Simulation of InGaN/GaN Quantum Dot LED

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Contents

- About InGaN QDOT LED.
- Our model.
- Simulate a realistic QDOT LED.
- Study of dot density dependence.
- Comparison with a QW LED.
- Conclusions.

Indium segregation in MOCVD growth of InGaN

Indium segregation and composition non-uniformity have been observed in InGaN/GaN heterostructures.

J. Crys. Growth

175/176, (1997)72

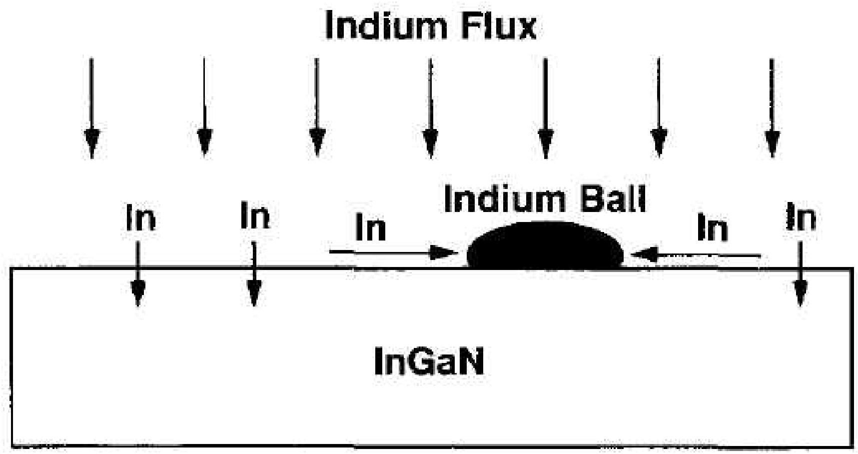


Fig. 2. Illustration of InGaN growth segregation model. The dual In incorporation results in the formation of In balls.

Thermal-dynamic analysis (PROCOM Simulation)

$In(g) + NH_3(g) = InN(alloy) + 3/2H_2(g)$

$Ga(g) + NH_3(g) = GaN(alloy) + 3/2H_2(g)$

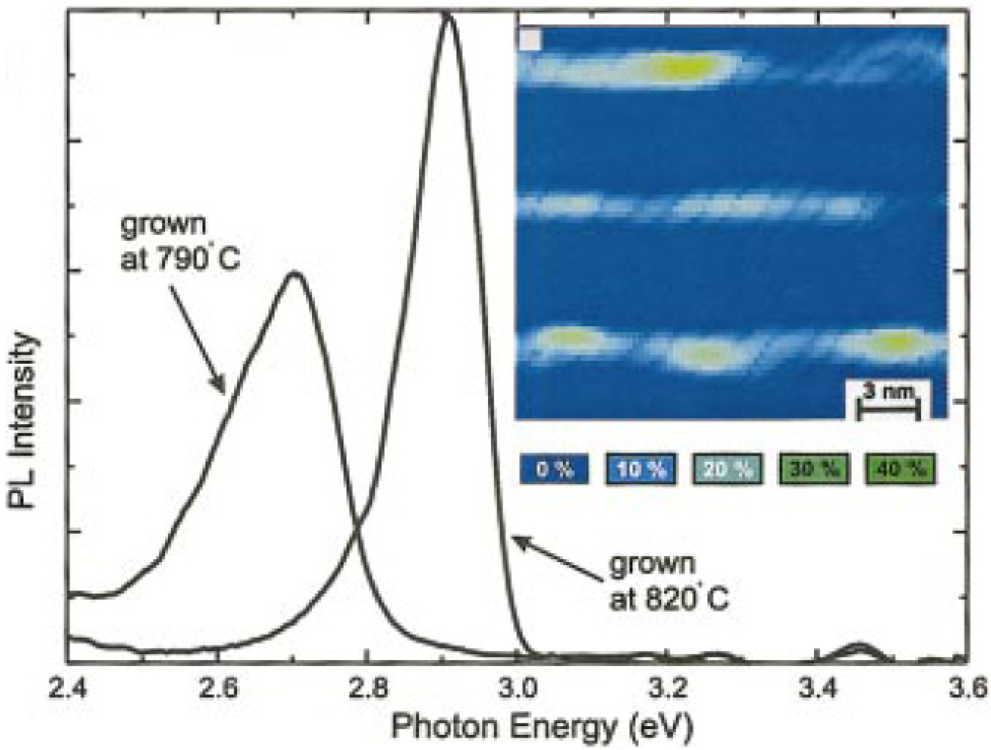
Since the equilibrium pressure of In is significantly higher than that of Ga, indium tends to form droplets➔ quantum dots

Effects of Indium segregations

- It is difficult to grow high In composition film. Higher gas In ratio results in even lower In incorporation in solids.
- Non-uniformity in the lateral composition of InGaN is observed and the interface abruptness is poor.
- The InGaN film quality is dependent on the experimental conditions due to kinetic effects.

The magic of quantum dots

- Surprisingly high efficient luminescence has been observed in material with high defect densities.
- Quantum dots magically attracts the injection carriers from defects centers.



PL and HRTEM image taken from I.L. KRESTNIKOV *et al.* Phys. Rev. B **66**, 155310 ~2002!

