Quantum Dot LEDs

2014. 5. 23.

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Part I: Properties and formation of semiconductor Quantum dots

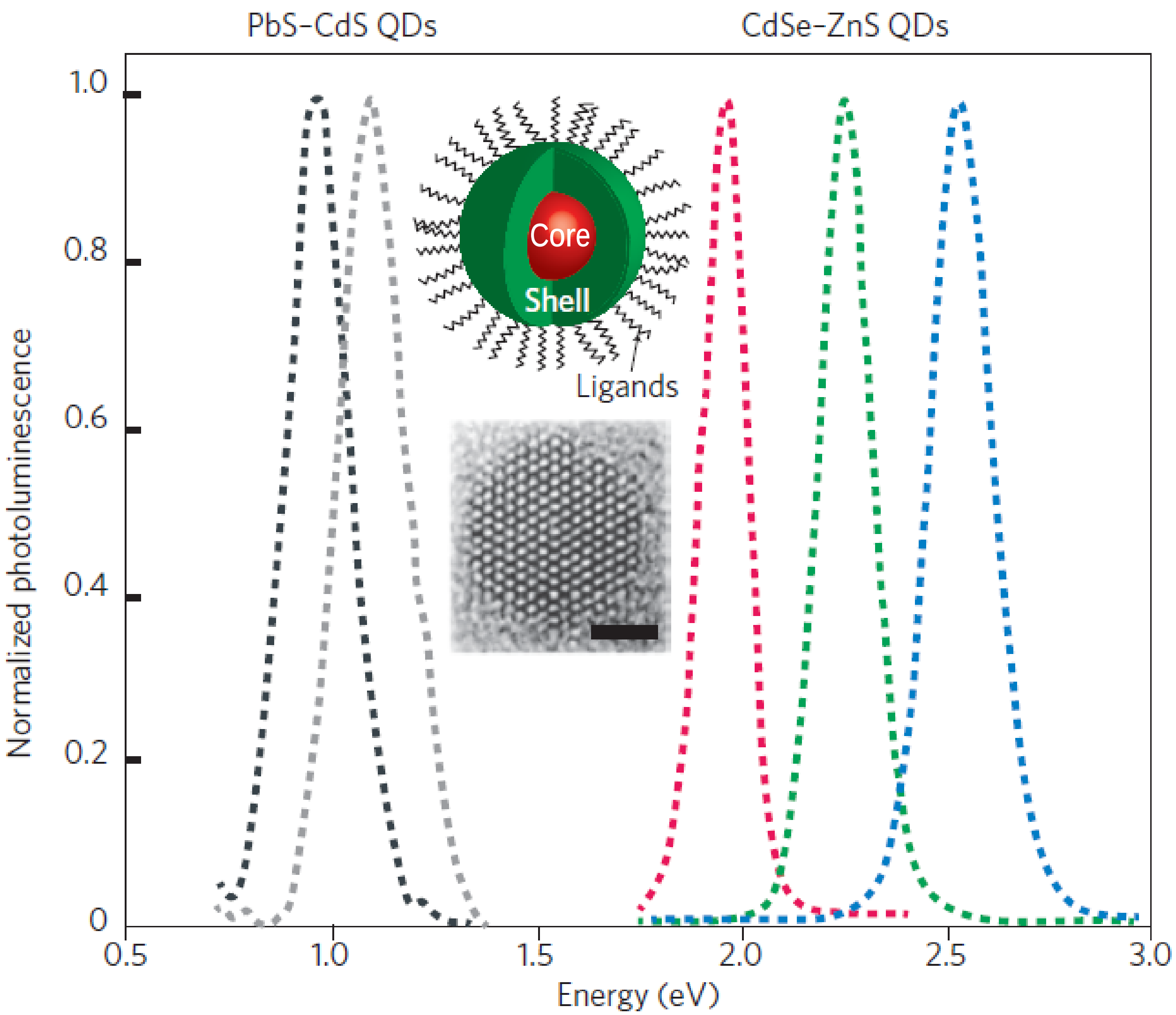
: Introduction
: Basic quantum mechanics applied to quantum dots (QDs)
: Basic properties of quantum wells and dots
: Formation of quantum dots

Part II: Colloidal Quantum dot LEDs

: QD-LED device structures and operating mechanism
: History of QD-LED development
: Inverted QD-LEDs
: Polymer–QD hybrid LEDs
: Cd-free QLEDs
: QD patterning

Part III. QD and Hybrid Solar Cells

Core/Shell Structured Colloidal Quantum Dots



Core

- Emission wavelength (size & composition)
- CdSe, CdTe, ZnTe, CdS (group II-VI)
- InP, InGaP (Group III-V)

Shell

- Surface passivation (i.e. dangling bond)
- Protection layer
- ZnSe, ZnS (group II-VI)
- GaP (Group III-V)

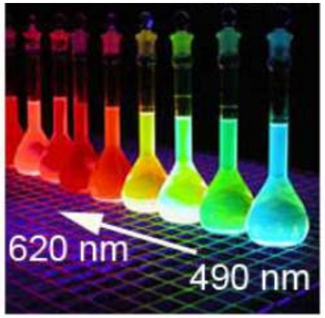
Ligand

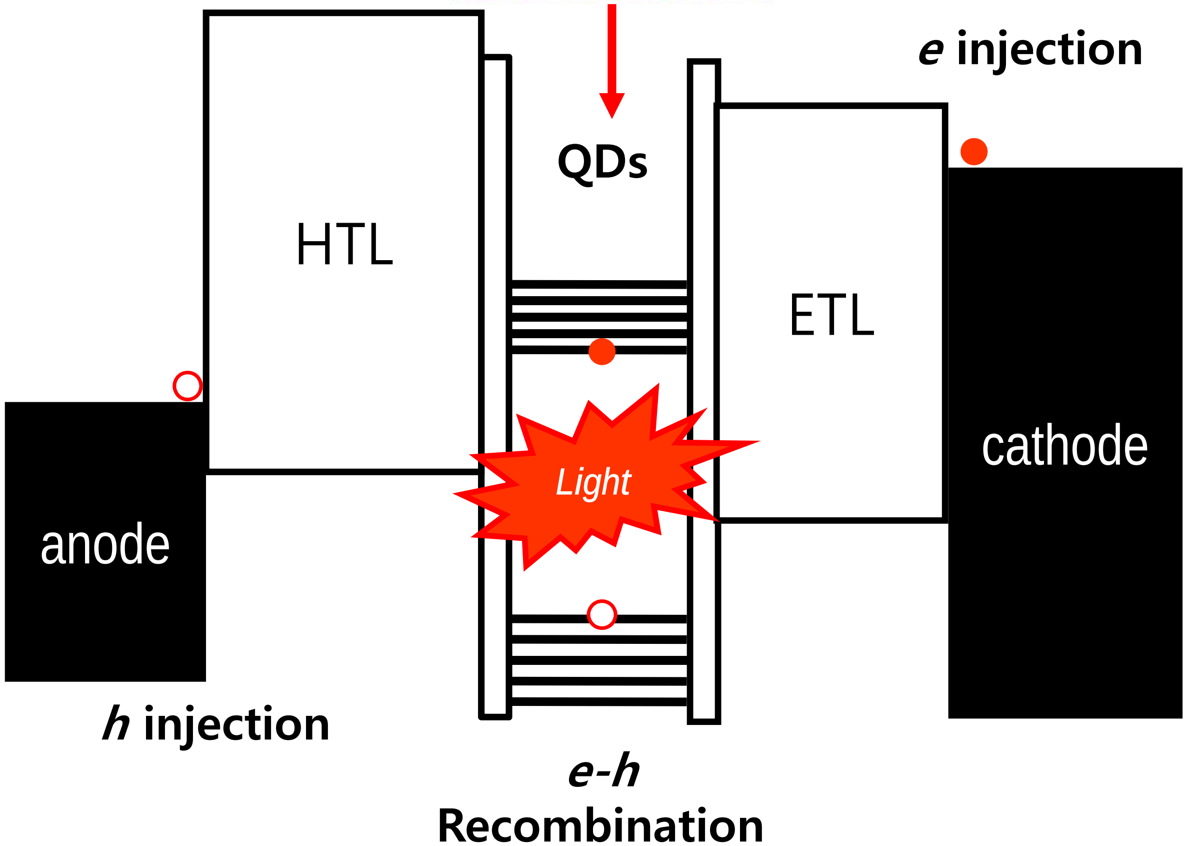
- Surface stabilizer
- QD solubility
- COOH, NH_2, P, PO, PO_3

Y. Shirasaki, G. J. Supran, M. G. Bawendi, V. Bulović, Nat. Photon. **7**, 13 (2013)

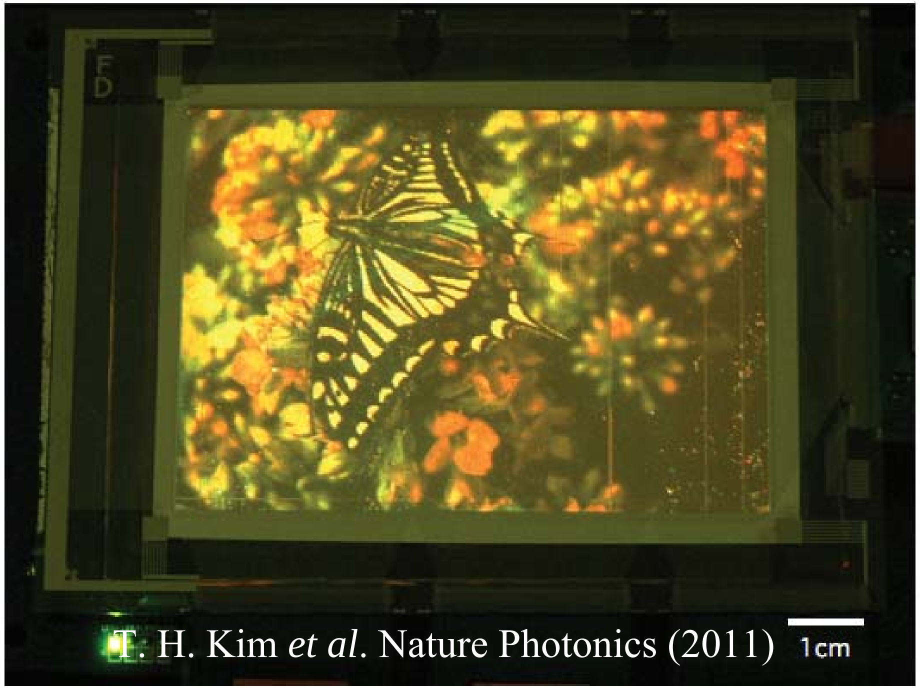
QLEDs: Operating Mechanisms and Advantages

QLEDs





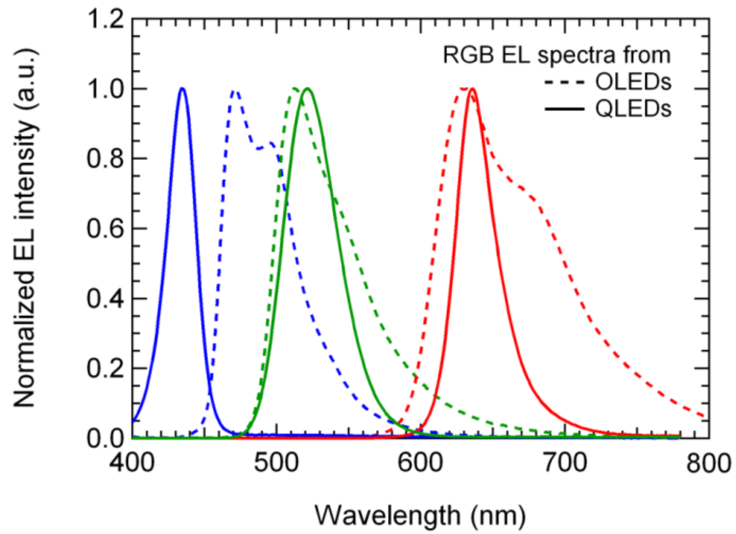
- Similar device architecture as OLEDs
- Size-tunable band-gaps (Color tunability)
- Narrow emission line widths (FWHM <30 nm)
- High PL quantum efficiency
- Good photostability
- Compatibility with solution processes



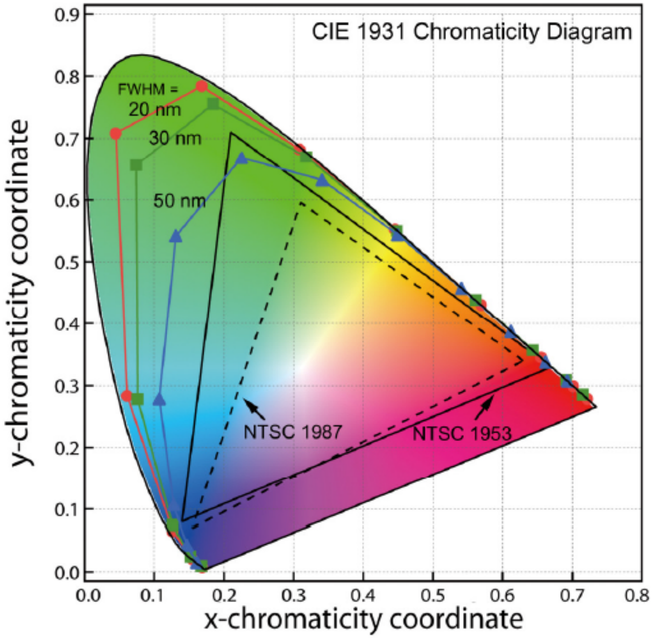
T. H. Kim *et al*. Nature Photonics (2011)

Comparison of QD-LED and OLED

Feature	QD-LED	OLED
Efficiency	Low	High
Emission bandwidth (color saturation)	Narrow FWHM<30nm	Broad FWHM<50-100 nm
Color Tunability	Excellent: Change QD size	Low: Different emitter
Cost of Emitter	Low: One procedure for all RGB emitters	High
Manufacturing process	Solution-based	Vacuum deposition Solution-based
Large display area	Yes	Yes
Flexibility	Yes	Yes
Near-IR emission (telecommunication, sensor)	Yes	No

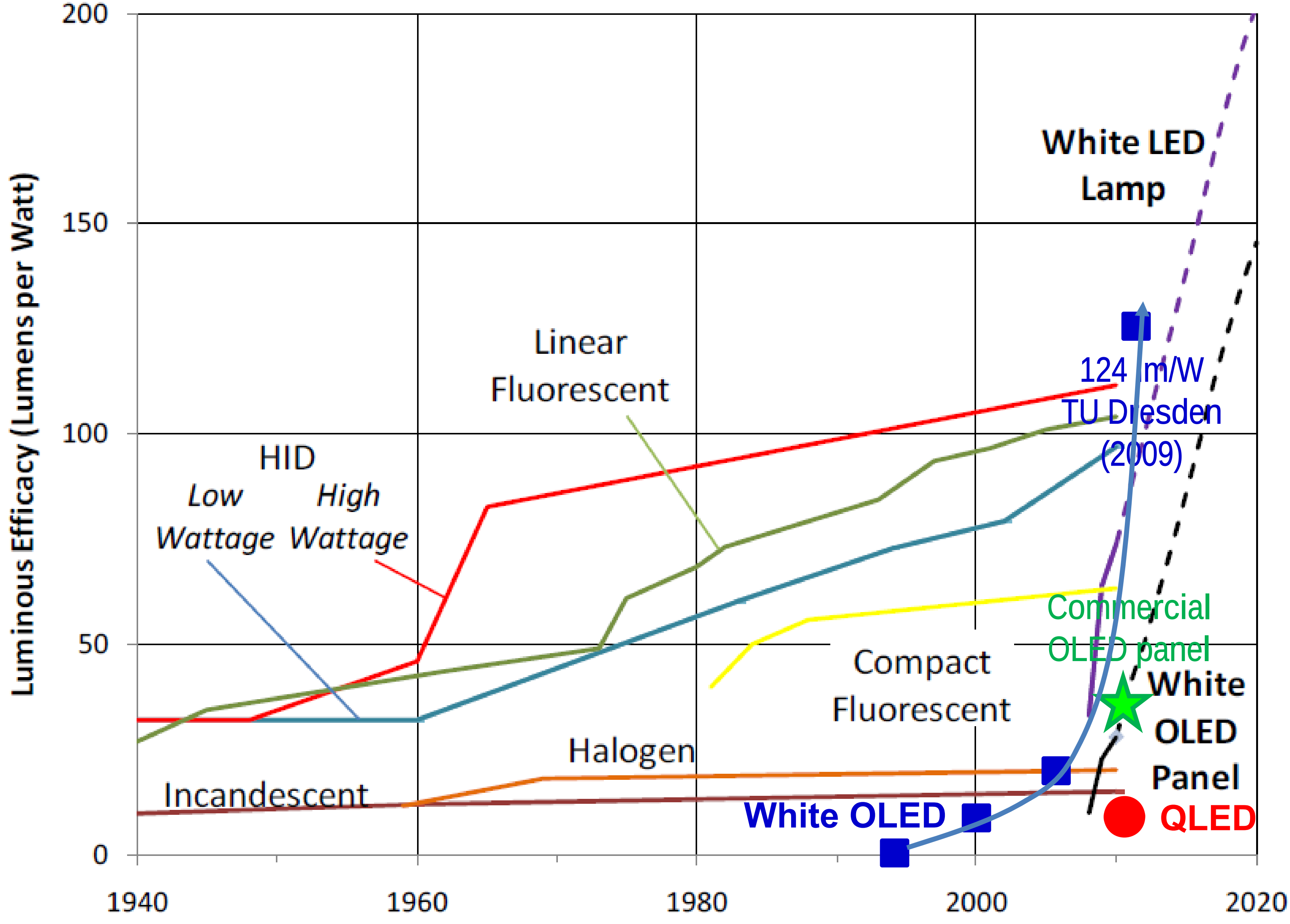


H. D. Cho, Ph.D. Thesis (SNU, 2012)



J. Lim, et al., Optical Materials Express **2** (5), 594 (2012).

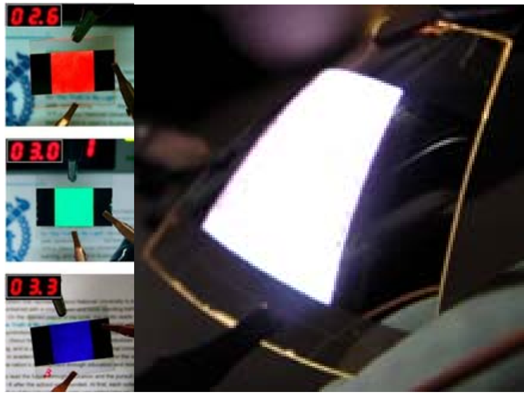
Comparison of luminous efficacy



DOE: Solid-State Lighting Research and Development: Multi Year Program Plan March 2011 (Updated May 2011)

OLED Lighting (NOVALED)

55" AMOLED 3D TV
(LG Display, 2012. 6)



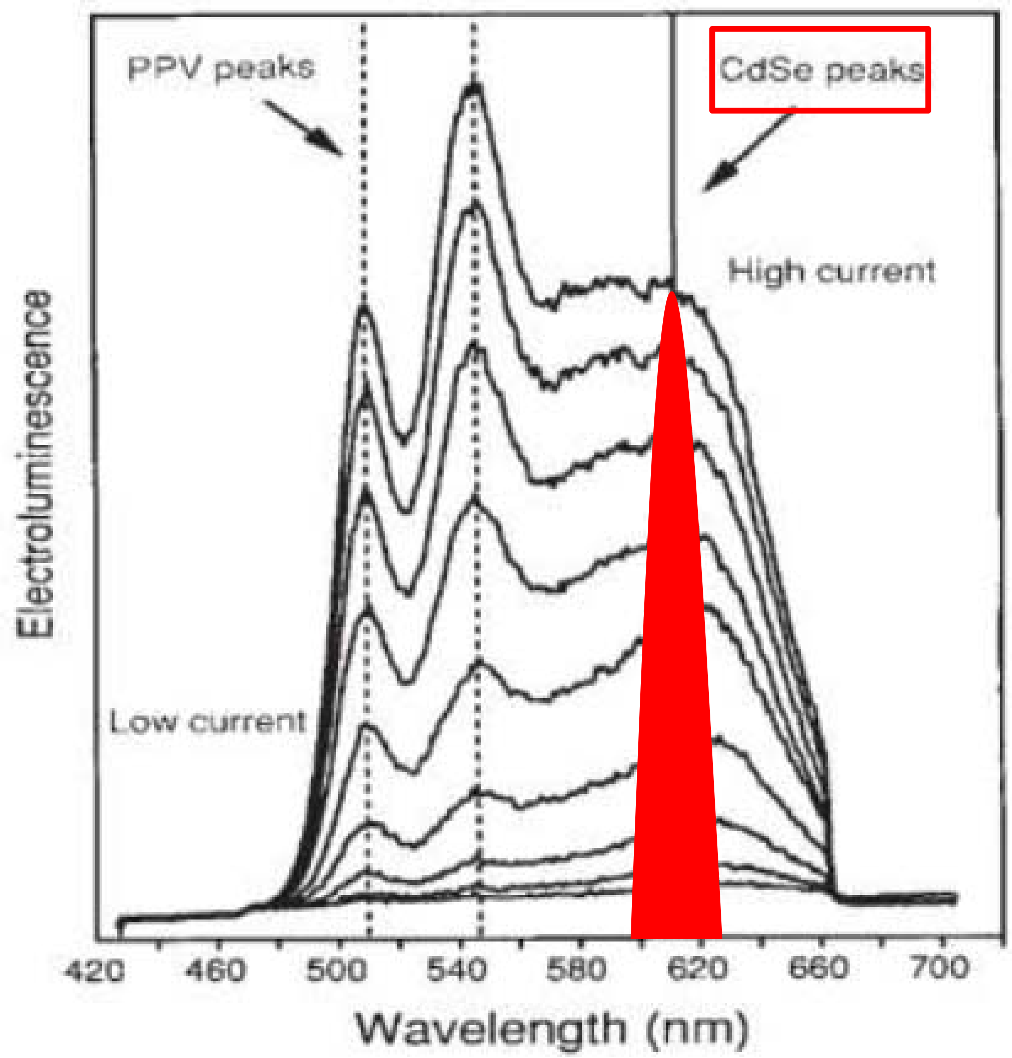
RGB White QLED (SNU)

1st QD-LEDs

- **Deposit CdSe QD layers on *poly(p-phenylene vinylene) (PPV)* layer**

V. L. Colvin, M. C. Schlamp,. A. P. Alivisatos, Nature **370**, 354 (1994).

- **Very low efficiency (EQE ~ 0.0005% - 0.2%)**
- **Significant emission from the organic host matrix**



V. L. Colvin, M. C. Schlamp,. A. P. Alivisatos, Nature **370**, 354 (1994).

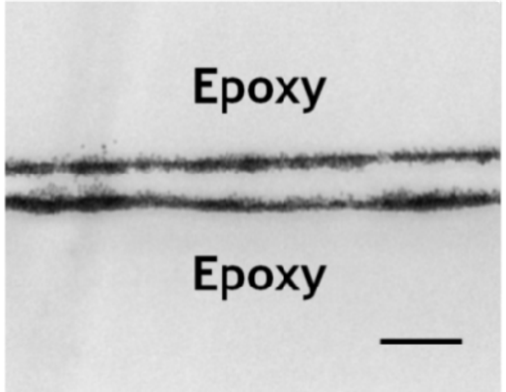
Multilayer QD-LEDs

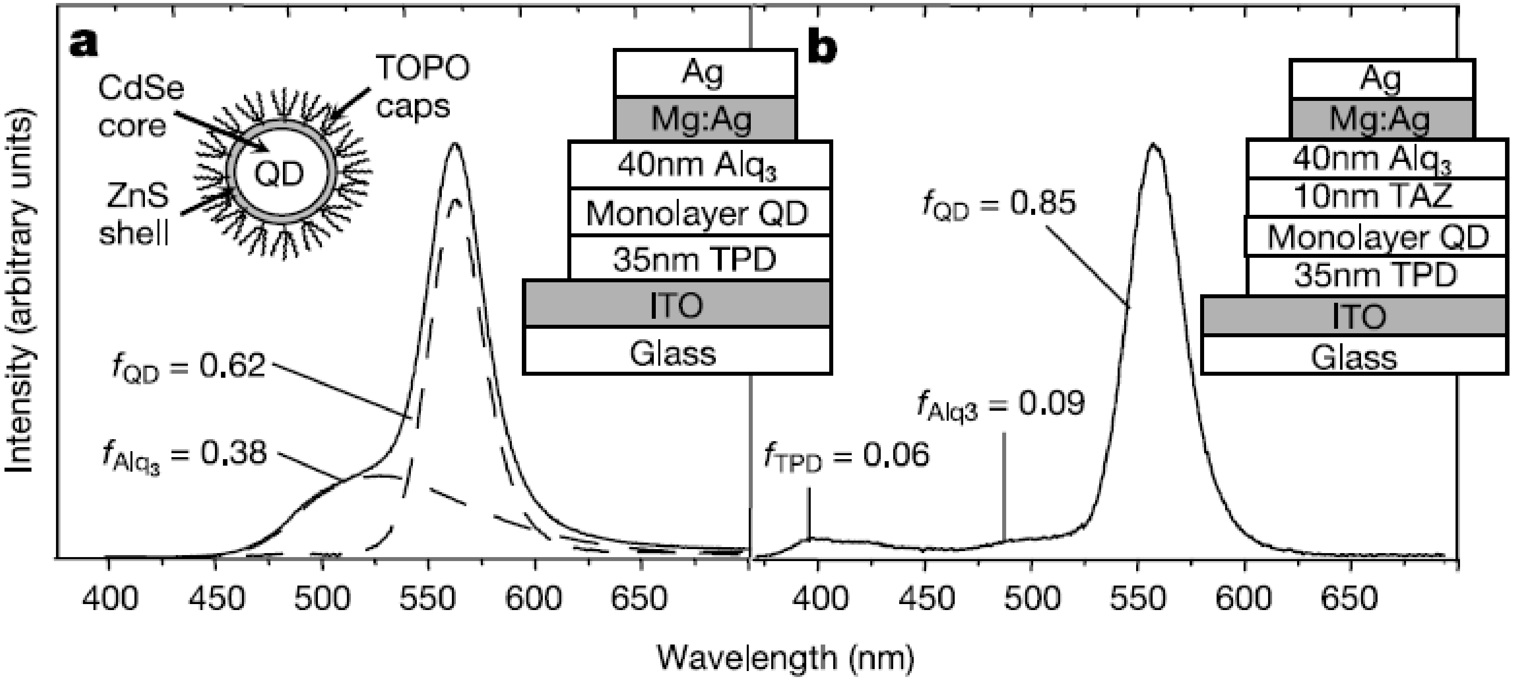
Multilayer device configurations as like OLEDs

→ independent optimization of materials for charge injection, transport, and emission.

- **QD monolayer was deposited through *phase separation* during spin-coating** (EQE~0.5% at 190 cd/m^2).

  S. Coe, W. K. Woo, M. Bawendi, V. Bulovic, Nature **420**, 800 (2002).





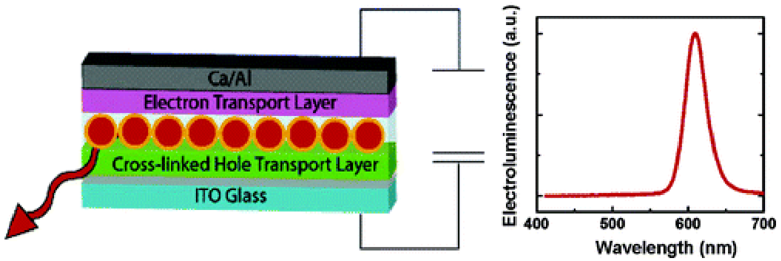
- Spin-coating nanoparticle layers onto hole transport layers (HTLs) **using incompatible solvents (orthogonal solvents)** that do not dissolve the underlying HTLs.

