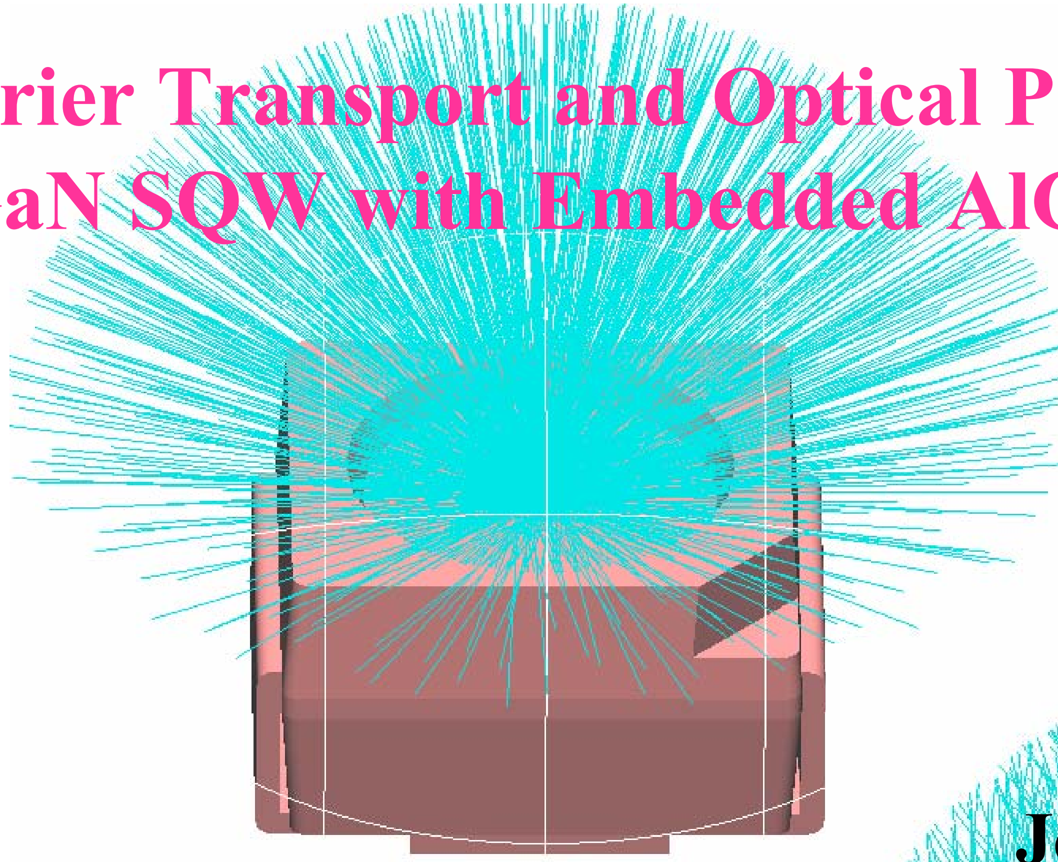
Carrier Transport and Optical Properties of InGaN SQW with Embedded AlGaN δ-Layer



Jongwoon Park
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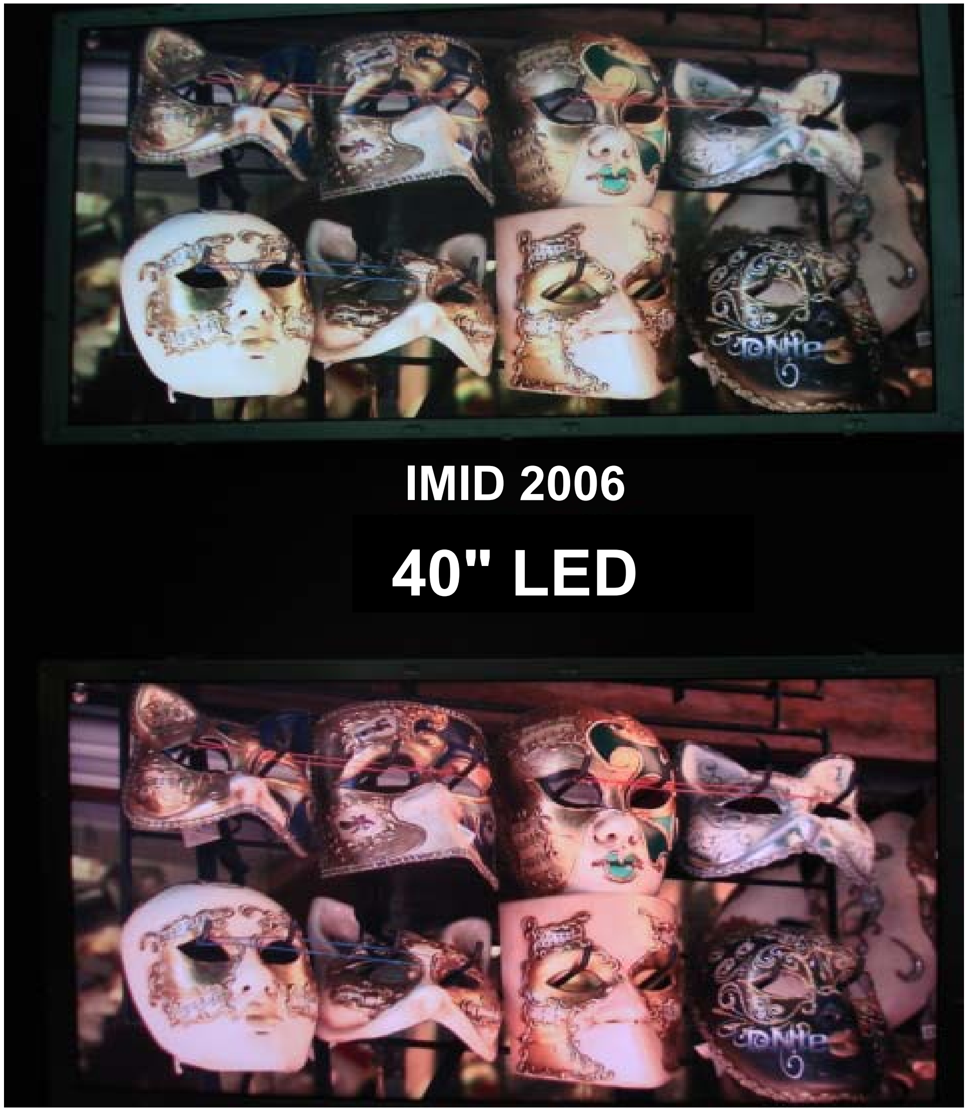
Japan

