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SAND96-0696C**Life-testing oxide confined VCSELs: too good to last?**K. L. Lear, S. P. Kilcoyne^(a), R. P. Schneider, Jr.^(b), and J. A. Nevers

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RECEIVED**MAR 15 1996****OSTI**^(a) Present address is Optical Concepts, Inc., 432 Commerce Blvd., Lompoc, CA 93436.^(b) Present address is Hewlett-Packard Laboratory, MS 26M10, 3500 Dear Creek Road, Palo Alto, CA 94304.**ABSTRACT**

The use of native oxides (selective oxidation) in vertical cavity surface emitting lasers has produced dramatic improvements in these laser diodes but has also been suspected of causing poor reliability because of incidental reports of short lifetimes and physical considerations. Here we discuss the results of thousands of hours life-tests for oxide confined and implant confined devices at current densities from 1 to 12 kA/cm². There was a single infant mortality failure from a sample of 14 oxide confined lasers with the remainder showing relatively stable operation. The failed device is analyzed in terms of light current characteristics and near-field electroluminescence images, and potential screening criteria are proposed.

Keywords: laser diode reliability, vertical cavity surface emitting laser, oxide confinement

1. INTRODUCTION

Recently, oxide confinement structures have produced dramatic improvements in vertical cavity surface emitting laser (VCSEL) performance parameters such as power conversion efficiencies over 50%¹ and threshold currents less than 10 μ A.² The improvement in these structures is attributed to their low loss even when scaled to small dimensions^{3, 4}. These lasers are attractive for parallel data communication and other applications. High device efficiencies reduce power supply and heat-sinking requirements and permit greater packing density while low operating currents can foster a reduction in drive circuit complexity. Low thresholds and high efficiencies also reduce waste heat generation and thus junction temperature, enhancing reliability. Nevertheless, short lifetimes in some experimental reports in conjunction with the presence of oxides and accompanying strain near the active region have led to concerns about the reliability of oxide confined VCSELs.

Oxide confined VCSELs contain insulating, low index oxide layers that define current paths⁵ and provide lateral optical confinement⁶. The more established implant confined VCSEL structure is shown schematically in Figure 1 along with the oxide confined structure. The former structure relies on an insulating region created by proton implant damage to funnel the current⁷ but has little or no built in index guiding⁸. The oxide layers in the latter structure are aluminum oxide akin to alumina in composition and are formed by the reaction of steam with epitaxial AlGaAs layers of high aluminum content⁹.

Both the oxide and implant damage are sources for crystalline imperfections that may promote defects which degrade lasers. Accordingly, both techniques were initially considered potentially unreliable. Subsequent evaluation of implant confined VCSELs^{10, 11} has greatly diminished concerns about their reliability and led to estimates of mean-time-to-failure of up to 3×10^7 hours¹². It is the purpose of this paper to document the encouraging results of initial lifetime studies of oxide confined devices toward the end of likewise establishing oxide confinement as a viable technology.

Concerns about the reliability of oxidized structures have exceeded those initial focused on implant confined structures in part because of early accounts of the rapid degradation of oxide confined VCSELs as well as physical considerations. Researchers at the University of Texas who initially incorporated oxides into diodes reported lifetimes as short as a few minutes¹³. Low threshold devices reported by the University of Southern California² also failed after initial experiments. These structures

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Figure 1. Schematic cross-sections of implant confined and oxide confined VCSEL structures.

were formed from the oxidation of pure AlAs and some also included oxide regions within a few hundred angstroms of the quantum wells. Sandia workers have previously reported that devices based on the oxidation of AlGaAs lasted hundreds of hours at room temperature¹⁴. Comparisons of similar structures based on oxides of AlAs and AlGaAs have shown the former to degrade much more rapidly and be susceptible to mechanical failure during rapid thermal annealing¹⁵. This mechanical failure is likely associated with large strains generated by thickness changes upon oxidation. Volume reductions exceeding 10% have been reported for aluminum oxide layers compared to the original AlAs¹⁶. Volume reductions are not apparent in transmission electron micrographs of oxidized $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ ¹⁴. Other pertinent physical considerations include the high recombination velocity at oxide interfaces¹⁷ and the oxide acting as a source for point defects or diffusing oxygen. Finally, it is ironic to note that the oxidation process was initially derived from experiments to accelerate the degradation of lasers using high temperature and humidity⁹, but now appears to be a suitable way of making VCSELs that have lifetimes which warrant additional investigation.

