary innovation in laser diodes has been the development of QW laser diodes. If the thickness of active layer of DH laser is reduced to a point where it becomes comparable to the de Broglie wavelength of the carriers, λ_B, the carrier movements in that direction becomes quantized and the structure is called the QW structure [18]. The de Broglie wavelength of charge carrier is given as

$$\lambda_B = \frac{h}{\sqrt{2m^* E}} \tag{1.11}$$

where, m* is effective mass of carrier (electron or hole) [19], and E is energy of the carrier.

In QW laser, thickness of the active region is of the order of 10 to 100 Å. The QW has further favorable optical properties due to its own quantum size effect, arising from the confinement of the carriers to the finite potential well formed by the conduction and valence band edges. Thus, one can solve the Schrödinger equation in order to get discrete energy levels in the QW rather than a continuum as in bulk diode laser as shown in figure 1.13. This means that the vertical variation of the charge carrier's wave function, and thus a component of its energy, is quantized. In figure 1.13, Eg_1 and Eg_2 are the bandgap of bulk materials of barrier and QW layers, respectively, e_i and hh_i (i=1..n) are the electron and heavy-hole sub-bands, respectively.

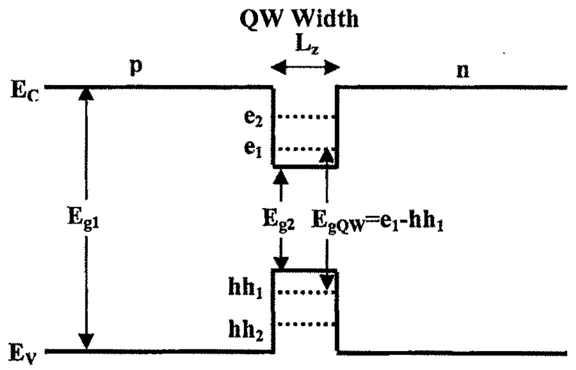

Figure 1.13: Schematic diagram describing the quantum size effect.

There are several causes of reduction of J_{th} in QW lasers - the density of states of electrons and holes in the bulk material (3-dimensional (3D)) varies as $E^{1/2}$ and from Fermi-Dirac statistics, it is known that probability of occupation of the levels in the bands decreases rapidly as E increases. The electrons are distributed over a wide energy range in the bands with a small density at the band edges due to which the population inversion is relatively difficult to achieve.

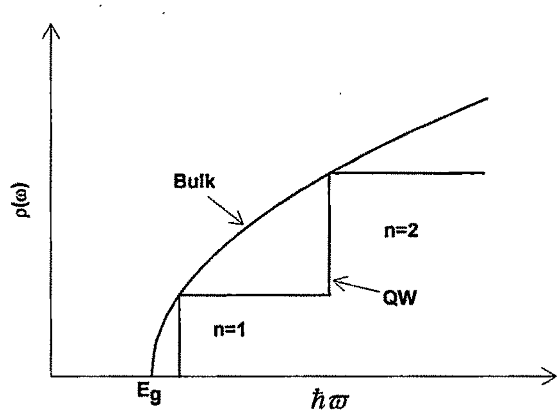

Figure 1.14: Schematic diagram showing the comparison density of states function in bulk and QW.

QW as active region causes significant enhancement in the density of states available in QW structure at the lowest transition energy as compared to the bulk materials as shown in figure 1.14. The figure shows the step like density of states function for QW (2D) structure and the continuous (3D) density of state function.

In the case of QW, due to abrupt increase of density of states at the sub band energy the electrons are spread over a smaller energy range with a high density at the sub band edge. This implies that the population inversion is achieved with lower injection carrier density in QW lasers than in conventional laser diode. As a consequence the threshold current density is reduced.

Moreover, the energy levels for QW depend on the width of the well, which allows one to fine-tune the lasing wavelength by changing the active layer thickness. Further, QW laser delivers gain with less change in refractive index than bulk lasers, resulting in lower chirp i.e. having narrower spectral line width [19]. However, the design of QW laser diodes imposes very strict requirements on the fabrication technique, which must provide an accurate control of the very thin (L_z < 10 nm) hetero-structures with abrupt interfaces that are free of defects.