Outline

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

LED BLU



← **CCFL**

← **Small chip LED**

# of LEDs: 2,160

► Low power consumption

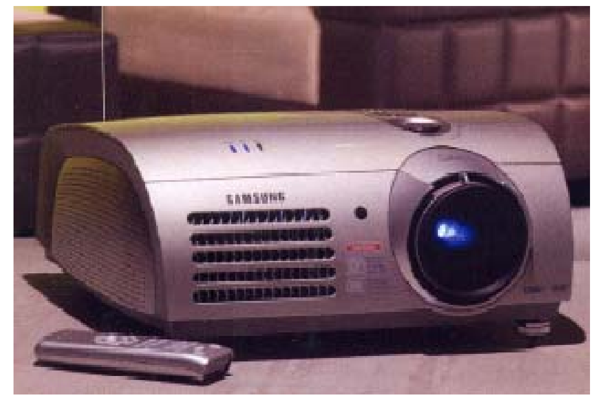
► Superior color representation

► No fan and no heat sink

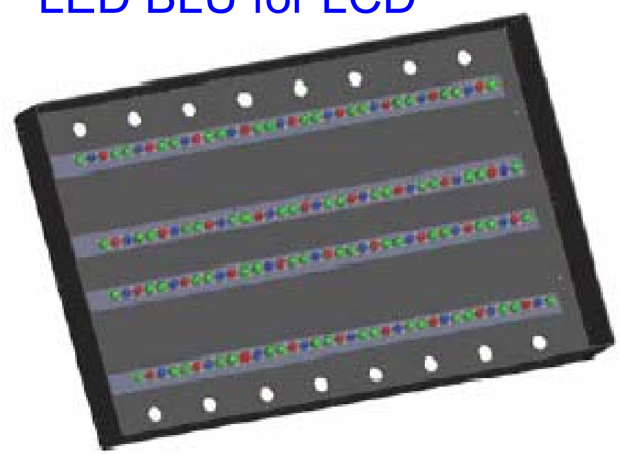
Why Green LEDs/Lasers So Important?

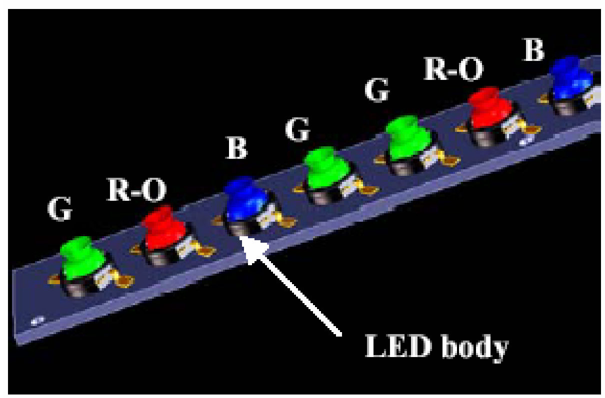
Samsung LCD HDTV

Projector

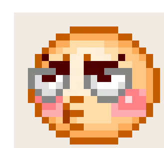


LED BLU for LCD





SAMSUNG SONY LG전자 LG Electronics

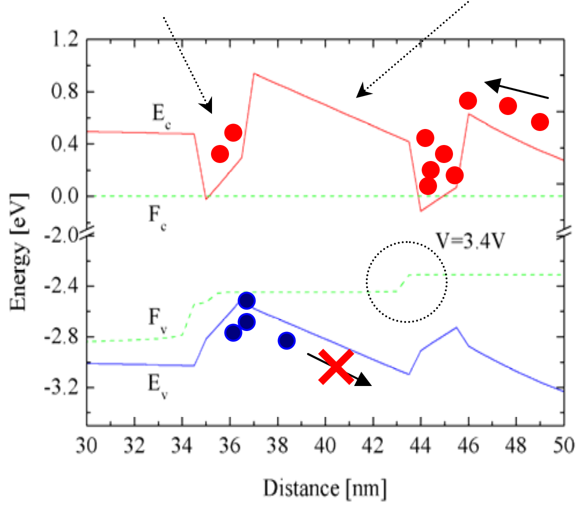


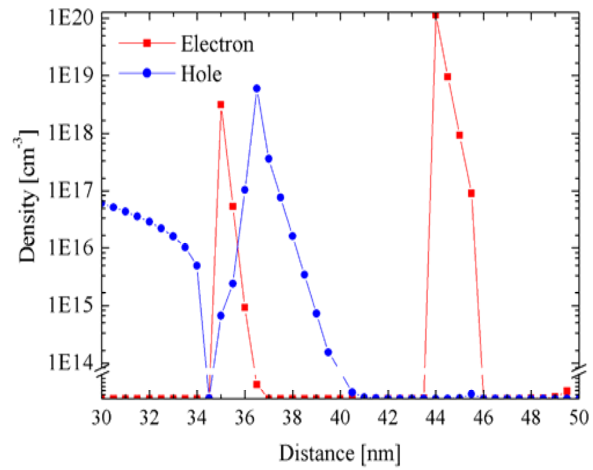
Problems with *Thin* InGaN MQW for Long-Emission Wavelengths

- 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 η_{int} : DQW, <485nm

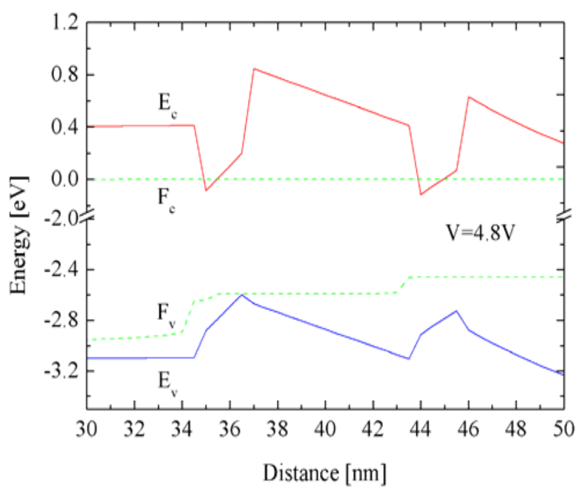
Carrier Transport in
Thin InGaN/AlGaN DQW

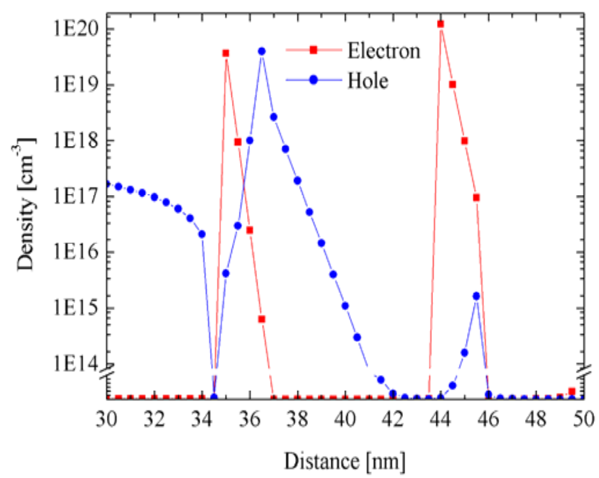
2nm-thick $In_{0.15}Ga_{0.85}N$ 7nm-thick $Al_{0.05}Ga_{0.95}N$





