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Cavity Structures for Low Loss Oxide-Confined VCSELs

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ABSTRACT

We examine the threshold characteristics of selectively oxidized VCSELs as a function of the number, thickness, and placement of the buried oxide apertures. The threshold current density for small area VCSELs is shown to increase with the number of oxide apertures in the cavity due to increased optical loss, while the threshold current density for broad area VCSELs decreases with increasing number of apertures due to more uniform current injection. Reductions of the threshold gain and optical loss are achieved for small area VCSELs using thin oxide apertures which are displaced longitudinally away from the optical cavity. We show that the optical loss can be sufficiently reduced to allow lasing in VCSELs with aperture area as small as 0.25 μm^2.

Keywords: vertical-cavity surface emitting lasers, selectively oxidized, oxide confined, low optical loss.

1. INTRODUCTION

Buried oxide apertures for electrical and optical confinement within vertical cavity surface emitting lasers (VCSELs) have enabled record laser diode performance.[1,2,3,4] A striking example is the decrease in VCSEL threshold current that has been achieved due to reduced absorption[4], increased spontaneous emission coupling[5], and efficient electrical[2,6] and optical[7] confinement in small active volumes.[8] However, a dramatic increase of threshold current density is observed for small area (< 50 μm^2) oxide-confined VCSELs.[1,9,10] It has been previously shown that both optical scattering[11,12] and leakage current[13] increase with decreasing aperture size, which leads to increased threshold current density. If these effects can be overcome, we can obtain scalable, ultralow threshold lasers with potentially high modulation bandwidths.[14] We thus examine the optical loss of monolithic selectively oxidized VCSELs as a function of the number, thickness, and placement of the buried oxide apertures to improve the optical loss of small area VCSELs. We show that the optical loss for small area VCSELs can be reduced using thin oxide apertures which are displaced longitudinally away from the optical cavity. Moreover, the reduction of optical loss allows lasing in VCSELs with cross section area as small as 0.25 μm^2.

2. VCSEL FABRICATION

The monolithic selectively oxidized 850 nm VCSELs under study have five 8 nm GaAs quantum wells separated by $Al_{0.2}Ga_{0.8}As$ barriers within a 1-wavelength thick optical cavity. The optical cavity is surrounded by distributed Bragg reflector (DBR) mirrors consisting of $Al_{0.16}Ga_{0.84}As/Al_{0.92}Ga_{0.08}As$ layers with compositionally graded interfaces to reduce series resistance. One or more low index

