❖ Summary and Scope for Further Work

➢ Summary

Laser diodes have the potential to supplant other bulkier lasers in scientific applications and are being integrated within electronic and telecommunications subsystems because of their small size, high efficiency, and long lifetimes. As mentioned in the chapter 1, the objective of the present thesis is to optimize technology and various processes for the fabrication of high power laser diodes.

The quantum well laser diode structure is grown and optimized using metal-organic vapor phase epitaxy (MOVPE) technique. The growth conditions like pressure, substrate temperature, precursor flow rate, V/III ratio, growth rate, etc., have been optimized for each layer of the multilayer structure individually. The epitaxial layers are characterized by High-Resolution X-Ray Diffraction (HRXRD), and Photoluminescence (PL). Carrier doping of epitaxial layers were characterized using electrochemical capacitance-voltage (ECV) profiling, and Hall-effect measurements. The post-growth processes have also been optimized for high-power laser diodes. Photolithography and lift-off techniques are used to define the transverse dimension of laser diodes. The stripe-geometry defines the threshold current and the external differential efficiency of laser diode. Thus, these steps play significant role in the operation of high-power laser diodes. The contact-deposition is also a very important process as it contributes to the series and thermal resistance of the devices. This process is optimized in order to minimize the resistance. The MOVPE growth and device processing of laser diodes were carried out at Semiconductor Laser Section, SSLD, RRCAT, Indore.

After cleaving the wafer into laser diode bars, the facets of the laser diodes are protected with a dielectric film, such as Al_2O_3, in order to increase the P_{COD} level. Moreover, in most of the applications, optical power output from only one of the two facets is useful. So we have designed and optimized the single layer anti-reflection (AR) and multi layer high-reflection (HR) coatings on the front and the back facet of the laser diode, respectively. The AR-HR films are deposited using electron beam evaporation technique. A special jig is designed and fabricated to hold the laser diode bar in the vacuum chamber during the facet coating. The AR-HR coatings have been optimized for various laser diode structures such as;

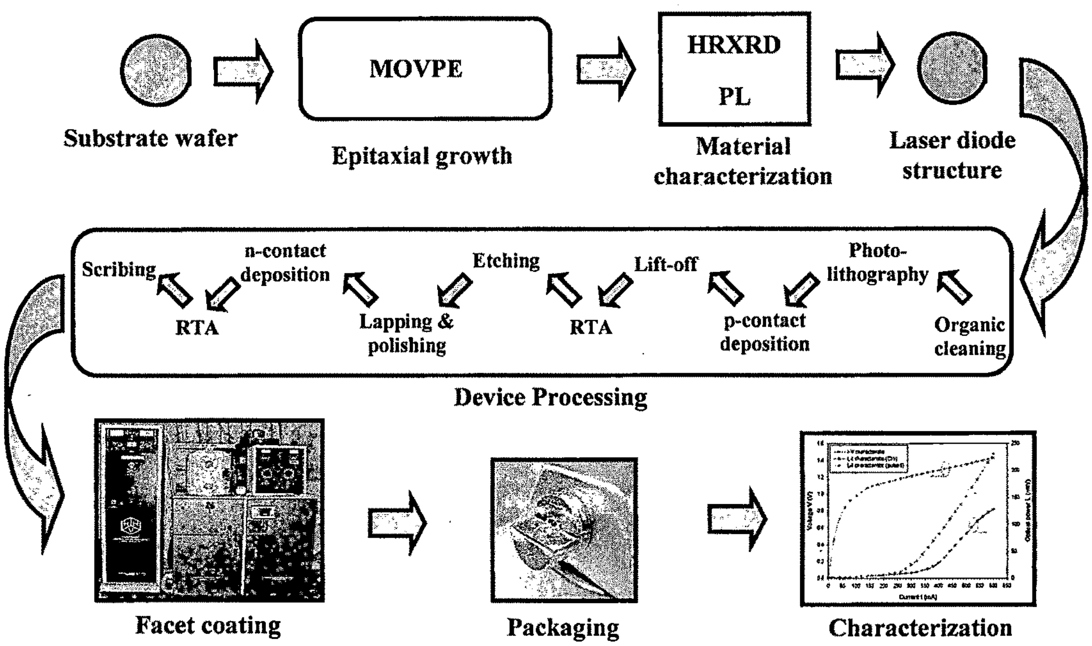
- ⇨ 650 nm (Red) ridge waveguide laser diodes
- ⇨ 820 nm AlGaAs based Separately Confined Heterostructure laser diodes grown by Liquid Phase Epitaxy
- ⇨ 850 nm GaAs single quantum well laser diodes grown by MOVPE
- ⇨ 890 nm AlGaAs/GaAs/AlGaAs Double-Heterostructure Laser diodes
- ⇨ 1.2 μm MOVPE grown High-power highly strained InGaAs quantum-well Laser diodes

