Chapter 5

Packaging and Testing of 650 nm and 980 nm High-Power Laser Diodes

5. Packaging and Testing of 650 nm and 980 nm High-Power Laser Diodes

The packaging is the final and the most important processing step of laser diode fabrication technology that significantly affects the laser diode performance, especially in continuous-wave (CW) mode. The packaging of the laser diode includes die- and wire-bonding. It provides electrical and thermal conduction to the device and makes it applicable to the outer world. The present chapter discusses optimization of bonding process for high-power laser diodes.

5.1 Introduction

The packaging of the high-power laser diodes (LD) is the most essential process of the device production. It provides not only the mechanical support but also the electrical and thermal conduction to the device and makes it applicable to the outer world. The leading factor in the laser diode packaging is the die-bonding and wire-bonding. The process to solder the laser chip or bar to the appropriate substrate by means of any solder material, viz. Indium (*In*), gold tin (*AuSn*), is known as die-bonding. While further electrical interconnection of the laser chip/bar to the contact lead of the package by means of gold wire or ribbon is known as wire-bonding. This chapter discusses optimization of bonding process for laser diodes. The packaging of high-power laser diode is demonstrated.

Laser diode must be bonded and sealed in a suitable package depending on its application, which can be hermetic or non-hermetic. Hermetic type sealing is impervious to dust and moisture and prevents ambient contamination to the laser. Hermetic packages are very robust and provide long term reliability to the laser diode. However, hermetic packaging technique is quite expensive, which increases the manufacturing cost significantly. Non-hermetic packaging, though not as reliable as hermetic one, is extensively used in a number of applications due to cost effectiveness and ease of implementation. Thus, selection between hermetic and non-hermetic packaging can be seen as a compromise between cost and performance. We have utilized a co-axial type non-hermetic type gold plated copper packages to optimize the packaging of the laser diode. The following sections discuss the solder material, the packaging substrate, and the die-bonding process for optimization the laser diode.

5.2 Die-Bonding

The packaging of laser diode includes die-bonding and wire-bonding of the laser diode chip/bar to the appropriate package. The bonding process affects the electrical and thermal properties of the laser diode [129] and need to be optimized in order to meet the requirements like, reliable operation with high output power and longer lifetime. The electrical and thermal resistance of the laser diode assembly should be as low as possible to efficiently reduce the device heating and better heat dissipation from the laser diode active layer under high-power operation. Thus, the overall efficiency and reliability depend largely on packaging techniques. Further, due to the mismatch in the coefficient of thermal expansion (CTE), the thermo-mechanical stresses generated at the interfaces of dissimilar materials during packaging are a big challenge to the realization of a durable system [130].

As discussed earlier, the operation of attaching the semiconductor chip (laser diode in our case) to the package is known as die-bonding. The semiconductor laser chip/bar is placed at an appropriate position in the package, at the edge in case of edge-emitting laser diode. There are some important requirements which have to be taken into account while optimizing the die-bonding process: (1) High electrical and thermal conductivity are essential, (2) Void- free contact formation between laser chip and package, which means good adhesion, and (3) Good matching of CTE between the laser chip and package material. A wide range of solder types and techniques are available for the die-bonding.

5.2.1 Types of Die-bonding

❖ Adhesive Bonding

As the name suggest, an adhesive bonding is formed by adhering the die to the package by means of some adhesive material. Adhesive bonding is conducted at roomtemperature and widely used for die-bonding of semiconductor chips. The adhesive material can be electrically conducting or insulating depending on the application of the device. It mainly consists of metal particles having size in microns, viz. silver flakes, suspended in a carrier like epoxy resin. The carrier provides adhesion and cohesion to make a bond with the correct mechanical strength, while the metal particles provide electrical and thermal conductivity. The adhesive bonding gives reduced void propagation underneath the die, with better heat transfer, leading to enhanced device reliability [131].

❖ Soldering

Soldering is the process in which die-bonding takes place by formation of the inter-metallic layer of solder material viz. soldering paste or solder preform. The formed inter-metallic layer not only provides mechanical integrity but also provides good electrical and thermal conductivity to the laser diode. The simplest method to perform the solder reflow is to heat the solder material by means of any heater. The reflow of solder material is usually performed under inert gas flow to prevent oxidation. To achieve good inter-metallic contact formation, the essential condition is to remove the surface oxide from the semiconductor chip, substrate, and solder material. This surface oxide makes a barrier on the semiconductor and solder surface and prevents the formation of intimate contact between them. Typical reflow of solder materials on a heater in air usually requires flux. The flux could be in form of either solid, liquid, or gas. The most widely used flux in semiconductor chip bonding is liquid type. This is a rosin based liquid that promotes wetting between two surfaces by removing surface oxide and also inhibiting further oxidation of the surfaces during the bonding process. However, use of liquid fluxes is questioned in the case of laser diode bonding since it produces residual impurities which may cause electrical and mechanical degradation of the device [132]. Moreover, it also requires further cleaning treatment to remove additional flux and residual contaminants which is not desirable in case of laser diode bonding. Hence we have used the no-clean liquid flux to remove the surface oxide from the semiconductor, solder and metal surfaces. The liquid fluxes may be eliminated through the use of gaseous flux like forming gas, mixture of nitrogen (N_2) and hydrogen (H_2), cover over a heater. The forming gas atmosphere provides a sufficient environment to inhibit oxide formation during the reflow operation. Generally, solder materials are classified into two types according to their yield strength i.e. soft solder and hard solder. Hence, the soldering can be achieved by soft soldering or by hard soldering (or eutectic bonding), depending on the solder material used.

- **Soft Soldering**

As the name suggest, the soft soldering has low yield strength compared with eutectic soldering. It is used for high-power devices, especially in power electronics where good electrical and thermal conductivity is required. Alloys like lead-tin (*PbSn*), silver epoxy, and indium (In) preform are most likely used soldering materials. Being soft in nature it is quite ductile and can undergo large plastic deformation before any mechanical damage, while device operation. Hence, they can withstand in case of thermal mismatch by plastic deformation and can help relieve the stress due to plastic strain or deformation. However, due to plastic strain soft soldering may suffer from the thermal fatigue and creep movement within the joint [133,134]. The most widely used solder materials in device packaging are *PbSn* and silver epoxy to reduce the effective production cost. However, at present, due to an environmental hazard of lead [134] and lower thermal and electrical conductivity of silver epoxy limit their utilization in laser diode packaging.

- **Hard/Eutectic Soldering**

The hard/eutectic solder consists of eutectic mixture generally an alloy of two or more dissimilar metals. The critical melting point of eutectic solder material is much below than that of the constituent material. The hard soldering has very high yield strength and exhibit only elastic strain while device operation. Therefore, it does not have thermal fatigue and creep movement like soft soldering. The eutectic bonding gives very good electrical and thermal contact and high mechanical strength. However, it does not help to release stresses generated in a joint structure because of lack of plastic deformation. Also, one has to take care about the temperature control and mechanical stability of the whole experimental setup because of the critical melting temperature of the solder material. An abrupt solidification may lead to cracks and voids in the joint. Moreover, the eutectic bond is brittle and the thermal mismatch may also cause the chip to crack during the bonding process or during thermal cycling.

There are plenty of new materials and alloys that are being developed to achieve good mechanical strengths and high thermal fatigues because die-bonding is still a major source of faults during assembly fabrication and require lots of process optimization. The bonding must be free of voids to attain minimum electrical and thermal resistance. Large number of voids in bonding causes an increase in thermal resistance and hence increases in the junction temperature. Also, high electrical resistance causes thermal roll-over due to device heating while operating under high-power operation. Moreover, solder voids near the front facet are not desirable as they can raise the facet temperature significantly and cause catastrophic optical mirror damage (COMD) [135]. However, it is almost impossible to achieve void-free bonds, since air-films are always trapped at the interfaces. The solder does not flow sufficiently to displace all this air to the die periphery and much of it remains trapped after soldering as voids within the bond. Thus, quality of void-free soldering depends on the wettability of the surfaces, the accuracy of the solder volume, and on protecting the process from oxygen. In addition, structural damage may also occur to the laser diode chip while mounting and bonding it on the package. Thus, mounting and die-bonding of a high-power laser diode on a package must be optimized to ensure satisfactory thermal and electrical coupling between the package and the laser diode chip.

