Chapter 4

Laser Diode Facet Coating Using Al_2O_3, SiO_2, TiO_2, and ZrO_2

4. Laser Diode Facet Coating Using Al_2O_3, SiO_2, TiO_2 and ZrO_2

The facet coating is one of the most important aspects of the high-power laser diode post-fabrication technologies. It protects laser diode from facet degradation and enhances the power level of catastrophic optical mirror damage (COMD) and eventually ensures long-term reliable operation. The facet coating is realized by an appropriate dielectric thin-film coating on the facets. This chapter discusses the optimization conditions for thin-film coating of various dielectric materials viz. Al_2O_3, MgF_2, SiO_2, TiO_2. *Study of anti-reflection (AR) and high-reflection (HR) coating on front and rear laser facets, respectively, and its effect on laser diode characteristic has been studied. Additionally, an in-situ reflectivity measurement technique has been optimized and described in detail.*

4.1 Importance of the Facet Coating

Laser diode facet coating is one of the most important phases in device fabrication technology. The laser mirrors are achieved by a three-step process: (1) Cleaving of the wafer into laser bars/chips, (2) Passivation of the cleaved surfaces, and (3) Coating for the desired reflectivity. The cleaved facets of the semiconductor crystal form the resonator cavity in a laser diode. Hence, the natural reflectivity of both the pure cleaved facets is nearly 32 % [6] and the laser diode emits an equal amount of light output from both the facets, as illustrated in Fig. 4.1 (a). However, in most of the practical applications, it is generally not possible to use the light from both facets of the laser. In order to make light emission from only one of the facets, one facet of the laser is coated with an antireflection (AR) coating and the other with a high reflection (HR) coating.

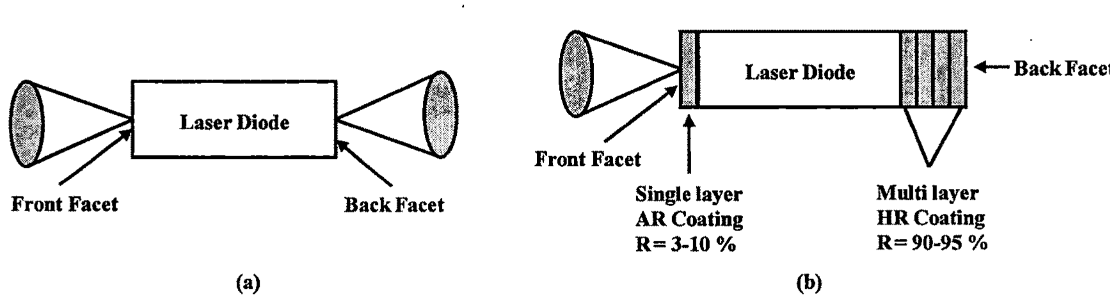


Figure 4.1: Schematic of facet coating on a (a) bare, without facet coating, laser diode chip with (b) single layer anti-reflection (AR) and multilayer high-reflection (HR) coating having reflectivity 3-10 % and >90 %, respectively.

The operation of the laser diode with a bare facet will lead to the facet oxidation, which causes the device degradation and sudden failure. The mirror coatings are deposited for passivation and protection of the sensitive laser facets. Consequently, one can either reduce or eliminate the laser diodes facet degradation by suitable coating. On the other hand, the facet coating will change the facet's reflectivity, allowing the light emission from the front facet and reducing the optical density inside the cavity, and hence, increasing the optical output power. Moreover, it also ensures long term and reliable device operation without affecting the mirror facet.

The facet coating must fulfill three crucial requirements: First, the preferred reflectivity should be realized, typically from 3 % to 10 % at front facet and > 90 % at the rear facet, as shown in Fig. 4.1 (b). Second, for higher mechanical and optical stability of lasing, the facet coatings have to exhibit a number of mechanical properties, viz. good adhesion to the facet surface, low mechanical stress, chemical and mechanical stability, and an excellent behavior with respect to lifetime and catastrophic optical mirror damage (COMD). In addition, for optical communication systems it is necessary that the beam characteristics of the laser devices do not change by facet coating. That means a stable optical operation and high transparency at the wavelength of emission is required after the facet coating. The third requirement is that the facet coating process must be cheap, reproducible, and technologically worthy for mass-production.

The dielectric thin film coating to the laser diode facets not only protects it from environmental influences but also reduces further chemical and thermal effects to the facets and eventually increases the device lifetime. Nonetheless, the electronic states at the interface between the laser facet and the coating can act as traps for minority carriers and cause nonradiative recombination of the carriers. Therefore, an appropriate material selection having good chemical and mechanical stability with sufficiently large bandgap than laser material can improve the laser performance. The particular characteristic viz. self-passivation, high density, and having an ability to withstand exposure to heat and humidity, of the facet coating makes it a low-cost alternative to the hermetic packages for the laser diode, indeed [92]. Facet coating reduces the degradation rate significantly [93,94]. The reflectivity modulation to the laser facets can lead to the better side modes suppression and show a narrower width of the spectral peak. *T. Guhne et al.* [95] has demonstrated the reduction in beam divergence off the axis perpendicular to the active region by 30 % by means of SiO_2 (silicon oxide) AR coating application. Also by proper design of the facet reflectivity the lasing transition of the quantum well can be tailored to take place either between the n = 1 or n = 2 sub-band [96].

4.2 Optical Thin Film Coatings

The reflectivity modulation works on the principle of interference in thin films. Optical interference in a thin film can be explained in terms of the wave theory of light. When a light wave traveling in a certain medium having refractive index, n_0, encounters a medium having different index of refraction, n_1, a portion of light reflects at the interface. The amplitude of this reflected light wave, which is equivalent to the electric field strength, depends on the refractive indices of a medium at the interface and can be given for normal incidence as

$$\rho = \frac{n_0 - n_1}{n_0 + n_1} \tag{4.1}$$

This Eq. 4.1 was developed by the French physicist *Augustin Jean Fresnel* in 1896 and also known as the Fresnel Equation. The Fresnel reflection coefficient ρ in the above equation is real. The sign of this coefficient determines that whether there is a phase shift between the incident and reflected wave or not and it depends on the difference between n_0 and n_1. One can modify the reflectance of a surface by coating the surface with single or multilayer dielectric thin films. In a multilayer coating, a portion of the incident wave is reflected at each of the interfaces. The phase difference between the incident and reflected light causes either constructive or destructive interference, accordingly, the reflectance of the coated surface increases or decreases, respectively. This phase difference depends upon the film's thickness and its refractive index, also known as *optical thickness.*

There are basically two types of coatings namely antireflection (AR), and high reflection (HR) coatings needed on a laser chip/bar facets to make them functional. A wide range of coating design and materials to be used in the coating has been studied. The most common material for laser facet is GaAs. This material has a high refractive index at various wavelengths. As discussed above, the reflectivity of pure cleaved facet is nearly 32 %. This value can easily be modified by coating of the facets with an appropriate layer or a stack of layers; particularly, the front facet coating should have a negligible absorption for the laser emission wavelength.

4.2.1 Antireflection Coating

Anti reflection (AR) coating is one of the essential processing technologies for realizing high-power operation of the laser diode. It is also essential to realize super luminescent diodes (SLDs) and semiconductor laser amplifier. For the amplifier application, it is necessary to achieve maximum optical power for minimum electrical consumption and to minimize the modal reflectivity at the end facets. The simplest method to obtain high-power is the AR facet coating to one of the laser facets [97,98]. Laser diodes with one or both of their facet reflectivity reduced by AR coating are transformed from oscillating cavities into gain media. Since the laser diodes with AR coating are continuously tunable over a wavelength range of more than 25 nm and having mode stability, they can be used as external cavity diode laser (ECDL) by means of coupling with a grating [99]. The wavelength stabilization on high-power laser diode can be achieved with an additional AR coating to the facets [100]. The catastrophic optical mirror damage (COMD), permanent damage to the laser mirrors by local facet heating, is the most prominent damage mechanism of the high-power laser diode. The non-absorbing facet coating to the device is the easiest way to suppress the COMD and increase device reliability [101,102] as it reduces the optical density at the front facets and reduce the facet heating effect.

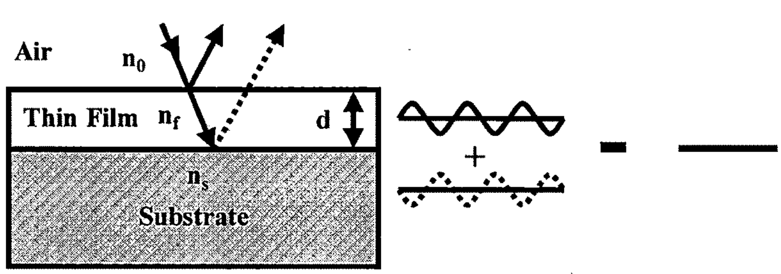


Figure 4.2: Destructive interference between light beams reflected from the upper and the lower surface of the deposited dielectric thin film for AR coating.

The antireflection coating works on the principle of the destructive interference of the light waves, reflected from the layer interfaces of the thin film. The coating is design in such a manner that the phase shift between the reflected light wave from the front and back surface of the thin film is 180°. If the light waves recombine destructively then there will be no reflection of the light at the front facet, as shown in Fig. 4.2, and hence the AR coating ensures the maximum light transmission form the front facet.

The simplest way to design AR coating is that the quarter-wave optical thick (QWOT) film deposition, where the optical thickness of the film should be quarter of the lasing wavelength i.e. $\lambda/4$, of the laser diode. Hence, the physical thickness, d, of the coating layer, for normal incidence of light, will be $\lambda/4n_f$, where n_f will be refractive index of the thin film. Beside the lasing wavelength and the thickness of the coating layer to optimize the AR coating, one has to look out for refractive indices of the substrate, n_s, and the thin film, n_f, and angle of incident , θ. For minimum reflectance, the refractive index of the film, n_f should be chosen so that, $n_f = \sqrt{n_0 n_s}$ where, n_0 is the refractive index of medium, usually air. The normal reflectance, R, of a single layer AR film is given by the Eq. 4.2 [5]. One can easily adjust the reflectivity minimum according to the laser emission wavelength by varying the film refractive index or in other words by changing the coating material.

$$R = \frac{(1-n_s)^2 \cos^2(\delta) + \left(\frac{n_s}{n_f} - n_f\right)^2 \sin^2(\delta)}{(1-n_s)^2 \cos^2(\delta) + \left(\frac{n_s}{n_f} + n_f\right)^2 \sin^2(\delta)} \tag{4.2}$$

where,

$$\delta = 2\pi \frac{n_f d}{\lambda} \tag{4.3}$$

Normally, the single layer AR coating does not provide very low reflectivity that can be realized by multilayer AR coating. However, in case of laser diode the reflectivity achieved by a single layer AR coating is usually sufficient. In addition to that, the design and optimization a single layer AR coating is very simple and cost effective. Therefore, we have used single layer AR coating for reflectivity modulation for our laser diodes.

4.2.2 High-Reflection Coating

The high-reflection (HR) coating is used to prevent the light emission from the rear facet of the laser diode and to reflect most of the light back into the cavity. To increasing the reflectivity of the laser facet, a multilayer dielectric thin film is utilized in general. Therefore, the HR coating consists of a number of bi-layer pairs of low and high refractive index materials. As its name suggests the basic working principle of HR coating is exactly opposite to the principle of AR coating, i.e. constructive interference. The light waves reflected from each consecutive surface of the multi-layer coating, all in phase, recombine constructively and this superposition of the light makes the coating highly reflecting. So, one can achieve very high reflective coating simply by increasing number of bi-layers. The HR coating consisting of a stack of alternating bi-layer films pair. Each pair consists of a QWOT low refractive index- (n_L) and high refractive index- (n_H) material layer according to laser diode wavelength. The actual structure of the multilayer HR coating is, Substrate (GaAs for most of the laser diode)-LH...LH-Air, where L be the low refractive index material, and H be the high refractive index material. The reflectance at the wavelength, λ, is given by [103],

$$R=\left[\frac{n_s^F - n_0}{n_S^F + n_0}\right]^2 \tag{4.4}$$

where, $F=\left(\frac{n_H}{n_L}\right)^{2p}$ and p is the number of bi-layer pairs. From the Eq. 3.4, it is clear that higher the ratio of (n_H/n_L) is, the required number of bi-layers for HR coating will be less. The reflectivity increases with the number of bi-layers. To reduce mechanical stress and to increase the stability of the coating, it is necessary to choose a material pair that exhibit good adhesion and reduces the number of bi-layers necessary to reach the desired reflectivity.

