Chapter 6

Life-time and Damage Threshold Estimation and Application of the High-Power Laser Diode

6. Lifetime and Damage Threshold Estimation and Application of the High-Power Laser Diode

The main factor which limits the high-power operation of the laser diode is the facet degradation. To overcome this limitation, optimization of the facet coating and packaging for the high-power laser diode has been done over here. However, while applying this coating to the high-power laser diode the quality of the thin-film has to be examined. The laser induced damage threshold (LIDT) of the optimized single layer QWOT dielectric films using high-power solid state Nd:YAG laser was carried out. The effect of packaging on the reliability and performance of laser diode by measuring the device life-time is also discussed in this chapter. Finally, the device application in photoluminescence spectroscopy of InAsP/InP quantum well samples was demonstrated.

6.1 Introduction

High-power laser diodes (HPLDs) cover a broad range of applications starting from a simple laser pointer to a pump source in solid state lasers. These applications requires long lifetime of the device and hence, the reliability is a common critical issue for HPLDs. The reliability of semiconductor lasers has been in constant improvement for about four decades, since continuous wave (CW) lasing at room temperature was achieved [81]. From the scientific point of view, the situation of strong competition, and the requirement of the commercial and technological secrecy, was not helpful for accelerating the research on the degradation mechanisms existing in HPLDs. Hence, reliable devices are available in the market however the knowledge of the degradation mechanism responsible for degradation is very poor.

In general, laser diode reliability may be defined as *"the ability to operate the device satisfactorily in a defined environment for a specified period of time"* [148]. Unfortunately, there are few industry standards that address laser diode reliability [149]. The problems resulting from this situation include issues such as the calculation of laser reliability (from accelerated life test data) and the interpretation of subsequent reliability claims. The chapter discusses in brief about various degradation modes and estimation of device lifetime. Also, the laser induced damage threshold (LIDT) measurements of different dielectric films has been demonstrated as an alternative to catastrophic optical mirror damage (COMD) testing to the device. Finally, we have demonstrated a successful application of indigenously developed laser package in photoluminescence (PL) spectroscopy of InAsP/InP quantum well.

6.2 Degradation Phenomena in High-Power Laser Diodes

The state of the art in applications of the high-power laser diodes (HPLD) are the forces that drive the growing importance of understanding the reliability and the degradation phenomena of laser diodes. Hence, for any application of laser diodes, the major degradation mechanism has to be recognized. There are several types of degradation modes depending on the initial period of degradation, degradation rate and the degree of degradation. Figure 6.1 illustrates various degradation mechanisms generally observed in laser diodes. These modes can be classified by location of degradation viz. internal or external degradation. The internal degradation occurs only inside the laser crystal which includes degradations of the active layer and p-n junction, whereas the external degradation occurs outside the laser i.e. degradation of facets, solder material, and contact electrodes.

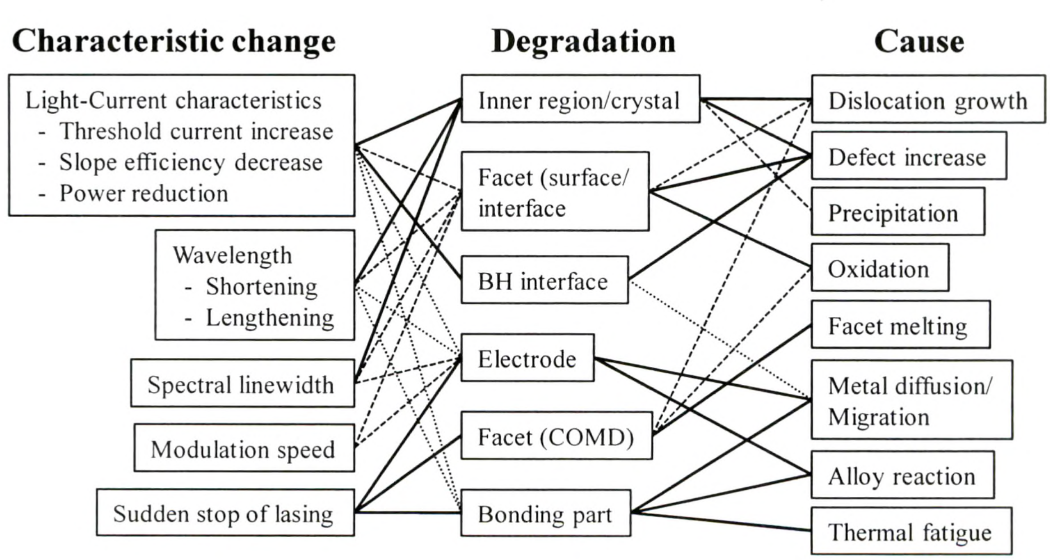


Figure 6.1: Main degradation mechanism of edge-emitting laser diode. The bold-lines, dashed-lines and dotted lines, respectively, indicates strong, moderate and weak correlation [150].

During the operation of the HPLD, usually decrease in the optical output power under a constant driving current or an increase in operating current during constant power operation indicates the device degradation. Typically, these changes are mainly caused by an increase in internal optical losses and decrease in injected carrier lifetime. These parameters directly affect the performance parameters of the laser viz. threshold current and differential or external quantum efficiency. Basically, based on the rate of change in device characteristic, for example optical output power, one distinguishes between three main failure modes: rapid, gradual, and catastrophic degradation, shown in Fig. 6.2 [151].

The rapid degradation occurs in the very initial phase of the device operation that can be detected by a very fast decrease in output power at a constant driving current or device efficiency. Basically the rapid degradation is characterized by an abrupt (< 50-100 hr) change to zero efficiency and is usually accompanied by the presence of dark-line defects–so called because they appear as regions of reduced efficiency in luminescence or lifetime plots.

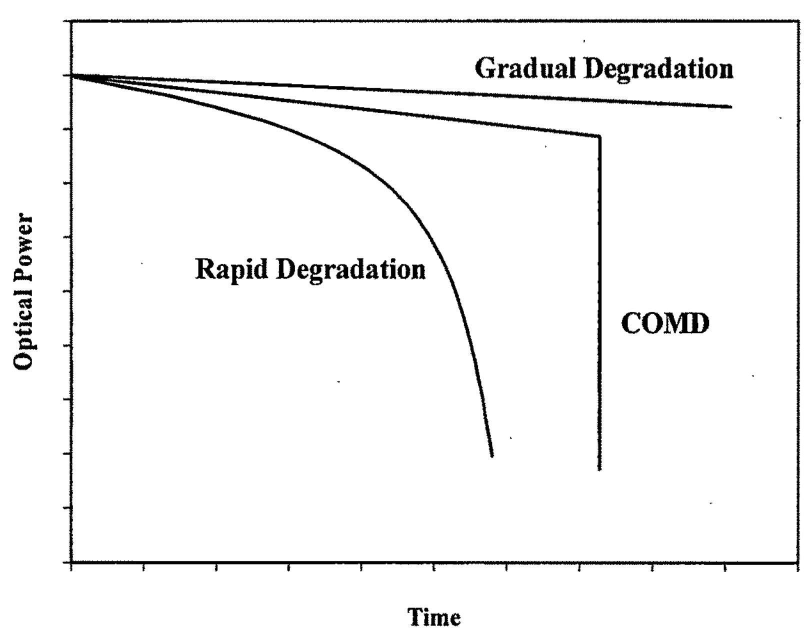


Figure 6.2: Various degradation modes of laser diode.

In today's high-quality quantum well (QW) lasers, rapid degradation phenomena rarely occur and the lifetime of lasers is generally limited by the other two mechanisms, i.e., gradual or catastrophic degradation. The gradual degradation can be described as a slow (~ 0.1-10 % per khr) decrease in efficiency which is, however, spatially uniform.

The point defect generation is responsible for this degradation mode. The ultimate lifetime of the laser diode is determined by gradual degradation which occurs over a long period. The lifetime can be estimated by extrapolating the power versus time curve at constant current or the drive current versus time curve for constant power until a definite change in value of respective entity is exceeded [152]. The maximum optical power of HPLD, however, is mostly limited by the catastrophic optical mirror damage (COMD). It is the irreversible failure of the device due to instantaneous melting at the facet at excessive power levels. The understanding of COMD mechanism is crucial, since it is one of the major killing factors for HPLDs.

6.2.1 Rapid Degradation

The rapid degradation process occurs in the active region, because of an increase in nonradiative recombination. The high-power operation of laser diodes at high input current densities creates high-energy carriers and thermal gradients, which have the potential to generate nonradiative recombination inside the active region. This increase in nonradiative recombination causes an increase in internal absorption loss and shortens the injection carrier lifetime. In general, when a laser diode is operated with constant output power or input current, there are cases in which operating current or optical power rapidly increases or decreases, respectively, within few hundred hours, known as '*rapid degradation*'.

The root cause for this degradation is generation and growth of the dislocations within the active region, and also formation of precipitate like defects of host atoms. The basic characteristics of the rapid degradation are: (1) rapid decrease in the optical output power of the laser diode during constant current operation (or increase in operating current while operating the laser diode at constant output power), (2) formation of the non-emitting regions within active layer viz. dark-spot defects (DSDs) [153], dark-line defects (DLDs) i.e. linear regions of significantly reduced radiative efficiency [154], and dark regions [155]. Here, in case of rapid degradation the life time of the laser diode is $\leq$ 100 hours at room temperature. This type of degradation is due to either recombination enhanced dislocation climb (REDC) or recombination-enhanced dislocation glide (REDG) [156].

6.2.2 Gradual Degradation

In contrast to rapid degradation, gradual degradation is characterized by a slow decrease in optical power or efficiency while operating the laser diode in constant current mode or increase in operating current in constant optical power mode of operation. The gradual degradation remains extent even after the complete removal of the rapid degradation and continuous over a long period. The rate of degradation depends on a variety of factors starting from device fabrication to its operating conditions viz. crystal growth parameters, material systems, strain, operating temperature and drive operation mode. The characteristic of the gradual degradation is a uniform darkening in the active region along with a gradual increase in deep level concentration [157]. The self destructing loop of nonradiative recombination generation at existing point-defects (vacancies and/or interstitial atoms of host elements) and development of new point-defects increase with time and this leads to reduced quantum efficiency. Point defects generated in the process can migrate and merge into defect clusters and micro-loops [158]. Ultimately, it is this mode that determines the lifetime of a component.