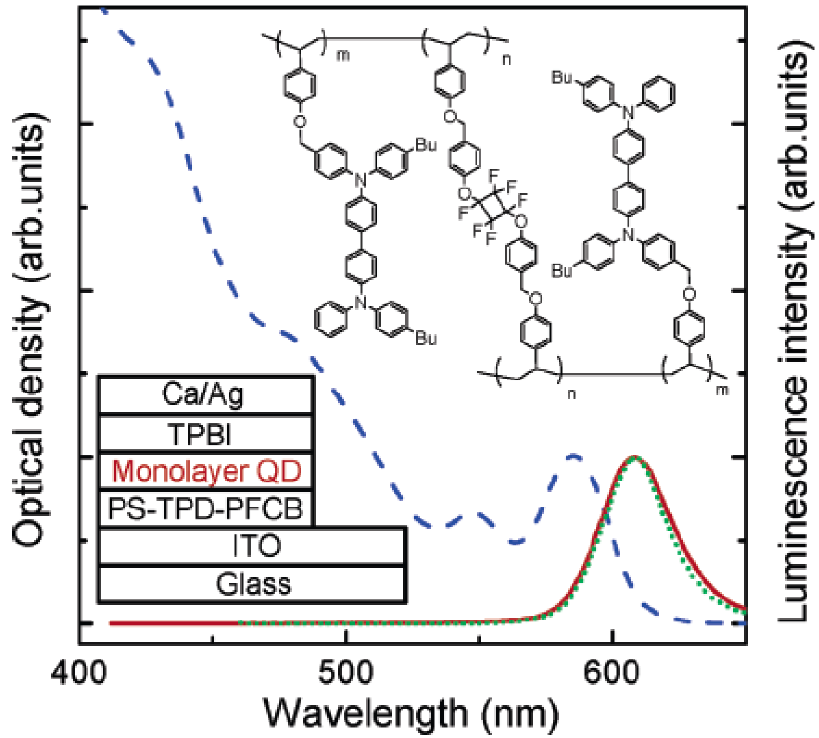
  Chaudhary *et al*., Appl. Phys. Lett. **84**, 2925 (2004).

Thermally cross-linked HTL: PS-TPD-PFCB

Hydrophobic thermally cross-linked HTL:
polystyrene (PS)-N,N'-diphenyl-N,N'-bis(4-n-butylphenyl)-(1,1'-biphenyl)-4,4'-diamine (TPD)-perfluorocyclobutane (PFCB).

CdSe/CdS Quantum Dot-LED





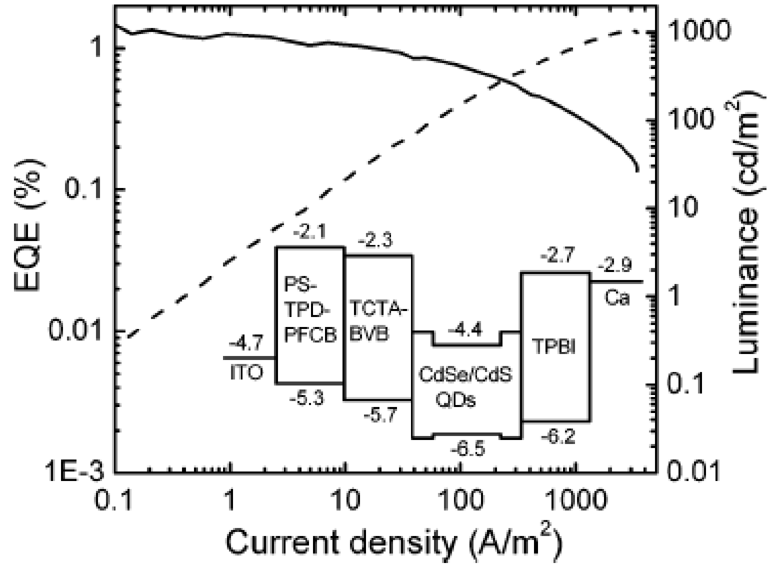
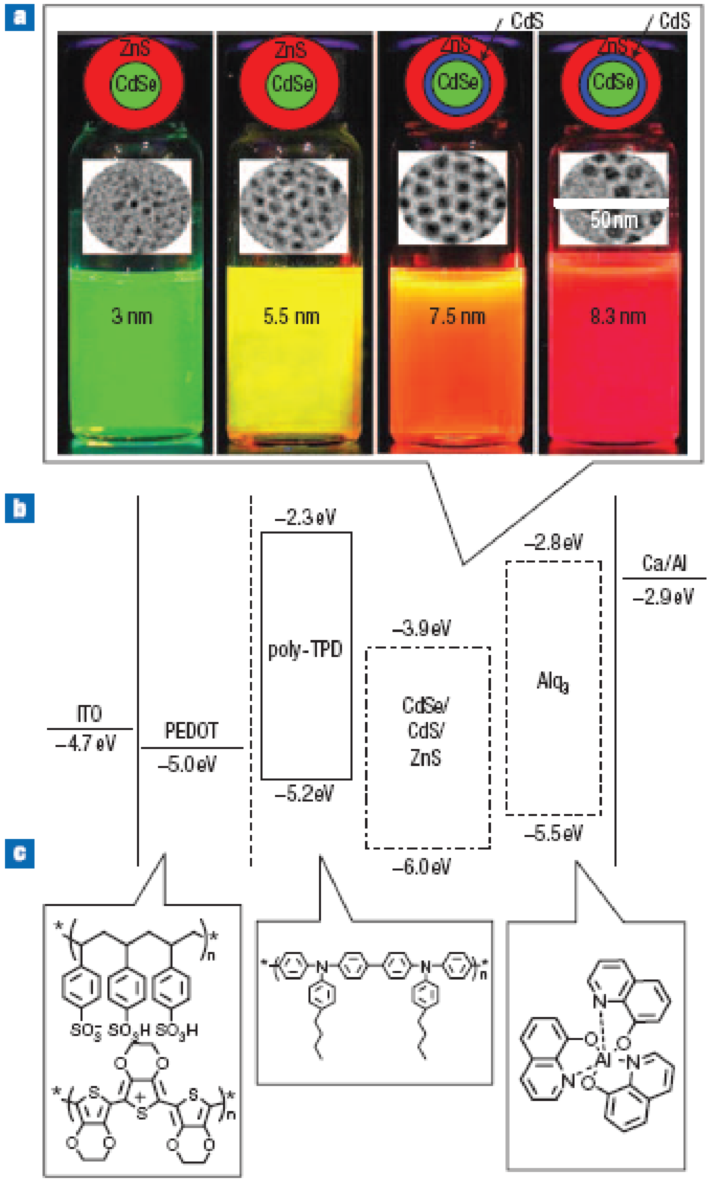


Figure 5. EQE (solid line) and luminance (dashed line) as a function of current density for the CdSe/CdS QD-LEDs with double HTLs. The LED structure is ITO/PS−TPD−PFCB (20 nm)/TCTA−BVB (20 nm)/CdSe QDs/TPBI (40 nm)/Ca (30 nm)/Ag (120 nm) and the energy level diagram of multilayered CdSe/CdS QD-LEDs is shown in the inset of this figure. The work functions of ITO, and Ca electrodes, and the electron affinities and ionization energies of PS−TPD−PFCB (TPD), TCTA−BVB (TCTA), TPBI, and CdSe/CdS QDs are taken from previous experimental data.[1,3,7,8,14,17,26]

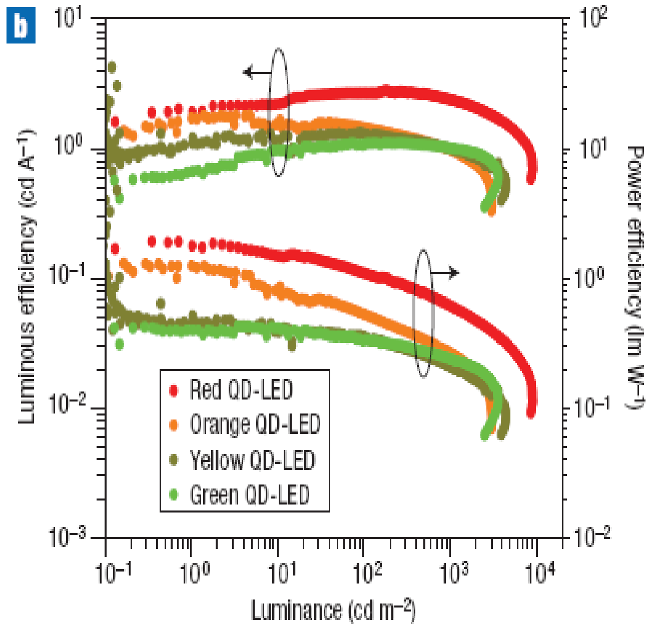
J. Zhao, J. A. Bardecker, A. M. Munro, M. S. Liu, Y. Niu, I-K. Ding, J. Luo, B. Chen, A. K.-Y. Jen, and D. S. Ginger (**U. Washington**), Nano Lett. 6, 463 (2006)

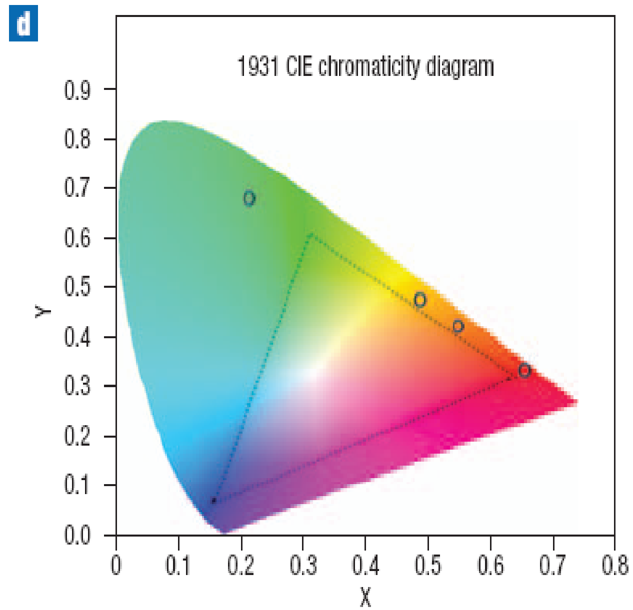
Thermally cross-linked HTL: poly-TPD



Thermally cross-linked HTL allows us to spin-coat QD layers without any damage.

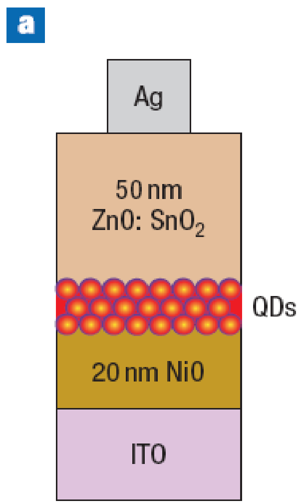
But there are not many such HTLs.

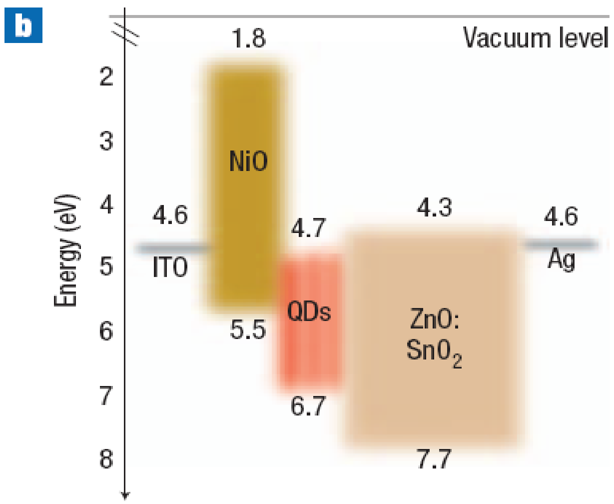


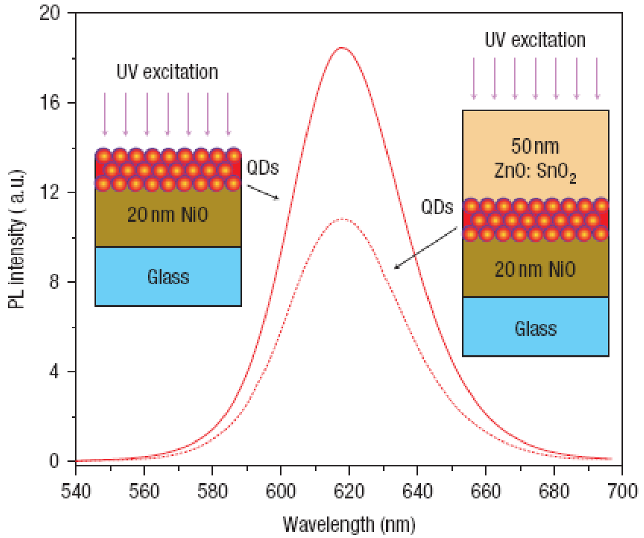


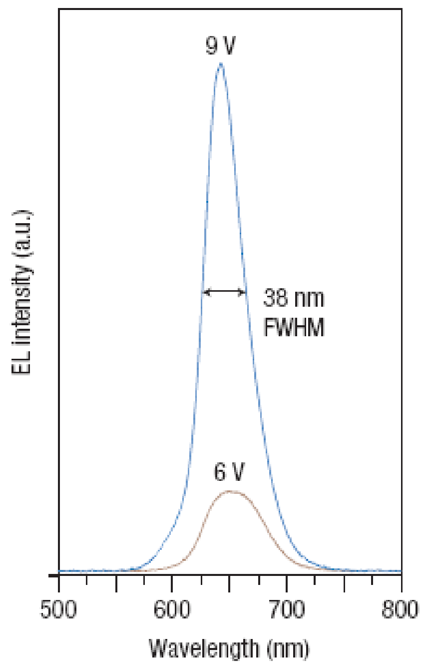
Q.-J Sun *et al.* (CAS, **Ocean NanoTech**, Penn State Univ.), Nature Photonics **1**, 717 (2007)

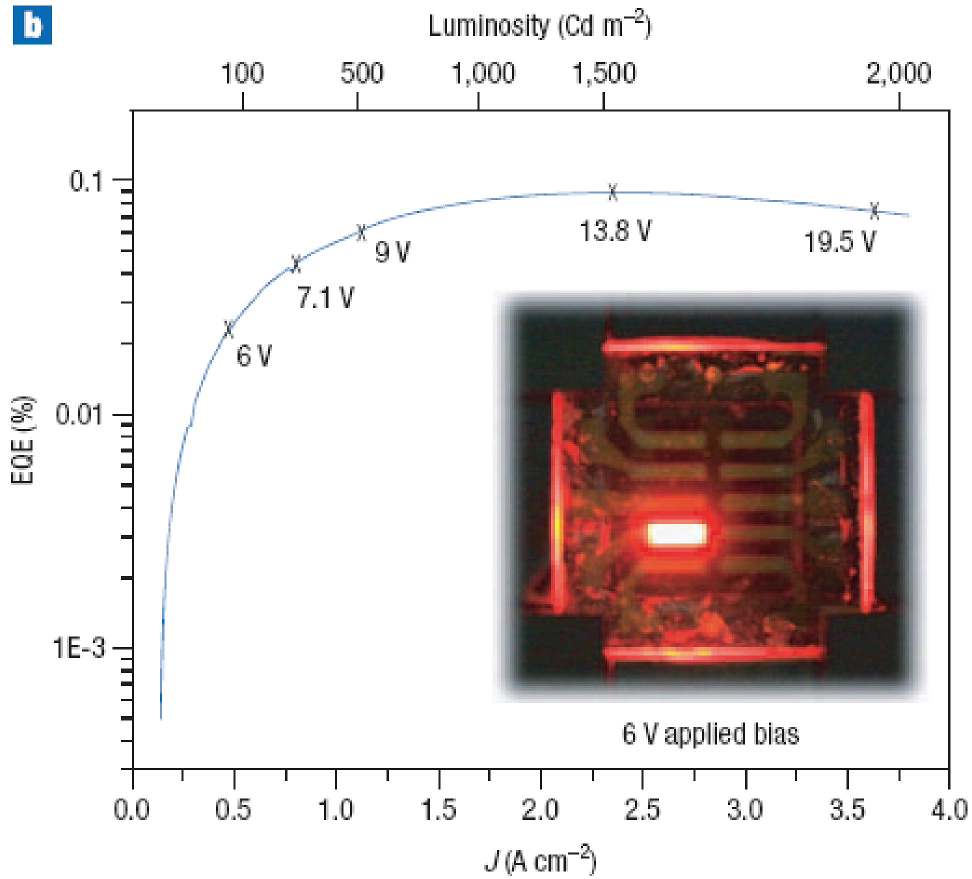
Metal-oxide charge transport layers







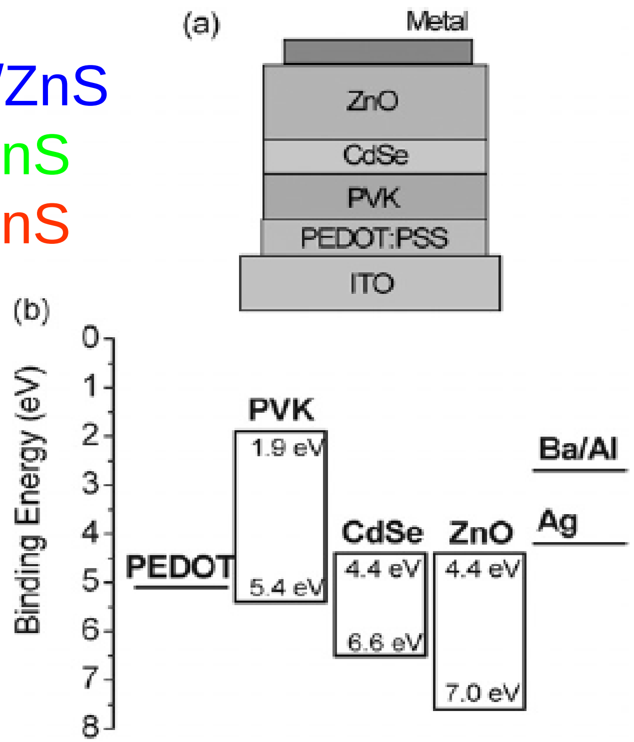


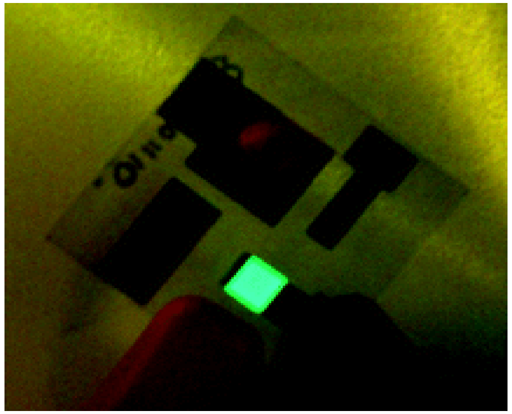


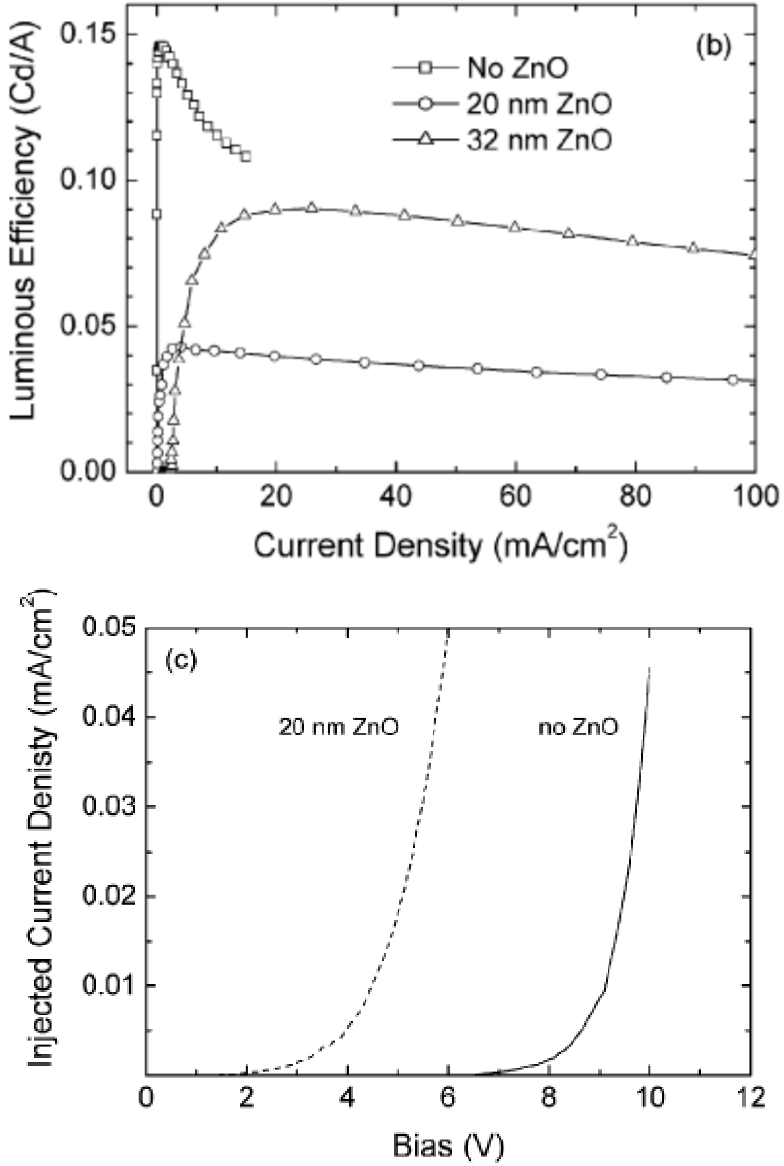
J. M. Caruge, J. E. Halpert, V. Wood, V. Bulovic, M. G. Bawendi (**MIT**), Nature Photonics **2**, 247 - 250 (2008)

Solution processable ZnO nanocrystal EIL

Blue CdSeS/ZnS
Green CdSe/ZnS
Red CdSe/ZnS

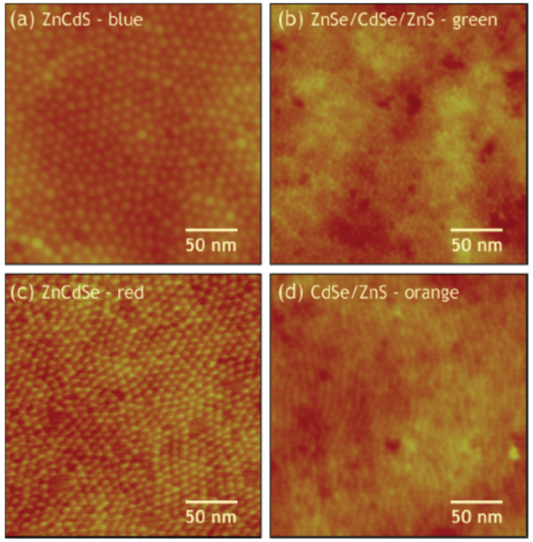


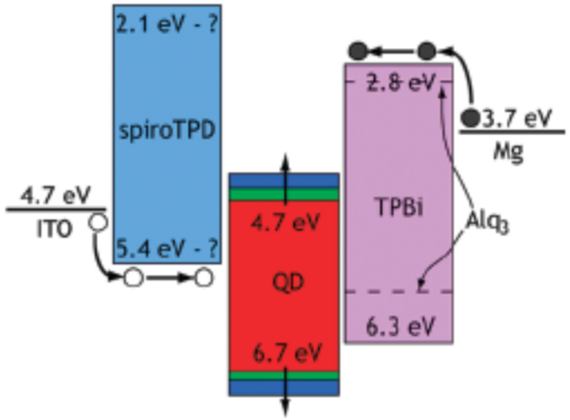




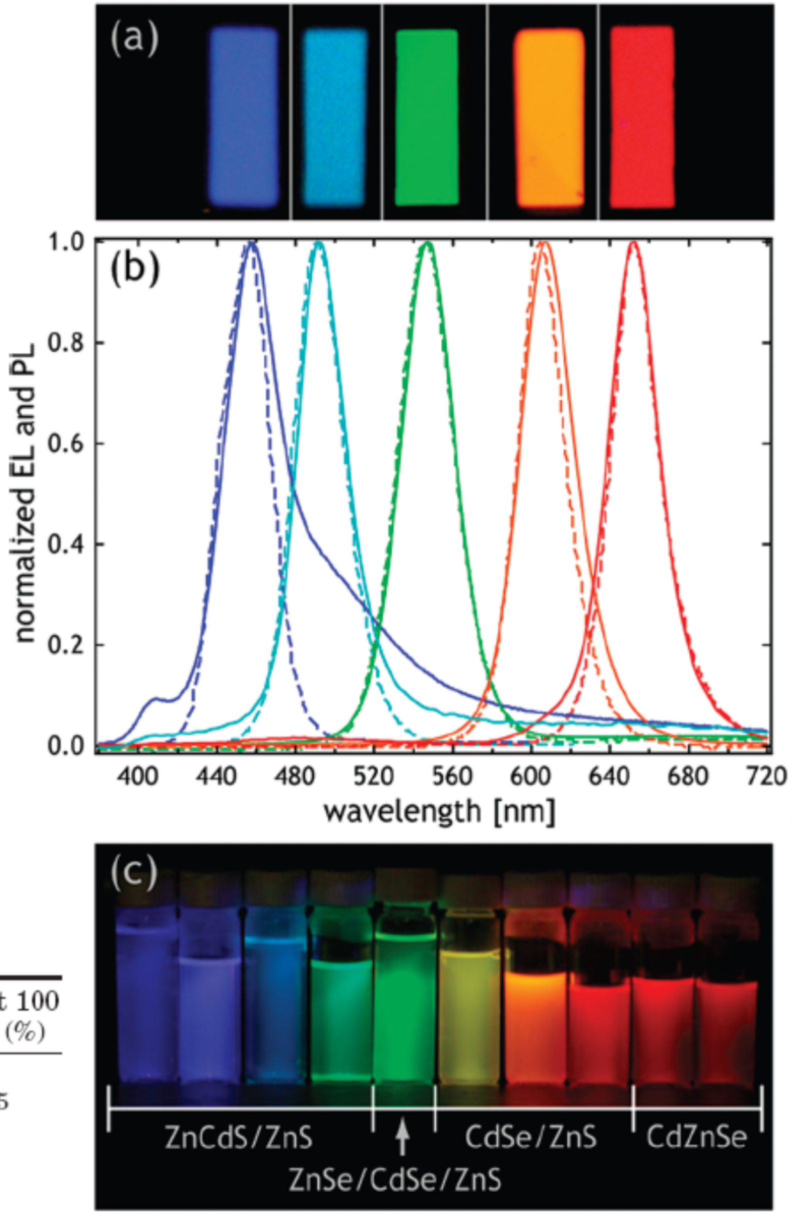
Jan W. Stouwdam and René A. J. Janssen (**Eindhoven University of Technology**), J. Mater. Chem., 2008, 18, 1889

