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RESEARCH PERFORMED UNDER ONR CONTRACT NO. N00014-91-J-1952

June 1, 1991 - May 31, 1994

P.I.: Dennis G. Deppe

AD-A280 389

The research performed under this contract centers around the study and development of semiconductor microcavity lasers in the GaAs/AlGaAs/InGaAs material system. In addition, theoretical modeling is developed to study the influence of small cavities on laser performance. In the course of this work we have developed and studied bistable vertical-cavity surface-emitting lasers (VCSELs) [1,5,6 of publications below], fabrication processes to realize low-threshold microcavity lasers [14,19,20], and detailed modeling describing the influence which the semiconductor microcavity exerts over the spontaneous emission and lasing characteristics [2-4,7-13,15-17]. I believe that our best and most interesting results have been achieved in our last year of funding. Since they build heavily on our earlier two years of research I will focus this final report on these results achieved in the final year.

Because of the VCSEL's vertical geometry, it appears ideally suited for applications involving high-speed integrated optoelectronics. There are important features unique to the VCSEL as compared to other forms of semiconductor lasers. The very short cavity length (several optical wavelengths long) selects a single longitudinal mode, and the vertical cavity allows wafer scale testing and easy monolithic integration with other devices. Also, the vertical cavity gives the potential to minimize both the optical mode volume as well as the gain volume. This ability to minimize the active volume of the VCSEL suggests that when optimized, this device structure will provide the lowest threshold current of any semiconductor laser. A reasonable estimate of the achievable minimum threshold current for a single 2μm diameter lasing spot is ~10μA (current density of ~300A/cm^2). Such low threshold currents point to the potential impact which the VCSEL can make in complex optoelectronic circuitry requiring a high degree of optical functionality, and to the use of the VCSEL in battery driven applications.

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Our research has sought to make such low values of threshold currents a reality through studies of the cavity influence on lasing in such microcavities, and in the development of novel processing techniques to efficiently pump such small laser structures. The cavity mirrors play a central role in the VCSEL in defining the lasing mode both spectrally and transversely, which is different than the longer edge-emitting lasers. Both our experimental and theoretical studies show the importance of high contrast Bragg reflectors in reducing the lasing threshold of planar VCSELs due to lateral optical mode confinement [18,20]. In direct comparison of photopumped Fabry-Perot microcavities having either low contrast AlAs/GaAs DBRs or the higher contrast ZnSe/CaF DBRs we show that the higher contrast ZnSe/CaF materials allow for significant reduction of lasing threshold (greater than a factor of ten) over the same range of active region dimensions in which the threshold remains fixed for the AlAs/GaAs DBRs [18]. We have studied the important role of the cavity reflectors in setting the transverse mode theoretically also, by developing the theory of the self-consistent lasing modes in planar microcavities directly from Maxwell's equations. Our theoretical work has also focused on a fully quantum mechanical theory of the lasing characteristics of microcavities. A main emphasis of this work is in understanding how the small cavity affects both the spontaneous emission rate and the stimulated emission rate into the lasing mode, and we now have the quantum theory for spontaneous emission into the lasing we believe fully calculated. Our recent yet

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unpublished theoretical effort in understanding both the stimulated emission dependence and the lasing mode photon lifetime dependence of the cavity have recently met with success also, and we hope to publish the full quantum theory of such laser structures in this summer of 1994.

In the course of the three years of experimental work on current driven VCSELs we have made several demonstrations of VCSEL performance improvements which play an important role in our most recent work. One significant achievement is the development of the ZnSe/CaF mirror system. This allows us great flexibility is designing the VCSEL for low threshold operation. Recently we have combined this mirror system with a new process for current confinement in a VCSEL [20]. The current confinement is based on a novel native oxide process developed at the University of Illinois in the group of Prof. N. Holonyak. In this process high Al composition AlGaAs is converted to a native AlxOy using a "wet" oxidation process. The oxidation is performed in the 450°C to 500°C temperature range, and proceeds selectively in the AlGaAs relative to GaAs. That is, only the AlGaAs is oxidized, while the GaAs remains intact. We use the process to form a novel buried oxide ring contact to the VCSEL. Based on this native oxide process, we have recently demonstrated VCSELs with continuous wave room temperature threshold currents of 225μA on 8μm square active region devices. To our knowledge this is the lowest threshold current yet achieved anywhere on a VCSEL. We have also demonstrated smaller device active regions of 4 and 2μm, but these have shown some increase in leakage currents, and accordingly higher thresholds. From our theoretical and experimental studies on transverse modes in planar microcavities, it would appear that 2μm diameter active regions should provide adequate optical confinement so that threshold currents could scale with device area. Based on the 225μA for the 8μm devices, a threshold current of 14μA may be speculated for a 2μm device.