6.2.3 Catastrophic Optical Mirror Damage (COMD)

The maximum output optical power of HPLDs is mostly limited by the catastrophic optical mirror damage (COMD). The COMD mechanism can be illustrated by a number of related degradation feedback loops at the cleaved laser diode facets as shown in Fig. 6.3.

At high optical output power, facet heating leads to the third degradation process, namely COMD. Todoroki et al. [159] and Brugger et al. [160] have measured the laser mirrors temperature up to 450 °C by means of Raman scattering spectroscopy during CW operation of the device. Such high temperatures drive the facet degradation process which is triggered by oxidation of the facets. Figure 6.3 shows the self-destructing feedback loops at the cleaved laser diode facets leading to the damage of the facet and so the failure of the device. All the processes leading to a degradation of a diode laser are described in detail in [161]. The reason for the initial absorption of stimulated emission at facets is that there are interface states at the semiconductor–insulator interface. These interface states are increased by oxidation of the semiconductor material. This absorption induces the nonradiative surface recombination of the excitons, electron-hole pairs, in the facet regions and hence the facet heating followed by bandgap reduction. This bandgap reduction increases the light absorption at the facets, and a feedback loop develops. This effect will be enhanced by current crowding at the facet due to the lower bandgap [162]. Finally, if the absorbed energy is high enough, a self-destructing feedback loop generates which leads to spontaneous facet damage, known as COMD.

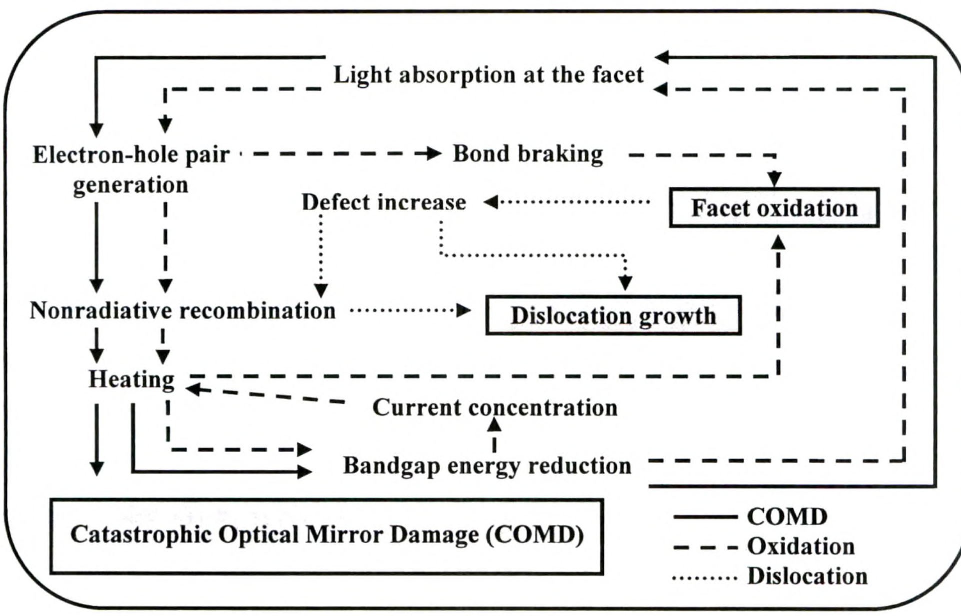


Figure 6.3: Degradation mechanism in edge-emitting laser diode. This self-destructing cycle of laser diode degradation finally comes to an end with catastrophic optical mirror damage (COMD). [163, 164]

In case of the HPLD the high-power density in a small volume can easily reach up to the order of MW/cm^2 at the facets region. This high-power is near to the damage threshold of the laser facet. To reduce the probability of the facet damage, various approaches have been reported. To decrease the initial light absorption at the facet, the bandgap near the facet has to be broadened. Also one can protect the facet from degradation by reducing the surface recombination velocity by means of cleaving the wafer into bars in ultrahigh vacuum or in a protective atmosphere and to evaporate an appropriate passivation layer on the surface [165]. The surface heating takes place by forward current due to the nonradiative recombination. This phenomenon will lead to decrease in bandgap at the facet. One can put off the supply of the carriers to the area close to the facet [166].

6.3 Laser Induced Damage Threshold Measurement

The utilization of the HPLDs increases with technological advancements. The application of the HPLD systems is not only limited to the consumer electronics but also used in high energy systems [167]. Hence the HPLD is required to operate over a long period of time without any significant degradation in performance. The high-power operation of the laser diode is primarily limited due to the thermal rollover and/or the laser facet damage. The thermal limitations of the laser diode can be eliminated by various laser structure designs e.g. quantum well intermixing [168,169] while the laser facet damage can be improved by facet coating with appropriate dielectric materials besides the laser structure improvement [164].

The laser diode performance improvement can be achieved by single-layer ($\lambda/4$ thick) anti-reflection (AR) and $\lambda/4$ thick multi-layer high reflection (HR) coatings at front-and-back facet, respectively [170]. This dielectric facet coating serves as passivation and protection against external effects viz. oxidation, moisture effects, etc. It also enhances the maximum output power and efficiency by modification in facet reflectivity [171,172], and shows good stability during the long term operation [173]. Hence, with the development of HPLD the facet coating with high damage resistance need to be optimized.

The most common practice to investigate the laser diode facet coating properties is the pre- and post-laser diode characterization viz. Optical power(L)–Current(I)–Voltage(V) testing. In addition to that some researchers put efforts to measure the long term reliability and catastrophic optical mirror damage (COMD) test of the laser diode after facet coating. The COMD of the laser diode is a spontaneous (occurs without prior significant) event due to the high-power density at the facet region. The COMD event is random and the theoretical models proposed for the damage mechanism are device dependent. The probability of COMD occurrence in most of the applications of the laser diode is infrequent, especially in case of longer wavelength devices. So it is good to characterize the facet only for its damage threshold rather than characterize it after device facet coating, which costs not only the material processing but also the whole device failure.

One possible way to find the damage threshold of the optical thin-film is the laser induced damage testing. The laser damage threshold (LDT) is defined as the fluence (energy density per unit surface area, J/cm^2) at which an irreversible damage/change occurs in the optical material as a result of laser illumination [174]. Various methods have been demonstrated for measuring the laser induced damage threshold (LIDT) of the thin-film optical coating viz. 1–on–1, S–on–1, R–on–1 etc. A common method is to expose a focused laser beam on to the sample and after illumination the coating is inspected for the damage using microscopy [175].

The present thesis discusses the LDT measurement of the optical thin-films deposited on to the GaAs samples with varying thicknesses viz. $\lambda/4$, $3\lambda/4$, and $5\lambda/4$. The diode pumped Q-switched Neodymium Yttrium Aluminum Garnet (Nd:YAG) laser (1064 nm) was used to damage the samples. The sample prepared for LDT was characterized for its reflectivity before the damage test. The laser induced damage was observed initially by visible flash and finally under microscopic observation. The preliminary results show that the damage on the samples was only due to the heating effect rather than optical absorption into the sample. Moreover, there was no significant effect observed on LDT as a function of film thicknesses.

6.3.1 Experimental

The single layer anti reflection (AR) coatings of the Al_2O_3, MgF_2 and SiO_2 (MERCK) were deposited in a 270° bend 6 kW electron beam evaporation system in a high vacuum coating unit (Hind High Vacuum Co. (P) Ltd.). The system is equipped with thin film deposition controller (SQC-122c SIGMA) to precisely monitor and control the thickness and deposition rate of the thin film. The single layer coatings were carried out on GaAs substrate and optimized for the wavelength ~1060 nm. The substrate was cleaned thoroughly using trichloroethylene (TCE), acetone, and methanol. The AR films have been deposited with constant rate of 2 Å/sec on a rotating substrate (30 rpm). Radiant heater was used to maintain the desired substrate temperature of 200 °C. The reflectivity of the deposited film on a GaAs substrate was measured ex-situ.

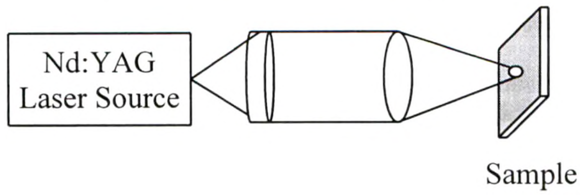


Figure 6.4: The schematic of the laser damage threshold measurement of single layer QWOT antireflection thin films deposited on the GaAs substrate.

The standard methods for the laser damage threshold measurement are 1–on–1, and S–on–1 tests [174]. The limitations of these methods are complex implementation and data analysis is time-consuming and each experimental condition requires exposing a sample to the new damage site. Hence, an unconventional laser damage test has been performed as per the available facility. Figure 6.4 shows the schematic of the laser damage threshold measurement of the single layer QWOT antireflection thin films deposited on the GaAs substrate. The LDT test was carried out using diode pumped Q-switched Nd:YAG laser system (Model. Hallmark Diode, Sahajanand Laser Technology Ltd., INDIA). The laser produced a beam with a gaussian spatial profile. The detail technical specification of the laser system used for pulse LDT is mentioned in Table 6.1.

