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HIGH-TEMPERATURE HIGH-FREQUENCY OPERATION OF SINGLE AND MULTIPLE QUANTUM WELL InGaAs SEMICONDUCTOR LASERS

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NOTICE

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13. ABSTRACT *(Maximum 200 words)*

High-speed semiconductor lasers operating at high temperatures are desired for future aircraft avionics systems to reduce weight, increase data rates, and eliminate undesired electromagnetic emissions. Strained InGaAs quantum well lasers have demonstrated excellent temperature performance and frequency response. To determine what trade-offs exist between high-temperature performance and high-speed performance In0.2Ga0.8As quantum-well lasers with one through four quantum wells were fabricated and tested to determine the optimum number of quantum wells to provide the highest frequency response at temperatures up to 150° C. This presentation reports on the design and development of high-frequency In0.2Ga0.8As single and multiple quantum well lasers for operation at high temperatures. The lasers were grown by molecular beam epitaxy and fabricated into gain-guided lasers for laser material characterization and ridge-waveguide lasers providing single-mode operation for net modal gain and high-frequency analysis. The ridge-waveguide lasers operated in continuous-wave current mode up to temperatures of 90° C for single quantum well devices and up to 150° C for multiple quantum well devices. The single quantum well lasers exhibited a -3 dB frequency response ~7 GHz for room-temperature operation and >3 GHz at 90° C. The four quantum well laser device had a -3 dB frequency response of ~14 GHz for room-temperature operation and ~5 GHz at 150° C. This is the highest temperature for high-frequency operation reported to date.

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High-Temperature High-Frequency Operation of Single and Multiple Quantum Well InGaAs Semiconductor Lasers

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1. Project Synopsis

This is the final report for the "High-Speed / High-Temperature Lasers for Avionic Interconnects Project, Project Number 2300AA15. The objective of this research project was to provide the best possible modulation bandwidths for laser diodes under high (100° C) operating temperatures. An in-house iterative approach was used throughout the design, growth, fabrication, and testing cycle to discover and demonstrate the best-performing laser design. The project succeeded in designing and developing diode lasers operating CW at 150° C with a small-signal modulation frequency ~5 GHz. This research resulted in one conference presentation at the 2001 Solid-State and Diode Laser Technology Review in Albuquerque, NM as well as the motivation for two masters theses at the University of Dayton.

2. Introduction

High-speed semiconductor lasers operating at high temperatures are desired for future aircraft avionics systems to reduce weight, increase data rates, and eliminate undesired electromagnetic emissions. Strained InGaAs quantum well lasers have demonstrated excellent temperature performance[1] and frequency response.[2] These lasers show excellent promise for local area network (LAN) applications where fiber dispersion and attenuation considerations are not as critical. To determine what trade-offs exist between high-temperature and high-speed performance $In_{0.20}Ga_{0.80}As$ quantum-well lasers with one through four quantum wells were fabricated and tested to determine the optimum number of quantum wells to provide the highest frequency response at temperatures up to 150° C. This presentation reports on the design and development of high-frequency $In_{0.2}Ga_{0.8}As$ single and four quantum well lasers for operation at high temperatures. The multiple-quantum well laser devices all performed better than the single quantum well laser device for both pulsed and continuous-wave (CW) high-temperature operation as well as temperature dependent high-frequency operation with the four quantum well laser performing the best. The four quantum well laser demonstrated a room temperature -3 dB frequency response ~13 GHz and -3 dB frequency response at 150° C ~5 GHz. This result is the highest temperature for high-frequency operation reported to date.[3]

3. Device Design, Growth, and Fabrication

The high-frequency laser structure was designed to operate with a single transverse mode as well as a single lateral mode. The epitaxial layer design ensured the single transverse mode while the fabrication of a ridge waveguide laser structure ensured single lateral mode operation for the high-speed laser devices. The laser material was fabricated into gain-guided lasers for laser material characterization and ridge-waveguide lasers for net modal gain and high-frequency analysis.