5.2.2 Bonding Configuration

There are two basic configurations in which a laser diode chip can be bonded on the package; junction (or p-side) -up and junction-down configuration. Figure 5.1 shows the schematic of the laser diode bonding configuration. Die-bonding processes for p-side up bonding is much explored and well established by the packaging industry [136]. The heat generated in the active region of the laser diode spreads laterally over the entire laser width and has to flow through the entire substrate (GaAs) before reaching to the heat sink. Due to the low thermal conductivity of ternary alloys and multiple hetero structures [137] of the laser diode, the heat generated in the active region cannot be dissipated onto the heat sink efficiently. As shown in Fig. 5.1 (b) the junction down bonding is more efficient in removing heat from the device since the epitaxial layers containing the active region are typically much thinner than the substrate [138,139,140] and the active region is only within the proximity of a few microns from the package surface. However, the reliability of a laser diode bonded in p-side down configuration is significantly impacted by electromigration in the die attach solder [135]. The electromigration can create and enlarge voids as well as accelerate the propagation of preexisting voids [141], which leads to the device failure. Also the stress associated with p-side down bonding may cause damage to the active layer and hence the device due to the mismatch in the coefficient of thermal expansion between the laser diode and the heat sink material. Above all, the technique to configure p-side down bonding is quite complex and requires special die-bonding tools which are some of the discouraging factors in the adoption of this technique [142]. Considering these facts and the unavailability of sophisticated instrumentation for die-bonding, we have employed the conventional junction-up method, which is relatively simple and provides sufficient heat dissipation up to moderate power. We experimented with different solder materials to die-attach identical laser diode chips on specially design packages [143].

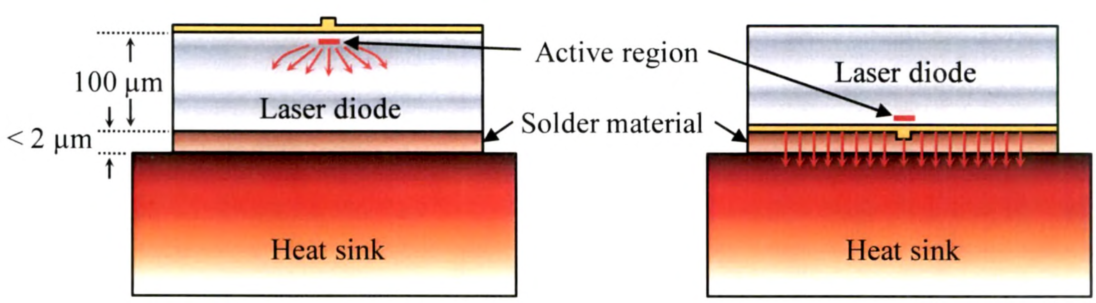


Figure 5.1: Different bonding configurations of ridge-waveguide laser diodes. (a) For p-side up bonded laser diode, the heat generated in the active region is ineffectively transferred through the substrate; (b) For p-side down bonded laser diode, the heat flux is effectively reached the heat sink within several microns.

5.2.3 Solder Materials for Die-bonding

A wide variety of solders are available for die-bonding of semiconductor components on the heat sink. However, selection of the most appropriate solder material is very important and involves many parameters such as die and package materials, operating conditions and reliability requirements. The most widely used solder materials in device packaging are *PbSn* and silver epoxy to reduce the effective production cost. However, at present, due to an environmental hazard of lead [134] and lower thermal and electrical conductivity of silver epoxy limit their utilization in laser diode packaging. We have used *In* and *AuSn* solder preform to bond the devices.

- **Indium (*In*) Preform**

Indium preform is one of the most widely used solders in die-bonding of high-power laser diodes. Indium solder has some advantages in laser diode die-bonding. Indium, being a soft solder, relaxes stress caused by mismatch of coefficient of thermal expansion (CTE) between the chip and package material effectively. Moreover, it is a low cost material with low melting point of 157 °C. It also has some concerns, however, especially in terms of reliability [134]. The thickness of the In-preform used in our experiment is 55 μm.

- **Gold-Tin (*AuSn*) Preform**

Gold-tin (*AuSn*) is the alloy most commonly used in the industry for GaAs assemblies due to its compatibility with gold-based components and its long-term reliability. The composition of the alloy used for the experiment is 80 % gold - 20 % tin, which is a eutectic alloy and has a melting point of 283 °C. Being a hard solder, *AuSn* overcomes the disadvantageous thermal-fatigue and creep-rupture properties of the soft solders, such as *In*, by staying in elastic deformation. However, the same property demands that the mismatch of CTE of the package material should be within the acceptable range. Large mismatch in the CTE may induce large strain and subsequently produce stresses during the thermal cycling, which may cause cracks in the die or detachment of the die.

5.2.4 Package Material and Design

The design of laser diode packages is one of the most extensive research areas in laser diode bonding and packaging. The packaging material and design selection for the laser diode is depends on the specific requirements of different cooling techniques viz. active or passive cooling. The package with active cooling consists of water cooled, micro-channel heat-sink while passive or conductive cooling to the package will provide by means of heat-sinks, generally made of copper, mounted on thermo-electric coolers. The packaging materials commonly having high thermal conductivity and the coefficient of thermal expansion (CTE) matched with the device's substrate material i.e. usually GaAs, is used for laser diode.

The standard heat sink material mostly used in all commercially available packages is copper, because of its good thermal and mechanical properties, and its low price. However, the mismatch in CTE between the laser bar and the copper has a major influence on the operation lifetime of the laser bars, as it causes a severe stress in to a laser bar. In addition to that, the increasing demand of high-power laser requires heat sink material with even high thermal conductivity with less CTE mismatch. Hence, the compound materials having moderate thermal conductivity like copper-tungsten (CuW) or diamond are used for laser packaging. Unfortunately, these materials are much costlier than copper and having moderated thermal conductivity. In addition, the mechanical machining properties of these materials are poor and hence it is too difficult to achieve desired package design. Hence, we have used gold plated copper (*Cu*) and KOVAR (Ni:Co:Fe::29:17:54 wt% [144]) as packaged substrate to optimize the bonding process. To compensate the difference of CTE between laser diode and package, we have used indium soft solder as bonding material. The laser diodes were die-attached on specially designed co-axial type gold-plated copper packages as shown in Fig. 5.2 (a). Gold leads, flattened at the front edge as shown in Fig. 5.2 (b), were inserted and fixed in the packages through ceramic isolators to carry out wire-bonding. Such a package, ready to be die- and wire-bonded, is shown in Fig. 5.2 (c).

(a) (b) (c)

Figure 5.2: (a) Gold platted copper package, (b) flattened-ended gold lead and (c) package with gold lead inserted and isolated through ceramic.

Here, in this work, we present the successful optimization of the high-power laser diode bonding process using *In* and *AuSn* soldering material on gold plated *Cu* and

KOVAR substrates. We have used uncoated laser diode chips with lasing wavelength of 650 nm, 808 nm, respectively for die-bonding process-optimization. The 980 nm GaAs/InGaAs double quantum well high-power laser diode element and bars were bonded using optimized bonding process parameters. Results of bonded and un-bonded devices are compared during the CW high-power operation.

5.3 Wire-Bonding

Once the laser diode chip is attached on the package, the next step in the packaging is assembly interconnection. The most common method for electrical interconnections is wire-bonding. It provides the electrical connection on p or n-type metallization of the laser diode. Thin metal wires are connected one by one between the contact stripe on the laser diode chip (die bonded p-side up) and the corresponding contact-lead on the package. For laser diode assembly, gold wires are normally used.

Wire-bonding is a very delicate procedure. The machine bonds one end of the wire, usually gold, to the metalized substrate using an ultrasonic pulse, creates a loop with the wire, and makes a second bond, cutting the wire at that end. Normally the wire-bonding techniques can be categorized into three major processes: thermo-compression bonding (T/C), ultrasonic bonding (U/S), and thermosonic bonding (T/S), depending on the bonding parameters i.e. ultrasonic power and/or heat. As the name suggest, T/C and U/S bonding process are accomplished by means of only bonding force/pressure aided by temperature and ultrasonic power, respectively. The most commonly employed technique to achieve wire-bonding is the thermosonic (T/S) bonding, performed at elevated temperature by ultrasonic power. The wire bond is formed with heat, pressure, and ultrasonic energy. The heat is provided through the bonding stage consists of heater. The bond head movement in vertical direction exerts pressure on the wire and ultrasonic energy from the transducer through the bond tool to the wire altogether form a wire bond, as shown in Fig. 5.3.