However, there is a trade-off. As the thickness of active layer reduces, the optical confinement factor, Γ, decreases significantly as it is proportional to square of the active layer thickness. A single QW is typically 10 nm in width, and offers very poor optical confinement, compared to a bulk active region since the size of optical mode becomes larger than that of thickness of the active region. The poor optical confinement gives rise to a much larger gain requirement for QWs, which leads to gain saturation. Thus, the lowering of threshold current density due to quantum size effects can be largely offset by the small width of gain region in a single QW laser. One answer to this problem is to use multiple QWs which creates a material with much higher differential gain than bulk material but has gain saturation intermediate between those of a single QW and bulk material. To further improve performance, strained QW is introduced in the active layer. The strain is created by mismatching the lattice constants of adjacent layers. The strain in the active layer modifies the band-structure of the QW and the matching between the density of states of the conduction band and the valence band is improved. This results in increased differential gain and subsequently reduced threshold current density of the laser diode. Another option to improve optical confinement in the QW structure is to use separate layers for photon confinement in addition to the QW. This is achieved by Separate Confinement Heterostructure (SCH)

1.4.4 Separate Confinement Heterostructure

In Separate Confinement Heterostructure (SCH), two sets of different bandgap materials are used for the confinement of the charge carries and optical mode as shown in figure 1.15 [a]. As shown in the figure, the active layer is sandwiched between two inner barrier layers of the material having larger bandgap than the active layer to confine carriers and hence called carrier confinement layer. These barrier layers are again sandwiched between cladding layers with material having larger bandgap than that of barriers. The cladding layers confine the optical mode. Thus, charge carrier and optical mode are confined separately in SCH.

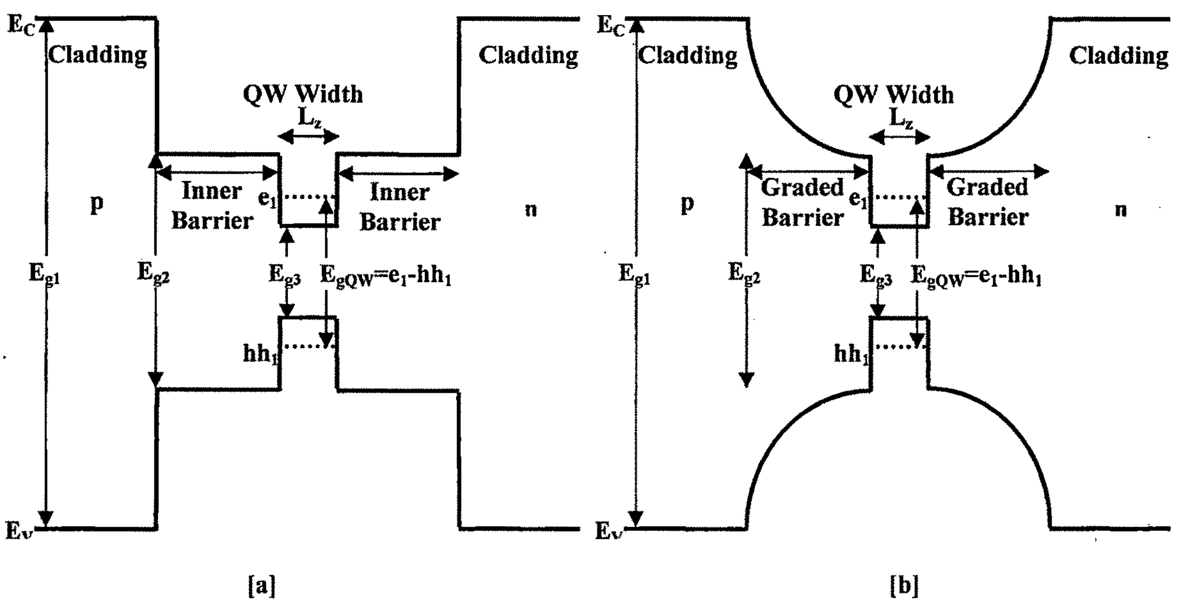

Figure 1.15: Schematic band diagram for [a] SCH and [b] GRINSCH laser.

It is also possible to grow the inner barrier layers with refractive index gradient rather than the abrupt variation in refractive index. This gives rise to further improved structure called the graded index separate confinement heterostructure (GRINSCH). Figure 1.15 [b] shows schematically the design of such a structure. Further improvements in the laser efficiency have also been demonstrated by reducing the quantum well layer to a layer of quantum-wires (QWRs) or to a *sea* of quantum-dots (QDs). Moreover, some applications require laser diode with single mode operation. However, the gain spectrum of a Fabry-Perot cavity is wide enough that many longitudinal modes experience gain. Although the central frequency experiences the most gain, the mode separation is small enough that several side modes will lase along with the central mode. Group velocity dispersion causes signal distortion and this severely limits the transmission distance of fiber optic systems. Hence, to achieve single mode operation, special type of laser diode structure such as distributed feedback (DFB) laser diode, is employed that incorporates a grating etched onto one of the cladding layers to achieve wavelength-selective feedback.

