Mode Selectivity in Oxide-Confined Vertical-Cavity Surface-Emitting Lasers

Włodzimierz Nakwaski and Robert P. Sarzała

Laboratory of Computer Physics
Institute of Physics, Technical University of Łódź
ul. Wólczańska 219, 93-005 Łódź, Poland

e-mail: nakwaski@p.lodz.pl rpsarzal@p.lodz.pl
Outline

• Radial electrical and optical VCSEL confinements
• Motivation
• The model
• VCSEL with a single oxide aperture
• VCSEL with two oxide apertures
• The SCO (Separate Confinement Oxidation) VCSEL
• Conclusions
Radial confinements of both a current injection and an optical field in GaAs-based VCSELs

$\text{Al}_x\text{O}_y$ layer – high electrical resistivity, low index of refraction, high thermal conductivity (probably)
Motivation

During the presentation, the designing strategy to enhance mode selectivity (i.e. to ensure the single fundamental $LP_{01}$ mode operation) in oxide-confined high-power VCSELs is presented.
The three-dimensional fully self-consistent model

The model is composed of four interrelated parts:

• **the optical model** describing for successive modes a distribution of an optical field within the resonator and enabling determination of its lasing threshold,

• **the electrical model** characterizing both the current spreading between the top and bottom contacts and injection of carriers of both kinds into the active region,

• **the thermal model** characterizing generation of a heat flux and its spreading from heat sources towards heat sink and

• **the gain model** enabling determination of gain spectra within the active region.

The calculation algorithm

START

Room-temperature carrier-less values of all model parameters

Set initial value of applied voltage

Determination of a 3D potential distribution

Is the assumed exactness achieved?

YES

Determination of 3D temperature profiles

Is the assumed exactness achieved?

NO

Set new 3D profiles of all model parameters

YES

New effective conductivity of the active region

Set a new value of an applied voltage

NO

Determinations of current injection into the active region

Determination of the active-region gain spectra

Determinations of 3D intensity profiles of successive radiation modes

Is the lasing threshold achieved?

YES

STOP

NO

Determinations of 3D intensity profiles of successive radiation modes

Is the lasing threshold achieved?

NO

YES
VCSEL with a single oxide aperture

**Vertical Cavity Surface Emitting Laser**

- **p-side DBR**
- **GaAs/Al\textsubscript{0.8}Ga\textsubscript{0.2}As** active region
- **n-side DBR**
- **GaAs/AlAs**

**Resonator**

- **3\textit{e}/2**
- **p-side DBR**
- **GaAs/Al\textsubscript{0.8}Ga\textsubscript{0.2}As**
- **oxidation**
- **active region**
- **n-side DBR**
- **GaAs/AlAs**

**Contacts**

- **upper contact**
- **bottom contact**
- **active region**
- **n-side DBR**
The GaInNAs/GaAs 1.3-μm VCSEL with a single oxide aperture

The VCSEL structure is similar (but not identical) to the one reported by Infineon in A. Ramakrishnan et al., J. Cryst. Growth **248** (2003) 457

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness nm</th>
<th>Refractive index $n_R$</th>
<th>$\frac{dn_R}{dT}$ 10^-4/K</th>
<th>Group refractive index $n_G$</th>
<th>Absorption coefficient $\alpha$ cm^-1</th>
<th>$\frac{d\alpha}{dT}$ 1/10^3 cmK</th>
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<tbody>
<tr>
<td>GaAs upper DBR</td>
<td>28* 95.6</td>
<td>3.4</td>
<td>3.0</td>
<td>3.654</td>
<td>1</td>
<td>1.28</td>
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<td>1.47</td>
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<td>p-GaAs</td>
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<td>1.28</td>
</tr>
<tr>
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<td>1.681</td>
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<td>0</td>
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<tr>
<td>p-GaAs</td>
<td>165.2</td>
<td>3.4</td>
<td>3.0</td>
<td>3.654</td>
<td>5</td>
<td>1.28</td>
</tr>
<tr>
<td>Ga$<em>{0.66}$In$</em>{0.34}$N$<em>{0.017}$As$</em>{0.983}$ quantum well</td>
<td>2* 6.5</td>
<td>3.8</td>
<td>3.0</td>
<td>4.62</td>
<td>0</td>
<td>0</td>
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<td>3.4</td>
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<tr>
<td>n-GaAs</td>
<td>171.6</td>
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<td>3.0</td>
<td>3.654</td>
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<td>1.28</td>
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<tr>
<td>GaAs bottom DBR</td>
<td>34* 95.6</td>
<td>3.4</td>
<td>3.0</td>
<td>3.654</td>
<td>0.5</td>
<td>1.28</td>
</tr>
<tr>
<td>AlAs bottom DBR</td>
<td>34* 111.5</td>
<td>2.915</td>
<td>1.34</td>
<td>3.056</td>
<td>0.5</td>
<td>1.28</td>
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</tbody>
</table>
VCSEL with a single oxide aperture at the anti-node position
VCSEL with a single oxide aperture at the anti-node position

