CHAPTER 3

Device Processing for Laser Diodes

3. Device Processing for Laser Diodes

A series of processing steps are required for the fabrication of edge-emitting laser diode bars and devices out of the epitaxially grown laser diode structures. Post-growth processing is a crucial issue for fabrication of high-power laser diode and demands very careful optimization for each step, since threshold current and external differential efficiency of laser diode depends largely on the device processing. This chapter presents a short report on processing steps used for the fabrication of edge-emitting high-power laser diodes after the structure is grown by metal-organic vapor phase epitaxy (MOVPE).

The wave-guiding in the vertical dimension, i.e. the transverse optical confinement, in a laser diode structure is provided by means of cladding and waveguide layers grown epitaxially. On the other hand, the lateral optical confinement is usually achieved by various post-growth processing steps that define the laser device geometry. Thus, the optical resonator for lateral wave-guiding is shaped by device processing.

The device processing is of great importance in the high-power laser diodes. Since, the high current density and high light intensity are involved in the case of high-power laser diodes, the processing procedures must be optimized for these devices (i) to minimize the series resistance of the device, (ii) to improve the optical and electrical confinement and (iii) to reduce the amount of stresses and damages experienced by the laser diode structure during the processing steps.

3.1 Various Laser Diode Geometries

The edge emitting laser diodes are fabricated mainly in two device geometries. These are broad-area geometry and stripe geometry.

3.1.1 Broad-Area Laser Diodes

The broad-area laser diodes are the most elementary form of edge-emitting laser diodes. In these lasers, the stripe width is much larger than the thickness of the laser structure. This allows uniform distribution of optical fields and injection current in the lateral direction. However, many transverse modes can sustain in this type of laser structures due to large lateral dimensions. Moreover, the current distribution is not necessarily uniform throughout the width in the lateral direction due to unavoidable material inhomogeneities and fabrication imperfections. As a result, the local current density may exceed the threshold level in some regions and may be below that level elsewhere.

Further, an important problem with broad area lasers is filamentation. This results from the increased refractive index due to excessive strain near imperfections in the structure. The optical fields concentrate in the high refractive index region resulting in the filamentation of light. These filaments are unstable and may vary with the injection current. Thus, broad area geometry causes inefficient and unstable operation of laser diode and therefore it is generally used only for high-power lasers.

3.1.2 Stripe Geometry Laser Diodes

The instabilities such as filamentation can be forcibly controlled by restricting the current to a narrow stripe, a few tens of μm wide. Laser diodes with this type of lateral current confinement are known as stripe geometry injection lasers. The stripe geometry laser diodes can again be categorized in two groups; gain-guided and index-guided stripe geometry lasers. The lateral wave-guiding in index-guided laser diode is achieved by means of difference of refractive indices of materials. In case of gain-guided laser diodes, the lateral wave guide is defined simply by contact geometry.

3.1.2.1 Gain-Guided Stripe Geometry Laser Diodes

A gain-guided laser diode relies upon lateral current confinement in the semiconductor material comprising the structural layers of the laser to guide the propagating radiation. The current confinement geometry, in turn, confines the optical wave laterally in the p-n junction. The real part of the refractive index remains the same in lateral dimension for the whole laser diode structure in the absence of injected charges. When the current is applied to the laser diode, the injected charge density and resulting high gain directly beneath the current confining region determines both the real and imaginary parts of the lateral refractive index profile. This lateral wave-guiding is totally dependent on the injected charge distribution. As a result, the laser characteristics will depend upon the widths of the current confining region.

The current is restricted in a narrow region by means of a contact window on the semiconductor surface. The current is injected into the active region through this contact window using an appropriate metallization. Areas outside this window have to be electrically isolated. There are a few different schemes to realize the current confinement in the contact window and insulation of rest of the area.

One way to attain insulation is to reduce the conductivity of the highly doped semiconductor contact layer strongly by ion implantation. Alternatively, a dielectric insulator can be placed between the semiconductor contact layer and the metallization layer. The insulation by ion-implantation is based on generation of vacancies in the semiconductor, which capture the free carriers and resist the current transport, thus decreasing the conductivity of the layers. Appropriate mask is used to select the area outside the contact window for ion implantation. In case of insulation by dielectric layer, the current barrier is formed by a thin layer of insulating material like SiO_2, SiN_x or Al_2O_3. The insulator has to be deposited by a low temperature process like sputtering for the use of the lift-off technique. Another approach to create a contact window is through diffusion of a dopant material; usually Zn. Selective diffusion requires a mask consisting of a stable dielectric insulator. The schematic cross-section of typical gain-guided stripe geometry for edge-emitting laser diode by dielectric insulation is shown in figure 3.1. For the processing of gain-guided high-power laser diodes, the ion-implantation and the dielectric layer are more commonly used techniques [1,2].