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Quantum drift-diffusion model

- **Quantum states of the QDOT/QW complex are solved to compute density of states and optical transitions.**
- **Includes two non-equilibrium quantum corrections to the equilibrium transport model: a) direct fly over the small QDOT/QW complex; b) quantum escape from the QDOT/QW.**
- **More details can be found in two other presentations "Introducing quantum drift-diffusion model" and "3D simulation of quantum dot devices" at http://crosslight.com/downloads/downloads.html**

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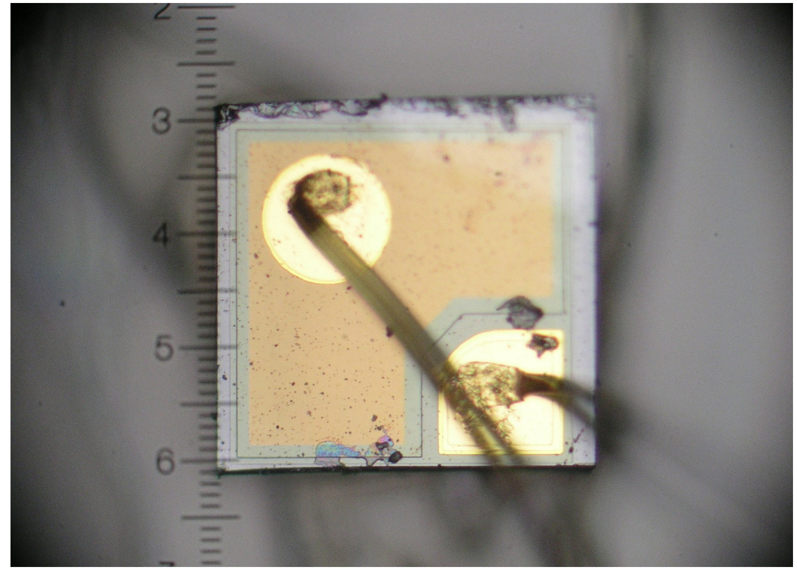
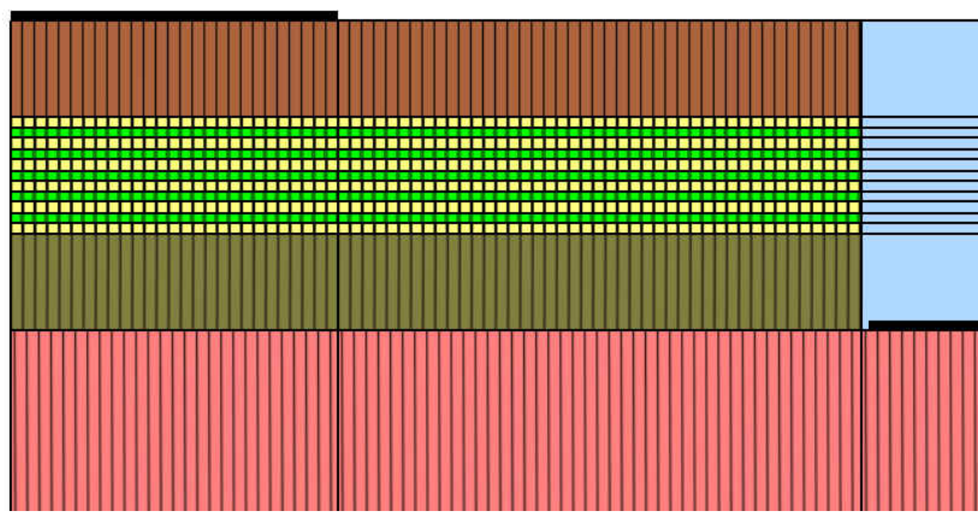
Simulated Structure of InGaN/GaN QDOT LED