Our future studies will be in studying the lasing modes in semiconductor microcavities, both theoretically and experimentally. We expect the native oxide processing we have demonstrated to play a central role in the experiments. We will continue to focus on the important role of the Bragg reflecting mirrors, and ways to further increase contrast ratios over that presently used.

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Bureau of Engineering Research

June 9, 1994

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Alexandria, Virginia 22304-6145

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Dear Sir,

Please find enclosed the reporting information for the ONR contract No. N00014-91-J-1952. Enclosed is a letter report and publication report for the period of May 31, 1991 through June 1, 1994 and a latest preprint to be published in Applied Physics Letters in July of 1994 describing our latest experimental results on semiconductor vertical-cavity lasers. Also included is a report for the last year of funding from May 31, 1993 through June 1, 1994. If I can supply more information on the work performed under this contract please let me know. The ONR support of our work in this time period has been crucial to our accomplishments in the area of semiconductor lasers.

Best regards,

Dennis Deppe

FINAL REPORT

OFFICE OF NAVAL RESEARCH

PUBLICATIONS / PATENTS / PRESENTATIONS / HONORS REPORT

for

31 May 91 through 1 June 94

R&T Number:
Contract / Grant Number: N00014-91-J-1952
Contract / Grant Title: Bistable Vertical-Cavity Surface-Emitting Laser Structures on GaAs and Si Substrates
Principal Investigator: Prof. Dennis G. Deppe
Mailing Address: Prof. D.G. Deppe
Microelectronics Research Center
The University of Texas at Austin
Balcones Research Center, MER 1.606/79900
Austin, Texas 78712-1084
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E-Mail Address: deppe@falcon.ece.utexas.edu

a. Number of Papers Submitted to Refereed Journals but not yet published: 2

b. Number of Papers Published in Refereed Journals: 18
(list attached)

c. Number of Books or Chapters Submitted but not yet Published: 0

d. Number of Books or Chapters Published: 0

e. Number of Printed Technical Report & Non-Refereed Papers: 0

f. Number of Patents Filed: 0

g. Number of Patents Granted: 0

h. Number of Invited Presentations at Workshops or Prof. Society Meetings: 3

i. Number of Presentations at Workshops or Prof. Society Meetings: 3

j. Honors / Awards / Prizes for Contract / Grant Employees: D.G. Deppe - Robert and Jane Mitchell Endowed Faculty Fellowship in Engineering The University of Texas at Austin - 1992 /1994

k. Total number of Graduate Students and Post-Docs Supported at least 25% on this contract grant:

Graduate Students 4 (50%) and Post Docs 0

[Grad Student Female 1

[Grad Student Minority 0

[Grad Student Asian e/n 2

[Post-Doc Female 0

[Post-Doc Minority 0

[Post-Doc Asian e/n 0

PUBLICATIONS UNDER ONR SUPPORT - 5/31/91 - 6/1/94

1. 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, 1064-1066 (December, 1991).

2. D.G. Deppe and C. Lei, "Spontaneous Emission and Optical Gain in a Fabry-Perot Microcavity," Appl. Phys. Lett. 60, 527-529 (3 February, 1992).

3. D.G. Deppe and C. Lei, "Electrodynamics and Controlled Spontaneous Emission in Microcavity Semiconductor Lasers," IEEE IEDM Tec. Dig., Dec. 8-11, 1991, Washington.

4. C. Lei and D.G. Deppe, "Optical Gain Enhancement in Fabry-Perot Microcavity Lasers," J. Appl. Phys. 71, 2530-2535 (15 March, 1992).

