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Simulation of InGaN/GaN multiple quantum well light-emitting diodes with Quantum Dot electrical and optical effects

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Outline:

- Introduction
  - Origin of luminescence of InGaN based LED
- Theoretical models for quantum dots
  - Calculation of electronic states of InGaN QD
  - Spontaneous emission
  - Quantum transport mechanism
- Simulation results
- Conclusion

Introduction

InGaN based MQW LED : traffic signals
full-color displays,
back lighting in liquid-crystal displays
replacement for conventional incandescent and fluorescent light bulbs in near future

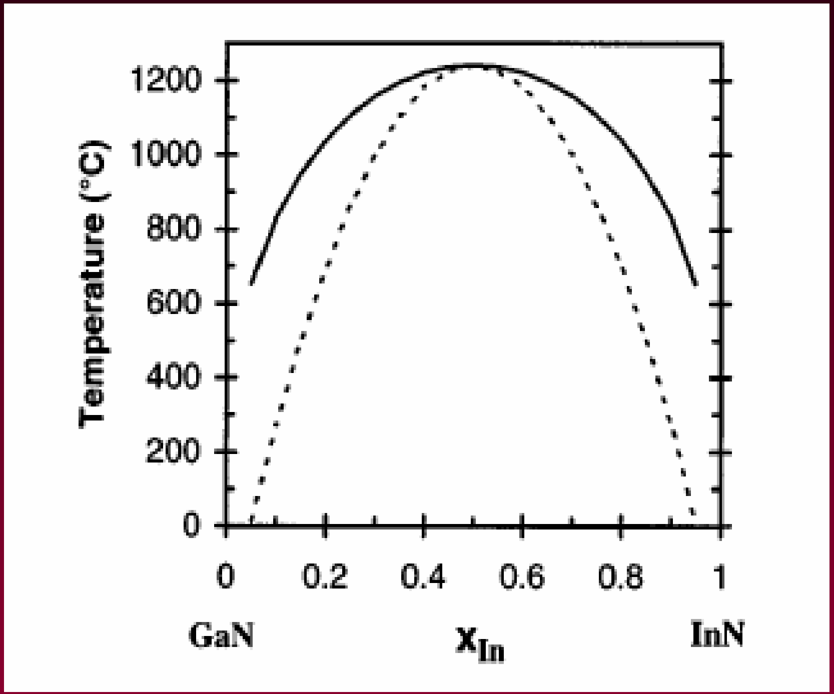
Blue, green and white LED has a high lumineous efficiency

External quantum efficiency : more than **12%**

Threading dislocation density : 10^8—10^{12}cm^{-2}

Origin of luminescence of InGaN MQW LED ????????

