COLD-CAVITY MEASUREMENT OF EXCESS OPTICAL LOSS
IN OXIDE-CONFINED VERTICAL CAVITY SURFACE EMITTING LASERS

BY

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THESIS

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**ABSTRACT**

Microcavity laser design and performance optimization requires a quantitative knowledge of the cavity optical losses. A generalized method using sub-threshold spectral measurements matched to model calculations is demonstrated to determine optical loss in microcavity lasers. Cold-cavity spectral characteristics are used to extract the size dependent optical loss for small diameter oxide-confined vertical cavity surface emitting lasers. For oxide aperture diameters less than 4 μm, the oxide scattering loss can be greater than 10 cm⁻¹, similar to the typical values of free carrier absorption loss.
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CHAPTER 1
INTRODUCTION

1.1 Background and Motivation

As suggested by its name, the vertical cavity surface emitting laser (VCSEL) is a microcavity semiconductor laser with output beam emitted vertically, perpendicular to the wafer surface, as opposed to the emission of an edge-emitting semiconductor laser. The VCSEL was invented by K. Iga at the Tokyo Institute of Technology in 1979 [1] and first demonstrated in continuous-wave (CW) operation at room temperature by Koyama et al. in 1988 [2]. Since then VCSELs have played an increasingly important role in the field of semiconductor lasers and are presently manufactured by numerous companies for a variety of applications [3-5].

The VCSEL has emerged as the dominant light source for short-range optical interconnects in optical switches, data centers, and high performance computing [6, 7]. Due to the inherent characteristics of the VCSEL structure, described in detail in Chapter 3, the VCSEL has many advantages over edge-emitting lasers for this application in terms of performance, integration, manufacturing, and packaging. Its relatively low divergence and circular output beam facilitates efficient coupling into optical fibers and integrated optoelectronics while eliminating the need for beam correction optics. Vertical surface emission enables enhanced functionality and integration with other elements and
allows for the fabrication of dense two-dimensional arrays for other possible schemes of increasing bandwidth, such as space division multiplexing, multiple-input multiple-output (MIMO), and multiple channel transmission through single multi-core optical fiber. The small cavity volume results in high intrinsic direct modulation bandwidth, single longitudinal mode lasing, less temperature sensitivity with lasing wavelength dictated by cavity resonance rather than by peak gain, and energy efficiency, enabling low threshold current and operating power. Furthermore, VCSELs benefit from standard planar fabrication processes, wafer-scale manufacturability, wafer level on-wafer testing prior to packaging, and ease of packaging which overall enable low-cost, high-volume manufacturing [4] with outstanding device reliability [3, 5]. There are several methods of transverse optical and electrical confinement in VCSELs, a few of the most common being etched air-post, ion implantation, and selective oxidation. Oxide-confined VCSELs in particular show superior performance in modulation bandwidth due to efficient electrical and optical confinement in small active volumes, and have thus been widely deployed for short-range optical interconnects.

Driven by the exponential increase of performance in information technology, data centers, and computational power, data transmission bandwidth is required to increase exponentially as well. Furthermore, as data centers become physically larger, utilizing more interconnects and requiring longer rack-to-rack fiber transmission distance, low power consumption and narrow spectral width for reduced signal dispersion become increasingly important [8, 9]. These ever-increasing performance requirements of optical interconnects tend to promote the use of small diameter oxide-confined VCSELs.
However, oxide-confined VCSELs do not exhibit properties that scale linearly with the size of the device [10-12]. For example, the threshold current density rapidly increases for lasers with small cross sectional area as a result of leakage current and increased optical loss from scattering due to interaction between the oxide aperture and electromagnetic field [10, 12, 13]. High threshold current density creates reliability issues for devices with small cavity size thus motivating the development of methods to characterize the cavity-size dependent optical loss for oxide-confined VCSELs.

1.2 Previous Work

The size-dependent optical loss has previously been analyzed for oxide-confined VCSELs using several different approaches. Analysis of the external quantum efficiency and the far-field radiation pattern has been used to determine the excess size-dependent scattering loss [12, 13]. In this analysis, the excess optical loss is extracted from measurements of the decrease in differential output efficiency. Analysis of intrinsic threshold voltage characteristics has also been used to determine the size-dependent scattering loss [10]. In this approach the excess optical loss is extracted from experimental intrinsic threshold voltage matched to a laser gain theory and the results compared to a numerical two-dimensional cavity simulation [10]. The results of the previous research indicate that excess optical scattering loss becomes significant for devices with aperture diameter less than 4 µm [12, 13], that this loss significantly contributes to an increase in threshold current density for small area lasers [10], and that the excessive loss may be reduced by the use of thin, displaced, or tapered oxide apertures [10, 12, 13]. These approaches to loss analysis, however, require lasing
operation in which thermal effects can obscure scattering loss, the latter of which can
dominate for small cavity diameters [14]. Sophisticated simulation packages may also be
used to extract the loss from exact modeling to match experimental VCSEL performance,
but this is not conducive to rapid device design and evaluation. A simple method to
directly extract cavity-size dependent optical loss from cold-cavity measurements to
avoid thermal effects may aid in the design and characterization of oxide-confined
VCSELs and other microcavity lasers, particularly for small cavity diameters.