5. 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, 3081-3083 (22 June, 1992).

6. 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, 734-736 (9 April, 1992).

7. D.L. Huffaker, C. Lei, D.G. Deppe, C.J. Pinzone, J.G. Neff, and R.D. Dupuis, "Controlled Spontaneous Emission in Room Temperature Semiconductor Microcavities," Appl. Phys. Lett. 60, 3203-3205 (29 June, 1992).

8. D.L. Huffaker, Z. Huang, C. Lei, D.G. Deppe, C.J. Pinzone, J.G. Neff, and R.D. Dupuis, "Effect on Spontaneous Emission of Quantum Well Placement in a Short Vertical Cavity," Appl. Phys. Lett. 61, 877-879 (24 August, 1992).

9. C. Lei, C.J. Pinzone, Z. Huang, D.L. Huffaker, D.G. Deppe, J.G. Neff, and R.D. Dupuis, "Room Temperature Spontaneous Emission in 5μm Long AlGaAs Vertical Cavities," J. Appl. Phys. 73, 3153-3157 (1 April, 1993).

10. Z. Huang, C. Lei, D.G. Deppe, C.C. Lin, C.J. Pinzone, and R.D. Dupuis, "Spectral and Intensity Dependence on Dipole Localization in Fabry-Perot Cavities", Appl. Phys. Lett. 61, 2961-2963 (21 December, 1992).

11. C. Lei, D.G. Deppe, Z. Huang, and C.C. Lin, "Emission Characteristics From Dipoles with Fixed Positions in Fabry-Perot Cavities," IEEE J. Quant. Electron. 29, 1383-1386 (May 1993).

12. C. Lei, Z. Huang, D.G. Deppe, C.J. Pinzone, and R.D. Dupuis, "Spectral Interference Effects in the Light Emission from Fabry-Perot Cavities," J. Appl. Phys. 73, 2700-2704 (15 March, 1993).

13. Z. Huang, C.C. Lin, and D.G. Deppe, "Spontaneous Lifetime and Quantum Efficiency From Light Emitting Diodes Affected by a Close Metal Mirror," IEEE J. Quant. Electron. 29, 2940-2949 (December 1993).

14. D.G. Deppe, D.L. Huffaker, and C. Lei, "Performance Issues Related to Dielectric Stack Reflectors in Vertical-Cavity Surface-Emitting Lasers," SPIE Proceedings on International Symposia on Optoelectronics Packaging and Interconnects, January 20-21, 1993, Los Angeles, Vol. 1851, pp. 128-137.

15. D.G. Deppe, C. Lei, D.L. Huffaker, and C.C. Lin, "Spontaneous Emission From Planar Microstructures," J. Mod. Optics. 41, 325-344 (February 1994).

16. C.C. Lin, D.G. Deppe, and C. Lei, "Role of Waveguide Light Emission in Planar Microcavities," IEEE J. Quant. Electron. 30, (October, 1994) to be published.

17. C.C. Lin and D.G. Deppe, "Calculation of Lifetime Dependence on Cavity Length of Er3+ in Half-Wave and Full-Wave Microcavities," J. Appl. Phys. 75, 4668-4672 (1 May, 1994).

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19. C.C. Hansing, H.Y. Deng, D.L. Huffaker, D.G. Deppe, B.G. Streetman, and J. Sarathy, "Low-Threshold Continuous-Wave Surface Emitting Lasers with Etched Void Confinement," IEEE Photon. Tech. Lett. 6, 320-322 (March 1994).

20. D.L. Huffaker, D.G. Deppe, K. Kumar, and T.J. Rogers, "Native-Oxide Defined Buried Ring Contact for Low Threshold Vertical-Cavity Lasers," Appl. Phys. Lett. 65, (July 1994) to be published.

CONFERENCE PRESENTATIONS

1. D.G. Deppe, D.L. Huffaker, 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, June 17-19, 1991, Boulder, paper IIIA4.

2. (Invited) D.G. Deppe and C. Lei, "Electrodynamics and Controlled Spontaneous Emission in Microcavity Semiconductor Lasers," International Electron Devices Meeting, Dec. 8-11, 1991, Washington, D.C.

