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Selectively Oxidized Vertical-Cavity Laser Performance and Technology

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Abstract—We discuss revolutionary performance advances in selectively oxidized vertical-cavity surface emitting lasers (VCSELs), which have enabled low operating power laser diodes appropriate for aerospace applications. Incorporating buried oxide layers converted from AlGaAs layers within the laser cavity produces enhanced optical and electrical confinement enabling superior laser performance, such as high efficiency and modulation bandwidth. VCSELs are also shown to be viable over varied environmental conditions such as ambient temperature and ionized radiation. The development of novel VCSEL technologies for advanced system applications is also described. Two-dimensional individually addressable VCSEL arrays exhibit uniform threshold and operating characteristics. Bottom emitting 850 nm VCSEL arrays fabricated using wafer fusion are also reported.

In this paper we review monolithic selectively oxidized VCSELs and VCSEL arrays which emit at infrared and visible wavelengths [1,2]. In Section 2 the VCSEL components and the use of selective oxidation of AlGaAs to fabricate oxide confined VCSELs are described. The performance of selectively oxidized VCSELs and evidence of VCSEL insensitivity to temperature variations and ionized radiation is presented in Section 3. New VCSEL technologies currently under development, such as 2-dimensional arrays and bottom emitting 850 nm VCSELs, are discussed in Section 4. Finally, Section 5 summarizes the VCSEL characteristics which make them appropriate for aerospace applications.

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1. INTRODUCTION

The unique attributes of vertical cavity surface emitting laser (VCSEL) diodes have generated both research and commercial interest worldwide. As their name indicates, VCSELs emit light perpendicular, rather than parallel, to the wafer surface. This topological distinction is enabled through the use of distributed Bragg reflector (DBR) mirrors for longitudinal optical confinement. Thus as depicted in Fig. 1, VCSELs and conventional edge emitting lasers differ in that the need to fabricate a facet mirror by either cleaving or dry etching is eliminated. Consequently VCSELs possess several inherent advantages over edge emitting lasers including: (i) a low divergence circular laser beam, (ii) the requirement of only standard fabrication processes, (iii) the capability of wafer level testing before packaging, and (iv) the fabrication of dense 2-dimensional laser arrays. These advantages make VCSELs appropriate for many aerospace applications as well as compatible with low cost manufacture.

Fig. 1. Sketch of Vertical Cavity Surface Emitting Laser (VCSEL) and Edge Emitting Laser Showing Differing Mirrors and Output Beam Geometry.

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Fig. 2. Cross Section Sketch of Ion Implanted and Selectively Oxidized VCSELs.

2. SELECTIVELY OXIDIZED VCSELS

As shown in Fig. 2, VCSELs consist of two high-reflectivity DBR mirrors separated by an optical cavity typically $1-\lambda$ thick (where λ is the wavelength of light in the semiconductor) to form a high finesse Fabry-Perot cavity [1,2]. The DBR mirrors are required for longitudinal confinement of light within the laser and are composed of repeating pairs of quarter-wavelength thick high and low refractive index monolithically grown semiconductor layers. The optical cavity contains the laser active region, usually consisting of 1 to 5 quantum wells. Electrical current is conducted through contacts made to the p- and n-type DBR mirrors to form the laser diodes.

Two laser structures for defining lateral confinement within a VCSEL are depicted in Fig. 2. In Fig. 2(a) ion implantation is employed to create crystalline damage around the laser cavity; the resultant insulating material will funnel the current into the active region [3]. Although an electrical path is defined, implanted VCSELs lack intrinsic optical confinement, which limits their threshold and modulation characteristics. Nevertheless, ion implanted VCSELs are presently being manufactured by several U.S. companies and deployed within new commercial products. A recent innovation for transverse optical and electrical confinement is to employ selective oxidation of buried AlGaAs layers [4] to form oxide apertures within the VCSEL [5,6] as shown in Fig. 2(b). Since the lateral oxidation of AlGaAs is extremely sensitive to Al-content, the layers that form the buried oxide apertures in Fig. 2(b) are engineered through

Fig. 3. Threshold for Ion Implanted and Oxidized VCSELs.

Fig. 4. Minimum Threshold Current for Selectively Oxidized VCSELs Emitting at Various Wavelengths.

control of their composition during epitaxial growth [6]. Introducing electrically insulating low refractive index oxide layers within the VCSEL effectively confines both electrons and photons and thus defines the laser cavity.

The improved electrical confinement arising from the oxide apertures is manifest as reduced threshold current and voltage for broad area lasers as compared to other VCSEL structures [7]. In Fig. 3 we compare selectively oxidized and ion implanted 850 nm VCSELs fabricated from the same epitaxial wafer. Since the oxide layers within the selectively oxidized VCSELs are adjacent to the optical cavity as depicted in Fig. 2(b), the charge carriers are efficiently injected into the quantum wells. By comparison, significant current spreading outside of the laser cavity occurs for the implanted VCSELs, which leads to higher threshold current.