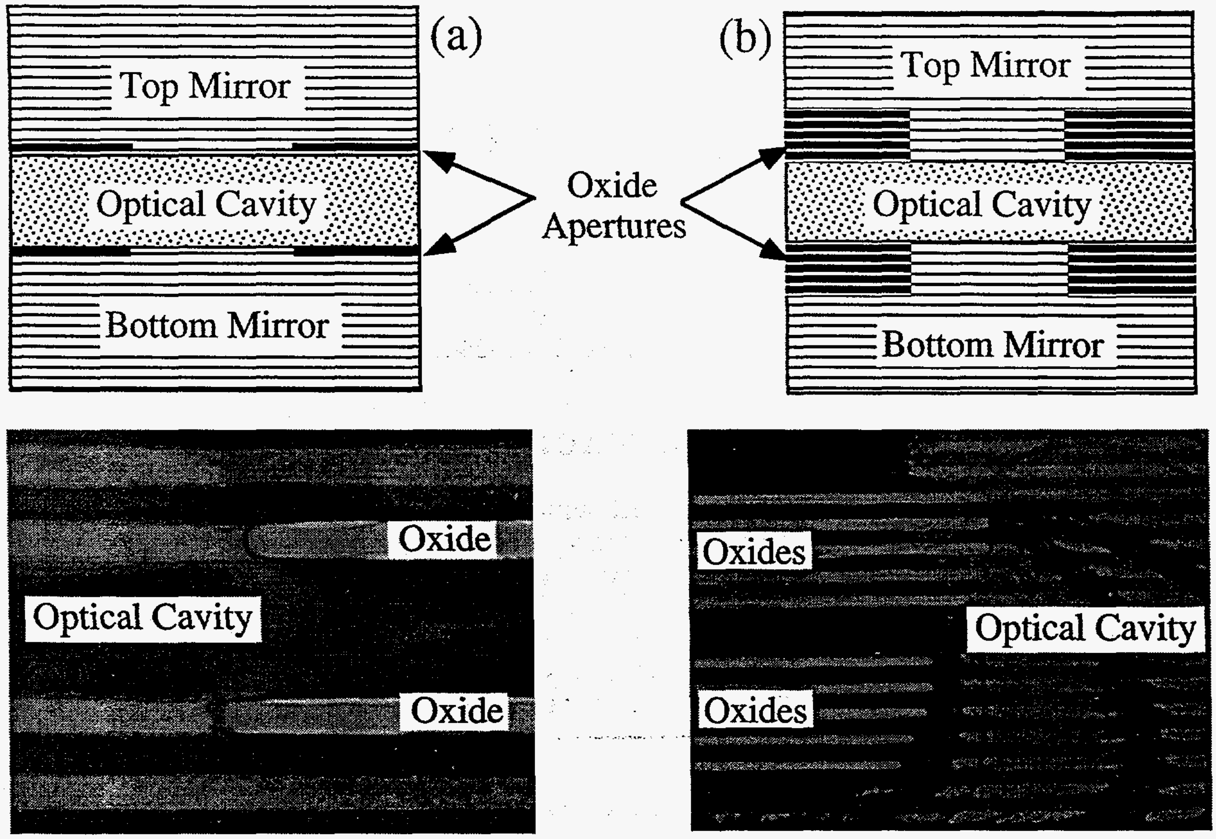

Figure 1. Sketch and transmission electron micrograph of selectively oxidized VCSELs with (a) single and (b) five quarterwave thick oxide apertures on each side of the optical cavity. The wavy lines apparent in (b) are TEM thickness interference fringes.

$Al_{0.98}Ga_{0.02}As$ layer(s) are grown on both sides of the optical cavity and are converted to a buried oxide[15] to obtain electrical and optical confinement. The higher Al-content in these layers leads to an increased oxidation rate relative to the other DBR layers thus enabling the selective oxidation for aperture definition.[2] Fig. 1 shows sketches of selectively oxidized VCSELs with 1 and 5 oxide apertures located on each side of the optical cavity. The transmission electron micrographs in Fig. 1 illustrate the lack of extended defects and strain near the oxide.[16]

In the following Sections we examine the threshold characteristics of selectively oxidized VCSELs fabricated from 3 wafers. The five laser structures compared are VCSELs with 1 or 5 quarterwave thick (42 nm) oxides located on top of the optical cavity, or on both sides of the optical cavity, and VCSELs with thin (20 nm) oxide layers embedded within the quarterwave thick low index layers that are in the third mirror period on each side of the optical cavity. For all VCSEL samples, square mesas with sides varying from 30 to 70 μm in steps of 0.5 μm are defined by reactive ion etching to expose the sidewall layers for oxidation of the buried oxide apertures.[17] In this manner VCSELs with current aperture areas varying from 0.25 to >1000 μm^2 are reproducibly fabricated. VCSELs with one or more oxide apertures located only at the top of the optical cavity are fabricated by etching the sample just to the active region, thus exposing only the uppermost high Al-content layers for oxidation of the oxide apertures.