4.2.3 Materials for AR – HR Coatings

In order to meet the demands of the laser diode facet coating and the coating process, the evaporation materials should fulfill a number of requirements viz. it should be depositable on the facets without causing any damage to the underneath layer, having a suitable refractive index and should be transparent for the lasing wavelength. The coating material should have refractive index equal to the square root of the effective refractive index of the laser facets at the particular wavelength to realize single layer antireflection coating having minimum reflectivity. Above all, the chemical purity of the material is to be of concern as it influences the properties of the coating. The impurities in the coating generate defects and causes optical losses in film e.g. scattering or absorption by changing the film stoichiometry. Normally, the material having 99.99 % purity can be utilized for the optical coating.

The first choice of the coating materials is based on its refractive index value and the transmission range, of course. As it is known, low absorption is obviously required so as the material do not absorb light at the wavelength of interest. The transmission range of materials is limited by the bandgap and the molecular vibrational absorption, at shorter and at longer wavelengths, respectively. Thus, the bandgap of the material should be much higher than the laser photon energy. Moreover, this is the reason why dielectric stack of low and high refractive index materials is preferred over metals for HR coating despite the fact that metals provides high reflection easily. Moreover, one also cannot ignore the possibility of shorting of the laser diode contacts due to the metal coatings to the facets. Above all, the coating material should exhibit a long-term stability over the atmospheric effects and even under the high-power operation of the laser diode.

The desired value of the modified laser diode facet reflectivity is about 3-10 % for the front and >90 % for the back facet. There are many materials suitable to modify the laser facet reflectivity. Typically, a single layer QWOT Al_2O_3, SiO_2, MgF_2, is used as antireflection coating at the front facet, and to increase the reflectivity at the back facet one of these materials will be paired with a material having higher index of refraction, say Silicon (Si), than that. Many materials have been reported for the AR coatings on the laser facets. For example, silicon nitride [104], and gallium oxide (Ga_2O_3) [105] were used to obtain single layer AR coating. In case of multilayer HR coating, the performance is strongly bound to the ratio of the refractive indices of the materials making up the stack. High refractive index value ratio provides wider bandwidth and requires fewer layers to obtain specific reflectance. Thus, for multilayer HR coating, one of the materials should have high refractive index compared to the other.

We have used QWOT Al_2O_3 and ZrO_2 for AR coating to 808 nm and 980 nm laser diode, respectively, while HR coating for these devices realized by means of multilayer QWOT pairs of Al_2O_3/TiO_2 and SiO_2/ZrO_2, respectively for 808 nm and 980 nm. Here, Al_2O_3 and SiO_2 are low-refractive index material in comparison to the TiO_2 and ZrO_2 being high-refractive index material. Table 4.1 (a) & (b) show the physical and optical properties of the bulk material used for facet coatings [24], respectively.

Table 4.1 (a) – Physical properties of the bulk materials used for AR – HR facet coating.

Material	Symbol	Color	Melting Point (°C)	Density (gm/cm^3)	z – factor
Aluminum Oxide	Al_2O_3	Clear white	2072	3.97	0.999
Titanium Oxide (IV)	TiO_2	White	1830	4.26	0.4
Silicon Dioxide	SiO_2	White	1610	2.65	1.00
Zirconium Oxide	ZrO_2	White	2700	5.89	1.00

Table 4.1 (b) – Optical properties of the bulk materials used for AR – HR facet coating.

Material	Refractive index	Wavelength range	Dielectric constant	Energy band-gap (eV)
Aluminum Oxide	~ 1.75 (at 808 nm)	50 nm – 6 μm	~ 10	10
Titanium Oxide (IV)	~ 2.48 (at 808 nm)	220 – 720 nm	~ 30	5.6 – 1.1
Silicon Dioxide	~ 2.00 (at 980 nm)	0.18 – 3.5 μm	~ 3.9	5.65
Zirconium Oxide	~1.45 (at 980 nm)	0.25 – 9 μm	~ 25	9

The refractive index of the Al_2O_3 is about 1.66, nearly same as to optimize single layer AR coating for the wavelength of our interest. As mentioned in Table 4.1(b), the useful transmission range of the Al_2O_3 extends from 50 nm to 6 μm. The Al_2O_3 has relatively high dielectric constant, k ≈ 10, wider bandgap, ~10 eV and high chemical stability [106]. It too exhibits high resistivity, high thermal conductivity, and stability with a thermal expansion coefficient of 8.4×10^{-6} /°C. In addition, the hardness and the high corrosion resistance favor Al_2O_3 as a passivation layer. Titanium dioxide (TiO_2) has been used in optical coating for many years as it provides high refractive index for the visible region i.e. 2.2 – 2.4 at 550 nm and it is hard and stable in comparison with other oxide materials. These features of the TiO_2 can be used for multilayer HR coating in combination with Al_2O_3 as low refractive index material, which gives more than 90 % reflectivity with only three bi-layer pairs of Al_2O_3-TiO_2. The deposition of AR and HR coatings on the facets of laser diode involve thin film deposition technology. We have carried out the facet coating on laser diodes using e-beam evaporation technique. The next section discusses issues related to optical thin film deposition using e-beam and optimization of coating conditions for laser diode facets.

The most widely used materials for 980 nm laser diode are aluminum oxide (Al_2O_3), silicon nitride (Si_xN_y) and silicon dioxide (SiO_2) for single layer AR coatings while silicon (Si) is used as high refractive index material in combination with Al_2O_3 or SiO_2, having low refractive index, to realize HR coating [6,97,107,108]. The sputtered Si_xN_y suffers from its reproducibility in the film index [109]. Although having very high laser damage threshold, the SiO_2 thin film prepared by ion assisted electron-beam (e-beam) evaporation shows quite variation in film refractive index with oxygen partial pressure and also continues to oxidized in air so the refractive index reduce with time [109]. The refractive index of Si strongly varies with wavelength and, for wavelength range up to near infrared the absorption becomes significant, leading to facet heating [6]. Moreover, contamination to the Si may cause device sorting.

Leading to these facts we have used zirconium oxide (ZrO_2) to realize the AR coating and HR coating in combination with SiO_2. The refractive index of ZrO_2 (i.e. $\approx$2 at 980 nm) is quite near to the geometric mean value of the refractive index needed for single layer AR coating. It is best suited material for GaAs (refractive index, $n \sim 3.6$) based laser diodes, because it has high dielectric constant ($\varepsilon \approx 25$), large bandgap ($E_g \approx 5.65$) [110] and high stability which prevents degradation of the devices. Further, stoichiometry in zirconia films can be achieved without the addition of oxygen into the vacuum chamber. It is also known that the laser damage threshold of ZrO_2 is higher than TiO_2, usually used as high refractive index (H) material in combination with Al_2O_3 or SiO_2 for HR coating of laser diode, so ZrO_2 will be more suitable material for HR coating for HPLDs. Similarly, SiO_2 ($n = 1.45$, $E_g \approx 9$ eV) [111] have low refractive index (L) and easy to evaporate. It also provides a high threshold for laser induced damage and it has good environmental stability, besides this SiO_2 also has compressive intrinsic stress [112]. Also, QWOT SiO_2/ZrO_2 multi layers are widely used for the facet coating of GaN based ultraviolet (UV) laser diodes, due to very high laser damage threshold [113]. To the best of our knowledge the combination of these materials for AR and HR coating on the facet of 980 nm laser diode is not reported.

4.3 Thin Film Deposition Technique

Generally, the term *thin film* is related to the layers having thickness ranging from few atomic layers i.e. nanometers to several microns or less (1 μm) [114]. On the other hand, thin film can also be defined in terms of the production process, i.e. material created initially by the random nucleation and growth processes of individually condensing atomic or molecular species on a substrate [115]. Any thin film deposition technique involves a controlled transfer of atoms and an atomistic growth of the overlay material to the substrate atom-by-atom. Thin films can be realized by various deposition techniques like physical vapor deposition (PVD), chemical vapor deposition (CVD), sol-gel technique, etc. The detail classification of the thin film deposition techniques is given in the Fig. 4.3.

THIN FILM DEPOSITION PROCESSE/S

- ***Physical Vapor Deposition (PVD)***
  - ***Evaporation:***
    - Thermal Evaporation
    - ***Electron Beam Evaporation***
    - Flash Evaporation
    - RF Induction Heating
    - Pulsed Laser Deposition
  - Sputtering:
    - DC Diode Sputtering
    - RF Sputtering
    - Magnetron Sputtering
    - Ion Beam Sputtering
- Chemical Vapor Deposition (CVD)
  - Pyrolysis (Thermal Decomposition)
  - Hydrogen reaction
  - Halide Disproportionate
  - Transfer reactions
  - Polymerization
  - Miscellaneous method

Figure 4.3: Classification of the thin film deposition techniques. Here, a suitable technique for the laser diode facet coating is the electron beam evaporation.

4.3.1 Physical Vapor Deposition

The Physical Vapor Deposition (PVD) involves three fundamental processes: (1) the vaporization from the solid or liquid source materials in form of atoms or molecules, (2) the transfer of vapor through vacuum ambient to the substrate and, finally, (3) the condensation of the vapor on the substrate and create overlay. Typical PVD deposition rates are 10–100 Å per second. The deposition is carried out essentially in a vacuum of the order of 10^{-5} to 10^{-9} mBar for the following reasons. First, it increases the mean free path length of the vaporized source material and thus easily reaches the substrate with little or no collision. Second, it reduces the boiling point of most of the materials. Third, it provides a very low level of gaseous contamination in the deposition system and reduces the probability of the reaction of the source and substrate materials. PVD processes generically involve individual atoms or perhaps small clusters of atoms, which are not normally found in the gas phase [116]. Typically, these atoms are removed from a solid or liquid source, transit an evacuated chamber, and impinge on a solid surface at which point the atoms stick and form a film. The main categories of PVD processing are vacuum evaporation, sputter deposition, and ion plating, classified by the method of removing the atoms from the original source. Depending on the method of applying heat to the source material, the PVD can be further classified in various techniques such as thermal evaporation, electron-beam (e-beam) evaporation, sputtering, pulsed laser deposition, etc.

❖ Electron Beam Evaporation Technique

AR coatings on laser diodes have previously been demonstrated using radio frequency (RF) sputtered Al_2O_3, silicon [97], and lead silicate [117]. RF sputtering is a convenient PVD method since the deposition rate is slow, enabling easy control over the thickness, and the films are uniform and show good adhesion properties. However, the high reflection multilayer coating cannot be carried out easily using RF sputtering, as it requires very complex system. Moreover, it is difficult to incorporate in-situ reflectivity monitoring in the system since the plasma is complex and easily disturbed. In addition, dielectric target for RF sputtering systems tend to be non-uniform, making it difficult to maintain reproducibility in the film refractive index. Deposition by e-beam evaporation is an alternative method, which can solve some of these problems. A large variety of dielectric materials can be deposited by e-beam evaporation and it allows multilayer deposition. In addition, the incorporation of in-situ monitoring system is easy in e-beam system.

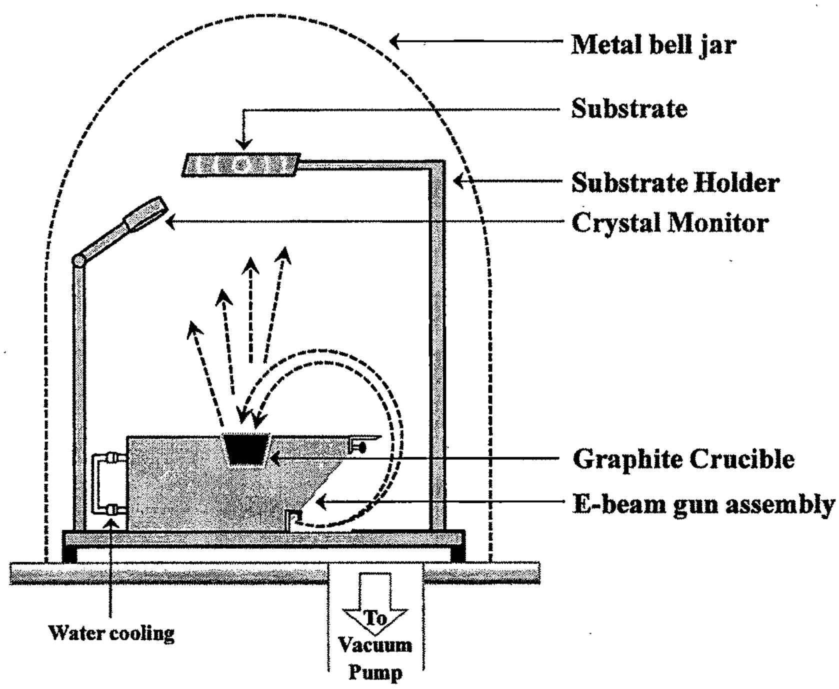


Figure 4.4: The above schematic diagram shows the e-beam evaporation using 270° bent e-beam gun assembly installed in a high vacuum chamber.