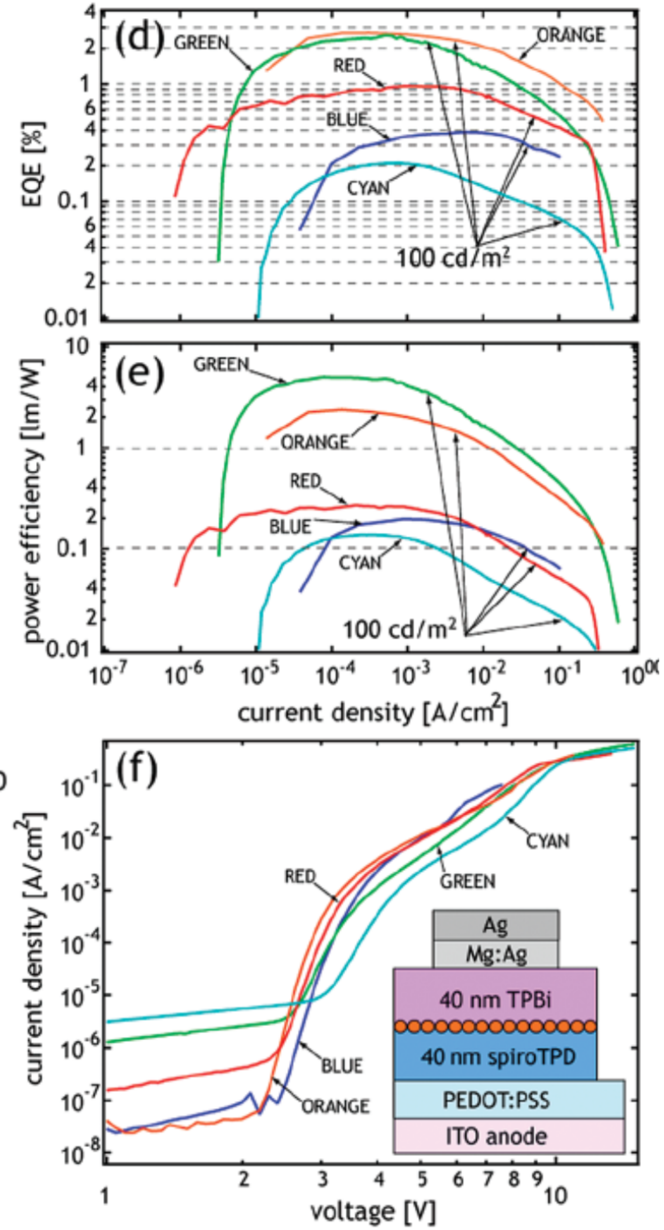
QD LEDs Tunable over the Entire Visible Spectrum





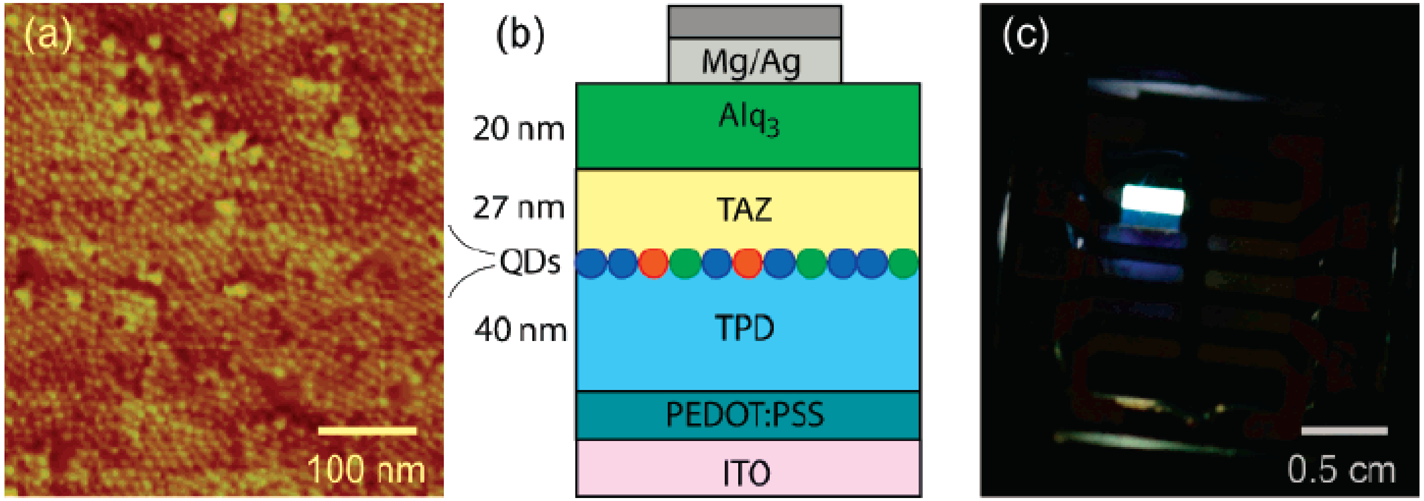
QD-LED color	peak EQE (%)	brightness at peak EQE (cd/m^2)	EQE at 100 cd/m^2 (%)
blue (EL_{max} at 460 nm)	0.4	15	0.3
cyan (EL_{max} at 490 nm)	0.2	3	0.05
green (EL_{max} at 545 nm)	2.6	28	2.2
orange (EL_{max} at 600 nm)	2.7	13	2.3
red (EL_{max} at 650 nm)	1.0	7	0.5

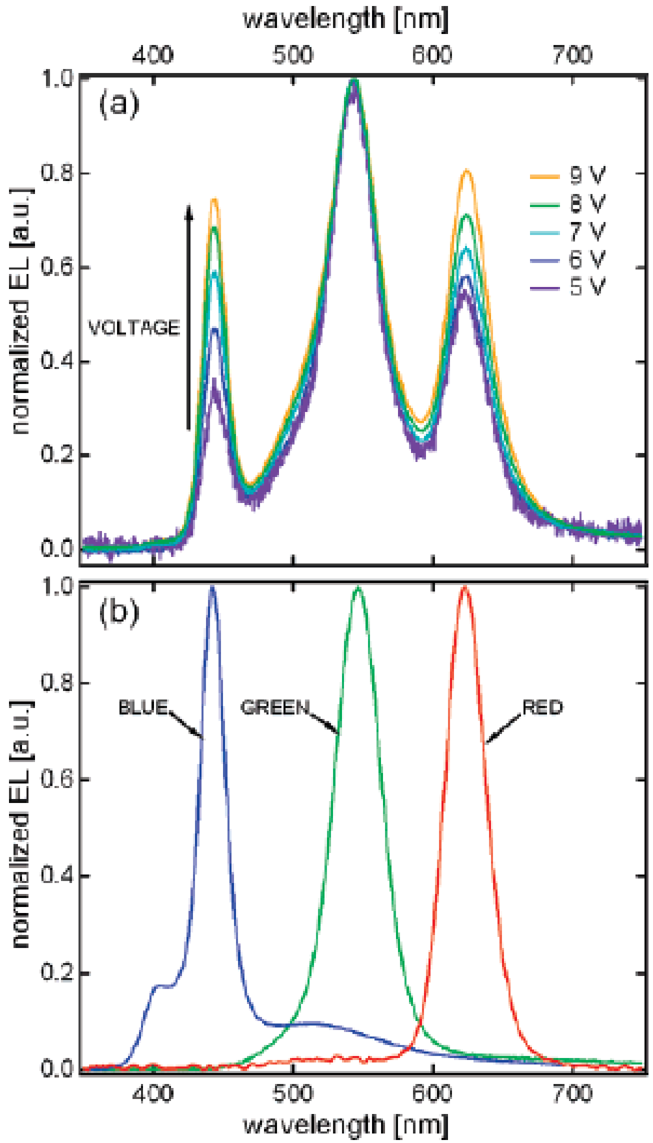


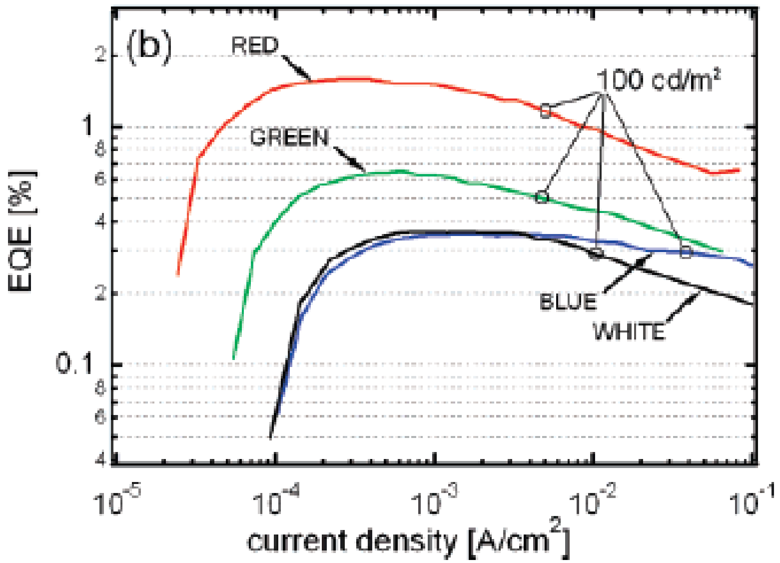


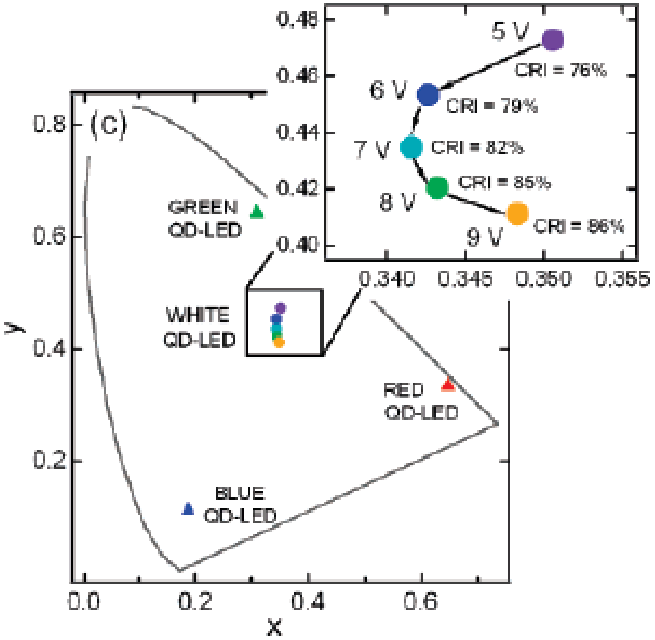
Polina O. Anikeeva, Jonathan E. Halpert, Moungi G. Bawendi and Vladimir Bulovic (**MIT**), Nano Lett., 2009, 9 (7), pp 2532–2536

White LEDs using a mixed R-G-B colloidal QD Monolayer









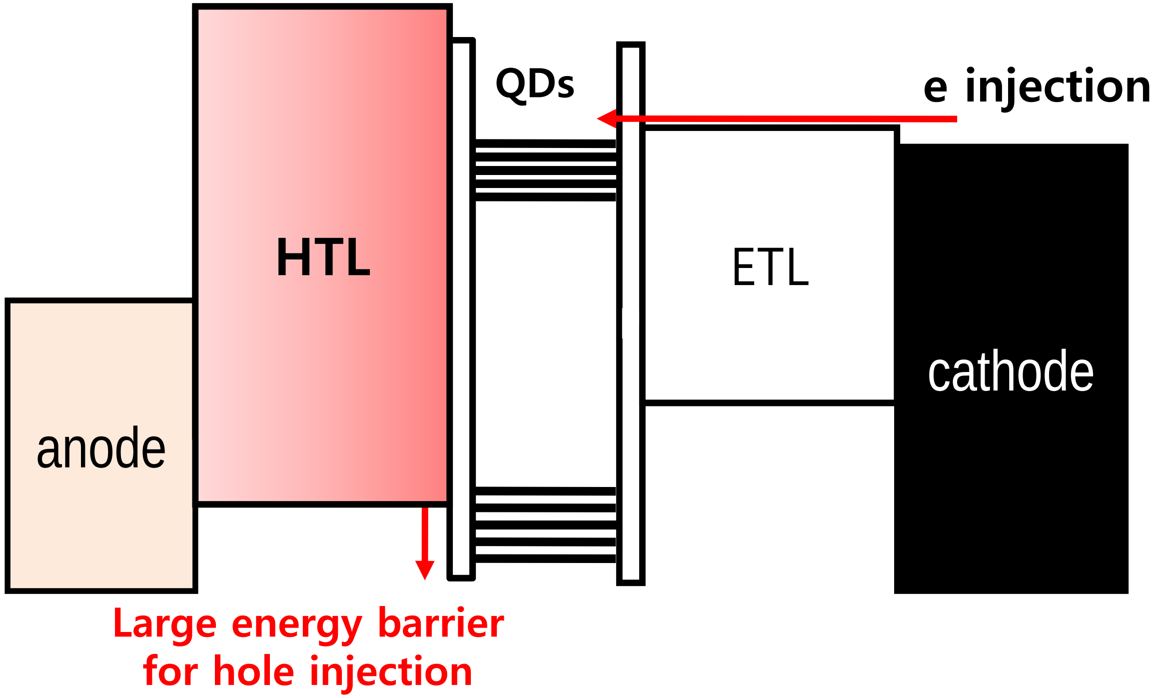
Polina O. Anikeeva, Jonathan E. Halpert, Moungi G. Bawendi, and Vladimir Bulović (**MIT**), Nano Lett. 7, 2196 (2007)

Poor carrier injection

- ***Poor hole injection into QDs***

→ *e-h unbalance*

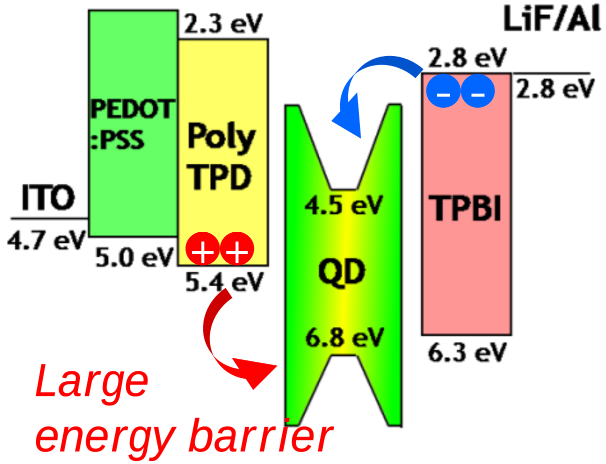
→ *low efficiency*

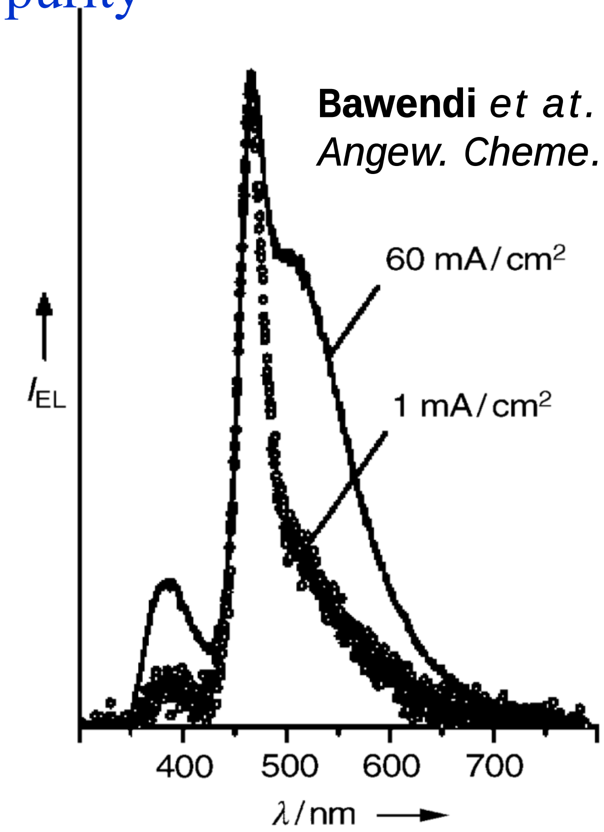


- Difficulty of depositing HTLs with high HOMO due to the damages from solvent used when depositing QD layers

Hole injection problem

Hole injection problem due to the large energy barrier between HTL/QDs
→ resulting disadvantages in
• device efficiency
• turn-on voltage
• color purity

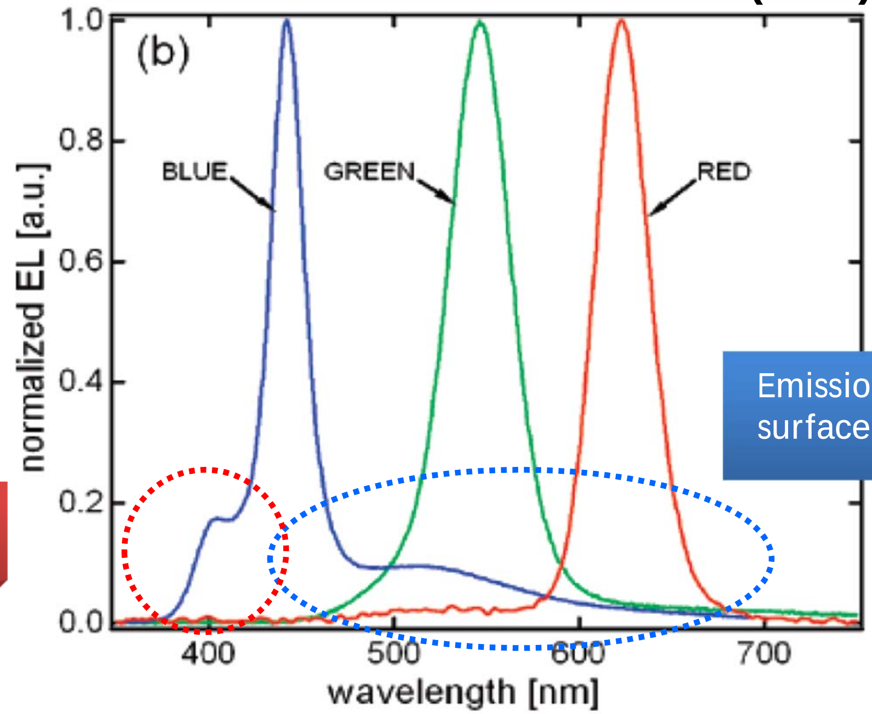




Bawendi *et al.*
Angew. Cheme. Int. Ed. **(2004)**

Emission from HTM/ETM

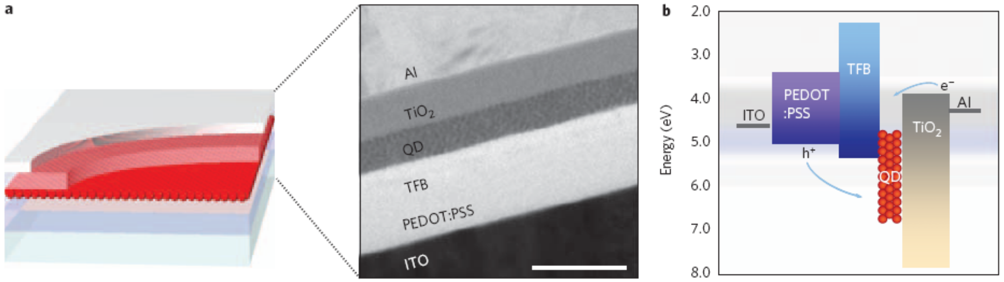
Bawendi *et al. Nano Lett.* **(2008)**



Emission from surface states

Modifying the organic ligands to reduce the HTL/QD band offset

"To reduce the band offset between the HTL and QD layer, the valence band of the QD layer is shifted upwards using a crosslinking method. During crosslinking, linker molecules become attached to the QD through exchange with pre-existing surfactants or by binding to empty sites on the QD surface. Adsorption of organic molecules can cause energy levels to realign through the formation of microscopic surface dipoles at the QD–surfactant interface."



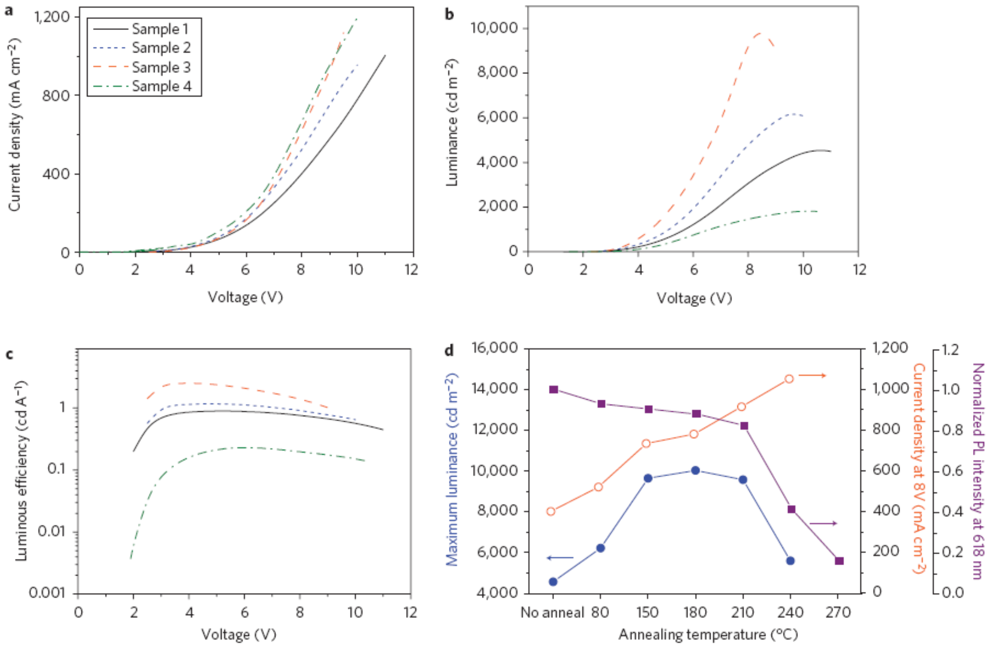


Figure 4 | Electroluminescence performance of QD-LEDs. a–c, Current density-voltage, luminance-voltage and luminous efficiency-voltage characteristics for the QD-LEDs with different QD manipulations: the QD layer crosslinked after spin-coating (sample 1), crosslinked and annealed at 80 or 180 °C, respectively, for 30 min under nitrogen (samples 2 and 3), and annealed at 180 °C for 30 min without crosslinking (sample 4). **d,** Maximum luminance and current density at fixed bias (8 V) for the QD-LEDs and the PL intensity for QD films as a function of annealing temperature after crosslinking the QD layer.

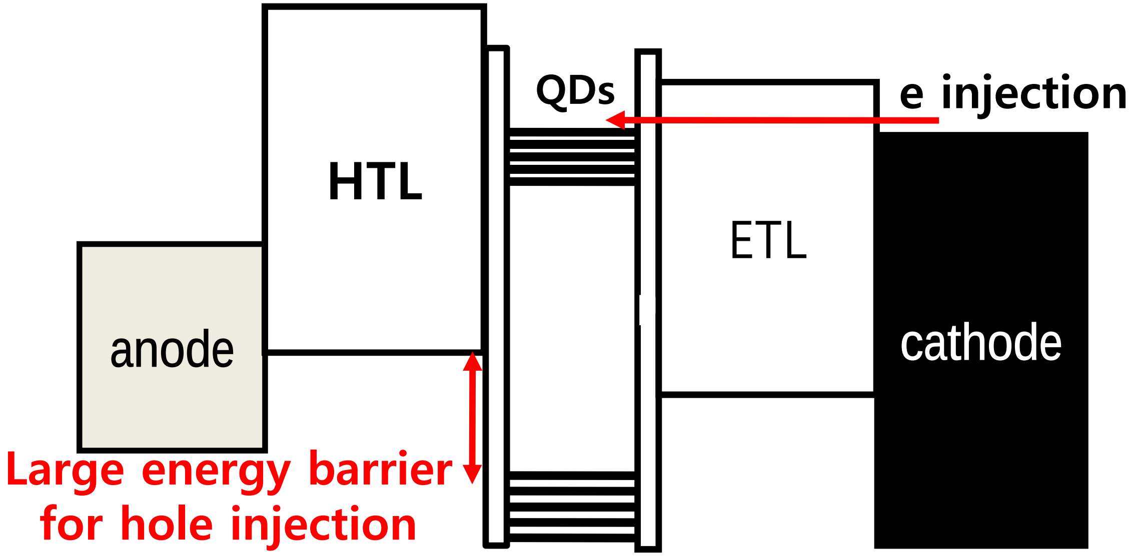
Table 1 | Ionization potential results for QD films from He II ultraviolet photoelectron spectroscopy.

QD film	Secondary cutoff, $E_{s,cutoff}$ (eV)	Valence band edge, $E_{v,edge}$ (eV)	Ionization potential* (eV)	Corresponding devices in Fig. 4
As-coated (f1)	36.59	2.63	6.85	—
Crosslinked (f2)	35.77	1.21	6.25	Sample 1
Crosslinked/annealed at 80 °C (f3)	35.90	1.33	6.23	Sample 2
Crosslinked/annealed at 180 °C (f4)	35.55	0.96	6.23	Sample 3
Annealed at 180 °C (f5)	36.67	2.70	6.84	Sample 4

*Ionization potential = 40.81 eV − ($E_{s,cutoff}$ − $E_{v,edge}$).

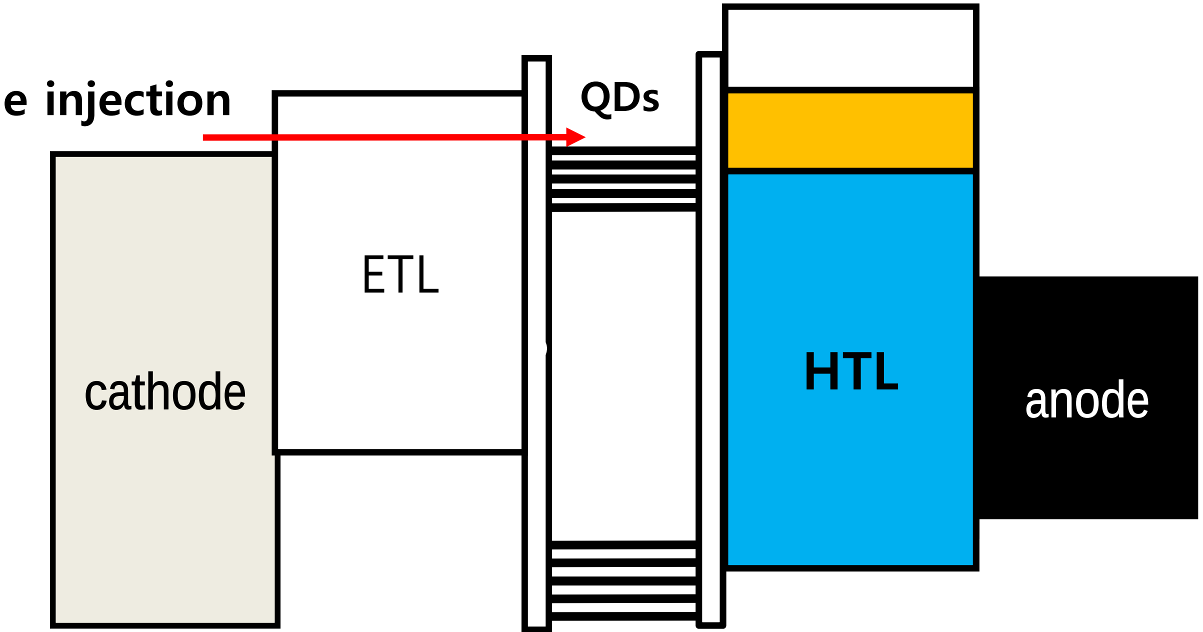
Kyung-Sang Cho, Eun Kyung Lee, Won-Jae Joo, Eunjoo Jang, Tae-Ho Kim, Sang Jin Lee, Soon-Jae Kwon, Jai Yong Han, Byung-Ki Kim, Byoung Lyong Choi and Jong Min Kim (**SAIT**), Nature Photonics 3, 341 (2009)

Inverted QLEDs for solving poor hole injection problem



Poor hole injection into QDs
→ e-h unbalance
→ low efficiency

We can solve this problem using an inverted device architecture.

