Analysis of Substrate Modes in a (Al,In)GaN/SiC Semiconductor Laser using Finite Element Approach

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Outline

- Motivation
- Problem definition
- Solution of the Helmholtz eq.
- Substrate modes explanation
- Design variations
- Conclusion and outlook
Motivation

Oscillations in Hakki-Paoli Gain Measurements

- (Al,In)GaN on SiC
- no oscill. on Sapphire

Secondary Lobes in Far Field

Far-field: z=20µm
Near-field: z=30nm
Facet: z=0

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(In/Al)GaN edge emitting blue laser (OSRAM)

Device Description

Device Description II

- p-dopant induces optical loss
- optical mode extends into substrate (1D TMM)

<table>
<thead>
<tr>
<th>opt. loss [1/cm]</th>
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<tbody>
<tr>
<td>Gold</td>
</tr>
<tr>
<td>p-doped GaN</td>
</tr>
<tr>
<td>n-doped GaN</td>
</tr>
<tr>
<td>SiC</td>
</tr>
</tbody>
</table>

for details:
APL 85, N. 9, 2004
APL 68, N. 5, 1996
APL 68, N. 22, 1996
APL 80, N. 1, 2002
JJAP 33, pp. 2479, 1994
Hypothesis:

substrate induces periodic variations in modal loss

\[ G = \Gamma \cdot g - \alpha_{\text{cavity}} - \alpha_{\text{mirror}} - \alpha_{\text{substrate}} \]
Solution of Helmholtz Equation

- finite element 2-D
- vectorial formulation to describe interfaces properly
- complex notation for refractive index (gain/loss)
- boundary conditions: Dirichlet + PMLs
- two steps: first guess for model including substrate
Solution of Helmholtz Equation

eigenvalue:
real and imaginary part of effective cavity index

eigenvector:
spatial distribution of electric field intensity

plot imaginary part of eigenvalue vs. photon energy
Available Data

- spectral optical gain (Hakki-Paoli)
- SiC optical loss vs. energy
- Epitaxial structure
- SEM picture (cross section)
Simulation Results

- evanescent wave excites propagating wave in substrate
- bottom gold reflects
- standing wave in substrate
  - analysis of cavity loss
Simulation Results

- **Cavity Loss**: 52 [1/cm]
- **Oscillation Amplitude**: 11 [1/cm]
- **Oscillation Period**: 12 [meV]

*Measurements*
*Simulations*

**Active region not pumped**

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**Photon Energy [eV]**

**Optical Cavity Gain [1/cm]**

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Origin of Oscillations in Spectral Gain

- $E_{ph} = 2.940$[eV]
- $E_{ph} = 2.935$[eV]

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Variation of Buffer Thickness

Buffer Layer Thickness Change [nm]

Optical Cavity Gain [1/cm]

Oscill. Amplitude [1/cm]

Photon energy

Gain

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Variation of Substrate Loss

![Graph showing the variation of Optical Cavity Gain and Oscill. Amplitude with Substrate Loss.]

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Variation of the p-doped Regions Loss

Optical Cavity Gain [1/cm]

Oscill. Amplitude [1/cm]

p-doped Material Loss [1/cm]

photon energy

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Variation of Insulating Layer Thickness

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Variation of Material Gain

Mode Gain [1/cm]

Optical Cavity Gain [1/cm]

Oscill. Amplitude [1/cm]

Photon energy

Gain

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Conclusions

1. Oscillations in gain spectra:
   - source is substrate mode
   - strong loss contribution by bottom gold at resonance

2. TCAD analysis of cavity loss:
   - main loss sources are p-cladding & top gold
Design Recommendations

1. To decrease oscillation amplitude:
   - increase buffer layer thickness
   - increase substrate loss

2. To decrease total cavity loss:
   - decrease p-dopant loss
   - increase insulating layer thickness
Thank You!

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