In the e-beam evaporation system, the source-material is placed either into a graphite crucible or in water-cooled metal (generally copper) cup, called hearth. Figure 4.4 shows the schematic diagram of the e-beam evaporation of the material, using a 270° bent e-beam gun assembly installed in a high vacuum chamber. The high energetic e-beam is thermionically emitted from a heated tungsten filament, which is shielded from the direct line-of-sight of the source material and the substrate. The emitted e-beam from the e-beam gun assembly is accelerated by means of the bias voltage, ranging 4-20 kV. In addition, a transverse magnetic field is applied to the e-beam, which provides the beam deflection in a 270° arc and is focused onto the source material using a permanent magnet and/or an electromagnet. The energetic e-beam imparts energy to the source material, melts it, and evaporates it. The emitting flux of the evaporant material is having almost a cosine distribution. Generally, there is a modest distance of about 10 to 50 cm between the source and substrate to cover larger deposition area and limit sample heating by optical radiation from the source. As discussed earlier, most evaporative deposition systems require high vacuum to operate efficiently. Aside from the issue of incorporation of impurity, it is desired that the mean free path of the evaporant-flux exceeds the distance from the source to the sample. This reduces in-flight scattering with the background gas, which can lead to reduced deposition rates. The scattering, which defines the mean free path, is related to the density and pressure of atoms and molecules in the gas phase. From the kinetic theory of gas, the mean free path, mfp, is calculated as [118]:

$$mfp = \frac{k_B T}{\sqrt{2}\,\mathrm{P}r^2\,\pi} \tag{4.5}$$

where k_B is Boltzmann constant, T is absolute temperature, r is molecular diameter, and P is pressure in Pascal. The scattering probability is given as fraction N/N_0 of molecules that are scattered in distance, d, during their travel through gas.

$$\frac{N}{N0} = 1 - e^{\frac{-d}{mfp}} \tag{4.6}$$

where, N_0 is total number of molecules, N is number of molecules that suffers collisions, d is distance between source and substrate.

➢ **Advantages of E-beam Evaporation Technique**

1. In practice, one can evaporate most of the materials viz. metals, oxides, and compounds at almost any rate as the temperature at the focused spot can be raised to as high as 3000 °C.
2. Since the temperature is high only at a focused spot, rest of the material including the crucible remain cool and thus there is reduced contamination.
3. Multi-source hearth makes parallel or multi-layer evaporation possible and thus it is very useful in multilayer coatings.
4. Offers many desirable characteristics such as high evaporation rate, relatively highly dense coating, good composition control, columnar and polycrystalline microstructure, good surface finish and a uniform microstructure.

➢ **Disadvantages of E-beam Evaporation Technique**

1. The electron energy is sufficient to ionize residual gas or evaporant molecules encountered along the way. Since ionization causes loss of beam-energy and

beam-focus, the pressure in the vacuum chamber must be below 10^{-4} torr, preferably 10^{-6} torr.

2. Generation of X-rays by the e-beam.

4.3.2 Substrate Preparation

It is essential to clean the substrate thoroughly before the deposition process, as the thin film growth and adhesion is primarily related to the initial substrate surface conditions. In industry, this is often done by using the etching chemicals or plasma etching. We have used GaAs substrate to optimize facet coating reflectivity. Any impurity on the surface may cause poor film quality and lead to the false reflectivity value. The substrate was cleaned by means of organic cleaning process consisting of trichloroethylene (TCE), acetone, and methanol. The substrate was cleaned thoroughly in a hot vapor bath of these chemicals one by one, respectively. The TCE removes most impurities, like grease and oil particles, from the substrate, which comes from the manufacturing process. Later, acetone and methanol were used to remove the preceding chemical effect, respectively, followed by drying the substrate under nitrogen flow.

4.4 Facet Coating Optimization

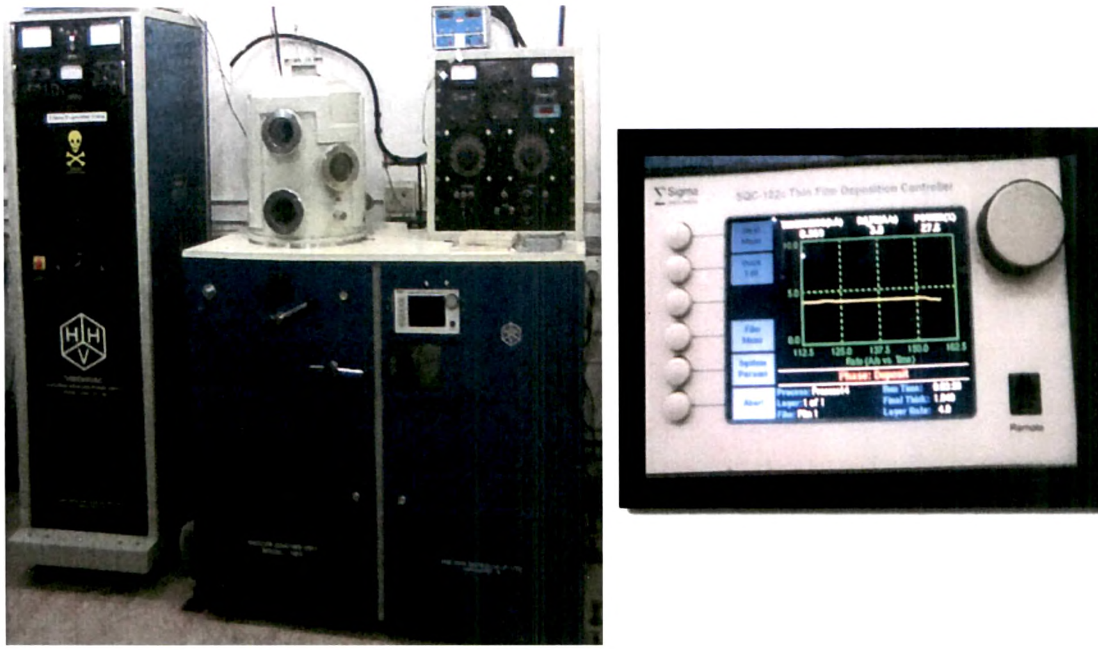
Optical coating on laser diode facets requires careful designing and a high degree of control over the deposited thin film parameters namely optical quality, film structure, morphology and stoichiometry. Low absorption coating requires compositionally pure starting materials and clean vacuum ambient. The e-beam evaporation offers high purity films and avoids contamination because only a small amount of energy can melt or sublime the source materials. The material exposed to the e-beam spot is only gets melted while the adjacent material remains at relatively low temperature and form an effective crucible of the source material itself. Therefore, the molten material is only in contact with an existing crucible made of the same material, and hence any chemical reactions with contaminants are eliminated.

The thin film structure plays a vital role in determining the optical properties of the films. Normally, thin films produced by the e-beam evaporation have columnar structure, which causes generation of channels for moisture incorporation cracks. These cracks can influence local electric field distribution surfaces, which are chemically active, and boundaries, which may be mechanically unstable. The substrate is rotated with a constant rpm during evaporation using a dc motor inside the vacuum chamber to attain a uniform film thickness on the substrate and to avoid columnar growth.

Optical coating for laser diode should be morphologically isotropic and compositionally stoichiometric to provide homogeneous material properties. The substrate temperature and the deposition rate affect the morphology and stoichiometry of thin film, respectively. Substrate temperature affects thin film properties viz. composition, nucleation growth, absorption, and diffusion. We have optimized the dielectric thin film for the facet coating at high substrate temperature by means of a radiant heater. The e-beam evaporation is known for causing 'spatter' from the source during deposition. At high e-beam power, the temperature is higher underneath the free surface, generating pressure differentials that are revealed via explosions. Under certain conditions, molten particles can be seen ejected from the source. The spattering is minimized by reducing the e-beam surface intensity and thereby reducing the evaporation rate. Thus, facet coating is carried out at a low evaporation rate. In addition, by controlling the beam intensity by means of either increasing the surface area of beam foot-print or by decreasing the beam energy, we can reduce the film thickness non-uniformities over the substrate and control the coating layer thickness. To improve these conditions, we used a sweeping e-beam at a high frequency on the material surface instead of steady electron beam.

4.4.1 Experiment: Al_2O_3 (AR) and Al_2O_3/TiO_2 (HR) Coating

The facet coatings were optimized in an electron beam evaporation system using 6 KW electron beam evaporator in a high vacuum coating unit (Hind High Vacuum Co. (P) Ltd.). The coating unit is equipped with 270^0 bend e-beam gun facility. As shown in the picture (Fig. 4.5), the e-beam evaporation system is interfaced with SQC-122c SIGMA Thin Film Deposition Controller to precisely monitor and control the thickness and deposition rate of the thin film. The thickness measurement involves piezoelectric quartz crystal placed inside the vacuum chamber. The oscillating frequency of the quartz crystal declines from its original frequency, i.e. 6 MHz, as coating materials are deposited on the crystal.



(a) **(b)**

Figure 4.5: (a) High vacuum coating unit assembled with 270° bent e-beam gun, (b) Thin film deposition controller, USA SQC-122c.

The rate of change of the crystal frequency depends on the mass of the deposited material. Consequently, the thickness of the coating on the crystal can be calculated by measuring the fall of the crystal's oscillation frequency, area of the crystal exposed to the film, and the density data of the material. The crystal is positioned at the center of the coating chamber to estimate the coating thickness on the substrate. The vacuum coating chamber is pumped down to achieve a pressure upto 1×10^{-5} mbar using an oil diffusion pump backed by a rotary pump. A special jig has been fabricated to coat the end facets of the laser bars. The jig uses two silicon wafers to hold the laser diode bar with a spring action of two springs. Figure 4.6 shows the pictures of jig to hold laser diode bar for facet coating.

The substrates are rotated with 120 rpm inside the vacuum chamber during deposition with the help of a dc motor in order to get uniform coating. The films have been deposited at 100 °C substrate temperature with a constant rate of 4 Å/s for the both Al_2O_3 and TiO_2. The substrate temperature is attained using a radiant heater.

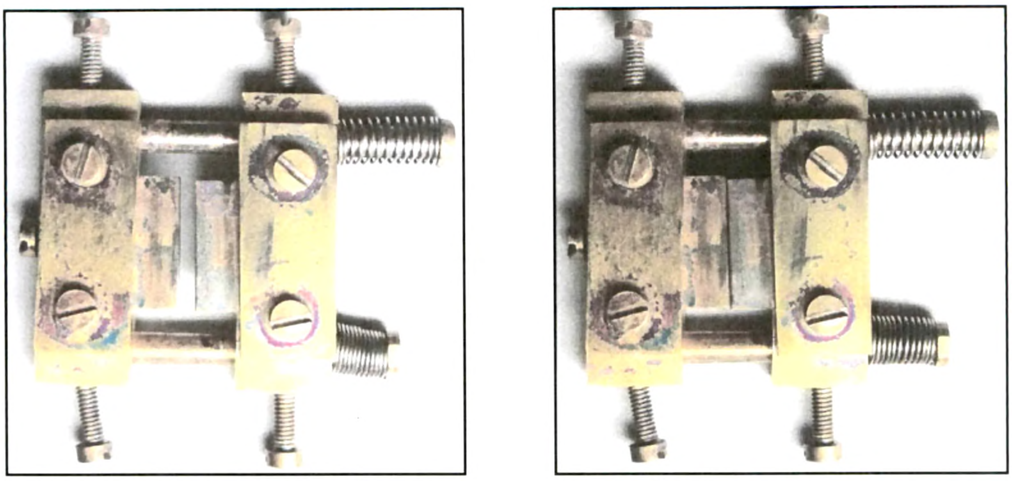


Figure 4.6: Jig to hold laser diode during facet coating.

4.5 Reflectivity Measurement

Since we are applying thin film optical coating for the reflectivity modulation, the main characterization necessary for our films is the reflectivity measurement. The facet coating is to be deposited on the facet of laser diode, which is made up of GaAs based materials. However, it is not convenient to measure directly the reflectivity of the facet. Therefore, we use GaAs substrate for the optimization of reflectivity. We have used the ex-situ reflectivity measurement setup for the optimization of facet coating.

4.5.1 Ex-situ Reflectivity Measurement

In ex-situ reflectivity measurement a tungsten-halogen lamp is used as a polychromatic light source. The light from the lamp is focused on the monochromator input slit using convex lens. We have used 1/8-m monochromater, CVI-CM 110. The output beam from the monochromater is chopped using a mechanical chopper. This chopped beam is then aligned on the sample and/or reference gold coated mirror, through a cube-beam splitter, near-normal geometry and the reflected beam is directed to the photo detector. The detector assembled with lock-in amplifier, SR-530, measures the intensity of the reflected beam. Figure 4.7 shows the schematic of the experimental set up to measure the reflectivity.