Experimental 3D structure →

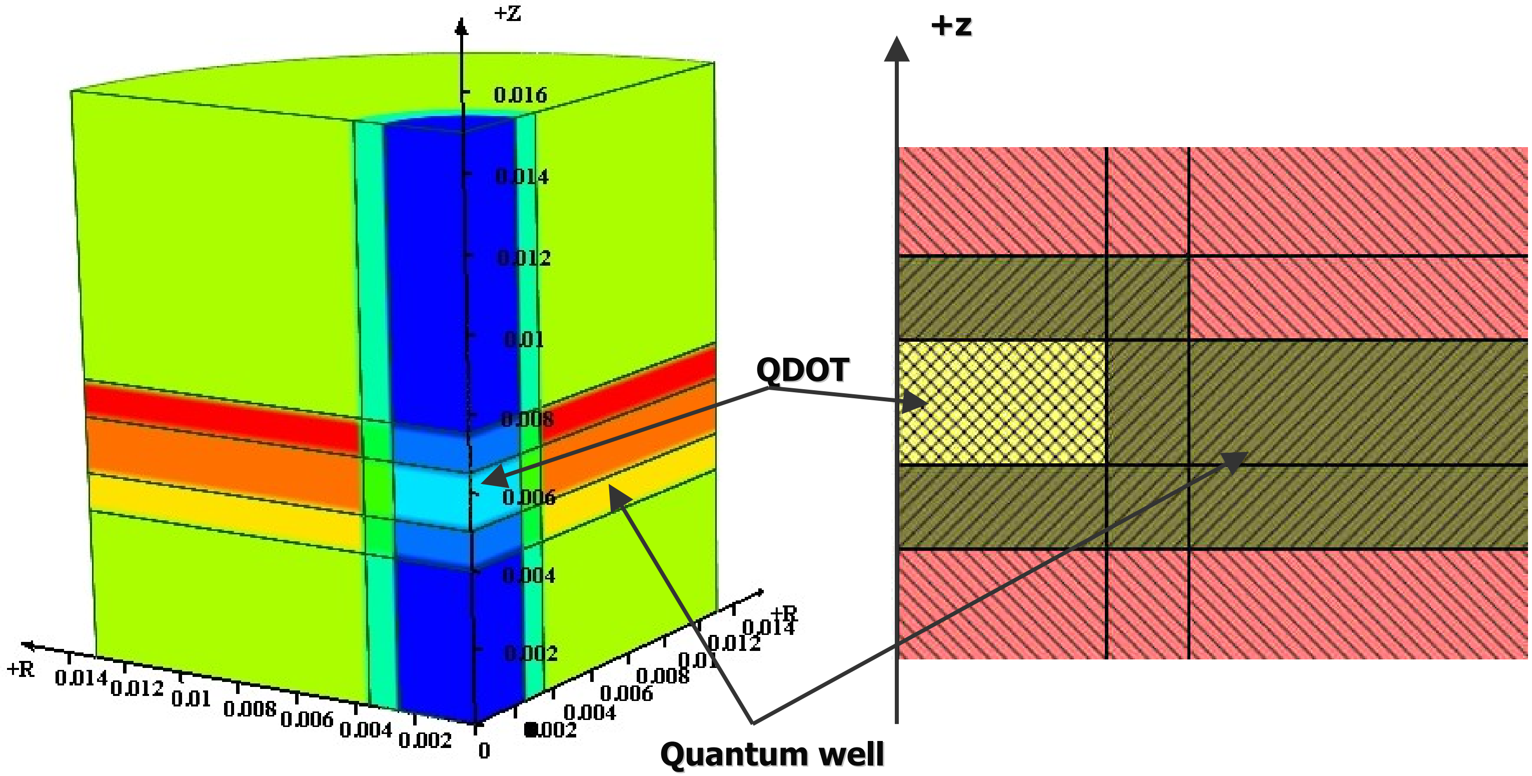


A certain density of QDOT is assumed to be embedded with the InGaN quantum well.

InGaN MQW With InGaN Quantum Dots →

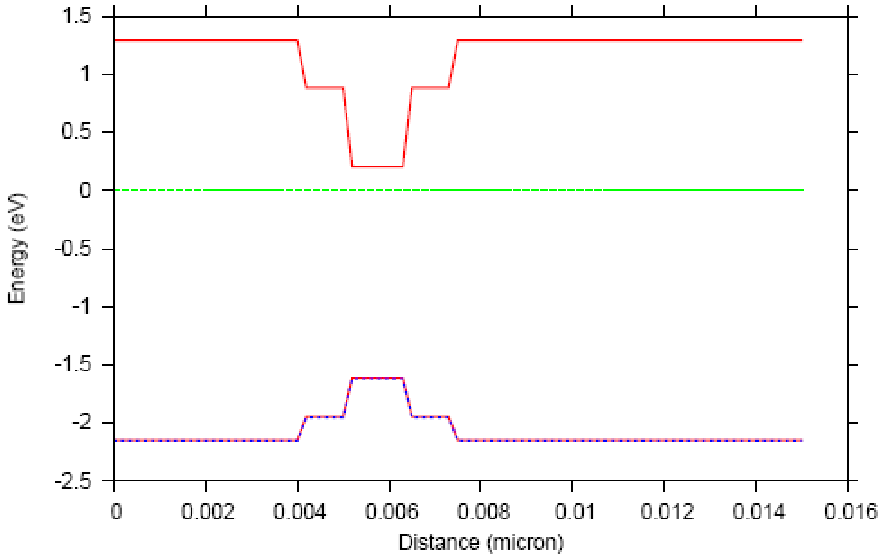


Disk-like 3D QDOT/QW

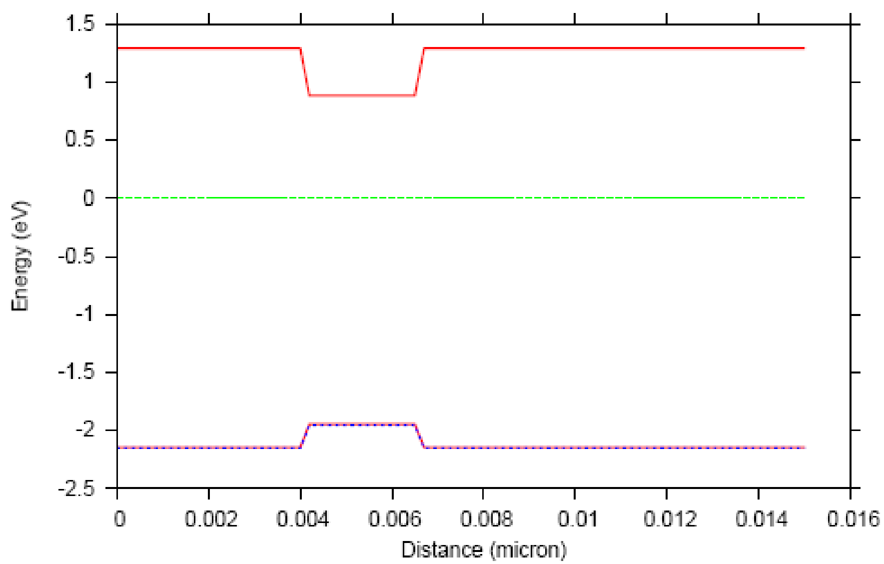


A QDOT is approximated by a disk-like high indium cylinder surrounded by quantum well material with lower indium composition to form a QDOT/QW complex → Solution of 3D quantum mechanical wave equation is reduced to 2D when using cylindrical coordinate system.