Sub-threshold spectral characterization combined with a Helmholtz waveguide
model incorporating complex refractive index has previously been used to characterize
the contributions of optical loss to modal properties in photonic crystal VCSELs [15]. By
extracting the difference in modal loss for the fundamental and transverse modes from
observed sub-threshold spectral-mode splitting, it was shown that the optical scattering
loss contributes significantly to the transverse optical confinement and supported modes.
We show here that this procedure is a general result that is not specific to the photonic
crystal VCSEL structure, and so it should be applicable to any microcavity laser
structure.

1.3 Scope of Thesis

This thesis discusses the use of a semi-empirical technique involving cold-cavity
spectral measurements combined with a Helmholtz waveguide model incorporating
complex refractive index to analyze the cavity-size dependent optical scattering loss of
small diameter oxide-confined VCSELs. Chapter 2 presents the semiconductor laser
structure and fabrication. We begin by introducing the basic VCSEL epitaxial structure with emphasis on the oxide-confined VCSEL. We then describe the structure of an array of oxide-confined VCSELs with varying aperture size and the corresponding fabrication process in greater detail. Chapter 3 presents the theory of cold-cavity loss analysis in microcavity lasers. We begin by describing the origin of excess cavity-size dependent optical loss in oxide-confined VCSELs. We then provide the lossy VCSEL model and the theory for extracting excess cavity-size dependent optical loss from cold-cavity spectral-mode splitting measurements. Chapter 4 presents the characterization and analysis of excess cavity-size dependent optical loss in oxide-confined VCSELs. We present the VCSEL performance characteristics of interest to indicate, extract, and validate excess cavity-size dependent optical loss. We then discuss the use of a probe station to measure the light output and voltage versus bias current and subthreshold spectra. We conclude by presenting the results of this thesis project. Chapter 5 summarizes the results presented in this thesis.

1.4 References


CHAPTER 2

LASER STRUCTURE AND FABRICATION

The VCSEL has emerged as the dominant light source for short-range optical interconnects in optical switches, data centers, and high performance computing [1, 2]. It is the inherent characteristics of the VCSEL structure that provide advantages for this application in terms of performance, integration, manufacturing, and packaging. In this Chapter, we present the laser device structure and fabrication. We begin by introducing the basic VCSEL epitaxial materials with emphasis on the oxide-confined VCSEL. We then describe the structure of an array of oxide-confined VCSELs with varying aperture size and the corresponding fabrication process in greater detail.

2.1 Vertical Cavity Surface Emitting Laser Epitaxial Structure

The basic VCSEL structure consists of two highly reflective distributed Bragg reflector (DBR) mirrors separated by an optical cavity, which together form a high finesse Fabry-Perot vertical laser cavity as depicted in Figure 2.1. The optical cavity has longitudinal length of a multiple of λ/2, usually one λ, where λ is the laser emission wavelength in the semiconductor material for which the VCSEL is designed. The optical cavity contains an active region, usually consisting of multiple quantum wells, that spatially overlaps the antinodes of the longitudinal electromagnetic field to provide optical gain, as shown in Figure 2.2. The composition of the quantum wells is selected to provide gain for the desired VCSEL emission wavelength.
Figure 2.1: Diagram of a VCSEL.

Figure 2.2: The refractive index profile and longitudinal electric field in the vicinity of the optical cavity within a VCSEL.
The DBR mirrors provide longitudinal optical confinement and must be highly reflective because of the low round-trip gain typical of VCSELs. The DBR mirrors consist of several periods of $\lambda/4$ thick alternating high and low refractive index layers composed of either epitaxially grown semiconductors or other dielectric materials [3]. Partial reflections at each high-to-low index interface add constructively when spaced a distance of $\lambda/2$ apart, thereby creating mirrors with near 100% maximum reflectivity for wavelengths in the stop-band of the mirror [3]. Both the width of the stop-band and the reflectivity of the mirror are proportional to the difference in refractive index between the DBR high and low index layers [4]. The wavelength $\lambda$ corresponding to the resonant frequency of the optical cavity lies within the stop-band but is partially transmitted and thus becomes the laser emission wavelength, as shown in Figure 2.3. The compositions of the DBR layers are selected to maximize their index contrast while remaining transparent to the laser emission wavelength [5]. Furthermore, the DBR mirrors and optical cavity are doped with electrical impurities to create the p-n junction necessary for the laser diode.
Figure 2.3: A calculated transmission spectrum for a GaAs/AlGaAs VCSEL showing the mirror stopband and the cavity resonance at 855 nm.