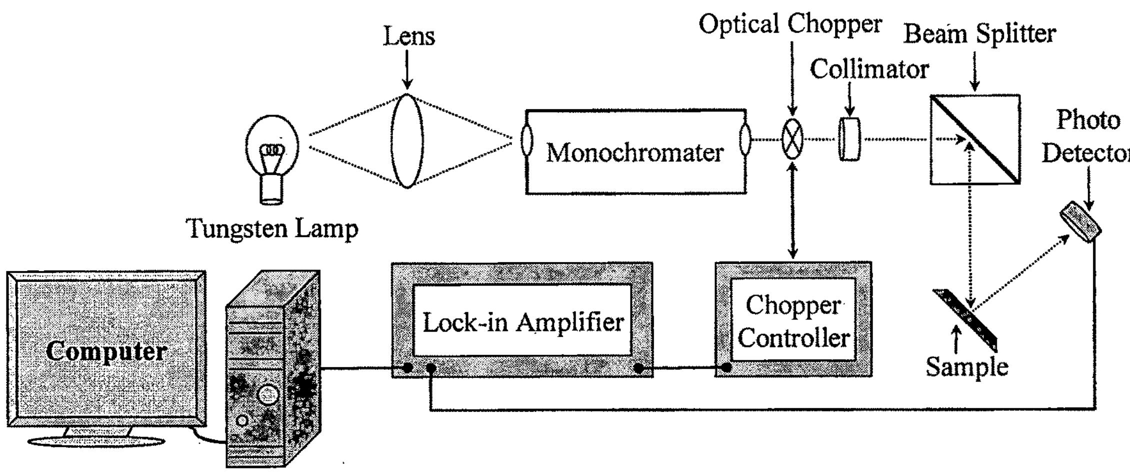


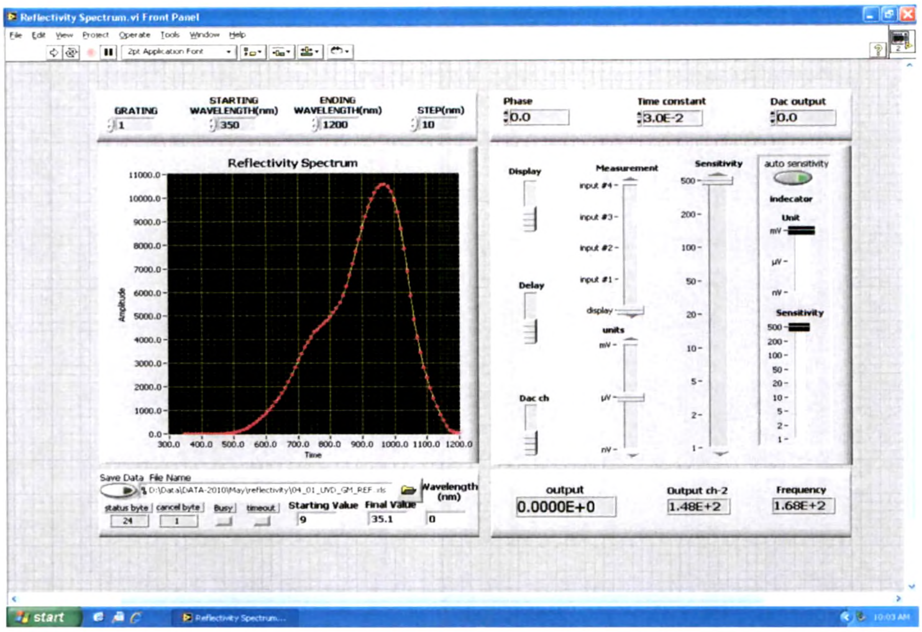
Figure 4.7: The above is a schematic of the ex-situ reflectivity measurement setup. The reference beam from the optical beam chopper, passing through the beam splitter, falls on to the reference Gold mirror and then on the sample, and, finally, on the detector, which gives the reflectivity.

The reflectivity of the sample at particular wavelength is found using the Eq. 4.7:

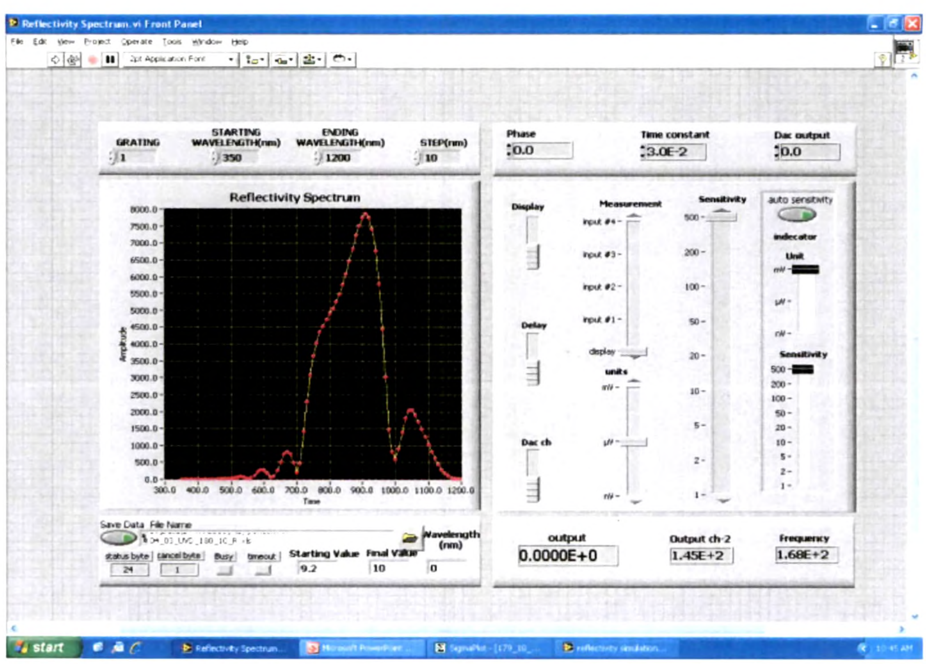
$$R_S = \frac{S_S}{S_{GM}} \times R_{GM} \ \% \tag{4.7}$$

where, R_S is the percentage reflectivity of the sample, S_S is signal from the sample, S_{GM} is signal from the reference gold mirror, and R_{GM} is the known reflectivity of the gold-mirror. The monochromator and the lock-in amplifier have been interfaced with the computer via communication (COM) port (RS-232) and general purpose interface bus (GPIB), respectively. The experiment is automated using LabVIEW-8.2 (laboratory virtual instrument engineering workbench–version 8.2). However, in this setup, since the reflectivity of the sample is measured with reference to the standard reflectivity gold mirror, we need to take two scans for complete spectral range of interest viz. one with slandered gold mirror and the other with the unknown sample.

The dedicated virtual instrument, made in LabVIEW-8.2, computes and displays the reflectivity spectrum simultaneously with data acquisition and storage. Figure 4.8 (a) and (b) show the front panel (control and displays) of the virtual instrument (VI) for reflectivity measurement displaying reflectivity spectrum of reference gold mirror and HR coated test substrates.



(a)



(b)

Figure 4.8: Graphical user interface for reflectivity measurement. (a) Reference signal from the standard gold mirror and (b) signal from HR coated GaAs test substrates with 5 bi-layer pair of $Al_2O_3 - TiO_2$.

As mentioned earlier, the reflectance of the multilayer non-absorbing dielectric films depends on constructive and/or destructive interference of the light from each consecutive boundary of the film interface. Therefore, the choice of an appropriate sequence of these layers with suitable dielectric materials and their thickness that best satisfy the desired spectral response for the application is a crucial issue. Thus, to design the multilayer dielectric thin films and to optimize their coating conditions, a reflectivity spectrum simulation of these optical thin films is an essential tool. We have used a LabVIEW-8.2 based simulator, that determines the 2 x2 '*characteristic matrix*' elements for each layer of the stack at particular wavelength and angle of incidence [119].

In addition, the refractive index and the physical thickness of the film are most important parameters for facet coating optimization. We have matched experimental data with simulation to optimize the process. Moreover, the thickness of the film was also optimized using simulation [119].

4.5.2 In-situ Reflectivity Measurement

We have optimized and automated the experimental in-situ reflectivity measurement system for the laser diode (LD) facet coating. The deposition of single layer MgF_2 and a QWOT three bi-layer pairs of MgF_2 - Si on GaAs test substrate were carried out under the high vacuum (10^{-5} mbar) using e-beam evaporation system (EBG-6K, HINDHIVAC). The quartz crystal monitor was used for measuring the thickness of the sample. The e-beam evaporation system is interfaced with the thin film deposition controller (SQC-112C, Sigma Instruments) for the better control of the deposition parameters viz. thickness and deposition rate. The substrate was rotated with 120 rpm inside the vacuum chamber during the deposition with the help of a dc motor in order to get uniform coating. The substrate was maintained at 100°C using a radiant heater during the deposition. The deposition rate was 4 Å/s.

Figure 4.9 shows a schematic diagram of the experimental setup for in-situ measurement of reflectivity. The laser beam enters into the vacuum chamber through a glass-view-port of the chamber and reflects back on the photo-detector (BPW-34) from the sample at normal incident angle. We have used a commercially purchased red laser diode (λ=650 nm) as a probe light source for the experiment. To check the stability of the optical power of the laser diode, we operated the laser diode in CW mode continuously for a few minutes before starting the deposition and monitored its optical power as a function of time. The signal from the photo-detector is fed to a computer through data acquisition card (NI-USB-6251). Figure 4.10 shows the acquired data in the front panel of the program built-in LabVIEW-8.2.

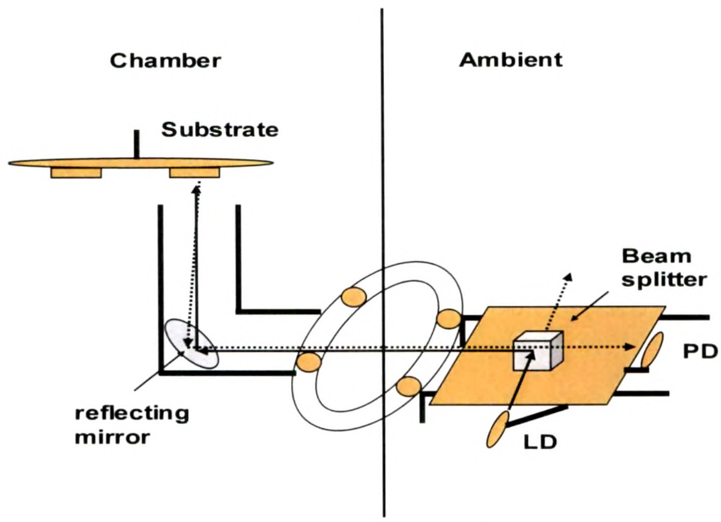


Figure 4.9: The above schematic shows the experimental setup for in-situ measurement of reflectivity.

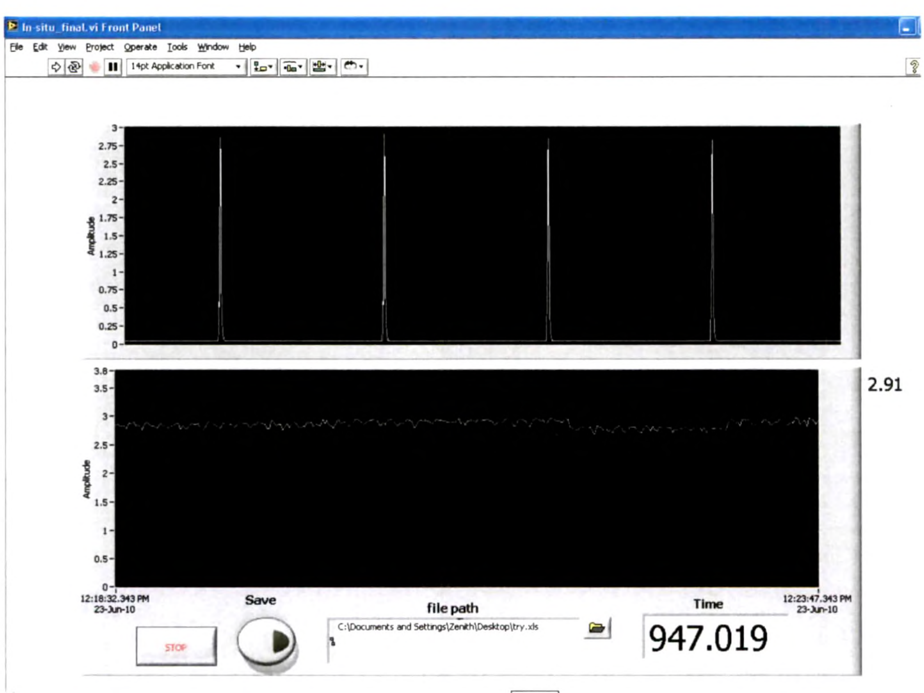


Figure 4.10: The LabVIEW-8.2 front panel showing real time data acquisition as the light reflects from the sample and is detected by the photodetector.