The lasers were grown by molecular beam epitaxy on a semi-insulating, 2° off-axis *(from the <100> to the <110> crystal plane)* GaAs substrate. The epitaxial layer structure beginning at the substrate consisted of a 1,000 Å Si-doped ($4(10^{18})$ cm^{-3}) GaAs buffer layer followed by a 10,000 Å Si-doped ($4(10^{18})$ cm^{-3}) $Al_{0.60}Ga_{0.40}As$ optical confinement barrier. The active region consisted of 2,000 Å or 1,775 Å $Al_{0.20}Ga_{0.80}As$ spacing layer (single quantum well or four quantum well, respectively), a 100 Å GaAs electrical confinement barrier followed by either one or four periods of 80 Å $In_{0.20}Ga_{0.80}As$ quantum well(s) and 100 Å GaAs electrical confinement barrier(s), and, finally, a 2,000 Å or a 1,775 Å $Al_{0.20}Ga_{0.80}As$ spacing layer. The top cladding layers consisted of a 10,000 Å Be-doped ($\sim 10^{18}$ cm^{-3}) $Al_{0.60}Ga_{0.40}As$ optical confinement barrier, and a 500 Å heavily Be-doped ($\sim 10^{19}$ cm^{-3}) GaAs cap layer.

Gain-guided lasers with widths of 20, 40, 60, 80, and 100 µm were fabricated for laser material characterization. The p-ohmic metal of Ti:Pt:Au was evaporated and annealed and then the p^+ cap was etched back. The substrate was lapped to a thickness of ~85 µm and an n-ohmic of Ni:Ge:Au:Ni:Au was evaporated and annealed. The laser bars were cleaved to cavity lengths from 200 µm to 800 µm and soldered onto gold plated copper submounts with a Au-Sn eutectic solder with a melting point of 280° C.

Single-mode ridge-waveguide high-speed lasers (shown in Figure 1) with 1, 2, 3, 4, and 5 µm wide stripes were then fabricated.[4] The p-ohmic metal was evaporated and annealed. The 40 µm wide trench was isotropically etched through the quantum well into the n-doped buffer layer and the n-ohmic contact metal was evaporated and annealed. The most critical step was to dry etch the 5 µm wide, 10,500 Å to 12,500 Å trench about each side of the p-ohmic metal laser stripes. This trench provided current confinement and optical confinement in the lateral direction. The structure was insulated with 2,500 Å of Si_3N_4, and gold plated testing pads were fabricated for use with high-speed cascade probes. The wafer was lapped to ~85 µm and metal was evaporated onto the backside of the wafer. The sample was cleaved into 200, 250, and 300 µm cavity length laser bars and mounted onto gold plated copper submounts with a Au-Sn eutectic solder.

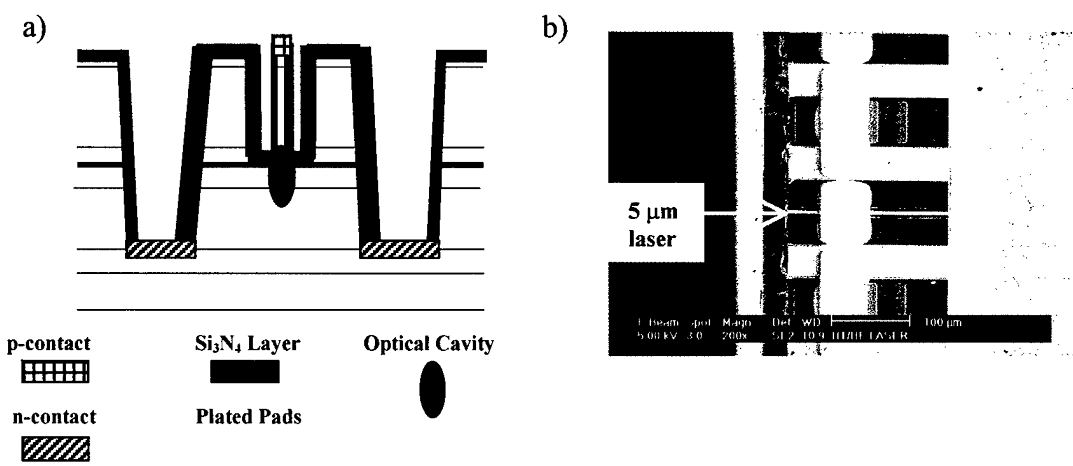

Figure 1: a) Schematic illustrating the layer structure and device structure for the ridge-waveguide laser. b) SEM micrograph of a 5 µm laser device with the gold plated cascade probable ground-signal-ground contact pads soldered onto a gold-plated copper submount.