There are several typical VCSEL device structures used for transverse optical and/or electrical confinement. The most common structures, shown in Figure 2.4, include the etched air-post, selectively oxidized, ion implanted [5], and ion-implanted with photonic crystal defect VCSELs [6]. In this thesis, we fabricate and characterize only selectively oxidized VCSELs, also referred to as oxide-confined VCSELs. The selectively oxidized VCSEL structure has buried oxide layers for both optical and electrical transverse confinement [5]. The monolithically grown semiconductor layers of a DBR mirror typically consist of AlGaAs layers with varying concentrations of aluminum. Buried oxide layers are formed via wet oxidation of exposed AlGaAs DBR layers. The oxidation rate of AlGaAs is highly dependent on the Al concentration; therefore, oxide apertures can be formed from layers with high aluminum concentration.
The oxide is an electrical insulator with a lower dielectric constant than the surrounding unoxidized semiconductor, and can therefore be used to confine both electrons and photons.

![Diagram of VCSEL device structures](image)

**Figure 2.4:** VCSEL device structures used for transverse optical and/or electrical confinement: (a) etched air-post; (b) selectively oxidized; (c) ion-implanted; (d) ion-implanted with photonic crystal defect.

### 2.2 Vertical Cavity Surface Emitting Laser Device Structure

Lasers with known, varying aperture size must be fabricated in order to obtain the size dependent optical loss caused by scattering from the optical aperture. The photolithographic mask set used in fabrication of the lasers produces the unit cell of lasers shown in Figure 2.5.
The devices shown in Figure 2.5 correspond to selectively oxidized VCSELs with square aperture size varying in length by increments of either 0.5 µm or 1 µm. The lithographic mask set consists of two levels, one for producing square mesas and one for the metal contact rings on the mesa tops. These top contacts are the anode contacts to the laser diode, and the cathode contact is a shared contact on the backside of the wafer. The square mesas with metal contact vary in size sequentially across each row, starting with the smallest mesa at 30 µm by 30 µm in size, shown in the bottom-right corner of Figure 2.5. The side length increases by 0.5 µm increments for adjacent mesas in the row so that the mesa at the opposite end of the row (bottom-left corner of Figure 2.5) is 36.5 µm by 36.5 µm in size. Similarly, mesas in the next row up increase in size by 0.5 µm increments in the reverse direction so that the mesa at the right-end of the second row (just above the smallest mesa) is 43.5 µm by 43.5 µm. This pattern continues for the top two rows except that mesas increase in size by 1µm increments. Thus, the mask set produces square mesas of size 30 µm by 30 µm up to 44 µm by 44 µm varying by 0.5 µm.
increments, and then varying by increments of 1µm up to 75 µm by 75 µm. The mesa etch exposes a high aluminum content layer so that when oxidized together during the wet oxidation process, this produces selectively oxidized VCSELs with aperture size varying by increments of either 0.5 µm or 1 µm.

2.3 Device Fabrication

The epitaxial semiconductor material used for the fabrication of the selectively oxidized VCSELs (sample 3152) was obtained from IQE (Europe) Ltd., in St. Mellons Cardiff, UK. The material designed to emit at 850 nm was grown by chemical vapor deposition (MOCVD) epitaxy on a 3-inch-diameter n-type GaAs substrate. The active region consists of three 6 nm GaAs quantum wells separated by 8 nm Al$_{0.3}$Ga$_{0.7}$As barriers within a 1λ-thick optical cavity. The optical cavity is surrounded by distributed Bragg reflector mirrors consisting of Al$_{0.12}$Ga$_{0.88}$As/Al$_{0.9}$Ga$_{0.1}$As layers with compositionally graded interfaces. There are 22 periods in the top DBR mirror and 34 periods in the bottom DBR mirror. The top DBR mirror is doped p-type by C while the bottom DBR mirror and substrate are doped n-type by Si. A low index 30 nm thick Al$_{0.98}$Ga$_{0.02}$As layer is grown between the optical cavity and the top DBR mirror to form the relatively thick oxide aperture via a wet oxidation process.

The selectively oxidized VCSEL fabrication process begins with the deposition of metal contacts. The n-type backside contact composed of 400 Å of Au$_{0.4}$Ge$_{0.6}$ alloy, 200 Å of Ni, and 1500 Å of Au was deposited under high vacuum (pressure below 2 × 10$^{-6}$ Torr) using electron-beam induced thermal evaporation. Next, the square-shaped ring top
contacts were patterned using standard lift-off contact photolithography. The p-type top contacts composed of 150 Å of Ti and 1500 Å of Au were deposited under high vacuum using electron-beam evaporation. The square-shaped ring contacts remained after an acetone metal-lift-off process.