3. D.G. Deppe, D.L. Huffaker, C. Lei, C.J. Pinzone, J.G. Neff, and R.D. Dupuis, "Controlled Spontaneous Emission in Room Temperature Microcavities," WOCSEMAD, Feb. 17-19, 1992, San Antonio.

4. (Invited) D.G. Deppe, C. Lei, D.L. Huffaker, Z. Huang, C.C. Lin, "Spontaneous Emission in Semiconductor Microcavities", Rank Prize Fund Minisymposium, September 21-24, 1992, Grasmere, England.

5. C. Lei, T.J. Rogers, D.G. Deppe, B.G. Streetman, "Low-Threshold-Voltage CW Vertical-Cavity Surface-Emitting Lasers Based on Low Growth Temperature Current Blocking Layer," IEEE/LEOS Annual Meeting, November 15-20, 1992, Boston, Post-Deadline Paper PD4.

6. C. Lei, D.G. Deppe, Z. Huang, C.C. Lin, C.J. Pinzone, and R.D. Dupuis, "Spontaneous Emission Characteristics from Dipoles with Fixed Positions in Fabry-Perot Cavities," 15th International Conference on Lasers & Applications, Dec. 7-11, 1992, Houston.

7. (Invited) D.G. Deppe, "Performance Issues Related to Dielectric Stack Reflectors for Vertical-Cavity Surface-Emitting Lasers", SPIE International Symposia on Optoelectronic Packaging and Interconnects, January 16-23, 1993, Los Angeles, Paper 1853.

8. 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 Reflectivity in Fabry-Perot Microcavity Semiconductor Lasers with High Contrast Mirrors", Quantum Optoelectronics Topical Meeting, March 17-19, 1993, Palm Springs, Paper QWA4.

9. (Invited) D.G. Deppe, "Electrodynamics in Semiconductor Microcavity Lasers", Workshop on Optical Properties of Mesoscopic Semiconductor Structures, April 20-23, 1993, Snowbird, Utah.

10. C.C. Hansing, H. Deng, J.M. Reifsnider, D.G. Deppe, and B.G. Streetman, "MBE Regrowth Over a Selectively Undercut GaAs Masking Layer," Materials Research Society Spring Meeting, 1994, San Francisco.

11. D.G. Deppe, D.L. Huffaker, C.C. Lin, and T.J. Rogers, "Nearly Planar Low Threshold Vertical-Cavity Surface-Emitting Lasers Using High Contrast Mirrors and Native Oxide," Conference on Lasers and Electro-Optics, May 8-13, 1994, Ananheim, late paper.

12. D.L. Huffaker, D.G. Deppe, K. Kumar, and T.J. Rogers, "Native Oxide Defined Ring Contact for the Vertical-Cavity Surface-Emitting Laser, 52nd Device Research Conference, June 20-22, 1994, Boulder.

Native-oxide defined ring contact for low threshold vertical-cavity lasers

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(Received 4 February 1994; accepted for publication 1 April 1994)

Data are presented characterizing a new process for fabrication of vertical-cavity surface-emitting lasers based on the selective conversion of high Al composition epitaxial AlGaAs to a stable native oxide using "wet oxidation." The native oxide is used to form a ring contact to the laser active region. The resulting laser active regions have dimensions of 8, 4, and 2 μm. The lowest threshold laser is achieved with the 8-μm active region, with a minimum threshold current of 225-μA continuous wave at room temperature.

It is well appreciated that high Al composition single-crystal AlGaAs is chemically unstable in the typical room-temperature atmospheric environment, and "hydrolyzes" into various oxides in times ranging from minutes to months or years.[1] This chemical instability can be deleterious to the performance of semiconductor devices which use the AlGaAs material. On the other hand, Holonyak and a variety of co-workers have developed a process whereby at elevated temperatures the chemical instability of high Al composition AlGaAs leads to the conversion of this material to stable "native" oxides of Al_xO_y.[2–5] An advantage of the oxidation process for III-V devices is that the high Al composition AlGaAs may be selectively oxidized as compared to lower Al composition AlGaAs, especially as compared to GaAs. This selectivity makes it possible to "bury" the oxidized layers, using lateral diffusion, below single-crystal GaAs layers.[3–5] We use this characteristic to form a ring contact to a vertical-cavity surface-emitting laser (VCSEL).