The optical output power of laser diode is enhanced by a significant amount from AR coated facet. We have also designed and installed a setup for automatic in-situ reflectivity measurement of AR and HR film during facet-coating for precise control and monitoring of thin film reflectivity. The effects of facet-coating on laser diode characteristics are studied and verified using analytical simulations.

The high-power laser diode characterization facility including L-I characteristics, I-V characteristics, spectral response, and thin film characterization viz. reflection/transmission spectra measurements have been automated with virtual instrumentation using LabVIEW in order to maintain the uniformity of measurement conditions with higher precision and reliability. Experimental setup and virtual instruments have also been established for measurements of characteristic temperature, thermal impedance, and lifetime.

After facet-coating and preliminary testing, the laser diode must be bonded on an appropriate package depending on the application. Packaging is last but one of the most crucial steps of fabrication that considerably affects the performance of high-power laser diode, especially in continuous-wave (CW) mode. To achieve high thermal conduction, solders are used as bonding media. We optimized the die-bonding of laser diode chip using different solder materials and then carried out the optimized process on facet-coated, high-power laser diode bar. After die-bonding, the top contact was provided by 1-mil gold wire using manual wire-bonding technique. Wire-bonded laser diode assemblies are then tested and characterized for high-power CW operation. We obtained 130 mW CW power from facet-coated, bonded laser diode assembly. The die-bonding and the wire-bonding processes are optimized for different high-power laser diode structures.

Optimized processes in the journey of laser diode from structure growth to packaging are summarized in the following figure.



➢ Scope for Further Work

We started the growth of laser diode structure with reported thicknesses of quantum well (QW) and optimized the thickness and related growth conditions in an empirical manner. However, this approach cannot be used for frequent optimization of the structure at different wavelengths. The emission wavelength can be tuned by varying the QW thickness and the composition of the semiconductor material in active layer. Thus, a simulation of QW laser diode structure can be a very useful tool to predict the energy levels in the QW and consequently the emission wavelength by playing with the QW thickness and composition. The simulation is already being developed by numerically solving the Schrödinger equation using finite difference method (FDM).

Further, high optical quality and temperature independence of the laser diode can be achieved by replacing the QW with the layer of quantum-dots (QDs) in the active layer. Quasi-zero dimensional systems, especially self-assembled semiconductor QDs grown in Stranski-Krastanove (S-K) growth mode have got enormous attention of researchers all over the world. InAs/GaAs QD system is particularly of interest as it can be tuned to emit in the wavelength range from 1080 nm to 1550 nm which is the useful window in optical communication systems based on silica fibers. However, requirement of high gain and small emission line-width for laser diode demands high QD density, uniformity and narrow size distribution. Further, to avoid gain saturation, stack of vertically coupled multiple QD layers is necessary. Presently we are optimizing the growth parameters for high-density InAs self-assembled QDs on GaAs using MOVPE. The optimized layers of QDs can then be used as active layer to obtain QD laser diodes.

Optimization and fabrication of dedicated assembly for in-situ reflectivity measurements of AR-HR coatings is required for the automation and control of facet-coating processes. Moreover, with proper multilayer design, electric field distribution can be varied in the dielectric stack and can be optimized for high-power operation. This requires experiments in synthesis and design of facet coating. Different dielectric materials, such as Hafnium Oxide (HfO_2), Tantalum oxide (Ta_2O_5), Zirconium oxide (ZrO_2), and other rare-earth oxides can also be tested and studied for facet-coating.

The operation of high-power laser diode is also influenced by instabilities such as filamentation and mode-hopping. Study of these instabilities is very important, particularly for high-power operation of laser diodes. We also observed thermal roll-over in case of high-power laser diode bonded in junction-up configuration. This indicates that a better heat dissipation is required for high-power laser diode. The simulation of heat-dissipation can be a useful tool for the thermal management and package-design in case of high-power laser diode.