The next step in the fabrication process is definition of the laser mesas. A layer of SiO$_2$ approximately 4000 Å thick is deposited by a SiH$_4$/N$_2$O plasma enhanced chemical vapor deposition (PECVD) process to be used as a protection mask for the mesa etching process. The SiO$_2$ layer is patterned into square-shaped mesas over the ring contacts by standard photolithography followed by a Freon 14 (CF$_4$) reactive ion etch (RIE) process. The VCSEL mesas are etched by a SiCl$_4$/Ar inductively coupled plasma reactive ion etch (ICP-RIE) process. Using in-situ optical reflectometry to monitor the ICP-RIE etch, the mesas were etched four DBR mirror periods past the active region to ensure device isolation and to expose the high aluminum content oxidation layer.

**Figure 2.6:** (a) Top-view image of fabricated oxide-confined VCSEL with mesa size of 44 µm and corresponding aperture diameter of 5 µm while lasing. (b) Side-view SEM image of fabricated oxide-confined VCSEL with close-up on the optical cavity and oxide aperture.
The last step in the fabrication process is the formation of oxide apertures for current confinement and transverse optical confinement. The oxide apertures were formed from the exposed high aluminum content layer by a wet oxidation process at 410°C. The oxidation rate is highly sensitive to the aluminum content of the oxidation layer. Therefore, calibration oxidations were necessary to determine the oxidation rate of the high aluminum content layer for this particular VCSEL sample. For calibration, the sample was cleaved for small test pieces containing a few sets of square mesas ranging in size from 30 µm to 70 µm in 0.5 µm to 1µm increments. The test pieces were then oxidized for a period of time such that larger mesas were still conducting and smaller mesas were “pinched-off” (i.e. the high aluminum content layer had oxidized completely through the mesa therefore leaving the mesa non-conductive). The oxidation rate could then be calculated from the size of the smallest conducting mesa, and in this case the oxidation rate was 0.21 µm/min. Using this oxidation rate the VCSEL sample was oxidized so that the lasing aperture would vary from 0.5 µm to 13 µm by increments of 0.5 µm. An SEM image showing the oxide aperture for the fabricated oxide-confined VCSEL is shown in Figure 2.6 (b). The SiO₂ mask from the previous step was removed by Freon 14 (CF₄) RIE and the oxide-confined VCSELs were then probed to test for lasing operation as shown in Figure 2.6 (a).

2.4 References


CHAPTER 3

THEORY OF COLD-CAVITY LOSS ANALYSIS FOR OXIDE-CONFINED MICROCAVITY LASERS

The analysis of cavity-size dependent optical loss for oxide-confined VCSELs has previously been performed by considering the external quantum efficiency [1, 2] or threshold voltage analysis [3]. These approaches, however, require lasing operation in which thermal effects can obscure scattering loss, which can dominate for small cavity diameters. Sub-threshold spectral characterization combined with a Helmholtz waveguide model incorporating complex refractive index has previously been used to characterize optical loss in photonic crystal VCSELs [4]. By extracting the modal loss from observed spectral splitting of the cold-cavity transverse optical modes, it was shown that the optical scattering loss arising from the etched photonic crystal hole pattern in the top mirror contributes significantly to the transverse optical confinement and supported modes. Here we generalize this semi-empirical technique and show the first analysis of cavity-size dependent optical scattering loss in oxide-confined microcavity lasers using cold-cavity spectral measurements.

3.1 Excessive Cavity-Size Dependent Optical Loss

The excessive cavity-size dependent optical loss in oxide-confined VCSELs results from scattering caused by the oxide aperture. While the oxide aperture has been previously modeled as an intracavity optical lens [5, 6], it cannot exactly compensate for
the diffraction of the mode due to its abrupt interface and thus creates scattering loss. The cavity-size dependent scattering loss has been quantified by propagating light through an unfolded cavity as shown in Figure 3.1 [7]. A parabolically tapered aperture (ideal lens) can exactly compensate for the mode and eliminate scattering loss whereas an abrupt aperture (non-ideal lens) gives rise to scattering losses [7]. Thin, displaced, or tapered apertures cause significantly reduced loss [1-3]. Two apertures evenly spaced in the unfolded cavity with separation close to a half-cavity length may also reduce loss as the mode diffracts over a half-cavity length before being partially refocused [8]. However, if spaced too little or too great the two apertures act as one thicker aperture resulting in higher losses.

Figure 3.1: Diagram of oxide-confined VCSEL and corresponding unfolded cavity model. Mirrors are approximated as hard mirror planes at diffraction equivalent distance $L_D$ from the incident plane. Scattering loss caused by the abrupt aperture is shown by the purple arrows.
The excess optical scattering loss depends sensitively on the spatial overlap of the oxide aperture and the longitudinal electromagnetic field. The oxide aperture layer is grown in the VCSEL structure preferably at a location which spatially overlaps a node of the longitudinal electromagnetic field, typically found at the low-to-high index interface of a DBR period near the active region as shown in Fig 3.2(b). This reduces aperture scattering by minimizing the interaction between the oxide and the electromagnetic field of the fundamental mode, especially in large diameter lasers. Analytical studies of diffraction loss show that it is relatively small for diameters > 5 µm [9]. However, the oxide layer has finite width and as the lasing aperture size decreases, approaching the size of the fundamental mode, optical loss increases significantly due to scattering off of the oxide apertures [1-3], as depicted in Figure 3.2(a). This cavity-size dependent excess optical loss introduced by the oxide aperture is what we wish to characterize in this work.