One of the attractive features about the VCSEL is its potential for low lasing threshold. This potential stems directly from the ability to minimize the active volume using the short, low-loss vertical cavity. The potential for low threshold current, along with single spectral mode lasing, good beam characteristics, and surface normal emission, makes the VCSEL an important device to consider for integrated optoelectronic applications. Earlier work has already been reported in which submilliampere threshold currents were achieved,[6,7] and more recently room-temperature continuous wave (cw) thresholds as low as 470 μA have been reported.[8] In this letter we report even lower threshold currents for devices which utilize the native-oxide process, with a minimum threshold current of 225 μA demonstrated for an 8-μm square device.

Figure 1 shows a schematic cross section representing the epitaxial layers of the VCSEL after oxidation. The epitaxial structure is grown on a GaAs substrate by molecular beam epitaxy (MBE) and consists of a 0.5-μm n-type GaAs buffer layer followed by a 26 pair, n-type AlAs/GaAs quarter-wave distributed Bragg reflector, an active region consisting of three 60-Å $In_{0.2}Ga_{0.8}As$ quantum wells separated by 100-Å GaAs barriers in a one-wavelength-thick GaAs spacer layer, and followed by one pair of quarter-wavelength layers of p-type AlAs/GaAs. A seven-period graded superlattice is used on both sides of the AlAs layers immediately surrounding the active region, which is effective in reducing the electrical series resistance.

After the MBE growth of the heterostructure, the lasers are fabricated by first defining 30- or 60-μm-diam photoresist dots on the p-type GaAs surface. The exposed p-type GaAs layer is then selectively removed to form shallow GaAs mesas using a succinic acid solution maintained at a temperature of 50 °C with the pH adjusted to 4.3.[9] After removing the photoresist from the GaAs mesas, the exposed AlAs layer is oxidized in a furnace set at 475 °C. The oxidation time is ~3 min. As described in the initial papers on the hydrolyzation process,[2–5] the furnace is supplied with a flow of N_2 bubbled through de-ionized water heated to a temperature of 95 °C. The oxidation of the AlAs layer proceeds laterally beneath the GaAs mesas due to diffusion. This buried oxide layer then defines a current path for carrier injection through the remaining intact p-type AlAs into the laser active region (see Fig. 1).

Figure 2 shows a scanning electron microscope photograph looking down at the top surface of the epitaxial structure after oxidation. The buried oxide shown in Fig. 2 forms a 4 μm×4 μm square region which serves as the current injection path. The square pattern formed by oxidation is indicative that the process has a crystallographic preference. From our studies of other heterostructures we have found that the resulting square geometry due to the oxidation is directly attributable to the graded superlattice layers grown

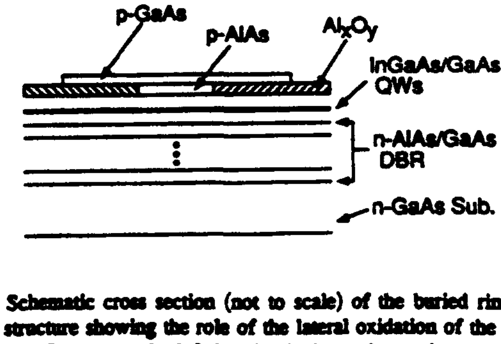

FIG. 1. Schematic cross section (not to scale) of the buried ring contact VCSEL structure showing the role of the lateral oxidation of the AlAs underneath the GaAs mesa in defining the device active region.