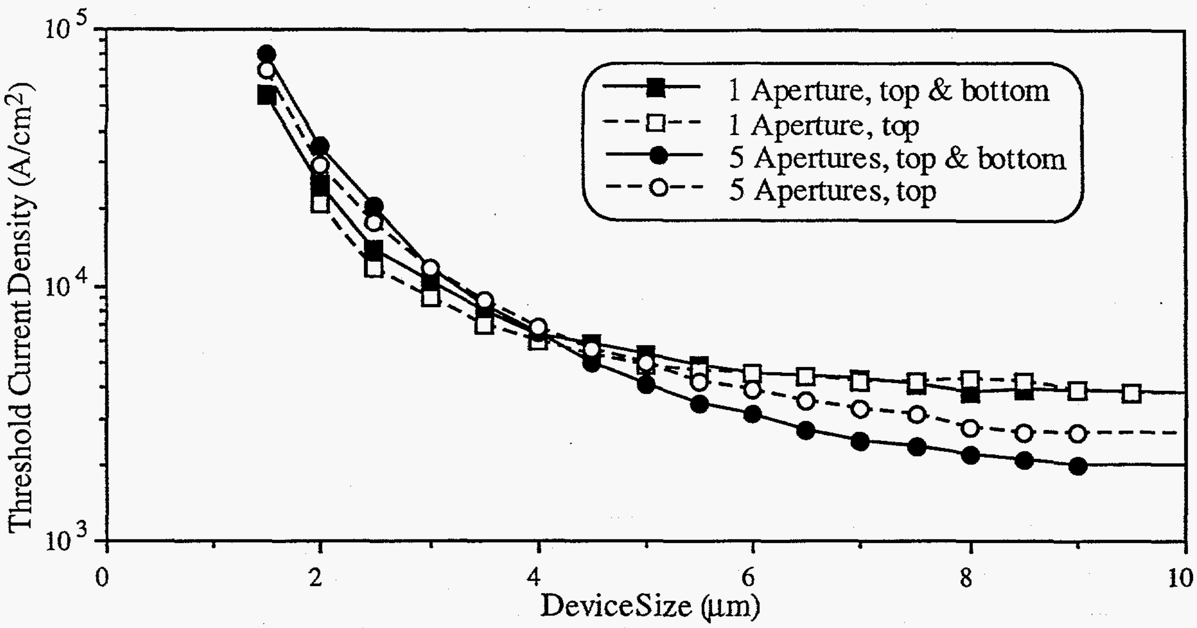

Figure 2. Threshold current density versus aperture size (i.e. length of square aperture edge) for various numbers of quarterwave thick oxides on top or on both sides of optical cavity.

3. OXIDE APERTURE NUMBER

In Fig. 2 we plot the threshold current density, J_{th}, as a function of aperture size. For all VCSEL samples with aperture size greater than ≈7x7 μm, a constant current density is obtained. However, J_{th} decreases with an increase in the number of oxide apertures for broad area VCSELs. For example, 8x8 μm VCSELs with 5 apertures on each side of the optical cavity have a J_{th} that is 50% lower compared to VCSELs with just one aperture surrounding the cavity. The decrease of J_{th} arises from greater uniformity of the current injection into the quantum wells. The lateral resistance of the DBRs is greater than the vertical resistance (particularly near the optical cavity where the DBR doping is reduced), thus leading to current crowding around the periphery of the oxide aperture. The VCSELs with 5 apertures have more uniform current injection across the aperture, since the current is funneled through a thicker high resistance (lower doping) region, as compared to VCSELs with a single aperture (see Fig. 1). The more uniform carrier profile provides greater overlap with the gain, thus lowering the threshold current. Numerical modeling of these structures, which takes account of both optical and electrical processes within a VCSEL,[18] shows that the difference of the carrier density at the center versus the edge of the aperture is reduced by half for VCSELs with 5 apertures compared to VCSELs with a single aperture. Finally as evident in Fig. 3(a), the threshold near-field profile of broad area VCSELs with single apertures exhibit brighter luminescence around the aperture periphery which is indicative of current crowding. By comparison, the near-field profile of the 5 aperture VCSEL in Fig. 3(b) has a more uniform near field profile. Thus for broad area VCSELs designed for high power applications, multiple oxide apertures provide more uniform current injection and correspondingly lower threshold current.

