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FINAL REPORT

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Final Report for JSEP Fellowship
(May 1991 - December 1992)

The graduate work of Thomas J. Rogers culminated in the successful completion of the requirements for a Ph.D., with a graduation date of December 1992, after his submission of the dissertation entitled "MBE Grown Microcavities for Optoelectronic Devices." In the dissertation work,[1] the precision of molecular-beam epitaxy (MBE) is taken advantage of in order to grow semiconductor reflectors, microcavities, and quantum wells for studies of vertical-cavity surface-emitting lasers (VCSELs) and the coupling between reflectors and the spatially localized dipoles of semiconductor quantum wells. The design of the structures and the choice of epitaxial growth parameters used for the structures are discussed in detail. Experimental techniques and results are discussed which relate to studies that advance the optoelectronics technology and our understanding of fundamental physics.

MBE is used to grow epitaxial structures in which a QW is precisely placed either in close proximity to a DBR,[2] or near the surface of the epitaxial layer,[3] so that a highly reflective mirror can be placed in close proximity to the QW. These structures are incorporated into studies of the rather unique effects resulting from the electrodynamics that occur when localized dipoles emit spontaneously within a coherence length of a reflector. The results of photoluminescence and electroluminescence measurements demonstrate that the coupling between the QW and reflector modifies the wavelength spectrum, intensity, spatial emission pattern, and total radiation rate for these devices. Proper placement of the mirror with respect to the QW results in a light-emitting diode (LED) with a narrow spectral linewidth, high intensity normal to the surface, and high directivity as compared to an LED without the reflector. In addition, it has been proposed that the coupling between the reflectors and the active region is important in VCSEL structures that have very short optical cavities.[4-7]

Quarter-wave stack AlAs/GaAs distributed Bragg Reflectors (DBRs) are epitaxially grown above and below an InGaAs/GaAs quantum well (QW) active region to form an optical cavity with the QW optical emission source within. This structure is fabricated into VCSEL diodes, devices that are of considerable technological importance due to advantages that are inherent to their geometry, including a wide mode spacing, potential for ultra-low threshold currents, a narrow, symmetric beam divergence, and

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compatibility with optoelectronic integration. The particular challenges that such experiments present to the MBE crystal growth technology are discussed, and unique abilities of MBE such as epitaxial growth of thin, highly resistive layers are applied to the advancement of VCSEL technology.

VCSEL diodes that incorporate MBE regrowth over patterned current-blocking layers within the *p*-type DBR above the laser active region have been designed, fabricated, and characterized. Both *pnpn* structures and semi-insulating, low-temperature grown (LT) AlGaAs layers are investigated for current blocking in these structures. Because of the lateral current injection employed in this structure, light is efficiently coupled from the top of the wafer, and the current funneling scheme results in a low series resistance. VCSEL devices containing the *pnpn* structure for lateral current confinement exhibit low current thresholds and high efficiency.[8,9] These devices also exhibit a hysteresis,[10-12] which can be taken advantage of for optoelectronic switching applications.[13,14]

It is demonstrated that layers of LT-AlGaAs as thin as 1000 Å are highly resistive for a bias below ~8 V and can be incorporated into surface-normal optoelectronic devices for lateral current definition. Lateral current confinement is demonstrated for both surface-emitting LEDs and VCSEL diodes, through the use of MBE regrowth over a patterned layer of LT-AlGaAs.[15] The VCSEL diodes incorporating the LT-AlGaAs for lateral current confinement[15-17] exhibit low current thresholds, high efficiency, and a voltage at continuous-wave room-temperature lasing threshold that is comparable to the lowest previously reported for pulsed operation. The performance of these lasers is largely due to a design that has inherently low series resistance, the avoidance of thermal expansion mismatches with materials near the active region, and an all-epitaxial current confinement structure with good heat sinking capabilities. This structure may also be promising for optoelectronic integration, for devices could be fabricated above the LT-AlGaAs layer that would be electrically isolated from the VCSEL active region.

The following publications, conference presentations, and a patent relate to the work discussed above and in the dissertation.

*1. T. J. Rogers, "MBE Grown Microcavities for Optoelectronic Devices," Ph.D. Dissertation, The University of Texas at Austin, December, 1992.

2. T. J. Rogers, D. G. Deppe, and B. G. Streetman, "Effect of an AlAs/GaAs Mirror on the Spontaneous Emission of an InGaAs-GaAs Quantum Well," *Appl. Phys. Lett.* 57, pp. 1858-1860 (29 October, 1990).