100%
PEC

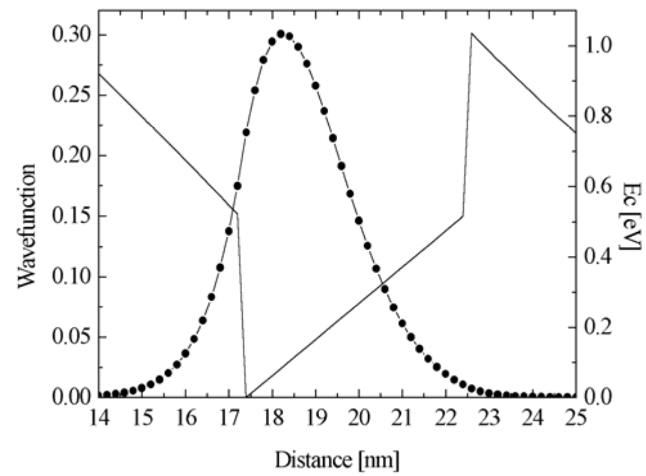


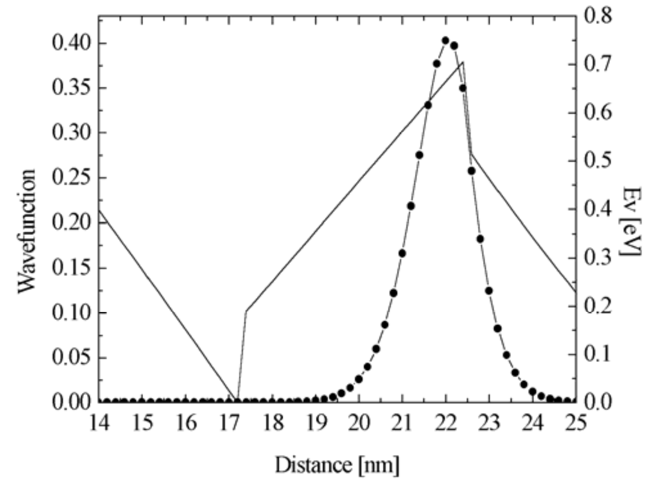


Problems with *Thick* InGaN QW

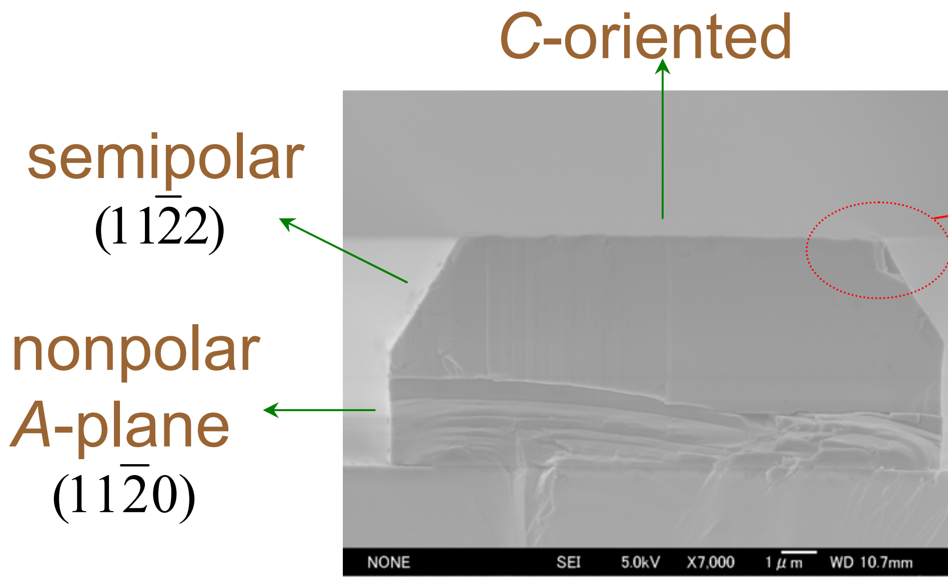
- Wavefunction overlap
  $\rightarrow$ long τ_c
- Low In-composition for long-wavelength tuning

5nm-thick $In_{0.15}Ga_{0.85}N$ SQW

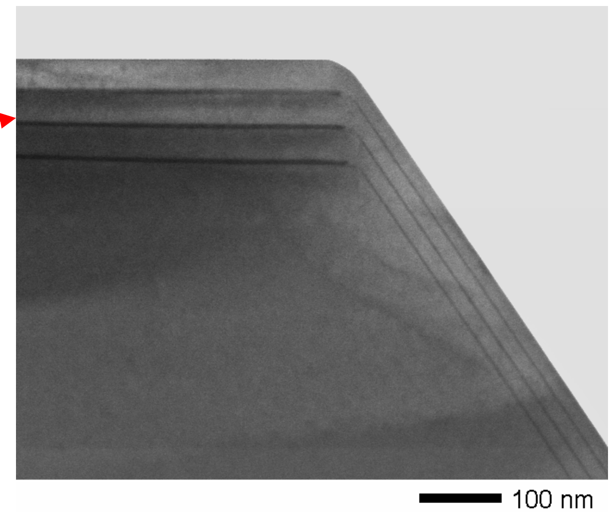




How To Tackle (1):
Growth on semipolar or nonpolar templates



Dr. Nishizuka, APL, 2004



- LED performance : *C*-plane
  - *C*-sapphire ≈ *C*-GaN

  η_{ext} ≈ 35%(blue), 30%(green)
- LED performance : *semipolar or nonpolar*
  - *r*-sapphire (η_{ext} ≈ 0.4%) < *semipolar* GaN (4~5%) at 420nm

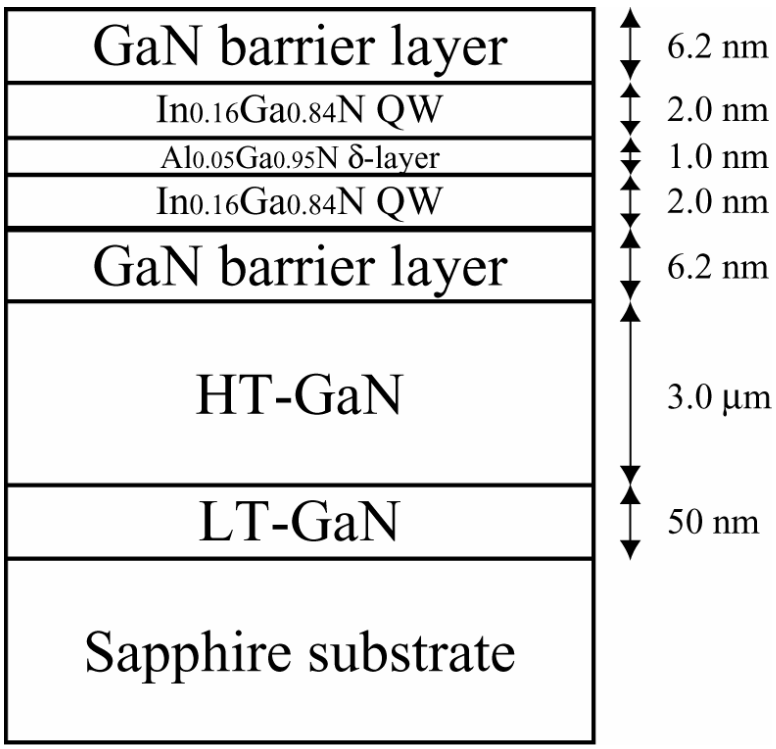
- Laser performance : *C*-plane
  - *C*-sapphire < *C*-GaN
- Laser performance : *semipolar or nonpolar*
  - Lasing is not feasible

