Systematic Study of the Effects of δ-p-doping on 1.3 μm Quantum Dot Lasers.


EPSRC National Centre for III-V Technologies, Department of Electronic & Electrical Engineering, University of Sheffield, Sheffield S3 7RH, UK.

M. Ishida¹², T. Yamamoto⁵, M. Sugawara⁴, Y. Arakawa¹²,³

¹Institute of Industrial Science, The University of Tokyo; ²Nanoelectronics Collaborative Research Center, The University of Tokyo; ³Research Center for Advanced Science and Technology, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan; ⁴Fujitsu Ltd.; ⁵Fujitsu Laboratories Ltd., 10-1 Morinosato-Wakamiya, Atsugi 243-0197, Japan

T.J. Badcock, D.J. Mowbray

Department of Physics and Astronomy, Hicks Building, University of Sheffield, Sheffield S3 7RH, UK.

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Outline

- Motivation
- Device structure
- Temperature sensitivity of $J_{th}$
- Laser characteristics
- Small signal modulation
- Conclusion
Motivation

$T_0$ is a measure of change of threshold current with temperature.

$$T_0 = \frac{\Delta T}{\Delta \ln(J_{th})}$$

Ref Arakawa & Sakaki APL Vol. 40 pp. 939-941, 1982

Effects of $\delta$-p-doping

Key assumption for infinite $T_0$:
Level spacing $\gg k_B T$

$\delta$-p-doping:
- Infinite $T_0$ (Otsubo, Bhattacharya), origins unclear
- Shown to increase $dg/dn$ in QW lasers
- Is it possible to achieve infinite $T_0$, high modulation rates, for practical applications?

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Rate Equation Model - QD Lasers

\[ \frac{\eta_{inj} I}{e V_{ac}} \quad \frac{N_c}{\tau^*_0} \quad \frac{N_G}{\tau_E} \quad \frac{N_c}{\tau_S} \]

Continuum

Ground State

\[ \frac{N_G}{\tau_S} \quad \nu_g g_m S_G \]
Solutions to Rate Equations

Frequency response of QD lasers is limited by damping (K-factor)

\[ f_{3dB_{\text{max}}} = \frac{\sqrt{2}}{2\pi} \left[ \left( \frac{1}{v_g \cdot \alpha_c} \right) + \left( \frac{\tau_0}{1 - 1/2 \left( 1 + \alpha_c / G_{\text{max}} \right)} \right) \right] \]

\( f_{3dB_{\text{max}}} \) is a function of cavity loss and saturated gain

\( F_{3dB_{\text{max}}} \) is k-factor limited bandwidth

\( \alpha_c \) is total cavity loss (\( \alpha_i + \alpha_m \))

\( \tau_0 \) is intrinsic capture time

\( G_{\text{sat}} \) is Saturated modal gain

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Device Structure - 7 DWELL

DWELL deposition:
- 2nm In$_{0.15}$Ga$_{0.85}$As
- 3ML InAs
- 6nm In$_{0.15}$Ga$_{0.85}$As
δ-p-doped DWELL

\[ T_g \]

620°C

510°C

15 nm

50 nm

9 nm

6 nm

0, 6, 12, 18 Acc/QD

Be doping
Temperature Dependence of $J_{th}$

For highest δ-p-doping

Infinite $T_0$ up to 25°C

$T_0$ increased from 40 to 120K (20-80°C)
Laser Characteristics

<table>
<thead>
<tr>
<th>Acceptors per QD</th>
<th>0</th>
<th>6</th>
<th>12</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Loss (cm(^{-1}))</td>
<td>3</td>
<td>4</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>(G_{sat}) (cm(^{-1}))</td>
<td>9-14</td>
<td>10-15</td>
<td>20-31</td>
<td>17-24</td>
</tr>
<tr>
<td>(dG/di) (cm(^{-1/2}) mA) @ 25mA</td>
<td>0.22</td>
<td>0.32</td>
<td>0.39</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Higher \(G_{sat}\) and \(dG/di\) from same number of QDs suggests more efficient filling of QD ground (hole) state and faster carrier scattering.
Optimization of Facet Coatings for Maximal K-Bandwidth

Knowing the internal loss and the gain, the mirror loss can be tailored to reach the maximum k factor limited bandwidth

\[
f_{3dB\,max} = \frac{\sqrt{2}}{2\pi} \left[ \left( \frac{1}{v_g \cdot \alpha_c} \right) + \left( \frac{\tau_0}{1 - 1/2(1 + \alpha_c/G_{\text{max}})} \right) \right]
\]
Small signal modulation: includes electrical parasitics but not non-linear effects.

\[
SSM = x + 20\log \left[ \left( 1 - \left( \frac{Freq}{Fr} \right)^2 \right)^2 + \left( \frac{Freq \cdot \gamma}{Fr^2} \right)^2 \right]^{\frac{1}{2}} + 20\log \left[ 1 + \left( \frac{Freq}{RC} \right)^2 \right]^{\frac{1}{2}}
\]
Frequency Response Fitting

Effect of damping similar to RC roll off

R and C are known, so RO and K-factor limit to modulation response can be determined

Laser Diode Modulation and Noise “K Petermann”

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SSM results and fitting

Modulation Response (dB) vs. Frequency (GHz)

18 acc/QD 1mm cavity HR1/HR2
Results from ft

\[ \text{RO Frequency (GHz)} = 0.75 \text{ GHz/mA}^{0.5} \]

\[ (I-I_{th})^{0.5} \cdot \text{mA}^{0.5} \]

\[ f(K-3dB) = 10.1 \text{ GHz} \]

18 acc/QD, optimised facet coatings
## Key Results

<table>
<thead>
<tr>
<th>Acc/ QD</th>
<th>K-Limit (GHz)</th>
<th>$\tau_0$ (ps)</th>
<th>RO Mod Eff (GHz/ mA$^{1/2}$)</th>
<th>Measured Max 3dB (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5.0</td>
<td>-</td>
<td>0.36</td>
<td>16</td>
</tr>
<tr>
<td>6</td>
<td>5.4</td>
<td>4.2</td>
<td>0.7</td>
<td>3.8</td>
</tr>
<tr>
<td>12</td>
<td>8.9</td>
<td>3.3</td>
<td>0.73</td>
<td>3.6</td>
</tr>
<tr>
<td>18</td>
<td>10.1</td>
<td>15</td>
<td>0.75</td>
<td>5.1</td>
</tr>
</tbody>
</table>
Conclusions:

- With increased $\delta$-p-doping:
  - Increased $T_0$ (20-80°C) and larger infinite $T_0$ temperature span
  - Increased saturated gain and differential gain
  - Increased internal loss
  - Increased K-factor limited bandwidth
  - Increased RO modulation efficiency
  - Decreased carrier relaxation times

- Reduction in RC can be expected to realize 10GBit lasers - via optimised cladding p-doping, cavity width/length reduction
- Optimisation of $\delta$-p-doping required to bring infinite $T_0$ into commercial range (20-80°C)
Acknowledgements