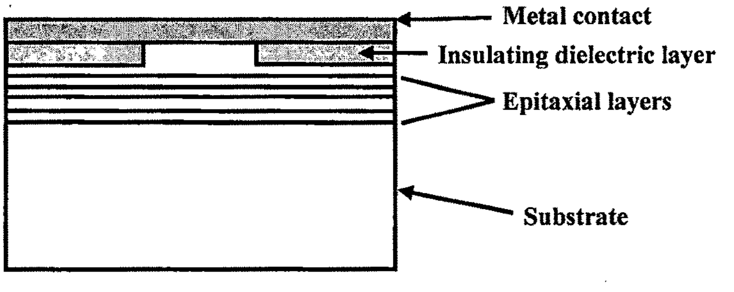


Figure 3.1: Schematic cross-section of gain-guided stripe geometry laser diode by dielectric insulation.

The limitation with gain-guided laser diode is large beam divergence along the p-n junction plane and greater beam-astigmatism.

3.1.2.2 Index-Guided Stripe Geometry Laser Diode

The index-guided structure is another common type of stripe geometry laser diode. In case of index-guided structure, a large difference of refractive index is generated in the lateral dimension to confine the light into the cavity. The difference in the refractive index of materials is created either by diffusion, e.g., Zn, along the plane of the p-n junction to create lateral wave guide or by the structural geometry of the laser diode, e.g., non-planar layers, substrate channels or mesas, or layer thickness variations etc., to guide the propagating radiation by a real refractive index waveguide. In the mesa isolated stripe, parts of the epitaxial layers, typically contact and cladding layers, in the regions outside the stripe are etched away and the index for that region outside the stripe is reduced to that of air, i.e. n = 1. This stripe geometry is very often used for a single-mode laser diode as very small mesa structure, a few microns wide, is possible to attain, giving rise to the ridge-waveguide laser diode. A special case of the ridge-waveguide laser diode with a lateral width of 60 μm to 200 μm of the mesa is used for high-power laser diode. In more complicated structures, the etched areas outside the confined region are re-grown by a second epitaxy step with another semiconductor material. This type of geometry is called buried heterostructure. Various index-guided stripe geometry laser diodes are shown in figure 3.2.

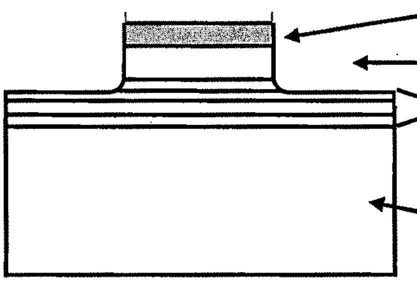


Figure 3.2: Schematic cross-section of index-guided mesa isolated stripe geometry laser diode.

The main advantage of the mesa structure is well-defined current confinement and a better optical confinement, which results in a somewhat lower threshold current density, especially for stripe widths smaller than 100 μm. Moreover, in an index-guided laser, the near field pattern of the laser can be imaged into a diffraction limited spot at an image plane with no correction for astigmatism because the beam waists in both the vertical and lateral directions lie substantially in the plane of the laser facet. These lasers usually emit a narrow wavelength spectrum and often single longitudinal mode operation is possible. However, most of the high-power laser diodes exhibit multi-mode emission.

3.2 Laser Diode Bars

An obvious approach to generate high optical output power from a laser diode is to increase the width of the emitting area. However, the large width of a single emitter leads to the severe problems like filamentation and lateral mode instabilities. This results in inhomogeneous power distribution along the facet and subsequently generates hot spots to degrade the device. In general, the output power of single-stripe emitters cannot be enhanced significantly for stripe widths exceeding about 200 μm. The practical alternative to increase the output power is to integrate many (20–70) optically and electrically isolated laser diodes into one laser diode bar. Each of these emitters is operated at a moderate output power simultaneously, and thus, does not suffer accelerated degradation of the output facet. It is possible to achieve several hundred watts of optical power by summing the power of all single emitters in the laser diode bar [3]. The length of such laser diode bars is generally kept one centimeter and the resonator cavity length varies from 600 μm to 1000 μm. The distance between the two emitters is about 50 μm to 200 μm and the filling-factor (the ratio of optically active area to the whole area of the laser bar) varies from 30% to 80%. Figure 3.3 shows a picture of such a laser diode bar with one of the laser diode stripe probed for characterization.

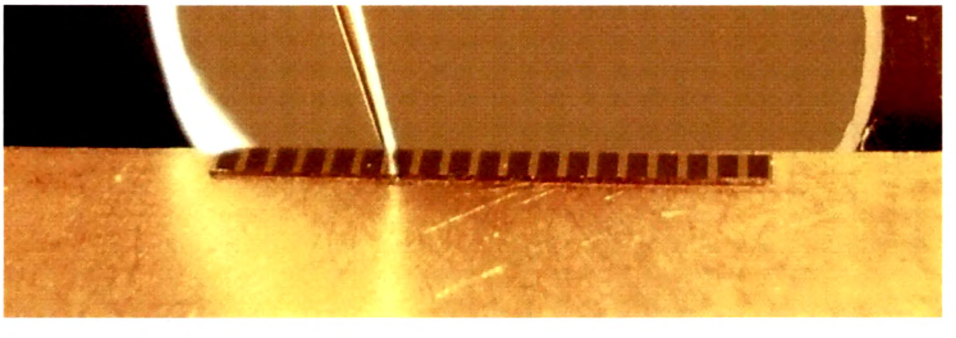


Figure 3.3: A laser diode bar probed for characterization.