Fig. 5. 980 nm Selectively Oxidized VCSEL Exhibiting 50% Power Conversion Efficiency.

Fig. 6. 980 nm Selectively Oxidized VCSEL Modulation Response at Various Bias Currents.

For small area VCSELs ($<50 \mu\text{m}^2$) in Fig. 3, the optical confinement afforded by the oxide apertures also contributes to low threshold current. In Fig. 4 we show the lowest threshold currents achieved to date for various VCSELs fabricated at Sandia which emit at different wavelengths. Notice that submilliamp threshold current is possible for VCSELs lasing at 650 to 1060 nm. The lower threshold at longer wavelengths arises due to greater confinement and the effects of strain in the quantum wells. The low threshold current/voltage obtained from selectively oxidized VCSELs produces laser sources with very low required input power.

3. SELECTIVELY OXIDIZED VCSEL PERFORMANCE

Due to their superior electrical and optical confinement, selectively oxidized VCSELs have exhibited the highest power conversion efficiency [8,9]. Shown in Fig. 5 is a

Fig. 7. Threshold Current for 850 nm Selectively Oxidized VCSEL at Various Ambient Temperatures.

Fig. 8. Light Output from 780 nm Implanted VCSEL Before and After Irradiation with 4.5 MeV Protons.

high efficiency VCSEL which produces 1 mW output with only 2 mW input power [8]. High efficiency lasers are appropriate for applications with low power budgets. Furthermore, combining small active volumes with the high photon densities possible in selectively oxidized VCSELs has enabled high modulation bandwidths. Fig. 6 demonstrates >16 GHz small signal modulation from a 980 nm selectively oxidized VCSEL [10]. Greater than 20 GHz modulation response has been achieved from a 850 nm selectively oxidized VCSEL [11]. Notice in Fig. 6 that very small drive currents are required to achieve high modulation bandwidth: in Fig. 6 a drive current of 1 mA permits modulation to beyond 10 GHz.

VCSELs are also insensitive to various environmental conditions. For example in Fig. 7 we plot the threshold current of a selectively oxidized VCSEL with ambient temperature varying from -100 to $+100$ °C. Note that over

(a) Operating 8x8 Individually Addressable VCSEL Array

Fig. 9. (a) 8x8 Individually Addressable Selectively Oxidized VCSEL Array Emitting at 1.06 μm; (b) Threshold Current and Voltage of 8x8 VCSEL Array; (c) Output Power with 2 mA Input Current to 8x8 VCSEL Array.

an 80 °C range the threshold current is less than 1 mA. The temperature dependence of the VCSEL threshold current in Fig. 7 arises from the spectral overlap of the cavity resonance and laser gain. The relatively high laser efficiency produces reduced parasitic heating which can degrade the performance in Fig. 7. Preliminary studies of the effects of ionized radiation on VCSELs are also encouraging. Shown in Fig. 8 is the response of an implanted VCSEL before and after exposure to 4.5 MeV proton bombardment up to a dose of 3.8×10^{13} cm⁻² [12]. The relatively small variation in threshold and output power arises due to the reduced VCSEL cross section area. To assess their potential for space deployment, further studies are underway to characterize the radiation hardness of selectively oxidized VCSELs [13].

4. VCSEL TECHNOLOGIES FOR APPLICATIONS

The ability to fabricate high density 2-dimensional arrays is an inherent advantage of VCSELs. High performance 2-dimensional VCSEL arrays are of interest for many applications, such as optical display, imaging, scanning, and free space data communication. For example, VCSEL arrays flip-chip bonded to GaAs or Si circuits could provide the building blocks for smart pixels such as optical signal processors or reconfigurable interconnects; in these applications bottom emitting arrays may be required. Uniformity of array characteristics such as threshold and operating current is an important consideration, particularly to simplify interfacing the array to microelectronic drive circuitry.

To achieve 2-dimensional array uniformity, both growth and fabrication uniformity issues must be considered. The VCSEL arrays fabricated at Sandia are grown by metal organic vapor phase epitaxy on a reactor that has been tailored for high growth uniformity [14]. The selectively oxidized VCSELs are fabricated using a wet oxidation process that has been developed for high uniformity and reproducibility [15,16]. An 8x8 individually addressable VCSEL array is illustrated in Fig. 9(a). Fig. 9(b) shows the room temperature threshold properties of an 8x8 array which emits at a wavelength of 1.06 μm. As evident in Fig. 9(b), the average threshold current is 447 ± 8 μA and the average threshold voltage is 1.265 ± 0.003 V. The low voltage implies reduced input power to the array, especially since the threshold voltage is only 100 mV above the photon potential. For many applications it is necessary to have not only uniform threshold characteristics, but also uniform operating performance. Fig. 9(c) shows that at 2 mA drive current the average output power of the 1.06 μm VCSEL array is 103.5 ± 1 μW across the entire array. Note that the corresponding operating voltage is less than 1.6 V, which is important for direct CMOS drive circuitry.