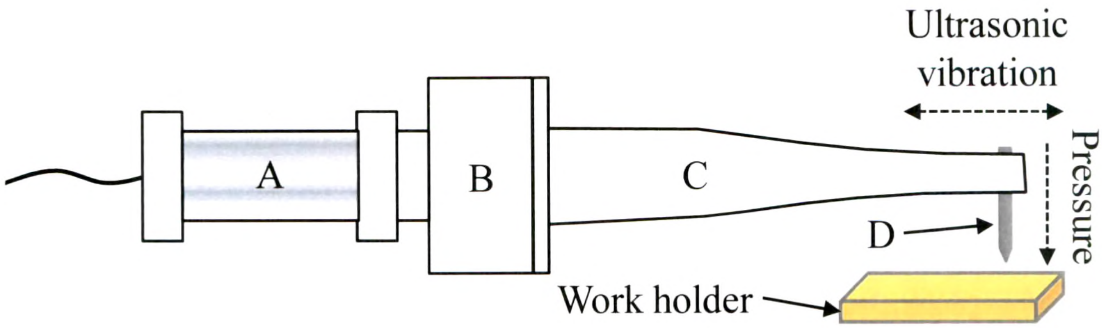
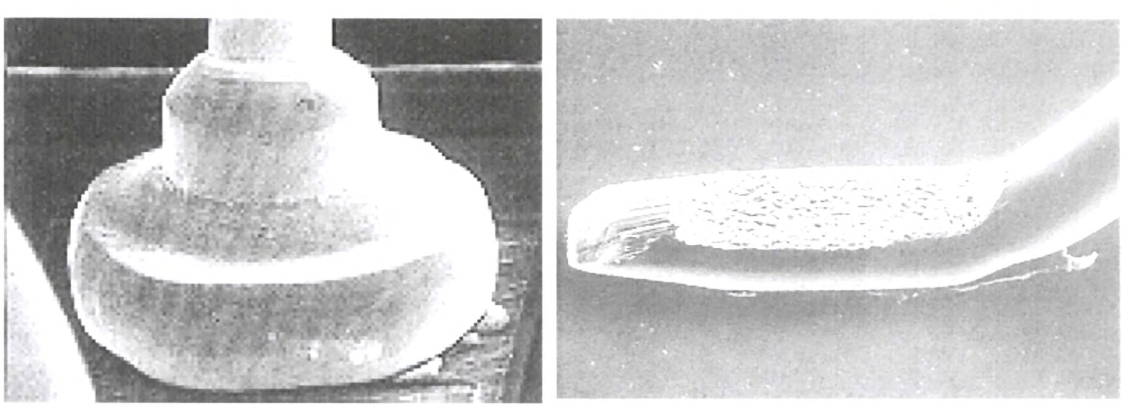


Figure 5.3: Typical ultrasonic transducer used for manual wire-bonding: (A) the ultrasonic transducer element; (B) the mounting clamp, which is located on a vibration node and is clamped to the bonding machine; (C) referred to as the horn (tapered to amplify the ultrasonic wave); (D) the tool/capillary, which is clamped perpendicular to the axis of the horn.

The various bonding parameters like ultrasonic power, pressure or force, temperature, and bond-time, determine the bond quality. Force, time, and ultrasonic power are critical for consistent wire bond and hence the reliability of the bonded device. There are two basic wire-bonding techniques: ball-bonding and wedge-bonding, as shown in Fig. 5.4, depending on that the bonding loop formation take place either in ball-wedge or wedge-wedge loop configuration. In case ball-wedge configuration first bond of the loop on the device is formed by a ball bonding following with the second bond as a wedge type. While, on the other hand, for wedge-wedge type bonding both the loop ends are formed by wedge bonding. The merits and demerits of both ball and wedge bonding are discussed in Table 5.1



(a) **(b)**

Figure 5.4: The SEM image of (a) Ball bond, and (b) wedge bond [145].

Table 5.1: Wedge bonding vs. Ball bonding

Wedge bonding	Ball bonding
Unidirectional bonding	Multi-directional bonding
Creates small bonds (1.1 to 2 times wire diameter)	Bond sizes range from 2.5 to 4 times wire diameter
Usually used with aluminum wire, however it is also used with gold wires.	Used mostly with gold wires
No electronic flame off (EFO) is employed	Requires EFO to form ball
Being unidirectional the wedge bonding is slower	It is comparatively faster than wedge bonding.

5.3.1 Wire-Bonding Process

The wire-bonding process consists of applying ultrasonic energy to form a strong, reliable, intermetallic connection between the wire and the pad, as well as between the wire and the lead. This is accomplished by inserting the wedge tool in the bonding head, which is coupled to a precision ultrasonic generator. The main phases of the wire-bonding, i.e. wedge-type in our case, bond-cycle is: 1^{st} bond, loop formation, 2^{nd} bond, and wire termination, respectively. Each phase is the result of several operations performed by the wedge. These operations can be presented by stages that complete the bonding cycle given below in Fig. 5.5.

The commercially available die and wire bonder comprise of automated parameter control and designed for dedicated device assembly bonding. All the bonding parameters like, bond location, bonding time, temperature can be programmed in this type of automated bonded and we can have definite quality bond. However, these commercial bonders for both die-bonding and wire-bonding are quite expensive. Hence, we have indigenously designed and developed the setup for die-bonding of the laser diode, while manual wire bonder is used to carry out wire-bonding.

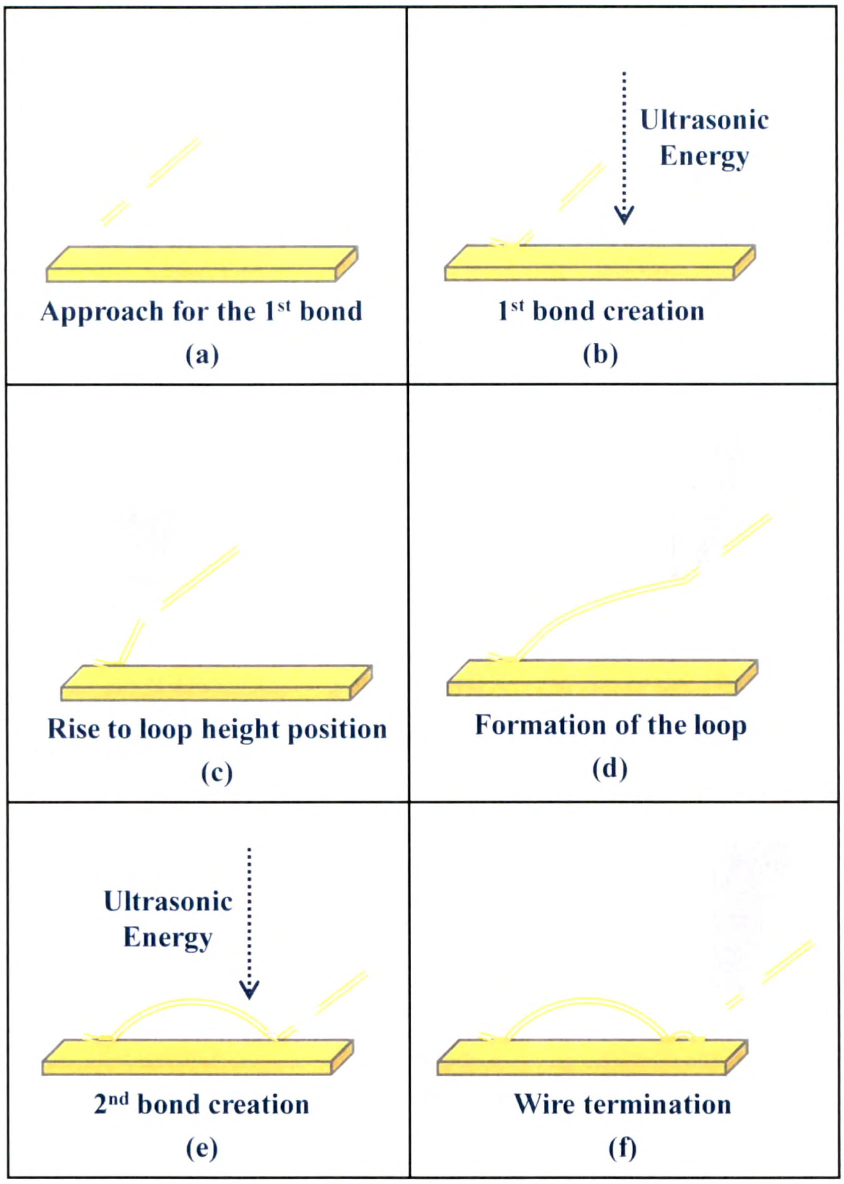
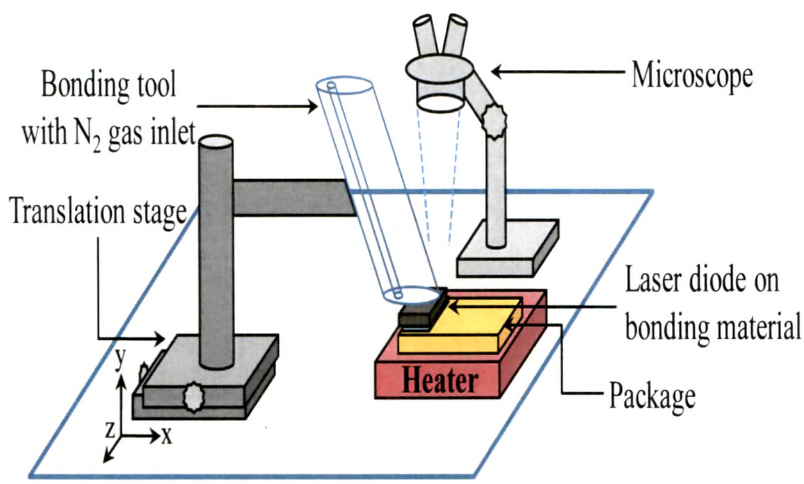


