Environmentally Robust Quantum Dot Downconverters for High Efficiency Solid State Lighting

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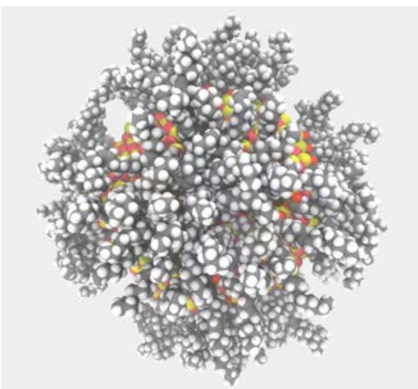

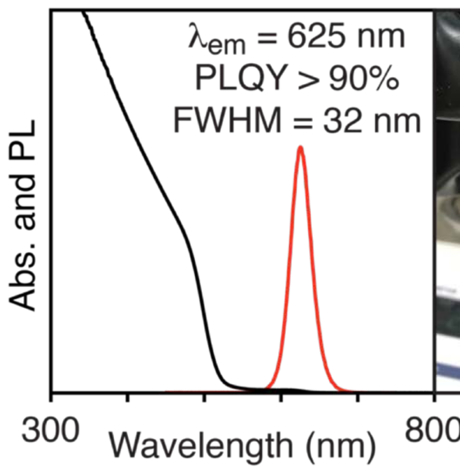

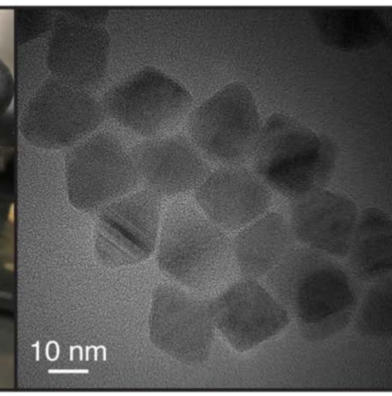

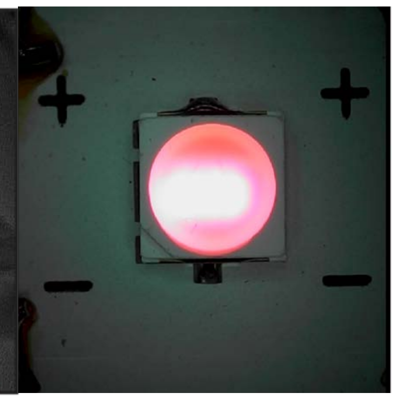

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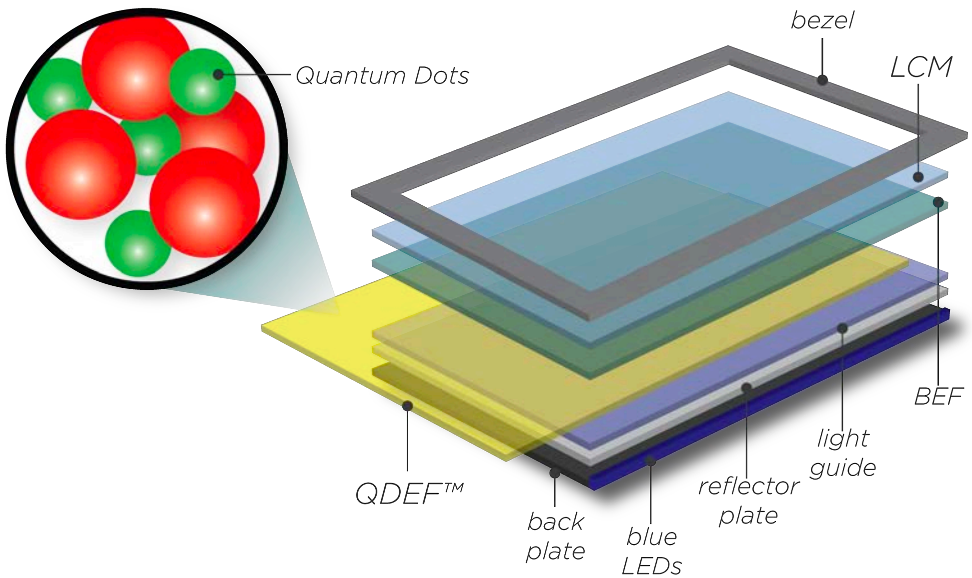
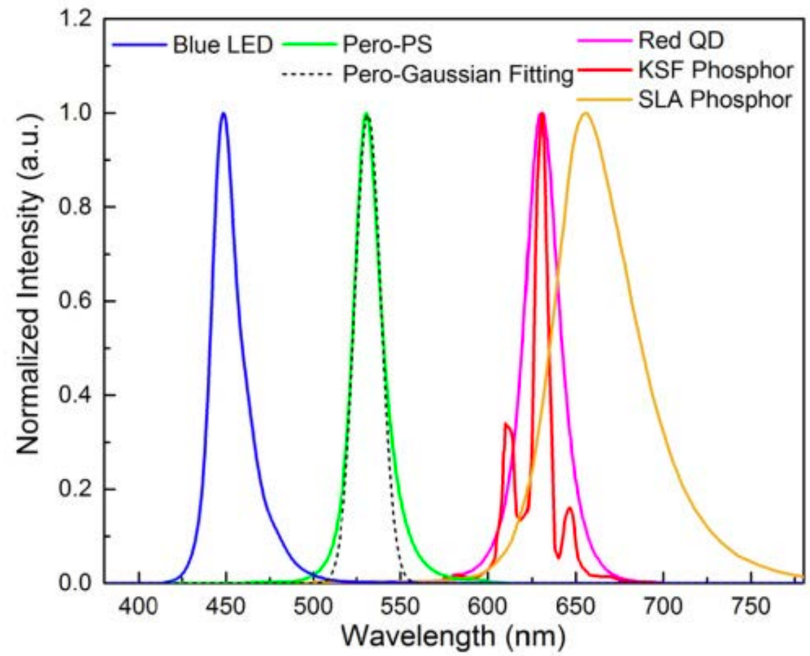