3. D. G. Deppe, J. C. Campbell, R. Kuchibhotla, T. J. Rogers, and B. G.Streetman, "Optically Coupled Mirror-Quantum Well InGaAs-GaAs Light Emitting Diode," *Electron. Lett.* 26, pp. 1665-1666 (27 September, 1990).

4. D. G. Deppe and T. J. Rogers, "Quantum Well Device With Control of Spontaneous Photon Emission, and Method of Manufacturing Same," U.S. Patent No. 5,089,860 (18 February, 1992).

5. D. G. Deppe, T. J. Rogers, and B. G. Streetman, "Gain Mechanism of the Vertical-Cavity Surface-Emitting Laser," 48th Annual Device Research Conference, Santa Barbara, June 26-28, 1990, post-deadline paper VB-3.

*6. D. G. Deppe, C. Lei, T. J. Rogers, and B. G. Streetman, "Semiconductor Microcavity Effect on Spontaneous Emission," *Proceedings of the Joint U.S.-Soviet Workshop on Semiconductor Lasers*, Leningrad, May 19-26, 1991.

*7. D. L. Huffaker, D. G. Deppe, C. J. Pinzone, T. J. Rogers, B. G. Streetman, and R. D. Dupuis, "Threshold Dependence on Cavity Length and Mirror Rreflectivity in Fabry-Perot Microcavity Semiconductor Lasers with High Contrast Mirrors," submitted to Quantum Optoelectronics Topical Meeting, March 17-19, 1993, Palm Springs.

8. C. Lei, T. J. Rogers, D. G. Deppe, and B. G. Streetman, "InGaAs-GaAs Quantum Well Vertical-Cavity Surface-Emitting Laser Using Molecular Beam Epitaxial Regrowth," *Appl. Phys. Lett.* 58, pp. 1122-1124 (18 March 1991).

*9. C. Lei, T. J. Rogers, D. G. Deppe, and B. G. Streetman, "ZnSe/CaF_2 Quarter-Wave Bragg Reflector for the Vertical-Cavity Surface-Emitting Laser," *J. Appl. Phys.* 69, pp. 7430-7434 (1 June, 1991).

*10. D. G. Deppe, C. Lei, W. D. Lee, T. J. Rogers, J. C. Campbell, and B. G. Streetman, "Bistability and Optical Switching in an AlGaAs-GaAs-InGaAs Vertical-Cavity Surface-emitting Laser," 49th Annual Device Research Conference, Boulder, June 17-19, 1991, paper IIIA-4.

*11. D. G. Deppe, C. Lei, T. J. Rogers, and B. G. Streetman, "Bistability in an AlAs-GaAs-InGaAs Vertical-Cavity Surface-Emitting Laser," *Appl. Phys. Lett.* 58, pp. 2616-2618 (10 June, 1991).

*12. D. G. Deppe, D. L. Huffaker, T. J. Rogers, C. Lei, Z. Huang, and B. G. Streetman, "First-Order Phase Transition in a Laser Threshold," *Appl. Phys. Lett.* 60, pp. 3081-3083 (22 June, 1992).

*13. D. L. Huffaker, W. D. Lee, D. G. Deppe, C. Lei, T. J. Rogers, J. C. Campbell, and B. G. Streetman, "Optical Memory Using a Vertical-Cavity Surface-emitting Laser," *IEEE Photon. Tech. Lett.* 3, pp. 1064-1066 (Dec. 1991).

*14. D. L. Huffaker, D. G. Deppe, C. Lei, T. J. Rogers, B. G. Streetman, S. C. Smith, and R. D. Burnham, "Cascadability of an Optically Latching Vertical-Cavity Surface-Emitting Laser," *Electron. Lett.* 28, pp. 734-736 (9 April, 1992).

*15. T. J. Rogers, C. Lei, B. G. Streetman, and D. G. Deppe, "Low Growth Temperature AlGaAs Current blocking Layers For Surface Normal

Optoelectronic Devices," North American Conference on Molecular Beam Epitaxy, Ottawa, Canada, October 12-14, 1992, to be published in *J. Vac. Sci. Technol. B*.

*16. T. J. Rogers, C. Lei, D. G. Deppe, and B. G. Streetman, "Low Threshold Voltage CW Vertical-Cavity Surface-Emitting Lasers," submitted to *Appl. Phys. Lett.* for publication.

*17. C. Lei, T. J. Rogers, D. G. Deppe, and B. G. Streetman, "Low-Threshold-Voltage CW Vertical-Cavity Surface-Emitting Lasers Based on Low Growth Temperature Current Blocking Layer," submitted to IEEE/LEOS Annual Meeting, November 15-20, Boston.

* Work completed during the period of the JSEP fellowship.