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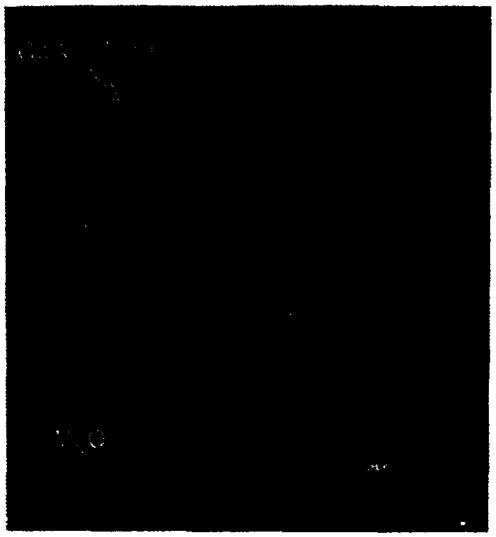

FIG. 2. Scanning electron microscope photograph of a native-oxide defined 4-μm square AlAs region buried beneath a 30-μm-diam GaAs mesa. The oxide layer surrounding and beneath the GaAs mesa provides device isolation for current injection.

during MBE between the GaAs and AlAs. A circular dot shape results even for submicron dimensions for the lateral oxidation of very similar heterostructures in which the graded interfaces are absent.

The 30-μm GaAs mesas are defined with 500-μm spacings, and electrical isolation between the laser devices is also provided by the exposed Al_xO_y layer. Electrical contact is made to the *p*-type GaAs surface and exposed Al_xO_y using Cr/Au metallization. The active areas of the laser are exposed using a lift-off process to remove metallization, forming a 10-μm-diam opening above the active region. The lift-off leaves 100 μm×400 μm rectangular contact pads around each device aligned on the 500 μm×500 μm grid. The top reflectors,which are an additional five pairs of quarter-wave $ZnSe/CaF_2$ layers, are then deposited on the *p* side using electron-beam evaporation. The $ZnSe/CaF_2$ materials have been shown to form high reflectivity, low-loss mirrors,[10,11] and possess advantages over the lower contrast AlAs/GaAs mirrors. Two advantages are the flexibility of probe wavelengths in optical addressing schemes,[12,13] and the reduction of the lateral mode for small active volume lasers.[14]

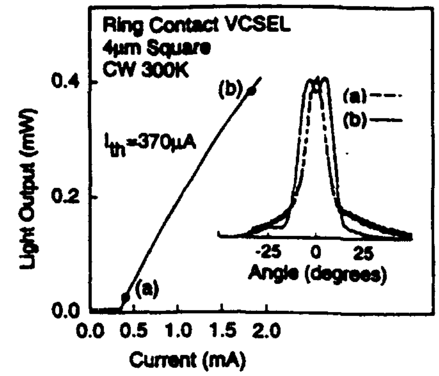

FIG. 4. Light vs current curve measured cw at room temperature for a 4-μm square VCSEL. The inset shows measured far-field radiation patterns at current levels of (a) 400 μA (dashed curve) and (b) 2.0 mA (solid curve).

Figures 3 through 5 show the light versus current characteristics and far-field radiation patterns for the native-oxide defined lasers with active regions of 8-, 4-, and 2-μm squares, respectively. The lowest threshold currents are achieved for 8-μm square devices, with a minimum cw threshold of 225 μA along with an output power of 0.46 mW at six times threshold (Fig. 3). The far-field radiation pattern remains a stable single lobe up to two times threshold, at which point side lobes appear. Also shown in Fig. 3 is the far-field radiation pattern at four times threshold with the side lobes evident.

Despite the low threshold current achieved in the 8-μm device, there is some leakage current due to the oxidation process which degrades the *p-n* junction. We speculate that this leakage current is stress induced by the oxide, and the problem becomes more severe for smaller device sizes. This leakage current is at least partly responsible for the increased threshold currents measured for the smaller active regions of 4 μm (Fig. 4) and 2 μm (Fig. 5). Comparison of the current-voltage characteristics on the three different device sizes show increasing forward current for a given voltage as the device diameter is decreased (data not shown). We have

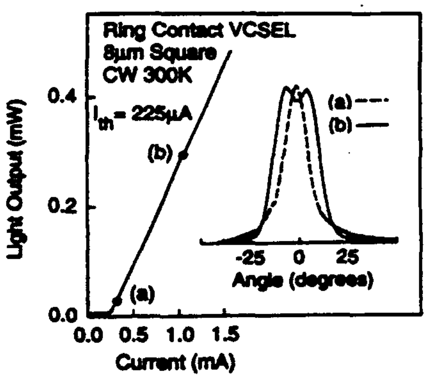

FIG. 3. Light vs current curve measured cw at room temperature for an 8-μm square VCSEL. The inset shows measured far-field radiation patterns at current levels of (a) 280 μA (dashed curve) and (b) 1.0 mA (solid curve).