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



MOVPE epitaxy growth

Numerical Models:
Inorganic Semiconductor Devices

< Poisson's equation >

$$\nabla \cdot (\varepsilon \nabla \psi) = -q(p - n + N_D - N_A) - \rho_{pol}$$

$$\rho_{pol} = -\frac{\partial}{\partial z}\left[e_{33}\varepsilon_{\perp}(x) + 2e_{31}\varepsilon_{\parallel}(x) + P_{sp}(x)\right]$$

$$\varepsilon_{\parallel}(x) = \frac{a_{sub} - a(x)}{a(x)} \qquad \varepsilon_{\perp}(x) = -2\varepsilon_{\parallel}(x)\, {}^{C_{13}}\!/_{C_{33}}$$

< Drift-Diffusion equation >

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \cdot (-q\mu_n n \nabla \phi_n) + G - R$$

$$\frac{\partial p}{\partial t} = \frac{1}{q}\nabla \cdot (-q\mu_p p \nabla \phi_p) + G - R$$

$$n = n_i \exp\left[\{(\psi + \theta - \gamma_n) - \phi_n\}/V_T\right]$$

$$p = n_i \exp\left[\{\phi_p - (\psi + \theta - \gamma_p)\}/V_T\right]$$

< effective-mass Schrödinger equation >

$$\sum_{j=1}^{6}\left(H_{ij} + \delta_{ij}E^{v}(z)\right)\varphi_m^{(j)}(z) = E_m^{v}\varphi_m^{(i)}(z)$$

$$H_{6\times 6} = \begin{bmatrix} H^U & 0 \\ 0 & H^L \end{bmatrix}$$

$$H^U = \begin{bmatrix} F & K_t & -iH_t \\ K_t & G & \Delta - iH_t \\ iH_t & \Delta + iH_t & \lambda \end{bmatrix}$$

$$F = \Delta_1 + \Delta_2 + \lambda + \theta, \quad G = \Delta_1 - \Delta_2 + \lambda + \theta, \quad \Delta = \sqrt{2}\Delta_3$$

$$\lambda = \frac{\hbar^2}{2m_0}\left(A_1 k_z^{\,2} + A_2 k_t^{\,2}\right) + D_1\varepsilon_{zz} + D_2(\varepsilon_{xx} + \varepsilon_{yy})$$

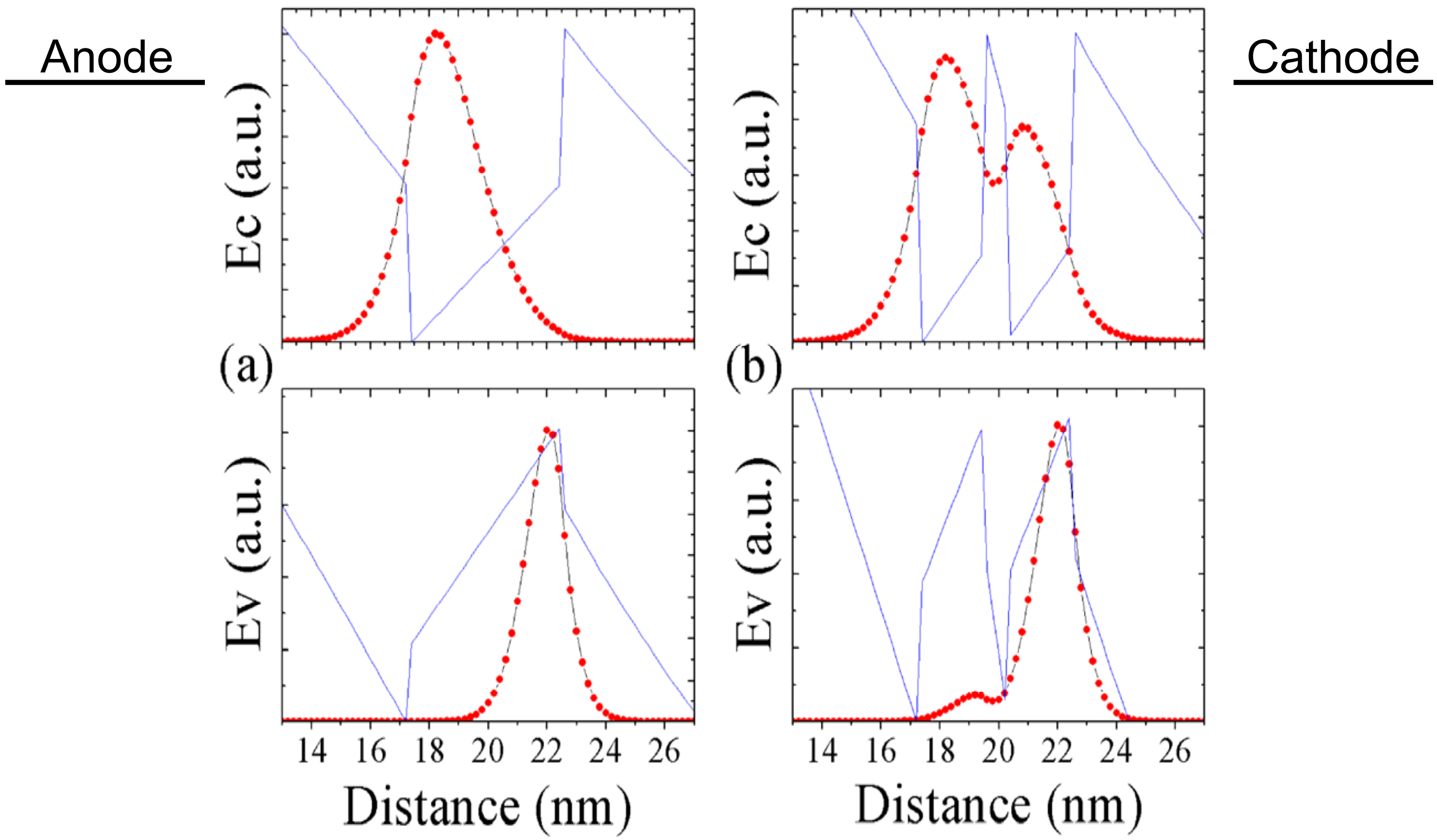
$$\theta = \frac{\hbar^2}{2m_0}\left(A_3 k_z^{\,2} + A_4 k_t^{\,2}\right) + D_3\varepsilon_{zz} + D_4(\varepsilon_{xx} + \varepsilon_{yy})$$

$$K_t = \frac{\hbar^2}{2m_0}A_5 k_t^{\,2}, \quad H_t = \frac{\hbar^2}{2m_0}A_6 k_z k_t$$