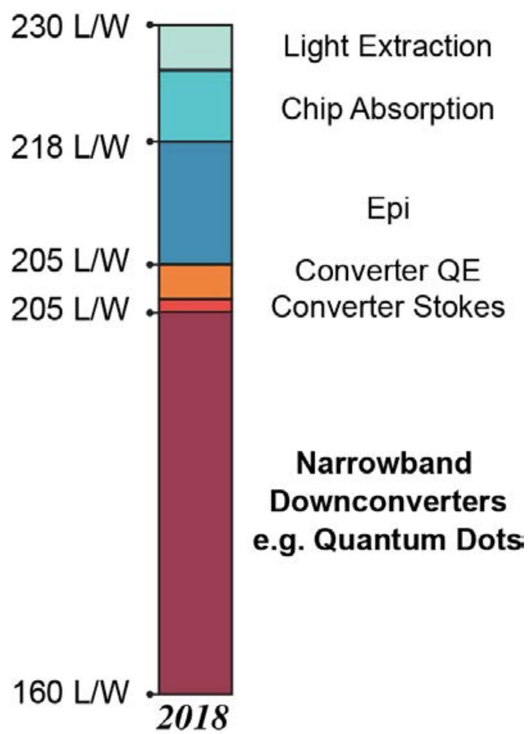
Samsung Q900 8K QLED TV
Samsung 49" CRG90 QLED Gaming Monitor

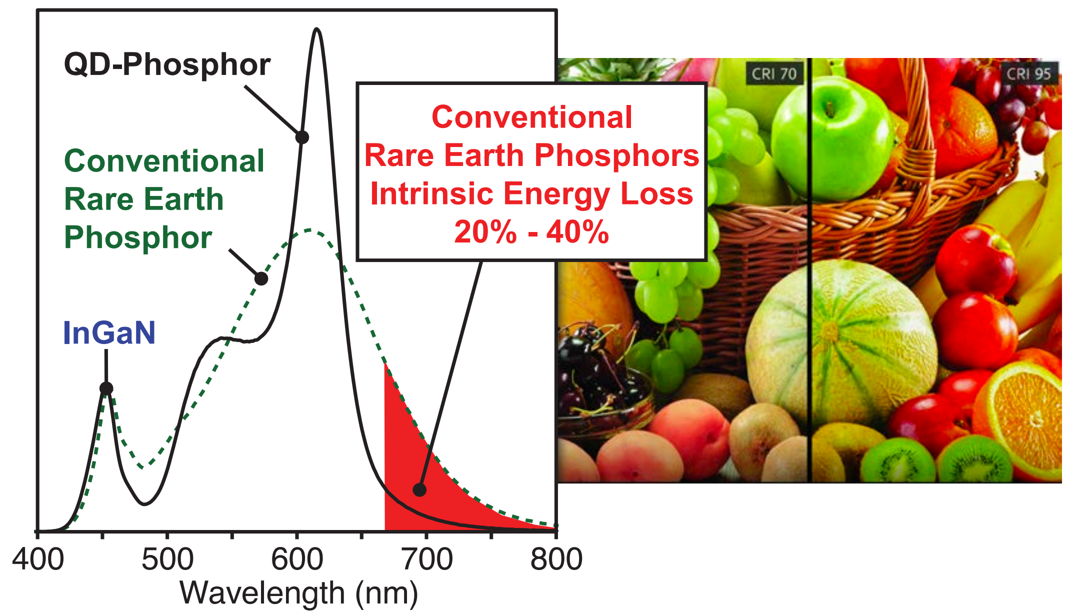
Vizio P-Series Quantum X
Vizio P-Series Quantum
Vizio M-Series Quantum

HP Pavilion 27

Reaching Theoretical Efficiency Limits of High CRI LED Lighting.

Projected sources of efficacy improvements in high CRI lighting.





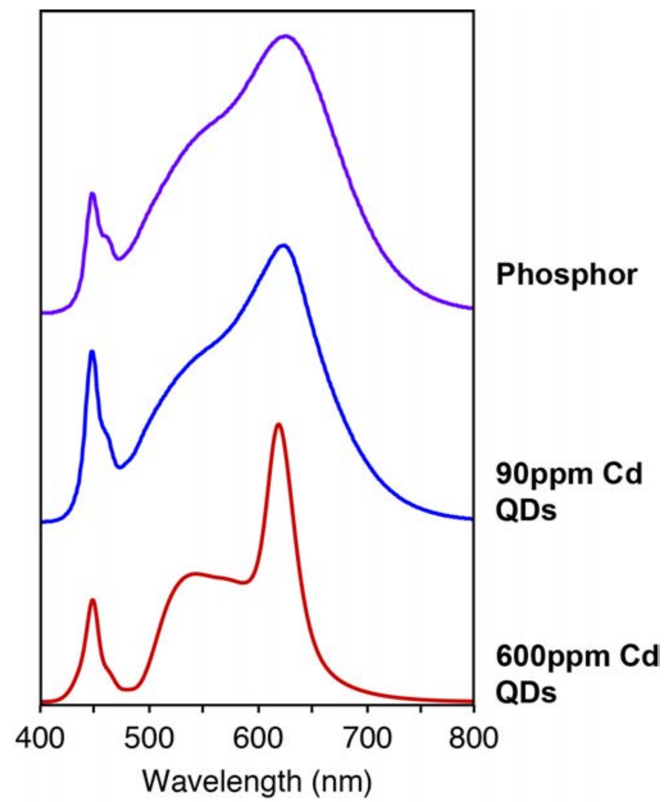
Quantum dots enable high efficiency, warm white (3000K) SSL devices with high CRI > 90.