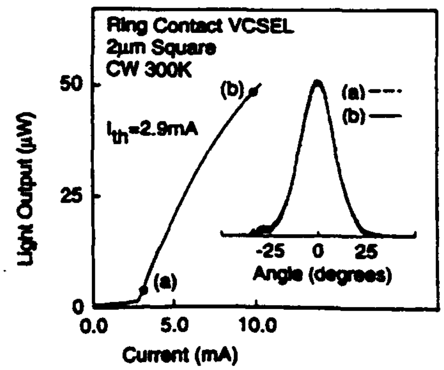

FIG. 5. Light vs current curve measured cw at room temperature for a 2-μm square VCSEL. The inset shows measured far-field radiation patterns at current levels of (a) 3.0 mA (dashed curve) and (b) 10 mA (solid curve).

found that the leakage current through the oxide is negligible, and again speculate that the leakage current arises due to minority carrier recombination at the oxide-semiconductor interfaces. If this leakage current is controlled, we expect threshold currents to scale with decreasing active area at least to the 4-μm dimension. An estimate of the lasing mode diameter from the threshold far-field radiation patterns suggests that the lasing mode is on the order of ~3–4 μm diameter in both the 8- and 4-μm devices, and therefore is well confined. In the smaller area devices the lasing mode is more stable, and remains single lobed up to four times threshold for the 4-μm square, at which point side lobes appear (see Fig. 4). The radiation pattern of the 2-μm square device, Fig. 5, shows an increased angular width due to the reduced active region, and remains single lobed over the range of measurement.

An inherent problem in VCSEL designs in which the hole current must pass through p-type semiconductor Bragg reflectors is high electrical series resistance. While there has been progress in reducing the mirror resistance through graded heterojunctions and localized doping, as the device dimensions continue to scale smaller this resistance problem will become more severe. An advantage of the buried native oxide in forming the ring contact to the VCSEL is that the hole current must pass through only one p-type heterojunction before injection into the active region. The 8-μm native-oxide defined laser, which shows little leakage current, has a threshold voltage drop of 1.9 V, with a voltage drop of 2.9 V at four times threshold.

In summary, we have presented a new process for the fabrication of VCSELs based on a native-oxide defined ring contact. Using this process we have demonstrated a low cw room-temperature lasing threshold of 225 μA. Since the native-oxide process is nearly planar, provides good electrical isolation, and does not require complex epitaxial regrowth, it should be useful for integrated optoelectronic circuits incorporating the VCSEL as well as for the discrete laser diodes demonstrated here.

The authors acknowledge useful conversations with N. Holonyak, Jr. concerning the oxidation of AlGaAs, and are also grateful to J. Sarathy and J. C. Campbell for assistance during this work. TJR acknowledges useful conversations with L. F. Lester. The work at the University of Texas at Austin has been supported by the Office of Naval Research under Contract No. N-0014-91-J-1952, the Joint Services Electronics Program under Contract No. F49620-92-C-0027, and the Texas Advanced Technology Program under Contract No. TP-024.

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6, 135 (1994).

OFFICE OF NAVAL RESEARCH

PUBLICATIONS / PATENTS / PRESENTATIONS / HONORS REPORT

for

31 May 93 through 1 June 94

R&T Number:
Contract / Grant Number: N00014-91-J-1952
Contract / Grant Title: Bistable Vertical-Cavity Surface-Emitting Laser Structures on GaAs and Si Substrates
Principal Investigator: Prof. Dennis G. Deppe
Mailing Address: Prof. D.G. Deppe
Microelectronics Research Center
The University of Texas at Austin
Balcones Research Center, MER 1.606/79900
Austin, Texas 78712-1084
Phone Number: (512) 471-4960
E-Mail Address: deppe@falcon.ece.utexas.edu

a. Number of Papers Submitted to Refereed Journals but not yet published: 2

b. Number of Papers Published in Refereed Journals: 6
(list attached)