2. APPARATUS

The nominally 970 nm lasers used in this study were fabricated as previously described by oxidation⁵ and implantation¹⁸. The epitaxial structure used for all the devices presented here was of the same design. It was based on a metalorganic vapor phase epitaxy sample with an active region of three 8 nm $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ quantum wells in a graded AlGaAs one-wavelength cavity between a 39 period Si-doped lower mirror and a 19 period C-doped upper quarter-wave mirror stack. The maximum aluminum alloy content of the mirror was $x=0.96$ except in the upper and lower mirror periods immediately adjacent to the cavity where it was increased to $x=0.98$ in order to enhance the oxidation rate of these layers. A proton dose of $1 \times 10^{14}/\text{cm}^2$ at an energy of 330 keV was used for the implant confined devices. Following the implant, adjacent devices were isolated by a mesa etch through the junction. For the oxide confined devices, the oxidation occurred at 425°C for 50 minutes. All the samples were planarized using photo-defined polyimide which encapsulated the exposed mesa sidewall. Ti/Au metallization for interconnection and bonding pads on the polyimide completed the wafer processing. The wafers were subsequently scribed into die approximately $1 \times 2 \text{ mm}^2$ with devices as close as 200 μm to the edge of the chip.

Two die of implant confined VCSELs and two die of oxide confined VCSELs were packaged for use in life-testing. The 500 μm thick die were attached to 28 pin ceramic leadless chip carriers (LCCs) with silver epoxy. Several devices on each chip were wire-bonded. The life-test package fixture is shown in Figure 2. The LCCs were placed in sockets that had been modified to allow them to be attached to a thick copper lid that was in thermal contact with the LCC. The temperature is

controlled using thermoelectric coolers. A large area photodetector is placed over an opening in the lid to collect the light emitted from all the lasers on the chip.

Figure 2. Fixtures and packaging for life-testing. Clockwise from left shows the temperature controlled burn-in socket and photodiode, a chip in a LCC, and a schematic of the power from 8 common cathode lasers going into a single large area photodetector.

The laser chips were connected to custom circuit boards each containing eight commercial, low cost laser diode driver modules with analog input modulation capability. The operating currents were controlled via the modules' analog modulation inputs by PC compatible digital-to-analog converter cards. The photodiode currents were fed into another PC compatible analog-to-digital converter card.

The lasers were operated under computer control in constant power mode with the drive current being automatically adjusted and logged once per day. Since the output of up to eight lasers per chip is directed into a single photodetector, individual lasers cannot be operated in constant power mode with continuous current adjustment. Instead, once per day, all lasers were turned off and then in turn each individual laser was momentarily operated in constant power mode to determine the operating current. All lasers were subsequently turned on at the newly determined operating current for the following 24 hours. The cumulative laser power on each chip was monitored continuously and typically remained within 5% of the expected total power indicating that the combined thermal dissipation did not substantially alter individual laser operating power.

3. LIFE-TESTS

3.1. Implant confined lasers

Figure 3 shows the operating current for nominally identical 15 μm diameter implant confined VCSELs as a function of time. One laser chip was operated with a package temperature of 25°C and the other at 50°C after an initial period of operation at an uncontrolled temperature of approximately 25°C prior to the installation of thermoelectric coolers. In all

cases, the operating currents for a constant output power of 1 mW per laser decreased in time. This behavior is attributed to implant damage annealing¹⁹ which reduces implant confined threshold current. No failures of any sort were seen in the 16 implant confined VCSELs during the life-test. The reduction of operating current due to implant annealing may mask other degradation mechanisms which would otherwise contribute to a slowly increasing operating current. Occasional erratic behavior is seen in a few of the implanted devices. This may be due to thermal instabilities in the operating characteristics of these devices⁸.

Figure 3. Operating current of implant confined lasers for constant power operation with a package temperature of (a) 25°C and (b) 50°C for the time period indicated.

3.2. Oxide confined lasers

Figure 4 shows the operating current for 14 oxide confined VCSELs as a function of time. Again, after installation of thermoelectric coolers, one chip was operated with a package temperature of 25°C and the second was operated at 50°C . The lasers ranged in size from $5 \times 5 \mu\text{m}^2$ to $21 \times 21 \mu\text{m}^2$ resulting in a range of current densities being required to operate at the specified 1 mW output power. Some observations about the limitations of the life-test apparatus are appropriate. First, only

Figure 4. Operating current of different sized oxide confined lasers for constant power operation with a package temperature of (a) 25°C and (b,c) 50°C for the time period indicated.

seven lasers per chip were operated because the eighth laser on each was $\sim 3 \times 3 \mu\text{m}^2$ and had a threshold current of only 200 μA which was lower than the minimum current of the laser diode driver modules. These lasers were disconnected from the life-test apparatus because they could not be turned completely off to allow for the adjustment of the operating current of other lasers on the same chip. Secondly, the increase in the operating current of the lasers in Figure 4b during the period from 400 to 718 hours was due to a failure in the mechanism which held the detector. The detector position was corrected at the 718 hours when the thermoelectric cooler was installed at which point the operating currents for the devices returned to normal.