Also, most of these laser diodes are edge-emitting lasers, i.e., light is emitted from the edge of the semiconductor chip. These laser diodes have typical cavity length of around 0.5 mm to 2 mm, which allows several numbers of longitudinal modes to sustain in the cavity. Thus, a number of modes exists within the band width of the laser spectrum. Moreover, the output beam profile of laser diodes is also very different from other lasers such as gas lasers or solid state lasers. Since the size of the optical mode is of the order of the size of the laser diode, and the emitting region is asymmetric, the beam profile tends to be elliptical and the beam divergence is rather large. These drawbacks of edge-emitting laser diodes can be eliminated, to some extent, in geometries like Vertical Cavity Surface Emitting Lasers (VCSELs) and Vertical external-cavity surface-emitting lasers, (VECSELs), where the light is emitted from the surface of the laser diode. In this type of lasers, the mirrors are either epitaxially grown with the laser structure itself or placed externally instead of cleaving the crystal facets. However, surface emitting laser diodes have not been included in this work.

1.5 Thesis Overview

The present thesis deals with the processes to fabricate high-power laser diodes. Fabrication of high-power laser diode involves a series of complex processes. These processes include structure growth, laser diode bar processing, facet-coating, die-bonding, wire-bonding and packaging. Each process plays a decisive role in determining the output power, efficiency and overall performance of the laser diode, and thus needs careful attention. The thesis describes the development and optimization of these processes for high-power CW operation of the laser diode. The thesis also incorporates various techniques to characterize laser diodes at different stages during the fabrication and automation of these characterization facilities.

Major issues concerning fabrication of high-power laser diodes are two fundamental failure modes that limit the output power of laser diodes: (i) thermal roll-over and (ii) catastrophic optical mirror damage (COMD) [24]. Both these phenomena have been illustrated in figure 1.16.

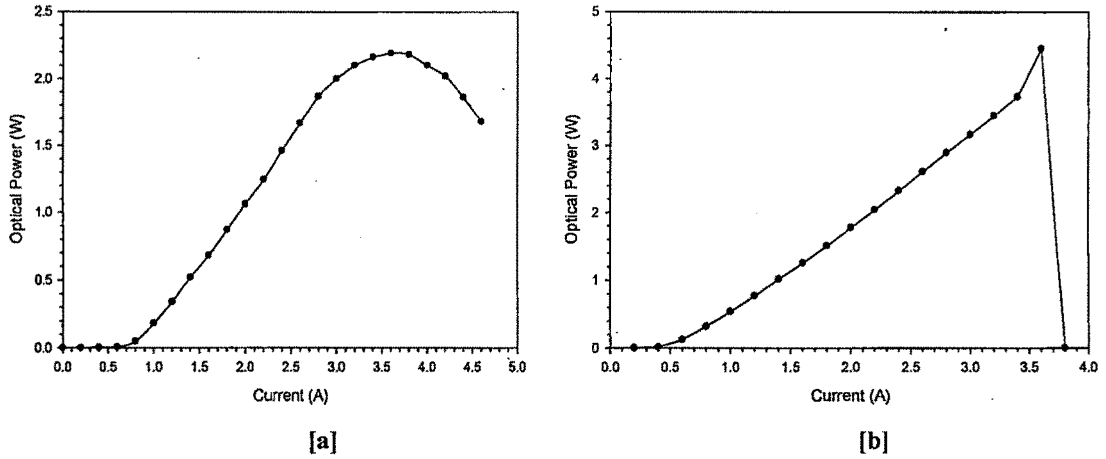

Figure 1.16: Failures in laser diode [a] thermal roll-over and [b] COMD.

The thermal roll-over occurs due to the heating of laser diode chip by the supplied electrical power. Heating of the device leads to an increase in the threshold current and decrease in the differential efficiency of the laser diode. Thus, after certain amount of current-injection, the optical output power of the laser diode decreases with increasing current, as shown in figure 1.16 [a]. Though thermal roll-over is a reversible phenomenon, it is of great concern for high-power laser diodes as it puts the limit on maximum achievable optical power, especially in CW operation. In the case of COMD, the device breaks down abruptly above a certain level of optical power and the laser diode is irreversibly damaged. This phenomenon is related to heating effect in a small volume at the laser facet. Due to the high concentration of nonradiative centers localized at the mirrors, where the crystal is abruptly interrupted by cleaving, the injected excess carriers in the active layer recombine at the facet nonradiatively, and thus release their energy via phonons to the lattice. This results in temperature-rise at the facet, which in turn lowers the bandgap locally and leads to an increased absorption of the laser radiation at the facet. The temperature further rises due to absorption of laser radiation and thus, a positive feedback process is initiated. The higher carrier density along with diffusion of carriers to the semiconductor surface leads to an effective power transfer into a small volume. Above a critical value of optical density at the facet, the temperature rises up to the melting point of the material. The laser diode is then permanently damaged as shown in figure 1.16 [b]. Due to the very small volume involved in laser diodes and high effective absorption, the COMD can occur on a very short time scale in the range of a few nanoseconds.