Table 6.1: Laser system specification used for the pulse LDT measurement

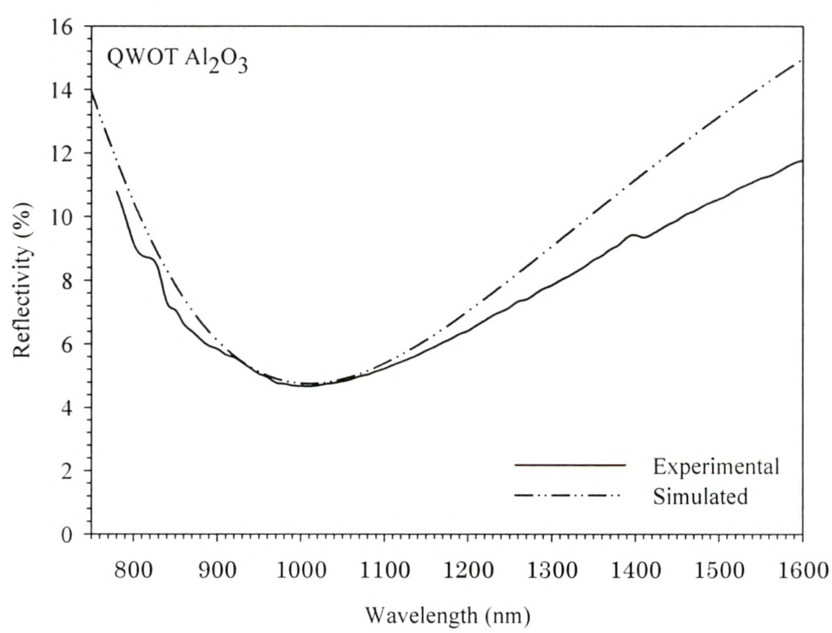
Laser Source	Diode Pumped, Q-switch Nd:YAG
Wavelength	1064 nm
Beam Mode	TEM_{00}, M2 < 1.2
Laser Power (Avg.)	0.5 to 1.5 W
Pulse width	100 ns
Pulse Frequency	200 Hz
Resolution	1 μ
Output beam diameter	6 mm ($1/e^2$)

The beam spot size was set by adjusting the distance between the sample and positive/focusing lens (focal length = 70 mm) i.e. 1.17 mm for pulse mode and 0.39 mm for continuous wave (CW) LDT measurement. (Focal length = 77 mm). To avoid the effect of interference and reflection of the irradiated laser from the sample to the source, the sample was adjusted slightly displaced from the normal. The average output power of the collimated laser beam was measured with power meter (Laser power meter, OPHIR Photonics). The servo-motor enables the sample to travel across the laser path (with speed of 200 mm/s) that irradiates the laser with frequency of 200 Hz. The damage sight on the coated sample was observed using a polarization microscope (LABOURLUX 11, Leitz).

6.3.2 Results and Discussion

❖ Reflectivity Measurement

The mirror polished GaAs sample was coated with single layer quarter wave optical thick (QWOT) of different dielectric materials viz. Al_2O_3, MgF_2, and SiO_2. The LDT was measured for the samples with different material thickness viz. $\lambda/4$, $3\lambda/4$ and $5\lambda/4$ optimized for the wavelength ~1060 nm. The reflectivity of the coated thin films on GaAs substrate was measured using self assembled reflectivity measurement setup. The experimental reflectivity was measured with reference to the standard gold mirror and compared with simulated results. Figure 6.5 shows the experimental and simulated reflectivity of the optimized sample. The reflectivity simulation was discussed by V. A. Kheraj et al. in detail [119]. The reflectivity measured for other samples with different thickness is shown in Table 6.2.



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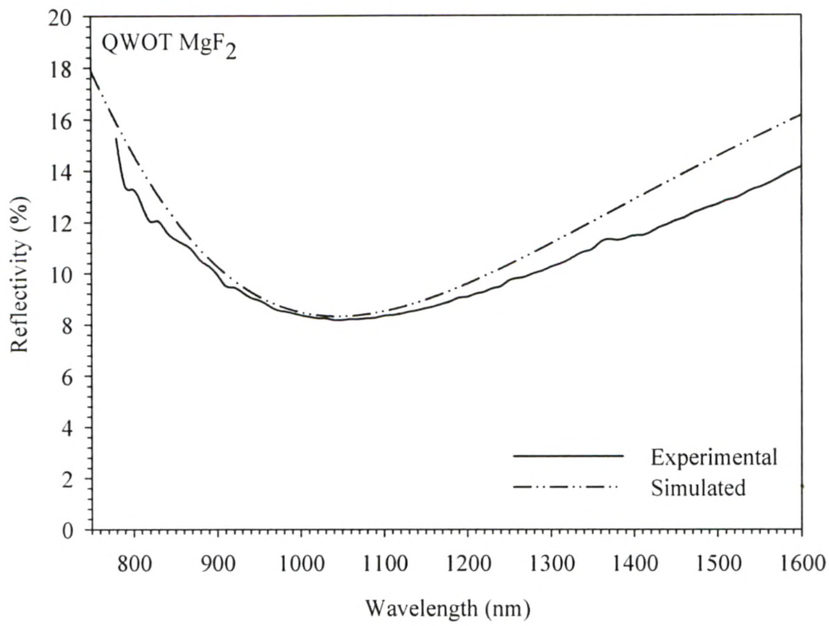

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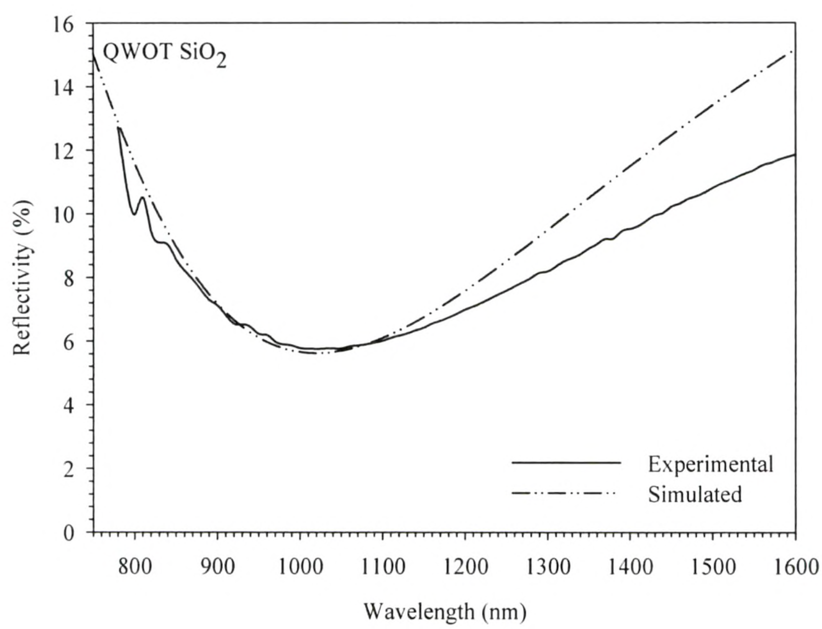

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Figure 6.5: Optimized QWOT single layer facet reflectivity curve for (a) Al_2O_3, (b) MgF_2 and (c) SiO_2

Table 6.2 – The measured and calculated thin film parameters.

Material	Thickness (Å)	Reflectivity (%)	
		Exp.	Sim.
Al_2O_3	$\lambda/4n$	4.89	4.97
	$3\lambda/4n$	6.63	7.09
	$5\lambda/4n$	5.63	6.32
MgF_2	$\lambda/4n$	8.21	8.33
	$3\lambda/4n$	7.04	8.24
	$5\lambda/4n$	6.60	6.75
SiO_2	$\lambda/4n$	5.83	5.75
	$3\lambda/4n$	5.20	5.32
	$5\lambda/4n$	6.57	6.61

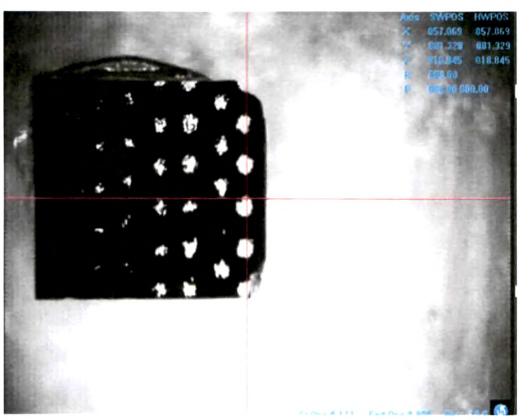
❖ LDT Measurement

The samples were irradiated with increasing beam fluence up to 1.5 W average power (starting from 0.1 W with 0.1 W step increase) for pulse LDT. In case of CW LDT measurement the power was increased up to the damage with 1 W step increase. The spacing between consecutive damage spot with different fluence was kept enough to avoid the intermixing of damage conditioning on nearby damage spots. The preliminary confirmation of the damage to the samples was by observing spark/flash during irradiation and also using CCD camera (75X zoom) mounted on the laser system. After each irradiation to the sample the damage site's snap shot was taken to compare the influence of the increasing damage fluence.

In case of pulse LDT measurement increase in the diameter of the damage spot with increasing laser power was observed for all samples, as shown in Fig. 6.6. Tables 6.3 and 6.4 contain the LDT data of Al_2O_3, MgF_2 and SiO_2 measured in pulse mode and CW operation, respectively.