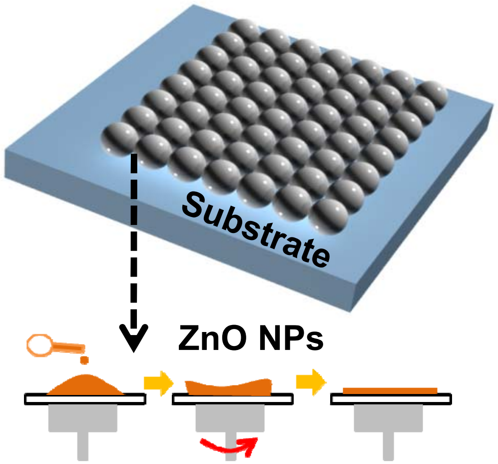


For an inverted device structure, we can deposit a variety of organic HTL materials using a thermal evaporation method in vacuum

ZnO nanoparticles: EIL and ETL

Requirement of an efficient electron injection layer (EIL)
→ transparency, low workfunction, good electron transporting property

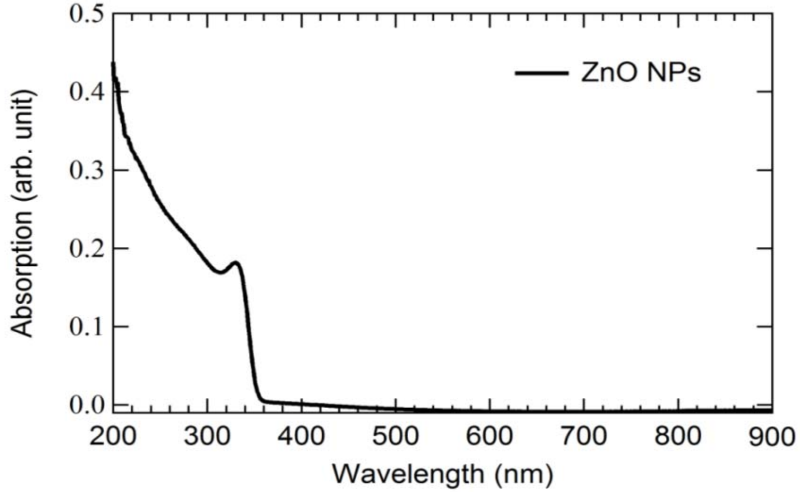
Low temperature solution-processibility



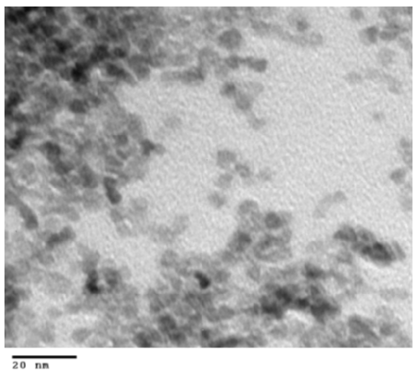
<Synthesized>

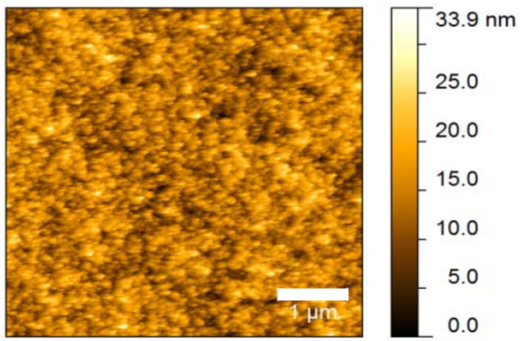
Dried at 90°C

Transparency in the visible spectral range



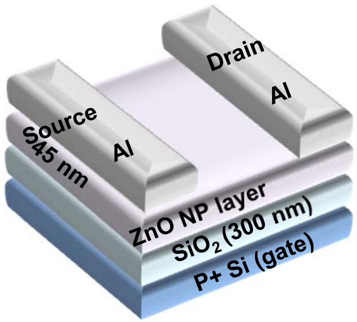
TEM and AFM image of ZnO NPs

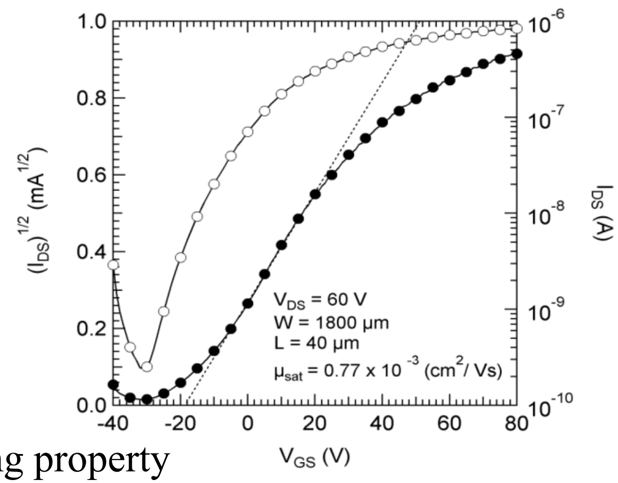




Particle size: 3~5 nm $\sigma_{RMS,\ ZnO\ (20\ mg/ml)}$ = 3.9 nm

Electron mobility of ZnO NPs

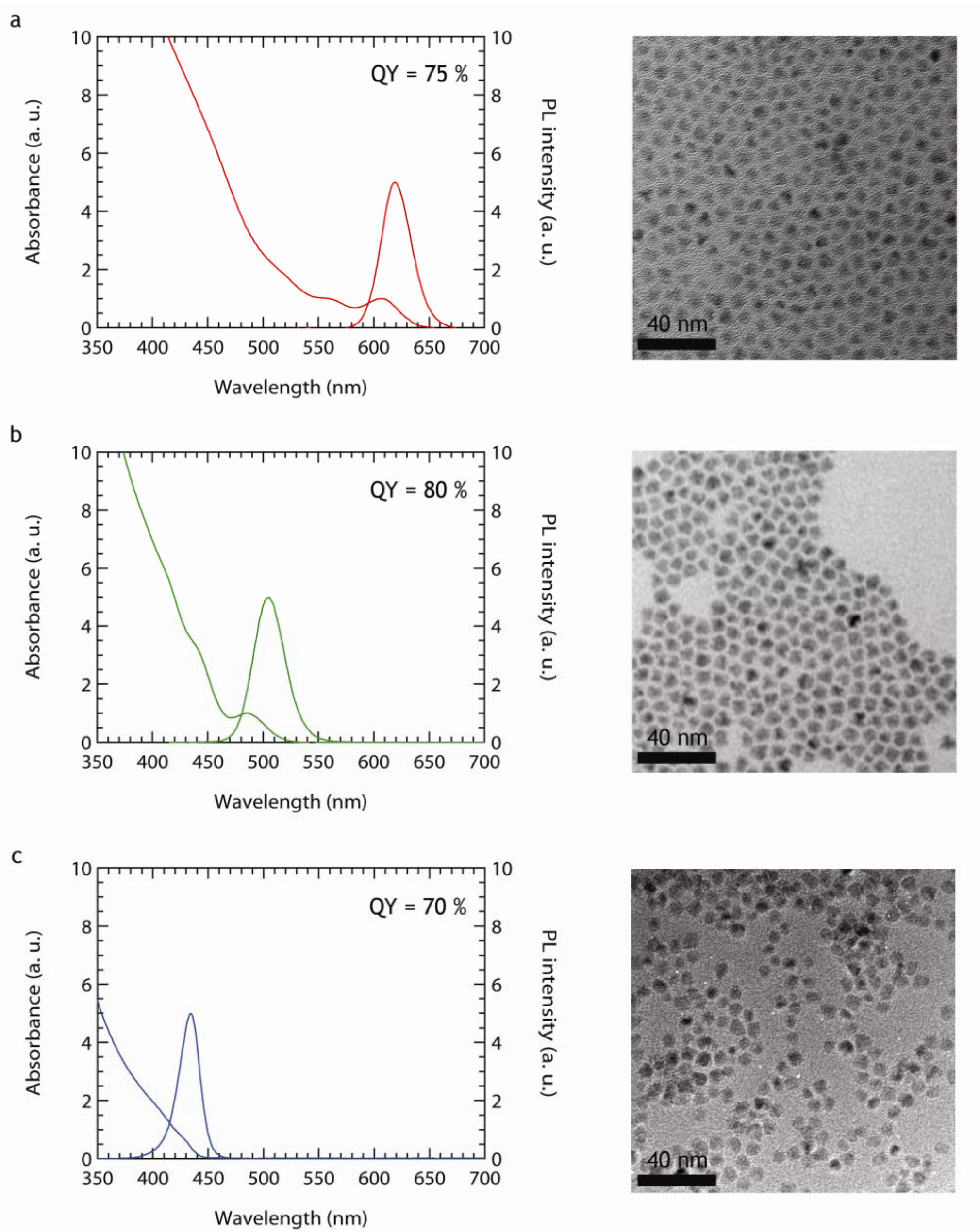




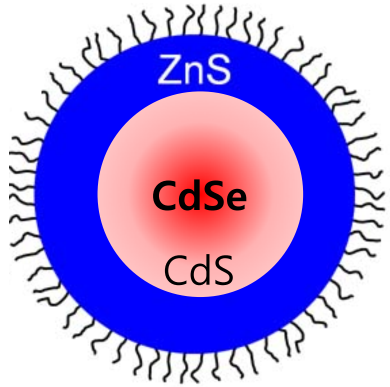
- High electron mobility
- Good electron transporting property

H. K. Lee *et al.*, Appl. Phys. Lett. **96**, 153306 (2010)

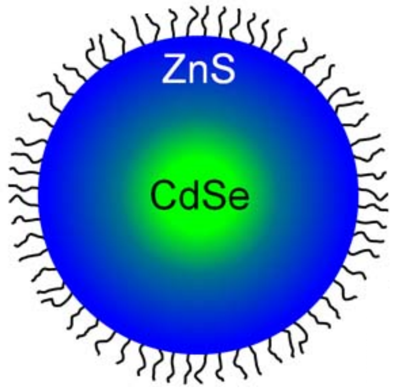
Red, Green, Blue QDs stabilized with oleic acids



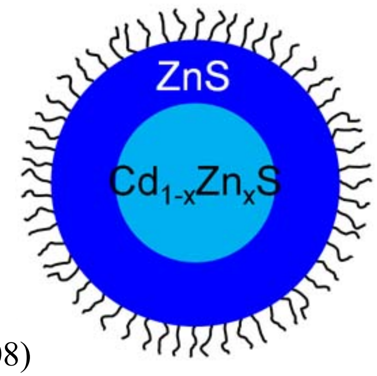
Red QDs
- CdSe/CdS/ZnS core/multishell QDs
- Diameter ~ 8 nm
- PL QY ~ 76 %



Green QDs
- CdSe@ZnS composition gradient QDs
- Diameter ~ 9 nm
- PL QY ~ 80 %

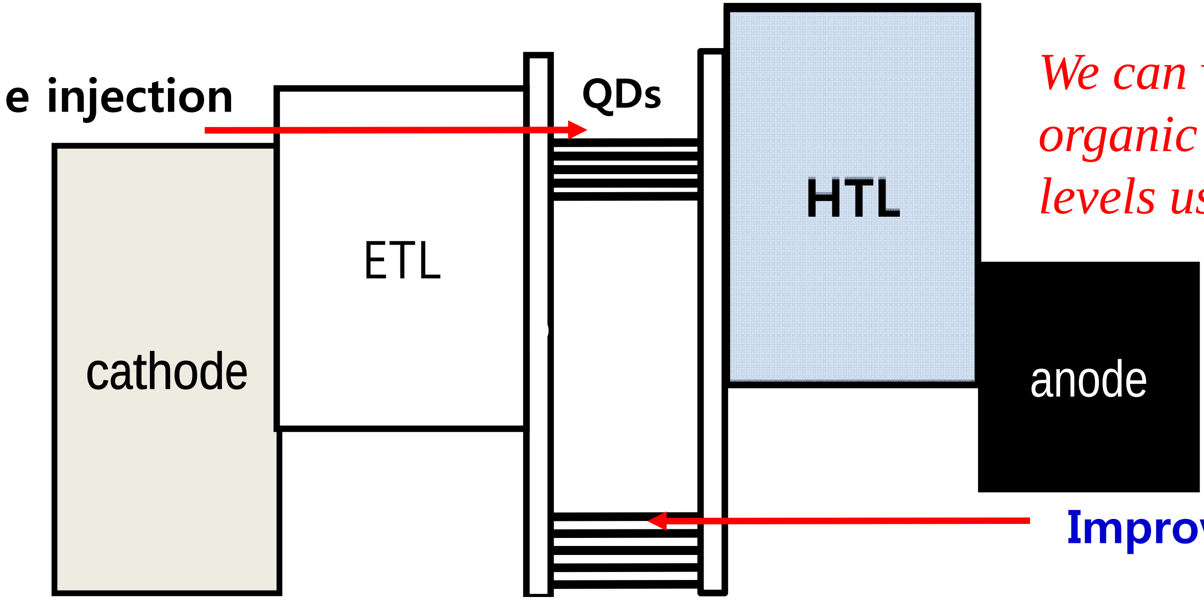


Blue QDs
- $Cd_{1-x}Zn_xS$/ZnS QDs
- Diameter ~ 8 nm
- PL QY ~ 70 %)



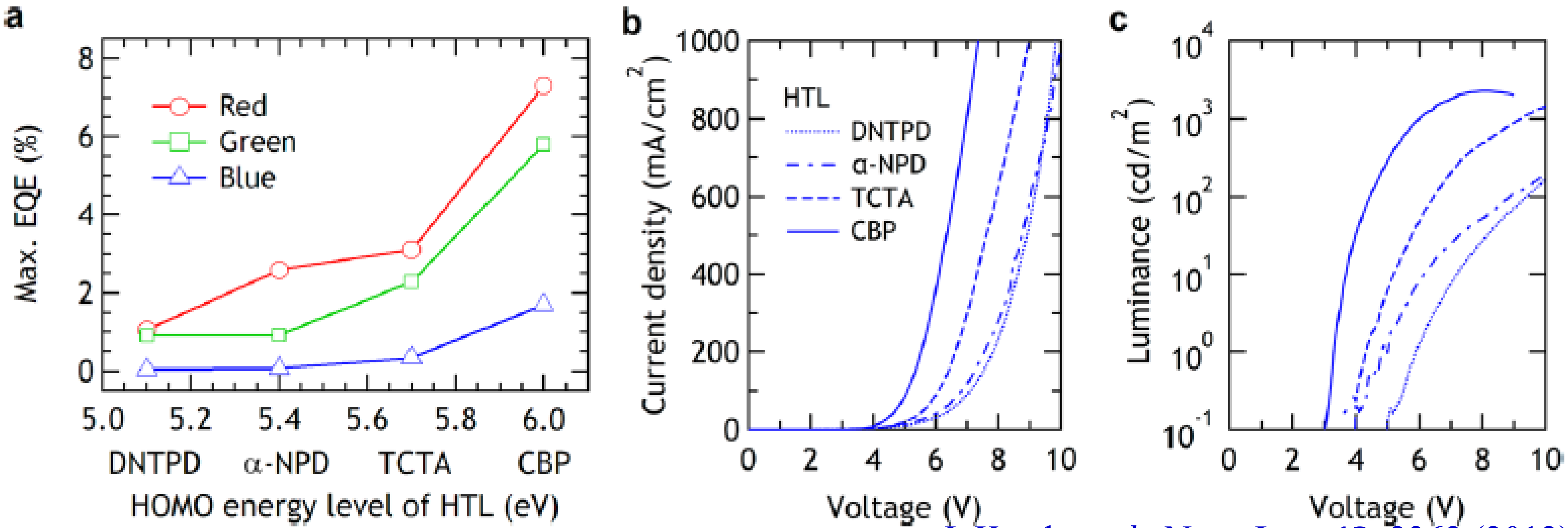
W. K. Bae *et al.*, *Chem. Mater.* **20**, 531-539 (2008)
W. K. Bae *et al.*, *Chem. Mater.* **20**, 5307-5313 (2008)

Inverted bottom-emission QLED



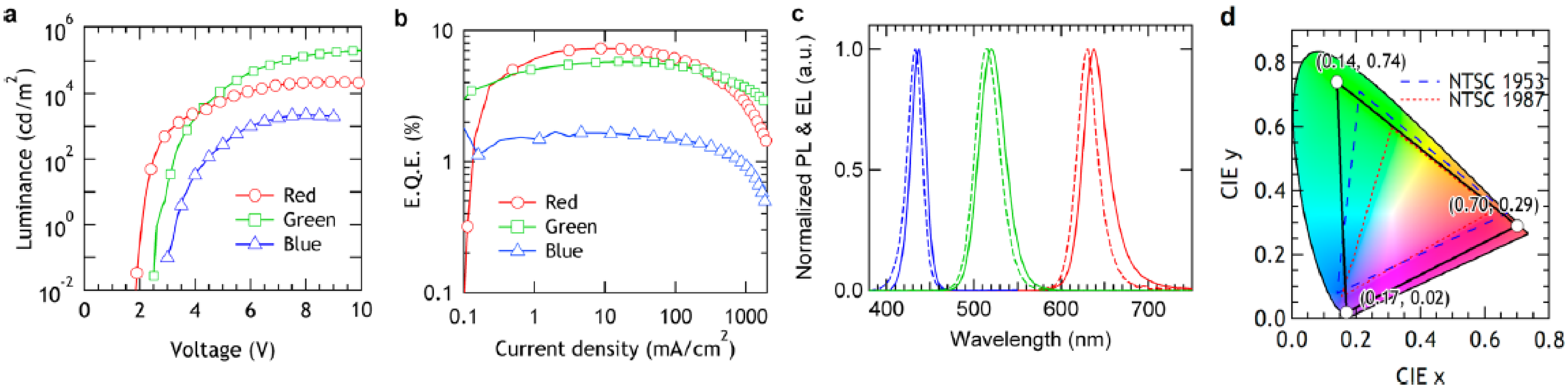
We can vacuum deposit a variety of organic HTL materials with high HOMO levels using an inverted device structure!

Improved hole injection → e-h balance



J. Kwak *et al.*, Nano Lett. **12**, 2362 (2012)

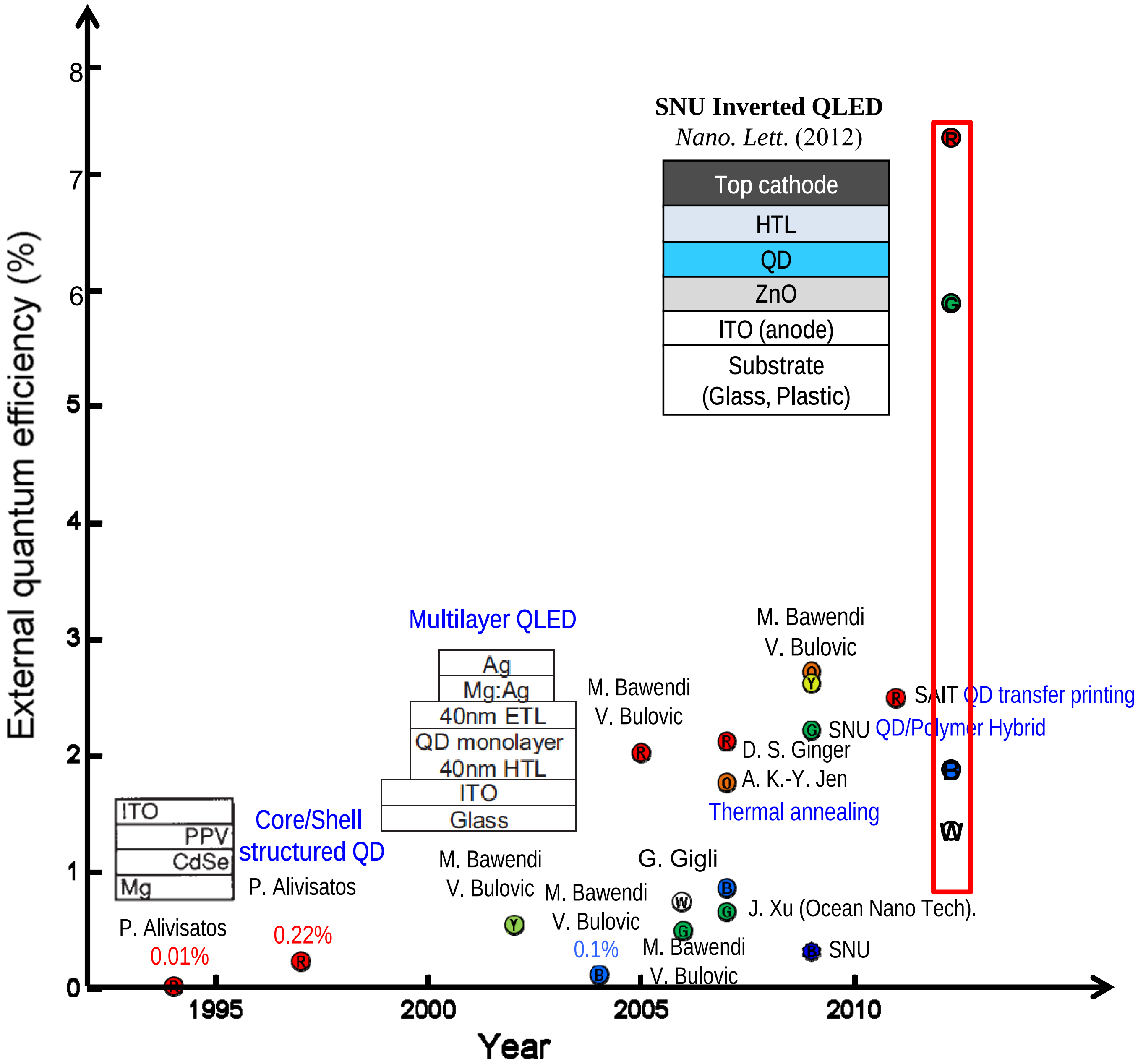
Performance of RGB QLEDs

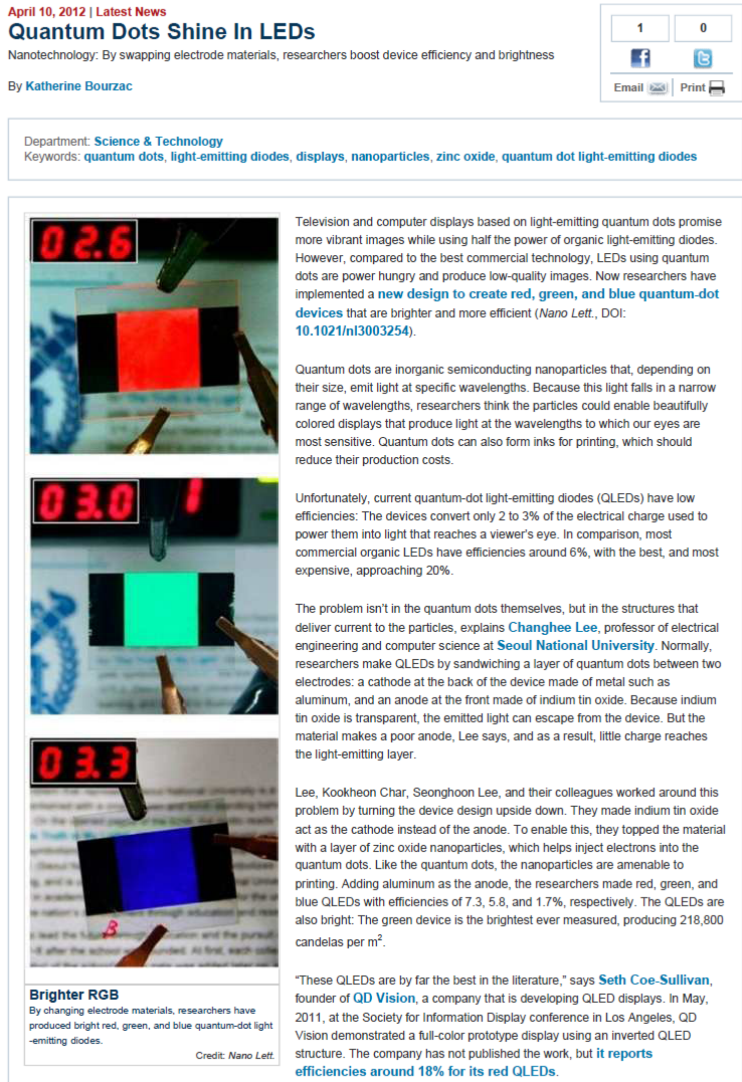


Color	PL λ_{max} (nm)	EL λ_{max} (nm)	V_{on}* (V)	Max. EQE (%)	Max. LE (cd/A)	Max. Luminance (cd/m^2)	CIE index (x, y)
Red	628	637	1.8	7.3	5.7	23,040	(0.70, 0.29)
Green	515	520	2.4	5.8	19.2	218,800	(0.14, 0.74)
Blue	433	437	3.0	1.7	0.4	2,250	(0.17, 0.02)

J. Kwak *et al.*, Nano Lett. **12**, 2362 (2012)

Progress of the efficiency of QLEDs




April 10, 2012 | Latest News

Quantum Dots Shine In LEDs

Nanotechnology: By swapping electrode materials, researchers boost device efficiency and brightness

By Katherine Bourzac

1 0
Email Print

Department: Science & Technology
Keywords: quantum dots, light-emitting diodes, displays, nanoparticles, zinc oxide, quantum dot light-emitting diodes

Television and computer displays based on light-emitting quantum dots promise more vibrant images while using half the power of organic light-emitting diodes. However, compared to the best commercial technology, LEDs using quantum dots are power hungry and produce low-quality images. Now researchers have implemented a new design to create red, green, and blue quantum-dot devices that are brighter and more efficient (*Nano Lett.*, DOI: 10.1021/nl3003254).

Quantum dots are inorganic semiconducting nanoparticles that, depending on their size, emit light at specific wavelengths. Because this light falls in a narrow range of wavelengths, researchers think the particles could enable beautifully colored displays that produce light at the wavelengths to which our eyes are most sensitive. Quantum dots can also form inks for printing, which should reduce their production costs.

Unfortunately, current quantum-dot light-emitting diodes (QLEDs) have low efficiencies: The devices convert only 2 to 3% of the electrical charge used to power them into light that reaches a viewer's eye. In comparison, most commercial organic LEDs have efficiencies around 6%, with the best, and most expensive, approaching 20%.

The problem isn't in the quantum dots themselves, but in the structures that deliver current to the particles, explains Changhee Lee, professor of electrical engineering and computer science at Seoul National University. Normally, researchers make QLEDs by sandwiching a layer of quantum dots between two electrodes: a cathode at the back of the device made of metal such as aluminum, and an anode at the front made of indium tin oxide. Because indium tin oxide is transparent, the emitted light can escape from the device. But the material makes a poor anode, Lee says, and as a result, little charge reaches the light-emitting layer.

Lee, Kookheon Char, Seonghoon Lee, and their colleagues worked around this problem by turning the device design upside down. They made indium tin oxide act as the cathode instead of the anode. To enable this, they topped the material with a layer of zinc oxide nanoparticles, which helps inject electrons into the quantum dots. Like the quantum dots, the nanoparticles are amenable to printing. Adding aluminum as the anode, the researchers made red, green, and blue QLEDs with efficiencies of 7.3, 5.8, and 1.7%, respectively. The QLEDs are also bright: The green device is the brightest ever measured, producing 218,800 candelas per m^2.

"These QLEDs are by far the best in the literature," says Seth Coe-Sullivan, founder of QD Vision, a company that is developing QLED displays. In May, 2011, at the Society for Information Display conference in Los Angeles, QD Vision demonstrated a full-color prototype display using an inverted QLED structure. The company has not published the work, but it reports efficiencies around 18% for its red QLEDs.