VCSEL arrays emitting at 850 nm are suitably matched to Si photodetectors and thus are being implemented into commercial optical fiber based data links. VCSELs which emit through their substrate (bottom emitting) are advantageous since the laser output is accessible at both facets, optical elements such as lenses can be fabricated into the substrate, and flip-chip bonding for hybrid integration to

(a) Bottom Emitting 850 nm VCSELs

Fig. 10. (a) Sketch of Selectively Oxidized 850 nm VCSELs Wafer Bonded to Transparent AlGaAs Substrate for Bottom Emitting VCSEL Array; (b) Light Output for Top and Bottom Emitting VCSELs From Same Wafer.

microelectronics is relatively straightforward. However, bottom-emitting 850 nm VCSELs are challenging since the GaAs substrate is not transparent. To overcome this obstacle, we have developed bottom-emitting 850 nm selectively oxidized VCSELs that are wafer fused to transparent AlGaAs or GaP substrates [17].

A sketch of a wafer fused bottom emitting VCSEL array is shown in Fig. 10(a). An optimized 850 nm VCSEL structure is grown on a GaAs substrate and then wafer fused to a transparent substrate using a novel fusion process employing low temperature (400°C) and inert gas annealing. The GaAs substrate is removed allowing contacts to the VCSELs to be fashioned as shown in Fig. 10(a). The device characteristics of top-emitting 850 nm VCSELs and bottom emitting wafer bonded lasers using the same VCSEL wafer are compared in Fig. 10(b). The threshold current is lower for the top-emitting VCSEL, due to lower mirror loss as a result of higher mirror reflectivity from the top semiconductor/air interface. The output power is reduced for

the bottom-emitting VCSEL because of absorption in the AlGaAs substrate; better performance is found using GaP transparent substrates. The novel wafer fusion technology may also allow bonding VCSELs to other materials, such as Si or InP, providing a means of microsystem integration or advanced packaging techniques.

5. SUMMARY

Selectively oxidized VCSELs have many attributes which make them suitable for aerospace applications. Utilization of buried oxide layers within selectively oxidized VCSELs has produced superior laser performance. The buried oxide efficiently confines the charge carriers within the laser active region and transversely confines the laser emission. This enhanced electrical and optical confinement has enabled low threshold current/voltage, high laser efficiency, and high modulation bandwidths. In particular the low operating power requirements for VCSELs will be important for weight sensitive applications with low power budgets such as in aircraft, spacecraft or satellite systems. VCSELs have also been shown to be relatively insensitive to temperature variations and ionizing radiation, attendant to many aerospace environments.

Uniform, low power, high density two-dimensional VCSEL arrays are attractive for smart pixel applications in advanced aerospace systems. Bottom emitting VCSEL arrays have been described which are appropriate for emerging data communication systems. An important consideration is the ability to integrate the VCSEL sources with microelectronics, optics, and perhaps even micro-mechanical elements. Thus a technology such as wafer bonding to combine various materials and devices into a micro-integrated system will be advantageous. Therefore, to meet the requirements of emerging aerospace applications, selectively oxidized VCSEL arrays with new integration technologies may play an important future role.

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6. REFERENCES

- [1] W. W. Chow, K. D. Choquette, M. Haggerot Crawford, K. L. Lear, and G. R. Hadley, "Design, Fabrication, and Performance of Infrared and Visible Vertical-Cavity Surface Emitting Lasers," *J. Quan. Electron.* **33**, 1810-1824 (1997).
- [2] K. D. Choquette and H. Q. Hou, "Vertical-Cavity Surface Emitting Lasers: Moving from Research to Manufacturing," *Proceedings of the IEEE* **85**, 1730-1739 (1997).
- [3] K. Tai, R. J. Fischer, K. W. Wang, S. N. G. Chu, and A. Y. Cho, "Use of Implant Isolation for Fabrication of Vertical-Cavity Surface Emitting Laser Diodes," *Electron. Lett.* **25**, 1644-1645 (1989).

[4] J. M. Dallesasse, N. Holonyak, Jr., A. R. Sugg, T. A. Richard, and N. El-Zein, "Hydrolyzation oxidation of $\text{Al}_x\text{Ga}_{1-x}\text{As-AlAs-GaAs}$ quantum well heterostructures and superlattices," *Appl. Phys. Lett.* **57**, 2844-2846 (1990).