Optimistic Projections: Alex Linkov, Osram OS, 2018.

2020 State Of The Art, 3000K Device Efficacies OSRAM OSCONIQ P 2226

	Efficacy (lm/W)	[Cd]	LER	CCT (K)	CRI	R9
Phosphor	158	0	298	2983	92	59
QDs	165	90	303	3018	93	56
QDs	**203**	**600**	357	2957	90	50

OSCONIQ P 2226 LED Packages



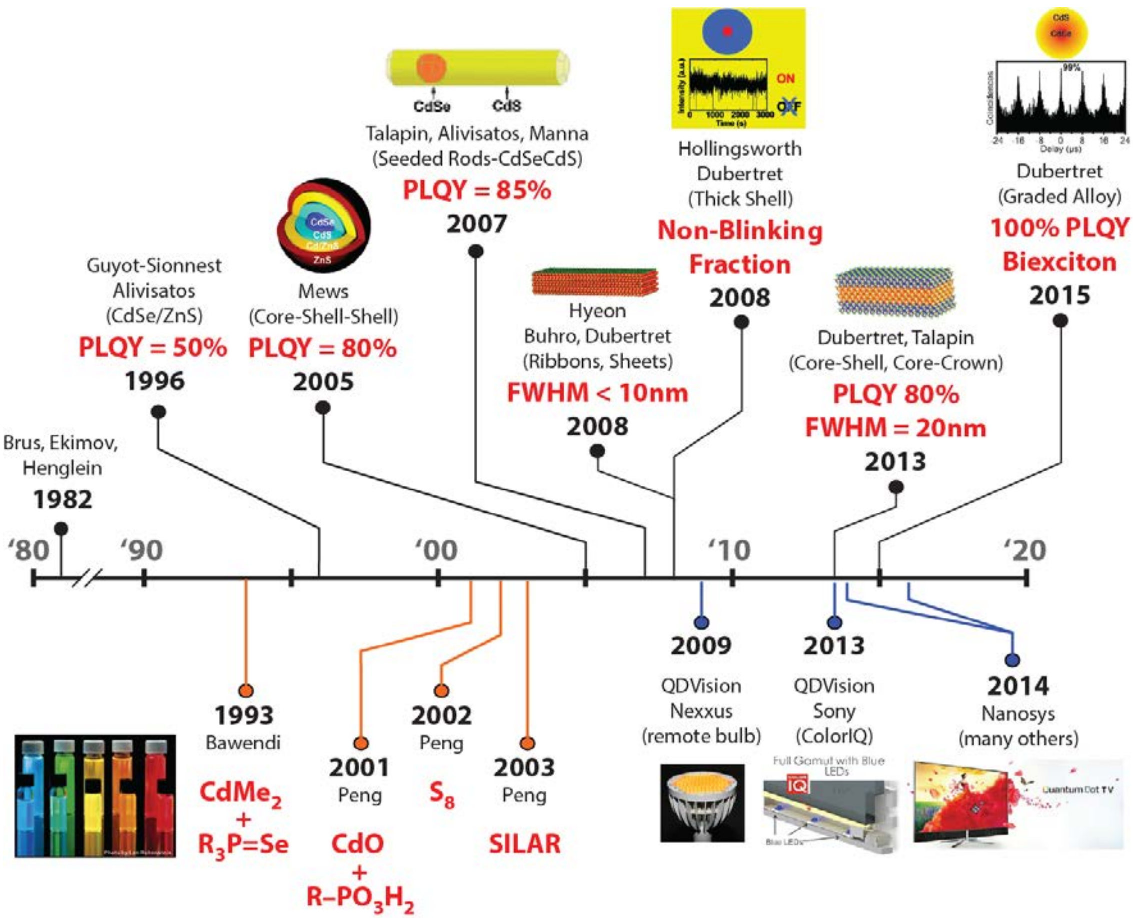
2018: State of the Art 3000K device efficacies.