We have also developed a reflectivity-simulator program, based on LabVIEW-8.2, which gives the reflectivity data as a function of the thickness of the film (single or multi-layer) for a given wavelength. It aids in optimizing the deposition parameters while monitoring the coating of the films in-situ. The light reflected from the air-film and the film-substrate interface give rise to the interference phenomenon, which results in the change in the reflected beam intensity as the film grows on to the substrate.

Figure 4.2 shows light incident on an air-film interface. The light reflected from the air-film and the film-substrate interface give rise to the interference phenomenon, which results in the change in the reflected beam intensity as the film grows on to the substrate. The reflectance co-efficient, r, of a non-absorbing multilayer dielectric thin-film is given as [5, 119]:

$$r = \frac{Y_0 m_{11} + Y_0 Y_S m_{12} - m_{21} - Y_S m_{22}}{Y_0 m_{11} + Y_0 Y_S m_{12} + m_{21} + Y_S m_{22}} \tag{4.8}$$

where, $Y_0 = \sqrt{\varepsilon_0/\mu_0 n_0'}$ and $Y_S = \sqrt{\varepsilon_0/\mu_0 n_S'}$ with n_0' and n_s' being the effective refractive indices of the incident medium and the substrate, respectively, and are given as $n_0' = n_0\, cos\theta_0$ and $n_S' = n_S\, cos\theta_S$ for s or perpendicular polarization. In case of p or parallel polarized light, n_0' and n_s' are given as $n_0' = n_0/cos\theta_0$ and $n_S' = n_S/cos\theta_S$. Here, n_0 and n_s are the refractive indices of the incident medium and the substrate whereas θ_0 and θ_s are the angles of incidence in the incident medium and the substrate, respectively. In Eq. 4.8, m_{11}, m_{12}, m_{21}, and m_{22} are the elements of characteristic matrix, M, of the entire system with p layers in a multilayer stack, which is the resultant of the product (in proper sequence) of the individual $2x2$ matrices for each layer in the multilayer stack, that is:

$$M = M_1 M_2 M_3 \ldots\ldots M_P = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \tag{4.9}$$

However, the layer matrix is a complex matrix [119]. Hence, elements m_{12} and m_{21} in above equations are purely complex whereas the other two elements, i.e. m_{11} and m_{22}, are real. Thus, the reflectance coefficient r is an imaginary quantity. So, the reflectance, $R = r \cdot r^*$ gives,

$$R = \frac{(n_0' m_{11} - n_S' m_{22})^2 + (n_0' n_S' m_{12} - m_{21})^2}{(n_0' m_{11} + n_S' m_{22})^2 + (n_0' n_S' m_{12} + m_{21})^2} \tag{4.10}$$

Equation 4.10 determines the reflectance of the non-absorbing multilayer dielectric thin-film. This equation is used in the computer simulation program. Figure 4.11 shows the front-panel of the LabVIEW program for reflectivity simulation of the optical thin film.

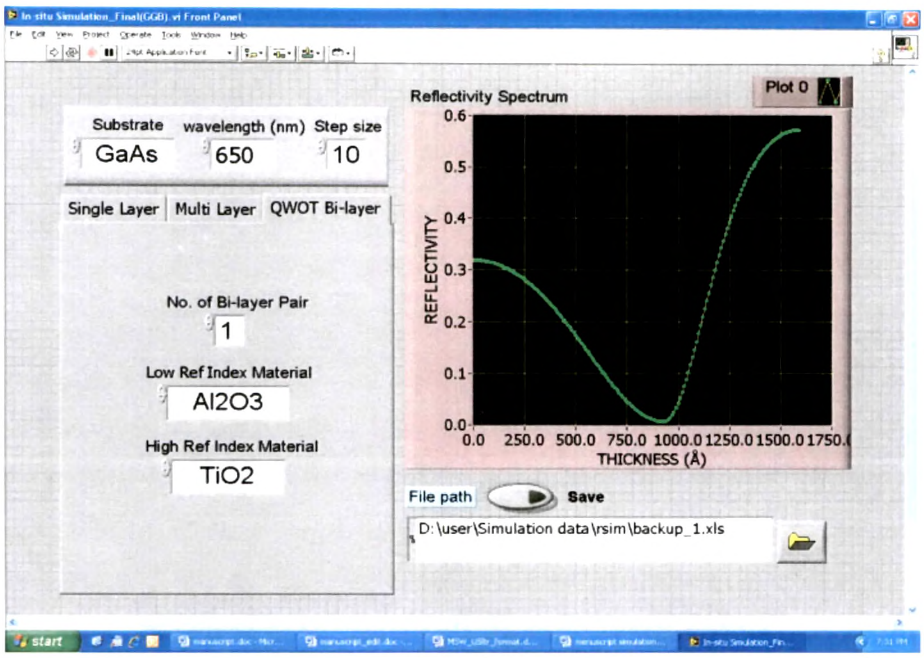


Figure 4.11: The front-panel of the LabVIEW program for reflectivity simulation of the optical thin film.

❖ Program execution

In the case of optical films, two parameters are necessary to determine the reflectivity of the thin film viz. the physical thickness and the refractive index of the material [120]. The other input parameters are the refractive index of the substrate material, wavelength of interest, and thickness (step size). All these parameters are provided on the front panel of the program, shown in Fig. 4.11. Figure 4.12 shows the other control parameters to be fed as the input. The program executes as per the data flow arranged using the graphical programming code in the back panel of the program viz. block diagram.

4.6 Facet Coating Optimization for 808 nm Laser Diode

The design of multilayer high-reflection (HR) coating and simulation of corresponding reflectivity spectra are carried out for 808 nm laser diode. The high reflection at the back

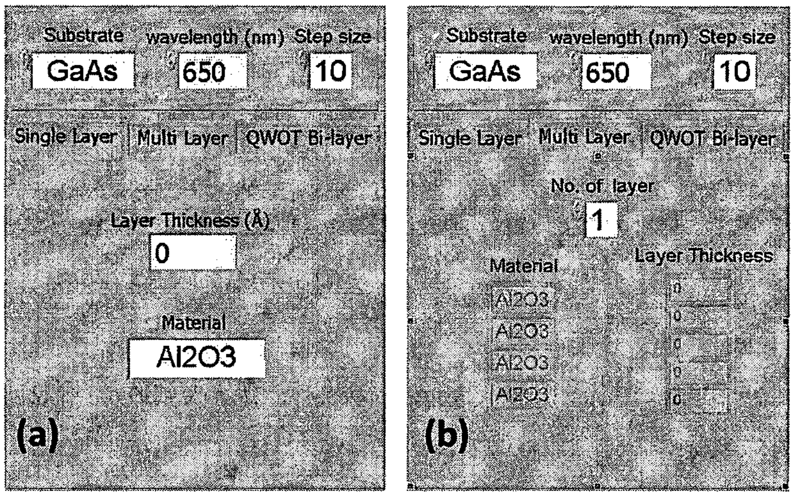


Figure 4.12: The input parameters for single layer (a) and multi layer (b) in-situ reflectivity simulation.

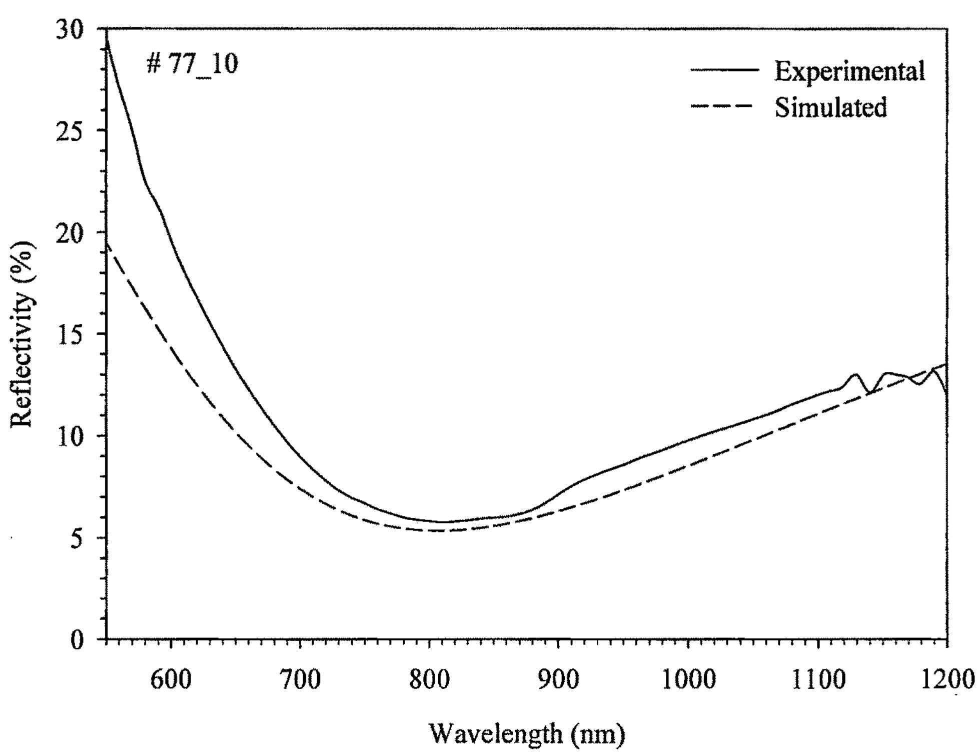
-facet of the diode laser is achieved by multilayer stack of alternating films. The structure of multilayer stack consists of alternating films of Low (L) and High (H) refractive index layers of quarter wave optical thickness ($\lambda/4$) at lasing wavelength. In our previous work, we used silicon (Si) as high refractive index material for HR coating [121]. However, Si has some limitation such as poor resistivity and finite absorption coefficient in visible and near IR. To overcome these limitations we replace Si with TiO_2 as high refractive index material in design of HR coating.

TiO_2 has been optimized as a high refractive index (H) material in combination with Al_2O_3 as a low refractive index (L) material for HR coating. The GaAs test substrate was used for the film deposition. The films were deposited at room temperature on the test substrates under high vacuum during optimization. The substrates were rotated with ~120 rpm during the deposition. In order to monitor and control the deposition rate and thickness of the film the vacuum coating unit had been facilitated with a thin film deposition controller. Also for the better adhesion, substrate temperature about 100 °C was attain by means of a radiant heater. The results of reflectivity measurement were compared with the simulated results.

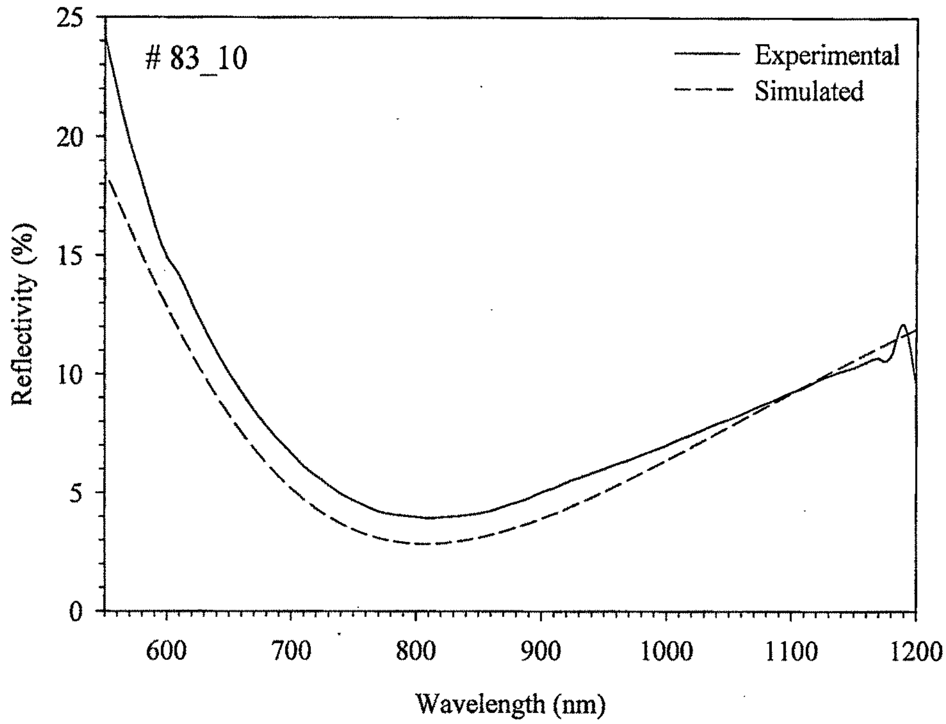
4.6.1 Results and Discussion

The laser facet coating structure is substrate – n (L H) – Air (here, integer *n* shows the no. of bi-layer pair of low and high refractive index material). As mentioned, Al_2O_3 was used as a low refractive index layer and TiO_2 as a high refractive index layer for HR coating. For the 808 nm, the quarter wave optical thickness was 202 nm for each layer. Hence, the physical thickness for Al_2O_3 layer (L) was 126.25 nm and that for TiO_2 layer (H) was 84.16 nm.