However, some issues in the processing technology of laser diode bars have to be attained cautiously. For example, a failure of one emitter can be the reason for the failure of the whole bar by current or thermal effects. Another problem arises from the fact that so many emitters share the same waveguide layers in a laser diode bar. This results in an appearance of so-called spurious modes propagating in the direction 'perpendicular' to the normal resonator modes. The number of such modes increases with increasing the filling factor of the bar. Such modes decrease the overall efficiency of the bar and have to be suppressed by introducing losses for such modes in the bar. This can be achieved by using mesa structure by etching the channels on both sides of the mesa up to the waveguide layer. This results in an asymmetrical field distribution of the optical mode propagating in this region and does not allow it to reach the lasing threshold due to high leakage. Using such kinds of mesa structures, no additional technological steps for the suppression of spurious modes are necessary. Thus, we used mesa stripe geometry for fabrication of laser diodes.

3.3 Fabrication of Laser Diode Bar with Mesa-Stripe Geometry

After the MOVPE growth of laser diode structures as described in chapter 2, the epitaxially grown wafers were processed to make laser diode bars using mesa-stripe geometry. For the device processing as a general rule, the grown wafer is first cleaned with high-purity warm organic solvents. The next step is to form the top ohmic contacts. The metal patterning in laser diode processing is usually accomplished by the photolithography and lift-off process. The photolithography involves applying an organic compound, called photoresist, on the wafer, and followed by baking, exposure through a pattern mask and development to determine the desired patterns. Device-isolation is usually carried out by wet chemical etching. The wafer is etched down to the appropriate layer of multilayered laser diode structure in the unmasked areas.

Further, the laser diode wafer has to be thinned down. Then marks are scribed along the edges at desired lengths and laser bars are cleaved. The processing is generally carried out in the class-10,000 clean-room, i.e., the room contains less than 10,000 particles of size more than 0.5 μm in a cubic foot of air. All these steps for fabrication of laser diode bars with mesa stripe geometry and their optimization for our structure is discussed in the next section in their processing sequence.

3.4 Optimization of Various Steps in Laser Diode Processing

The post-growth device processing of laser diodes were carried out at Semiconductor Laser Section, SSLD, RRCAT, Indore. The wafers were first cleaved into small pieces of about 1 to 2 cm^2 area. Here, it is important to observe that Fabry-Perot cavity should be devised parallel to the primary flat on the substrate, which is the long straight line along the periphery of the wafer, and positioned originally to identify crystalline directions lying within the surface plane. This is very useful since the wet etch profile is good in the direction of primary flat and it is easy to cleave the sample in the direction perpendicular to the primary flat in order to obtain the cavity mirrors.

3.4.1 Organic Cleaning

Prior to any processing step, the semiconductor wafer needs to be cleaned from various contaminants. The pieces of these wafers were organically cleaned to remove dust and greases (oily impurities) from the samples. The samples were first degreased in warm trichloroethylene (TCE). The TCE is then removed from samples by treating the samples with acetone. Methanol is then used to remove acetone and finally the samples were cleaned by de-ionized (DI) water. These organic solvents are effective in removing oils, greases, waxes and organic materials such as photoresists from the sample surface. The samples were then blown dry using nitrogen and made ready for patterning with photolithography.

Here, it should be noted that if a cleaned GaAs, which is a cap layer on the top of epitaxially grown laser diode structure, is exposed to open air, about 30 Å thin oxide-carbon layer is formed on its surface affecting the contact quality adversely [4]. It is also necessary to take precautions against possible hazards of organic solvents before using them. For example, TCE is carcinogenic, acetone is flammable and methanol is toxic by skin adsorption.

After cleaning, the samples were processed with photolithography to define the transverse dimension of laser diode.

3.4.2 Photolithography

Photolithography is an optical means of transferring a pattern from photo mask onto the semiconductor surface. The pattern is transferred via an intermediate photo-sensitive polymer film called photoresist. Photoresist is applied in the form of liquid thin film that can be spread out onto the surface, exposed with a desired pattern, and developed into a selectively placed layer. The remaining pattern can then be replicated in other materials in subsequent processing, using techniques such as etching, metallization, etc. Photolithography is a binary pattern transfer: there is no gray-scale, color, nor depth to the image. The resolution is limited by the diffraction effect, which increases with the square root of the wavelength and with the gap between the mask and the wafer [5]. Various steps involved in photolithography are given below.

3.4.2.1 Photoresist Coating

Photoresist materials are photosensitive materials. They have definite properties of good adhesiveness and cohesiveness. Photoresist materials are of two types: positive photoresist and negative photoresist.

❖ Positive photoresist material

The positive photoresist (PPR) becomes more soluble in a developer after exposure to the ultraviolet (UV) light. It consists of two parts, resin and photoactive compound. Photoactive compound is dissolution inhibitor, and gets destroyed on exposure to the light to make the resin more soluble in developer. Positive resist decomposes on exposure to the UV light. The resist is exposed with UV light wherever the underlying material is to be removed. The exposed resist is then washed away by the developer solution, leaving windows of the bare underlying material. The mask, therefore, contains an exact copy of the pattern which is to remain on the wafer.