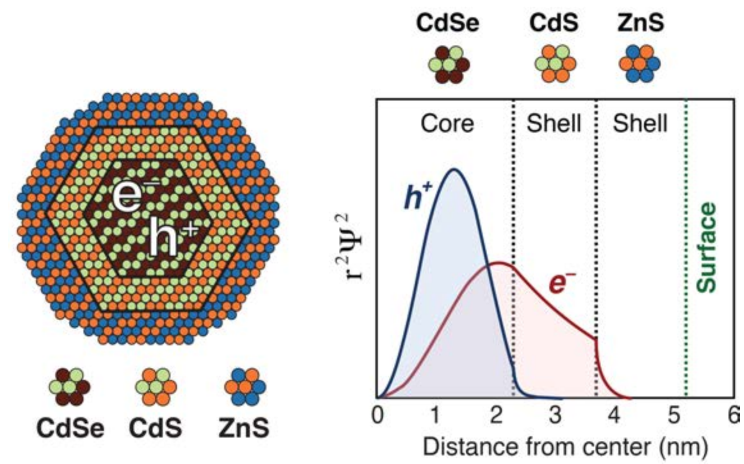
CRI	Nichia	Lumileds	OSRAM
80	195 lm/W	191 lm/W	191 lm/W
90	163 lm/W	163 lm/W	163 lm/W

25% higher device efficacy from QD enhanced SSL!

OSRAM Opto Semiconductors

Milestones in the Development of Colloidal QDs

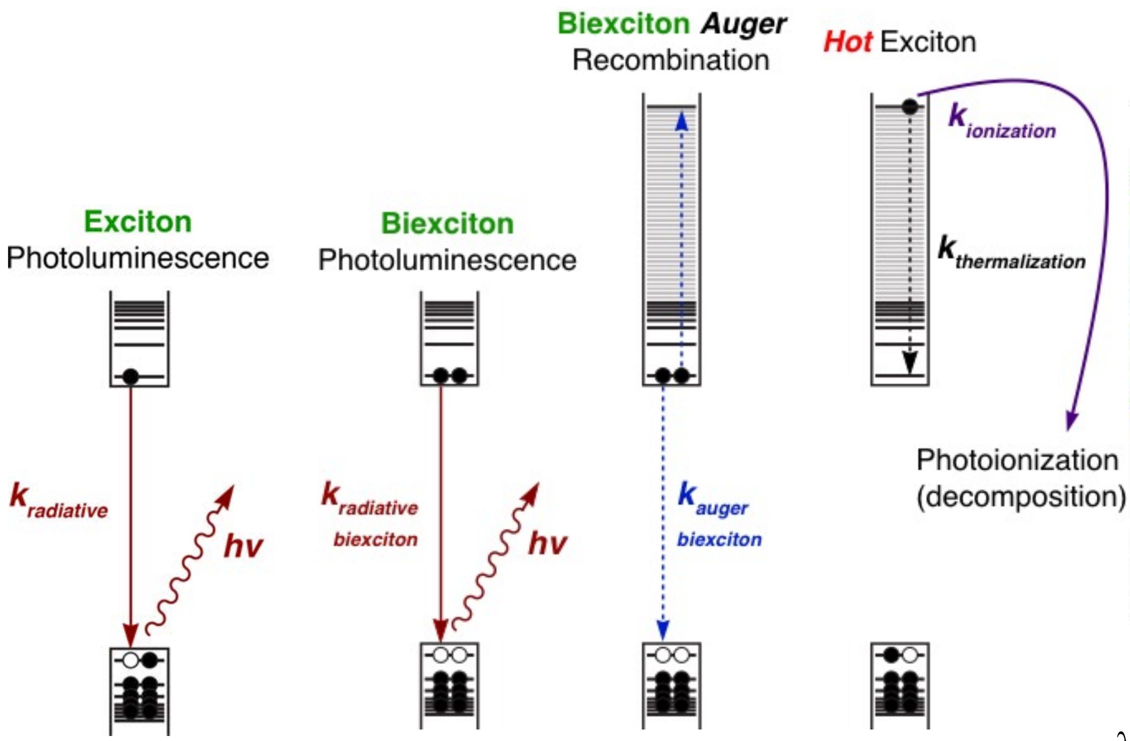




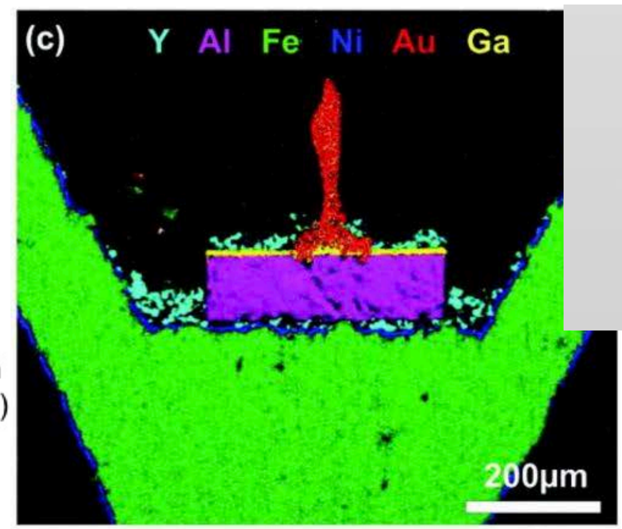
Tuning of architecture controls recombination kinetics, brightness, color, and spectral linewidth.

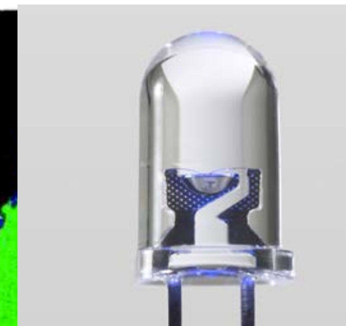
Owen and Brus, *JACS*, **2017**.