**Figure 3.2:** Diagram of oxide-confined VCSEL structure with insets showing (a) transverse mode profile with aperture scattering at small cavity size and (b) VCSEL longitudinal standing wave pattern for a one-wavelength optical cavity.
3.2 Complex-Index Oxide Confinement

To apply the Helmholtz equation using cylindrical geometry, we first construct a complex refractive index oxide confinement model. We reduce our VCSEL structure to a simple cylindrical waveguide model where the region within the lasing aperture is the core and the region above and below the surrounding buried oxide layer is the clad, much like a cylindrical step-index optical fiber. The core refractive index is taken as entirely real (no loss) while a complex index is used for the cladding region which contains the lossy oxide aperture. The optical loss is classified broadly as scattering and diffraction loss from the oxide aperture [1-3] formed by wet oxidation of a high aluminum content layer [10] in the first period of the top distributed Bragg reflector (DBR) nearest the active region of the VCSEL. The oxide-confined VCSEL and the corresponding complex-index oxide model is depicted in Figure 3.3. Note from Figure 3.3 that the oxide aperture has approximately a square geometry, but is modeled as a circular aperture in our analysis.

**Figure 3.3:** Cross-section view of VCSEL structure (left) and its corresponding simple waveguide model (right). Red arrows within the blue region indicate light confined by the lasing aperture. Purple arrows pointing into the light purple regions indicate optical loss due to scattering from the lossy cladding region.
To find the properties of an index-guided VCSEL modeled as a cylindrical step-index optical fiber, an effective index approach can be used [5, 11]. A transmission matrix calculation is performed to find the resonances and real effective indices for the entire DBR structure. A finite-difference approach is used to solve for the VCSEL modes from solutions to the scalar Helmholtz equation given by

$$\nabla^2 U(r, \phi, z) + n^2(r)k_0^2 U(r, \phi, z) = 0$$  \hspace{1cm} (3.1)

with solutions of the form

$$U(r, \phi, z) = u(r)e^{i\phi}e^{i\beta z}$$  \hspace{1cm} (3.2)

where $U$ is the field profile, $n$ is the refractive index profile, $k_0$ is the wavenumber, $l$ is an integer, and $\beta$ is the propagation constant. Inserting (3.2) into (3.1) and taking a finite-differences approach to facilitate more easily an iterative fit to experiment gives the eigenvalue problem [4],

$$\begin{bmatrix}
    u_{j+1} - 2u_j + u_{j-1} \\
    \frac{1}{\Delta r} \frac{u_{j+1} - u_{j-1}}{r_j} - \left( \beta^2 + \frac{m^2}{r^2} \right) u_j
\end{bmatrix} = -n_j^2 k_0^2 u_j$$  \hspace{1cm} (3.3)

where $j$ is an index associated with a point in space, eigenvalues $k_0$ are mode resonances, and eigenvectors $u$ are mode profiles. The variable parameters that determine the solutions to (3.3) are the real core refractive index, $n_{core}$, and complex cladding refractive index, $n_{clad} = n'_{oxide} + in''_{oxide}$. By inclusion of a complex refractive index for the cladding region in solving for the modes, we obtain complex wavenumbers, $k_0$, from which the real valued resonances, $\lambda_0$, can be calculated by

$$\lambda_0 = \frac{2\pi}{\text{Re}\{k_0\}}$$  \hspace{1cm} (3.4)

and the field amplitude loss, $\alpha$, can be extracted by
\[ \alpha_i = \text{Im}\{k_0\} \]  

(3.5)

The field amplitude loss (in inverse distance) is multiplied by a factor of two for intensity-based loss.

As previously mentioned, a transmission matrix calculation using the VCSEL epitaxial information is performed to find the real effective indices \( n_{\text{core}} \) and \( n'_{\text{oxide}} \) [12]. For the epitaxial structure of VCSELs fabricated in this research, as described in Chapter 2, the real effective indices \( n_{\text{core}} \) and \( n'_{\text{oxide}} \) are found to be approximately 3.248 and 3.248, respectively, by transmission matrix calculation. These values can then be used to solve for the fundamental and first higher order mode resonances, \( \lambda_{01} \) and \( \lambda_{11} \) respectively, without loss being considered. Then the imaginary term \( n''_{\text{oxide}} \) in the complex cladding refractive index can be added and used as an iterative fitting parameter to fit the model to experiment, meaning that we find the value \( n''_{\text{oxide}} \) giving mode resonances with spectral splitting, \( \Delta \lambda = \lambda_{01} - \lambda_{11} \), equal to that of experimentally collected sub-threshold spectral data (where \( \lambda_{01} \) is the wavelength of the fundamental Gaussian mode, and \( \lambda_{11} \) is the wavelength of the first higher order transverse mode). Complex refractive index gives complex wavenumbers from which real valued resonances and field amplitude loss may be extracted, as noted in Equations (3.4) and (3.5). Using Equation (3.3), the calculated spectral splitting between the fundamental and first higher order mode as a function of aperture size is shown in Figure 3.4.
Figure 3.4: Plot of calculated spectral splitting between fundamental and first higher order mode as function of aperture size for varying values of $n''_{oxide}$ equal to 0, 5, 10, and 15 cm$^{-1}$ for the 3.5 $\mu$m aperture VCSEL with values of $n_{core}$ and $n'_{oxide}$ approximately equal to 3.248 and 3.240 respectively.