Table 6.3: Laser damage threshold (Pulse mode) of materials with beam diameter = 1.17 mm, frequency = 200 Hz, Pulse width = 100 ns

Experimental Parameters	Materials		
	SiO_2	Al_2O_3	MgF_2
Average Power (W)	0.85	0.8	0.7
Energy / pulse (mJ)	4.25	4.00	3.50
Peak power (kW)	42.5	40.0	35.0
Peak power density (MW/cm^2)	3.95	3.72	3.26



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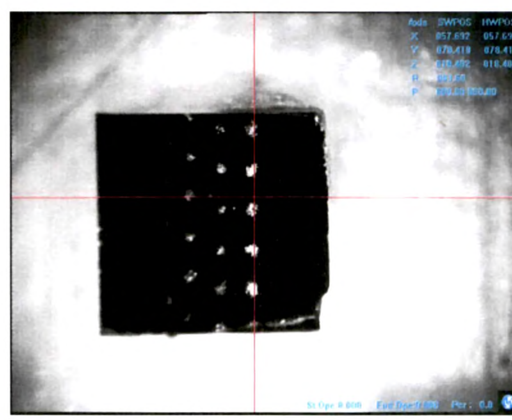

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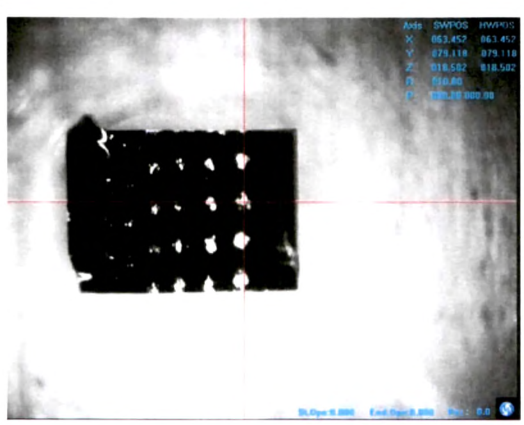

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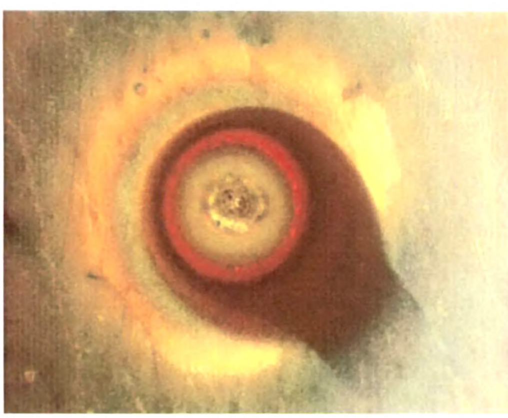
Figure 6.6: Photographs of pulse laser induced damage for single layer QWOT (a) Al_2O_3, (b) MgF_2, and (c) SiO_2 on GaAs substrate

The damage threshold of the sample with different thickness is almost equivalent and there is no observable difference found on the sample observed under the microscope. It has been reported by T. W. Walker et al. [175] that the LDT of the oxide materials shows no significant change as a function of thickness while MgF_2 shows small variation in LDT with thickness. The microscopic observation of the CW laser induced damaged site clearly illustrates the melt substrate material as shown in Fig. 6.7.

Table 6.4: Laser damage threshold (CW mode) of materials with beam diameter = 0.39 mm

Experimental Parameters	Materials		
	SiO_2	Al_2O_3	MgF_2
Average Power (W)	10	16	11
Power density (kW/cm^2)	8.37	13.39	9.21



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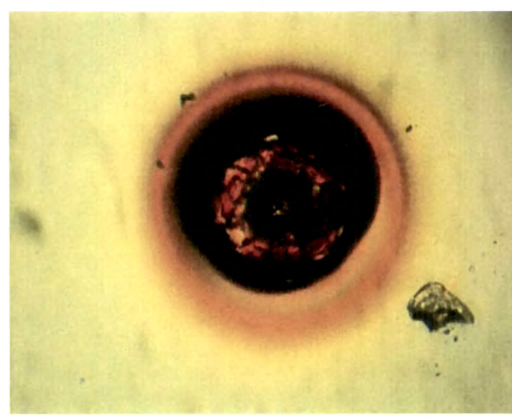

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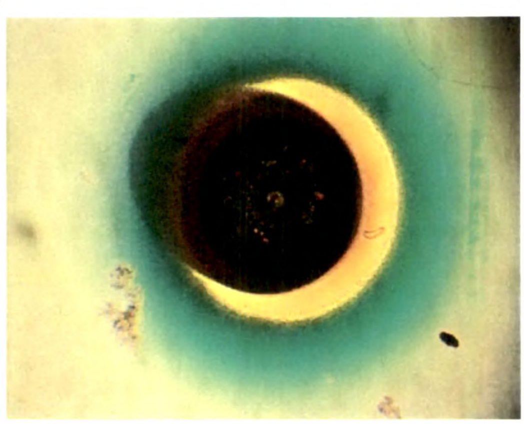

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Figure 6.7: Microscopic view of the single layer QWOT (a) Al_2O_3, (b) MgF_2, and (c) SiO_2 CW laser induced damage site.

The damage to the sample is entirely because of the heating effect. The impurity percentage and surface defects in the substrate and the deposited material play a vital role in absorption and hence heating into the sample. The absorption of the laser energy leads to the nonradiative relaxation on excited electrons and hence causes the heating. The heat around the irradiated area cause expansion of material and finally melts it. Also, A.V. Kaunar et al. have reported that the GaAs with mirror polished surface has less surface absorption than other rough surfaces and hence higher laser damage threshold [176]. The average damage spot site diameter was ~150 μm, which leads to CW LDT >55 kW/cm^2. The catastrophic optical damage (COD) limit of the commercially available bare HPLDs is of the order of few hundred watts. Hence we can certainly utilize this facet coating to improve laser diode COD limit.

6.4 Lifetime Measurement

Lifetime measurement is an important phase for the study of device degradation as well as reliability testing during the fabrication process of laser diodes. Life tests generally involve monitoring the operation of a laser diode under carefully controlled conditions. Degradation is observed and recorded throughout the test by precise measurement of changes in the laser's operating characteristics. However, it is not possible to obtain sufficient amount of test data within specific time period while operating the device under normal use condition, especially when device having high reliability and long lifetime. Therefore it seems impractical to run the device over a long period of time only to measure its lifetime. Hence, the lifetime measurements are performed at high stress conditions to get enough data within relatively small time period and that can be fitted to various empirical models depending on stress parameters. Usually stress parameters includes in lifetime testing are temperature, current, power, voltage, humidity and ambient pressure either taken singly or in combination.

We have developed the VI using LabVIEW (ver. 8.2) that allows the life time measurement. Generally the lifetime of the laser diode can be measured in either automated current control (ACC) or automated power control (APC) mode. In ACC mode the laser drive current should remain constant while in APC mode the laser output power should remain constant. Moreover, for accelerated aging, the experiment can be carried out at higher temperature. We have estimated the lifetime of the laser diode using ACC mode under accelerated aging condition. The constant operating current is supplied to the laser diode using constant current source meter (Keithley 2420C). The voltage across the diode is also measured by Keithley 2420C. The output light is made to fall into the integrated sphere and the signal from the photodetector is measured with the help of PCI-6024E Data Acquisition (DAQ) card. The laser diode is kept at constant temperature using a TEC (Thermo Electric Cooler) to avoid temperature instability during the experiment. The experiment is carried out in a dark room to avoid effects of other light sources. The VI records and displays the current, the voltage across the laser diode and the optical power at the desired interval of time.

The whole experiment is provided with the UPS backup system in order to avoid problems of electrical power failures during the experiment which runs for a few days. Further, Laser diode life test studies require the accurate measurement of changes in laser operating parameters as small as a few percent over thousands of hours. Consequently, the stability of the measurement equipment must be very high, typically on the order of 0.1 % per 1000 hours. The DAQ card PCI-6024E provides the stability of 0.01 % per 1000 hours.

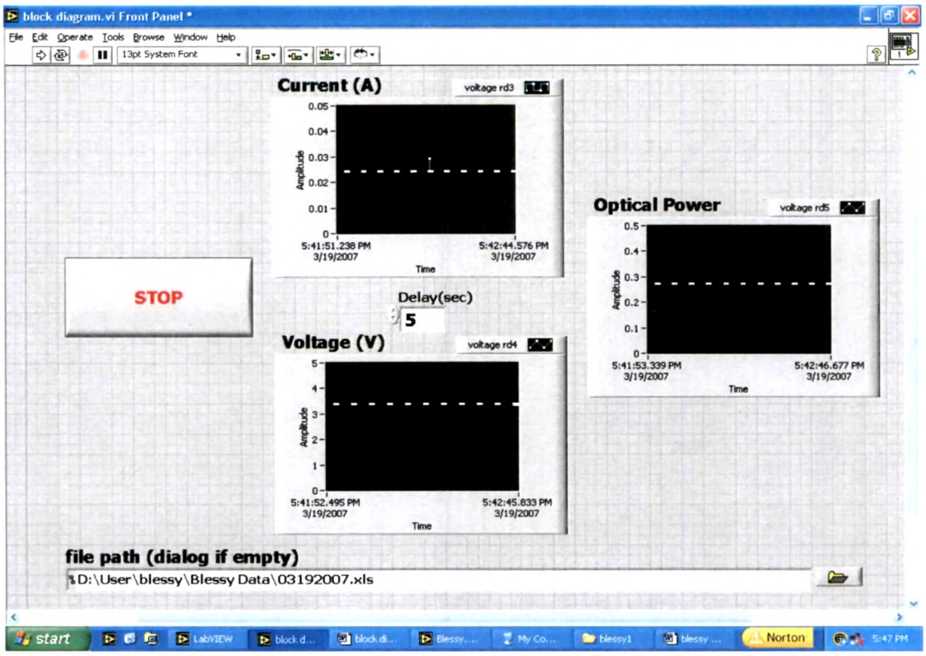
In ACC mode, when user stops the experiment, the VI plots the optical power over the complete experiment time and the power versus time curve is fit to the exponential decay curve of the type

$$y = A\exp[-Bx] \tag{6.1}$$

Thus, from Eq. 6.1, we get the life time of the laser diode as

$$\tau = \frac{1}{B} \tag{6.2}$$

The final result of life time is displayed on the front panel and recorded in the file along with the sample details and measurement mode. The front panel and the block diagram of the VI are shown in Figs. 6.8 (a) and (b) respectively.