❖ Negative photoresist material

The negative photoresist (NPR), on exposure to the UV light, becomes less soluble in developer. It consists of two parts viz., chemical inert rubber and photoactive agent. Exposure to the UV light causes the negative resist to become polymerized, and more difficult to dissolve. Therefore, the negative resist remains on the surface wherever it is exposed, and the developer solution removes only the unexposed portions. Masks used for NPR, therefore, contain the inverse (or photographic "negative") of the pattern to be transferred.

Table 3.1: Differences between positive photoresist and Negative photoresist.

NPR	PPR
Swells during develop	No swelling during develop
Marginal step coverage	Good step coverage
Organic solvent developer	Aqueous developer
Sensitive to O_2	Operate well in air [6]

Table 3.1 shows differences between a PPR and a NPR. The photoresists should have a good adhesion to the substrate. It is deposited on the semiconductor surface by means of spin coating.

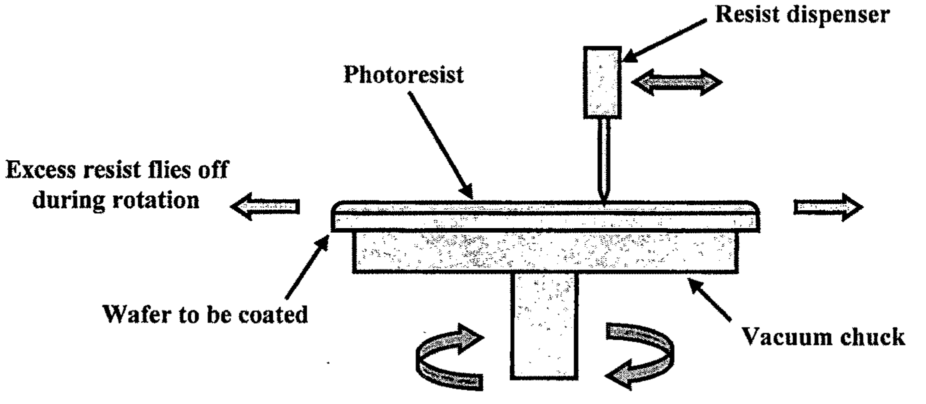


Figure 3.4: Photoresist spin coating.

The wafer is held on a spinner chuck by vacuum. The photoresist is dispensed in liquid form on the wafer. The resist is then subjected to centrifugal force by spinning the wafer about its axis at a speed of several thousand revolution per minute (rpm). The centrifugal force, in turn, spreades the resist, flings off the excess resist, and leaves a thin layer adhering to the surface of a wafer as the solvent evaporates. The faster the spin speed, thinner the resulting layer of resist. Average thickness of resist can be varied by adjusting the rate of spin or resist viscosity. The spin speed should be in a certain range for uniform coating. We used OiR-960 positive photoresist (S1813) for photolithography of laser diode samples.

After the resist is spun, it must be baked for a good adhesion to the GaAs surface. This process is called soft-baking, which hardens the resist by removing the solvent and water remaining in the film after spinning. The heating is generally applied by convection in oven or by conduction on a hot-plate. In convection heating, the heating starts from the surface and may cause the solvent-trapping. We used resistive hot-plate for soft baking. Hot-plating the resist is usually faster, more controllable, and does not trap solvent like convection oven baking, since the heating starts from the bottom. The temperature was kept at 90 °C for one minute.

We measured the resist thickness for different spin speeds before and after the soft-bake, which is shown in figure 3.5. The standard data from the literature is also shown for reference. Thickness of resist is measured with the help of a Surface Profilometer. It is clearly observed from figure 3.5 that the resist thickness decreases with increasing spin speed and after softbake the thickness gets reduced due to evaporation of volatile material.

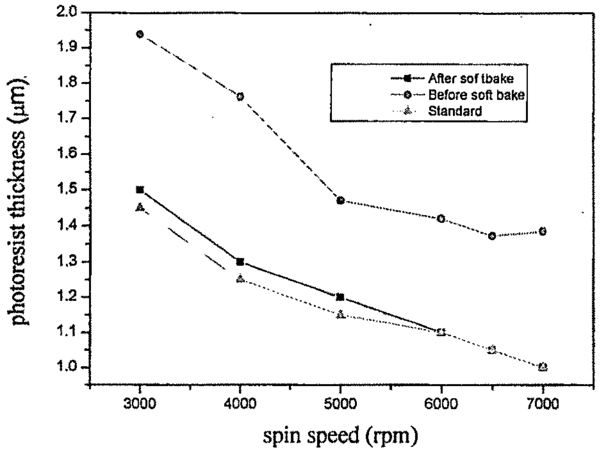


Figure 3.5: Spin speed- thickness curves for S1813 photoresist :before softbake, after softbake and standard (from the catalogue).