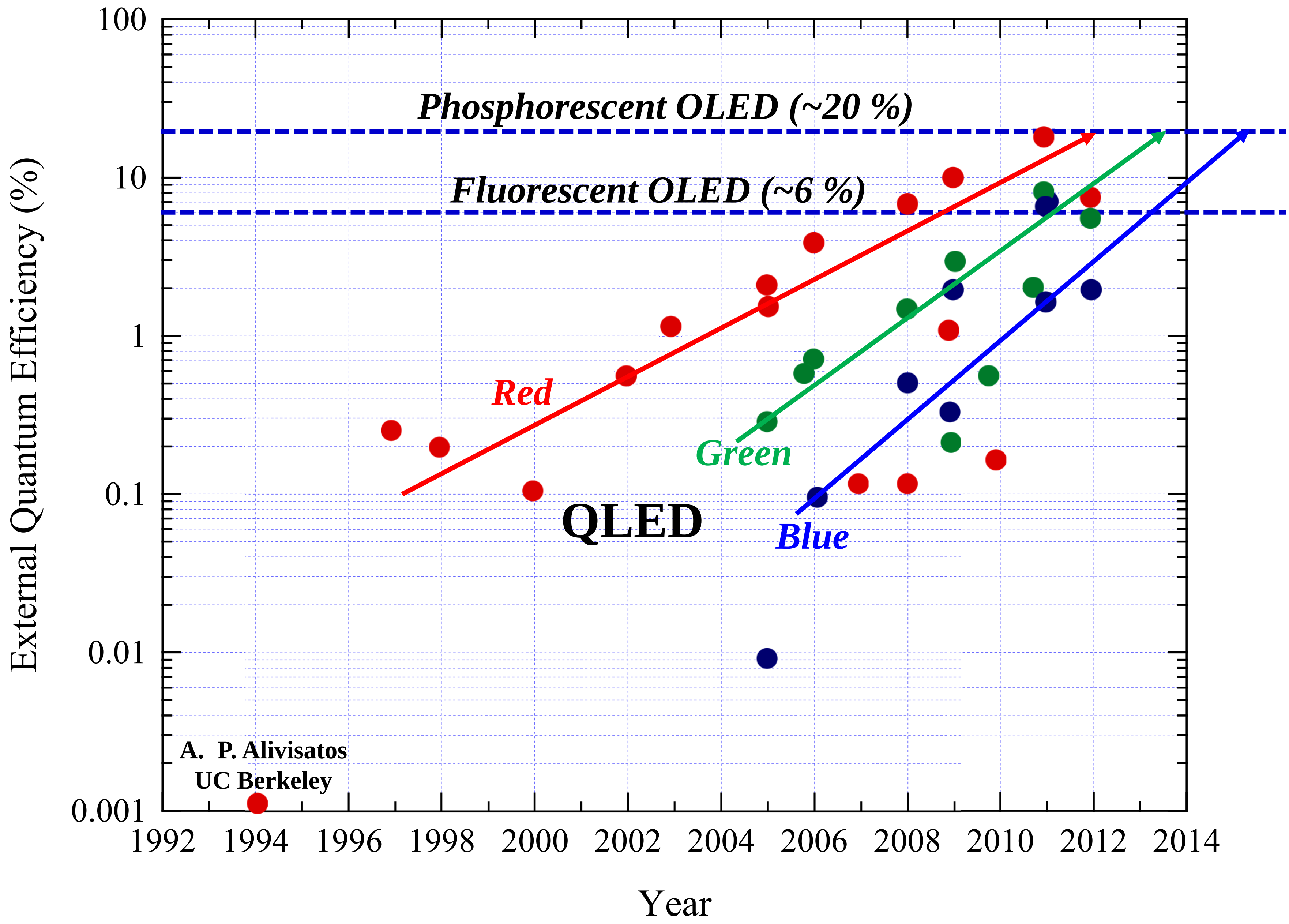
0 2.6
0 3.0
0 3.3

Brighter RGB
By changing electrode materials, researchers have produced bright red, green, and blue quantum-dot light -emitting diodes.
Credit: *Nano Lett.*

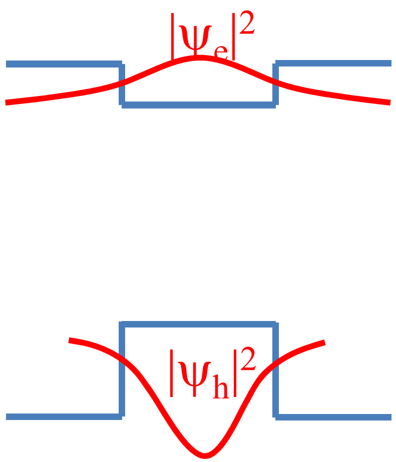
C&E News 2012. 4. 10.

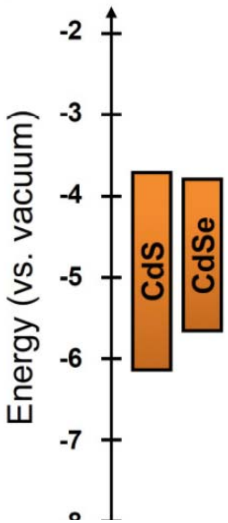
"Quantum dot LEDs get brighter, more efficient." April 20th, 2012.
http://phys.org/news/2012-04-quantum-dot-brighter-efficient.html

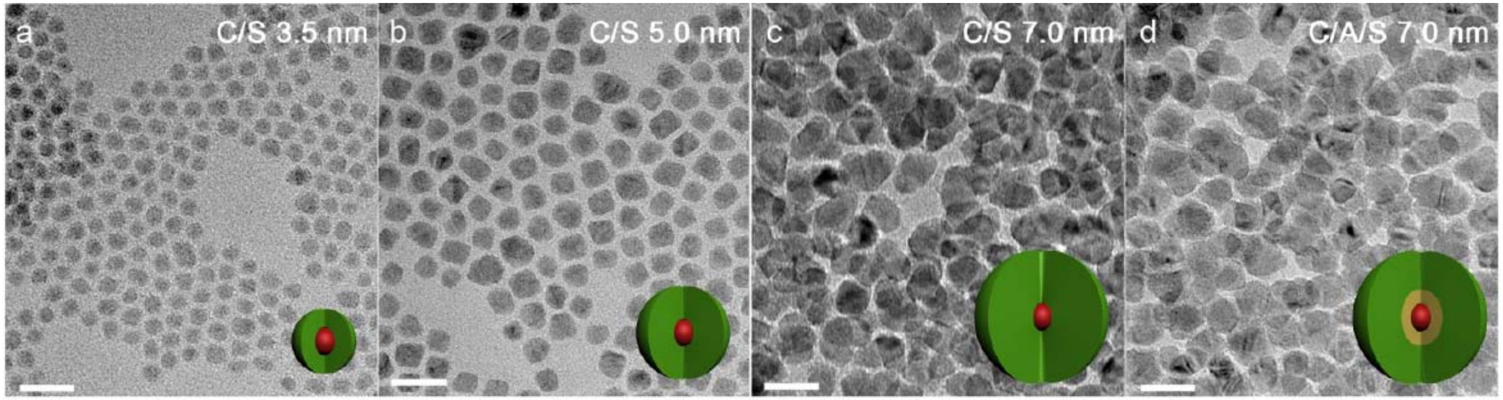
Progress of the efficiency of QLEDs

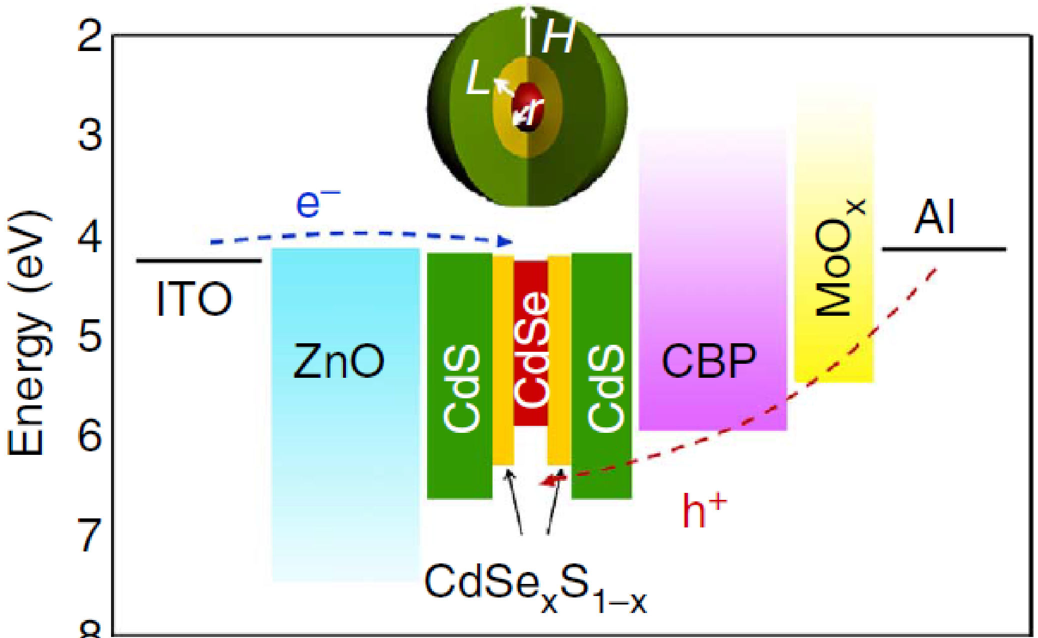


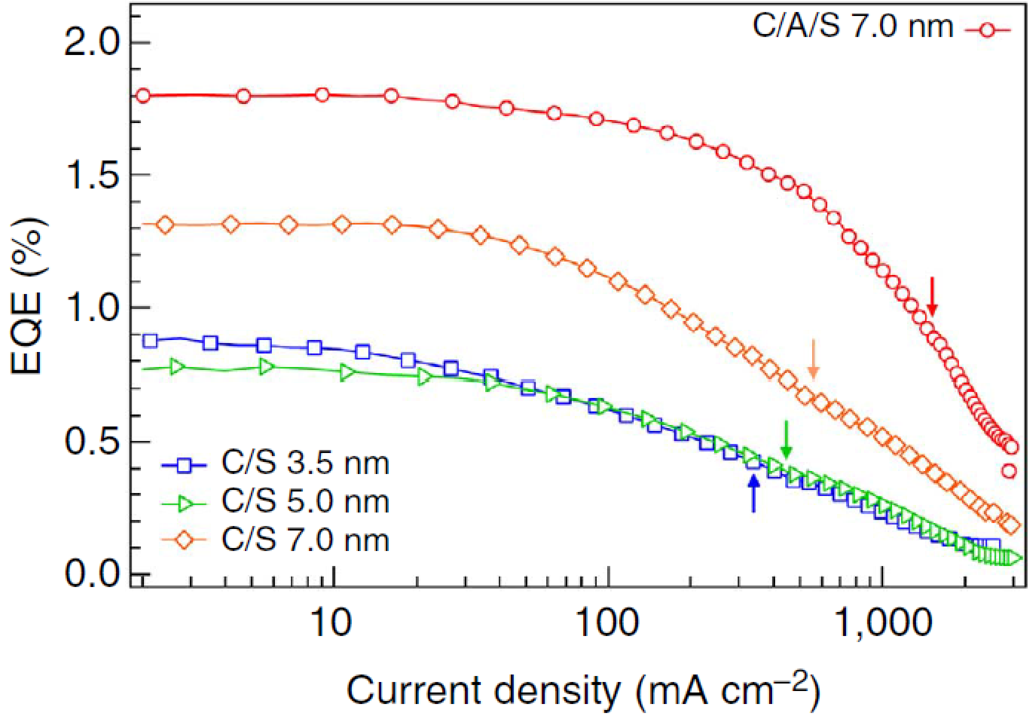
Efficiency roll-off due to Auger recombination







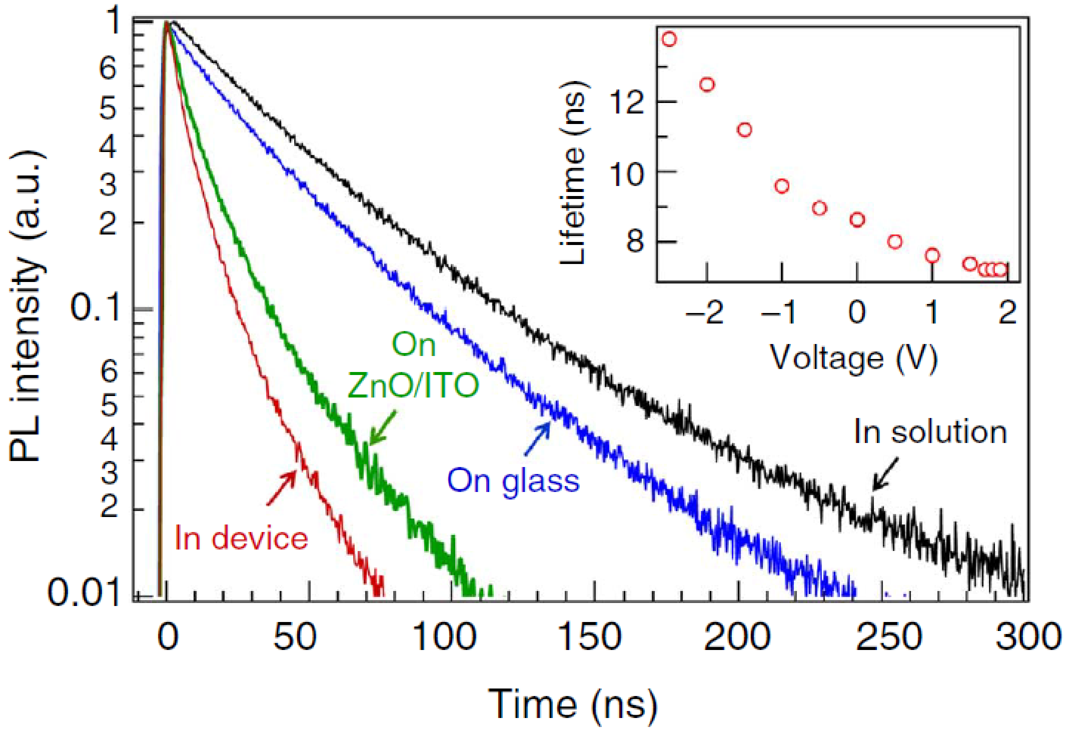


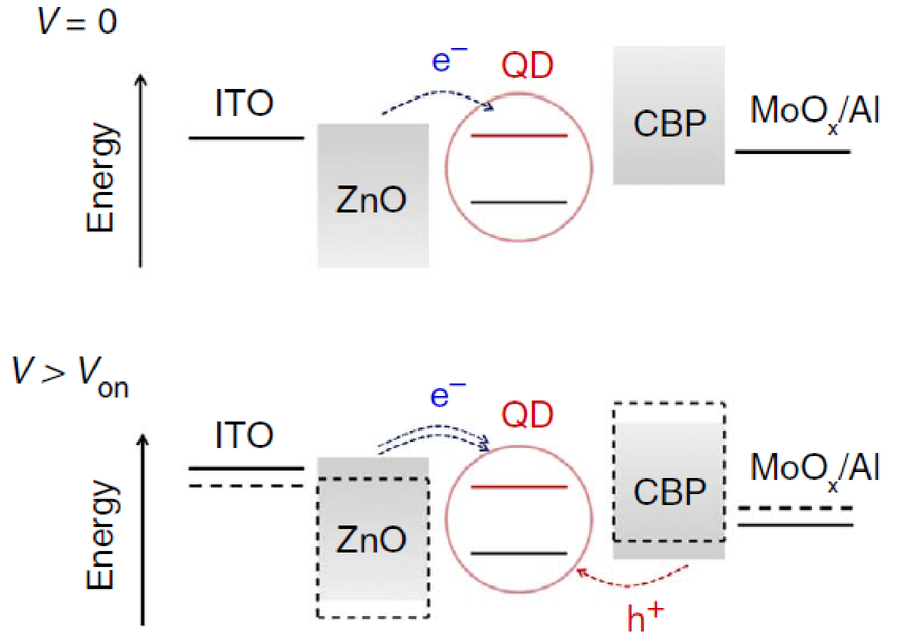


W. K. Bae *et al.*, Nat. Commun. **4**, 2661 (2013. 10. 25.)

PL decay dynamics affected by Auger recombination

PL decay dynamics of (4) C/A/S QDs (1.5/1.5/4.0/0, total radius 7.0 nm)



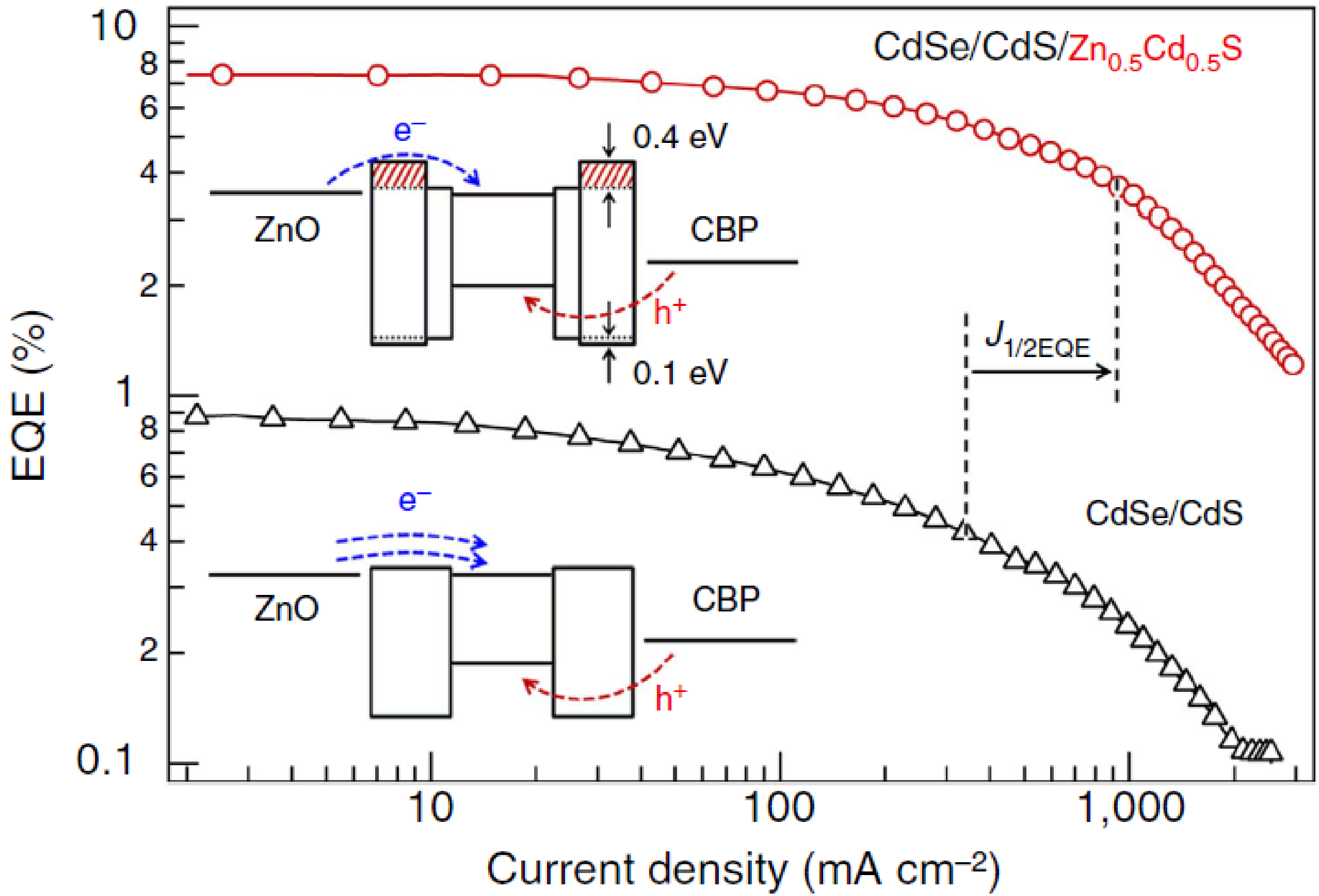


QD sample	r/L/H/B (nm)	Solution PL QY (%)	τ_X (ns)	τ_{X^-} (ns)	τ_{XX} (ns)	q_{X^-} (%)*	V_{on} (V)	Peak EQE (%)	$J_{1/2EQE}$ (mA cm^{-2})
(1) C/S	1.5/0/2.0/0	80	20	0.54	0.1	5.4	2.0	0.9	337
(2) C/S	1.5/0/3.5/0	60	28	1.6	0.29	11.4	2.0	0.8	442
(3) C/S	1.5/0/5.5/0	40	49	5.0	0.35	20.4	2.0	1.3	555
(4) C/A/S	1.5/1.5/4.0/0	40	40	7.0	1.0	35.0	2.0	1.8	1,500
(5) C/S/S	1.5/0/0.5/1.5	80	20	0.5	0.1	5.0	2.0	7.5	970

EQE, external quantum efficiency; PL, photoluminescence; QD, quantum dot; QY, quantum yield.
*Relative PL QY of a negative trion: $q_{X^-} = \frac{2\tau_{X^-}}{\tau_X} \times 100(\%)$.
†$J_{1/2EQE}$ is the current-density at which the EQE of a QD-LED becomes half of its peak EQE.

W. K. Bae *et al.*, Nat. Commun. **4**, 2661 (2013. 10. 25.)

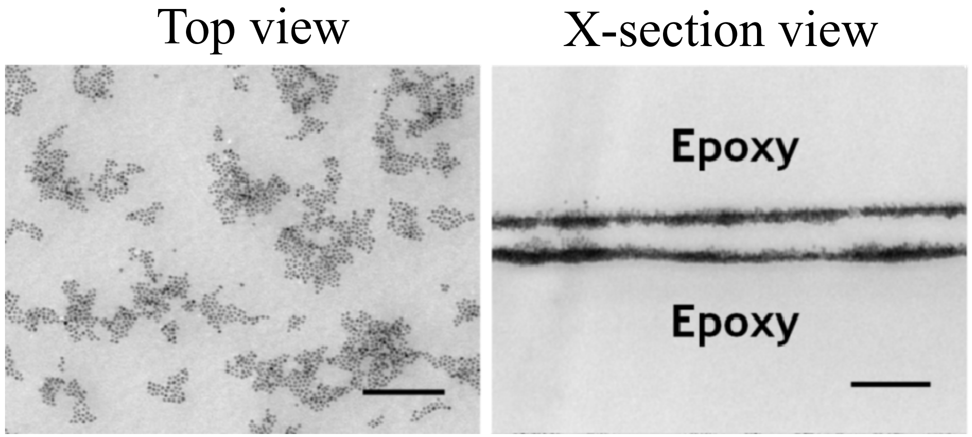
Reduced eff. roll-off with improved *e*-*h* balance



W. K. Bae *et al*., Nat. Commun. **4**, 2661 (2013. 10. 25.)

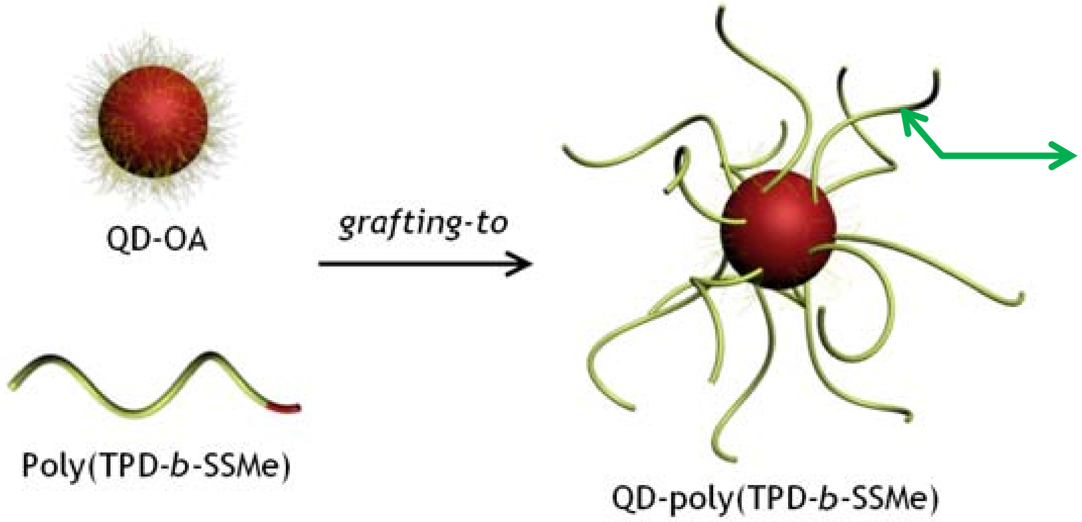
How can we solve the QD aggregation problem?