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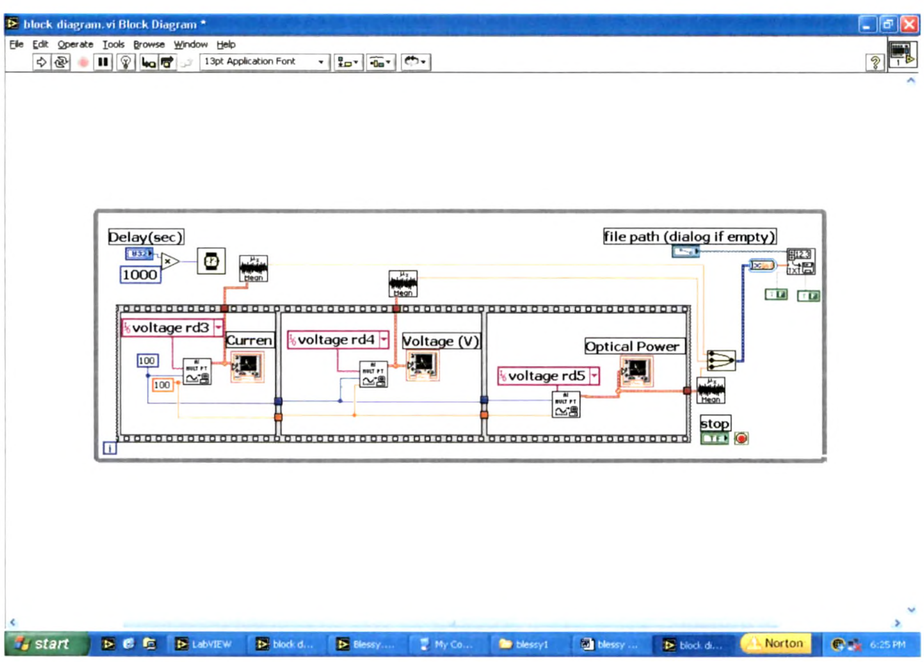

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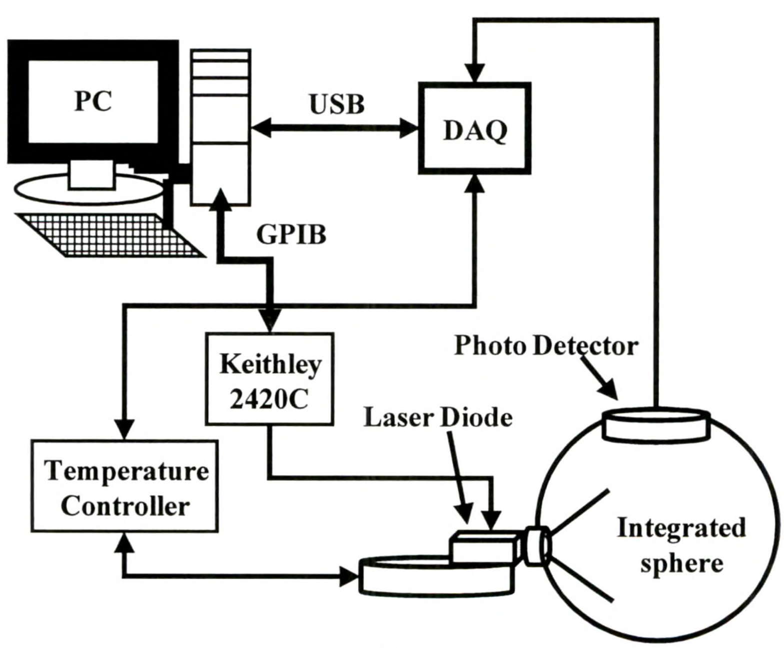
Figure 6.8: (a) Front panel and (b) block diagram of the laser diode life-time measurement VI.

6.4.1 Upgradation in Lifetime Measurement

We have upgraded an automated lifetime measurement facility for testing of laser diodes. The InGaP quantum well laser diode (λ = 650 nm) was tested for the optimization of the setup. Program itself monitors the input parameter viz. operating temperature and current. The optical output power data will be stored and the extrapolation of this optical power as a function of time gives device life-time. The device was degraded by means of ACC mode, for measurement of laser diode lifetime. As the name suggest in ACC mode laser current is held constant for the duration of the test and the optical output power is monitored continuously. We have developed a (VI) using LabVIEW (ver. 8.2) that allows the measurement of output power being the function of time for accelerated aging.

The experiment was carried out at temperature, 80 °C. The applied constant operating current and device operating voltage across the diode was monitored using source meter (Keithley 2420C). The output light was made to fall into the integrated sphere (Lab-sphere 819IS) and photo-detector (Newport 818SL) assembly and output power was measured through PCI 6024E DAQ card. The laser diode was kept at constant temperature to avoid temperature instability during the experiment. The experiment was carried out in a dark room to avoid effects of other light sources. The schematic and photograph of the experimental setup is shown in Fig. 6.9.



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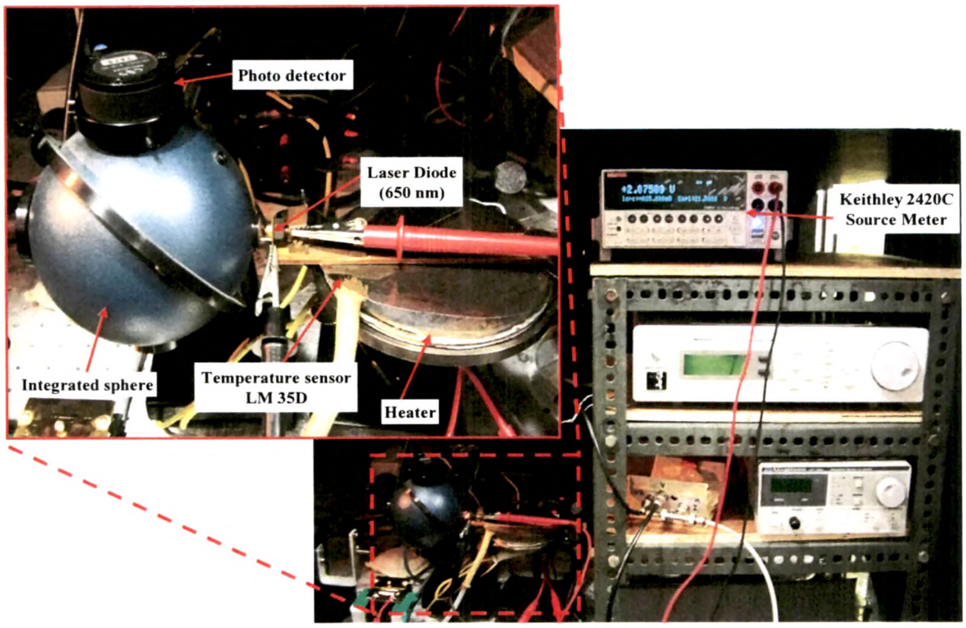


(b)

Figure 6.9: Experimental setup to find device lifetime, (a) Schematic and (b) photograph.

The developed program flow for the automation of the experiment and data acquisition follows the flowchart shown in Fig. 6.10. The front user panel and the LabVIEW block diagram are shown in Fig. 6.11 (a) and (b), respectively.

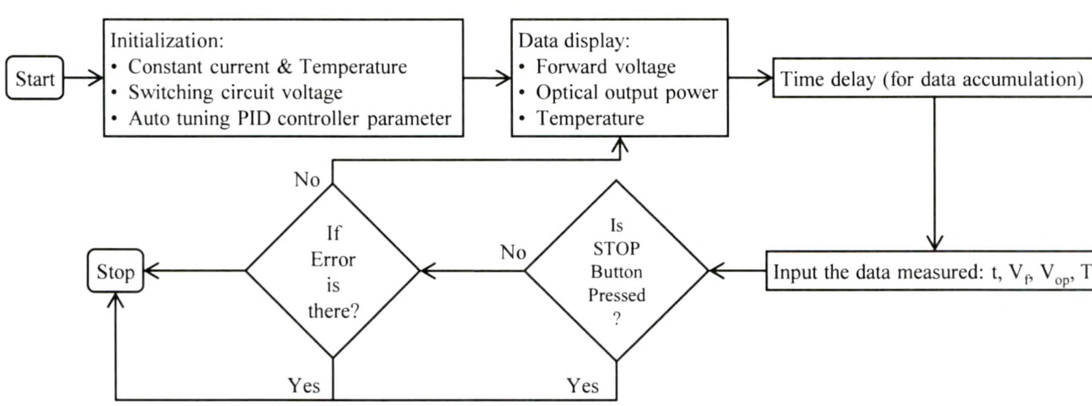
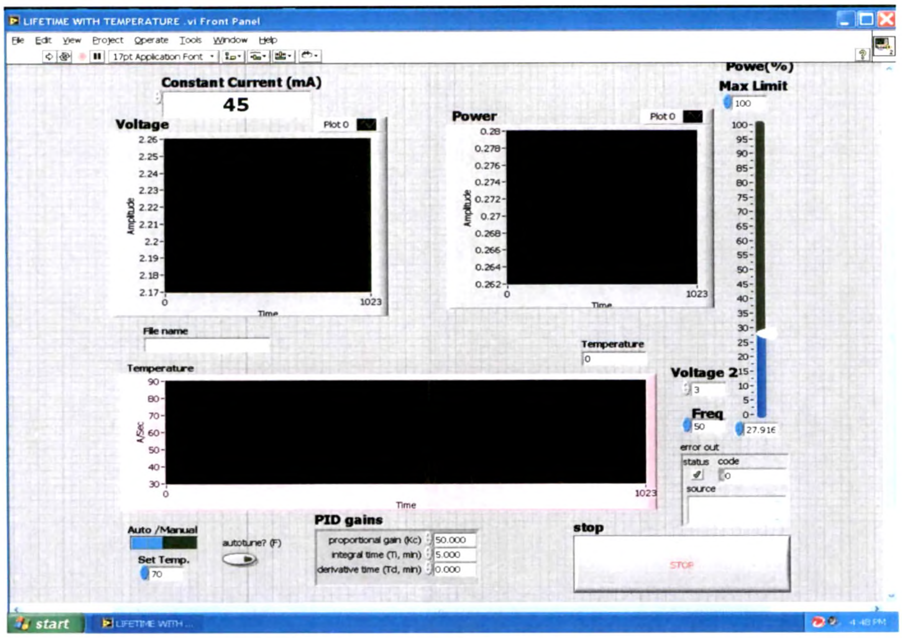
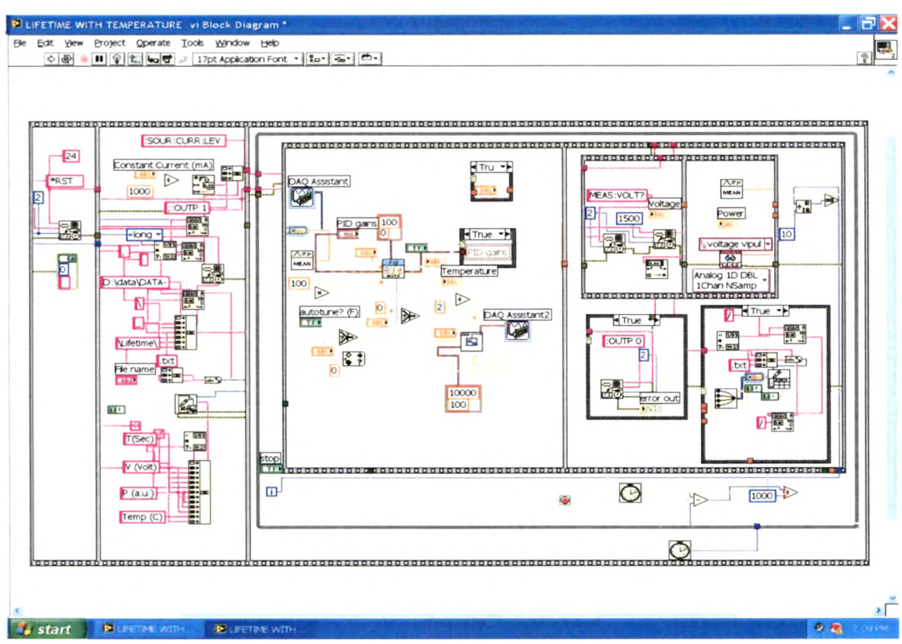


Figure 6.10: Flow of the program shows programming initialization as well as conditions to fulfill user requirement of the instrument automation and data acquisition.