4. Laser and Small-Signal Characterization

Temperature-dependent pulsed (pulse width = 5 μs & pulse interval = 100 μs) light-output power versus injected current (L-I) characterization was performed on ~400 μm long single-quantum well devices, as shown in Figure 2a, and four-quantum well devices, shown in Figure 2b. For the single quantum well device with dimensions of 20 μm by 385 μm room temperature threshold was ~50 mA with laser operation up to 140° C with a threshold current of ~240 mA. For the four quantum well device with similar dimensions of 20 μm by 380 μm room temperature threshold was ~35 mA and laser operation up to 240° C was measured with a threshold current of ~360 mA.

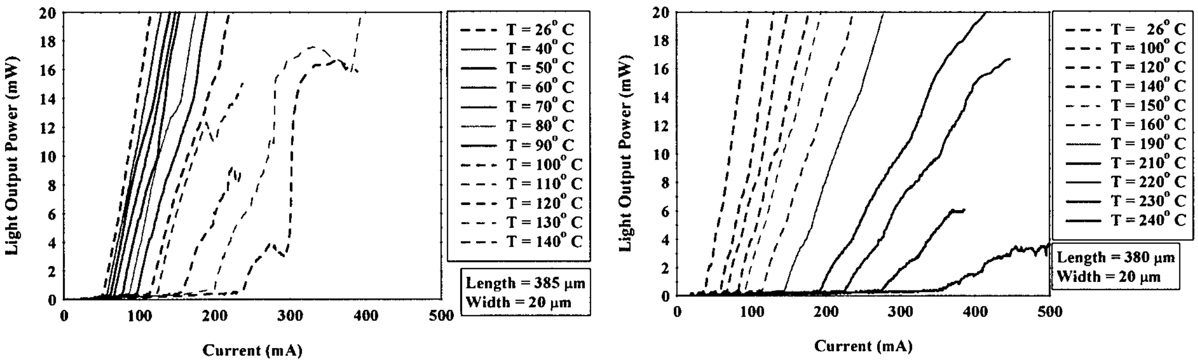

Figure 2: Temperature dependent pulsed (pulse width = 5 μs and pulse interval = 100 μs) light output power versus injected current for a) single quantum well laser device and b) four quantum well laser device.

The 2 μm wide by ~250 μm long ridge-waveguide lasers operated in CW current mode up to temperatures of 90° C for single quantum well devices and up to 150° C for multiple quantum well devices[5], as shown in Figures 3a and 3b, respectively. The single quantum well lasers exhibited a -3 dB frequency response ~7 GHz for room-temperature operation and >3 GHz at 90° C, as shown in Figure 4a. The four quantum well laser device had a -3 dB frequency response of ~14 GHz for room-temperature operation and ~5 GHz at 150° C, as shown in Figure 4b.

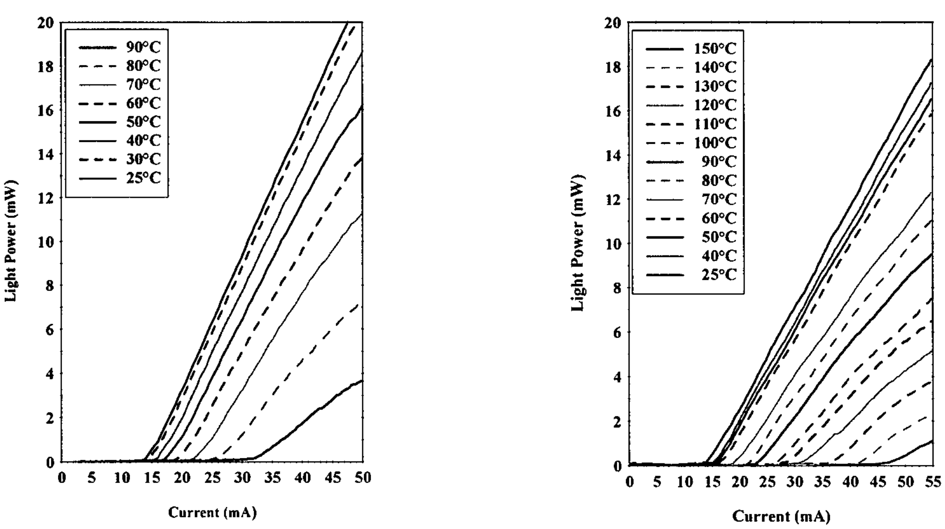

Figure 3: Temperature dependent CW light output power versus injected current for laser devices with dimensions on the order of 2 μm by 250 μm with a) single quantum well and b) four quantum well.