SQW with δ-Layer (=DQW):

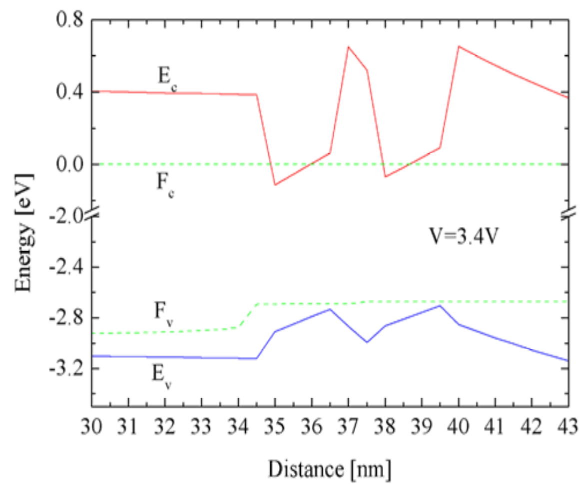
Wavefunction Overlap

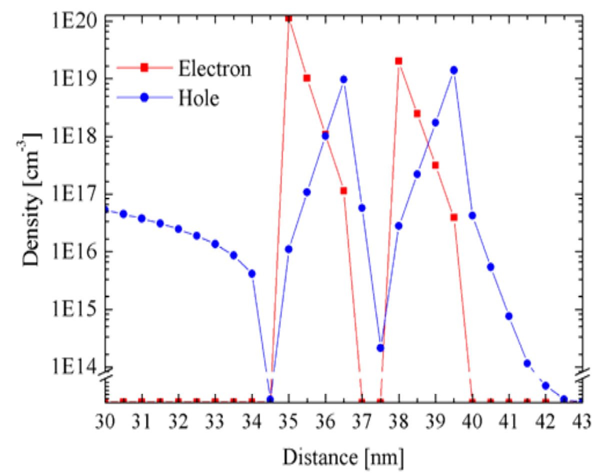
- 5-nm $In_{0.15}Ga_{0.85}N$ QW
- 10-Å $Al_{0.05}Ga_{0.95}N$ δ-layer

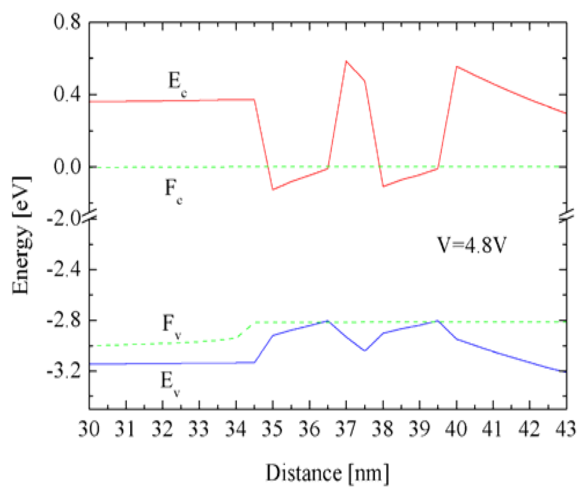


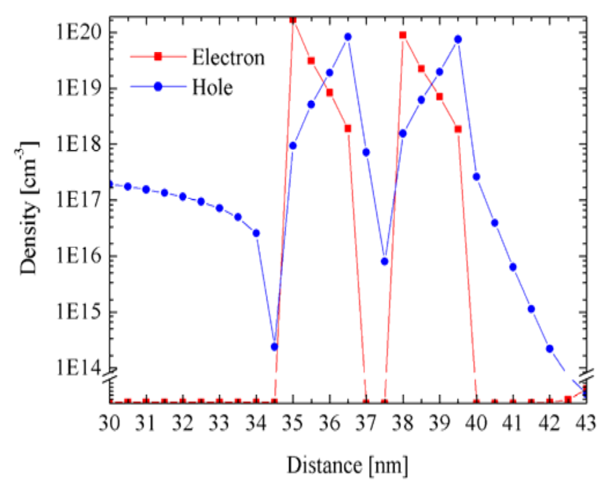
SQW with δ-layer:

Carrier Transport



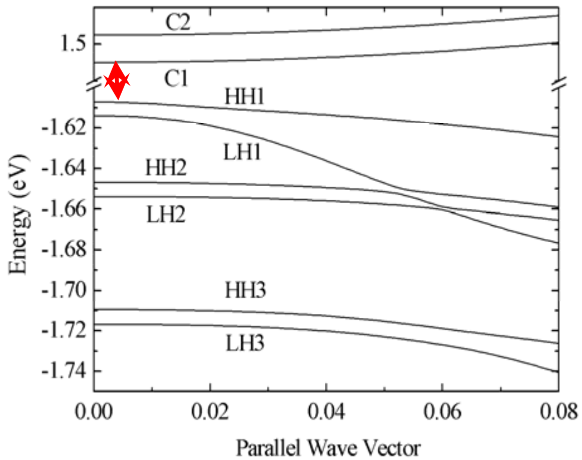




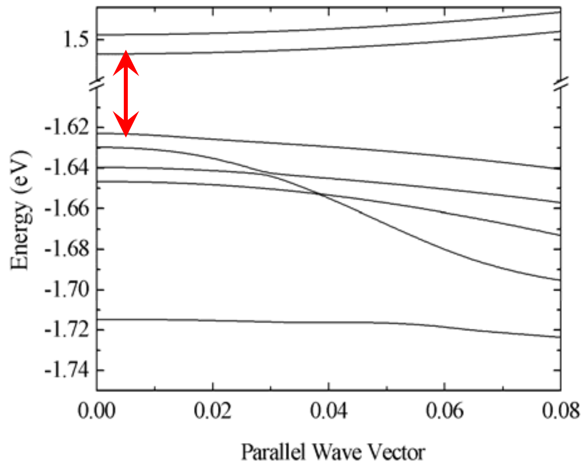


Band Structure of QW with δ-layer

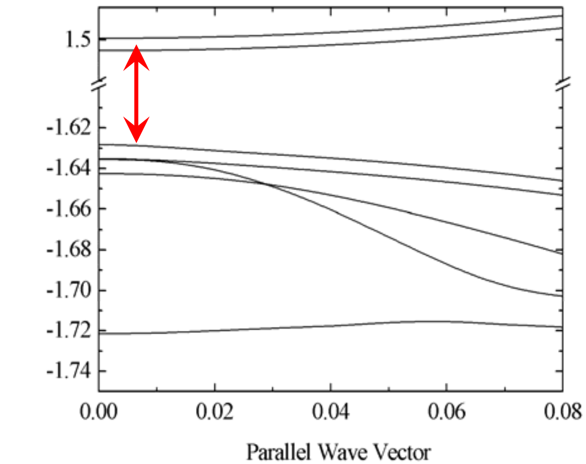
[4nm SQW]