c. Number of Books or Chapters Submitted but not yet Published: 0

d. Number of Books or Chapters Published: 0

e. Number of Printed Technical Report & Non-Refereed Papers: 0

f. Number of Patents Filed: 0

g. Number of Patents Granted: 0

h. Number of Invited Presentations at Workshops or Prof. Society Meetings: 0

i. Number of Presentations at Workshops or Prof. Society Meetings: 2

j. Honors / Awards / Prizes for Contract / Grant Employees: D.G. Deppe
Robert and Jane Mitchell Endowed Faculty Fellowship in Engineering
The University of Texas at Austin - 1993 /1994

k. Total number of Graduate Students and Post-Docs Supported at least 25%, this year on this contract grant:
Graduate Students 2 (50%) and Post Docs 0

[Grad Student Female 0

[Grad Student Minority 0

[Grad Student Asian e/n 2

[Post-Doc Female 0

[Post-Doc Minority 0

[Post-Doc Asian e/n 0

PUBLICATIONS UNDER ONR SUPPORT - 5/31/93 - 6/1/94

1. Z. Huang, C.C. Lin, and D.G. Deppe, "Spontaneous Lifetime and Quantum Efficiency From Light Emitting Diodes Affected by a Close Metal Mirror," IEEE J. Quant. Electron. 29, 2940-2949 (December 1993).

2. D.G. Deppe, D.L. Huffaker, and C. Lei, "Performance Issues Related to Dielectric Stack Reflectors in Vertical-Cavity Surface-Emitting Lasers," SPIE Proceedings on International Symposia on Optoelectronics Packaging and Interconnects, January 20-21, 1993, Los Angeles, Vol. 1851, pp. 128-137.

3. D.G. Deppe, C. Lei, D.L. Huffaker, and C.C. Lin, "Spontaneous Emission From Planar Microstructures," J. Mod. Optics. 41, 325-344 (February 1994).

4. C.C. Lin, D.G. Deppe, and C. Lei, "Role of Waveguide Light Emission in Planar Microcavities," IEEE J. Quant. Electron. 30, (October, 1994) to be published.

5. C.C. Lin and D.G. Deppe, "Calculation of Lifetime Dependence on Cavity Length of Er3+ in Half-Wave and Full-Wave Microcavities," J. Appl. Phys. 75, 4668-4672 (1 May, 1994).

6. D.L. Huffaker, C.C. Lin, D.G. Deppe, T.J. Rogers, and B.G. Streetman, "Mode Dependence on Mirror Contrast in Fabry-Perot Microcavity Lasers," IEEE Photon. Tech. Lett. 6, 135-138 (February 1994).

7. C.C. Hansing, H.Y. Deng, D.L. Huffaker, D.G. Deppe, B.G. Streetman, and J. Sarathy, "Low-Threshold Continuous-Wave Surface Emitting Lasers with Etched Void Confinement," IEEE Photon. Tech. Lett. 6, 320-322 (March 1994).

8. D.L. Huffaker, D.G. Deppe, K. Kumar, and T.J. Rogers, "Native-Oxide Defined Buried Ring Contact for Low Threshold Vertical-Cavity Lasers," Appl. Phys. Lett. 65, (July 1994) to be published.

CONFERENCE PRESENTATIONS UNDER ONR SUPPORT - 5/31/93 - 6/1/94

1. D.G. Deppe, D.L. Huffaker, C.C. Lin, and T.J. Rogers, "Nearly Planar Low Threshold Vertical-Cavity Surface-Emitting Lasers Using High Contrast Mirrors and Native Oxide," Conference on Lasers and Electro-Optics, May 8-13, 1994, Ananheim, late paper.

2. D.L. Huffaker, D.G. Deppe, K. Kumar, and T.J. Rogers, "Native Oxide Defined Ring Contact for the Vertical-Cavity Surface-Emitting Laser, 52nd Device Research Conference, June 20-22, 1994, Boulder.

3. D.L. Huffaker, D.G. Deppe, K. Kumar, J. Shin, B.G. Streetman, and T.J. Rogers, "Hetersotructure Dependence of Buried Native-Oxides for Vertical-Cavity Devices Grown by Molecular Beam Epitaxy," North American Conference on Moelecular Beam Epitaxy, October, 1994, Urbana, submitted for presentation.