Photoexcitation Intensity of LED Packages: 10-100 W/cm^2



Phosphor Converted InGaN LEDs



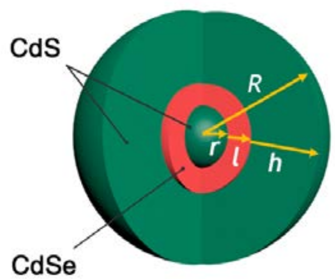


λ_{max} = 625 $\pm$ 5 nm, PLQY > 95%, FWHM < 35 nm, at 150°C and 1 W/mm^2.

Adoption of Light-Emitting Diodes in Common Lighting Applications, **2013**, DOE SSL Program.

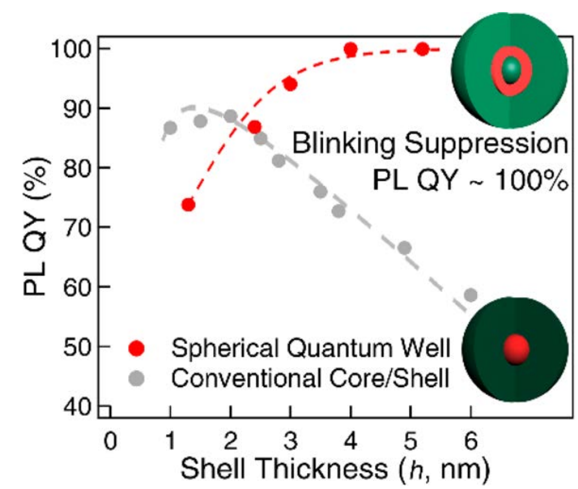
Flux Stable, Graded Alloy, Spherical Quantum Wells

Spherical Quantum Well Architecture Reduces Strain and Defects



Critical thickness for misfit defects (h_c):

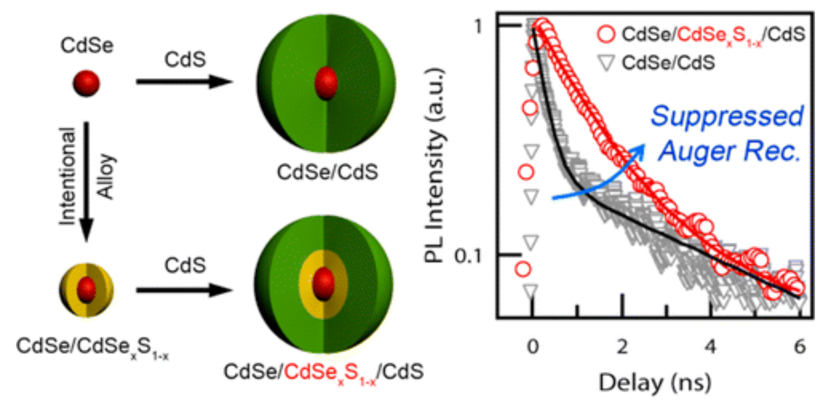
$$h_c = \frac{b}{2\pi f}\frac{(1-\nu\cos^2\alpha)}{(1+\nu)\cos\lambda}\left(\ln\frac{h_c}{b}+1\right)$$



Jeong (Bae) et al. ACS Nano **2016**, *10*, 9297.
Matthews and Blakeslee, J. Cryst. Growth **1974**, *27*, 118-125.

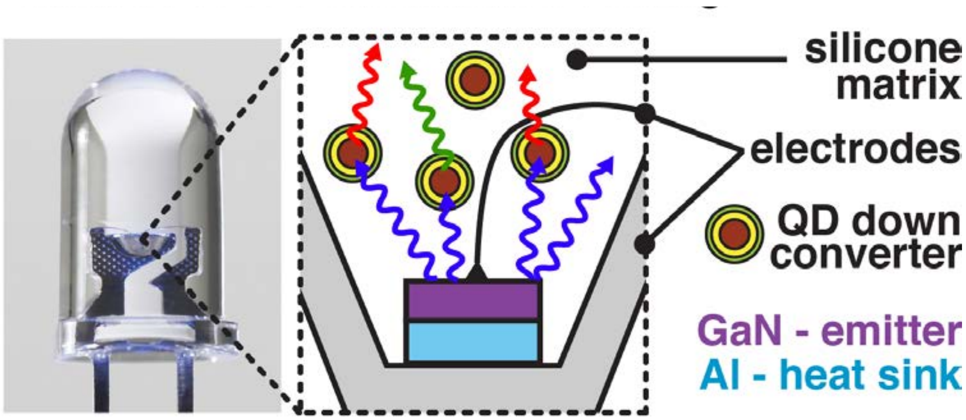
Large, Graded Alloys Suppress Auger Recombination

Dubertret, *Nano Lett.* **2015**.
Pietryga and Klimov, *ACS Nano* **2013**.
Klimov, Htoon *Phys. Rev. Lett.* **2011**.
Cragg and Efros, *Nano Lett.* **2010**.
Rabani and Baer, *Chem. Phys. Lett.*, **2010**.