(a) (b)

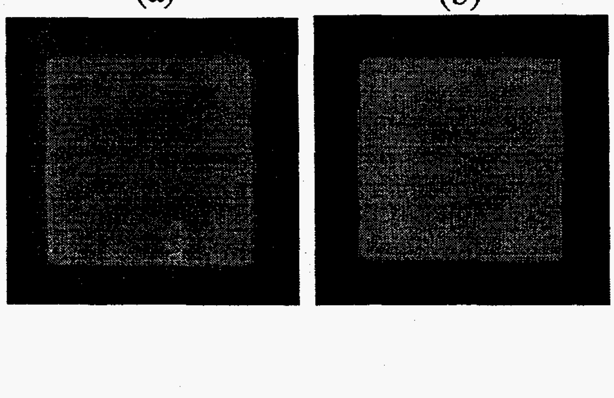

Figure 3. Near-field profile at threshold for VCSELs with (a) one or (b) five apertures surrounding cavity. Note the brighter lines around the aperture periphery in (a) compared to more uniform profile in (b).

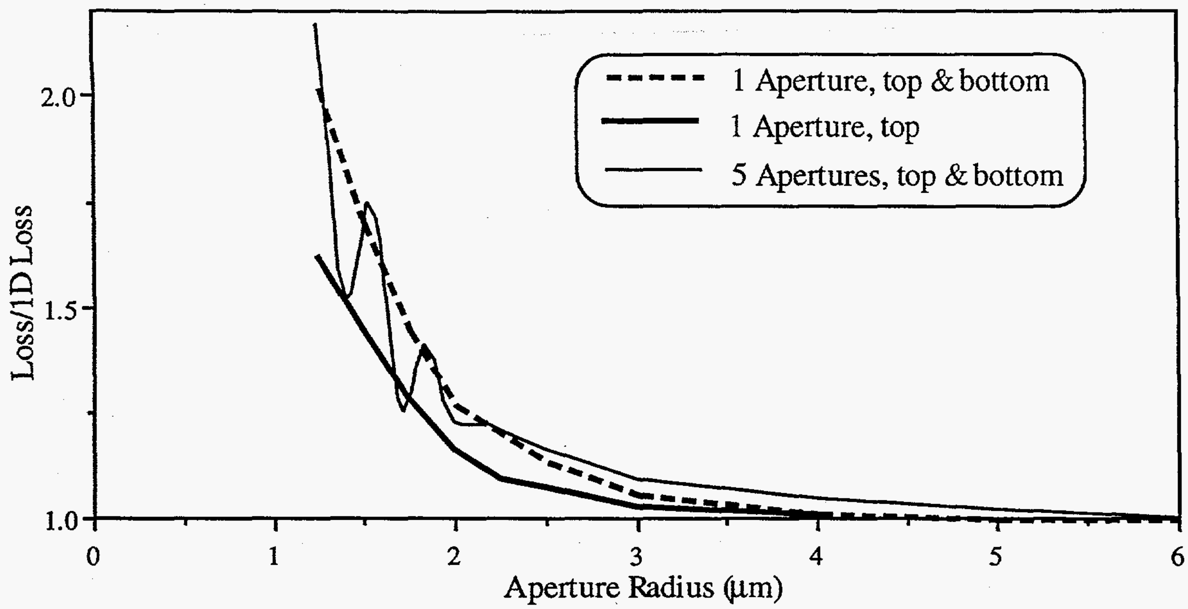

Figure 4. Calculated scattering loss (relative to the 1-dimensional loss) of the fundamental mode for various numbers of quarterwave thick oxides on top or on both sides of optical cavity.