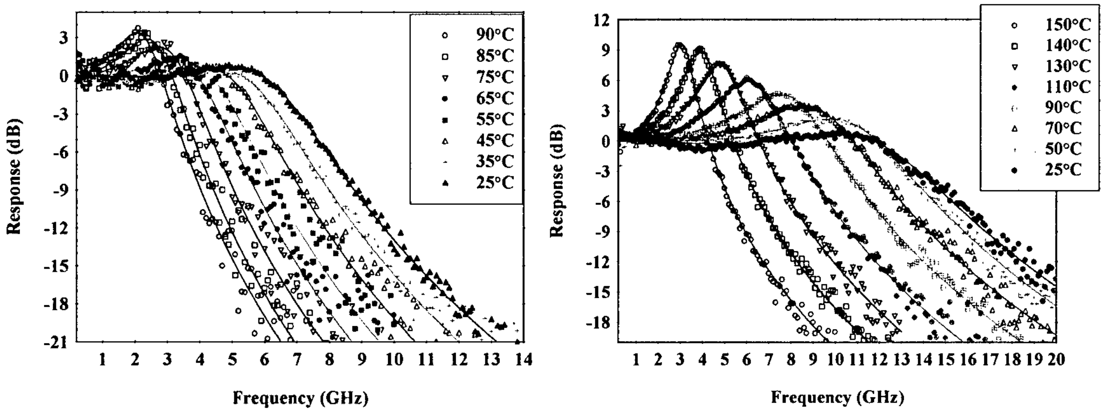

Figure 4: Temperature dependent frequency response for 2 μm by 250 μm laser device with a) single quantum well and b) four quantum well.

5. Conclusions

InGaAs quantum well devices offer excellent transmitter capability for local area networks required to operate in extreme temperature environments. High-frequency high-temperature InGaAs quantum well lasers have been demonstrated to operate up to temperatures of 150° C. The four quantum well devices performed significantly better than the single quantum well devices in both high-temperature operation as well as high-frequency operation. Increased capability can be achieved by increasing the indium content of the quantum wells, facet coating, and mounting the devices epi-side down for improved heat dissipation in the junction. Future directions include developing devices more compatible with the telecommunication wavelengths of 1.3 μm and 1.55 μm. Dilute nitride quantum wells have shown promise to achieve GaAs-based 1.3 μm laser operation. Another area to improve the efficiency of the devices would be to introduce tunnel junctions into the devices in-between separate multiple active regions. This monolithically connects a number of lasers in series thereby increasing the output power while keeping the threshold current relatively the same as for one active region device.

References

[1] P. L. Derry, R. J. Fu, C. S. Hong, E. Y. Chan, and L. Figueroa, *"Analysis of the high temperature characteristics of InGaAs-AlGaAs strained quantum-well lasers,"* IEEE J. Quantum Electron., **(28)**, no. 12, pp.2698-2705, 1992.

[2] S. Weisser, I. Esquivias, P. J. Tasker, J. D. Ralston, and J. Rosenzweig, *"Impedance, modulation response, and equivalent circuit of ultra-high-speed $In_{0.35}Ga_{0.65}As/GaAs$ MQW lasers with p-doping,"* IEEE Photon. Technol. Lett., **(6)**, no. 7, pp. 782-785, 1994.

[3] K. Czotscher, E. C. Larkins, S. Weisser, W. Benz, J. Daleiden, J. Fleissner, M. Maier, J. D. Ralston, and J. Rossenzweig, *"Uncooled high-temperature (130 °C) operation of InGaAs-GaAs multiple quantum-well lasers at 20 Gb/s,"* IEEE Photon. Technol. Lett., **(9)**, no. 5, pp. 575-577, 1997.

[4] W. J. Siskaninetz, *"Thesis: Net modal gain analysis of high-frequency $In_{0.20}Ga_{0.80}As$ semiconductor lasers operating at high temperatures,"* University of Dayton, Dayton, OH, 1998.

[5] H. D. Jackson *"Thesis: Small-signal frequency response characterization of single and multiple quantum well $In_{0.20}Ga_{0.80}As$ semiconductor lasers operating at high temperature,"* University of Dayton, Dayton, OH, 2001.