Figure 5.5: Wire bond loop formation steps for wedge bonding.

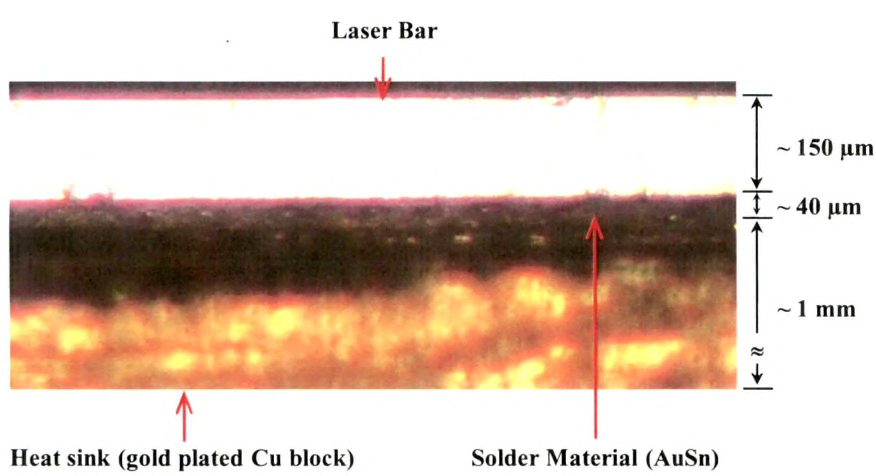
5.4 Experimental

5.4.1 Die-Bonding

We have used two types of bare facet, without facet coating, 650 nm and 980 nm laser diodes for die-bonding optimization. The 650 nm lasers are commercial devices while 980 nm devices are fabricated at RRCAT, Indore [25]. The die-bonding is carried out using an indigenously developed setup. The experimental setup consists of bonding pad (Heater), the bonding tool with inert gas (N_2) flow outlet mounted on travelling stage and the microscope for better alignment to view the device and solder preforms i.e. *In* and *AuSn*. Figure 5.6 (a) shows the schematic of the experimental setup for the die-bonding process. The bonded laser diode bar and *AuSn* preform on the edge of the laser diode package is shown in Fig. 5.6 (b).



(a)



(b)

Figure 5.6: (a) The schematic diagram of the experimental setup of the self assembled manual die bonder. (b) p-side up die-bonding configuration of the 980 nm InGaAs/GaAs ridge waveguide laser diode bar.

The bonding tool was made to press laser diode with controlled force on a substrate in such a manner that it neither disturbs the alignment nor damages the device as well. After proper alignment, the assembly was heated up to the melting point of the soldering material and kept for curing. The whole experiment was done under nitrogen ambient (N_2 flow at pressure 0.25 Bar) to reduce the environmental oxygen effect on the bonding quality. To achieve good bonding between device and substrate, soldering flux (*Kester #952-D6*) was used. The optimized parameters of die-bonding along with physical and electrical parameters of the materials used are shown in Table 5.2 and Table 5.3.

Table 5.2: Physical and electrical parameters of the materials [51,146].

#	Melting Temperature (°C)	Thermal Conductivity (W/m °C)	Thermal Expansion Coefficient (ppm/°C)	Electrical resistivity (μΩ.cm)
GaAs	1238	54	6.5	~10000
In	157	80	32.1	8.8
AuSn	283	57.3	15.9	16
Cu	1085	400	17.8	1.68
KOVAR	1450	15	5.8	40-50

Table 5.3: Optimized bonding parameters for *In* and *AuSn*.

Curing Temperature (°C)	Curing Time (s)	Natural cooling in presence of N_2 gas
170	80	Till 70 °C
300	57	Till 100 °C

In addition to that we also have bonded 650 nm laser diode bar to the c-type gold plated copper module package, where both contact ends of the bar are die bonded to the package as shown in Fig. 5.7. The base to hold this packaging module is alumina substrate having conductive stripe. This module die-bonding process is carried out in rapid thermal annealing (RTA) furnace in presence of forming gas, i.e. a mixture of 92 % nitrogen and 8 % hydrogen at elevated temperature. Specially fabricated jig for facet coating was used to hold the module package along with device and bonding material inside the furnace, shown in the Fig. 5.8. The optimized bonding parameters are shown in Table 5.4. One of the features of this type of bonding is that there is no need to wire bond the device further.

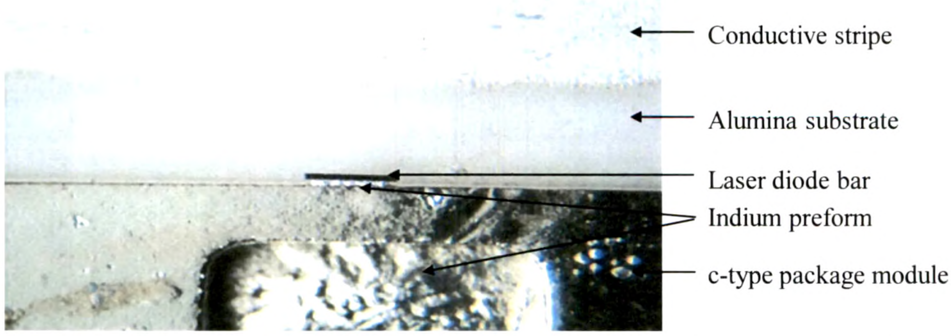


Figure 5.7: 650 nm laser diode bar bonded on c-type package with indium preform. The base for the bonding of this module is alumina substrate with conductive stripe.