For VCSELs with oxide aperture areas less than 50 μm^2 we observe J_{th} to rapidly increase as shown in Fig. 2. Analysis of this size dependence indicates that increased optical loss from the oxide apertures occurs for reduced aperture size.[11,13] In contrast to the broad area VCSELs, J_{th} increases with increasing number of oxide apertures for small area VCSELs. For example, 2x2 µm VCSELs with one aperture on each side of the optical cavity have a J_{th} that is 30% lower compared to VCSELs with five apertures surrounding the cavity. Fig. 4 shows a comparison of the calculated optical loss using a 2-dimensional finite difference numerical model that solves the Helmholtz equation (in the scalar approximation) for the entire VCSEL structure, including the mirror layers, quantum wells, and oxide layers.[19] For a given cross section area, a greater number of apertures within the cavity leads to increased optical loss, in agreement with the experimental measurements in Fig. 2. Hence, for quarterwave thick oxides, a single aperture provides the lowest optical loss and threshold current.

4. OXIDE APERTURE THICKNESS AND PLACEMENT

To mitigate the aperture optical loss for small area VCSELs, we wish to diminish the interaction between the electric field and the oxide apertures and yet maintain lateral optical confinement The former can be accomplished by reducing the oxide thickness, and/or moving the apertures away from the optical cavity where the field intensities are highest.[12,13] However, these steps also reduce the transverse optical confinement, causing the mode to expand laterally, thus increasing scattering loss. The lateral effective index difference, Δn_{eff}, arising from the oxide aperture can be calculated[20] from the oxide cavity resonance.[6] In Fig. 5 we plot the Δn_{eff} produced from oxide layers of varying thickness (embedded in the center of a quarterwave thick layer) and a varying number of periods on each side of the optical cavity. From Fig. 5 we see that for a given value of Δn_{eff}, decreasing the oxide thickness requires that the apertures be closer to the optical cavity. We want Δn_{eff} to be several times the thermally induced refractive index, which is typically 3-5x10^{-3}. The design criteria that we chose is a minimum value of Δn_{eff}=0.015 for sufficient optical confinement, and an oxide thickness of approximately 20 nm to insure a thickness independent oxidation rate. Fig. 5 indicates 20 nm oxide apertures should be positioned in the 3rd period from each side of the optical cavity to satisfy these requirements. This VCSEL structure is denoted as "thin oxide VCSEL" in Fig. 5. For comparison, the "thick oxide VCSEL" denoted in Fig. 5 corresponds to a quarterwave thick oxide on each side of the optical cavity (see Fig. 1(a)).

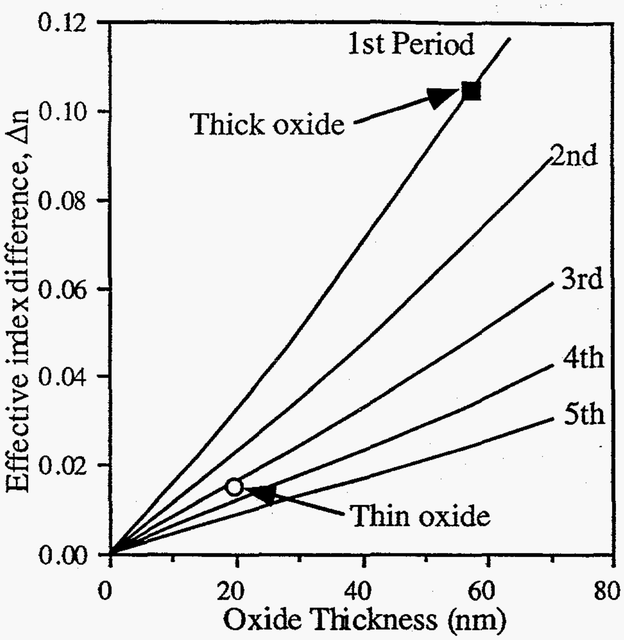

Figure 5. Cavity effective index difference resulting from oxides of various thickness embedded within quarterwave low index layers away from each side of optical cavity.