Massive QD aggregation



Functionalization of QDs with hole conducting co-polymers

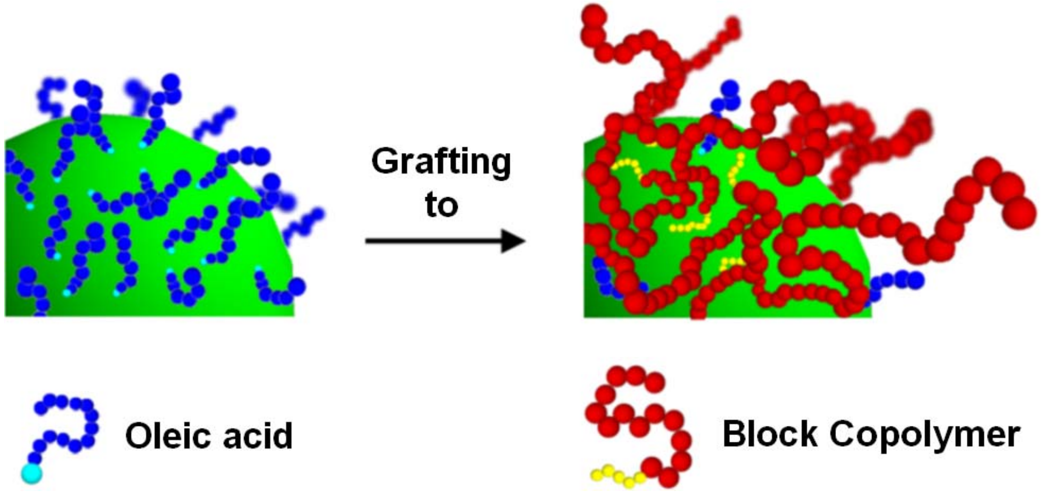
→ *"Polymer/QD Hybrid"*



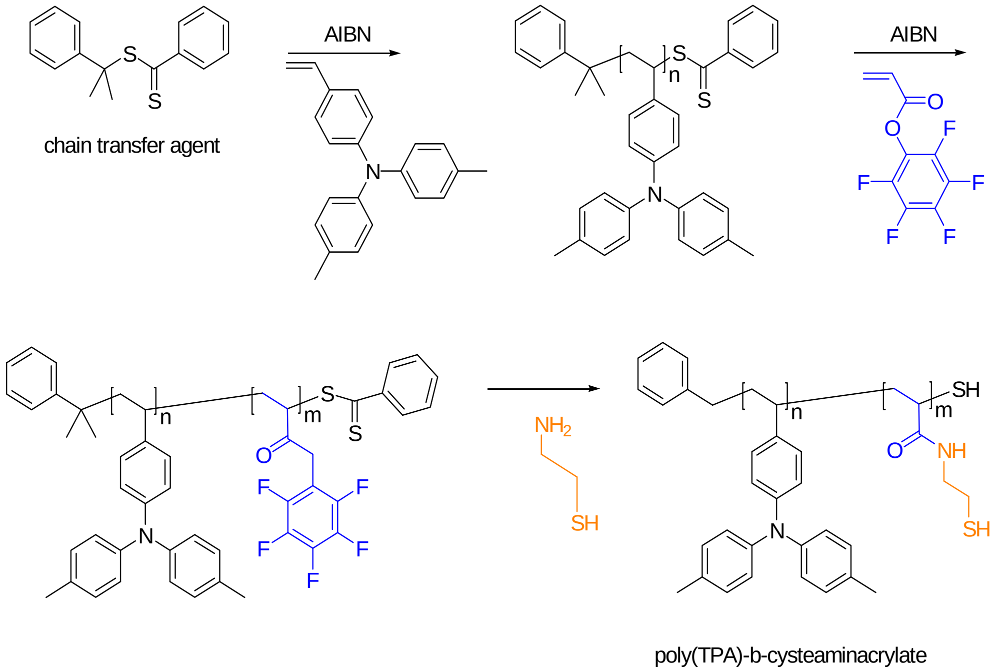
- *p*-type conducting polymers
- Larger chain → Reduces QD aggregation
- High h^+ mobility
- Process capability

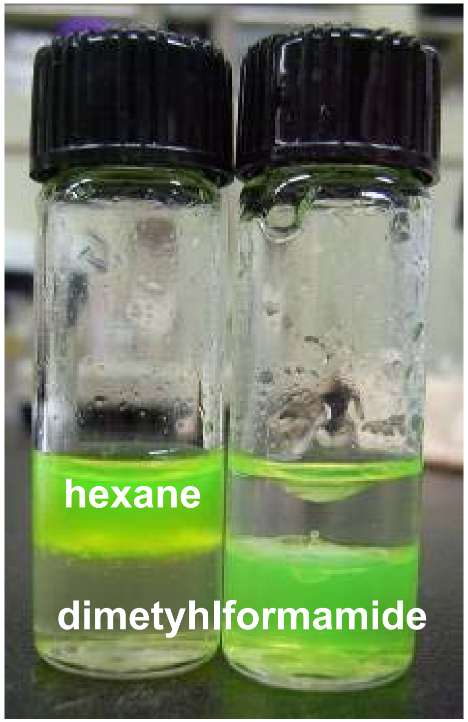
- *Improved colloidal stability*
- *Uniform QD distribution*
- *Facilitated carrier injection*
- *Solution process capability*

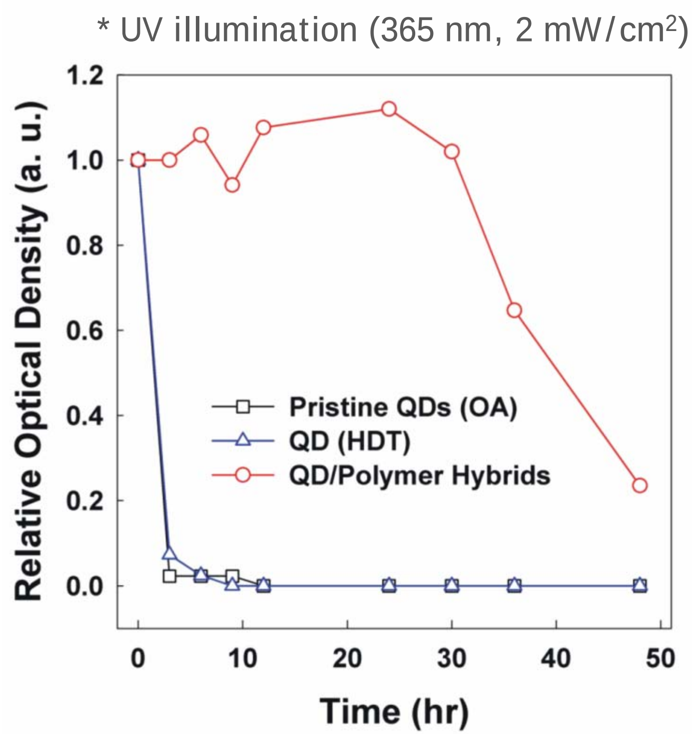
Quantum Dot / Conducting Polymer Hybrid



Surfactants were replaced by copolymers containing hole-conducting triphenyl amine (TPA) derivatives. printing







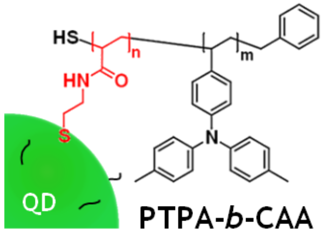
Improved colloidal stability with hybrids

Longer polymer brushes around QDs enhanced steric stabilization of the colloidal QD dispersions preventing agglomeration of QDs

M. Zorn *et al*., ACS Nano **3**, 1063 (2009)

Comparison of QD/Polymer Hybrid and Blend

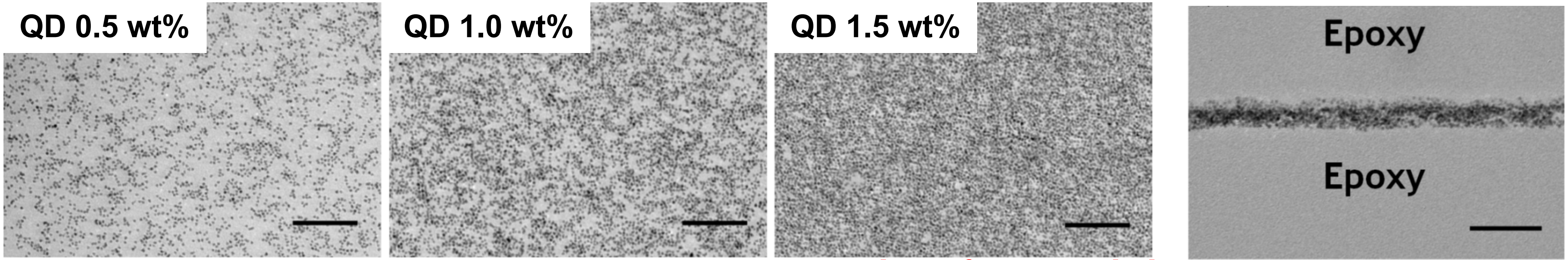
Hybrid Films



PTPA-*b*-CAA

- The thiol anchor groups in the CAA block replace the surface ligands (oleic acid) of QDs, leading to QD/conducting polymer ***hybrid*** films.
- **PTPA-*b*-CAA**: poly(*para* methyl triphenylamine-*b*-cysteamine acrylamide)

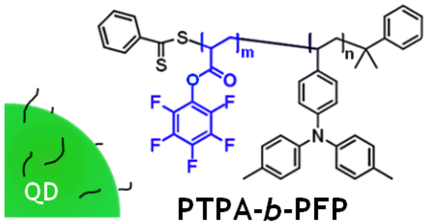
TEM Top view / **TEM cross-section**



** Scale bars in the figure are 200 nm.*

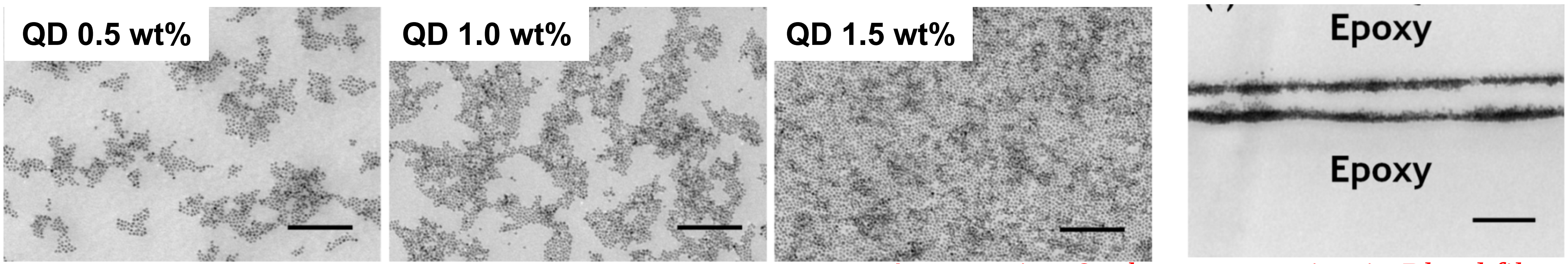
Nanoscale uniform morphology of QD/polymer hybrids

Blend Films



PTPA-*b*-PFP

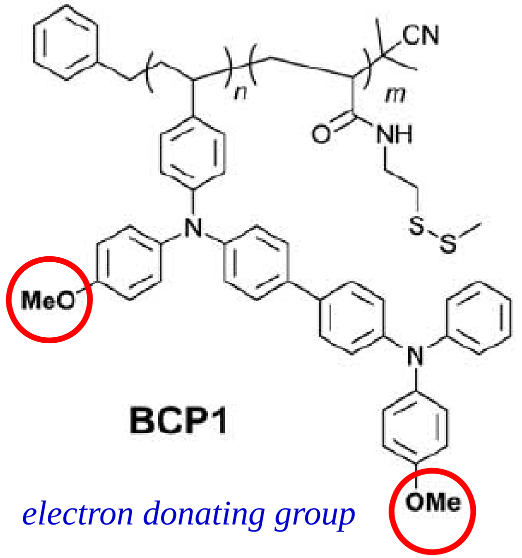
- The fluorinated block (PFP) with low surface energy does not have specific interactions with QDs, resulting in QD/conducting polymer ***blend*** films.
- **PTPA-*b*-PFP**: poly(para methyl triphenylamine-b-pentafluorophenole)



Aggregation & phase separation in Blend film

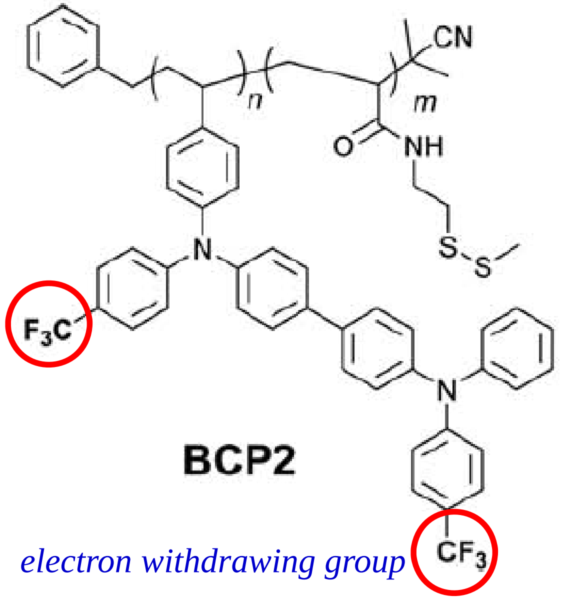
J. Kwak *et al*., Adv. Mater. **21**, 5022 (2009)

Energy level alignment of block copolymers



BCP1

electron donating group

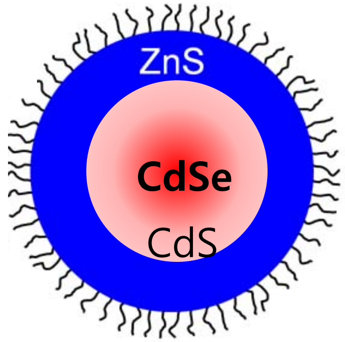


BCP2

electron withdrawing group

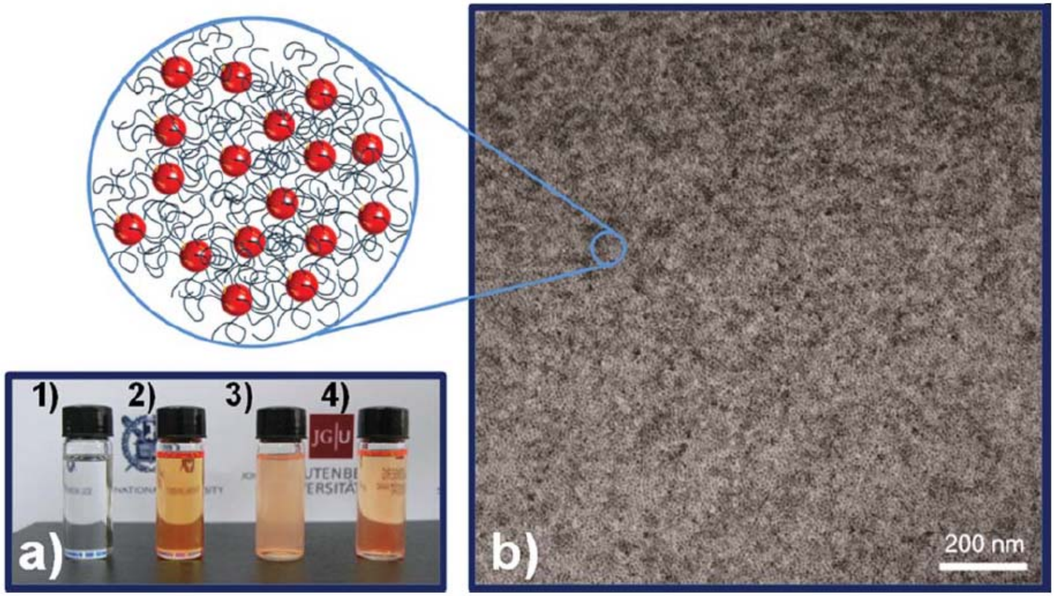
	M_n[a] [g mol^{-1}]	M_w/M_n[a]	HOMO[b] [eV]	LUMO[c] [eV]
P1	15 000	1.05	−5.2	−2.6
BCP1	16 300	1.07		
P2	12 600	1.09	−5.9	−2.7
BCP2	13 800	1.07		

[a] GPC, polystyrene standard. [b] Cyclovoltammetry in *o*-DCB with tetrabutylammonium fluoride as conducting salt. [c] UV/Vis in *o*-DCB.



Red QDs

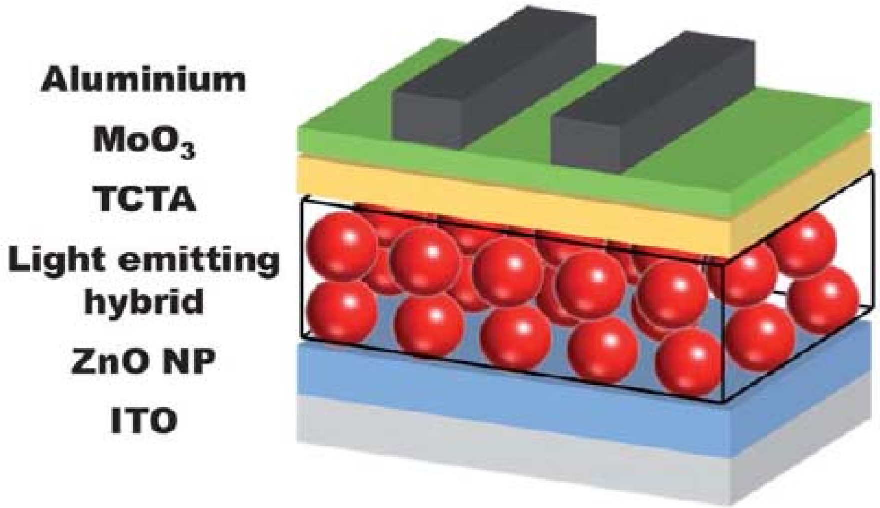
- CdSe/CdS/ZnS core/multishell QDs
- Diameter ~ 8 nm
- PL QY ~ 76 %

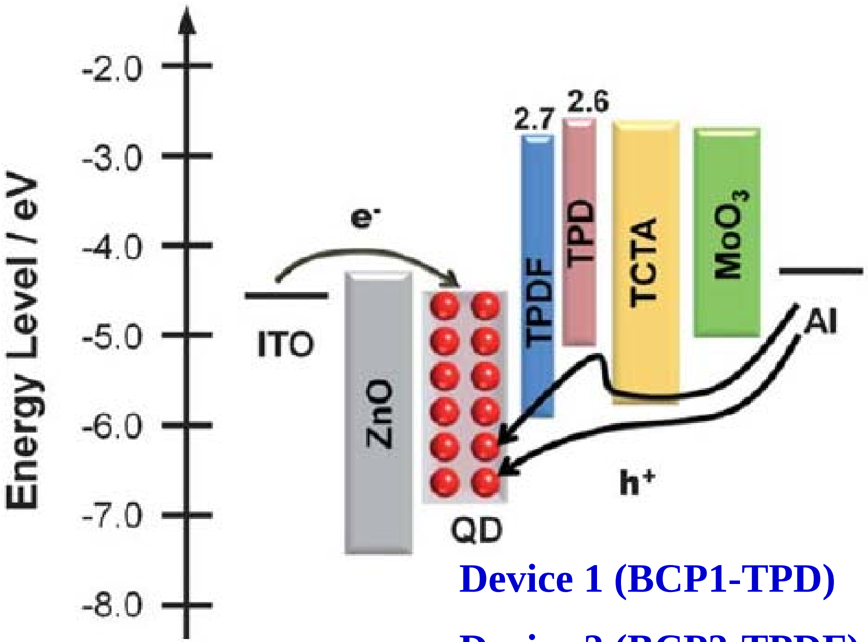


(1) pure polymer in toluene, (2) hybrid in toluene, (3) hybrid in hexanes, and (4) QDs in hexane

J. Mater. Chem. C **1**, 1722 (2013)

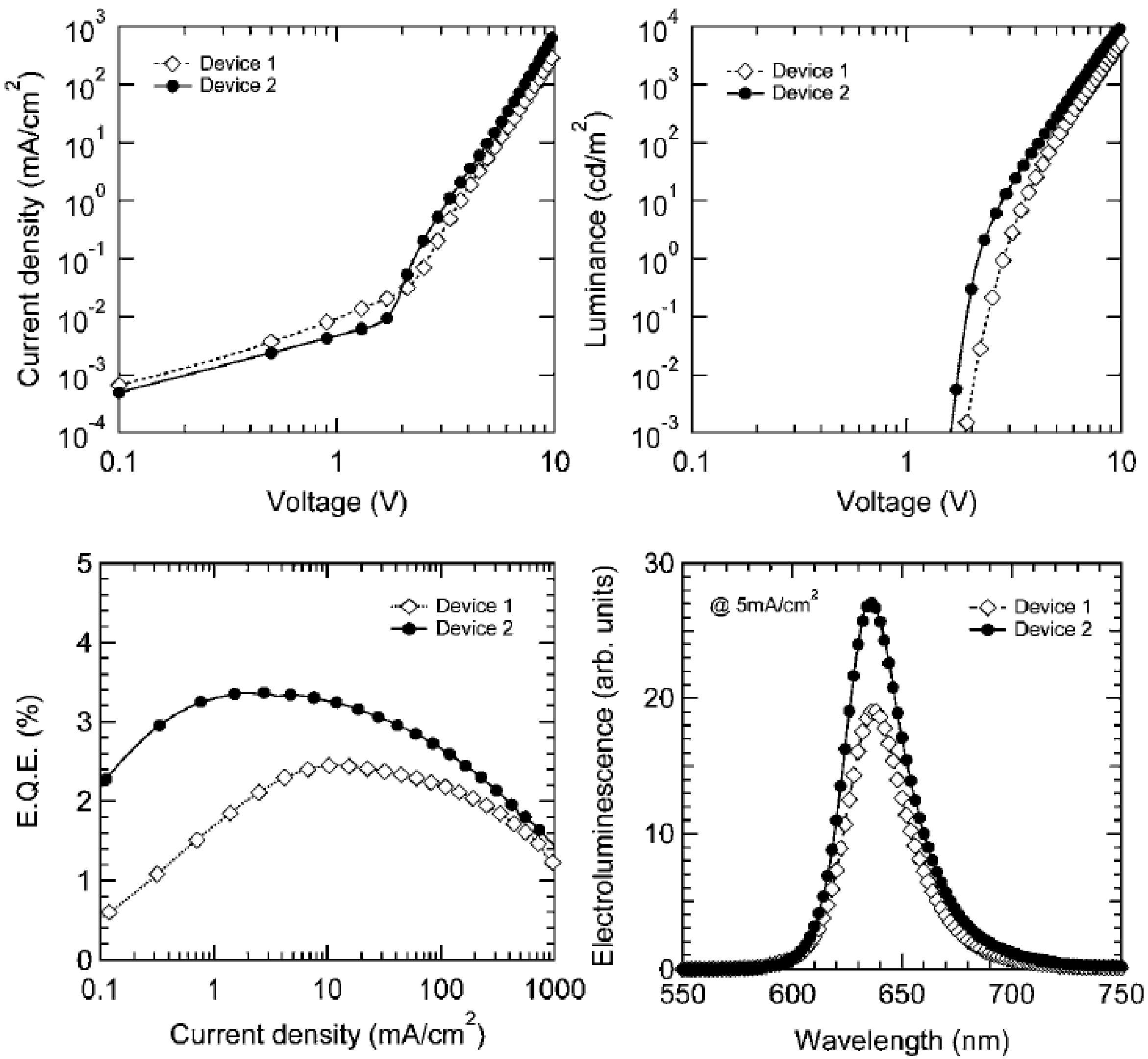
Improved performance for BCP with higher HOMO





Device 1 (BCP1-TPD)

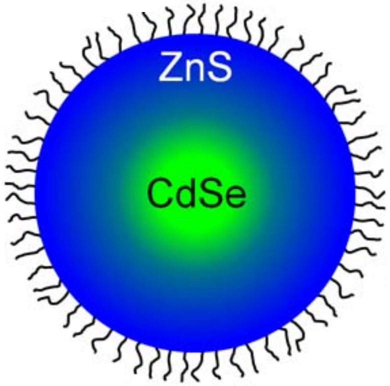
Device 2 (BCP2-TPDF)



The smaller hole injection barrier of BCP2 towards the QDs compared to the one from BCP1 results in better device performance.

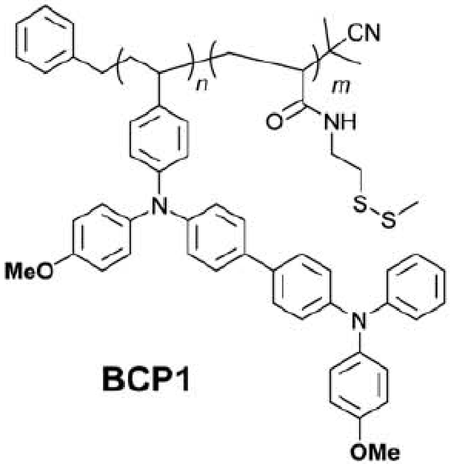
J. Mater. Chem. C **1**, 1722 (2013)

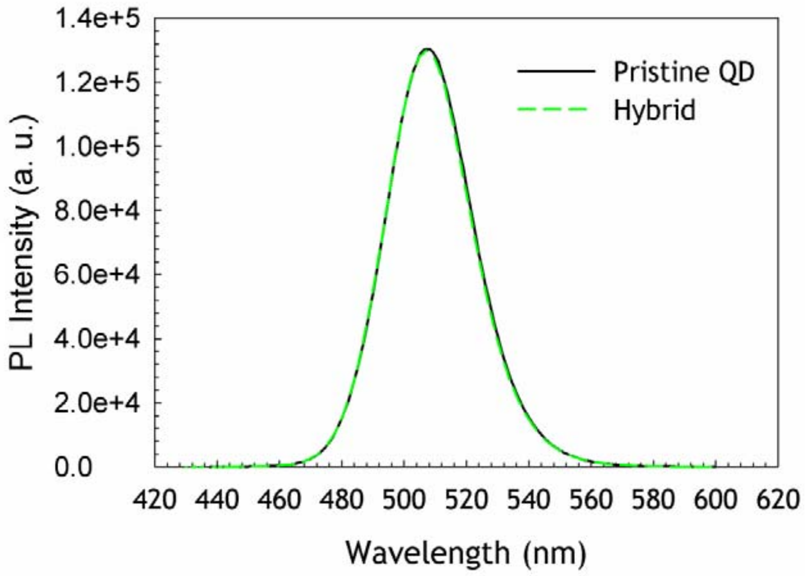
Green QD-poly(TPD-b-SSMe) hybrid



Green QDs

- CdSe@ZnS compositi gradient QDs
- Diameter ~ 9 nm
- PL QY ~ 80 %

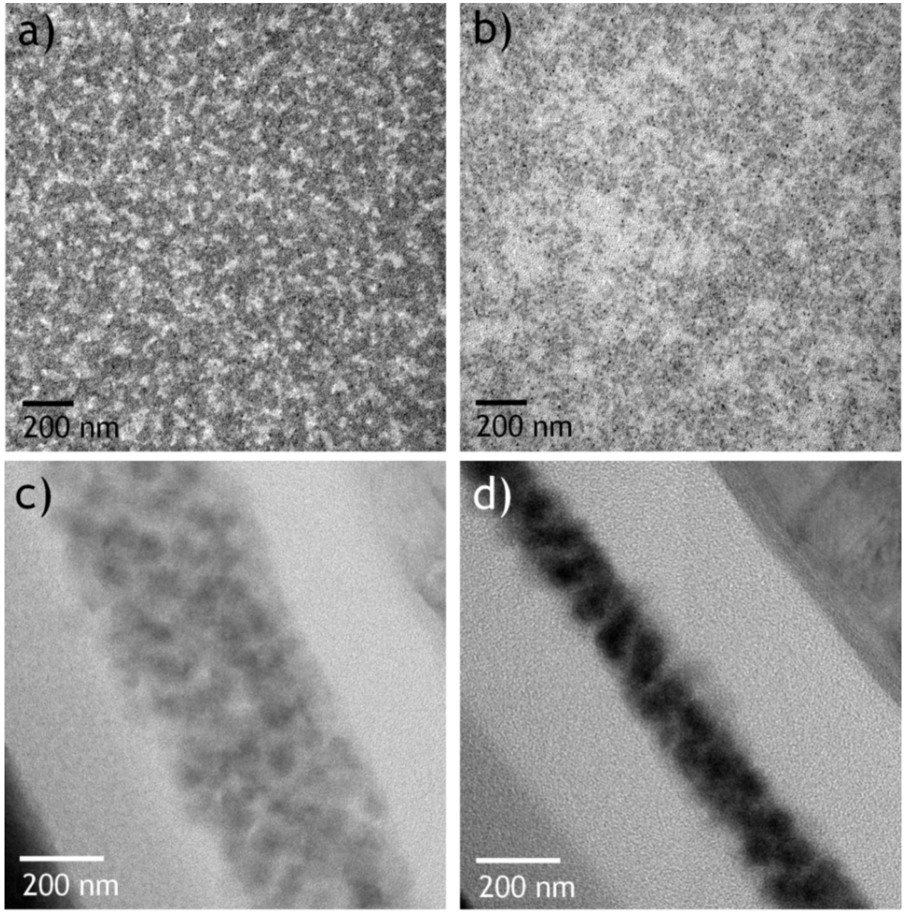




PL spectra (excited at 420 nm) of pristine QDs stabilized with oleic acids dispersed in toluene (solid line, optical density at 420 nm = 0.1) and QD-poly(TPD-b-SSMe) hybrids dispersed in toluene (dotted line, extinction coefficient at 420 nm = 0.1).