It should be noted that the results of the calculation depend sensitively on the values of real effective indices $n_{core}$ and $n'_{oxide}$, and that it is an assumption to consider these values known by using the transmission matrix method and epitaxial information. The core refractive index can be calculated with relative accuracy by transmission matrix method and has a value of approximately 3.2 to 3.5 for typical 850 nm VCSELs. The cladding refractive index is less accurately calculated by transmission matrix method due to variation in physical properties of the buried oxide layer such as its refractive index, thickness, and spatial overlap with the longitudinal electromagnetic field. However, the calculation is sensitive to the difference in real effective indices $\Delta n_{eff} = n_{core} - n'_{oxide}$, not necessarily the absolute values of $n_{core}$ and $n'_{oxide}$. Therefore, an accurate value of $\Delta n_{eff}$ will diminish the uncertainty of the real refractive indices found by transmission matrix
method. A procedure for determining the value of $\Delta n_{\text{eff}}$ is discussed in our experimental method in Chapter 4.

3.3 References


CHAPTER 4

DEVICE CHARACTERIZATION AND ANALYSIS

This chapter begins with a description of VCSEL performance characteristics of interest to indicate, extract, and validate excess cavity-size dependent optical loss. We then describe the experimental setup for loss characterization of oxide-confined VCSELs emitting nominally at 850 nm. Electrical, optical, and spectral properties are investigated, including light output versus current and voltage (LIV) characteristics and subthreshold optical spectra. The procedure for determining the value of real refractive index for the cladding region is described. Finally, the cavity-size dependent excessive optical scattering loss for the fundamental mode is extracted using subthreshold spectral data. The calculated loss is compared with device performance characteristics to further validate the results.

4.1 Device Characterization

There are two conditions that must be satisfied for a laser to operate in the stimulated emission regime. The phase condition requires that the phase of the electric field be reproduced after each round trip through the laser cavity for constructive interference. The amplitude condition requires that the optical gain available be equal to the total optical loss. This can be summarized by [1]

\[ r_1 r_2 e^{i2 \beta_{lo}} = 1 \]  

(4.1)
where complex propagation constant $\beta$ and complex reflection coefficients $r_1$ and $r_2$ are

$$\beta = \beta_c + i \frac{\left( \alpha_i - \Gamma \gamma_{th} \right)}{2}$$  \hspace{1cm} (4.2)

$$r_i = |r_i| e^{i \phi_i}$$  \hspace{1cm} (4.3)

$$r_2 = |r_2| e^{i \phi_2}$$  \hspace{1cm} (4.4)

giving threshold phase condition:

$$\phi_1 + \phi_2 + 2 \beta_c L = 2m\pi$$  \hspace{1cm} (4.5)

and threshold amplitude condition:

$$G_{th} = n_w \Gamma \gamma_{th, w} = \alpha_i + \frac{1}{2L_{eff}} \ln \left( \frac{1}{R_1 R_2} \right) = \alpha_i + \alpha_m$$  \hspace{1cm} (4.6)

where parameters include intrinsic loss $\alpha_i$ due to scattering and absorption inside the cavity, number of quantum wells in the active region $n_w$, mode confinement factor $\Gamma$, threshold material gain $\gamma_{th}$, threshold modal gain $G_{th}$, effective cavity length $L_{eff}$, and mirror reflectivities $R_1$ and $R_2$.

The mirror loss from the second term in (4.6) is often known from the device structural design, such as the composition of the layers and the number of periods in distributed Bragg reflector mirrors. The intrinsic loss $\alpha_i$ is less straightforward to determine and contains both cavity-size independent (such as free carrier absorption) and dependent contributions (such as scattering and diffraction from transverse optical confinement). As excess optical scattering loss increases for smaller diameter VCSELs, the modal gain required to reach threshold increases. The threshold current density for a multiple quantum well laser is given by[1]

$$J_{th} = \left( \frac{n_w J_0}{\eta} \right) \exp \left[ \left( \frac{\gamma_{th}}{g_0} \right) - 1 \right]$$  \hspace{1cm} (4.7)
where $\eta$ is injection efficiency into the quantum wells, $g_0$ is a gain coefficient parameter, $J_{0e^{-1}}$ is transparency current density, and $\gamma_{th}$ is given by Equation (4.6). Therefore, excessive optical loss is indicated by an exponential increase in threshold current density.