1.5 \lambda
QW - 6.5 nm
In - 35%
N - 1.8%
VCSEL with a single oxide aperture

\[ g_{th,\text{max}} \text{ [cm}^{-1}\text{]} \]

Distance from the anti-node position [nm]

\[ \lambda \text{ [nm]} \]

\[ r_A = 7.5 \mu \text{m} \]
VCSEL with a single oxide aperture

<table>
<thead>
<tr>
<th>Number and structure symbol</th>
<th>$r_A$ [$\mu$m]</th>
<th>$U_{th}$ [V]</th>
<th>$I_{th}$ [mA]</th>
<th>$T_{A,max}$ [K]</th>
<th>$g_{th,max}$ [cm$^{-1}$]</th>
<th>mode</th>
<th>$\lambda$ [nm]</th>
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<tbody>
<tr>
<td>1 SN</td>
<td>10</td>
<td>3.65</td>
<td>21.13</td>
<td>316.83</td>
<td>4432</td>
<td>LP$_{01}$</td>
<td>1303.2</td>
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<tr>
<td>2 SA</td>
<td>10</td>
<td>2.09</td>
<td>8.24</td>
<td>304.28</td>
<td>1644</td>
<td>LP$_{11.1}$</td>
<td>1295.1</td>
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<tr>
<td>3 SN</td>
<td>7.5</td>
<td>2.55</td>
<td>10.22</td>
<td>308.16</td>
<td>2792</td>
<td>LP$_{01}$</td>
<td>1302.4</td>
</tr>
<tr>
<td>4 SA</td>
<td>7.5</td>
<td>1.94</td>
<td>5.72</td>
<td>303.76</td>
<td>1539</td>
<td>LP$_{71}$</td>
<td>1295.8</td>
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<tr>
<td>5 SN</td>
<td>5</td>
<td>1.99</td>
<td>5.11</td>
<td>305.18</td>
<td>2174</td>
<td>LP$_{01}$</td>
<td>1302.1</td>
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<tr>
<td>6 SA</td>
<td>5</td>
<td>1.68</td>
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<td>4.85</td>
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<td>1302.3</td>
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<tr>
<td>8 SA</td>
<td>2</td>
<td>1.27</td>
<td>0.86</td>
<td>301.50</td>
<td>1189</td>
<td>LP$_{01}$</td>
<td>1298.2</td>
</tr>
</tbody>
</table>
VCSEL with a single oxide aperture

No further improvements are available in VCSELs with a single oxide aperture. Then two extreme cases are possible:

- **Index-guided VCSELs**: To reduce a VCSEL threshold current, the radial index-guiding is necessary achieved with the aid of the oxide aperture located at the anti-node position of the resonator standing wave. But then, in the case of higher-output large-size VCSELs, higher-order transverse modes exhibit the lowest thresholds.

- **Gain-guided VCSELs**: To ensure the fundamental-mode $\text{LP}_{01}$ operation, the radial gain-guiding should be used realized in the VCSEL design with the oxide aperture located at the analogous node position. Then its threshold current is considerably higher.

Further improvements may be possible in VCSELs with two oxide apertures.
VCSEL with two oxide apertures
The VCSEL structure is similar (but not identical) to the one reported by Infineon in A. Ramakrishnan et al., J. Cryst. Growth 248 (2003) 457
General strategy

Much more improvements may be expected in the oxide-confined VCSEL when:

• one of its oxide apertures is localized in a VCSEL cavity at the antinode position of the optical standing wave, where it is working as both the electrical aperture confining radially the current injection into the active region and the optical aperture introducing the built-in radial optical confinement mechanism,

• the second oxide aperture on the opposite side of the active region is shifted to the analogous standing-wave node position, where it is working as the electrical aperture only.
The **SCO VCSEL** – new concept

Diameters of both the apertures may be changed independently giving an additional degree of freedom for VCSEL designing. Then the second aperture, located at the node position, will influence the current spreading only, whereas the first one, in the anti-node position, will mostly introduce the radial waveguiding effect. Both radial confinements influencing the current spreading and the electromagnetic field may be achieved separately, analogously to their axial confinements in the SCH (Separate Confinement Heterostructure) diode lasers. That is why we call this laser structure the SCO (Separate Confinement Oxidation) VCSEL.

