Analysis of the Leakage Current of GaInP/AlGaInP High Power Lasers with a self-consistent Simulation Model

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Work supported by IST project 2005-035266 WWW.BRIGHTER:EU, and by MEC (Spain) projects TEC2006-13887 and TEC2007-29619.
Outline

- Introduction and goals
- Experimental characterisation
- Simulation model
- Analysis of leakage current: sensitivity to model parameters
- Conclusions
High Power Red Lasers

Main applications:

- Photodynamic Therapy
- Fluorescence Imaging of Cancer
- Laser Display Technology
- Pumping of Solid State Lasers

Main problems:

- High dependence of threshold current with temperature
- Decrease of slope efficiency with temperature
- Catastrophic Optical Damage
- Gradual degradation
GaInP/AlGaInP Red Lasers

**Band-gap vs. composition**

![Graph showing band-gap energy vs. composition for Al$_x$Ga$_{1-x}$In$_{0.49}$P with $x = 0.58$.]

**Schematic band alignment**

![Diagram illustrating energy levels and band alignment for GaAs, AlGaInP confinement, GaInP Quantum Well (QW), and AlGaInP Clad layers.]

**Epitaxial direction**

**Confinement**  **Clad**

**Energy**

GaAs  AlGaInP confinement  GaInP QW  AlGaInP Clad.
Leakage Current in Red Lasers

Analytical Model

\[ J_{\text{LEAK}} = J_{\text{DRIFT}} + J_{\text{DIFFUSION}} \]

Leakage current depends on:
band-offset, mobilities, carrier lifetime....
Goals

- Analyze leakage current with a self-consistent laser model
- Evaluate the sensitivity of the results to the values of some material parameters
- Evaluate the effect of some design parameters: p-doping
Laser Devices and Experimental characterisation

Epitaxial design

- AlGaInP p-cladding
- AlGaInP confinement
- GaInP 1QW
- AlGaInP confinement
- AlGaInP n-cladding

Wavelength: 635 nm

Broad Area Lasers
100 µm x 1.2 mm

Threshold current (A)

Slope efficiency (W/A)

Temperature (ºC)

Pulsed

Wavelength: 635 nm
Self-consistent laser model

Main features:

- Complete semiconductor equations: Poisson + continuity electrons + continuity holes
- QW carrier capture/escape processes
- Gain calculations using parabolic fitting of VB structure (calculated by \( k.p \) band mixing model)
- \( \Gamma \) and \( X \) valleys in the CB
Model for multiple valleys in CB

- Assumption: thermal equilibrium between electrons in different valleys
- Single CB minimum with equivalent effective mass and mobility
- $m_e^{eq}$ and $\mu_e^{eq}$ are calculated analytically

$$m_e^{eq} = f_m(m_e^X, m_e^\Gamma, E_C^X - E_C^\Gamma, T)$$

$$\mu_n^{eq} = f_\mu(\mu_n^X, \mu_n^\Gamma, E_C^X - E_C^\Gamma, T)$$

Equivalent effective electron mass
Main model parameters affecting leakage

- Electron/ hole mobilities
- Electron/ hole capture times
- Band line-ups
- Γ and X valleys effective masses
- **SRH recombination parameters**: trap density, trap energy, trap carrier capture section
Band profiles under bias

\[ T = 20 \, ^\circ\text{C}; \, I = 2 \, \text{A} \]
No SRH recombination

 ✓ Low $I_{th}$; weak temperature dependence
 ✓ High $\eta_S$; weak temperature dependence
No SRH recombination

Current density profile

Electron Flow

n-side

p-side

QW

Epitaxial Direction

Leakage current

I = 2 A

Jn, Jp (kA/cm²)
Role of SRH recombination

**Graph 1:**
- Threshold current vs. Temperature (°C)
- Graph shows a trend line for "Increasing SRH" with data points for No-SRH, SRH-1, SRH-2, and SRH-3.
- The graph indicates that as the temperature increases, the threshold current also increases for each SRH level.

**Graph 2:**
- Slope efficiency vs. Temperature (°C)
- Graph shows a trend line for "Increasing SRH" with data points for No-SRH, SRH-1, SRH-2, and SRH-3.
- The graph indicates a decrease in slope efficiency as the temperature increases for each SRH level.