For high-power laser diodes, complete or partial laser failure may also occur as a result of mechanical damage of the facet in the region of intense optical emission [25,26]. The damage can be a local dissociation of material [27] which can sometimes extend up to a significant distance into the laser diode [28]. It is important to note that the *damage-threshold* (P_{COMD}) reduces if mechanical flaws exist at the laser facet. The optically induced facet damage initiated at these faults spreads into the other regions of the facet, too [29]. Thus, mechanical damages also create severe problem in case of high-power CW operation of the laser diodes.

The performance of a high-power laser diode is also limited as to how it is packaged. For high-power CW operation of laser diode, the laser diode bar is bonded to a mount made of metal for high electrical and thermal conduction. Thermal management is an important factor for high-power diode lasers because the expected lifetime and output wavelength are closely related to the temperature. The chip material, the bonding medium and mount may have different thermal expansion coefficients. As a result, significant stresses are produced on the bonded structure. These stresses may induce chip cracking and joint fracture thereby causing the device failure.

For achieving maximum power, overall efficiency and reliability in high-power laser diodes, following measures are considered to be effective and have to be taken into consideration.

- Realization of high internal efficiency
- Introduction of asymmetric coating for low mirror loss
- Realization of low internal loss
- High thermal dissipation

Structural optimizations have to be made because there is a trade-off among the factors listed above. The introduction of a long cavity, for example, is effective for low thermal resistance. However, increase of the threshold current and decrease of external quantum efficiency are observed in long cavity lasers. In laser design, the internal efficiency and the internal losses are mostly related to the growth of epitaxial layers, whereas the external efficiency, the threshold current density, and the series resistance are more influenced by the post-growth processing as well as by the facet-coating, bonding and packaging. These processes have been optimized in view of above mentioned problems associated with high-power laser diodes and are presented in following chapters

1.6 Organization of Thesis

A laser diode is a very complex semiconductor structure and is commonly fabricated using epitaxial techniques such as Metal-Organic Vapor Phase Epitaxy (MOVPE). Study of growth process of high-power laser diodes using MOVPE technique is described in chapter 2. The chapter also includes design and growth of multilayer QW structure and optimization and characterization of the individual layer of the structure to attain high optical power.

The ex-situ device fabrication processes are as crucial in achieving high-power CW operation as the epitaxial growth process. Chapter 3 presents optimization of post-growth processes to make laser diode bars out of grown wafers of QW structures. These processes comprise optimization of metal-semiconductor contacts and contact-deposition process, photolithography and lift-off technique to make stripes, optimization of stripe dimensions, and scribing.

Chapter 4 deals with AR and HR facet-coating respectively on the front and the back facet of high-power laser diodes. Deposition and characterization of thin films on facets including in-situ reflectivity measurements are discussed in this chapter. The chapter also incorporates study of facet-coating effects on the performance of high-power laser diode by means of its various parameters such as threshold current, external differential quantum efficiency, etc. Analytical simulation of L-I characteristics for different laser diode structures before and after the facets-coating is also given.

Various characteristics of high-power laser diodes and optimization of their characterization processes are included in chapter 5. This chapter also covers setup and automation of various characterization facilities for high-power laser diodes using virtual instrumentation in LabVIEW. Various characterization take account of measuring L-I characteristics, I-V characteristics, spectral response and reliability testing. In addition to the dynamic data acquisition and display, the data analyses and extraction of important laser diode parameters like lasing wavelength, threshold current, external differential quantum efficiency, turn-on voltage, series resistance, characteristic temperature, thermal impedance, lifetime and degradation rate of high-power laser diodes are also automated.

The last part of the thesis is focused on optimization of packaging process. The packaging process consists of mounting of high-power laser diode bar on the heat sink, called die-bonding and providing electrical connection on top of the laser diode chip, called wire-bonding. The packaging and testing of facet-coated high-power highly strained InGaAs QW laser diode have been demonstrated in chapter 6.

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