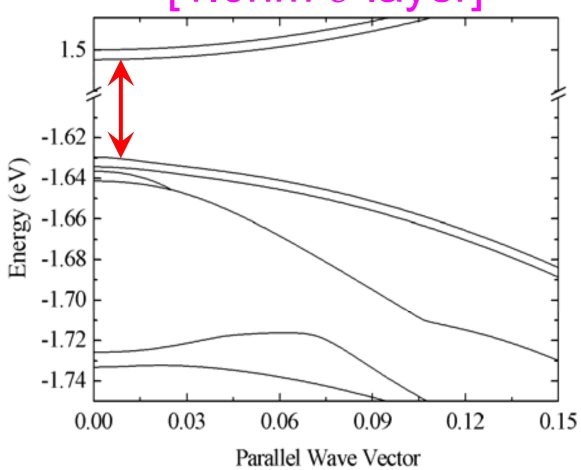
[0.4nm δ-layer]



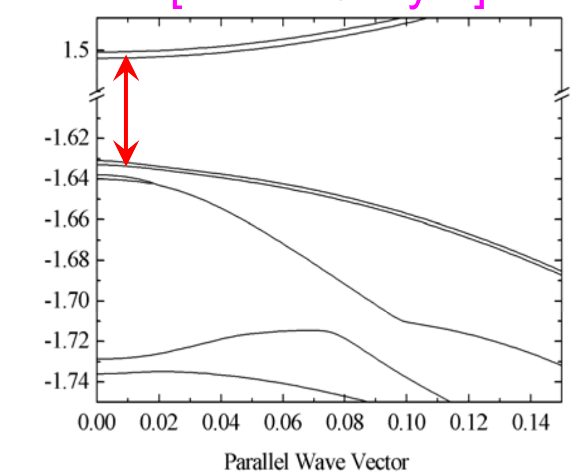
[0.8nm δ-layer]



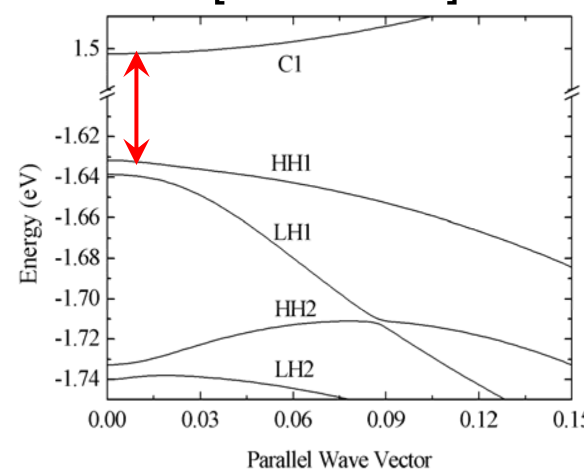
[1.0nm δ-layer]



[1.4nm δ-layer]

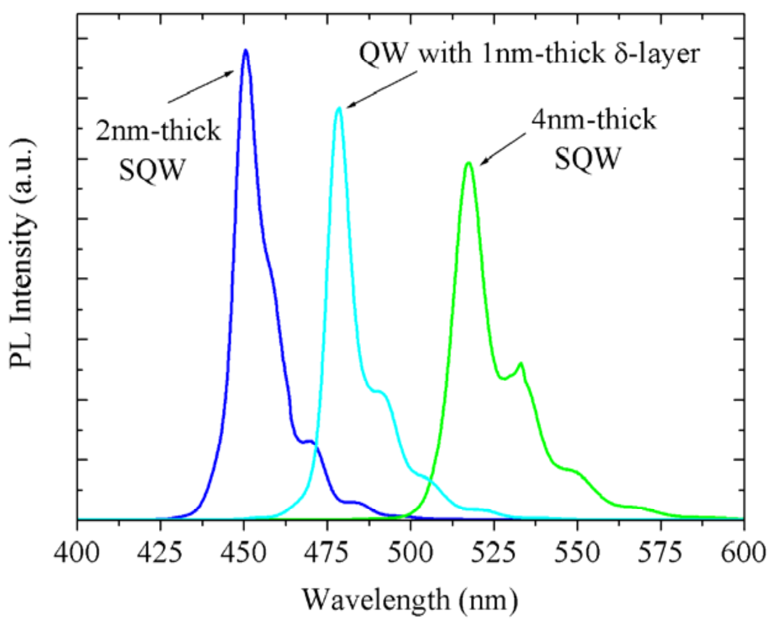


[2nm SQW]

