Chapter Six *Conclusions and Future Work*

This thesis presents modeling and theoretical studies of semiconductor laser diode in general, with emphasis given to Vertical-Cavity Surface-Emitting Lasers (VCSELs) operating at 1.55 μm wavelength. It was expected that VCSELs would be the next-generation laser diode employ for long wavelength (1.3-1.55) μm optical-fiber telecommunications system, displacing the DFB and DBR laser of the conventional EELs. The commercialization of VCSELs for short wavelength (0.85-0.98) μm applications in optical communication have been demonstrated recently.

In this thesis, modeling and simulation of 1.55 μm VCSELs diode have been performed. The DBR mirrors and the active region of the VCSELs have been simulated by using HS_Design version 1.0. Three types of material system are studied for the DBR mirror simulation that is InGaAsP/InP, GaAs/AlGaAs and SiC/MgO which each representing the epitaxially-grown, wafer-fused and dielectric-deposited mirror, respectively. The wafer-fused mirror of GaAs/AlGaAs system exhibited high reflectivity, high electrical conductivity and low thermal resistivity which are the requirements of DBR mirror. As for the VCSELs active region, simulations of strain percentage, composition level, QW thickness and the number of QW are carried out where high optical gain is recorded around 1.55 μm.

Based on the simulation results for each of the device component, a complete 1.55 VCSELs diode employing n- and p-DBR GaAs/AlGaAs mirrors wafer-fused to strain compensated MQW InGaAsP is proposed. LaserMODE version 2.0 is used to simulate the device characteristic. Device profile simulation such as refractive index profile, doping profile and energy band profile verified that the geometry and material parameters of the proposed VCSELs is optimized. The simulation of mode analysis shows that the fundamental optical mode is overlapping the active region. A symmetric, narrow and circular emitted beam is observed from the near-field and far-field distribution of the proposed VCSELs resulting in high coupling efficiency. The simulated PL spectra and optical spectrum demonstrates that the device lasing wavelength is at 1.55 μm with single longitudinal mode operation. As for the L-I-V characteristic simulation, the proposed 1.55 μm VCSELs diode exhibit comparable electrical properties with the highest performance 1.55 VCSELs to date.

In addition to the studies and results demonstrated in this thesis, there are still many areas that are worth investigating for future work. The proposed 1.55 μm VCSELs diode can be fabricated if the MBE or MOCVD facility becomes available. Then, a comparison of the simulation results obtained in this work with experimental findings can be made. It would also be interesting if the modeling and simulation tools used in this work can simulate the pulsed and CW operation for the device to have a complete electrical properties simulation. The temperature effect should also be included in the simulation to study the laser operation at various operating temperature. Besides, more advanced doping profile such as pulsed doping and delta-doping can be incorporated to improve the electrical conductivity between the material interfaces. The current confinement scheme through oxidized aperture layer and proton-implantation that are used for current VCSELs device will certainly improved the simulation results if it can be employ in the modeling tools.

Finally, continuing research and rapid development efforts are aim toward advancing the VCSELs performance for various future applications. It is critical that VCSELs structures, designs and the fabrication technologies can be transferred into the manufacturing level. VCSELs have attracted commercial interest and are beginning to have an impact on the market. The continuing interest in VCSELs indicates its important role in the future optoelectronics and photonics industry.

Honeywell VCSELs Comparison to Other Source Technologies, Ref: [114]

VCSEL Optical Products
Comparison to Other Source Technologies -

Technology Comparison	LED	IPL/EEL/CD Laser	VCSEL	VCSEL Benefit
Electrical Parameters				
Operating Current (mA)	100	30	10	• lower current requirements of VCSEL are good for battery-driven applications • Improves power budget efficiencies
Series Resistance (Ohms)	3	3	25	• Higher resistance eases electrical design and performance
Modulation Bandwidth (GHz)	>0.1	<2	>10	• Higher data rates possible • Faster information transfer
Power Dissipation (mW)	200	100	20	• Better temperature stability
Relative Intensity Noise (dB/Hz)		-120	-120	• Low EMI (FCC & FDA compliance advantages)
Optical Parameters				
Threshold Current (mA)	NA	25	3	• Very little power needed to produce output
Wallplug Efficiency (%)	1	2	10	• More output per unit of input current
Slope Efficiency (mW/mA)	0.001	0.3	0.25	
Beam Angle (FWHM,degrees)	180	40 perpendicular 10 parallel	15	• Allows for simpler optics/greater sensing distances • Symmetric and narrow beam • Improves sensing accuracy & coupling thru fiber
Spectral Width (nm)	50	0.3	<0.3	• Reduces/eliminates need for filtering in sensing applications • less "loss" in fiber applications
Rise and Fall Times (nm)	5	<0.1	<0.1	• On/off in 1/trillionth of a second
Astigmatism (μm)	0	3	0	• easier optics and better performance
Temperature Parameters				
d(wavelength)/dT (nm/°C)	0.3	0.3	0.06	• temperature stability

Worldwide semiconductor laser sales for various applications in the year 2002, Ref: [24]