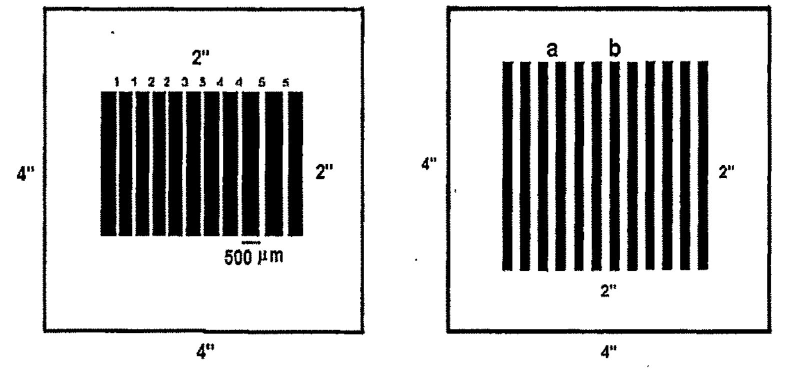
The laser diode samples were spin-coated with 1.3 μm thick OiR-960 positive photoresist (PPR) using 3500 rpm spin speed for 1 min. Samples were then soft baked at 90 °C on a hot plate for 1 min.

3.4.2.2 Chlorobenzene Soak

After softbake and prior to UV exposure, the top surface of the PPR was chemically modified to develop at a slower rate than the underlying resist. This was accomplished by soaking the resist coated samples in Chlorobenzene for 2 minutes. The chlorobenzene reacts with upper layer of photoresist upto certain depth and makes that part of the resist harder than the part which is not reacted with chlorobenzene. In this way, we get two layers of the resist where upper part is harder than the lower one. The samples were then blown dry with nitrogen.

3.4.2.3 Alignment

After the chlorobenzene soak, photomask is aligned on the laser sample. The mask contains alternate transparent and opaque lines according to which we have to pattern the laser samples. Two masks used to define the dimensions of the laser diode structures are shown in figure 3.6. The stripe widths vary from 30-200 μm and are separated with 500 μm space in mask type A as shown in figure 3.6 [a]. The mask type B contains equal stripe width 'a' and separation 'b' for all stripes as shown in figure 3.6 [b].



[a] [b]

Figure 3.6: Mask used in photolithography for laser diode stripe pattern; [a] variable-stripe width: No. 1 = 30 μm, 2 = 50 μm, 3 = 80 μm, 4 = 100 μm, and 5 = 200 μm, [b] constant stripe-width.

3.4.2.4 Exposure

In optical lithography, the formation of images with visible or UV radiation occurs on the photoresist using contact, proximity or projection printing. The light intensity I(λ,z) which is effective in exposing a volume element of resist at height, z, above the substrate depends on the reflectivity of the semiconductor surface, thickness of the photoresist T (T>z) and convolutin of the absorption spectrum of the resist with the spectrum of the incident light [7].

We used contact printing, in which light is incident on the mask which is in contact with wafer, i.e., there is no gap between wafer and mask. This prevents the diffraction losses and we get high resolution. However, there is a drawback of this method that it may produce defects in both, the wafer and the mask. The samples were exposed using a Quintel 4TL mask aligner for 20 seconds with 11 mw, 365 nm UV radiation [8]

3.4.2.5 Development

The exposed photoresist is dissolved into a suitable developer which is different for different photoresists. Here we discuss the role of chlorobenzene. When the wafer is dipped into a developer, the upper part of the resist, which is harder due to chlorobenzene soak, dissolves with a slower rate than the lower part. This results in an undercut, which facilitates the lift-off process. Simple solvents are generally sufficient for development of non-postbaked photoresists. Acetone, TCE and phenol-based strippers (Indus-Ri-Chem J-100) are generally used for positive photoresists. The NPRs usually employ methyl ethyl ketone (MEK) and methyl isobutyl ketone (MIBK). Finally the wafer is dried with N_2 gas.

After exposure and development, a second bake step (hard bake) is sometimes applied. However, this is not preferable because this may cause lift-off problems by changing the shape of the resist profiles.

3.4.3 Top Metal Contact Deposition

After lithography, we have a wafer having alternate lines of photoresist material. The next step is the deposition of top ohmic contact on the wafer. The purpose of metallizing the p-sides and n-sides of the diode laser is to provide an ohmic contact to allow electrical current to flow through the diode. The contact should have a linear I–V characteristic, and be stable in the time and temperature domain. The contribution to the series resistance of the diode should be as small as possible. Requirements for electrode metals are, therefore, low contact resistance, ease of fabrication, good adhesion, low temperature for contact formation, and thermal stability [5]. The metallization is also the basis for the mounting of the diode laser on a heat sink. Therefore the metallization should also allow soldering on a submount for heat transfer and wire bonding. For high-power diode lasers based on GaAs substrates in the wavelength range between 650 nm and 1100 nm, the semiconductor contact layer consists typically of GaAs. If this contact layer is highly enough doped, almost any metal placed in intimate contact with the surface will result in an ohmic contact without having to be alloyed. We used following sequence to deposit p-type ohmic contacts:

- Titanium (Ti): thickness~200Å
- Platinum (Pt): thickness~100Å
- Gold (Au): thickness~3000Å

Gold provides a very high conductivity and a soft surface quality for possible bonding purposes. Putting Pt and Ti before Au, results in much better adhesion of Au to the surface, and in this way minimizes the series resistance. The front contacts to the p+ GaAs capping layer of the laser structures were deposited using a metal coating unit with thermal evaporation system at high vacuum (3×10^{-6} mbar pressure)

3.4.4 Lift-off Process

In this step, we remove the metal layer from the top of mesas, by putting the samples in acetone bath. Lift-off process is a simple method for patterning films which are deposited on the sample. After metal coating, we dip the wafer in acetone & boil it for 3-4 minutes. The application of acetone removes the photoresist left on the sample below metal films by causing the resist to dissolve, therefore swelling and losing adhesion to the wafer. When photoresist dissolves in the acetone, the unwanted metal deposited on the photoresist is removed while metal directly deposited on the wafer remains unchanged, revealing the final structure of the front p-contact surface as shown in figure 3.7.

