Simple Understanding of Waveguiding in Oxidized VCSELs

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In this contribution, the waveguiding mechanism in oxidized vertical-cavity surface-emitting laser diodes is explained in an instructive manner. It is shown that the detuning of the cavity in the oxidized section results in the formation of an effective index guide, the effectiveness of which is strongly dependent on both the thickness of the oxide layer and its position in the standing wave field of the cavity. From the induced index step, the wavelength separation of different transverse modes can easily be inferred.

1. Introduction

In the last year, vertical-cavity surface-emitting lasers (VCSELs) employing selectively oxidized AlAs layers for current confinement have set new performance standards for devices operating in the 980 nm as well as in the 650 nm short wavelength regimes [1]-[4]. With conversion efficiencies up to 50 % [1], [3], thermally induced index guiding is expected to play no longer the dominant role for mode guiding, as is usually the case in proton-implanted lasers [5]. For the investigation of the transverse mode behavior of oxidized VCSELs, a theoretical understanding of the waveguiding mechanism and thus of the influence of the oxide layer is of crucial importance. This article attempts to give an understanding of the index waveguide formation in the device with an intuitive rather than a strictly theoretical approach [6]. It provides a method for calculating an effective index step from a given layer structure and to get information about the wavelength separation of different transverse modes.

2. Formation of an Effective Index Guide

In Fig. 1, the reflectivity spectrum $R_c(\lambda)$, determined with the one-dimensional transfer matrix method [7]-[8], is shown for a VCSEL with a one-wavelength thick inner cavity tuned to an emission wavelength of 980 nm, a 24 pairs Al$_{0.67}$Ga$_{0.33}$As-GaAs top and a 25.5 pairs AlAs-GaAs bottom Bragg reflector. As also schematically illustrated in Fig. 1, a single AlGaAs layer in the top mirror, adjacent to the inner cavity, is replaced by AlAs and is partially oxidized in a wet vapor atmosphere. The resulting aluminum oxide is electrically isolating and thus provides an aperture for current injection from a top ring contact into the active layer. For further details of the oxidation process and the layer structure, especially in the inner cavity, the reader is referred to other articles in this annual report.

Measurements have indicated that the refractive index of the oxide has a value of $n_{ox} = 1.55$ [9] and is thus considerably smaller than that of AlAs, $n_{as} = 2.97$. The calculation of the reflectivity spectrum $R_{ox}(\lambda)$ in the oxidized section of the VCSEL consequently shows that the cavity resonance is shifted to shorter wavelengths by an amount $\Delta \lambda_{ox}$. For an AlAs layer thickness of $d_{as} = d_{ox} = 82.5$ nm, a wavelength shift of $\Delta \lambda_{ox} = -19.2$ nm is read from Fig. 1.\footnote{An observed shrinkage of the layer during oxidation [9]-[10] is not taken into account here. In fact, the structural and geometrical details at the oxidation front are still unknown.}
The detuning of the cavity in the passive part of the laser can also be considered as to be a result of a reduction of the mean refractive index \( \langle \tilde{n} \rangle \) in the laser for radii larger than the active radius \( r_a \). The effective cavity model of a VCSEL as a resonator with a fixed geometrical length \( L_{\text{eff}} \) accordingly implies a cavity index variation

\[
\Delta \tilde{n}_{\text{eff,c}} = \Delta \lambda_{\text{ox}} \cdot \frac{\langle \tilde{n} \rangle}{\lambda},
\]

which is proportional to the wavelength shift. With \( \lambda = 980 \, \text{nm} \) and \( \langle \tilde{n} \rangle = 3.3 \), the effective cavity index step is calculated to be \( \Delta \tilde{n}_{\text{eff,c}} = -6.5 \cdot 10^{-2} \) in the example of Fig. 1, which turns out to provide a rather strong waveguiding. For illustration, a temperature variation of more than 200 K from the center of the laser to the active radius would be necessary to give the same amount of thermally induced index guiding, if a temperature coefficient \( \Delta \tilde{n}/\Delta T = 3 \cdot 10^{-4} \, \text{K}^{-1} \) of the semiconductor is assumed \cite{11}. For a deeper understanding of the influence of the oxide layer, the cavity detuning has to be investigated in more detail.

3. Understanding of the Cavity Detuning

The representation of the multilayered VCSEL structure as an effective cavity with length \( L_{\text{eff}} \) provides a first analytical estimate for the theoretically observed wavelength shift. According to this model, the change of the mean refractive index in the oxidized cavity translates into a detuning of

\[
\Delta \lambda_{\text{ox}} = \lambda \cdot \frac{d_{\text{ox}}}{L_{\text{eff}}} \cdot \frac{\tilde{n}_{\text{ox}} - \tilde{n}_{\text{se}}}{\langle \tilde{n} \rangle},
\]

which varies linearly with the oxide thickness. A more accurate description can, however, only be obtained numerically, for example with the matrix method. In Fig. 2, the wavelength detuning is plotted as a function of the oxide thickness for three different positions of the oxide layer in the cavity, namely in the first, second, or third Bragg pair of the top mirror, as seen from the active zone. The remainder of the quarter-wavelength layer not being occupied by the oxide is again replaced by \( \text{Al}_{0.07}\text{Ga}_{0.93}\text{As} \).
With increasing distance from the active layer, the detuning of the cavity becomes smaller and a saturation of $\Delta \lambda_{ax}$ is observed when the thickness of the oxide approaches that of the quarter-wavelength layer. The nonlinear dependence $\Delta \lambda_{ax} = \Delta \lambda_{ax}(d_{ax})$ results in a large deviation from the analytical estimation (2) for thicknesses $d_{ax} > 30$ nm.