QDOT Band Diagrams

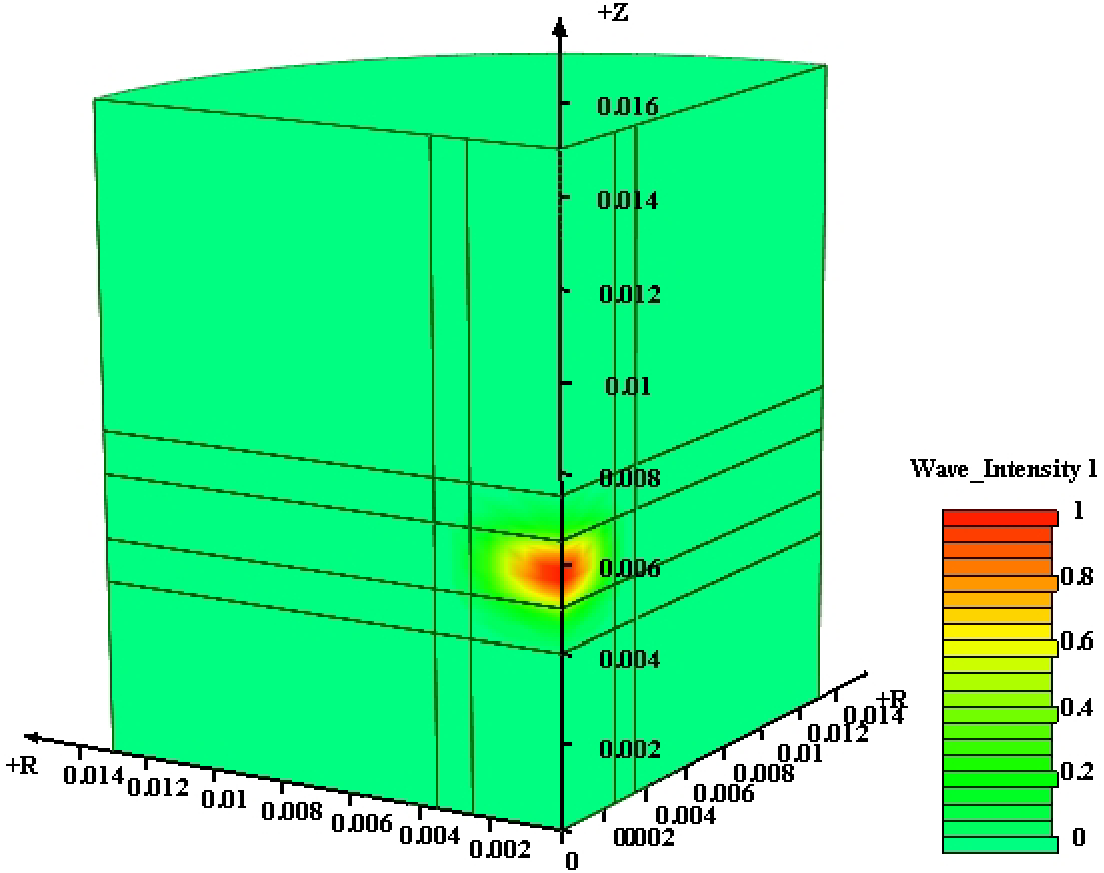


Cut through QDOT

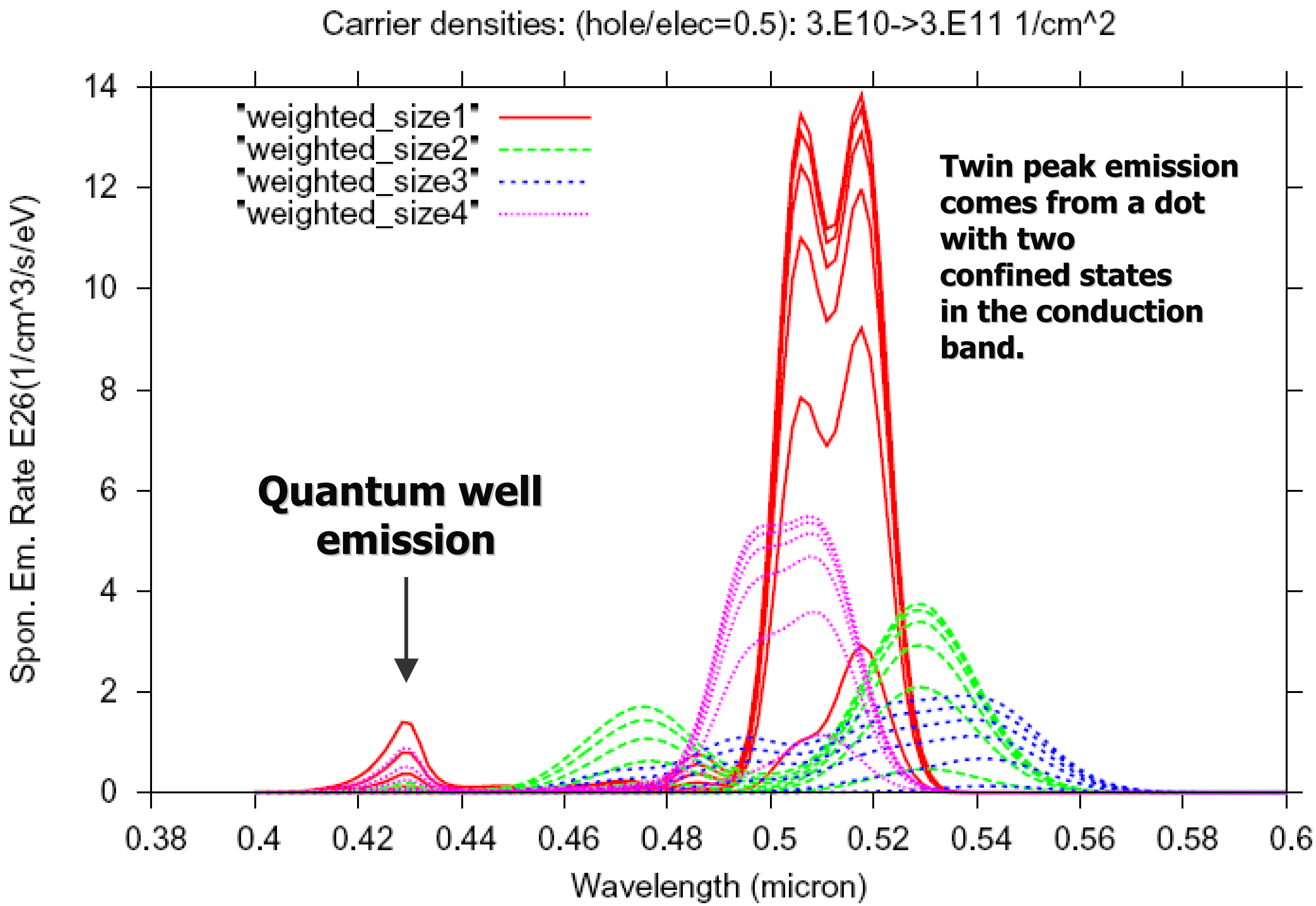


Cut through QW

3D QDOT Cond. Band 1st State

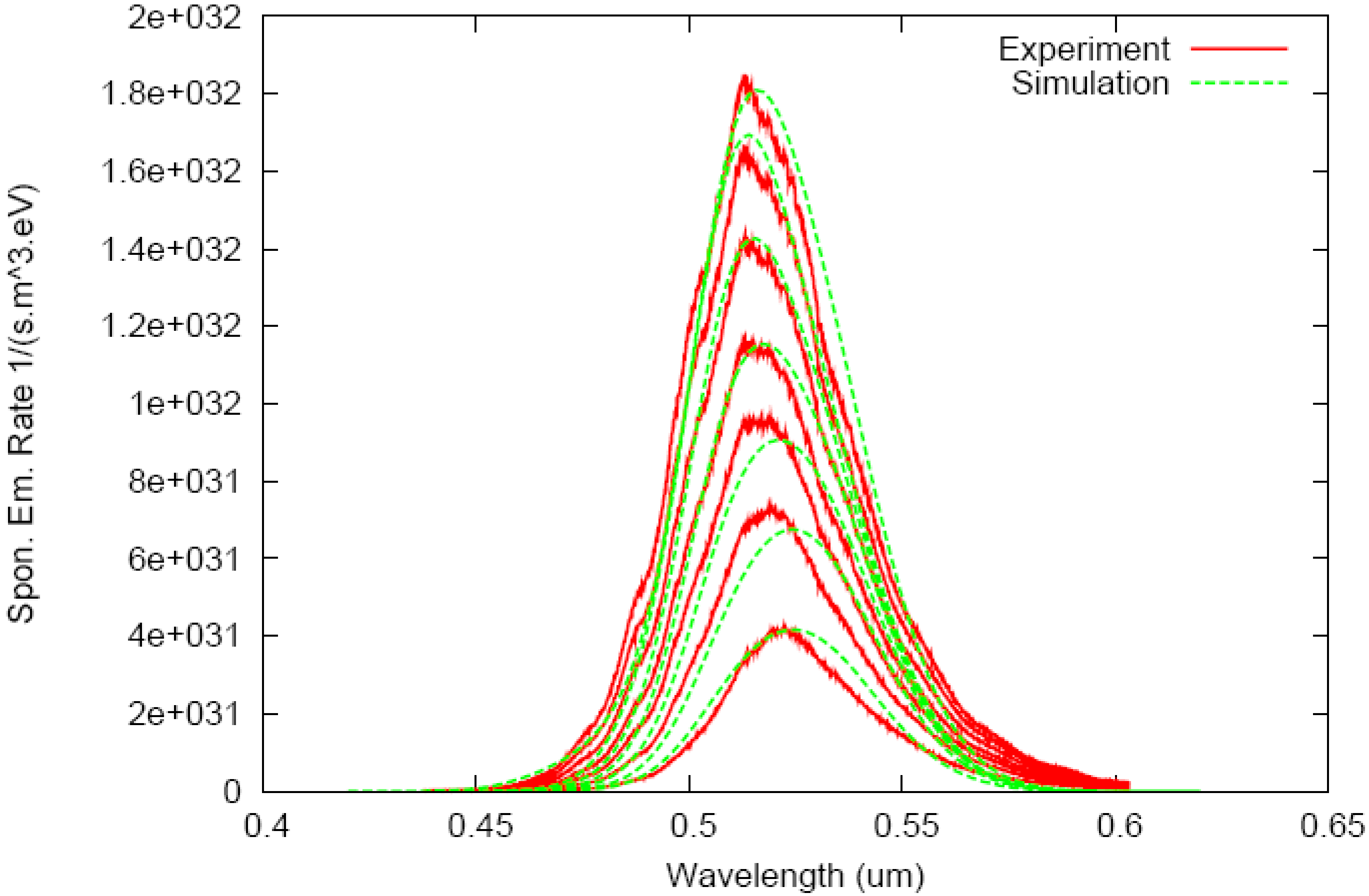


Engineering the EL spectrum



With the same injection conditions, contributions from several types of QDOT's of different diameters are added with different weights.

EL Spectrum Comparison



Experimental data taken from:
C.S. Xia, W.Lu, Z.M.Simon Li, Z.Q.Li, "Modeling and simulation of GaN-based LED with quantum dots electrical luminescence effect", 15th semiconductor conference of China, Oct. 16-19, 2005, Chendu, China.