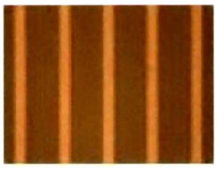


Figure 3.7: Photograph of metal contacts on laser structure after lifting off.

Any deposited film can be lifted off provided that the substrate does not reach the temperature high enough to burn the photoresist during the deposition and the film is thin enough to allow solvent to seep underneath. Various mechanisms from resist coat to lift off are shown in figure 3.8 [9].

[a] [b] [c] [d] [e]

Figure 3.8: Lift-off technique: (a) overlying layer of OiR 960 and underlying resist layer modified with chlorobenzene (b) area of OiR 960 resist exposed to UV (c) developed resist (d) following metal deposition (e) following lift-off and clean.

3.4.5 Rapid Thermal Annealing of Top Contact

Rapid thermal annealing (RTA) is very crucial for obtaining good metal-semiconductor ohmic contacts [10]. It helps the diffusion of the metal into the GaAs crystal, and reduces the barrier-height at the junction by alloying the semiconductor and the metal at the junction. This results in the reduction of series and thermal resistance of the devices. The annealing should be very rapid to avoid unwanted processes like redistribution of impurities and increment in escape probability of volatile materials. The RTA also provides good adhesion for metal to semiconductor contacts.

Heating by an array of incandescent lamps is a popular method for RTA. In this method, many incoherent lamp sources like tungsten–halogen lamps are mounted in a cylindrical box. The box contains a quartz tube in which samples are placed on the

Silicon wafer. Silicon wafer has high absorption for infrared radiation, which is emitted by tungsten halogen lamps and hence causes the heating of the sample up to desired temperature. In the literature, annealing temperature between 400 °C to 500 °C is suggested [5]. We carried out RTA at 480 °C. Rapid heating of a sample with temperature and desired dwelling time is a difficult job and this is achieved by a computer controlled PID temperature controller. A thermocouple is used to measure the temperature of wafer. For abrupt cooling, proper coolant like N_2 gas is used. The temperature-time graph of RTA process is shown in figure 3.9.

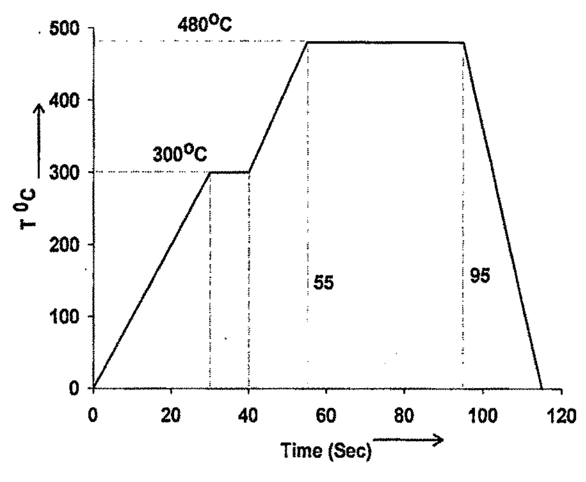


Figure 3.9: Temperature-time graph of RTA process.

3.4.6 Etching

To isolate individual devices in a laser diode bar to form the mesa structure, the wafer is etched till the upper cladding layer by using suitable etchant. The etching of the mesa can be carried out either by wet etching or dry etching methods. In wet etching, areas of the wafer outside the desired stripe are removed by dissolving them in a wet chemical solution. The dry etching involves reaction of materials in such areas, to be removed, with gases in plasma to form volatile products. In this work, because of its simplicity [11,12], and depth control, wet etching was preferred giving reliable results for laser diode devices.

In the case of wet chemical etching, only solutions which exhibit anisotropic etching and strictly proceed downwards into the material are preferred. If the etching is isotropic, a large undercut occurs resulting in breaks and degradation of metallization films and the structure [5]. An often-used etching solution for GaAs and AlGaAs is the $H_2SO_4/H_2O_2/H_2O$ system. This system shows moderate etching rates and excellent etching profiles in the fundamental crystal-lattice directions. Another wet etchant is composed of HCl and water or H_3PO_4, which is used for InGaP. However, these systems exhibit very high etching rates, making the etching process difficult to control. For InP, InGaAsP and related compounds, an etching solution based on bromine, viz. Br_2: $H_2O/HBr/H_2O$, is also used.

We used $H_3PO_4+H_2O_2$+DI water (1:1:8) solution. The etching rate was determined with the help of surface profilometer by etching on the dummy samples and desired etching depth was achieved by controlling time of etching. After etching, wafers were dried by N_2 gas.