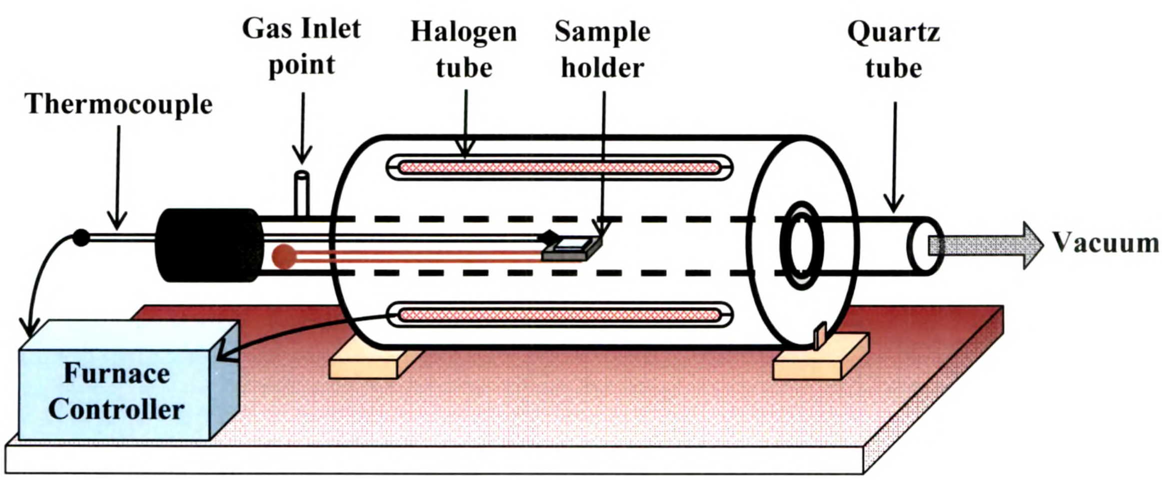


Figure 5.8: Schematic of vacuum based rapid thermal annealing (RTA) furnace [147].

Table 5.4: Optimized bonding parameters for module type package with In preform in RTA furnace.

Temperature (°C)	275
Bonding time (m)	7
Forming gas flow rate (sccm)	70

5.4.2 Wire-Bonding

After the die-bonding of the laser diode, the top contact on the chip/bar was provided through wedge-type wire-bonding. The 1 mil (25.4 μm) diameter gold wire was used to connect device and contact lead. The wire-bonding was achieved using manual wire bonder (K & S make universal bonder) shown in Fig. 5.9. The wire bonder mainly consists of ultrasonic power supply, transducer, bonding head, bonding tool, heating stage, temperature controller, and microscope. Figure 5.10 shows the photograph of bonding tool for wedge bonding.

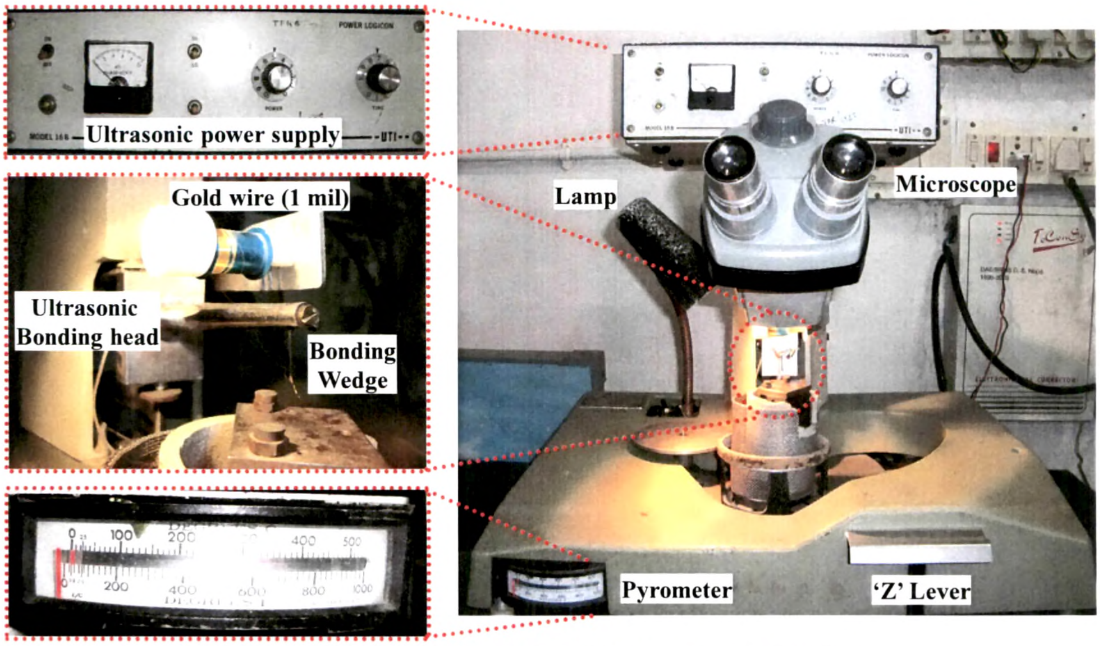


Figure 5.9: K & S make universal ultrasonic wire bonder.

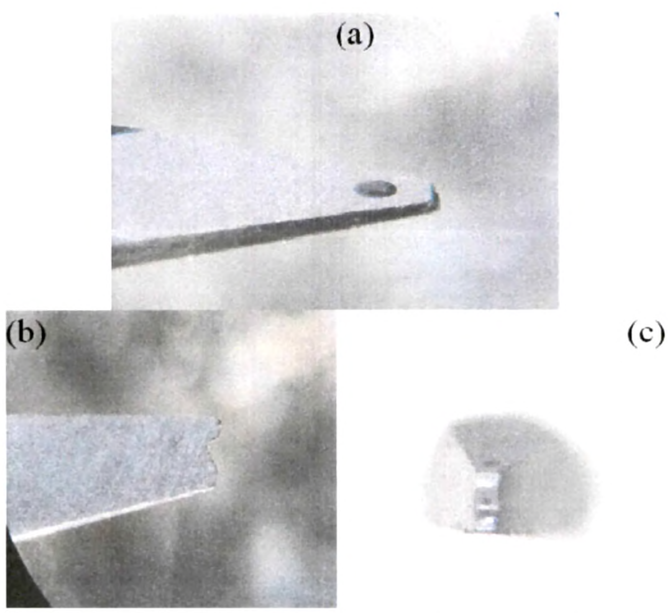


Figure 5.10: A microscopic view of the wedge used for the bonding. (a) Wedge tip, (b) Side view Wedge tip, (c) Front view Wedge tip

A good wire-bonding can only be attained by optimizing the parameters viz. bonding force, temperature, ultrasonic power, and finally the bonding time in a sequential manner. The complete bonding process was optimized on a specially fabricated and organically cleaned gold plated printed circuit board (PCB), shown in Fig. 5.11. The bonding optimization was carried out with different conditions of possible combinations of different parameters and finally observing the foot-prints of the formed bond-loop under microscope. Table 5.5 shows the experimental and optimized wire-bonding parameters.

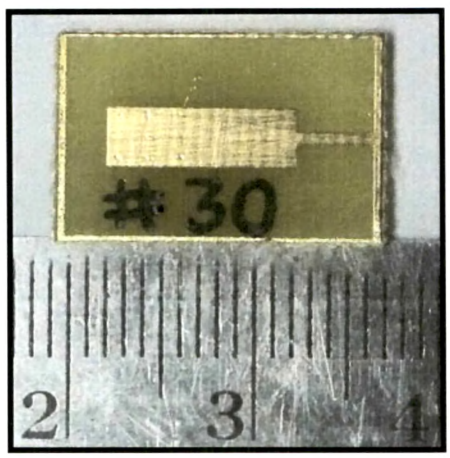


Figure 5.11: Elecroless Ni-Au coated PCB used as the wire bond pad.

Table 5.5: Optimized wire-bonding parameters on PCB.

Parameters	Experimental	Optimized
Bonding force (gm)	8 – 12	11 – 12
Temperature (^{o}C)	RT, 50 & 100	RT & 50
Ultrasonic power (unit)	0.3 – 1.0	0.5 – 0.7
Bonding time (unit)	1 – 10	4 – 6

Here, the whole range of optimized parameters is known as the process window. If the value of bonding parameters set below or above this process window, it will result in either no bonding or wire breakage and further damage to the substrate. Figure 5.12 (a) shows the optimized bond footprint while Fig. 5.12 (b) shows the bond neck break due to excess ultrasonic power applied during wire-bonding process.