QD Performance Testing "On Chip" (DE-EE0007628)

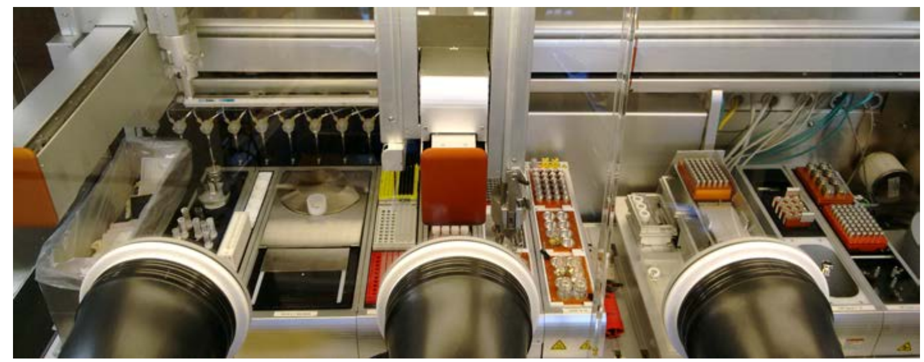
Device Architecture



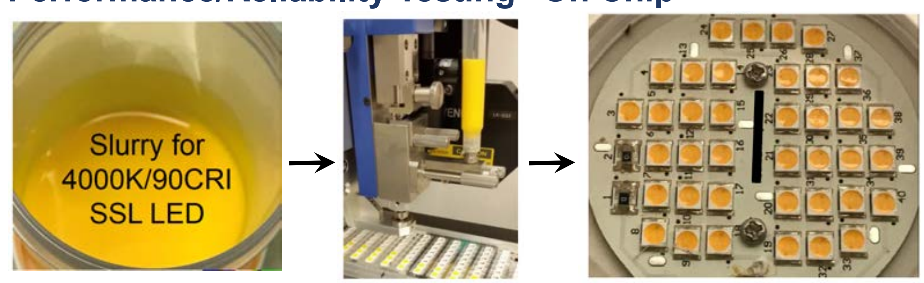
Can narrow band emitting QDs, especially red emitters, maintain PLQY on LED chips during operation?

Flux = 10–100 W/cm^2
Temperature = 100–150˚C
PLQY > 90 %
Humid air and >10,000 hour operating lifetimes

High Throughput QD Synthesis Robotics

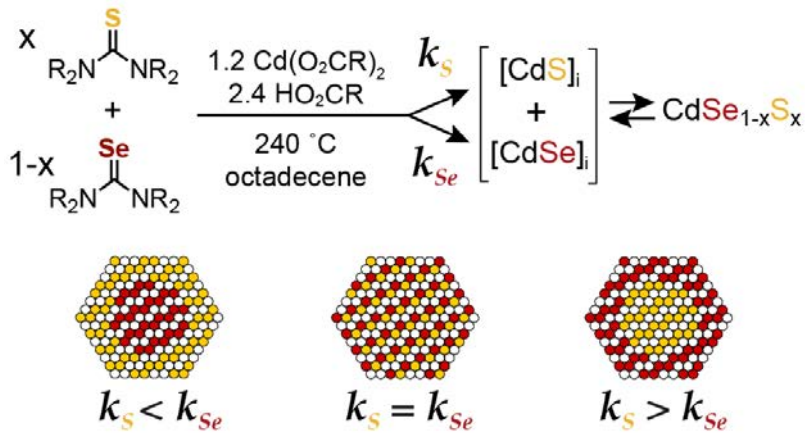


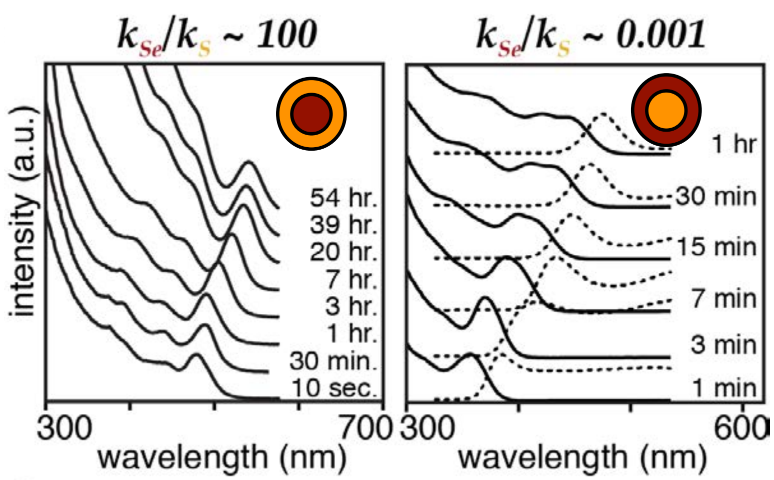
Performance/Reliability Testing "On Chip"