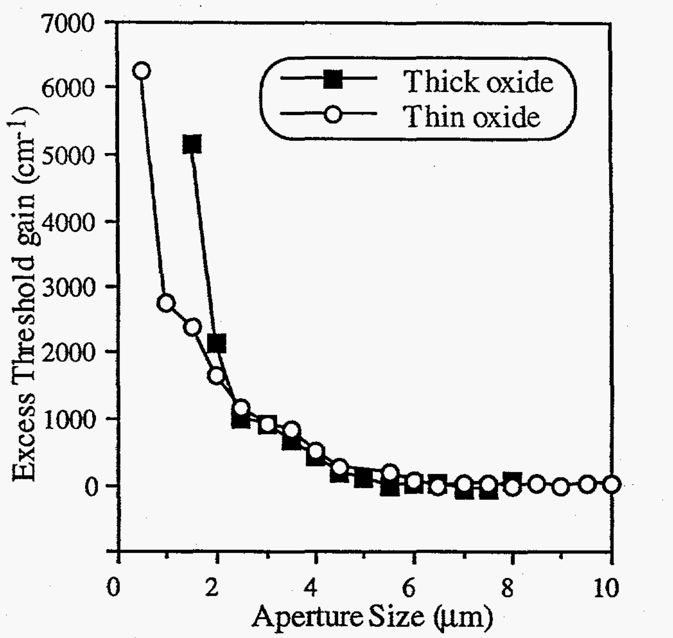

Figure 6. The excess threshold gain versus aperture size for thick (42 nm oxides on each side of cavity) and thin (20 nm oxides in 3rd period on each side of cavity) oxide-confined VCSELs.

Fig. 6 is a comparison of the measured excess threshold gain for the thick and thin oxide aperture VCSELs described in Fig. 5. The excess gain is the threshold gain above that measured for broad area (>50 μm^2) VCSELs. We compare the excess threshold gain in Fig. 6 in order to emphasize the size dependence and eliminate the effects of differing mirror loss between the two oxide VCSEL structures. The threshold gain is determined from experiment using an intrinsic voltage analysis.[9] The intrinsic threshold voltage is found by subtracting the ohmic voltage drop from the measured threshold voltage. The intrinsic threshold voltage is then equated to the calculated quasi-Fermi level splitting arising from the carrier density in the quantum wells which produces the gain. In this manner, the VCSEL material gain at threshold can be determined from simple electrical measurements matched to a many-body laser gain theory.[21] The reduced oxide scattering of the thin oxide VCSELs produce lower excess threshold gain in Fig. 6 for aperture sizes ≤ 2 μm. This enables small aperture VCSELs that could not be realized with the thick oxide aperture structure. Note that thick oxide aperture VCSELs will not lase for aperture area < 2 μm^2 due to the extremely high (> 7000 cm^{-1}) threshold gain required! The VCSELs with thin oxide apertures set back from the cavity exhibit reduced threshold gain (i.e. reduced optical scattering) and lower threshold current density for the smallest aperture areas considered.

5. CONCLUSIONS

In summary, we have examined the influence of the number, thickness, and position of buried oxide apertures within selectively oxidized VCSELs for the purpose of optimizing low loss small area lasers. The number of oxide apertures is found to have opposite effects on small area versus broad area VCSELs. For high power applications requiring broad area VCSELs, multiple apertures provide more uniform current injection and lower threshold current density. For low power and low threshold current VCSELs, a single aperture provides lower optical loss than multiple apertures. To further reduce the optical scattering loss in small area lasers, the oxide apertures can be positioned away from the optical cavity and the oxide thickness reduced, but with an accompanying reduction of transverse optical confinement.

Based on our findings, we have demonstrated a modified VCSEL design using a 20 nm thick oxide longitudinally offset 3 periods away from the optical cavity which exhibits improved threshold characteristics for small area VCSELs, allowing lasing for apertures as small as 0.25 μm^2.

6. ACKNOWLEDGMENTS

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