Figures 4.13 (a) and (b) show the reflectivity spectra for the optimized single layer TiO_2 and Al_2O_3 quarter wave optical thickness and deposition parameter, respectively. The reflectivity achieved so far for the five bi-layer pairs of Al_2O_3 – TiO_2 is about 94 %, as shown in Fig. 4.14. The difference between the simulated and experimental reflectivity is because of dispersion in refractive index value of the material. Furthermore, the refractive index value of the e-beam evaporated film changes with deposition conditions, which leads to the difference in simulated and obtained reflectivity.



(a)



(b)

Figure 4.13: Reflectivity spectra of optimized single QWOT layer (a) TiO_2 and (b) Al_2O_3 for 808 nm.

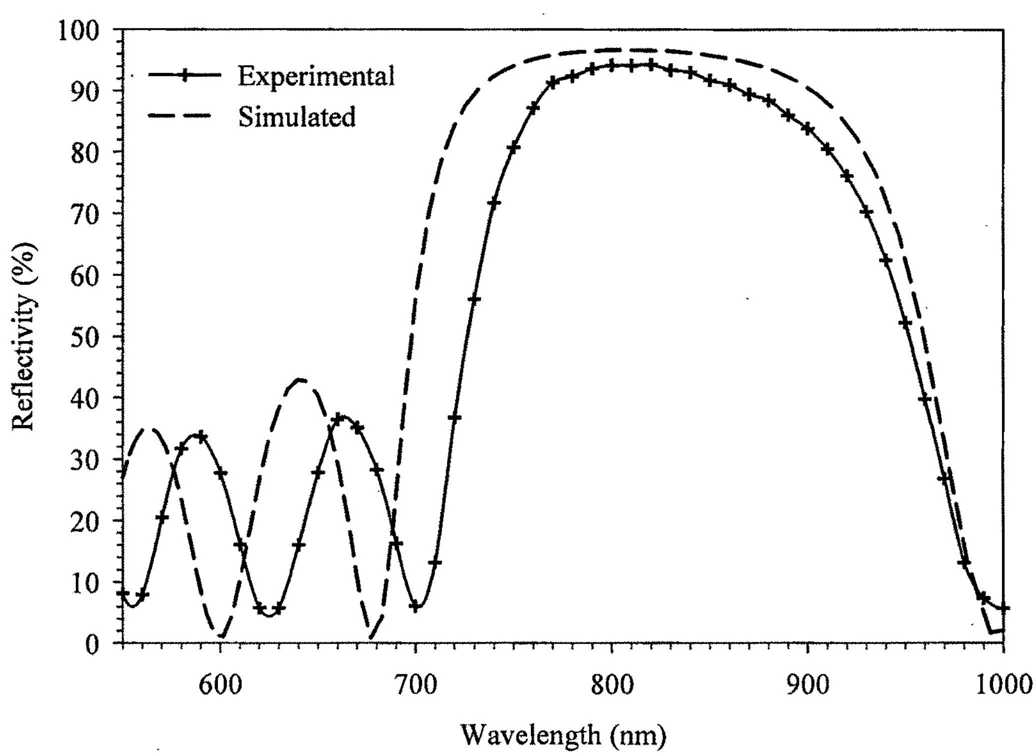


Figure 4.14: Experimental and simulated reflectivity spectra of HR coated GaAs test substrates optimized for 808 nm laser diode.

❖ In-situ Facet Reflectivity Measurement

Thin film optical coating is used for modulating the reflectivity in different kinds of optical components viz. beam splitters, optical filters, polarizers, lenses of cameras and telescopes, including anti-reflection (AR) and high-reflection (HR) coating on the laser diode facets [122]. Owing to its importance, it is essential to monitor the thin film deposition parameters like the deposition rate, substrate temperature, and thickness of the thin film during the deposition.

We have developed an in-situ reflectivity measurement system for optimization of facets-coating process for laser diodes. We have performed in-situ reflectivity measurements on single layer MgF_2 and a quarter-wave optical thick (QWOT) three bi-layer pairs of MgF_2 and silicon on GaAs as a substrate for both the cases. The measurements were optimized using a simulation program that gives the reflectance of non-absorbing dielectric single or multilayer, or QWOT bi-layer optical facet coatings for the Laser Diode (LD) using LabVIEW-8.2 Since the set-up is custom-built for our specific application, it is quite simple, cost-effective, and an efficient tool for quick optimization and automation of the process.

The single layer MgF_2 film was deposited at room temperature on the GaAs substrate at the deposition rate of 4 Å/s. Figure 4.15 shows the acquired data of the reflected laser light intensity versus time.

It is known that there is a direct relation between the film's thickness and the film's deposition rate. So, one can easily estimate the thickness of the deposited film. Moreover, the natural reflectivity of the substrate GaAs is ~32 % and which modifies as the film grows on it. Hence, we can directly get the film reflectivity from the reflected intensity. Figure 4.16 (a) and (b) shows the experimental as well as the simulated data of the reflectivity of single layer MgF_2 and multilayer stack of three QWOT bi-layer pair of MgF_2 and Si where the former has a low refractive index and the latter has a high refractive index.

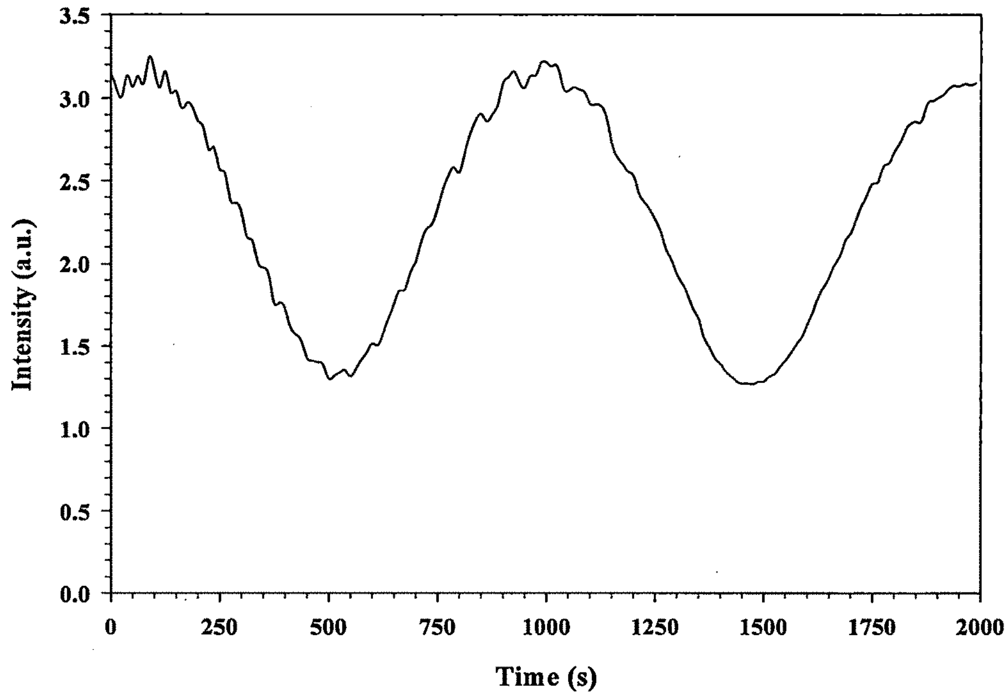
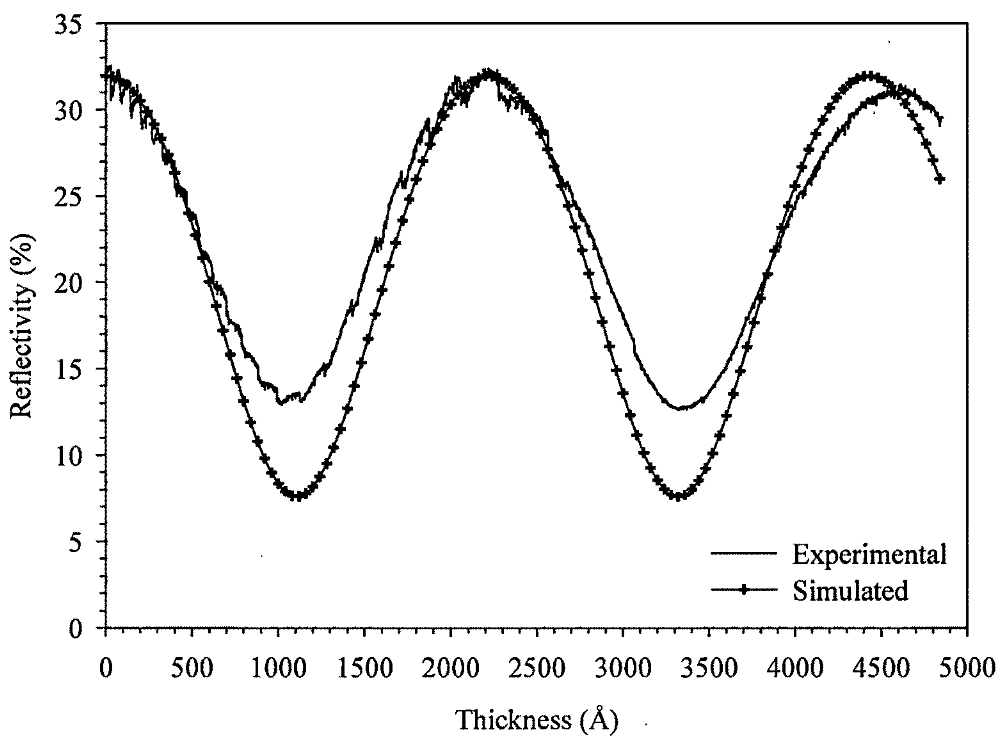
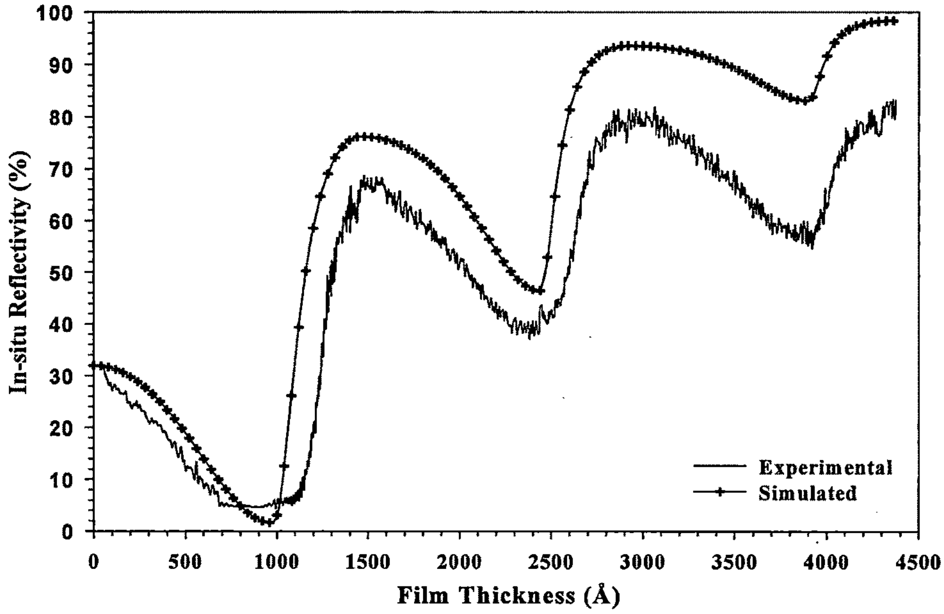


Figure 4.15: Intensity measurement curve as a function of time for the MgF_2 thin film deposited on GaAs substrate.



(a)



(b)

Figure 4.16: In-situ reflectivity and simulated reflectivity plots, (a) for a single layer MgF_2 and (b) for three QWOT bi-layer pairs of MgF_2-Si, deposited on GaAs substrate.

In order to confirm the obtained results, we measured the reflectivity spectrum of the coated samples ex-situ with the standard setup using a broad-band light source, a monochromator, photo-detectors and a lock-in amplifier. Figure 4.17 shows the reflectivity spectrum for a three QWOT bi-layer pairs of MgF_2-Si measured ex-situ.