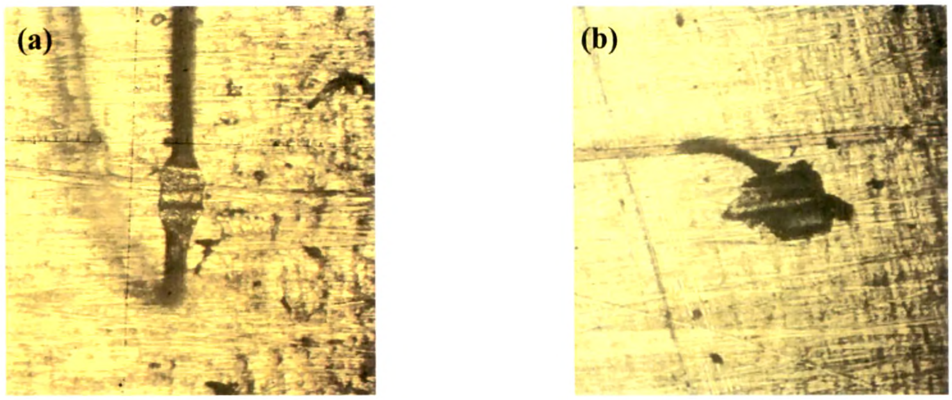


Figure 5.12: Wedge bond foot prints under microscope: (a) Optimized bond, and (b) Failed bond due to excess ultrasonic power, which results in bond neck-break.

5.5 Results and Discussion

The laser diodes with emitting wavelengths 980 nm and 650 nm have been bonded with two different methods and tested for its L-I-V characteristics after the successful optimization and implementation of all bonding parameters. The detail results are discussed in subsections, mentioned below.

5.5.1 Mechanical Properties (Adhesion)

- **Effect of Flux Application**

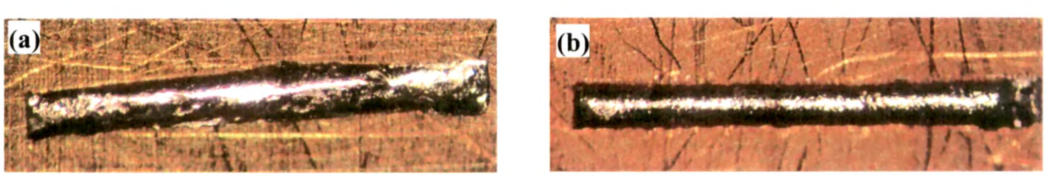


Figure 5.13: The photograph shows effect of flux applied on melting of Indium preform. (a) While melting 'In' without flux application only shrink and don't show adhesion, on the other hand (b) 'In' melted with flux applied shows uniform melting and better adhesion to the substrate.

The die-bonding of the laser diode to the substrate was done by means of the intermetallic compound formation and further diffusion of the bonding material to the both contact layers i.e. LD's n/p- contact layer and substrate. To achieve good intermetallic contact formation, the essential condition is to remove the surface oxide from the substrate and solder material. This surface oxide makes the barrier between the semiconductor and solder surface. It also prevents the formation of intimate contact between them. In order to remove the surface oxide from the semiconductor, solder, and metal surfaces flux was used. Figure 5.13 shows the effect of applied flux on melting indium preform.

❖ Effect of Packaging Material

The effect of bonding on L-I characteristics of the device with different packaging material was measured by operating it under pulse mode and continuous wave (CW) condition. In case of high-power laser diode the heat generation within small volume is too large and should be removed effectively. Hence, high-power laser diode was configured to bond p-side down to reduce the heat diffusion path. However, one has to take care of the coefficient of thermal expansion (CTE), which should match with the composition material of the device. An epitaxially grown thin layer will experience the strain due to the mismatch in CTE and hence will leads to poor device performance. Here two laser-diode bars are bonded on different gold plated substrates i.e. Cu and KOVAR. The *Cu* is most widely used material in laser diode packaging due to its high electrical and thermal conductivity. However, the high CTE mismatch with GaAs (laser substrate) makes it less favorable in packaging, especially in case of p-side down configuration. On the other hand, KOVAR has moderate electrical and thermal conductivity compared to *Cu*, but its good matching of CTE with GaAs makes it more suitable material for laser packaging. The device was bonded p-side up with *In*-preform on gold plated substrates (*Cu* and KOVAR).

5.5.2 Output Power versus Injection Current Characteristics

❖ Pulse Operation

Initially, the bonded lasers were operated with 0.5 ms pulse repetition interval (PRI) and 2 μs pulse width (PW). The output parameters of the bonded laser are shown in the Figure 5.14 (a). It is noted that there is no distinguished effect of different substrates (*Cu* and KOVAR) during pulse mode operation. This is due to the fact that during the pulse mode operation there was no excess device heating. In addition to that we have also bonded a laser bar having three elements on *Cu* package with p-side down configuration. This laser diode bar operated under pulse mode with duty cycle = 1:5000 has given total integrated output power 7.5 W, shown in the Fig. 5.14 (b).

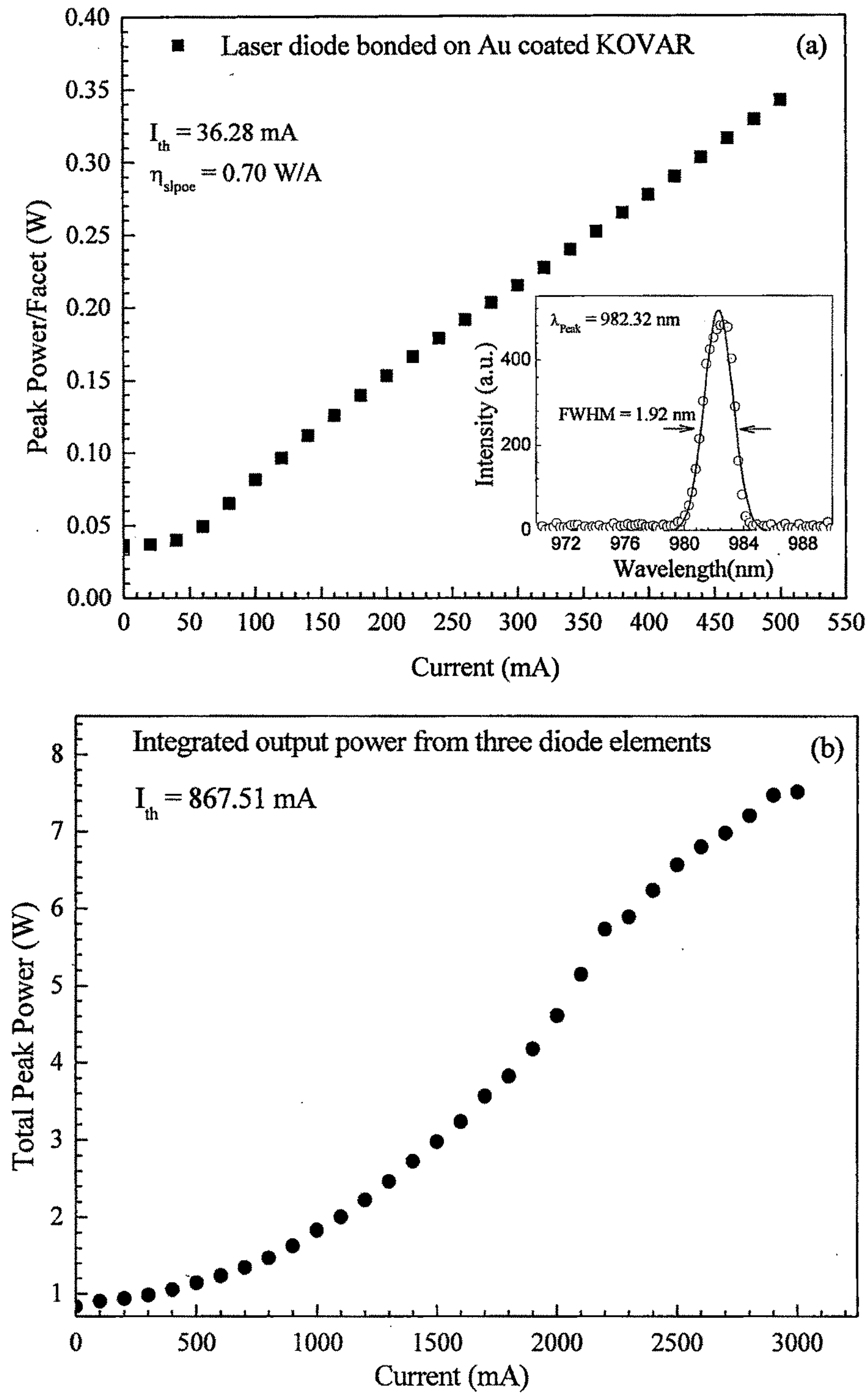


Figure 5.14: (a) Pulse L-I characteristic curve of laser diode elements bonded p-side up with In preform on gold plated KOVAR, inset figure shows typical emission spectrum. (b) Pulse L-I characteristic curve of laser diode bar with three elements bonded p-side down configuration.