[5] D. L. Huffaker, D. G. Deppe, K. Kumar, and T. J. Rogers, "Native-oxide defined ring contact for low threshold vertical-cavity lasers," *Appl. Phys. Lett.* **65**, 97-99 (1994).

[6] K. D. Choquette, R. P. Schneider, Jr., K. L. Lear, and K. M. Geib, "Low threshold voltage vertical-cavity lasers fabricated by selective oxidation," *Electron. Lett.* **30**, 2043-2044 (1994).

[7] K. D. Choquette, K. L. Lear, R. P. Schneider, Jr., and K. M. Geib, "Cavity Characteristics of Selectively Oxidized Vertical-Cavity Lasers," *Appl. Phys. Lett.* **67**, 3413-3415 (1995).

[8] K. L. Lear, K. D. Choquette, R. P. Schneider, Jr., S. P. Kilcoyne, and K. M. Geib, "Selectively Oxidized Vertical Cavity Surface Emitting Lasers with 50% Power Conversion Efficiency," *Electron. Lett.* **31**, 208-209 (1995).

[9] B. Weigl, M. Grabherr, G. Reiner, and K. J. Ebeling, "High efficiency selectively oxidized MBE grown vertical-cavity surface emitting lasers," *Electron. Lett.* **32**, 557-558 (1996).

[10] K. L. Lear, A. Mar, K. D. Choquette, S. P. Kilcoyne, R. P. Schneider, Jr., and K. M. Geib, "High Frequency Modulation of Oxide-Confined Vertical-Cavity Lasers," *Electron. Lett.* **32**, 457-458 (1996).

[11] K. L. Lear, V. M. Hietala, H. Q. Hou, M. Ochiai, J. J. Banas, B. E. Hammons, J. C. Zolper, and S. P. Kilcoyne, "Small and Large Signal Modulation of 850 nm Oxide-Confined Vertical Cavity Surface Emitting Lasers," *OSA Trends in Optics and Photonics* **15**, 69-74 (1997).

[12] R. F. Carson, E. W. Taylor, A. H. Paxton, H. Schone, K. D. Choquette, H. Q. Hou, M. E. Warren, and K. L. Lear, "Surface Emitting Laser Technology and its Application to the Space Radiation Environment," *SPIE Critical Reviews of Technology*, **CR-62**, 121-151 (1997).

[13] A. H. Paxton, R. F. Carson, H. Schone, E. W. Taylor, K. D. Choquette, H. Q. Hou, K. L. Lear, M. E. Warren, "Damage from Proton Irradiation of Vertical-Cavity Surface Emitting Lasers," *IEEE Trans. Nuclear Science* **44**, 1285-1287 (1997).

[14] H. Q. Hou, H. C. Chui, K. D. Choquette, B. E. Hammons, W. G. Breiland, and K. M. Geib, "Highly Uniform and Reproducible Vertical-Cavity Surface Emitting Lasers Grown by Metalorganic Vapor Phase Epitaxy," *Photon. Tech. Lett.* **8**, 1285-1287 (1996).

[15] K. M. Geib, K. D. Choquette, H. Q. Hou, and B. E. Hammons, "Fabrication Issues of Oxide-Confined VCSELs," K. D. Choquette and D. Deppe, Editors, *Proc. SPIE* **3003**, 69-74 (1997).

[16] K. D. Choquette, K. M. Geib, C. I. H. Ashby, R. Twisten, O. Blum, H. Q. Hou, B. E. Hammons, D. Mathes, and R. Hull, "Advances in Selective Wet Oxidation of AlGaAs Alloys," *Select. Topics in Quantum. Electron.* **3**, 916-926 (1997).

[17] K. D. Choquette, B. Roberds, K. M. Geib, H. Q. Hou, R. D. Twisten, K. L. Lear, and B. E. Hammons, "Bottom-Emitting 850 nm Selectively Oxidized VCSELs Fabricated using Wafer Bonding," 1997 LEOS Annual Meeting, San Francisco, CA (Nov. 1997).

7. BIOGRAPHY

Kent D. Choquette received B.S. degrees in engineering physics and applied mathematics from the University of Colorado-Boulder in 1984. He received the M.S. and Ph.D. degrees in materials science from the University of Wisconsin-Madison in 1985 and 1990, respectively. After a postdoctoral appointment at AT&T Bell Laboratories in Murray Hill, NJ, where he developed vacuum integrated fabrication processes for optoelectronic devices, he joined in 1992 Sandia National Laboratories in Albuquerque, NM. As a Principal Member of Technical Staff at Sandia he has been engaged in research into the design, fabrication, and physics of vertical-cavity surface emitting lasers and other optoelectronic devices. Dr. Choquette is a member of the IEEE Laser and Electro Optical Society and the Optical Society of America.

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