Solid phase immiscibility in InGaN alloys



Ho et al. APL. 69. 2701（1996）

the large difference in Interatomic spacing between GaN and InN

The binodal and spinodal curve

InGaN region with high In content

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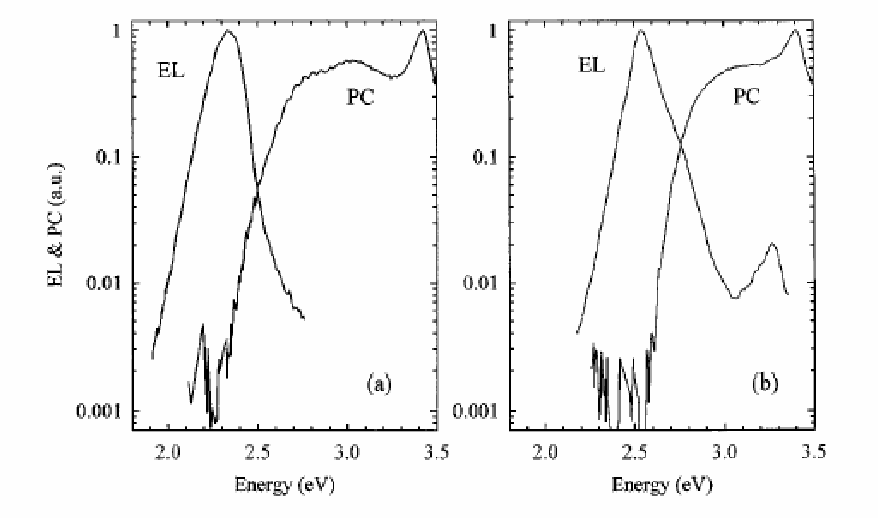
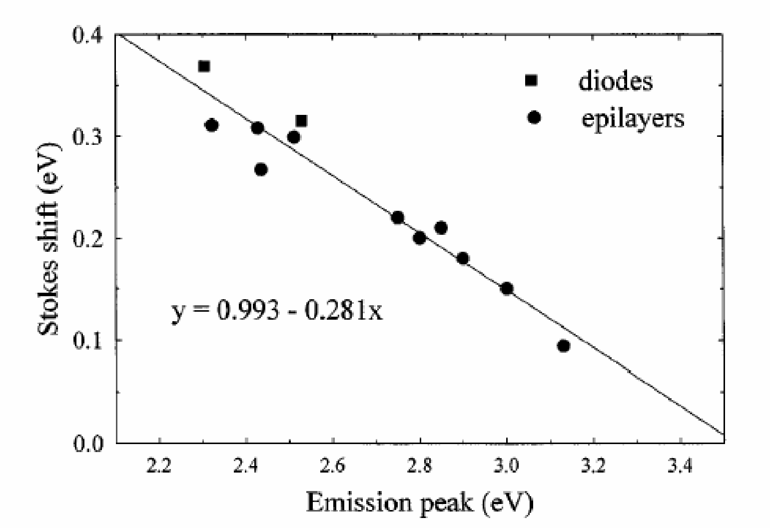
Donnell et al. PRL, 82, 237 (1999)