QD-poly(TPD-b-SSMe) hybrid film

QD/polyTPD bilayer film with 1.5 QD monolayers

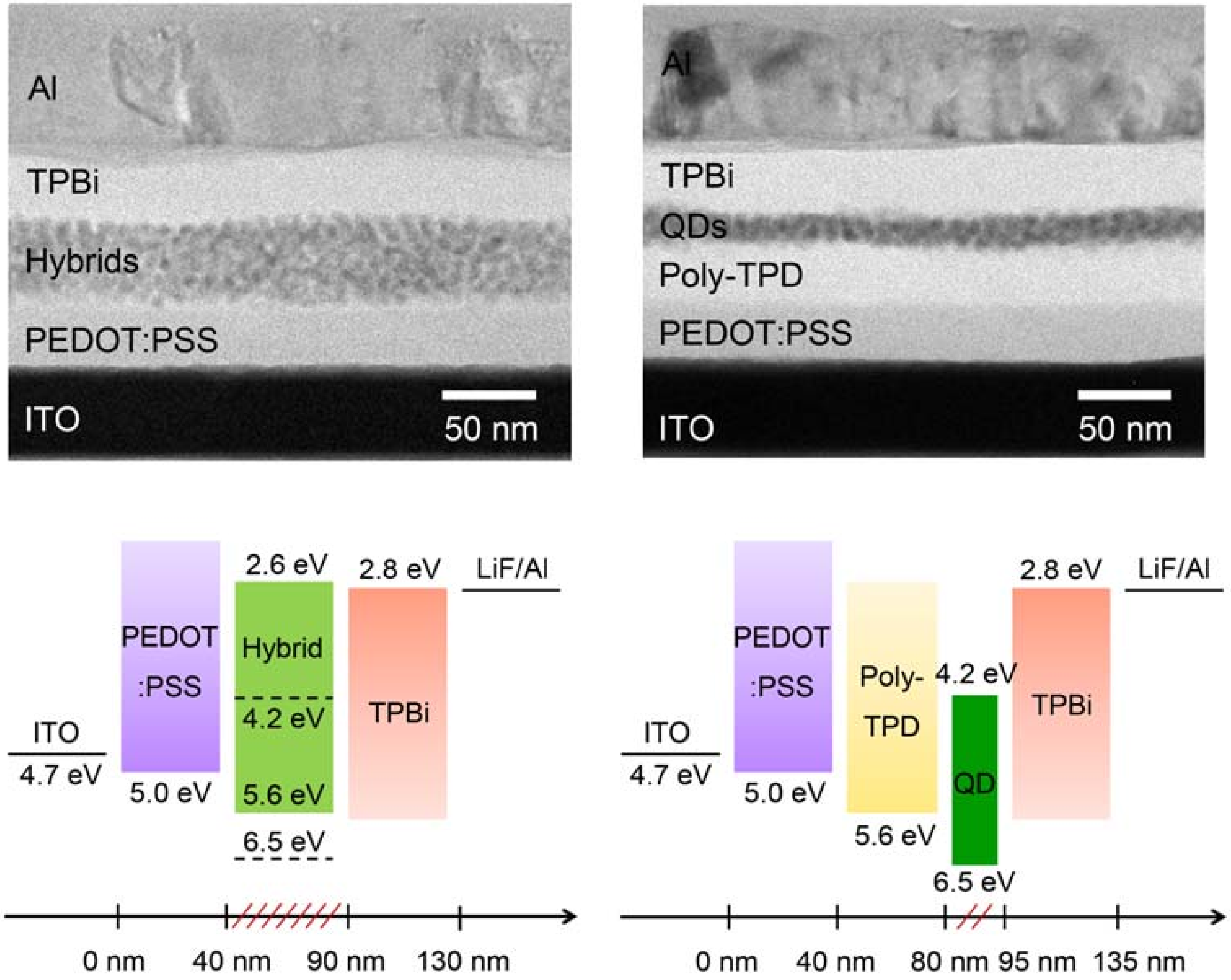


W. K. Bae et al., J. Mater. Chem. C (2014)

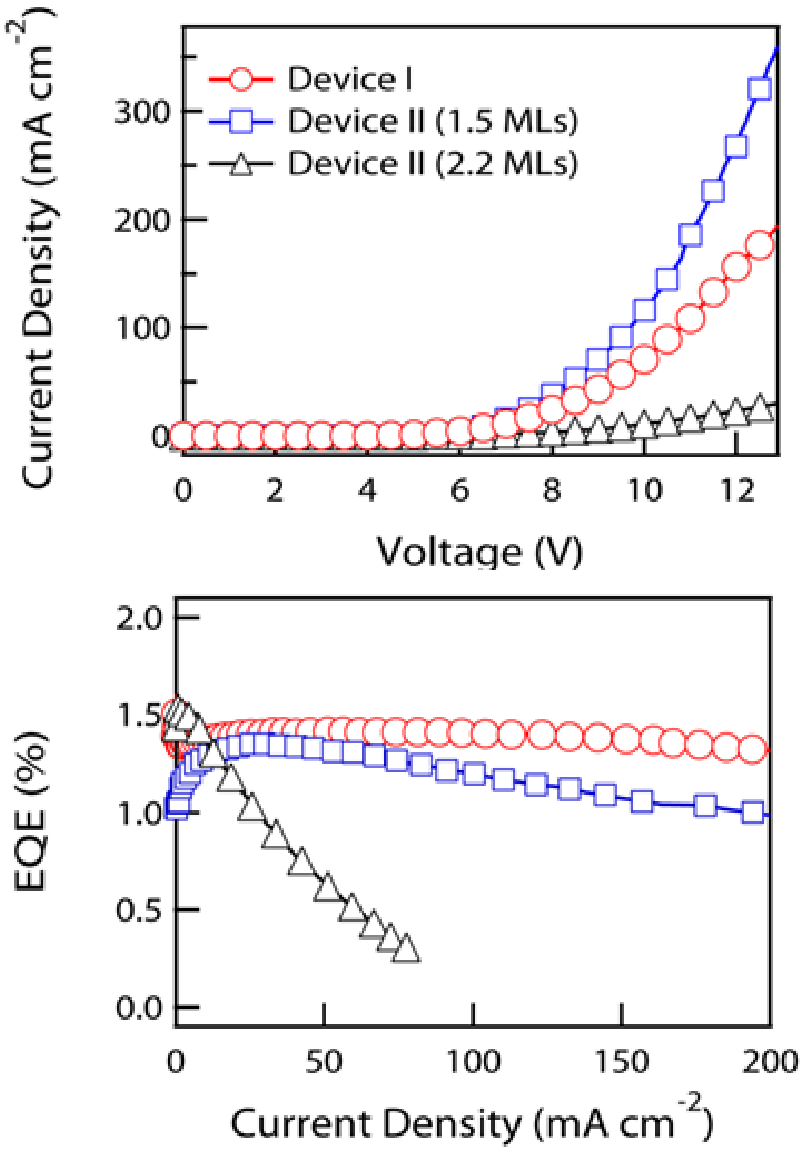
Device performance of QD/polymer hybrid LEDs

Device I (QD/polymer hybrids)

Device II (QD layers)



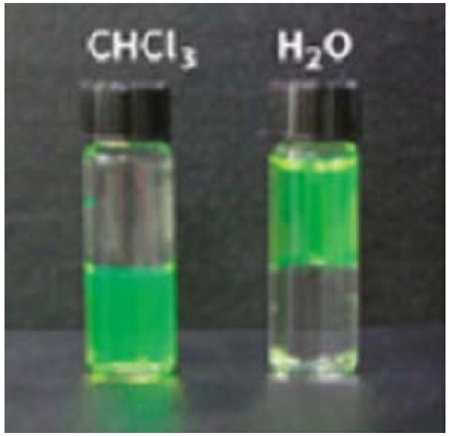
W. K. Bae et al., J. Mater. Chem. C (2014)

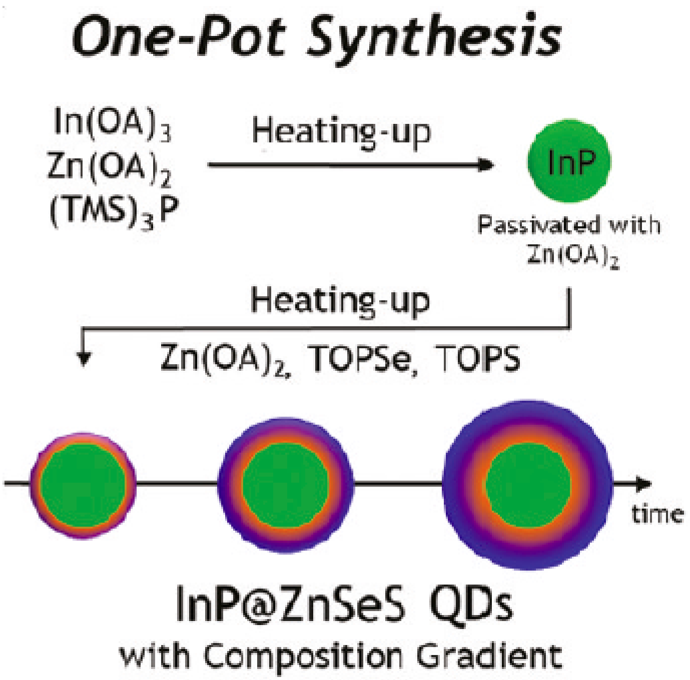


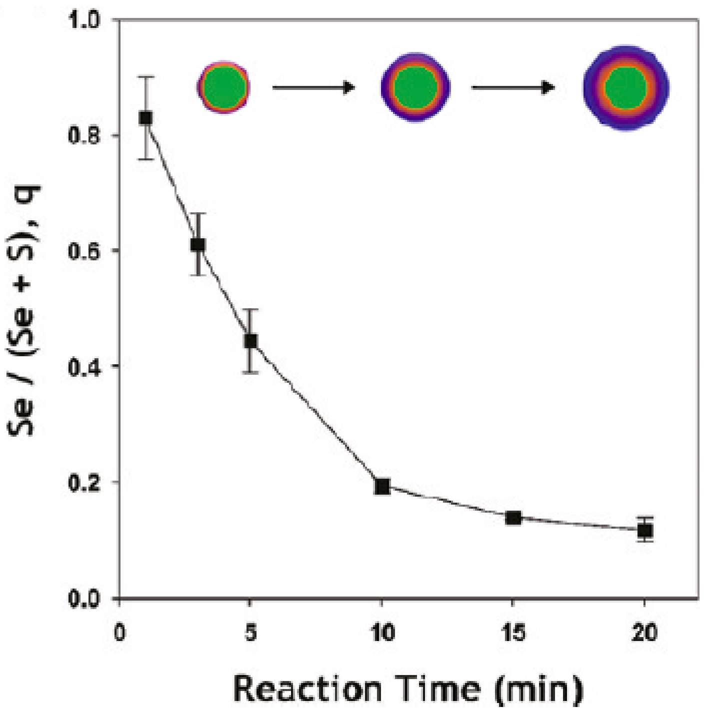
Reduced efficiency roll-off were realized using QD-conducting polymer hybrids.

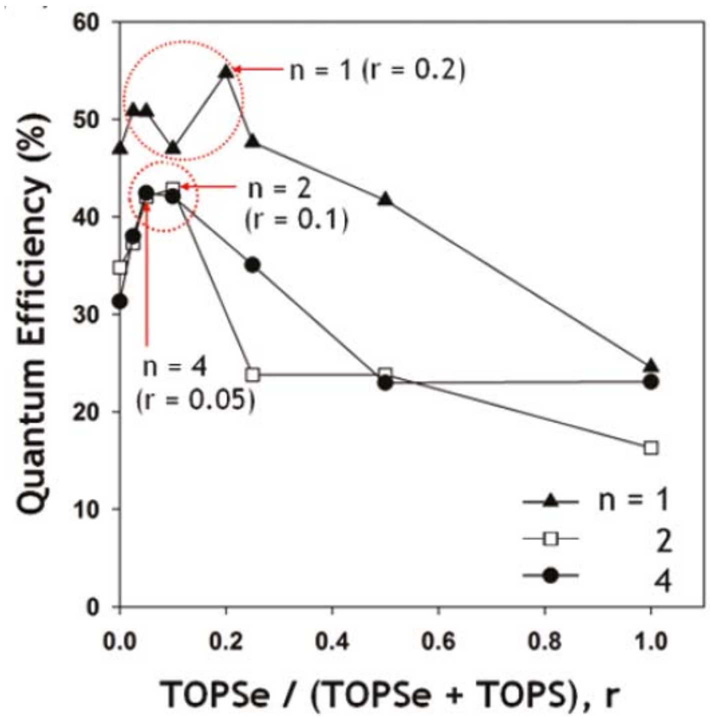
InP Quantum Dots by Composition Gradient $ZnSe_xS_{1-x}$ Shells

Synthesis of InP QDs with high QE and photo/chemical stability: Utilizing the reactivity difference between TOPSe and TOPS, we synthesized InP@ZnSeS QDs with the composition gradient in a radial direction where ZnSe alleviated lattice strain and ZnS protected QDs from degradation.



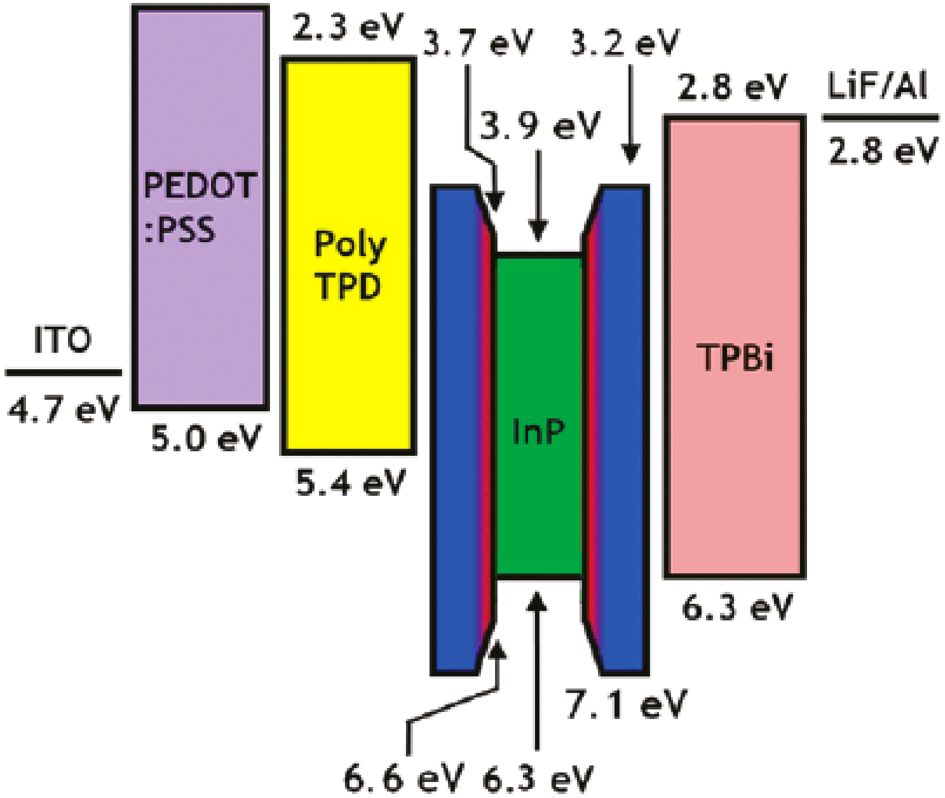


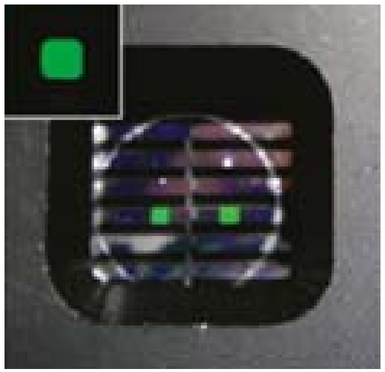


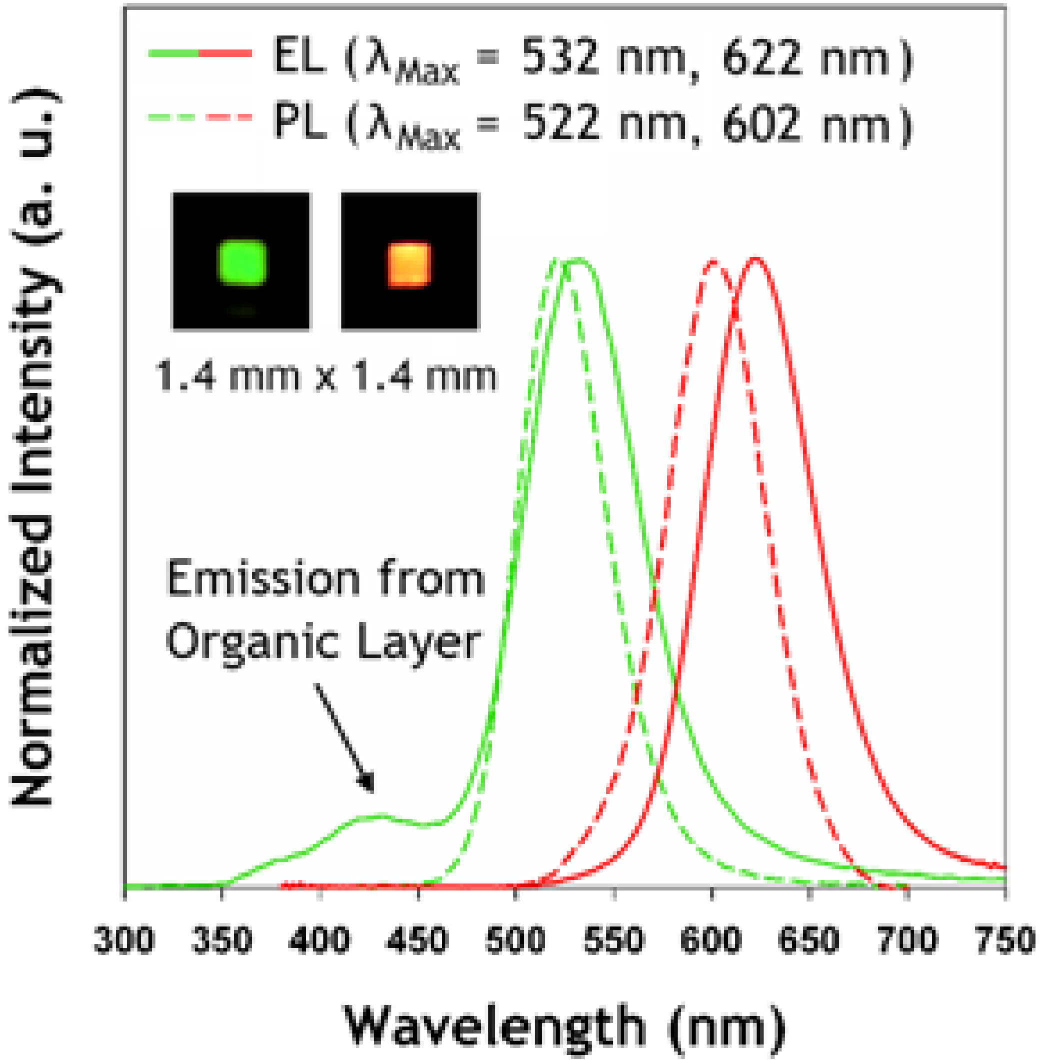


J. Lim et al., Chem. Mater. **23**, 4459 (2011)

InP Quantum Dots by Composition Gradient $ZnSe_xS_{1-x}$ Shells







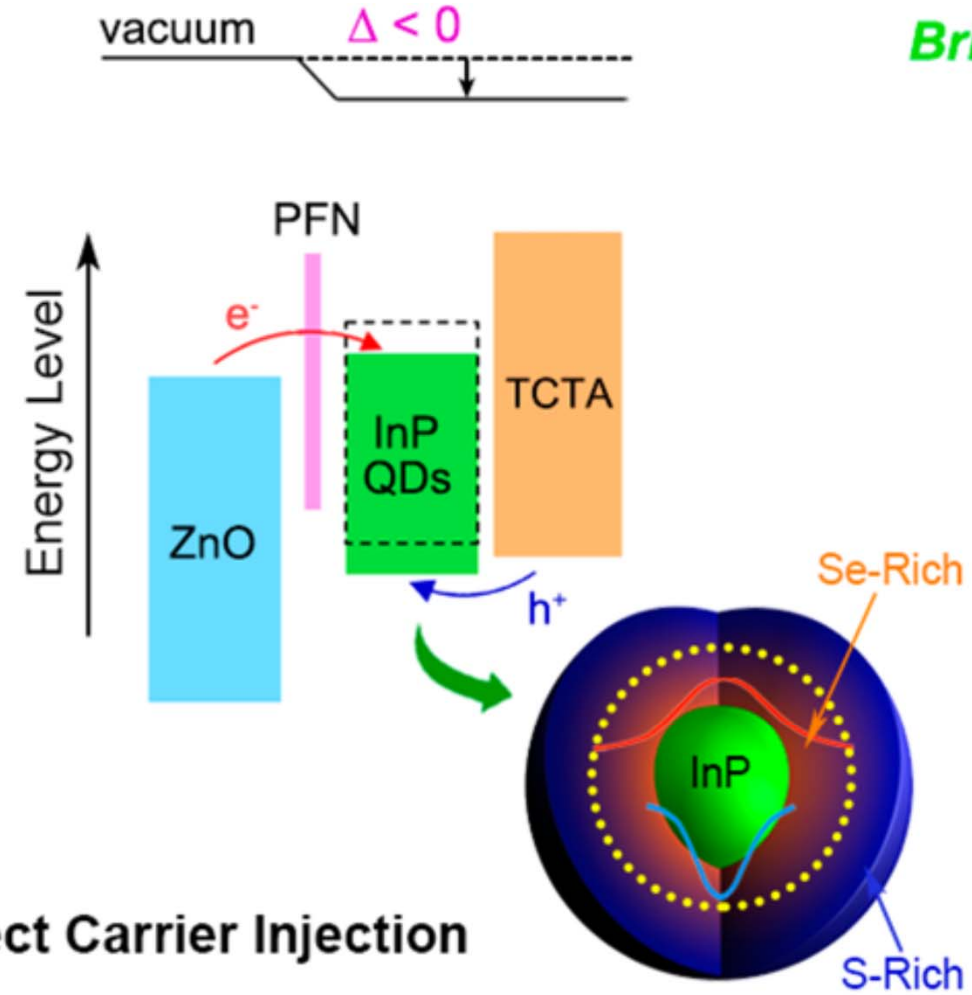
J. Lim et al., Chem. Mater. **23**, 4459 (2011)

Poor hole injection

→ low efficiency: EQE ~ 0.008%

→ Parasitic emission from organic layer

High efficient InP QLEDs

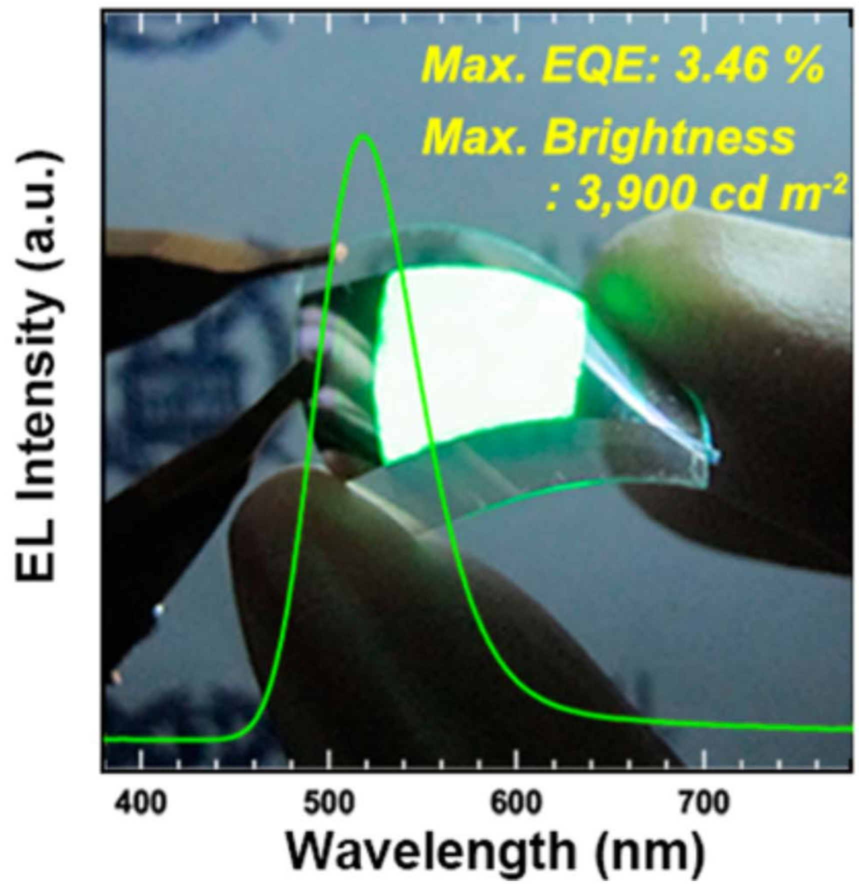


Direct Carrier Injection

& Efficient Exciton Recombination

Bright, Efficient & Envionmentally-Benign

InP@ZnSeS Quantum Dot LEDs

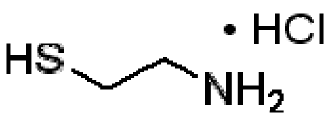


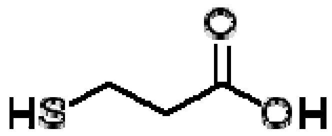
J. Lim et al., ACS Nano **7**, 9019 (2013)

Multilayer QLEDs and Exciton recombination zone

Preparation of oppositely charged QDs

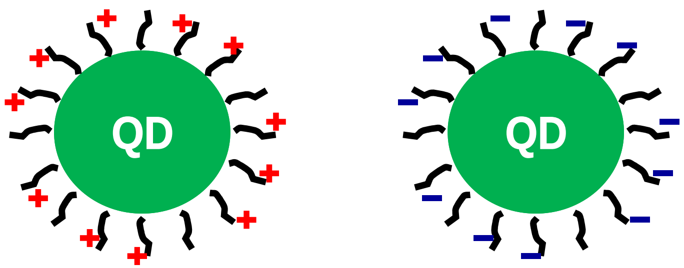
Oleic acid capped CdSe@ZnS QDs (7 nm)





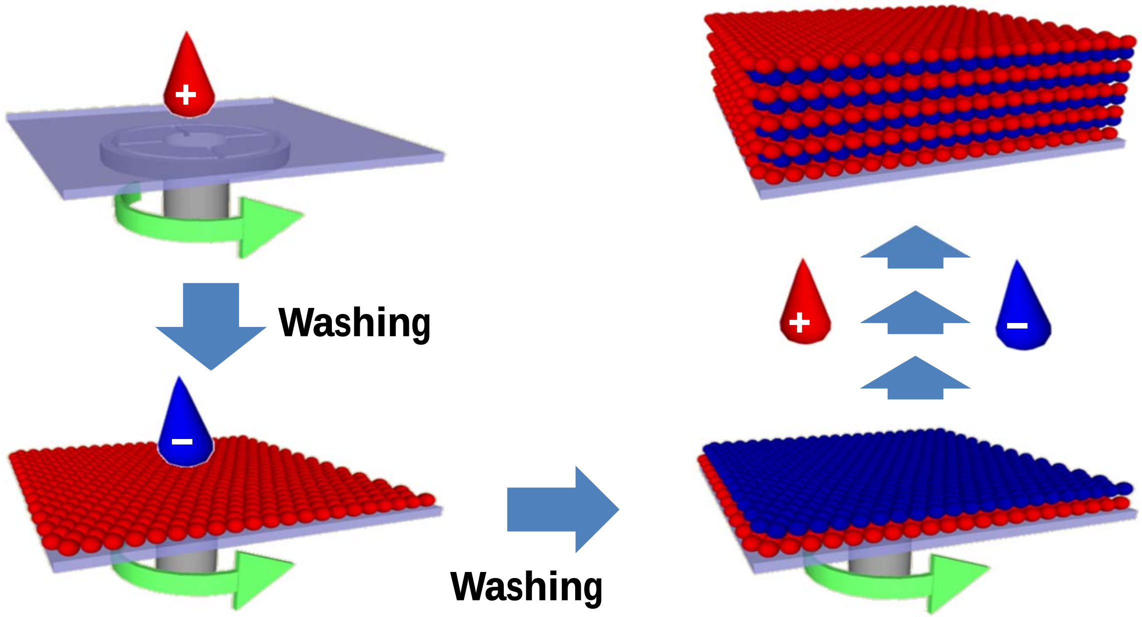
Cysteamine hydrochloride (CAm)
for (+) charge

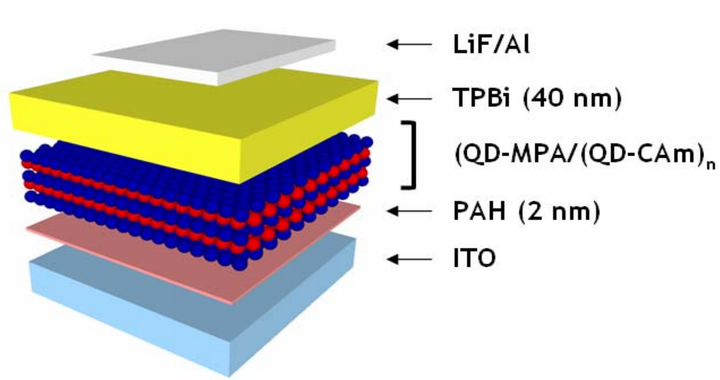
3-Mercaptopropionic acid (MPA)
for (-) charge