3.4.7 Lapping & Polishing

In order to reduce the thermal resistance of the device and to facilitate the scribing procedure, it is necessary to thin down the wafer by reducing the substrate thickness. This is accomplished by reducing the thickness of n^+ GaAs wafer to around 125 μm by lapping and polishing the wafer using ECOMET 3000.

3.4.8 Bottom Metal Contact Deposition

After the samples are thinned by lapping and polishing, it is necessary to cover this surface entirely, for the n-contact of the laser devices. The most common approach of fabricating ohmic contacts on n-GaAs is to apply an appropriate metalization to the wafer, and then alloy the metal into the GaAs. During the alloying and cooling period, a component of the metal enters into the GaAs and highly dopes the surface layer. This doping decreases the schottky barrier and the tunneling dominates the conduction mechanism. The doping agent is generally chosen to be germanium (Ge). Gold-germanium (Au-Ge) is usually applied with an overlay of another thin metal layer such as nickel (Ni). Addition of Ni to Au-Ge leads to lower contact resistance as well as serving to maintain a smooth surface morphology after alloying the contact metallization [13].

The Au-Ge alloy has a poor sheet resistance, is very difficult to wire-bond and is not solderable to a heat sink. This requires an additional gold layer to be deposited on the Au-Ge alloy. The sequence for bottom ohmic contact deposition on n-type substrate is,

- Gold-Germanium Alloy (Au-Ge): thickness~200Å
- Nickel (Ni): thickness~100Å
- Gold (Au): thickness~3000Å

3.4.9 RTA of Bottom Contact

The samples are annealed again at a temperature of 480^0 C to reduce the series resistance to its minimum value. Figure 3.10 shows cross section of the laser diode structure after formation of bottom contact.

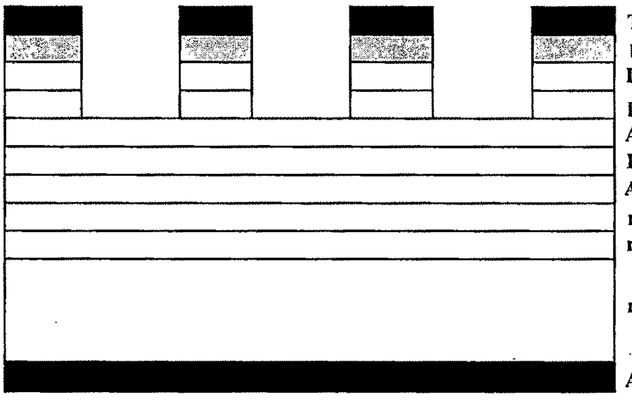


Figure 3.10: Laser diode structure after back contact.

3.4.10 Scribing

Finally the wafer is cleaved along the cleavage plane perpendicular to laser diode stripes using Micro Suss HR 100 manual scriber to get laser diode bars with different cavity lengths ranging from 0.5 mm to 2 mm. Each bar contains several laser diodes with stripe widths varying from 30 μm to 200 μm.

3.5 Detailed Process Layout

The complete process layout for the processing of laser diode is given in figure 3.11.

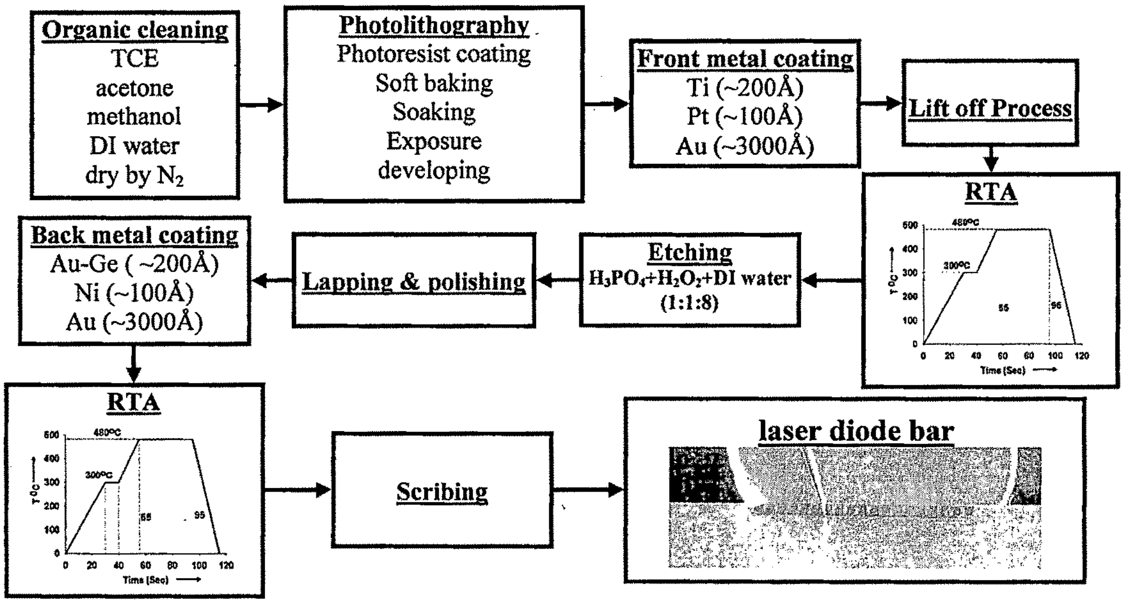
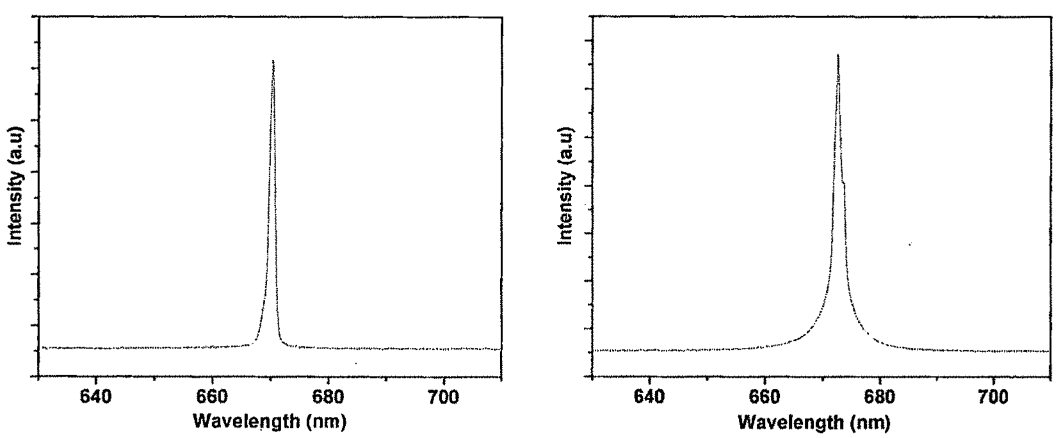