❖ Continuous Wave Operation

Figure 5.15 (a) & 5.15 (b) shows the comparative results of output power, voltage and wall plug efficiency as a function of injection current of un-bonded and bonded devices under CW operation. Inset photographs of Fig. 5.15 (a) & 5.15 (b) shows the emitted output power for the bonded and un-bonded devices. The bonded laser diode could be operated at high injection current i.e up to 2 A in comparison with 1.5 A of un-bonded one. Thus the output power of bonded device is ~ 28 % higher than un-bonded one. This indicates more effective heat removal from the bonded laser diode mounted on the thermoelectric cooler (TEC). The comparative results of laser diode parameters are given in Table 5.6.

Table 5.6: Comparative results of laser diode parameter.

Parameters	Without die-bonding	With die-bonding
Threshold Current I_{th} (mA)	94	94
Maximum Power/Facet P_{max} (mW)	520 at 1.5A	670 at 2A
Slope Efficiency η (W/A)	0.82	0.81
Differential quantum efficiency η_d (%)	65	65
Wall plug efficiency W (%) at 700 mA	53	51

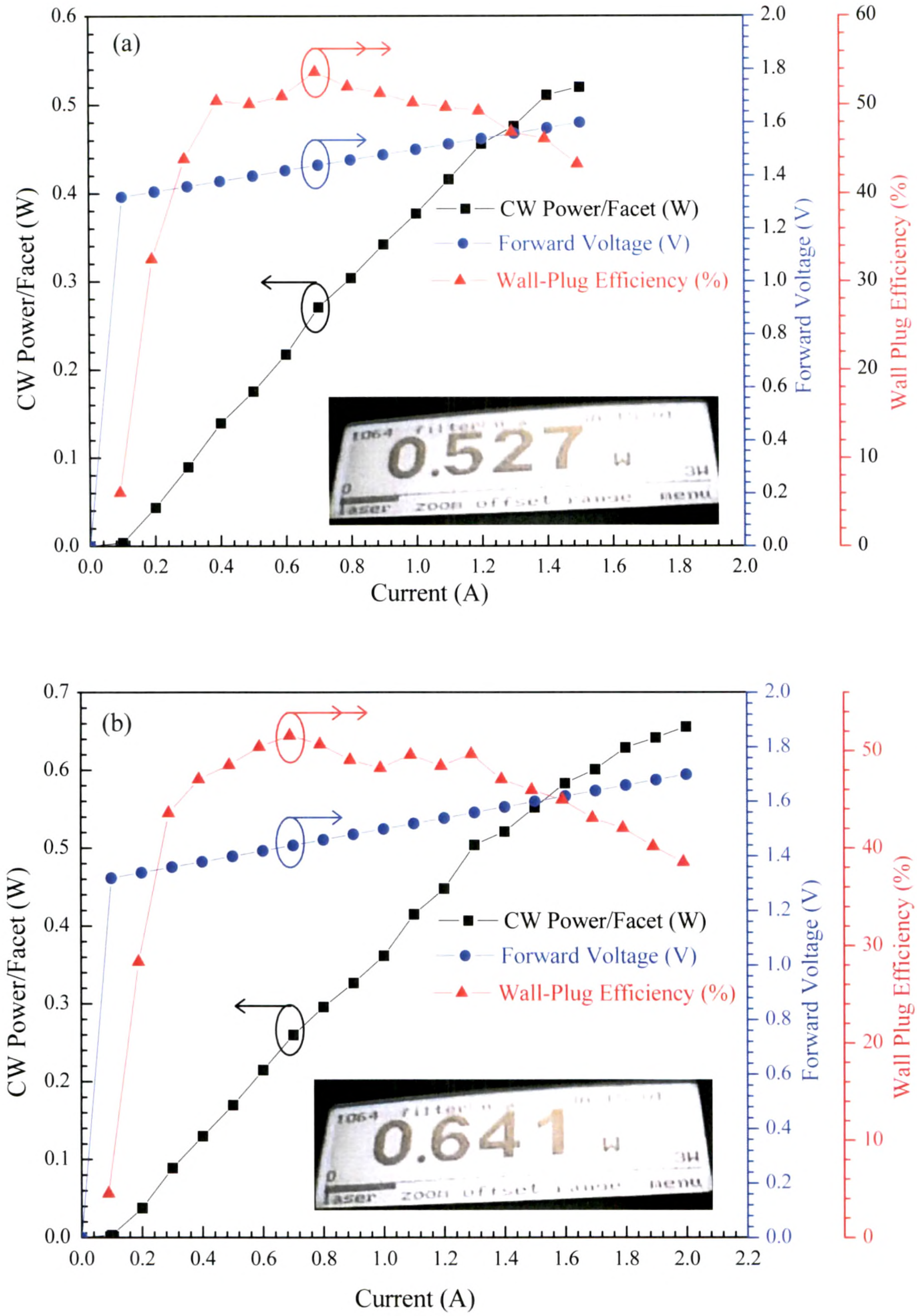


Figure 5.15: Optical output power/facet of the 980 nm GaAs/InGaAs quantum well laser (a) un-bonded and (b) bonded as a function of CW current. The device was bonded p-side up on the gold plated Cu package with indium preform.

5.5.3 Dynamic Resistance Calculation

The low dynamic resistance of the die bonded laser diode exhibits good bonding quality. Consequently, the lower electrical resistance implies low thermal impendence of the bonded device, and hence lower device heating, which makes it reliable for long term operation. We have tested the bonded device for its I-V characteristic in CW mode and found out the dynamic series resistance is about 1 Ω for the 980 nm laser diode bonded on gold plated copper mount with indium preform. Though the series resistance we have find is quite low, this measurement was not completely precise because it also consists of lead and external circuitry resistance. Hence, we have measured this external circuitry resistance, by connecting only the package, having value of about 810 mΩ, shown in Fig. 5.16.

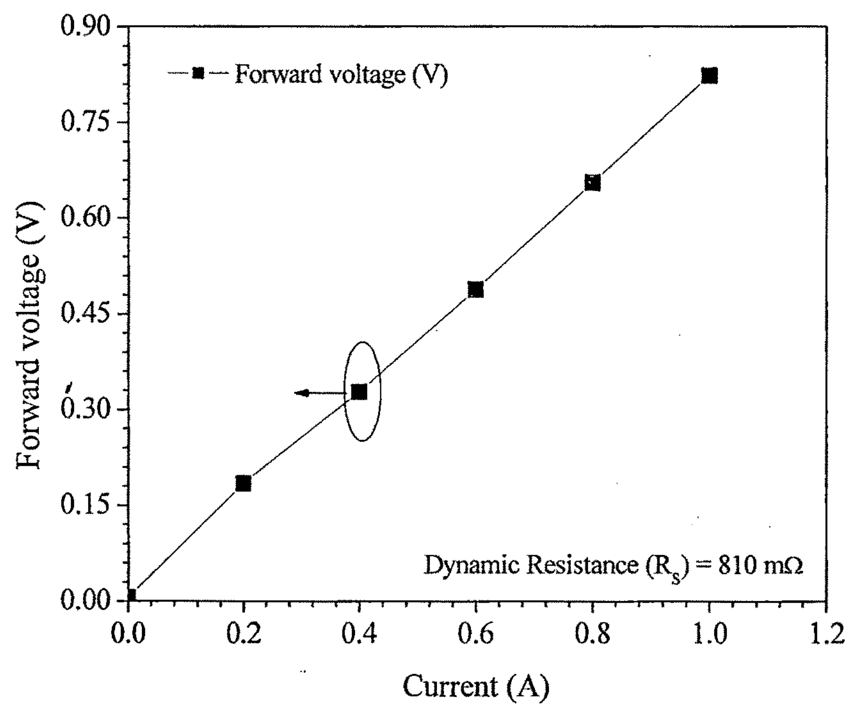


Figure 5.16: Dynamic resistance of the L-I-V measurement circuit, to be subtracted from the total resistance measured while device under operation.