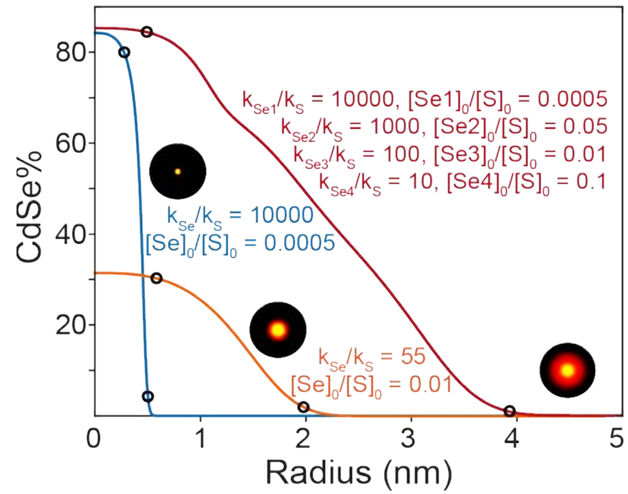


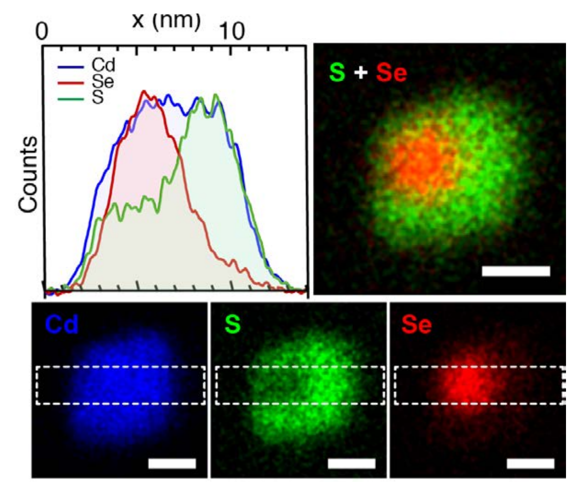
Silicone/QD Slurry → Deposit → Environmental Reliability Testing

Single Injection of Mixed Precursors: Precursors Control Alloy Microstructure

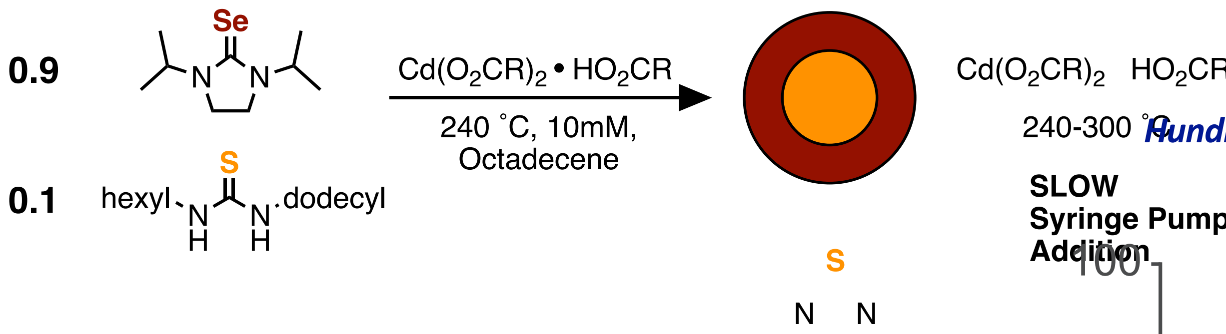




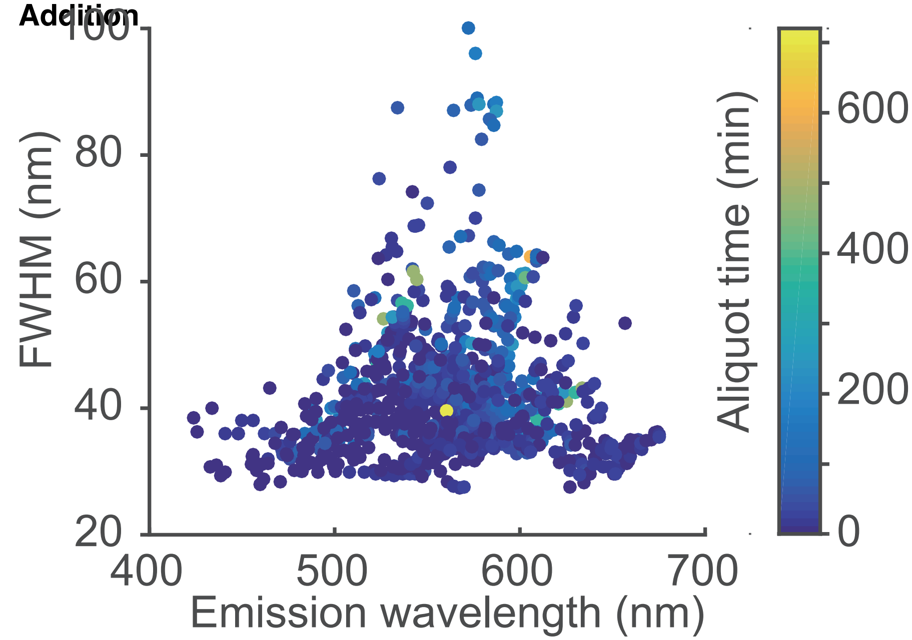




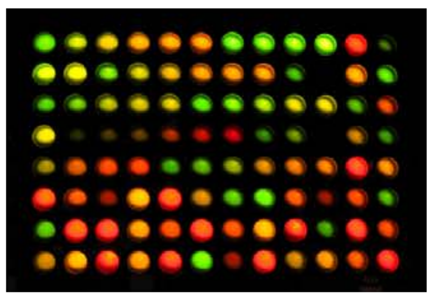
High Throughput Screening: "One Pot" Synthesis of CdSe/CdS QDs