4. ANALYSIS

One infant mortality failure was seen in 14 oxide confined VCSELs with the remainder showing slow increases in operating current. Careful inspection of Figure 4b shows that operating current for the one failed device went from 3.5 mA to 10.4 mA within 24 hours. Subsequently this device continued to operate although its operating current increased more rapidly than the other devices. Figure 5 shows the near field electroluminescence at the end of the life-test for the failed device along with a nominally identical good device. The interior bright square (approximately $8 \times 8 \mu\text{m}^2$) corresponds to the aperture in the oxide while the bright ring around the outside comes from carriers which diffuse outward into the region between the oxide layers before recombining radiatively^{6, 20}. A dark line in the $\langle 110 \rangle$ direction is evident in the image of the failed device operating just below threshold at 3.3 mA. This orientation is correlated with a dislocation associated with relaxation of the strained InGaAs quantum wells. Strain relief might be anticipated for this triple InGaAs quantum well structure which is metastable with respect to the criteria for both the single-kink and double-kink relaxation mechanisms. Interestingly, the degraded laser still operates in the presence of this defect by adjusting to a higher order mode that minimizes the overlap of the optical field with the dark line. The undegraded device which has a much lower threshold current is shown operating in its fundamental mode. A comparison of the light and voltage characteristics before and after the life test are shown in Figure 6 for both the failed and good devices. Calibration factors may account for the small difference in the light output for the good device. The failed device shows a large increase in threshold current and a substantial decrease in the power output at 10 mA. Although unnoticed prior to the life-test, the failed device initially exhibited a threshold current approximately twice that of the good device indicating that threshold current might have been a useful parameter for screening lasers. Alternatively, a 24 hour burn-in would have detected the gross degradation in the failed device.

Figure 5. Near field electroluminescence images of a degraded device just (a) below and (b) above threshold along with (c) a good device just above threshold.

Figure 6. The light and voltage versus current characteristics of the (a) good and (b) degraded lasers pictured in Figure 5 before (solid line) and after (dashed line) the life-test.

The normalized increase in operating current during the last thousand hours of operation for all 14 of the oxide confined VCSELs as shown in Figure 4 is plotted as a function of operating current density in Figure 7. In order to assess the significance of the data, the details of the current versus time traces should be examined. In Figure 4a, the four lowest current traces show strong correlations indicating that some of the apparent operating current increase is likely due to instrumentation rather than diode degradation. The details of Figure 4b are expanded in Figure 4c for the low current devices with a package temperature of 50°C. The sudden steps in current at 1704 and 1712 hours corresponded to system shutdowns. The two higher current devices have relatively constant operating current before and after this event so the change for these devices as quantified in Figure 7 is largely associated with the glitch at the shutdown. The same event contributed to the rise in the current of the other devices as well although they show some smooth increase in current as well. Because of the uncertainties of instrumentation effects, the normalized increases in Figure 7 should be taken as estimates with unspecified large error bars. Given that caveat, the fractional operating current increase is generally larger at higher current densities but appears relatively independent of the package temperature with the exception of the two data points at 4 kA/cm². It should be noted that these are the two lowest current devices in Figure 4c, so the low absolute current magnifies the fractional increase. These devices also have metal contact apertures that are closer to the oxide aperture than the remaining lasers on the 50°C chip. The corresponding devices on the 25°C chip have a current increase that is clustered with the others at 2 kA/cm².

While this analysis allows the results of the oxide confined life-tests to be quantified, absolute failures rather than questionable levels of degradation are necessary to extrapolate mean-time-to-failures. However, the promising nature of these tests can be summarized in the fact that there was only a single infant mortality in the 14 oxide confined VCSELs with a cumulative total of 30,000 hours of operation.

Additional steps that might improve the reliability of these devices include the placement of oxide layers at greater distances from the cavity, the use of thermodynamically stable rather than metastable strained layers, and further refinement of the composition and structure of the layers to reduce residual stress due to volume shrinkage associated with the conversion of AlGaAs to aluminum oxide.

Figure 7. The ratio of the operating current increase to the starting current for the last 1000 hours of operation taken from the data in Figures 3 and 4. The data is plotted as a function of the current density.

5. CONCLUSIONS

In conclusion, we have reported the results of initial life-tests on oxide confined VCSELs. Despite preceding reports of short lifetimes in some devices and physical reasons to suspect the reliability of these devices, we have seen promising results including stable operation at 50°C for more than a thousand hours. One device out of 14 suffered an infant mortality that was accompanied by a dark line in the electroluminescence image. A short burn-in or threshold current examination could have screened out this device. The increase in operating current for the remaining devices was 1-10% per thousand hours for current densities ranging from 1-12 kA/cm² although the rates are within the uncertainty that might be attributed to instrument error. We are undertaking life tests on larger numbers of oxide confined VCSELs at higher temperatures with refined apparatus in an effort to generate sufficient failures to perform a statistical analysis of the mean time to failure in the future.

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