(a)



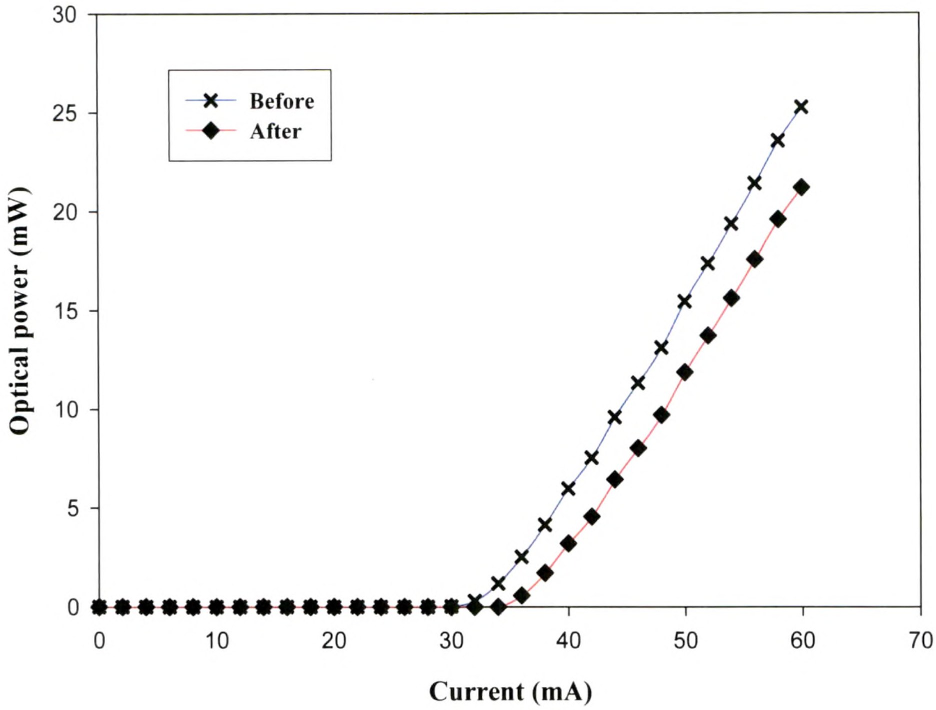
(b)

Figure 6.11: LabVIEW VI for Automated Lifetime Measurement: (a) User front panel enables the user to control all attached instruments and experimental parameter. (b) Block diagram shows graphical user interface and programming facility of LabVIEW.

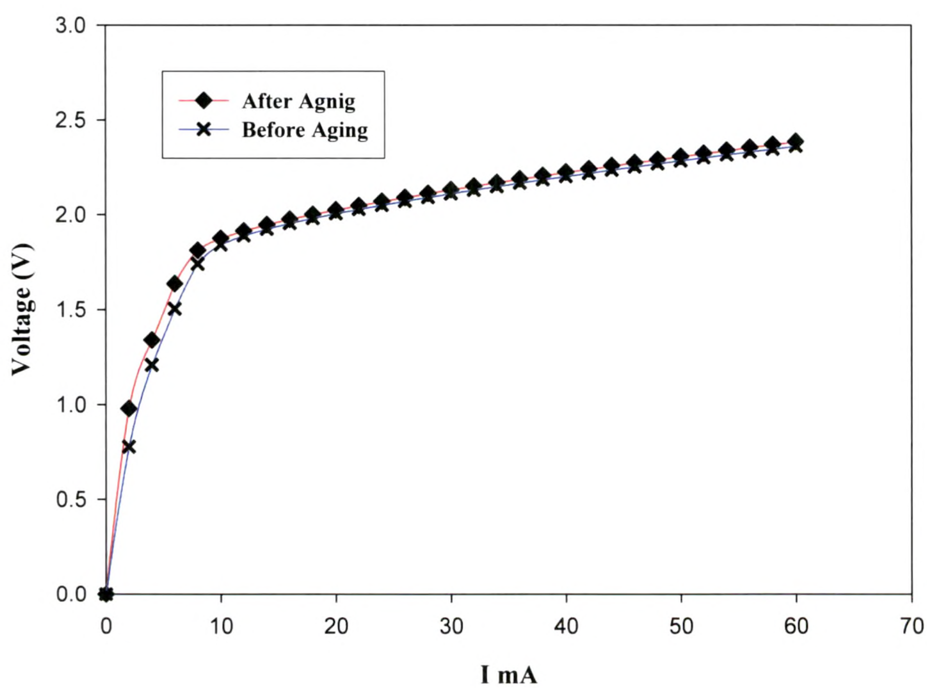
6.4.2 Results and Discussion

Pre and post L–I–V tests at room temperature (24 °C) produced typical, well-behaved parametric curves for output optical power and voltage vs. operating current. These L–I–

V tests were performed before and after the 80°C burn-in. The results of these tests are shown in Fig. 6.12 (a) and (b).



(a)



(b)

Figure 6.12: (a) L–I curve, (b) I–V curve of LD at room temperature before and after the reliability test.

Usually, the lifetime of laser diode is defined as the time period for 20 % decrease in optical output power or 20 % increase in operating current while operating the device under ACC or APC mode, respectively. Considering the same end-of-life criterion of 20 % increase of laser operating current over its initial value, Yajun Li [177] has reported lifetime extrapolation of 650 nm InGaAlP laser diodes measured at 70 °C for 1000 h under APC mode. Similarly, the lifetime of the 100 μm stripe width 650 nm broad area lasers has been estimated about 100,000 h at room temperature [178]. In our case, an aging test of 195 hr of the laser diode shows the degradation of device, as shown in Fig. 6.13, operating at 80 °C in automatic current control mode. By extrapolation of the data using Eq. 6.2 we find the device lifetime is ~ 35,000 hr, at 45 mA operating current and 80 °C ambient temperature.

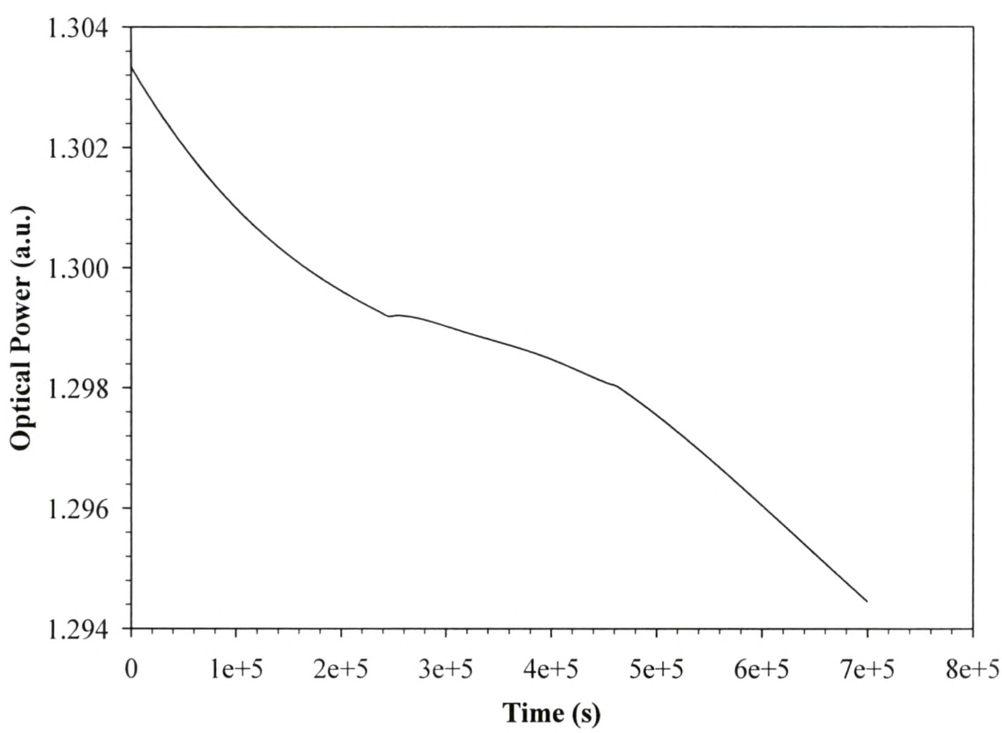


Figure 6.13: Optical output power of laser diode at constant operating current, 45 mA, as a function of time at 80 °C in ACC mode.

❖ Conclusion

The reliability of the 650 nm InGaP quantum well laser diode was measured using automated constant current (ACC) mode with accelerated aging. Extrapolation of the data for optical output power versus time gives the lifetime of device of the order of 10^5 hour at room temperature. The junction temperature was measured using electrical test method. Though the variation in forward voltage with respect to temperature is very small we find the quite good relation between junction temperature and operating current. We also observed that for the higher injection current value the linear relation does not hold true.