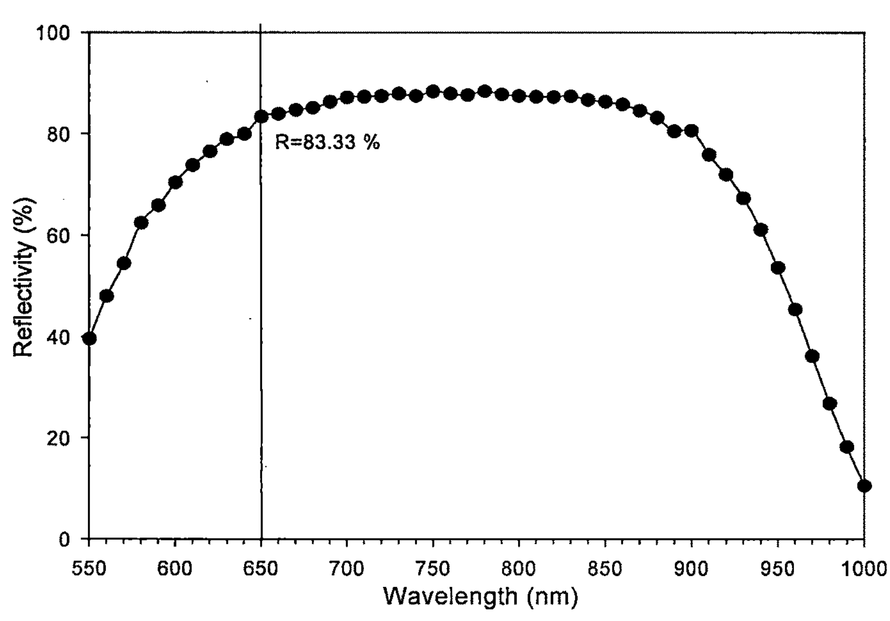


Figure 4.17: Reflectivity spectrum for three QWOT bi-layer pairs of MgF_2-Si measured ex-situ.

We have optimized and automated the experimental in-situ reflectivity measurement system for the laser diodes facet coating [39]. We have also developed a reflectivity-simulator program that gives the reflectivity data as a function of the thickness of the film (single or multi-layer) for a given wavelength, which aids in optimizing the above parameters while monitoring the coating of the films in-situ. We report the results for the in-situ reflectivity of a single layer MgF_2, and a quarter-wave optical thick three bi-layer pairs of MgF_2 and silicon, on GaAs as a substrate for both the cases. We have achieved up to 83 % experimental reflectivity for the latter case.

❖ Laser Diode Facet Coating

In order to study the effects of facets coating on optical power output, we deposited AR and HR films on, respectively, front and back facet of laser diodes with 808 nm lasing wavelength. Figure 4.18 shows the L-I characteristic of laser diodes before and after the facets coating. The L-I measurements were carried out in pulse-mode with 400 ns pulse-width and 0.25 % duty-cycle. The collective effect of AR and HR coating leads to boost the optical power output from front facet by almost 40 % at 850 mA input current [36].

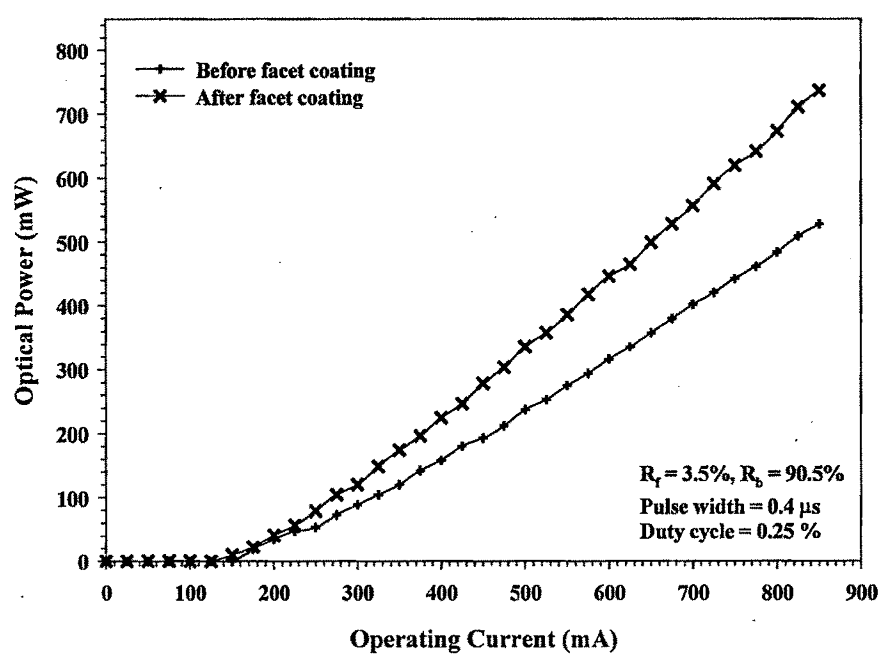


Figure 4.18: L-I characteristics of 808 nm laser diode before and after facets-coating.

❖ Conclusion

The in-situ reflectivity measurement of the single and multilayer optical thin films has been demonstrated. The change in intensity of the laser light after reflection has been measured to obtain the reflectivity as a function of thickness. In addition, we have developed an in-situ reflectivity simulation for the optimization of the in-situ film deposition. The reflectivity simulator provides a very good tool for designing the optical thin films with desired reflectivity response. Moreover, one can use the simulator for determining the material and the deposition conditions viz., film thickness, and deposition rate for single or multilayer films.

4.7 Facet Coating Optimization for 980 nm Laser Diode

The high power laser diodes (HPLDs) emitting at 980 nm are the key components for applications such as pump source for erbium-doped fiber amplifiers (EDFAs) or solid state lasers because of their low noise characteristic and high efficiency [123,124,125]. It is also utilized in medical therapy viz. dentinal surgery, due to handling flexibility and ease of operation [126]. An another advantage of the 980 nm laser diode is that there is no excited state absorption exists for this wavelength and hence high pumping efficiency is achieved [127]. The simplest way to achieve high power operation is to fabricate a simple ridge waveguide structure and dielectric facet coating.

4.7.1 Experiment: ZrO_2 (AR) and SiO_2/ZrO_2 (HR) Coating

Recently we have developed InGaAs/GaAs/AlGaAs based laser diode for 980 nm with output power of 670 mW/facet at the injection current of 2 A. These results are from the bare surface of cleaved facet of laser diode. To increase the output power and the stability of the spectrum, suitable dielectric materials single and multilayer coatings are desired. In view of this single layer of ZrO_2 and five pairs of SiO_2/ZrO_2 (L/H) multilayer are coated on the front and rear facet of laser diode for AR and HR respectively. The e-beam evaporation method is used for deposition of these thin films to minimize damage to the semiconductor surface. The properties of facet coated laser diode were compared with that of the bare devices.

Metalorganic Vapor Phase Epitaxy grown laser diode structures based on InGaAs/GaAs double quantum well were processed through conventional optical lithography, n- and p-type metal contact by e-beam/thermal evaporation, lift-off process and rapid thermal annealing of metal contacts. After making a smooth walled mesa-structure using H_3PO_4:CH_3OH:H_2O_2 etchant solution, electrical isolation and side-wall passivation was realized by SiO_2 layer deposition between the metal stripes. Details of growth and processing parameters of the device structures were presented elsewhere [25,37,128]. Finally, the structure was thinned down to ~150 μm and several laser stripes of different dimensions were cleaved.

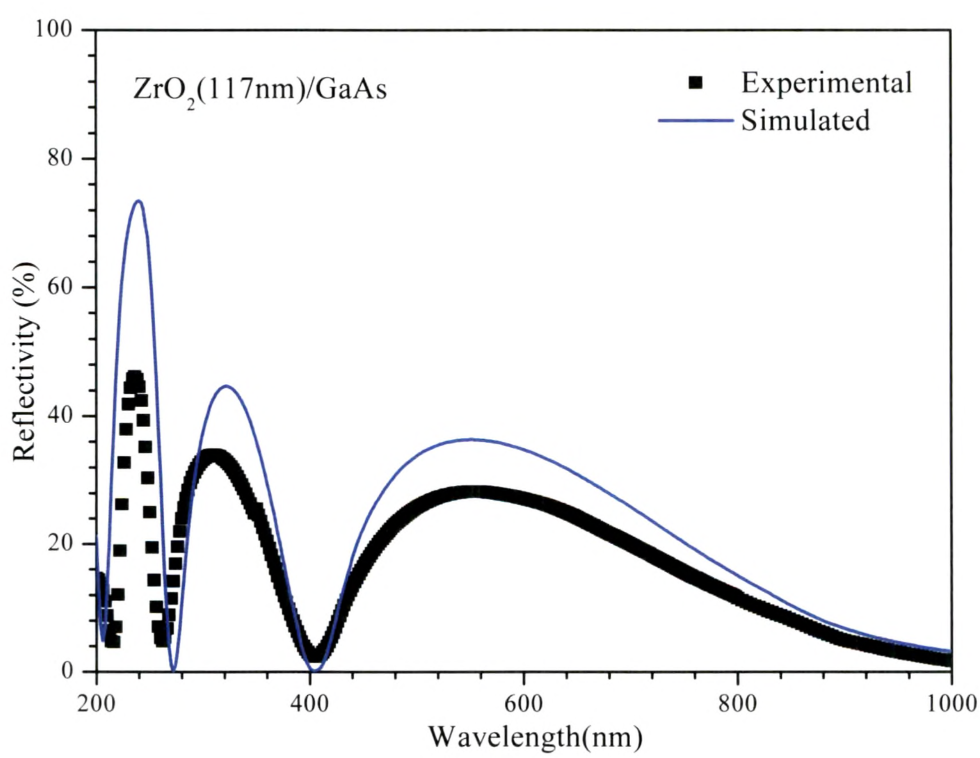
The AR and HR coatings were carried out using e-beam evaporation method. The e-beam evaporation system is interfaced with a thin film deposition controller (SQC-310C, Inficon) to precisely monitor and control the thickness and deposition rate of individual dielectric layers. Initially the thin films of ZrO_2, SiO_2 and multilayer's of SiO_2/. ZrO_2 were deposited on chemically cleaned GaAs substrates with a typical deposition rate of ~3-4 Å/s at 80 °C using e-beam source (EBG-PS-3K, Hind HIVAC) in a vacuum coating unit (12A4T, Hind HIVAC) at a pressure of ~6 X 10^{-6} mbar. The thickness of individual layer is monitored in-situ using quartz crystal. Subsequently, thickness of the films is measured from stylus (Dektak 150, Veeco) and also estimated from the theoretical fitting (FILMETRICS) [19] of the measured reflectivity data that is recorded using UV-VIS-NIR spectrophotometer (Cary 5000, Varian). After achieving the desired results of reflectivity on the GaAs substrates, the cleaved laser diode bar is clamped in the appropriate mounting jig that is placed in the vacuum chamber for antireflection and high reflection coatings in sequence. The laser diode characteristics are evaluated in the home made testing setup that is equipped with precision pulse laser diode driver (LDP-3840-3B, ILX Lightwave), power meter (OPHIR), spectrometer (HR 4000 CG, Ocean Optics), mounting stage, microscope etc [70].

4.7.2 Results and Discussion

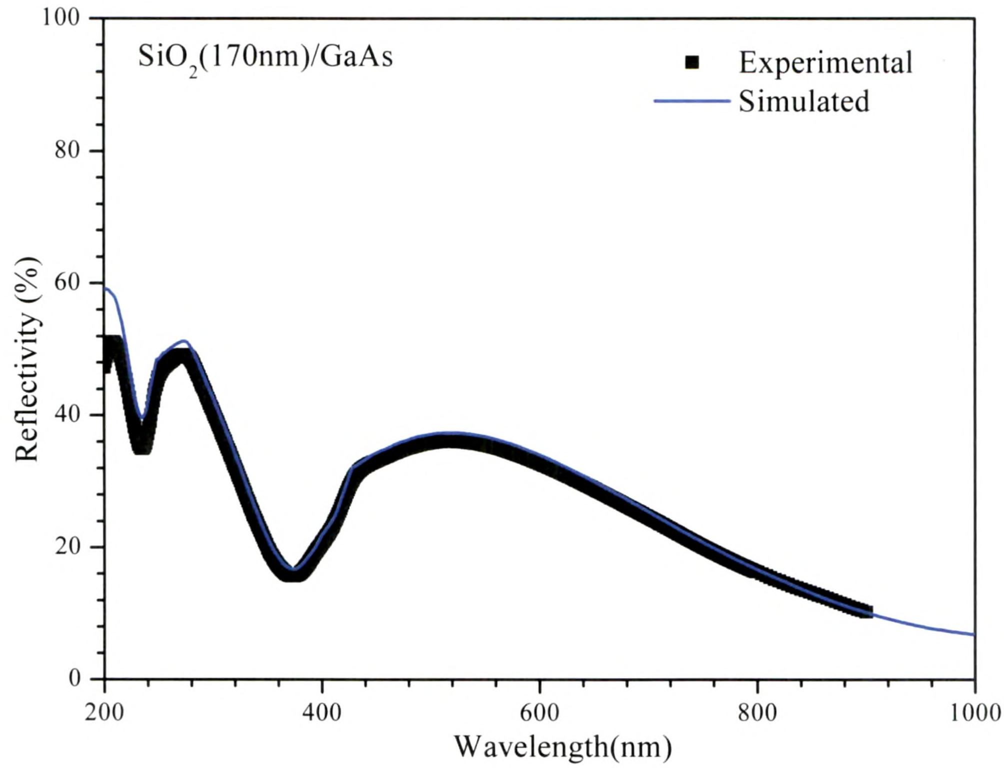
❖ Anti-Reflection and High-Reflection Coatings

➢ ***AR Coating***

The AR coating is typically a single layer coating. The laser diode in the present studies is mainly grown on GaAs substrate that has a fairly high refractive index. This substrate can be perfectly antireflection coated with a low refractive index material equal to the square root of the refractive index of substrate at the particular wavelength. Thus single layer of QWOT ZrO_2 (≈117 nm) is deposited on the GaAs substrates. Subsequently, reflectivity of deposited ZrO_2/GaAs heterostructure is measured from 200 to 1000 nm. Figure 4.19 (a) shows the measured and simulated curves of reflectivity of ZrO_2/GaAs heterostructure. The measured value of reflectivity is about 2 % at 980 nm and good enough to be used as AR coating material on the facet of laser diode with lasing wavelength of 980 nm. Reflectivity of single layer of SiO_2 (≈170 nm) deposited on GaAs is shown in Fig. 4.19 (b). The combination of these single layers of SiO_2 and ZrO_2 are used for HR coatings.