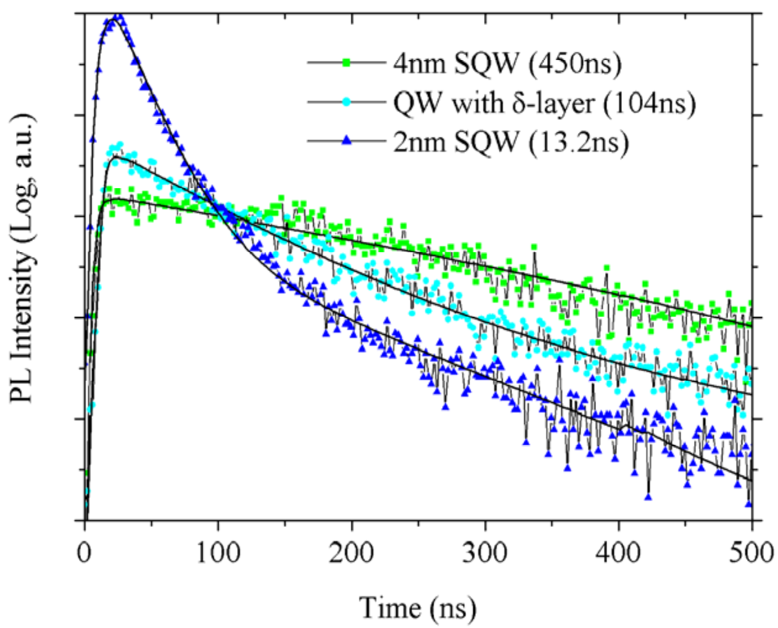


Experimental Results: PL peak wavelength and PL lifetime

PL spectra & efficiency

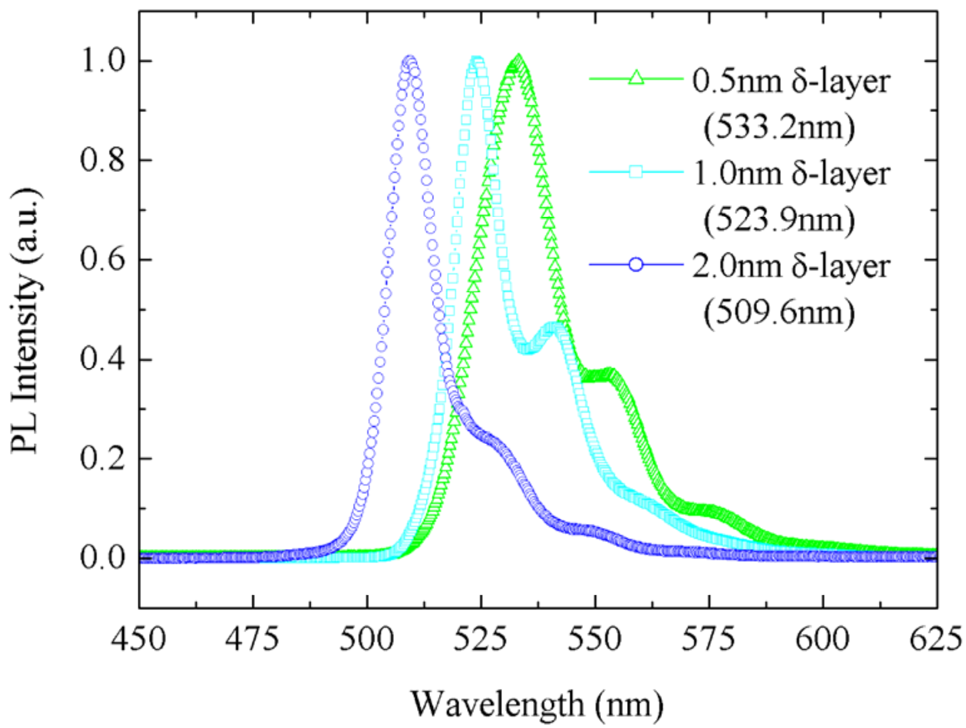


PL decay dynamics

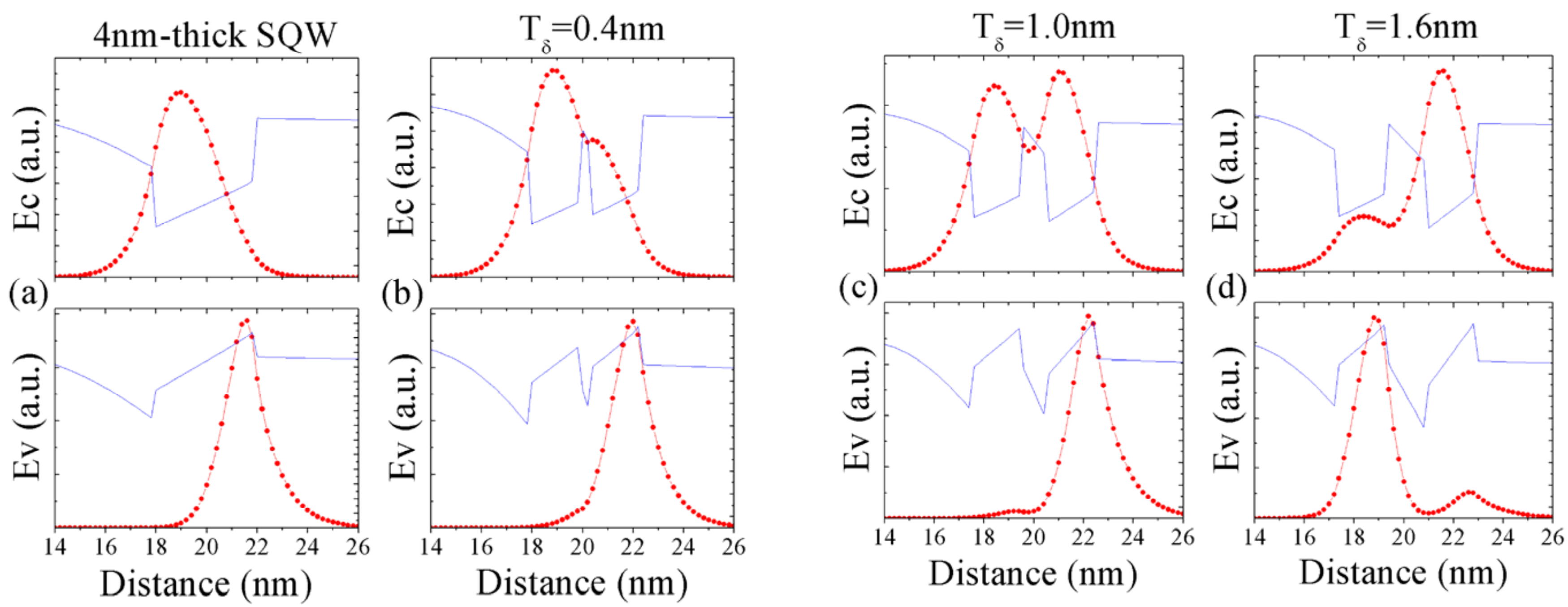


PL Spectra: Different δ-Layer Thickness

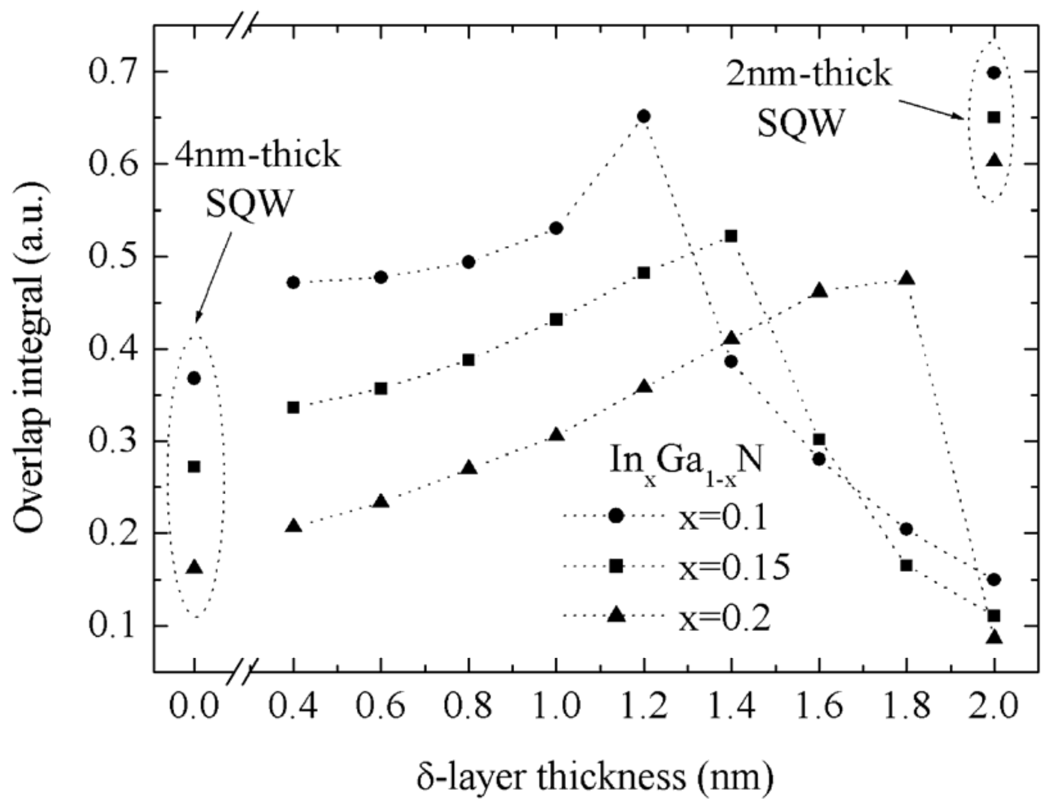
► QW with 1nm δ-layer requires about 4% less indium for green emission, compared to 2-nm-thick SQW