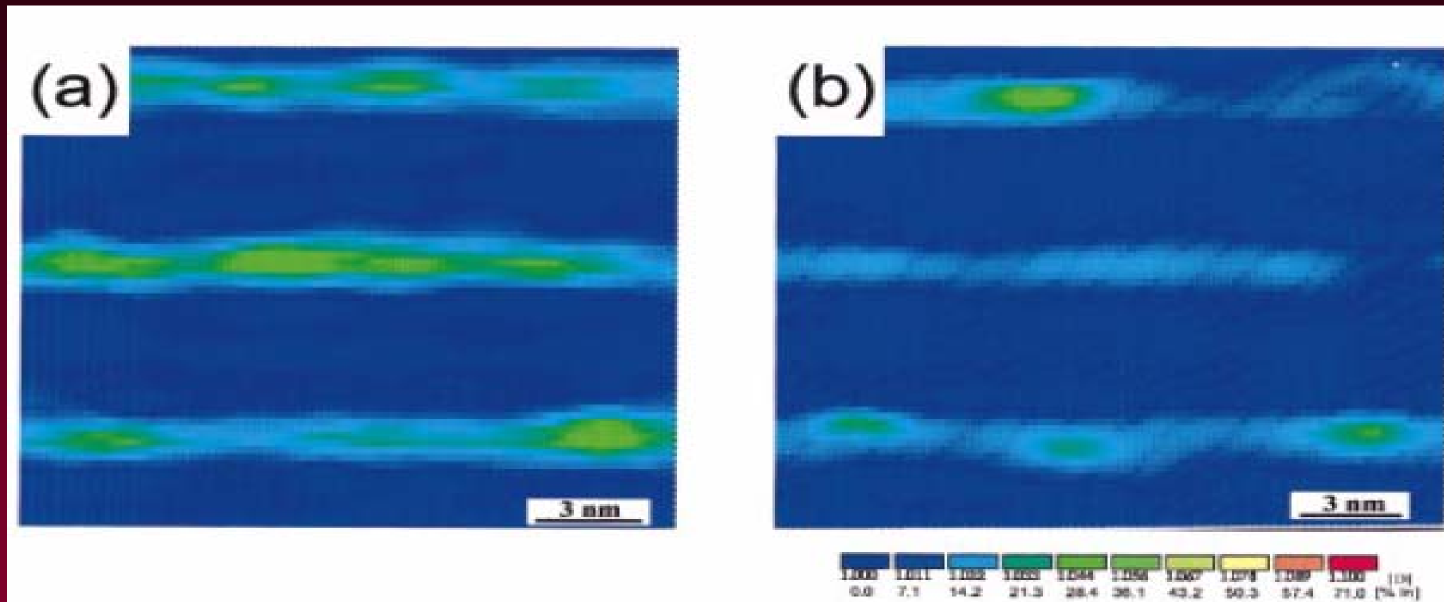


EL and PC spectra form green and blue inGaN based LED



Stokes shift plotted against emissin peak energy for inGaN based LED

Large Stokes shift shows origin of luminescence comes from InGaN quantum dots with high In content



HRTEM images for blue InGaN LED Musikhin et al APL,80,2099(2002)

InGaN quantum dots: 3～5 nm

In content 35%

The mechanism of luminescence in InGaN-based MQW LEDs

the radiative recombination within the In-rich quantum dots

Numerical simulation is an effective method to study and optimize the characteristics of optoelectronic devices

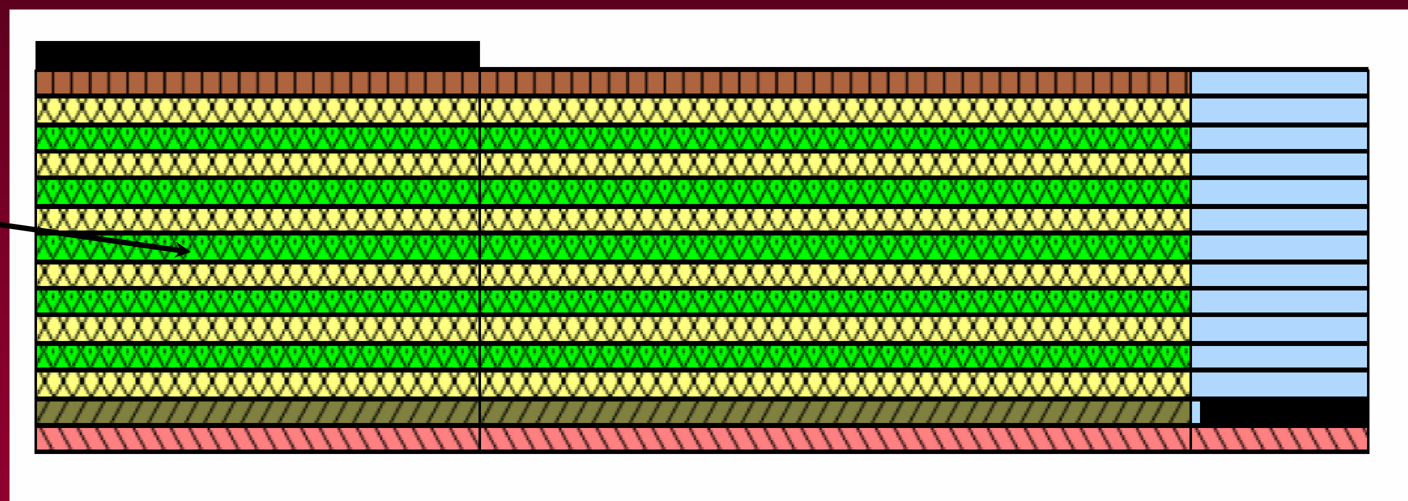
There is few simulation considering the QD origin of luminescence for InGaN-based MQW LEDs

Simulate $In_{0.22}Ga_{0.78}N$/GaN MQW green LED by APSYS software based on Quantum Dot model