**Table:**

<table>
<thead>
<tr>
<th>SRH</th>
<th>Traps in p-conf</th>
<th>Traps in p-clad</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRH-1</td>
<td>1·10^{17} cm^{-3}</td>
<td>0.5·10^{16} cm^{-3}</td>
</tr>
<tr>
<td>SRH-2</td>
<td>3·10^{17} cm^{-3}</td>
<td>1·10^{16} cm^{-3}</td>
</tr>
<tr>
<td>SRH-3</td>
<td>5·10^{17} cm^{-3}</td>
<td>1.5·10^{16} cm^{-3}</td>
</tr>
</tbody>
</table>
Role of electron capture time

Increasing $\tau_{\text{cap}}$

$\tau_{\text{cap}} = 20$ ps
$\tau_{\text{cap}} = 10$
$\tau_{\text{cap}} = 5$

$\tau_{\text{cap}} = 20$ ps
$\tau_{\text{cap}} = 5$ ps
$\tau_{\text{cap}} = 10$

Threshold current (A)

Temperature (°C)

Slope efficiency (W/A)

Temperature (°C)

(Increasing electron density in confinement layers)
Role of carrier mobility in p-clad

\[ \mu_p \text{ (majority)} \uparrow \quad \Rightarrow \quad I_{\text{leakage (drift)}} \downarrow \]

Lower Electric field \( J_p = q\mu_p E \)

\[ \mu_n \text{ (minority)} \uparrow \quad \Rightarrow \quad I_{\text{leakage (diffusion)}} \uparrow \]

Higher diffusion coefficient \( J_n \text{ (dif)} = \mu_n kT \frac{dn}{dx} \)
Role of carrier mobility in p-clad

\( \mu_p \) (majority)

\[ \mu_p = 20 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \]

Increasing mobility

\( \mu_n \) (minority)

\[ \mu_n = 50 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \]

Increasing mobility
Role of doping in p-cladding

T = 20 °C

Increasing p-doping

Power (W)

Current (A)

T = 20 °C; I = 2 A

Epitaxial direction

n-side

p-side

Jp

Jn

Increasing p-doping

Jp

Jn

T = 20 °C; I = 2 A

Opto Semiconductors

NUSOD’08 Nottingham. September 08-18
Role of doping in p-cladding

- Increasing p-doping reduces drift leakage
Conclusions

- Self-consistent model predicts leakage current over p-cladding
- Leakage current is very sensitive to model parameters
- Need to determine basic material parameters to optimize red lasers
- Simulation emphasizes the important role of increasing p-doping level.
Role of doping in p-cladding

Threshold current (A) vs. Temperature (°C)

- Decreasing $N_A$
- $1 \cdot 10^{18}$ cm$^{-3}$
- $2 \cdot 10^{18}$ cm$^{-3}$

Slope efficiency (W/A) vs. Temperature (°C)

- EXP
- $1 \cdot 10^{18}$ cm$^{-3}$
- $2 \cdot 10^{18}$ cm$^{-3}$

Decreasing $N_A$
Role of electron capture time

\begin{align*}
\text{Increasing } \tau_{\text{cap}} \quad &
\begin{cases}
\tau_{\text{cap}} = 20 \text{ ps} \\
\tau_{\text{cap}} = 5 \text{ ps} \\
\tau_{\text{cap}} = 10 \text{ ps}
\end{cases}
\end{align*}

\begin{align*}
\text{EXP} \quad &
\begin{cases}
\tau_{\text{cap}} = 20 \text{ ps} \\
\tau_{\text{cap}} = 5 \text{ ps} \\
\tau_{\text{cap}} = 10 \text{ ps}
\end{cases}
\end{align*}
Role of hole mobility in p-clad

Decreasing mobility

\[ \mu_p = 5 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \]
\[ \mu_p = 10 \]
\[ \mu_p = 20 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \]

Threshold current (A) vs. Temperature (°C)

Slope efficiency (W/A) vs. Temperature (°C)
Role of electron mobility in p-clad

Increasing mobility

\( \mu_n = 300 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \)

\( \mu_n = 150 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \)

\( \mu_n = 50 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \)
Role of electron mobility in p-clad

Increasing mobility

\[ \mu_n = 300 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \]

\[ \mu_n = 50 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \]

\[ \mu_n = 150 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \]
Role of hole mobility in p-clad

Decreasing mobility

Threshold current (A)

Temperature (°C)

μ_p = 5 cm^2V^{-1}s^{-1}

μ_p = 10

μ_p = 20 cm^2V^{-1}s^{-1}

μ_p = 5

μ_p = 10

Slope efficiency (W/A)

Temperature (°C)