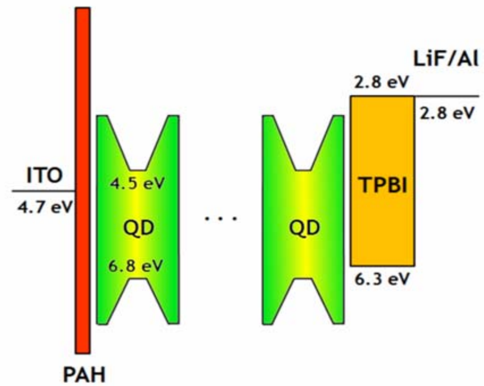


QD-Cam **QD-MPA**

Layer-by-Layer Assembly of All-QD Multialyer Films







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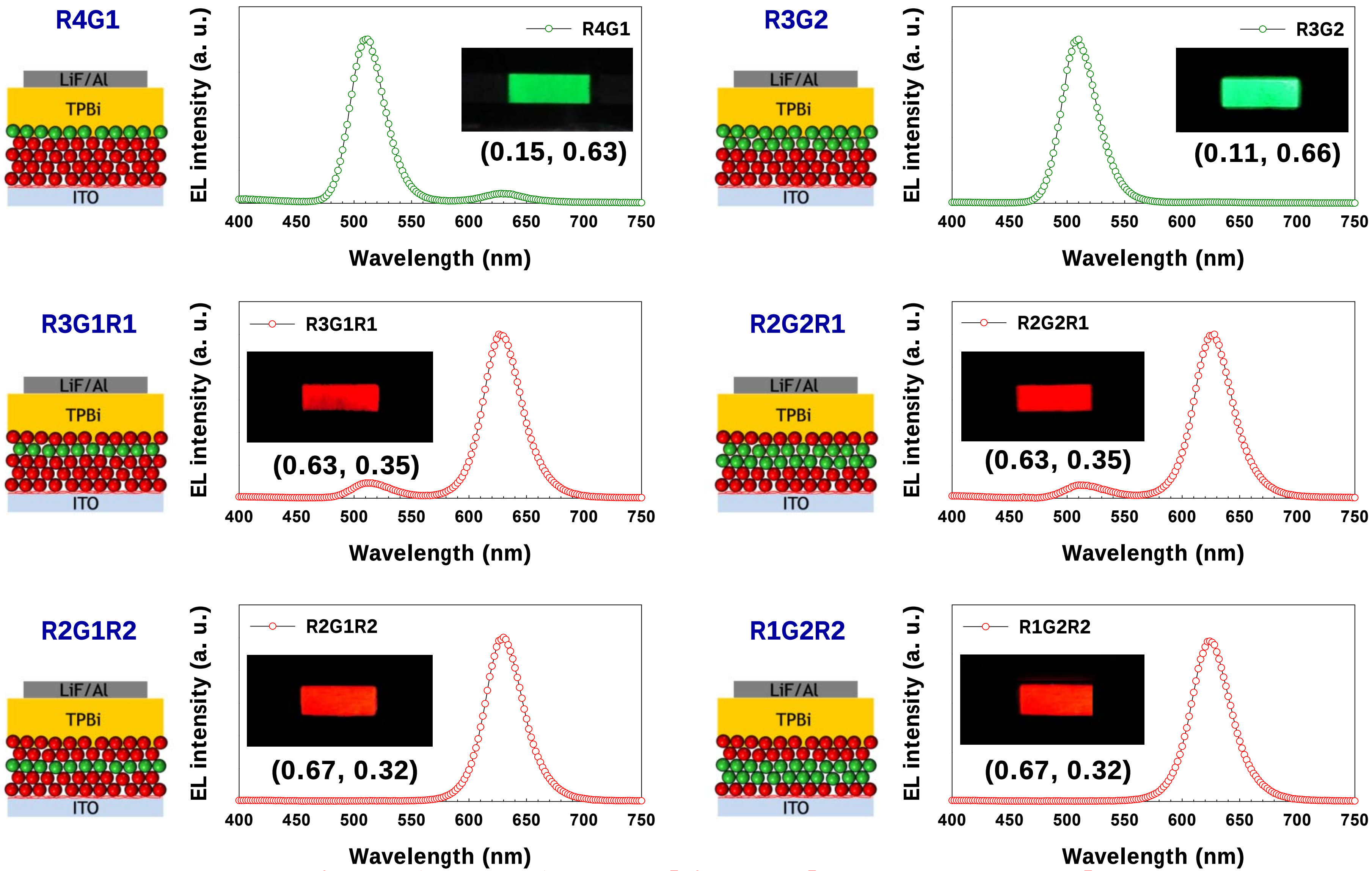
Exciton Recombination Zone within QLEDs



- **Most excitons (> 90 %) recombine at the top QD monolayer**

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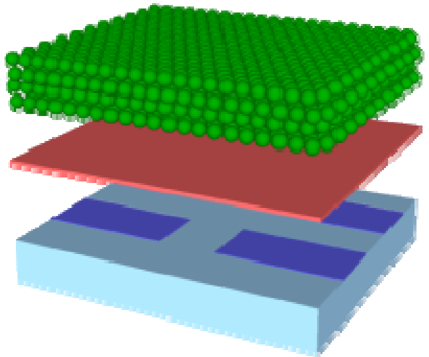
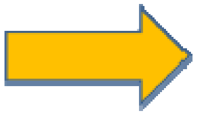
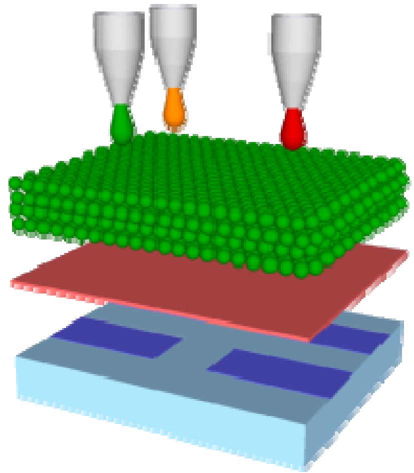
Multicolor QLEDs with common device platform

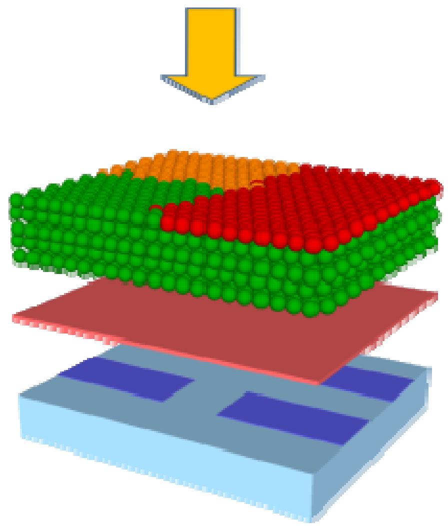
1 Deposition of **G4** common layer on ITO/PAH



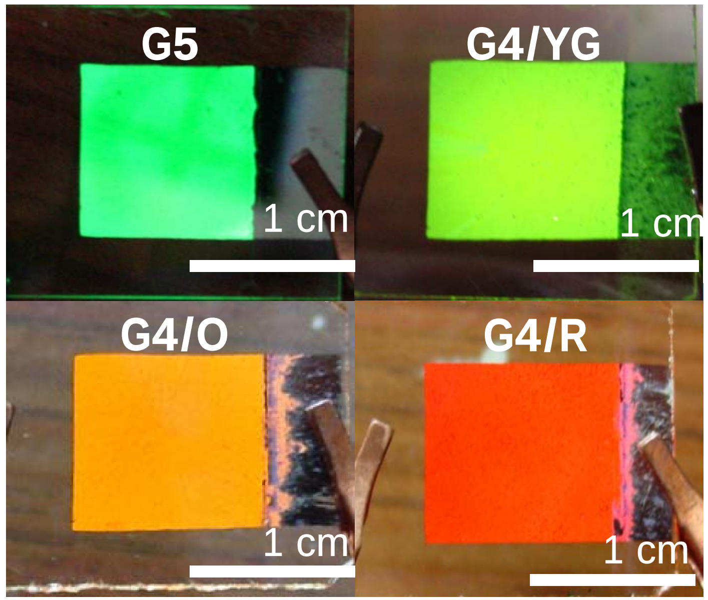




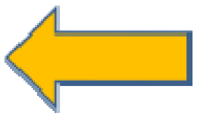
2 Deposition of various colored QDs (green, orange, and red) on ITO/PAH/G4

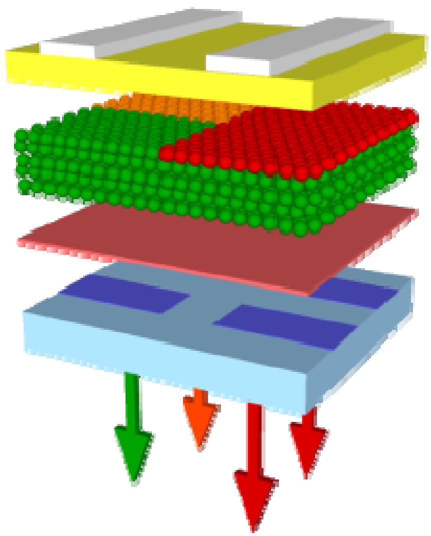


Multicolor emitting single QLED device



3 Deposition of TPBI, LiF, and Al





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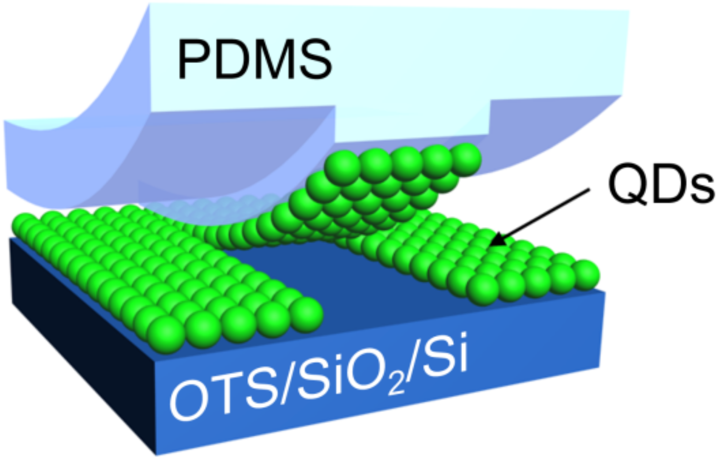
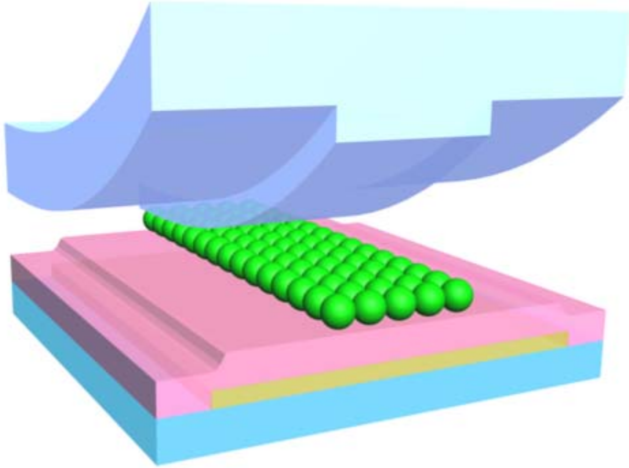
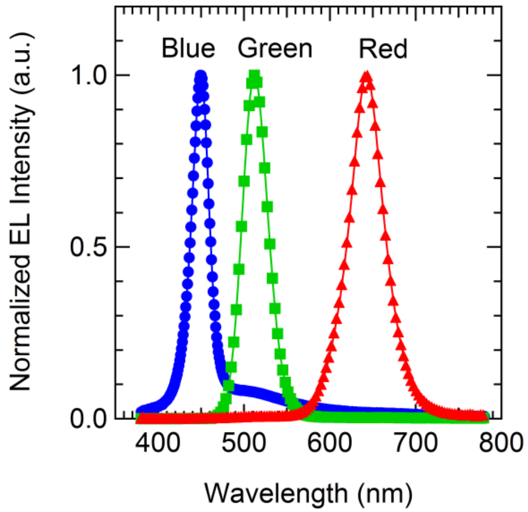
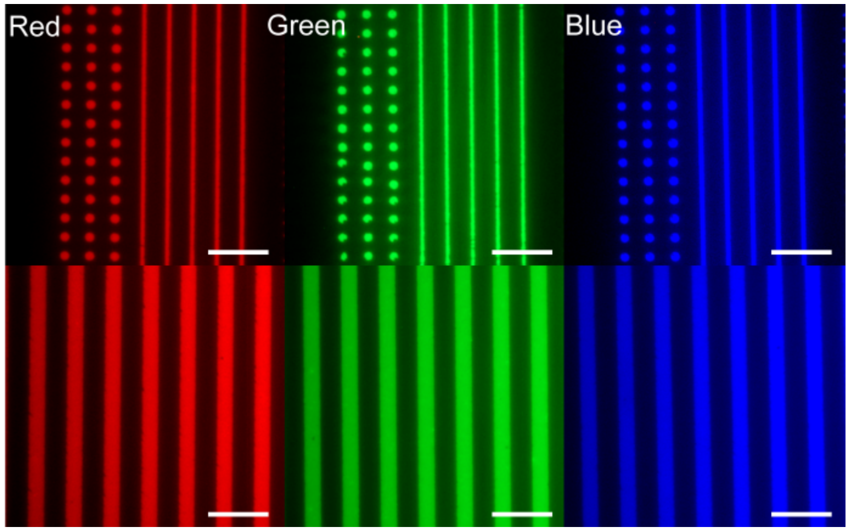
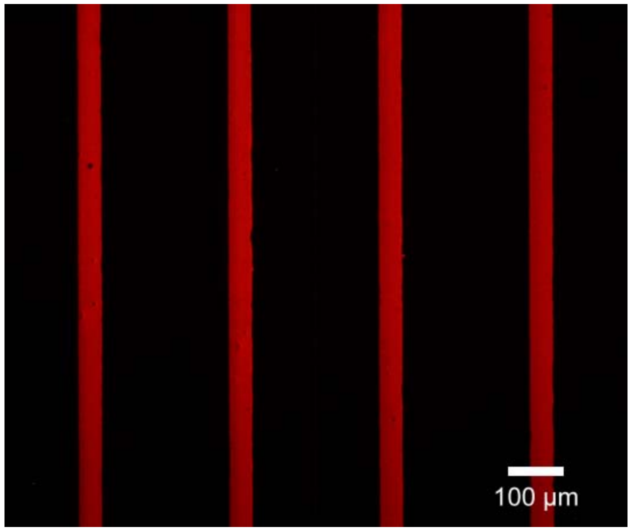
Full-color patterning of QD layers

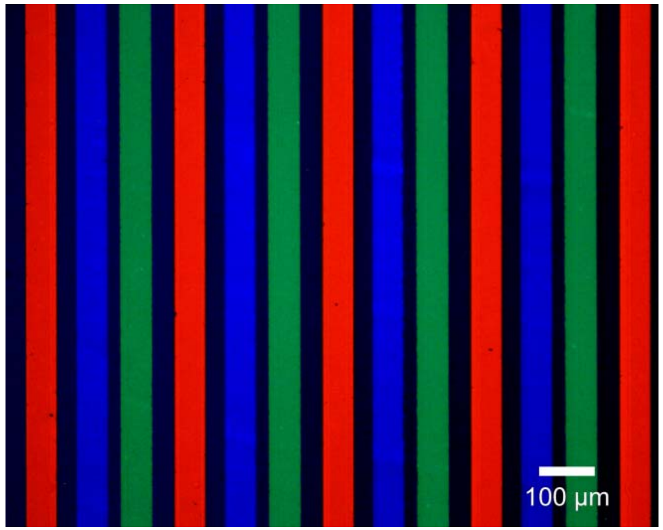




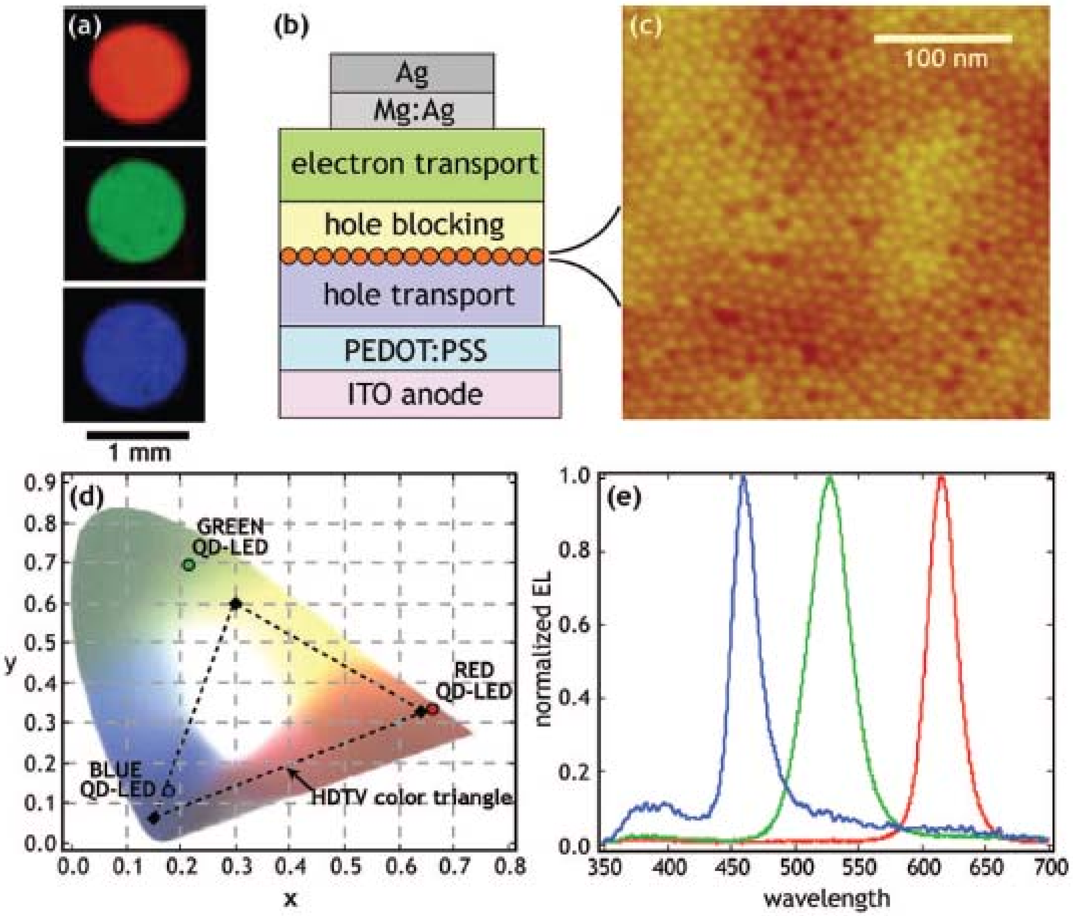


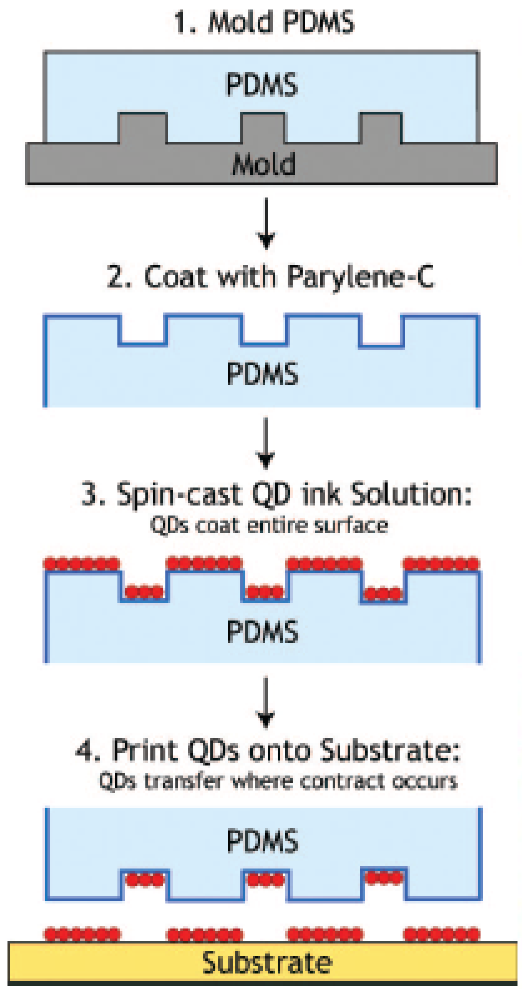


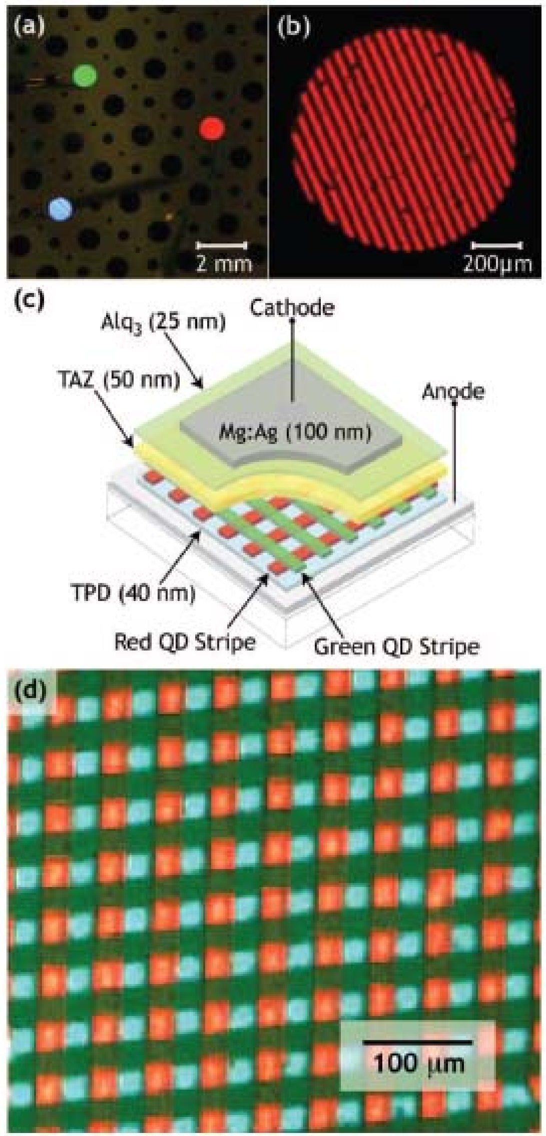




Patterning of QD LEDs: Contact Printing

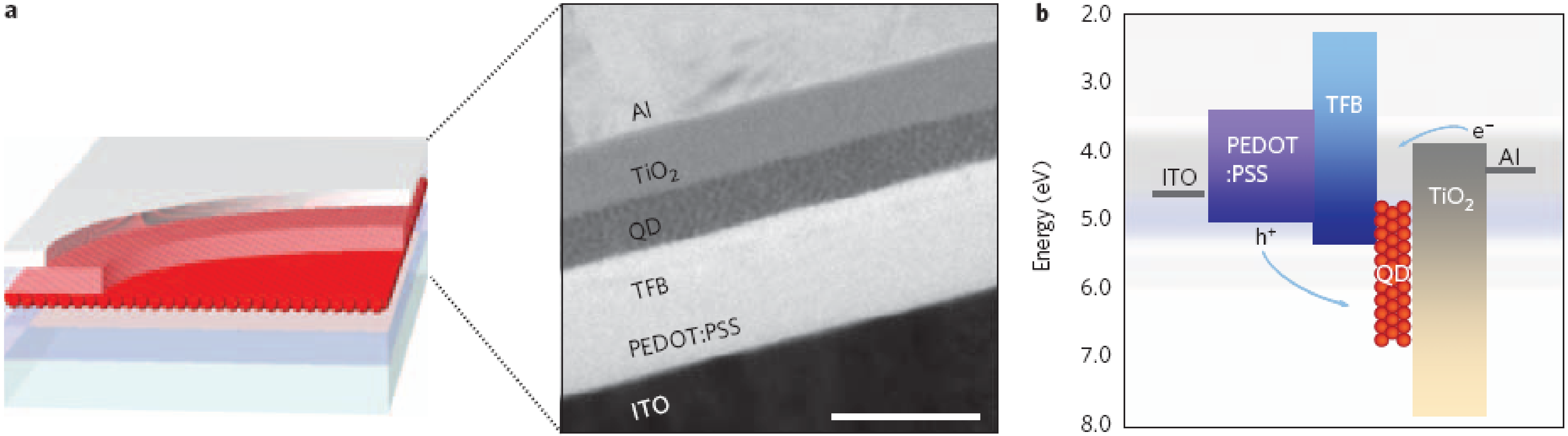


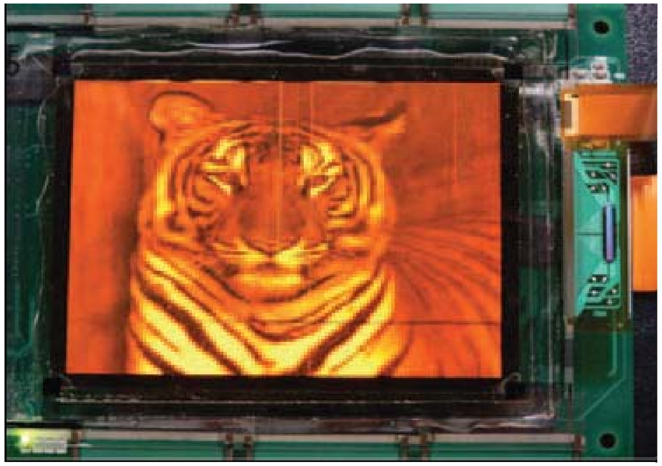


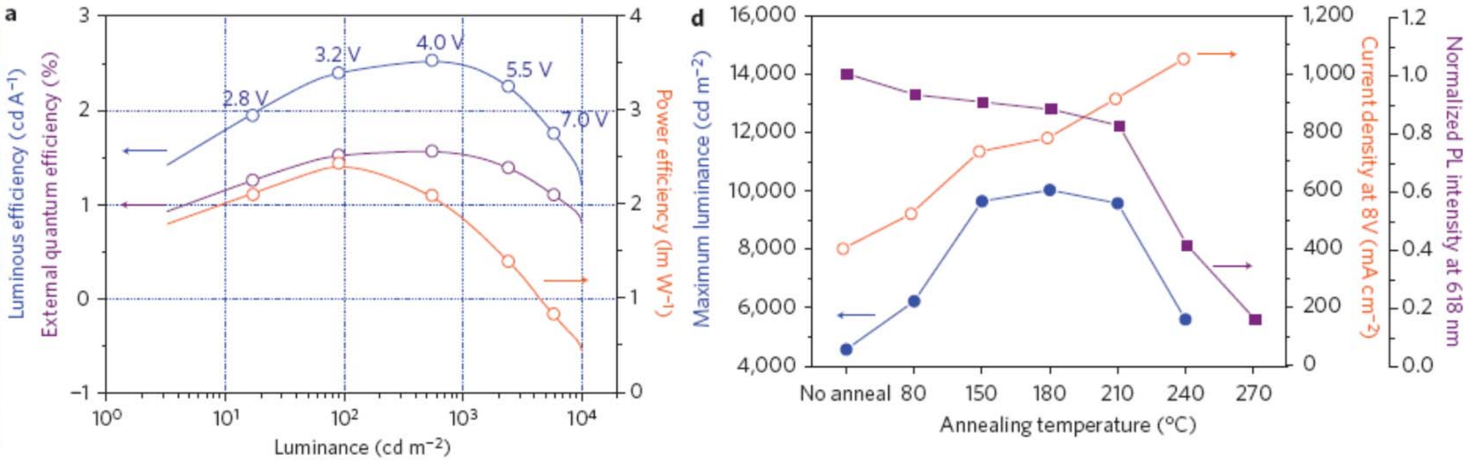


LeeAnn Kim, Polina O. Anikeeva, Seth A. Coe-Sullivan, Jonathan S. Steckel, Moungi G. Bawendi and Vladimir Bulovic (**MIT**), Nano Letters 8, 4513 (2008)

QD LED Display with a-Si Backplane







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