Theoretical models for quantum dots

1. Quantum dot structure

InGaN MQW
with InGaN QDs



A certain density of QDs is assumed to be embedded in InGaN quantum well

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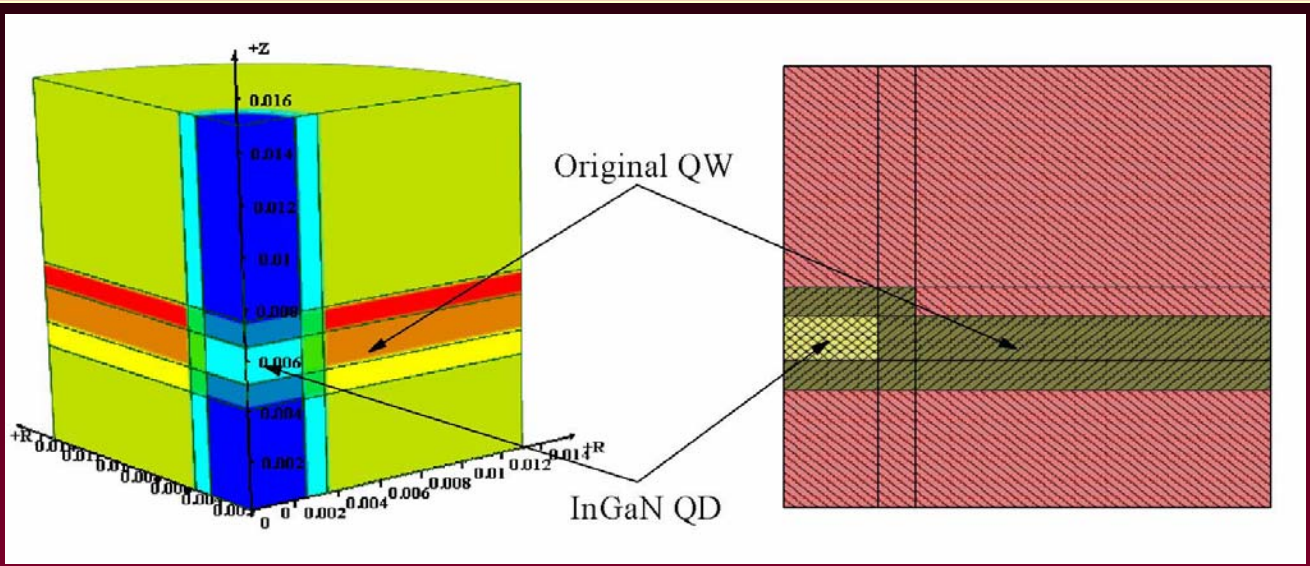


QD structure is approximated by a disk-like high indium cylinder surrounded by QW material with lower indium composition to form a dot/well complex system

InGaN QD parameters:

In content: 0.56

QW In content: 0.22

Size: height 1.5nm

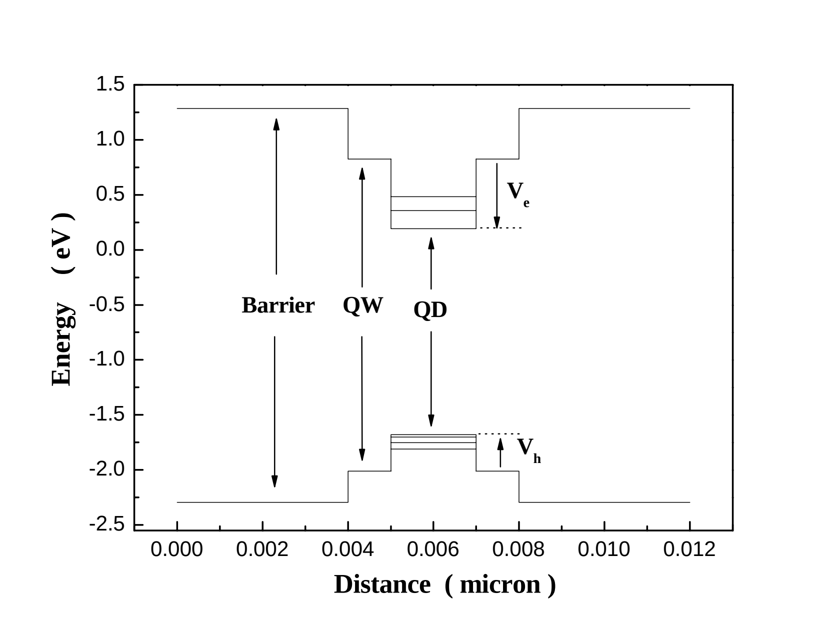
diameter 3.6nm and 5nm

2. Calculation of electronic states of QD

$$\left[-\frac{\hbar^2}{2m^*}\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right)+\frac{\partial^2}{\partial z^2}\right)+V(r,z)\right]\varphi(r,z)=E\varphi(r,z) \qquad (1)$$

Disk like shape dot/well system

cylindrical coordinates to describe QD potential distribution of electron and hole.



Energy band diagram of an InGaN quantum dot in a quantum well

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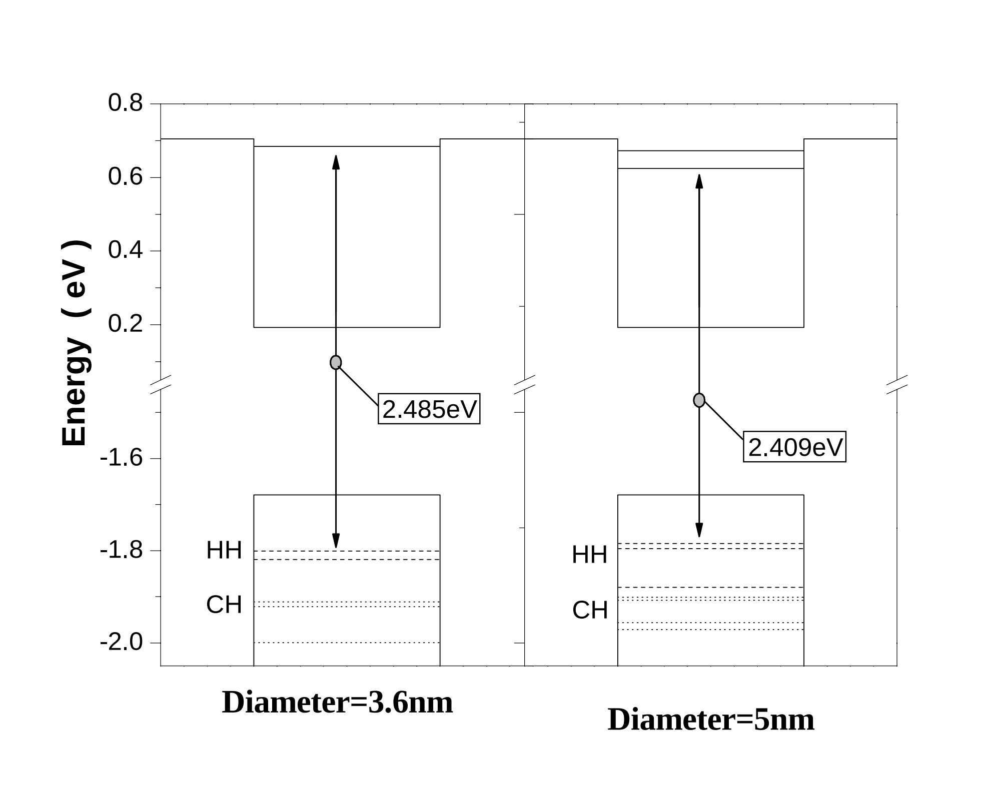
Confined dot levels for InGaN quantum dots with height of 1.5nm, diameter of 3.6nm and 5.0nm



the interband transition between confined dot levels close to the bottom of dot potential is responsible for the LED emission

3. Spontaneous emission

In dot/well system, spontaeous emission comes from two part:

QD

$$r_{qd}^{sp}(E) = \sum_{s}\sum_{i,j}\frac{q^2 n_r E M_b^2 N_{qd}(s)}{\pi\varepsilon_0 m_0^2 \hbar^2 c_0^3 t_{cmplx}}\left|\langle\varphi_{is}|\varphi_{js}\rangle\right|^2 G_s(E-E_{ijs}) f_c(1-f_v) \quad (2)$$