Once threshold is achieved, the optical output power of the laser is expected to have a linear relationship with the injected current as given by[1]

$$P_{out} = \frac{h\omega}{q} \frac{\alpha_m}{\alpha_m + \alpha_i} (I - I_{th})$$

(4.8)

where $P_{out}$ is the output power of the laser, $h\omega$ the photon energy, $q$ the elementary charge, $I$ the injection current, and $I_{th}$ the threshold current. This linear relationship is not valid for an unlimited range of injection current. Junction heating due to increased injection current will cause spectral misalignment between the peak gain and cavity resonance, resulting in saturation and rollover of the optical output power. Over the range of injection current for which Equation (4.8) is valid, optical loss $\alpha_i$ is correlated to the laser slope efficiency, $\eta_{slope}$, by the proportionality

$$\eta_{slope} = \frac{dP_{out}}{dI} \propto \frac{\alpha_m}{\alpha_m + \alpha_i}$$

(4.9)

where $\alpha_m$ is mirror loss. Therefore, a linear relationship between excessive optical loss and inverse laser slope efficiency may be used to validate the results of our analysis.

**4.2 Experimental Measurement Setup**

To assess VCSEL performance and conduct our analysis, dc characterization of devices was performed upon completion of their fabrication process. The LIV properties and optical spectrum were measured using the setup shown in Figure 4.1. As shown in
the figure, the VCSEL sample is placed on a platen of an electrically grounded x-y adjustable probe station. Cascade Microtech MMP-51 pin probes are used to make electrical contact and to bias VCSEL devices. The injection current for biasing devices is supplied by a Keithly 236 DC current source. For LIV measurements, the injection current is controlled by an Agilent 4156C semiconductor parameter analyzer (SPA). To measure the optical output power, a broad area infrared photodetector is connected to the SPA. To examine the optical spectrum, the emitted light from lasers may also be coupled into a multimode fiber connected at one end to the microscope objective of the probe station and at the other end to an Agilent 86141B optical spectrum analyzer (OSA) which has a spectral resolution of 0.06 nm. The Agilent 4156C SPA is controlled by a Microsoft Windows XP workstation running National Instruments LabVIEW 6.1 for convenience and storage of data.

**Figure 4.1:** Experimental setup for measuring the dc characteristics of VCSEL devices.
4.3 Experimental Procedure and Results

In our experimental procedure, we first examine the LIV characteristics of VCSELs with varying size of oxide aperture using the Agilent 4156C semiconductor parameter analyzer. Figure 4.2 presents the LIV characteristics of a VCSEL with aperture size of 6x6 μm. For our analysis we are primarily concerned with the aperture-size dependent threshold current density characteristics, shown in Figure 4.3. Aperture scattering loss is significant for small aperture VCSELs but is insignificant for broad area VCSELs due to less interaction between the electric field and oxide aperture. Excessive optical loss results in greater gain being required to reach lasing threshold. This causes threshold current and most importantly threshold current density to increase significantly for smaller devices. As shown in Figure 4.3, threshold current density scales approximately linearly with the cavity size until the aperture scattering loss and concomitant leakage current become significant for VCSELs with small apertures [2]. For the set of lasers examined in Figures 4.2-4.4, it was determined that the smallest device for which threshold current density scales linearly with aperture size had an aperture size of 6 μm. Therefore, the device with aperture size of 6 μm is considered to have little aperture scattering loss, whereas all VCSELs with smaller apertures are considered to have excess optical loss arising from interaction between the mode and the oxide aperture.
Figure 4.2: Power versus current (LI) and voltage versus current (IV) measurements of VCSEL with aperture size of 6 μm x 6 μm.

Figure 4.3: Threshold current and current density versus oxide aperture size.
We next use the Agilent 86141B optical spectrum analyzer to obtain the necessary cold-cavity spectral measurements. The spectral splitting between the fundamental mode and the next higher order mode is obtained (an example is shown in Figure 4.5) for each device biased at approximately 0.9 times threshold current in order to avoid thermal effects. It should be noted that for devices with aperture size smaller than 3.5 μm, we were unable to obtain spectral splitting data at a bias of 0.9 times threshold current because of the low output power or lack of lasing. Figure 4.4 presents the measurement of subthreshold spectral splitting for a VCSEL with aperture diameter of 6 μm by 6 μm. The mode spacing is inversely proportional to the aperture radius and further increases with excessive optical loss [3]. The mode spacing of the fundamental mode and the next higher order mode without loss for a VCSEL of aperture size \( a \) emitting nominally at \( \lambda_B \) is given by

\[
\Delta \lambda = \left| \lambda_{01} - \lambda_{11} \right| = \frac{\sqrt{n_{\text{core}}^2 - n_{\text{oxide}}^2} \lambda_B^2}{\sqrt{2n_{\text{core}} \pi} n_{\text{core}} a}
\] (4.10)

and the mode spacing of any other adjacent modes is an integer multiple of this [4]. It should be noted that Equation (4.10) is derived using a truncated parabolic refractive index profile, while our model uses a step index profile. Using our model, the calculated mode spacing of the fundamental mode and next higher order mode for different values of imaginary cladding index, as in Figure 3.3, are compared with the measured subthreshold spectral measurements of VCSELs in Figure 4.5. As apparent in the figure, the expected behavior is observed for increased spectral splitting with decreasing aperture size and increasing excessive optical loss.
Figure 4.4: Screen-shot of subthreshold spectral splitting measurement for VCSEL with aperture diameter of 6 µm x 6 µm.

