Carrier Transport and Optical Properties of InGaN SQW with Embedded AlGaN δ-Layer

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Outline

- Importance of green LEDs/Lasers
- How to circumvent piezoelectric field effects
  - Growth on nonpolar or semipolar planes
  - Embedding a $\delta$-layer into a SQW
- Simulation & Experiment results
- Overall conclusion
LED BLU

IMID 2006
40" LED

← CCFL

← Small chip LED
# of LEDs: 2,160
► Low power consumption
► Superior color representation
► No fan and no heat sink
Why Green LEDs/Lasers So Important?

Samsung LCD
HDTV

LED BLU for LCD

Projector

LED body
Problems with Thin InGaN MQW for Long-Emission Wavelengths

- High In-composition for long-wavelength tuning
  - CQ-related issues (trap at deep localized states and nonradiative spots)
- High PEC:
  - Wavefunction overlap
  - Carrier transport
- High $I_{th}$, Low $\eta_{int}$: DQW, <485nm
Carrier Transport in
Thin InGaN/AlGaN DQW

2nm-thick In$_{0.15}$Ga$_{0.85}$N  7nm-thick Al$_{0.05}$Ga$_{0.95}$N

100% PEC
Problems with *Thick* InGaN QW

- Wavefunction overlap
  \[ \rightarrow \text{long } \tau_c \]

- Low In-composition for long-wavelength tuning
How To Tackle (1):
Growth on semipolar or nonpolar templates

C-oriented

- **LED performance**: C-plane
  - C-sapphire ≈ C-GaN
  - $\eta_{\text{ext}} \approx 35\%$ (blue), $30\%$ (green)

- **Laser performance**: C-plane
  - C-sapphire < C-GaN

- **LED performance**: semipolar or nonpolar
  - $r$-sapphire ($\eta_{\text{ext}} \approx 0.4\%$) < semipolar GaN (4~5\%) at 420nm

Dr. Nishizuka, APL, 2004
How To Tackle (2):
Thick SQW with Embedded AlGaN δ-Layer

- less In-composition for long-wavelength tuning (compared to thin SQW)

- Increase wavefunction overlap (compared to thick SQW)

- Uniform carrier distribution
Layer Structure & Growth

Layer Structure

<table>
<thead>
<tr>
<th>GaN barrier layer</th>
<th>6.2 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>In_{0.16}Ga_{0.84}N QW</td>
<td>2.0 nm</td>
</tr>
<tr>
<td>Al_{0.05}Ga_{0.95}N &amp;-layer</td>
<td>1.0 nm</td>
</tr>
<tr>
<td>In_{0.16}Ga_{0.84}N QW</td>
<td>2.0 nm</td>
</tr>
<tr>
<td>GaN barrier layer</td>
<td>6.2 nm</td>
</tr>
<tr>
<td>HT-GaN</td>
<td>3.0 (\mu)m</td>
</tr>
<tr>
<td>LT-GaN</td>
<td>50 nm</td>
</tr>
<tr>
<td>Sapphire substrate</td>
<td></td>
</tr>
</tbody>
</table>

MOVPE epitaxy growth
Numerical Models:
Inorganic Semiconductor Devices

< Poisson’s equation >
\[ \nabla \cdot (\varepsilon \nabla \psi) = -q(p - n + N_D - N_A) - \rho_{pol} \]
\[ \rho_{pol} = -\frac{\partial}{\partial z} \left[ e_{33} \varepsilon_{\perp}(x) + 2e_{31} \varepsilon_{\parallel}(x) + P_{sp}(x) \right] \]
\[ \varepsilon_{\parallel}(x) = \frac{a_{sub} - a(x)}{a(x)} \quad \varepsilon_{\perp}(x) = -2 \varepsilon_{\parallel}(x) \frac{C_{33}}{C_{11}} \]

< Drift-Diffusion equation >
\[ \frac{\partial n}{\partial t} = \frac{1}{q} \nabla \cdot ( - q \mu_n n \nabla \phi_n ) + G - R \]
\[ \frac{\partial p}{\partial t} = \frac{1}{q} \nabla \cdot ( - q \mu_p p \nabla \phi_p ) + G - R \]
\[ n = n_i \exp \left[ \left( (\psi + \theta - \gamma_n) - \phi_n \right) / V_T \right] \]
\[ p = n_i \exp \left[ \left( \phi_p - (\psi + \theta - \gamma_p) \right) / V_T \right] \]

< effective-mass Schrödinger equation >
\[ \sum_{j=1}^{6} (H_{ij} + \delta_{ij} E^v(z)) \phi_{m}^{(j)}(z) = E_{m}^{v} \phi_{m}^{(i)}(z) \]
\[ H_{6x6} = \begin{bmatrix} H^U & 0 \\ 0 & H^L \end{bmatrix} \]
\[ H^U = \begin{bmatrix} F & K_t & -iH_t \\ K_t & G & \Delta - iH_t \\ iH_t & \Delta + iH_t & \lambda \end{bmatrix} \]
\[ F = \Delta_1 + \Delta_2 + \lambda + \theta, \quad G = \Delta_1 - \Delta_2 + \lambda + \theta, \quad \Delta = \sqrt{2} \Delta_3 \]
\[ \lambda = \frac{\hbar^2}{2m_0} \left( A_1 k_x^2 + A_2 k_i^2 \right) + D_1 \varepsilon_{zz} + D_2 (\varepsilon_{xx} + \varepsilon_{yy}) \]
\[ \theta = \frac{\hbar^2}{2m_0} \left( A_1 k_x^2 + A_4 k_i^2 \right) + D_3 \varepsilon_{zz} + D_4 (\varepsilon_{xx} + \varepsilon_{yy}) \]
\[ K_t = \frac{\hbar^2}{2m_0} A_5 k_x^2, \quad H_t = \frac{\hbar^2}{2m_0} A_6 k_z k_t \]
SQW with δ-Layer (=DQW):

Wavefunction Overlap

- 5-nm In$_{0.15}$Ga$_{0.85}$N QW
- 10-Å Al$_{0.05}$Ga$_{0.95}$N δ-layer
SQW with δ-layer: Carrier Transport

![Energy vs Distance](image1.png)

![Density vs Distance](image2.png)

![Energy vs Distance](image3.png)

![Density vs Distance](image4.png)
Band Structure of QW with δ-layer

[4nm SQW]

[0.4nm δ-layer]

[0.8nm δ-layer]

[1.0nm δ-layer]

[1.4nm δ-layer]

[2nm SQW]
Experimental Results:
PL peak wavelength and PL lifetime

PL spectra & efficiency

PL decay dynamics

- 2nm-thick SQW
- 4nm-thick SQW
- QW with 1nm-thick δ-layer

- 4nm SQW (450ns)
- QW with δ-layer (104ns)
- 2nm SQW (13.2ns)
PL Spectra: Different $\delta$-Layer Thickness

A QW with 1nm $\delta$-layer requires about 4% less indium for green emission, compared to 2-nm-thick SQW.
Wavefunction Overlap: Different $\delta$-Layer Thickness

(a) 4nm-thick SQW
(b) $T_\delta=0.4\text{nm}$
(c) $T_\delta=1.0\text{nm}$
(d) $T_\delta=1.6\text{nm}$
Overlap Integral: Different Indium Composition
Overlap Integral:
Different Aluminum Composition

In=15%
Overlap Integral: δ-doping
The δ-layer offers an extra degree of freedom in tuning the emission wavelength.

The δ-layer enable us to tune long-wavelength with lower indium composition.

The δ-layer increases the wavefunction overlap between holes and electrons, the PL lifetime by which is expected to shorten.