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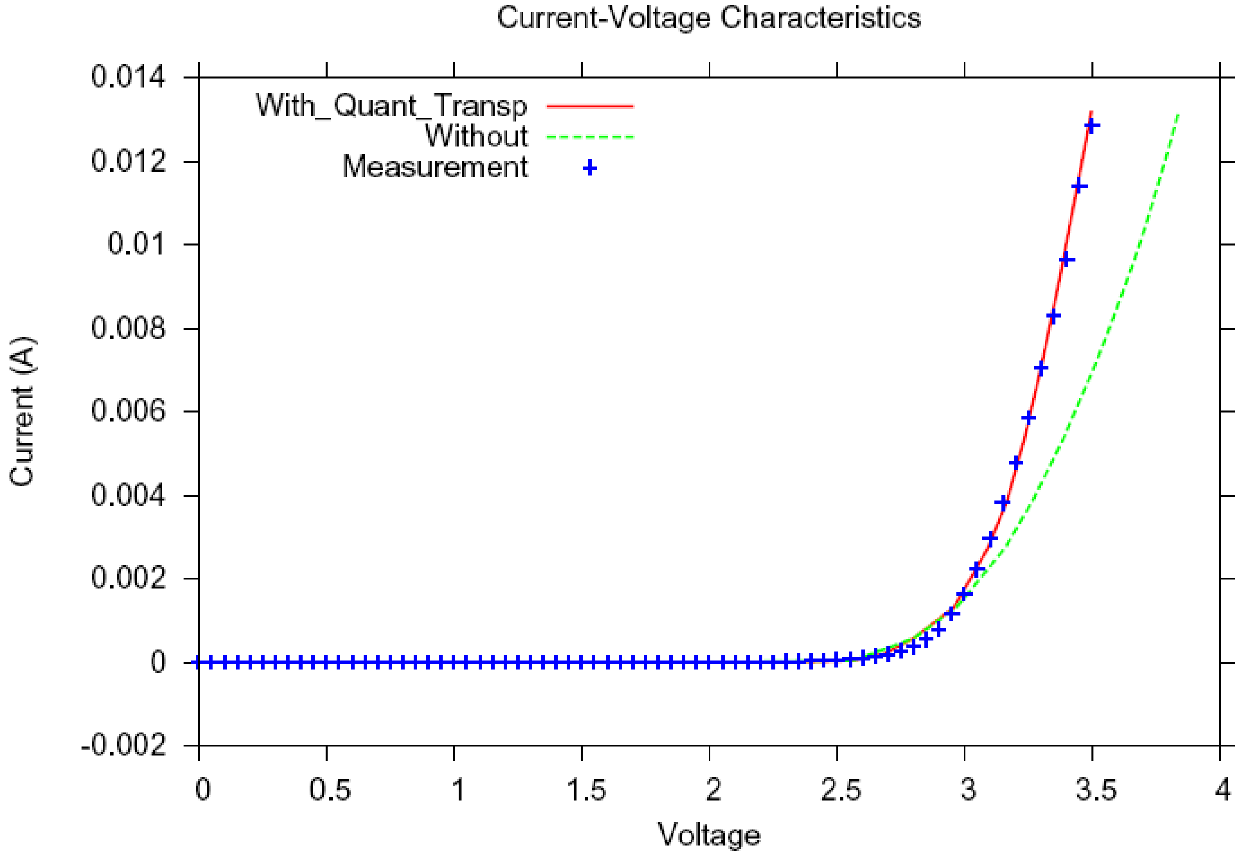
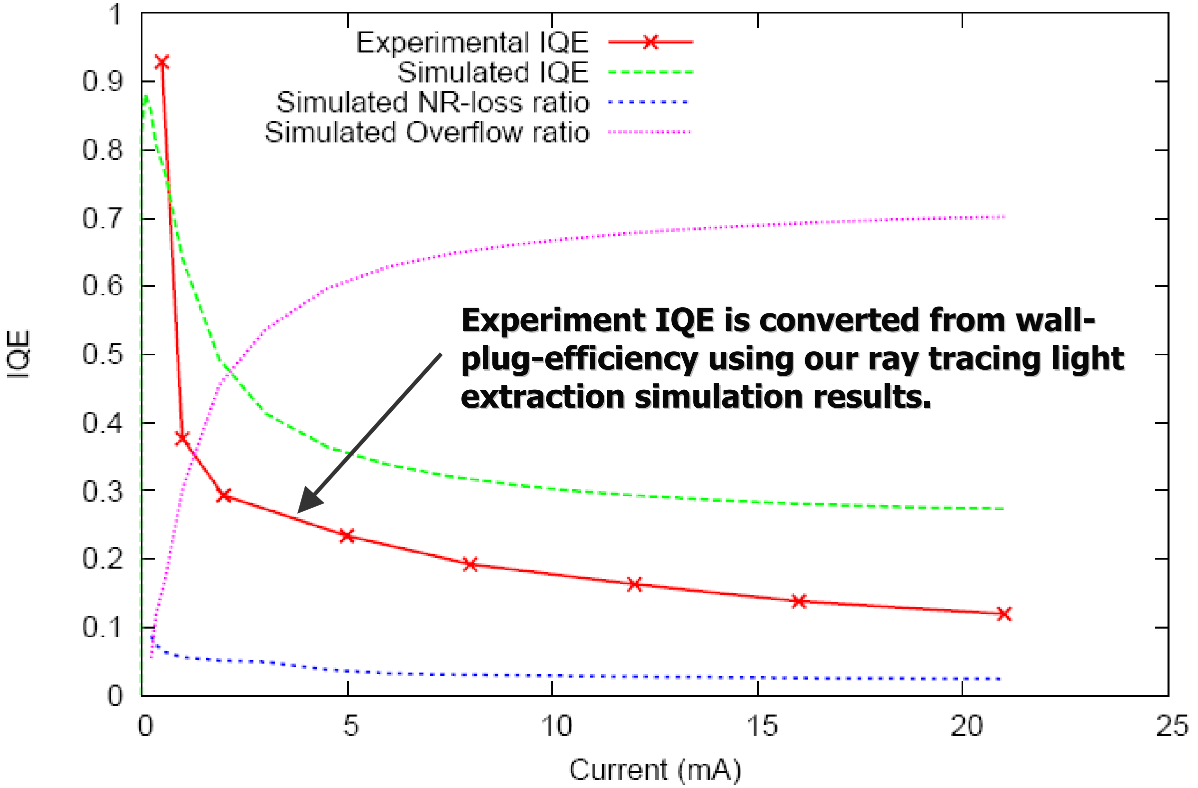
I-V (quantum transport effect)



Remark: Experimental data is hard to explain with Quasi-equilibrium transport model.

Data taken from ref: C.S. Xia, W.Lu, Z.M.Simon Li, Z.Q.Li, "Modeling and simulation of GaN-based LED with quantum dots electrical luminescence effect", 15th semiconductor conference of China, Oct. 16-19, 2005, Chendu, China.