Figure 4.5: Plot of measured subthreshold spectral splitting between fundamental and first higher order mode as function of aperture size with error bars corresponding to the 0.06 nm resolution of the optical spectrum analyzer. The curves are calculated from Equation (3.3) for varying values of $n_{\text{oxide}}$ equal to 0, 5, 10, and 15 cm$^{-1}$ for the 3.5 µm aperture VCSEL.
As mentioned previously in Chapter 3, the results of the loss calculation depend sensitively on the values used for the real effective indices $n_{\text{core}}$ and $n'_{\text{oxide}}$. Moreover, it is further a large assumption to calculate these values using the transmission matrix method with the nominal epitaxial layer thicknesses and compositions. In order to determine reasonably accurate values of the real refractive indices, we match our calculation to the experimental point where loss is not significant, i.e. for the VCSEL with 6 μm aperture size. Using the measured spectral splitting for this laser for which threshold current density scales linearly with aperture size, we solve Equation (3.3) for the value, $\Delta n_{\text{eff}}$, of the real effective refractive index difference between the core and cladding regions that gives equivalent spectral splitting, $\Delta \lambda$, between the fundamental mode and next higher order mode for a lossless aperture (with no imaginary $n''_{\text{oxide}}$ term in the calculation). For the VCSELs under study here, the value calculated for $\Delta n_{\text{eff}}$ is 0.007757 (which is very close to the value of 0.008 calculated by transmission matrix method). By using this value of $\Delta n_{\text{eff}}$ in our loss calculations, we extract the excessive optical loss for all smaller aperture VCSELs.

The results for the excessive fundamental mode loss due to aperture scattering are shown in Figure 4.6. As apparent in this figure, the calculated loss from the oxide aperture in the cladding region of our model increases with decreasing aperture size, as expected. We can also compare the loss values to other VCSEL performance, such as the laser slope efficiency. Optical loss $\alpha_i$ can be correlated to the laser slope efficiency $\eta_{\text{slope}}$ by the proportionality

$$
\eta_{\text{slope}} \propto \frac{\alpha_i}{\alpha_i + \alpha_m}
$$

(4.11)
where $\alpha_m$ is mirror loss and $\alpha_i$ is the optical loss, which for the small aperture lasers includes the effects of the oxide aperture. Figure 4.7 reveals that the calculated optical scattering loss is inversely proportional to experimental measurements of the laser slope efficiency for corresponding devices, as expected from Equation (4.11).

Figure 4.6: Excessive optical scattering loss for the fundamental mode as a function of aperture size.
Figure 4.7: The measured inverse laser slope efficiency versus the excessive fundamental mode loss.

4.4 References


CHAPTER 5

SUMMARY

Theoretical and experimental analyses of oxide-confined vertical-cavity surface-emitting laser (VCSEL) arrays have been presented. A semi-empirical technique involving cold-cavity spectral measurements combined with a Helmholtz waveguide model incorporating complex refractive index was used to analyze the cavity-size dependent optical scattering loss for small diameter oxide-confined VCSELs.

Arrays of oxide-confined 850 nm VCSELs with varying aperture size were fabricated. The manufactured devices were characterized under continuous wave operation, which included power versus current (LI) behavior, voltage versus current (IV) behavior, and subthreshold spectral characteristics. The excess optical scattering loss was then obtained for excessively lossy devices using the described analysis procedure.

The results of this analysis correspond well with theory and other experimentally measured laser performance characteristics such as threshold current density and laser slope efficiency. The results also correspond well with those produced by previous research indicating that excess optical scattering loss becomes significant for oxide-confined VCSELs with aperture less than 4 µm in diameter. It was observed for smaller
lasers that the scattering loss obtained exceeds 10 cm$^{-1}$, which is of the order of typical values of free carrier absorption loss for microcavity lasers.

This analysis procedure is thus shown to be appropriate for oxide-confined VCSELs, and should also prove to be a generally applicable technique for other microcavity lasers. The direct extraction of cavity-size dependent optical loss from cold-cavity measurements may aid in the design and characterization of oxide-confined VCSELs and other microcavity lasers. A future endeavor may be to check if the excess fundamental mode optical loss and complex index profile calculated for a device could be used to accurately calculate its other modal properties, such as the spectral splitting between other higher order modes.