QW

$$r_{qw}^{sp}(E) = \sum_{i=j}\left(\frac{2\pi}{\hbar}\right)\left|H_{ij}\right|^2 f_j^{'}(1-f_i^{'}) D(E)\rho_{ij} \quad (3)$$

Total spontaneous emission determined by:

$$r_{2d}^{sp}(E) = r_{qw} r_{qw}^{sp}(E) + r_{qd}^{sp}(E) \quad (4)$$

4. Quantum transport mechanism

Non-equilibrium quantum transport model

1) fly directly over the small QDs

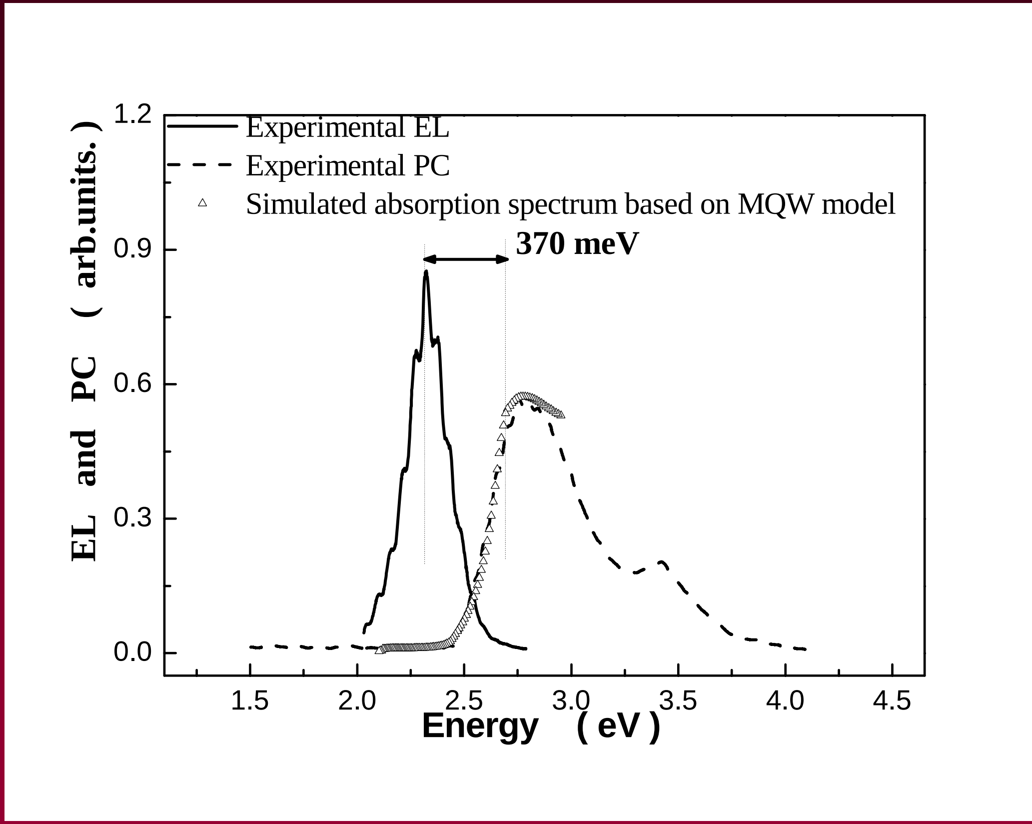
2) escaping from the deep QD potential before being thermalized