Efficiency analysis



Analysis of experimental data shows a low non-radiative material loss which confirms to common belief that QDOT attracts carriers away from defects and thus reduce non-radiative recombination.

➔ Major concern for this LED: high overflow loss associated with non-equilibrium carriers escape from QDOT.

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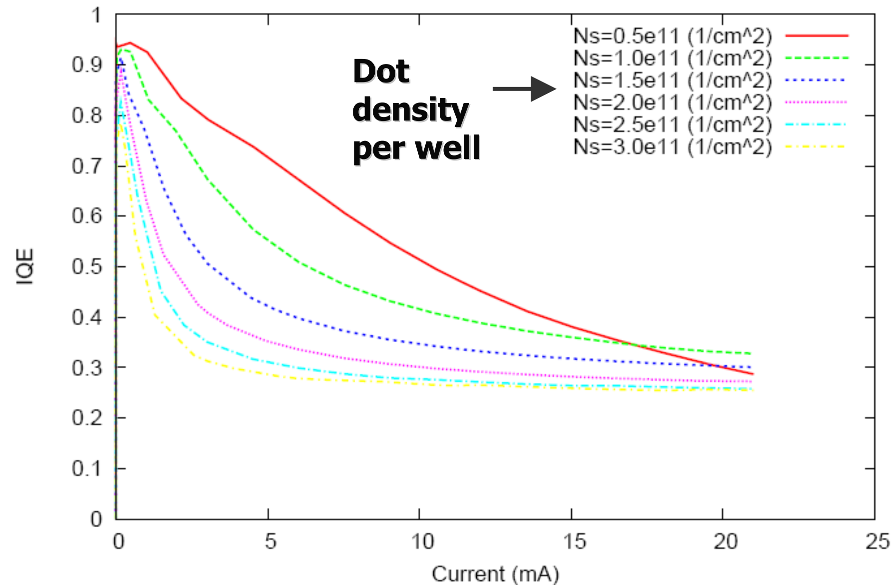
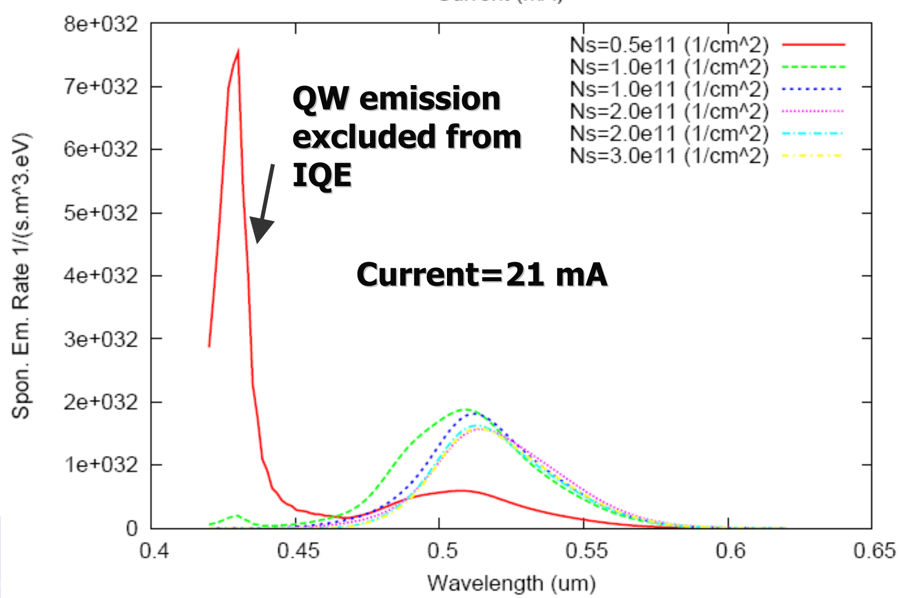
QDOT density dependence





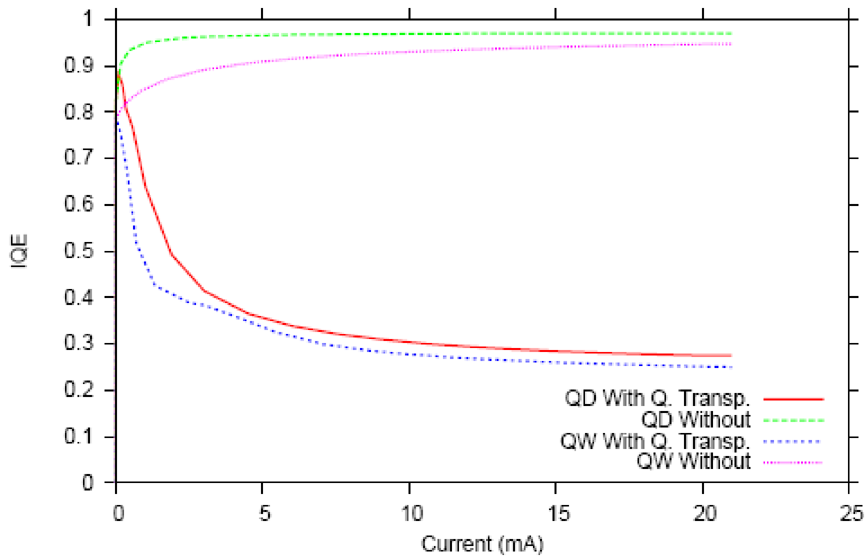
Simulation indicates the existence of an optimal dot density: A low dot density results in higher dot occupancy → higher spontaneous emission rate thus better IQE. However at the extreme low dot density limit, dots are fully occupied leading to carrier spilling over to quantum well, causing undesirable QW emission.