6.5 Application of 980 nm Laser Diode in Photoluminescence (PL) Spectroscopy

6.5.1 Photoluminescence

Photoluminescence (PL), as its name suggests, is define as the photon assisted spontaneous light emission from the material. Or, in other words, we can say that the excitation of an electron from ground state to higher energy state by absorbing a photon of energy $h\nu \geq E_g$ and subsequent emission of light when electron return to the ground state. Photoluminescence (PL) has been developed as a sensitive technique for semiconductor material analysis as the energy of the light emitted from the material corresponds to the difference in energy between the excited state and the equilibrium state involved in the electronic energy transitions. Hence, it is used to characterize semiconductor material for bandgap determination, detect and identify impurity level, recombination mechanism analysis, material quality measurement, etc. The radiative emission intensity is proportional to the impurity density. Impurity identification by PL is very precise because the energy resolution is very high.

Figure 6.14 shows usually observed transitions with PL. Excitation of a sample occurs via absorption of a photon and create electron-hole pair, called excitons. Eventually, these excitons will de-excite/recombine either radialtively or non-radiatively. Here, the primary interest in PL is the radiative recombinations since it is observable with very high sensitivity. These various possible radiative recombination processes are illustrated in Fig. 6.14.

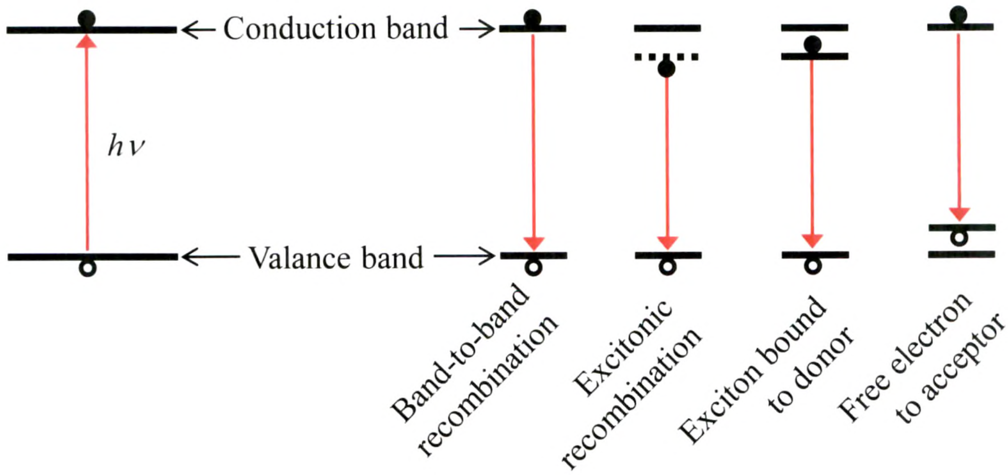


Figure 6.14: Transition during Photoluminescence. [179]

The analysis of PL data will give the following information.

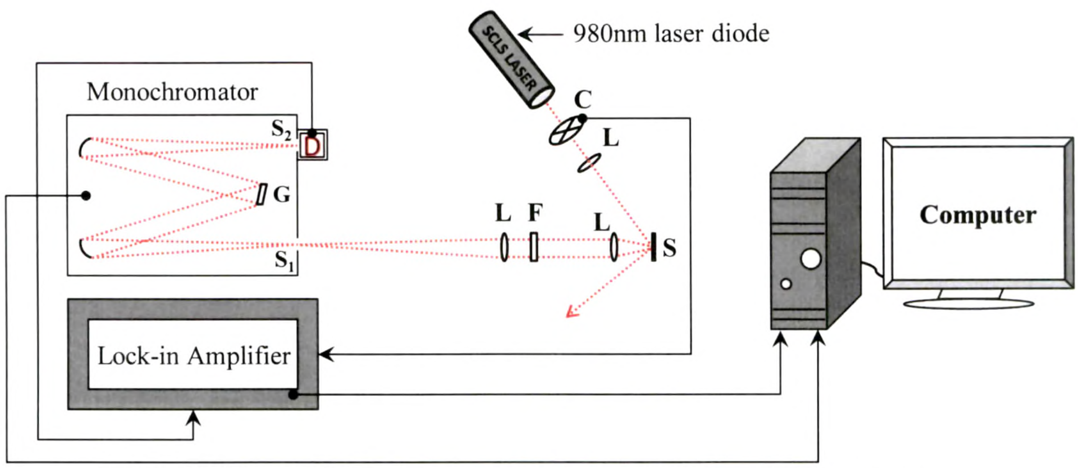
1. The peak intensity gives information about the optical quality of sample. Higher the intensity better is the quality.
2. Bandgap related information.
3. The full width half maximum (FWHM) of the peak tells about the uniformity of layers (compositional and spatial). Narrower the FWHM better is the layer uniformity.

The main strength of the PL spectroscopy lies in its sensitivity to detect very weak signals (high signal to noise ratio), which depends on the quality of the sample. Its main limitation is weak or no PL signal for indirect bandgap materials. It provides only the lowest excited state information for quantum structures and requires low temperatures to suppress the luminescence from defects in case of low quality samples.

6.5.2 Experimental

A typical PL spectroscopy setup is illustrated in Fig. 6.15. Usually, the experimental set up of PL spectroscopy consists of an excitation source, a monochromator, photo detector and lock-in amplifier. Lasers are generally used as excitation source in most cases since they are capable of delivering monochromatic and highly collimated beam. Also laser allows localized spatial resolution and determination of the penetration depth. The optics used in the set up is such a way that to ensure maximum light collection from the sample.

The apparatus shown in Fig. 6.15 has a lens system which is closely matched to the f-number (in our case, 4) of the monochromator. Here, C is chopper, F is filter, L is lens, S is sample, S_1 and S_2 are input and output slits of monochromator respectively, G is grating and D is detector (in our case Ge detector).



C – chopper, D – Ge detector, F – filter, G – grating, L – lens, S – sample, S_1 & S_2 – slits

Figure 6.15: Block diagram of Photoluminescence set up.

In this setup is we have used laser that we have developed having wavelength 980 nm operated at 4.7 mW/facet CW power and germanium (Ge) detector is used which detect wave length ranges from 1050 nm to 1600 nm. This laser beam is chopped using a mechanical chopper (whose frequency is set using a lock-in amplifier). Chopping is necessary to improve the signal to noise ratio (~ 10^{-6}). The chopped beam is focused on the sample using lenses. We have used triplet lens which is a combination of two convex and one concave lens to collect and concentrate the beam coming out of the laser diode.

6.5.3 Sample Detail

We have done PL spectroscopy by using indigenously developed laser diode package on two InAsP/InP quantum well (QW) samples having thickness of 28 Å and 38 Å, as shown in Fig. 6.16. The structure of sample consists of $InAs_xP_{1-x}$ sandwiched between two undoped InP barrier layers. Then there are cap layers on the top side and the buffer layer on substrate is of InP which is doped with Si with doping density 2.6 x 10^{17} cm^{-3}. The whole structure is grown on n^+ InP (001) substrate having doping density is of 1x 10^{18}

cm^{-3}. Further details regarding the sample growth and characterization are discussed elsewhere [180].

n^+ InP, 1470 Å, 2.6 x 10^{17} cm^{-3}
Undoped-InP, 50 Å
Undoped-$InAs_xP_{1-x}$ QWs, 28 & 38 Å, x = 0.38
Undoped-InP, 50 Å
n^+ InP, 1470 Å, 2.6 x 10^{17} cm^{-3}
n^+ InP (001), Substrate 1 x 10^{18} cm^{-3}

Figure 6.16: InAsP/InP single quantum well sample structure.

6.5.4 Photoluminescence Measurement

The laser diode, developed in semiconductor laser section (SCLS), Raja Ramanna Center for Advance Technology (RRCAT), Indore, has been used as a source of excitation in photoluminescence (PL) spectroscopy. The PL of InAsP/InP single QW has been measured with CW power 4.7 mW at low temperature, 10 K. The measurement has been carried out at low temperature to reduce losses due to scattering and leakage of carriers. Two different laser sources, one 532 nm commercial laser and the second one is 980 nm semi-package LD developed at SCLS. Figure 6.17 shows the PL with SCLS laser as a source of excitation to find the electronic transition in the QW samples which is confirmed with reproduction of the results using commercial laser.

As shown in the Fig. 6.17, the first peak at 1000 nm corresponds to source wavelength itself. There is shift in source laser wavelength may be due to continuous use and thermal degradation of device. The recorded peaks at ~1120 nm and at ~1230 nm corresponds to the sample with QW thickness 28 Å and 38 Å, respectively.