Simulation results

Stokes shift is 370meV

QD emissin in our green LED

photocurrent is from the inter-subband transition in InGaN quantum wells



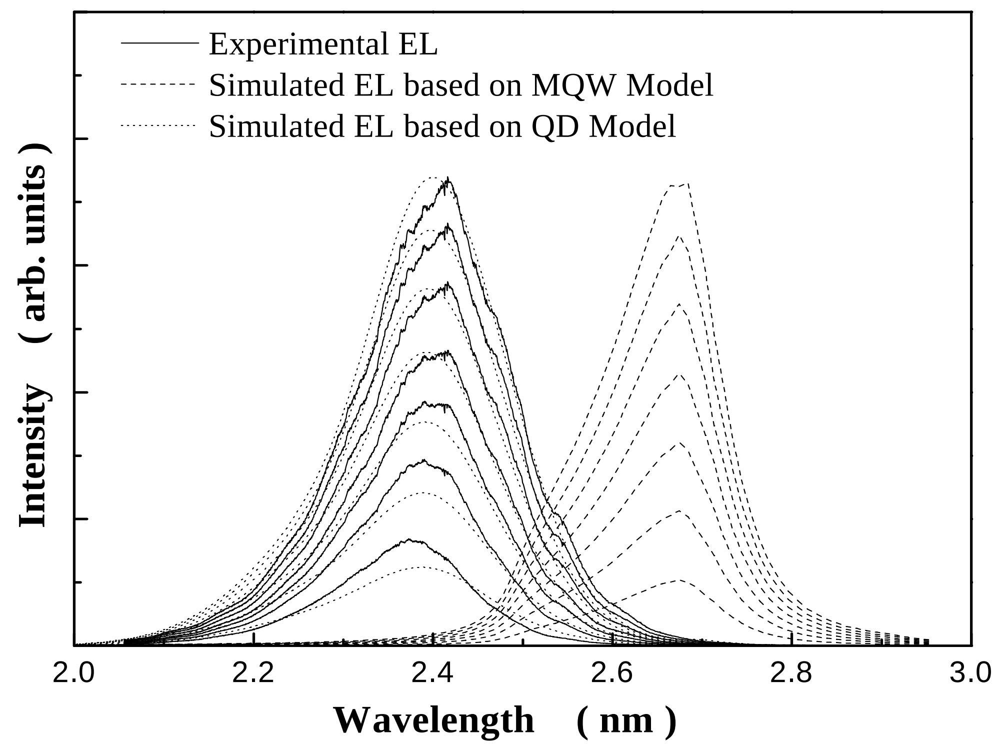
EL, PC spectrum and simulated absorption spectrum based on MQW model with In content of 0.22