Contents

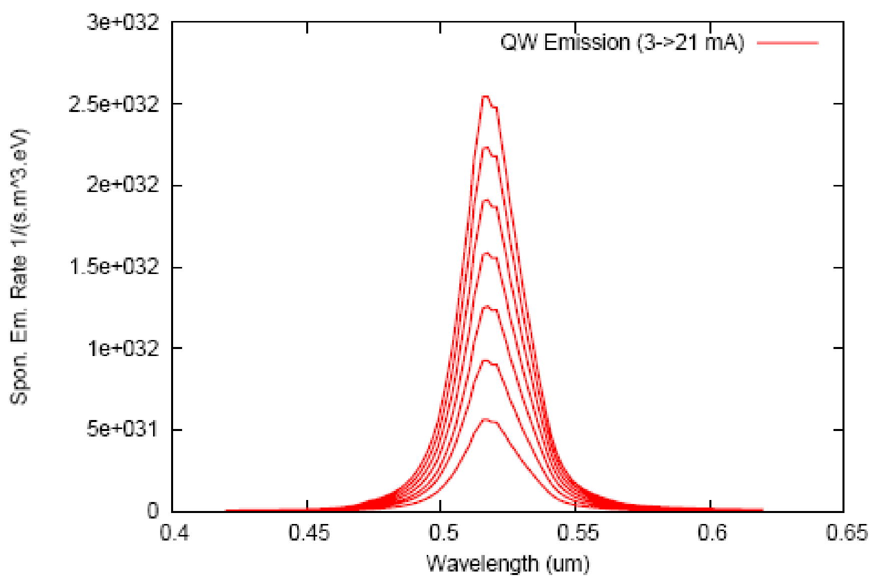
QDOT LED versus QW LED

- **Consider a numerical experiment of purely QW LED using the same material parameters as QDOT LED.**
- **QW indium composition is adjusted to emission at the same 520 nm.**
- **Non-radiative loss is assumed to be higher (double) than QDOT LED.**

IQE and EL spectrum from QW



Simulation shows QW LED to have slight lower IQE and a narrower EL spectrum.



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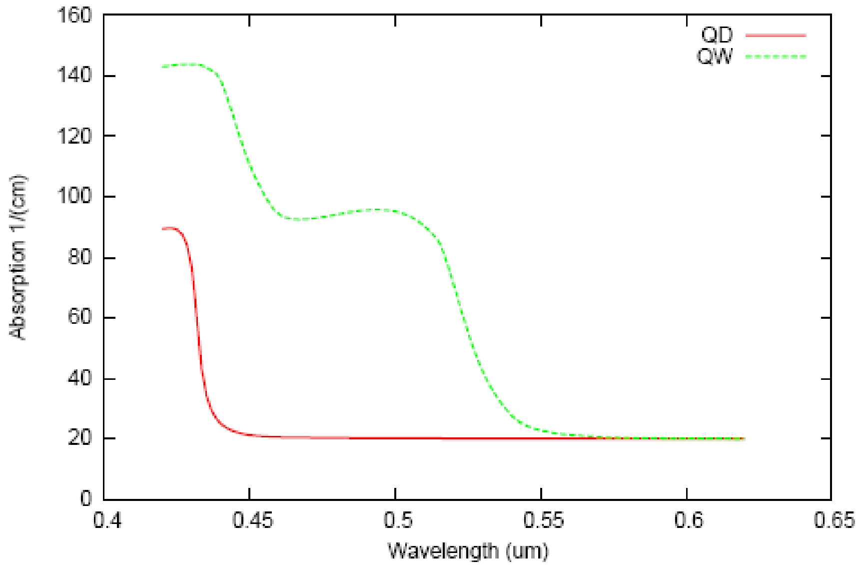
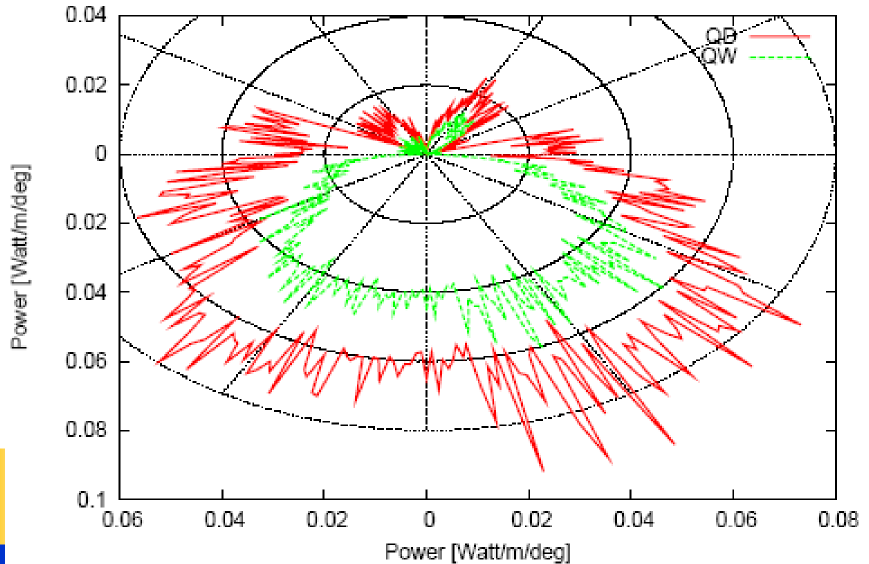
Absorption loss comparison



QW LED has a much higher average material absorption loss due to higher density of states.



A higher material loss in QW degrades light extraction.

QDOT LED Extraction=0.53

QW LED Extraction=0.32

Conclusions

- **Crosslight's APSYS QDOT module accurately accounts for experimental data of QD LED.**
- **Non-equilibrium transport mechanisms may be needed to explain the current injection process of a QDOT-LED with small QDOT sizes.**
- **Comparative study indicates a QDOT LED generally performs better than a QW LED, especially when it comes to material absorption loss and light extraction issues.**