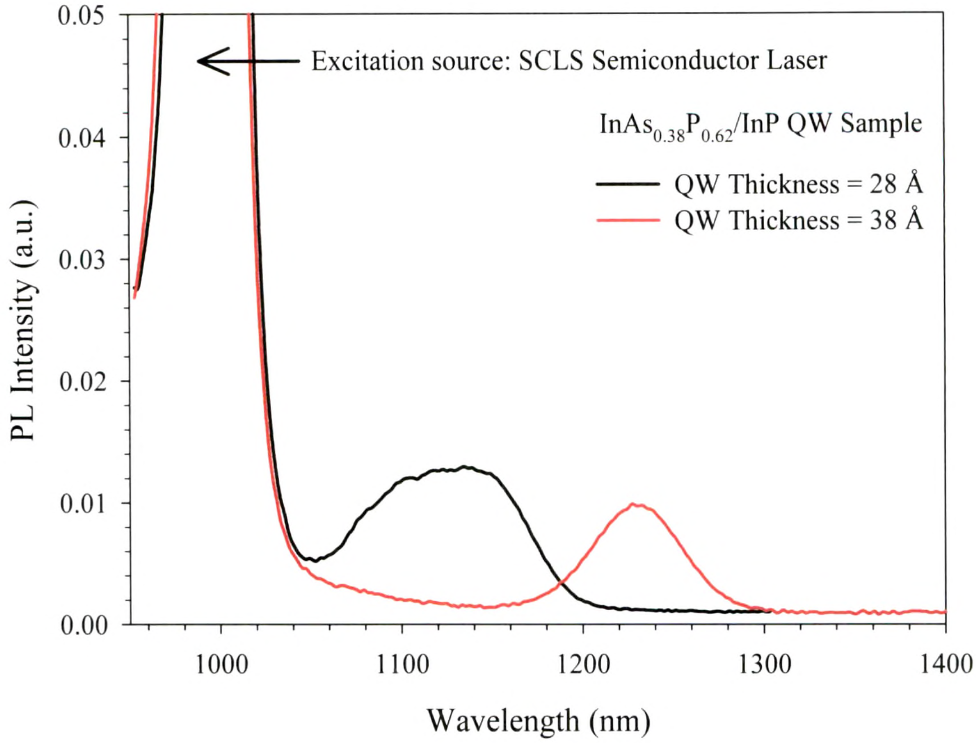


Figure 6.17: PL with 980 nm SCLS Laser

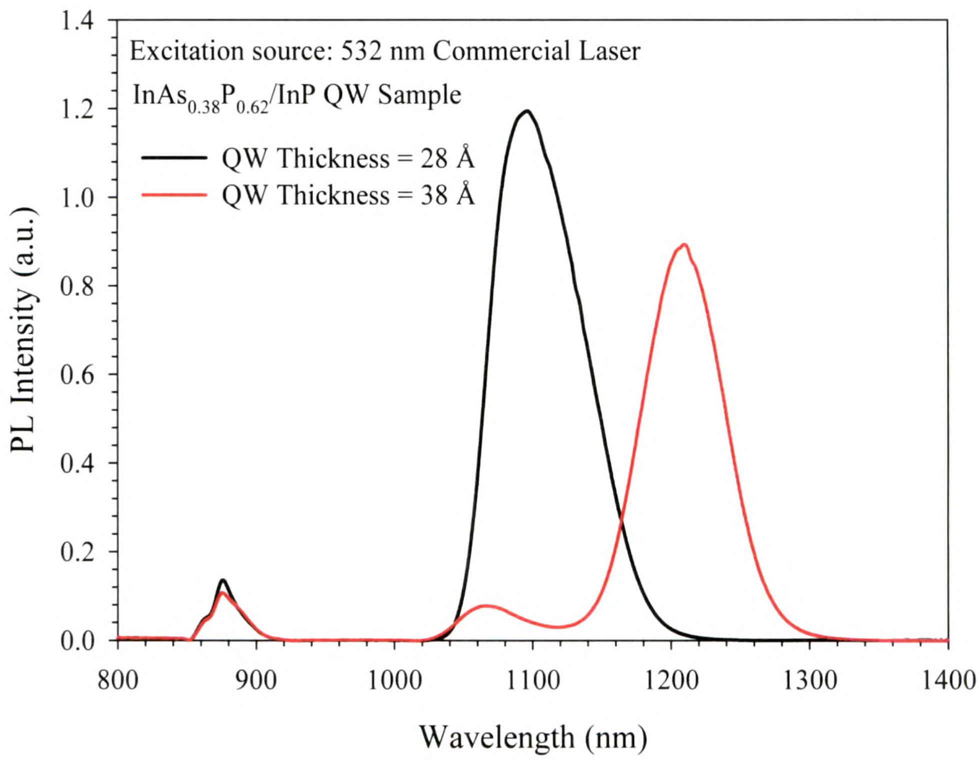


Figure 6.18: PL with 532 nm Commercial Laser

It is known that the bandgap of InP is 1.42 eV at 10 K and on adding InAs, bandgap of material reduces. Calculated bandgap, from Eq. 6.3, related to the wavelength

1120 nm is about 1.107 eV which corresponds to 28 Å thick $InAs_{0.38}P_{0.62}$ QW. Further, there is decrease in energy bandgap of QW sample if we increase the thickness of the QW. Hence the peak observed for 38 Å thick QW sample is at 1230 nm, which corresponds 1.01 eV.

$$E = \frac{1.24 \times 10^{-6}}{\lambda} \tag{6.3}$$

The similar results have been verified with PL measurements using commercial 532 nm source. As the source energy is high we can also able to excite the barriers i.e. InP. The energy bandgap of InP at 10 K is about 1.40 eV, which is related to the 880 nm, shown in Fig. 6.18, for both the samples irrespective of the QW thicknesses. The subsequent peaks from the QW samples, 28 Å and 38 Å, in Fig. 6.18 is 1067 nm and 1208 nm which correspond to energies by Eq. 6.3, 1.162 eV, and 1.02 eV, respectively. This verifies the results we have achieved using 980 nm SCLS laser.

❖ Conclusion

We have successfully measured the laser induced damage threshold (LIDT) of single layer Al_2O_3, MgF_2, and SiO_2 thin films deposited on the GaAs. The measurement was done by using Q-switched Nd-YAG laser in both pulse mode and CW mode. The laser induced damage on the samples was only due to the heating effect. The effective damage radius on the samples was ~150 μm and average continuous wave laser induced damage threshold was found >10 W. Hence, we can say that the optimized single layer QWOT thin films have potential for laser diode facet coating application. In addition to that we have demonstrated the design of experimental setup to measure laser diode accelerated lifetime in ACC mode and estimated the device lifetime about ~ 35,000 operated at 80 °C. Finally, we have successfully demonstrated an application of indigenously developed laser diode (980 nm) package for PL spectroscopy.

* * *

❖ Summary and Future Outline

➢ Summary

The present thesis deals with the various laser diode (LD) post growth fabrication technologies and process optimization viz. structure processing, facet coating, packaging, and the development of characterization facilities. Finally it improves the device life-time and its reliability. In addition we also have successfully demonstrated an application of indigenously developed a complete LD package in photoluminescence (PL) spectroscopy.

It is of much importance to have appropriate LD characterization facilities to evaluate the LD performance after each process optimization and its application to the laser. Hence, the development and upgradation of the LD characterization technique is an inevitable part of the research. Here various LD characterization systems has been developed and are automated using LabVIEW GUI for proper and accurate real time data acquisition and analysis as well. The characterization techniques are developed to measure: L-I-V characteristic, spectral response, junction-temperature and life-time estimation, P_{max} at COMD level, ex-situ and in-situ reflectivity and LIDT measurements of various thin films.

We have successfully processed and developed LD mesa-stripe structure of MOVPE grown double QW InGaAs/GaAs high-power laser diode. The experiments were optimized for post growth processing includes photolithography, lift-off processes, mechanical lapping and polishing, insulation and metal contact layer deposition. A 980 nm laser bar with 100 μm stripe width and 150 μm thickness was operated very well under pulse mode and CW operation.

The second step to improve LD performance is the laser facet coating which not only prevents the device facet degradation but also enhances the laser output power from respective facet depends on the coating type either AR or HR. We have optimized QWOT single layer of various dielectric materials for facet coating viz. Al_2O_3, SiO_2, MgF_2, TiO_2, and ZrO_2. The QWOT single layer Al_2O_3 and ZrO_2 AR coating has been optimized for 808 nm and 980 nm laser diodes, respectively. For HR coating to the device is released by multilayer QWOT pair of Al_2O_3/TiO_2 for 808 nm LD bar and SiO_2/ZrO_2 for 980 nm LD bar. Laser diode with AR and HR facet coating shows improvement in output power level than the bare, without coated, devices. The optimized facet coating have also been tested for laser-induced-damage threshold (LIDT) measurements and proved to be a suitable facet coating for HPLD

Finally, the laser diode packaging has been realized by means of laser diode die-bonding and wire-bonding. The die-bonding of the 980 nm laser diode with indium and gold-tin (AuSn) preform has been optimized using indigenously developed setup. The substrates used for die-bonding were of copper and KOVAR with gold plating on them. After die-bonding, wire-bonding on the device is also optimized using manual wire bonder for thin gold wire (diameter - 1 mil). A complete package has been successfully tested and the measured dynamic series resistance of the device is low enough (200 mΩ) to confirm quality bonding. Beside this, we also have optimized a bonding process to make laser diode package module with die-bonding on the electrodes for 650 nm laser diode bar.

The device performance to estimate its life-time using accelerated aging technique with constant CW current and high temperature (80 °C) has been tested. The life-time of the device has been estimated about 10^5 h at room temperature. The improved device performance has successfully been demonstrated after applying various optimized post growth process to the HPLDs. Single laser diode element with effective packaging gave an output power of ~670 mW/facet at ~ 2 A under CW operation with the dynamic series resistance of ~ 200 mΩ. Subsequently, the developed semi-package, non hermetic, laser diode was used for the characterization of electronic transitions of InAsP/InP quantum well in photoluminescence (PL) spectroscopy.

➢ Future Outline

The field of research is its own kind of ocean of information, so, as we go deep into it we can get more and more information and hence there is a huge scope of improvement in future. We have tried our best to improve the device performance but still there are some aspects needed to be kept in attention for technological development of more reliable device package.

The following topics could be considered in future technological development of high-power laser diode fabrication.

- Internal structure of the device can be improved by using strained QW or QD based laser structure growth.
- Contact layer deposition while device processing can be done and optimized by means of electroless gold plating instead of thermal evaporation.
- Cleaving of laser diode bar or chip with proper facets is the most crucial job of laser diode processing and can be improved with wafer cleaver.
- Conventional method of facet coating, i.e. QWOT film coating, can be improve by multilayer coating of varying thicknesses for AR and HR coating.
- Different dielectric materials, such as Hafnium Oxide (HfO_2), Tantalum oxide (Ta_2O_5), and other rare-earth oxides can also be tested and studied for facet coating.
- Thermal management is one of the main aspects of the laser diode packaging. Hence, simulation of the heat dissipation through the device package can improve the understanding of thermal management.
- One can choose the materials like diamond or copper tungsten (CuW) having higher thermal conductivity than copper, used as a submount, for device packaging.
- Degradation study of the laser diode itself is a subject that needs deep and concentrated research. Research on causes of degradation can lead us to improve the device structure and hence the better performance of the device.
- Study of degradation can also help researchers to improve the reliability of the device further.

* * *