Different aperture diameters may be obtained taking advantage of the dependence of radial oxidation kinetics on a composition and a thickness of the oxidized layer (see W. Nakwaski et al. *Semicond. Sci. Technol.* **19** (2004) 333)
SCH
Separate Confinement Heterostructure

SCO
Separate Confinement Oxidation
The SCO VCSEL

Separate Confinement Oxidation

DQW - GaInNAs/GaAs 6.5 nm/25 nm active region

28 pair p-side DBR

34 pair n-side DBR

Heat Sink

3λ resonator

oxide - optical aperture

oxide - electrical aperture

• 1300 nm
The SCO VCSEL

- Oxide layer (electrical aperture)
- Oxide layer (optical aperture)
- DQW
- 3λ resonator
- n-side DBR
- p-side DBR

SCO structure:
- \( r_A = 7.5 \, \mu m \)
- \( r_E = 5.0 \, \mu m \)

Intensity [a.u.]

Distance from bottom n-side DBR [\( \mu m \)]
The SCO VCSEL

SCO  \( r_E = 3.75 \ \mu m, \ r_A = 5.0 \ \mu m \)
\( U_{th} = 1.56 \ \text{V} \)

\( U_{th} = 1.27 \ \text{V} \)
\( r_E = r_A = 2.5 \ \mu m \)

\( T_{HS} = 300 \ \text{K} \)
DQW - 6.5 nm, 3\( \lambda \)
In - 34%  
N - 1.7%
The SCO VCSEL

Intensity [a.u.]

\[ \phi = 2r_A = 15 \, \mu m \]
The SCO VCSEL

\[ r_A = 5 \, \mu m \]
\[ T_{HS} = 300 \, K \]
The SCO VCSEL

\[ \phi = 2r_A = 10 \, \mu m, \ 3\lambda \]

DQW - 6.5 nm

N - 1.7%

\ln - 34%

\[ \Delta T_{A,max} \]

\[ I_{th} \] [mA]

\[ \ln(I_{th}) \]

\[ T_0 = 50 \, K \]

\[ T_0 = 60 \, K \]

\[ T_0 = 71 \, K \]

\[ T_0 = 108 \, K \]

SCO

\[ r_E = 3.75 \, \mu m, \ r_A = 5 \, \mu m \]

\[ r_E = r_A = 5 \, \mu m \]
## The SCO VCSEL

<table>
<thead>
<tr>
<th>Name of structure</th>
<th>$r_A$ [μm]</th>
<th>$r_E$ [μm]</th>
<th>$U_{th}$ [V]</th>
<th>$I_{th}$ [mA]</th>
<th>$T_{A, max}$ [K]</th>
<th>$g_{th, max}$ [cm$^{-1}$]</th>
<th>MOD</th>
<th>$\lambda$ [nm]</th>
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<tr>
<td>1 SN</td>
<td>10</td>
<td>-</td>
<td>3.65</td>
<td>21.13</td>
<td>316.83</td>
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<td>11 D</td>
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<td>LP$_{01}$</td>
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</tr>
</tbody>
</table>

**SN** – single oxidation at the node position  
**SA** – single oxidation at the anti-node position  
**D** – two identical oxidations  
**SCO** – new SCO VCSEL
Conclusions

The new SCO VCSEL structure demonstrates advantages of both the previous oxide-confinement VCSELs:

- **the stable single-fundamental-mode operation** of the gain-guided VCSEL with the oxide aperture located at the standing-wave node position, and

- **the low lasing threshold** of the index-guided VCSEL with the aperture shifted to the analogous anti-node position.

Therefore, the traditional VCSEL design with the oxide aperture located at the standing-wave node position may be recommended for the room-temperature operation of large-active-region VCSELs because of their relatively simple technology. In all other cases, the new SCO VCSEL structure ensures much better performance.