Figure 3.11: Procedure of device processing.

3.6 Testing of Laser Diode Bars

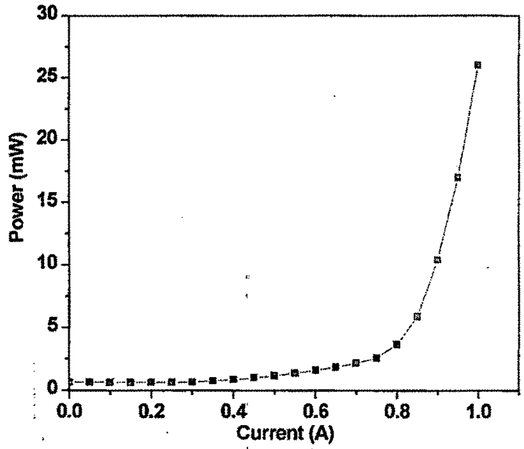
The processed red laser diode samples 2107086 and 2107088 were tested for emission wavelength and optical power measurement. Emission wavelength of these laser diodes are measured by Ocean Optics HR4000 spectrograph. The detail of setups and automation of various characterizations for laser diodes are discussed in Chapter 5. Results of laser spectra from samples 2107086 and 2107088 are shown in figures 3.12 [a] and figure 3.12 [b] respectively. It is observed that lasing wavelength for the samples 2107086 and 2107088 are 670 and 672 nm respectively.



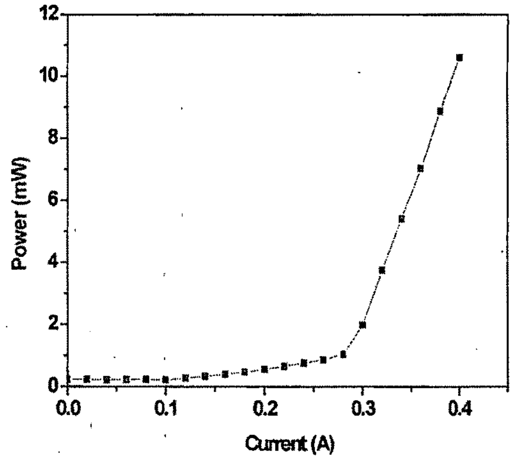
[a] [b]

Figure 3.12: Laser diode spectra: [a] sample 2107086 [b] sample 2107086.

The optical output power versus injection current (L-I characteristics) for samples 2107086 and 2107088 are shown in Figure 3.13 [a] and figure 3.13 [b] respectively. L-I characteristics have been measured by applying a current in pulse-mode with pulse width of 1000 ns and repetition rate of 2 kHz.



[a]



[b]

Figure 3.13: L-I characteristics: [a] sample 2107086 [b] sample 2107088.

Various parameters for laser diode like threshold current density, slope efficiency have been extracted from the L-I characteristic of laser diode. Measured values of threshold current density and slope efficiency of the red laser diode samples 2107086 and 2107088 are listed in Table 3.2.

Table 3.2: Wavelength, slope efficiency and threshold current density of laser diodes.

Sample	Wavelength (nm)	Slope efficiency (W/A)	Threshold current density
2107086	670	0.05	950 Amp/cm^2
2107088	672	0.08	1080 Amp/cm^2

Though the optical power and slope efficiency of these laser diodes are low, we obtained around 25 mW and 10 mW optical power consistently from almost all laser diode devices of sample 2107086 and 2107188, respectively. Some devices also emitted high-power up to 200 mW. However, these devices were not reliable and got burnt during high-power operation due to thermal heating. Thus, better heat-dissipation arrangement with optimized passivation and bonding of laser diode is essential for high-power operation.

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