Experiment 2.35-2.40eV

MQW model 2.67eV

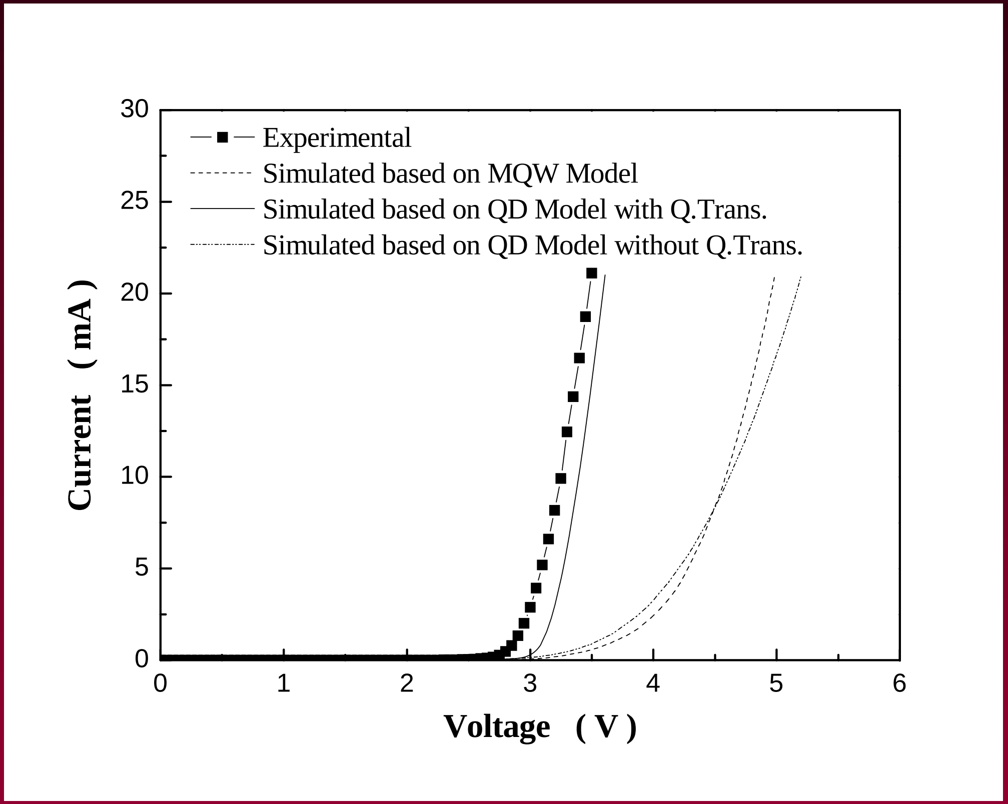
QD model

good agreement with experiment



Calculated and experimental EL spectrum

QD model with Quantum Transport
close to experiment



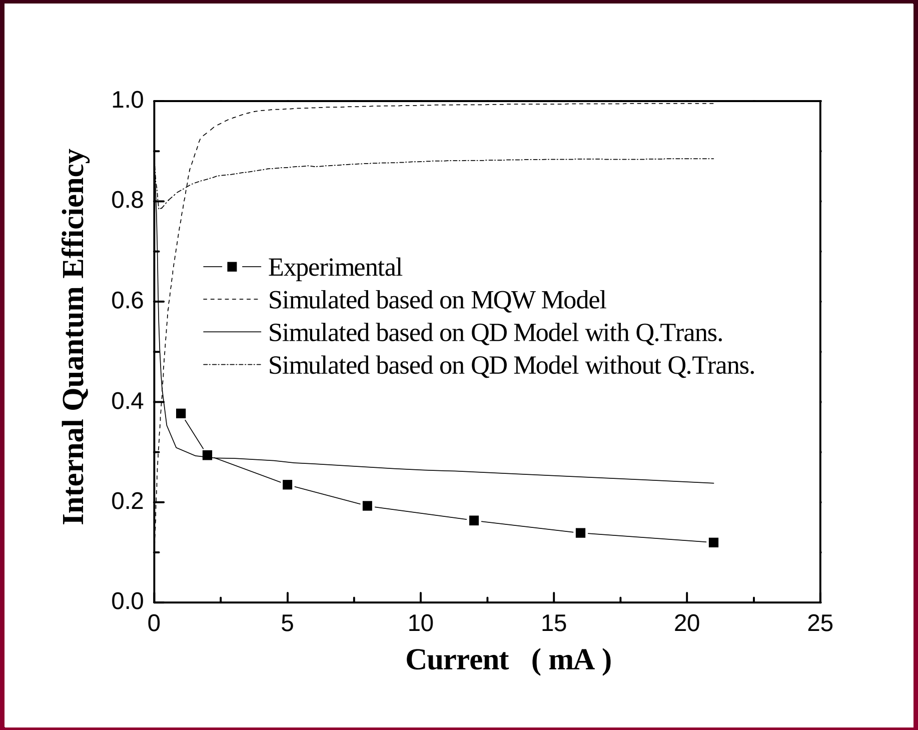
The I-V characteristics of InGaN-based LED

MQW model
QD model without Q.Trans

90%～100% which is overestimated

QD model with Q.Trans

close to experiment



The IQE of InGaN-based LED

It indicates that quantum transport mechanism plays an important role in the InGaN-based MQW LED

Conclusion

1) QD model with Q.Trans. accurately accounts for the experimental data of InGaN based LED

2) Quantum dot emission and non-equilibrium quantum transport played very important roles in the InGaN-based MQW LEDs

3) The simulation allows us to understand better for the quantum states effect in the device performance

4) With our more delicate model, one may be able to optimize the InGaN-based LEDs performance

Thank you for your attention!