Therefore, by subtracting the external circuitry resistance we have extremely low dynamic series resistance value, i.e. ≈200 mΩ. To verify this we also have calculated the resistance (R) of the device by means of existing resistivity (ρ) values of each layer, from Eq. 5.1, of the laser diode structure discussed in Chapter 3. The resistivity was estimated trough Eq. 5.2 where the value conductivity (σ) and mobility (μ) was taken from the standard available literature.

$$R = \frac{\rho l}{A} \tag{5.1}$$

where, l = length of the layer, i.e. laser cavity length, A = area of the layer.

$$\rho = \frac{1}{\sigma} \tag{5.2}$$

where, σ = conductivity of layer. For intrinsic semiconductor, $\sigma = q\ (\mu_n n + \mu_p p)$. For extrinsic semiconductor, $\sigma = q\ (\mu_n n)$ for n-type semiconductor and $\sigma = q\ (\mu_p p)$ for p-type semiconductor. Here, μ is mobility of the carrier, n and p is the carrier concentration.

5.5.4 Testing of the Laser Diode Bar Package Module

The commercially purchased 650 nm laser bar having 11 elements on it was bonded on c-type gold plated copper package module with indium preform. The LD bar was sandwiched between two pieces of package and bonded together as an assembly with indium on an alumina substrate having conducting strips, as shown in Fig. 5.17. The bonded device was tested in both CW and pulse operation. The CW operation and I –V of the bar is shown in Fig. 5.18. The low series resistance value, i.e. 6.78 Ω, implies the good bonding quality. Also, the laser was tested under pulse mode with 1 % duty cycle and 5 μs pulse width, shows very low threshold current and total output power of about 50 mW. Figure 5.19 shows the pulse L-I characteristics of the LD bar package module.

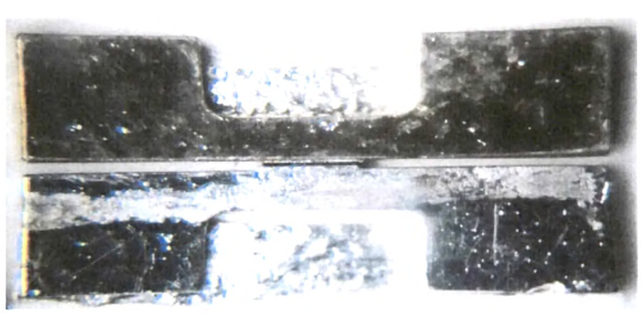


Figure 5.17: Laser diode bar is die bonded on c-type package using indium preform on an alumina substrate.

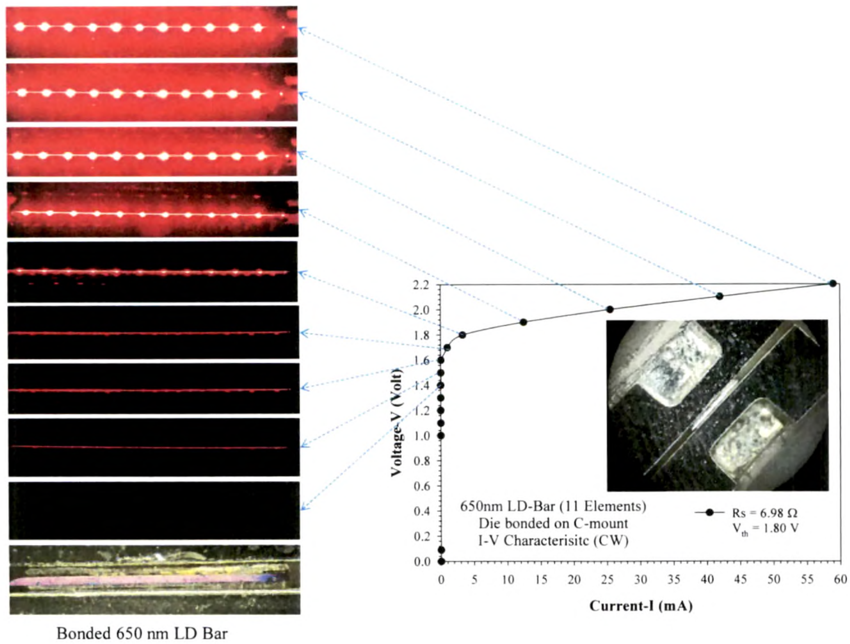


Figure 5.18: CW I-V characteristics and luminescence at different electrical power from the 650 nm laser diode bar package module (illustrated in inset photograph).

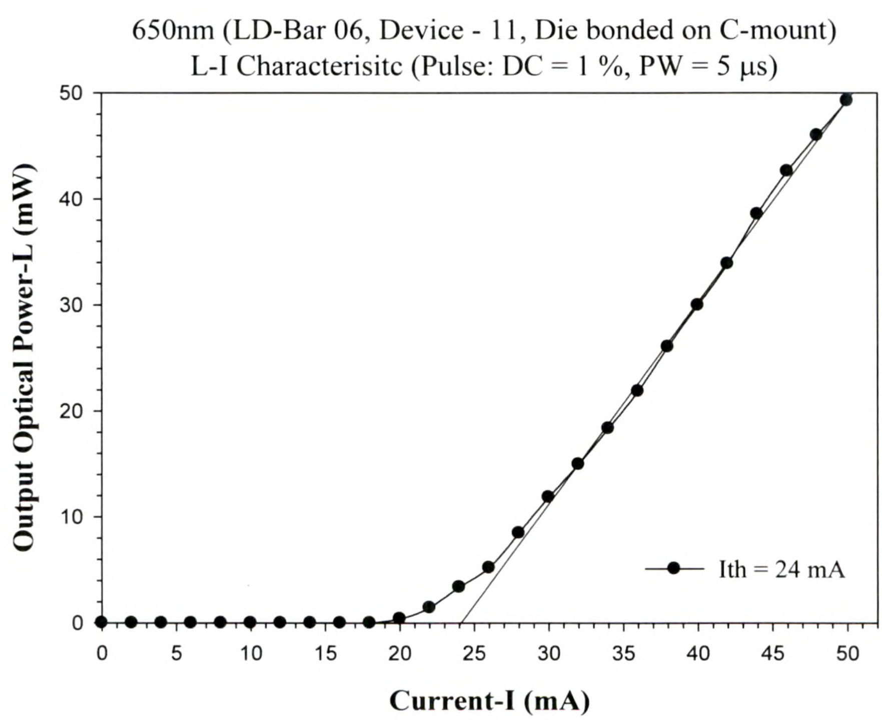


Figure 5.19: Pulse L-I characteristics of Laser diode package module

❖ Conclusion

The successful optimization of the high-power laser diode die-bonding and wire-bonding process parameters has been demonstrated. The solder material used for the die-bonding was *In* preform and *AuSn* eutectic alloy. The effect of the die-bonding on the device performance can easily be observed from the L-I characteristic measurement while operating it under CW mode. We have utilized the liquid soldering flux for surface wetting and better adhesion of the device to the substrate. In addition to that, we also have used the forming gas as gaseous flux for laser diode bar package module to remove surface oxide and proper adhesion. Single laser diode element with effective die-bonding gave an output power of ~ 670 mW/facet at ~ 2 A under CW operation with the dynamic resistance of ~ 200 mΩ. Identical characteristics of the three elements, such as threshold current density, and emission wavelength, L-I characteristics, were also achieved under pulse mode operating condition. The integrated pulse output power of ~ 7.5 W from these three devices was also achieved. Subsequently, the developed semi-packaged laser diode was used for characterization of electronic transitions of InAsP/InP quantum well in photoluminescence spectroscopy whose details will be discussed in the next chapter.

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