(a)



(b)

Figure 4.19: Reflectivity as a function of wavelength for (a) ZrO_2/GaAs (b) SiO_2/GaAs.

➢ ***HR Coating***

HR coating is based on the constructive interference of light reflected from successive boundaries of multilayer dielectric thin films and gathers in phase at the emergence of one surface to provide the maximum reflectance. The designed HR coating consists of multi-layer stack of alternating films of 170 nm thick low SiO_2 (L) and 117 nm thick high ZrO_2 (H) refractive index layers. The thicknesses of the layers were estimated from the optical thicknesses ($\lambda/4$) at the lasing wavelengths. The complete optimized structure consists of five pairs of LH layers. Figure 4.20 shows the relative increase of reflectivity from single to five pairs of LH layers.

As can be seen from Fig. 4.20 the reflectivity value is ~ 90 % for five pairs of LH layers. It is also noted that the values of measured reflectivity for AR and HR coated substrates are lower by around 5 to 10 % as compared to the simulated value of the reflectivity. This is predominantly due to the usage of bulk values of the material parameters during reflectivity simulations. Also, oxides film grown using e-beam evaporation exhibit a variation in refractive index with film thickness. Thus single layer with optimum thickness 117 nm of ZrO_2 is used on the laser diode facet coating. Similarly five pairs of SiO_2 (L)/ZrO_2 (H) layers are used for HR coatings. The complete structure on laser diode with partial reflectivity of 2/90 is "Air-AR-front facet-rare facet-$(LH)^5$-Air".

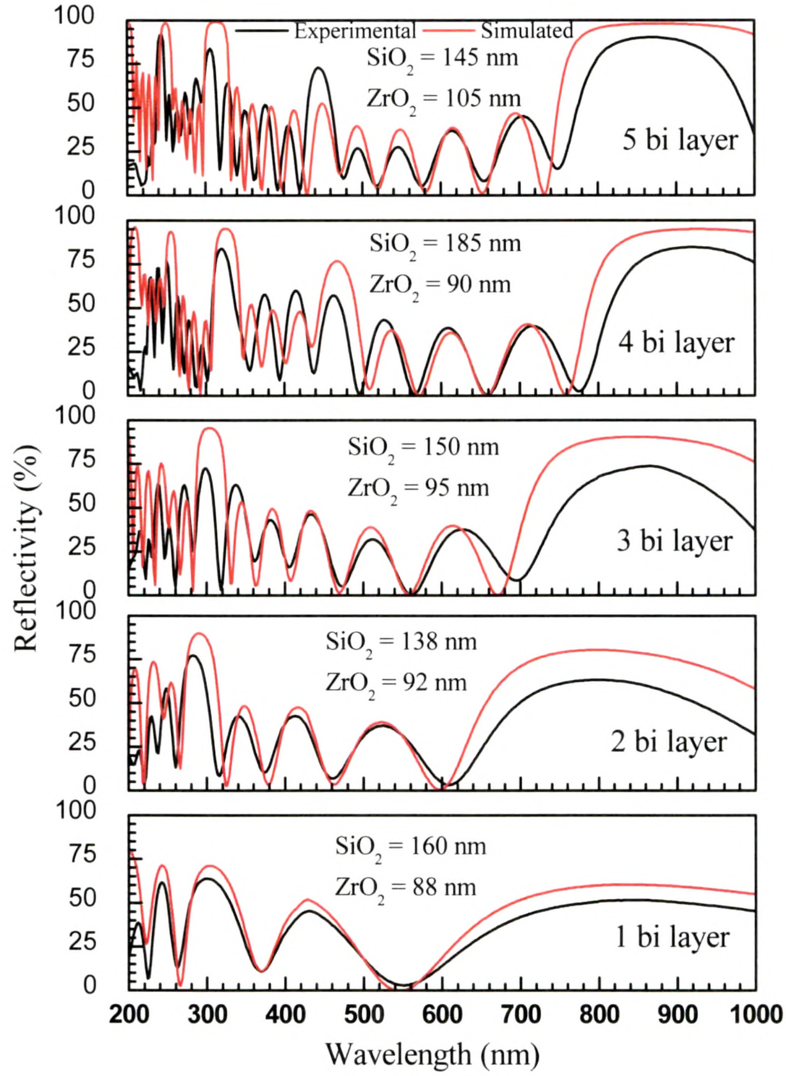
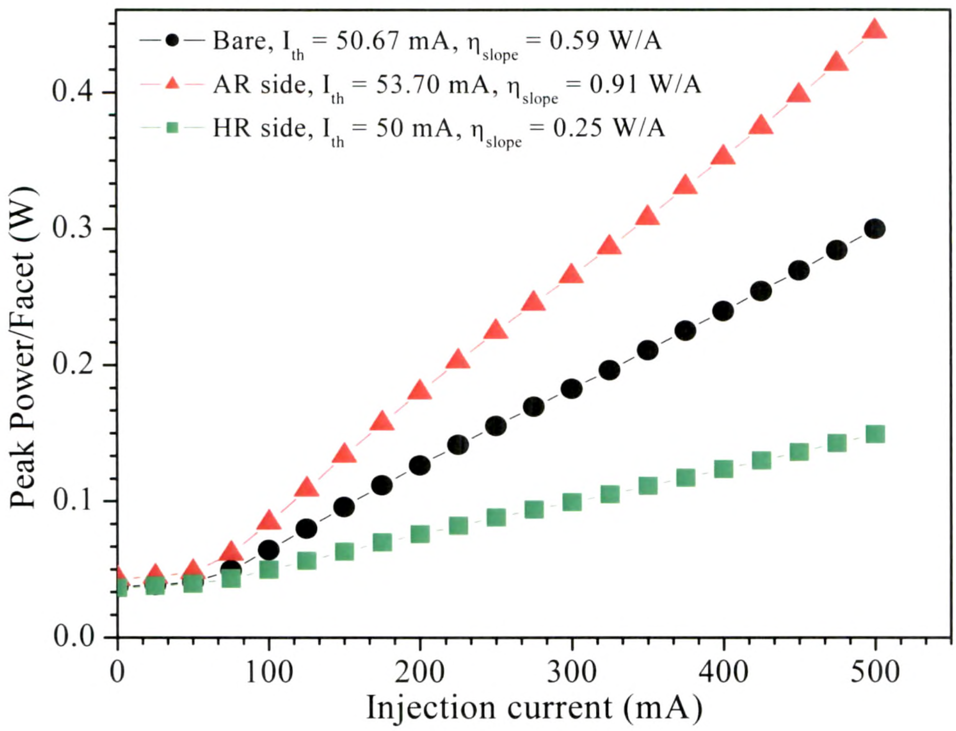


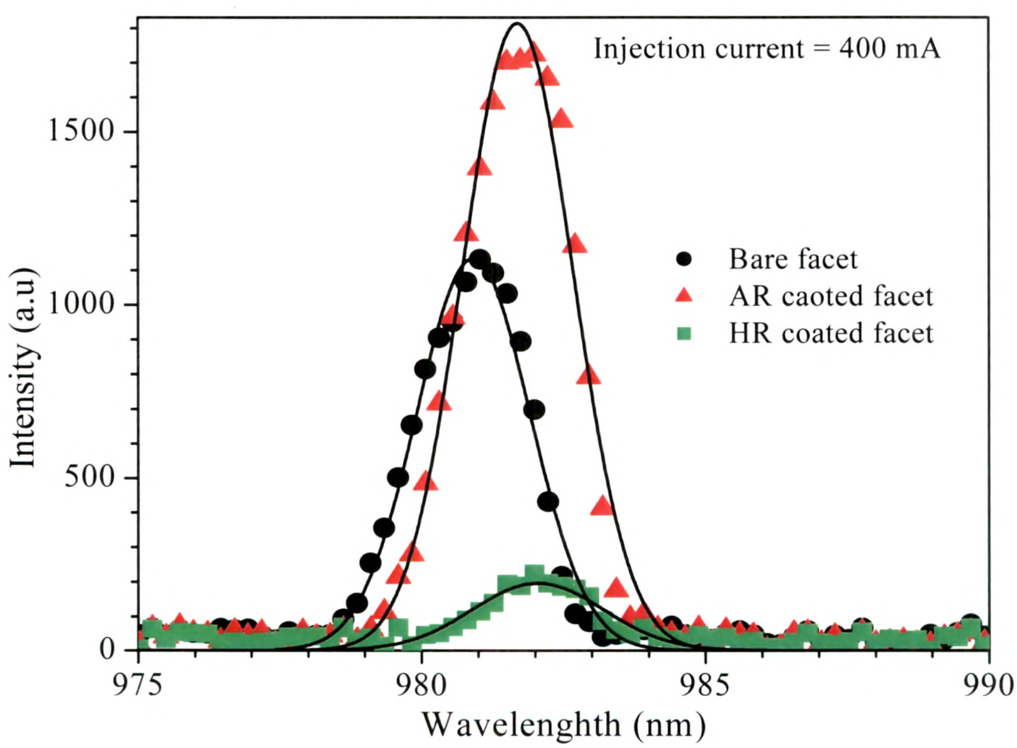
Figure 4.20: Reflectivity as a function of wavelength for $ZrO_2/SiO_2/GaAs$ multilayer.

❖ Optical Light Output Power vs. Current Characteristics of AR/HR Coated Laser Diode

The optical light output power-injection current (L-I) characteristics and spectral response of the lasers without AR/HR coatings and with AR/HR coatings are shown in the Fig. 4.21 (a) and (b), respectively.



(a)



(b)

Figure 4.21: (a) L-I characteristics of laser diode (b) Emission spectra of laser diode

The threshold current of lasers with AR/HR coatings did not change compared to the uncoated ones, however the slope efficiency (*dP/dI*) increased by 1.5 times. This is due to the fact that a laser diode provides equal optical power from both the front and the back facets. However, in most instances, only the power output from one of the facet is useful. The optical power output from the front facet of laser diode is given by, $P^{T}_{out} = P_c (1-R_f)(1+R_r)/2(1-R_fR_r)$ where R_f, R_r are the reflectivity of the front and back facet of laser diode, respectively. The total optical power generated in the cavity (P_c) is calculated as a function of input current. In the present structure considering the 2 % and 90 % reflectivity $P_{out} = 0.94\times P_c$, thus justifying the pertinent facet coating of laser diode by Eq. 4.11 [38].

$$dP^{T}_{out} / dI = (dP^{f}_{c}/dI + dP^{r}_{c}/dI)^{T}_{coated} = 0.94\times(dP_c/dI + dP_c/DI)_{uncoated} \tag{4.11}$$

Figure 4.21 (b) shows the emission spectra of laser diode without and with coating. It is noted that the position of emission spectrum of the facet coated surfaces are nearly similar to that of uncoated surface. The small shift of ~1 nm may be due to the variation of the operating temperature of the peltier cooler assembly. Subsequently, these laser diodes (die bonded p-side down with indium (In) preform on a gold plated copper package) were also operated under continuous wave (CW) mode of operation. The total output power from the facet coated laser diode was 745 mW at ~3.3 A injection current.

❖ Conclusion

Single layer of QWOT ZrO_2 (AR) and multilayer stack of SiO_2/ZrO_2 (HR) coatings on the front and rear facets of high power InGaAs QW laser diodes are deposited using e-beam methods. Reflectivity of 2 % and 90 % of the front and rear facet, respectively, are achieved in the configuration "Air-AR-front facet-rare facet-$(LH)^5$-Air" of laser diode. L–I characteristics have been measured before and after facet coatings. Significant output power enhancement for laser diodes due to AR and HR coatings is achieved. The slope efficiency is increased and the experimental results are in good agreement with the theoretical estimated.

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