![Diagram showing dependence of cavity wavelength shift on oxide layer thickness](image)

**Fig. 2:** Dependence of the cavity wavelength shift from the thickness of the oxide layer, which is located in the $m$th Bragg pair of the top mirror (left) and the resonant standing wave pattern in the oxidized VCSEL section for the case $m = 1$ and $d_{ax} = 50 \text{ nm}$ in the vicinity of the 3 QW inner cavity (right). In contrast to the solid curves, the dashed curve for $m = 2$ in the left diagram is calculated for the oxide being located at the top surface side of the quarter-wavelength layer. Also included is the analytical relation $\Delta \lambda_{ax}(d_{ax})$ as the dash-dotted line according to (2) and the conversion (1) of the wavelength shift into an effective cavity index variation for $\lambda = 980 \text{ nm}$ and $< \tilde{n} > = 3.3$.

The shape of the solid curves in Fig. 2 is well understood by looking at the standing wave pattern in the VCSEL, depicted in the second diagram of the figure. The decreasing wavelength shift with increasing Bragg pair number $m$ is apparently due to the decaying field amplitude in the top mirror. The perturbation of the cavity is the stronger, the higher the field amplitude in the oxide layer is. For a large thickness $d_{ax}$, the index perturbation is introduced near to a node of the electric field, thus resulting in the observed saturation behavior of the wavelength shift. This effect is even better seen if the oxide is located at the top surface side of the quarter-wavelength layer, as is the case for the dashed curve in the left part of Fig. 2.

The above discussion clearly shows the importance of correctly placing the oxide layer in the laser cavity and of deliberately choosing its thickness if one wishes to achieve a certain amount of index guiding in addition to current confinement.

4. Transverse Mode Spacing

As explained in section 2, an oxidized VCSEL, from the waveguiding point of view, can be approximated by a step index guide of diameter $2r_a$ and index difference $\Delta \tilde{n}_{eff,c}$. The properties of the guided modes in such a waveguide have been intensively investigated in optical fiber theory. In an optical resonator, the difference in propagation constants between the transverse modes translates into a resonance wavelength shift to satisfy the phase condition for a complete round trip of the optical field. Using the approach taken in [12], Fig. 3 shows the wavelength
spacing between the lowest order LP\textsubscript{01} and LP\textsubscript{11} transverse modes as a function of the laser active diameter for a number of cavity index steps \(\Delta \tilde{\eta}_{eff,c}\). An increase of mode spacing with decreasing active diameter and increasing index difference is observed. High values of several nm are predicted for small diameter devices, e.g., \(\Delta \lambda_{01-11} = 3\) nm for \(d_a = 2r_a = 3\ \mu m\) and a moderate index step of \(\Delta \tilde{\eta}_{eff,c} = -0.05\). For weak guiding, the higher order mode cutoff can be reached, as is the case for \(\Delta \tilde{\eta}_{eff,c} = -0.01\) at a diameter of \(d_a = 2.9\ \mu m\) in Fig. 3.

\begin{equation}
\Delta \lambda_{01-11} = \lambda_{01} - \lambda_{11} = \frac{\lambda^3}{2(2\pi < \tilde{\eta} > r_a)^2} \left(x_{11}^2 - x_{01}^2\right),
\end{equation}

where \(x_p\) is the \(p\)th zero of the Bessel function \(J_p\). In this limiting case, the wavelength spacing is inversely proportional to the active area \(A_a = \pi r_a^2\). With \(x_{01} = 2.41\) and \(x_{11} = 3.83\), the relation (3) is also plotted in Fig. 3. As expected, the deviation from the curves calculated for index guiding vanishes for large diameter devices. It is important to note that the factor \(\lambda^3\) in (3) can account for considerably different mode spacings in short or long wavelength VCSELs, compared to Fig. 3.

5. Conclusion

In this article, a simple method for investigating the induced index guiding in oxidized vertical-cavity lasers has been presented. It is based on the one-dimensional evaluation of the resonance condition in the active as well as in the passive sections of the device and leads to the representation of the VCSEL in terms of a step index waveguide. From the properties of the guided eigenmodes, the wavelength spacing of different transverse modes is readily obtained. Due to the strong guiding and the improved power conversion compared to proton-implanted devices, thermally induced index guiding is expected to be of less importance, relieving the necessity of employing more elaborate models for cavity analysis [13].
References