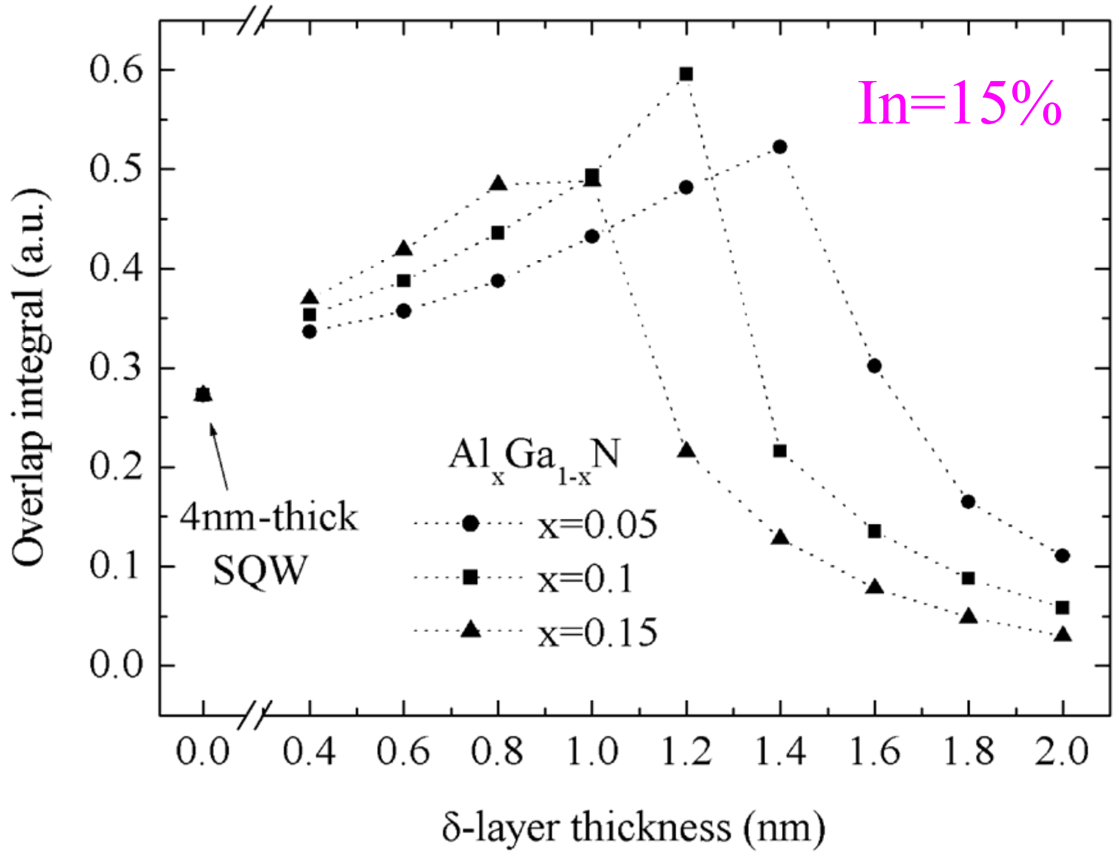
Wavefunction Overlap: Different δ-Layer Thickness



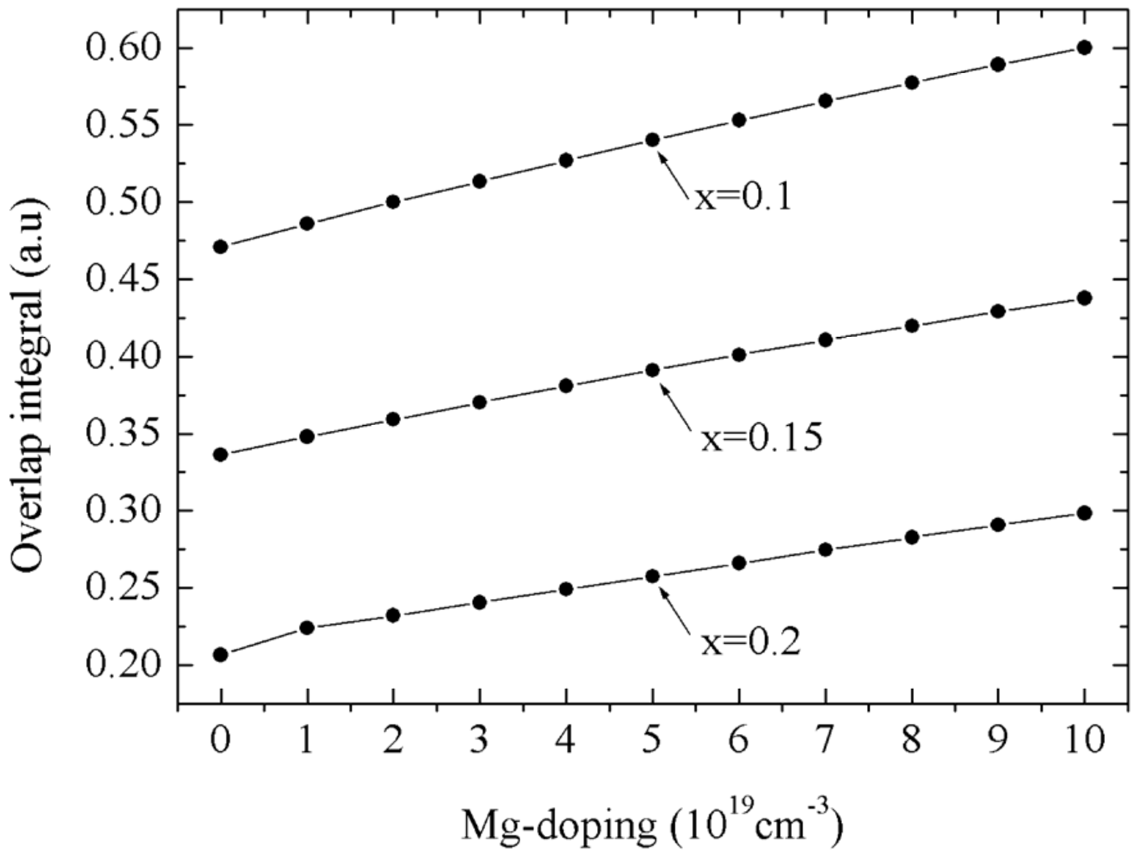
Overlap Integral: Different Indium Composition



Overlap Integral: Different Aluminum Composition



Overlap Integral: δ-doping



Summary

- 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.