Hundreds of Conditions and Precursors Tested
Many are polydisperse



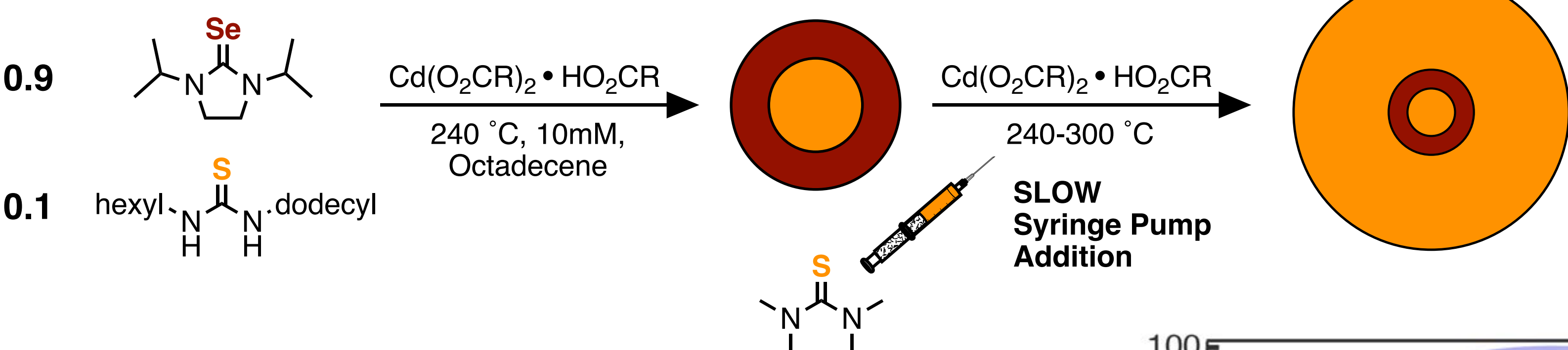
High Throughput Screening Robotics
Molecular Foundry Lawrence Berkeley Lab

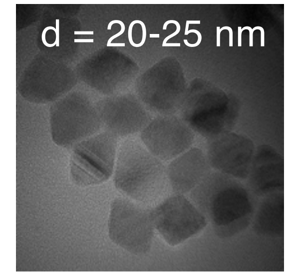


Photoluminescence of QDs in 96 Well Plate

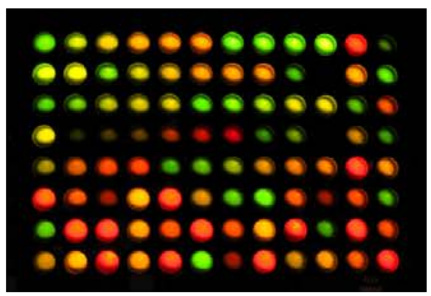
Chan, Cohen, Milliron, and Owen, *Nano Lett.* **2010**.

High Throughput Screening: "One Pot" Synthesis of CdSe/CdS QDs

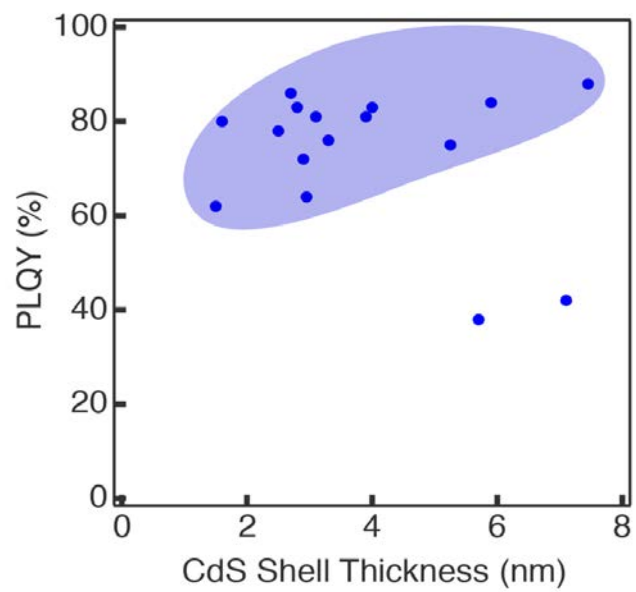




High Throughput Screening Robotics
Molecular Foundry Lawrence Berkeley Lab



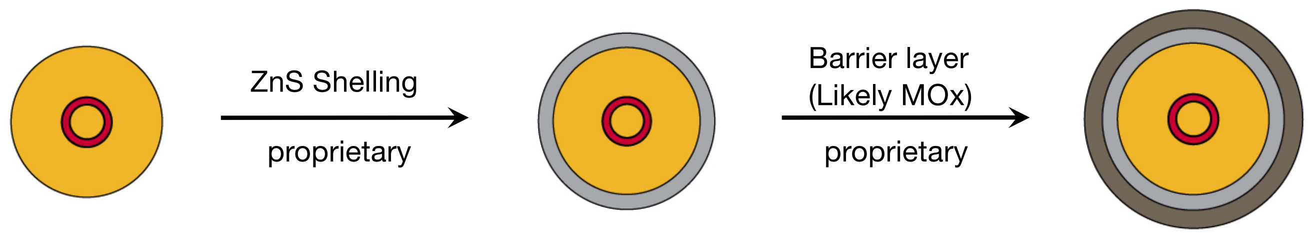
Photoluminescence of QDs in 96 Well Plate



Chan, Cohen, Milliron, and Owen, *Nano Lett.* **2010**.

Shelling and Encapsulation Prior to Reliability Testing on Chip

1) ZnS/MOx Shelling

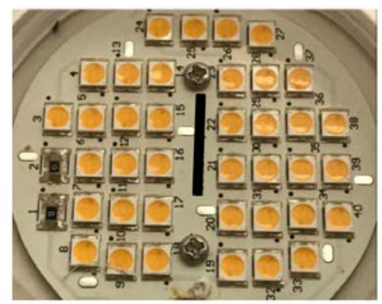


2) Device incorporation ("on-chip")

Silicone/QD slurry

Slurry applied to LED chip

Silicone cure
150°C

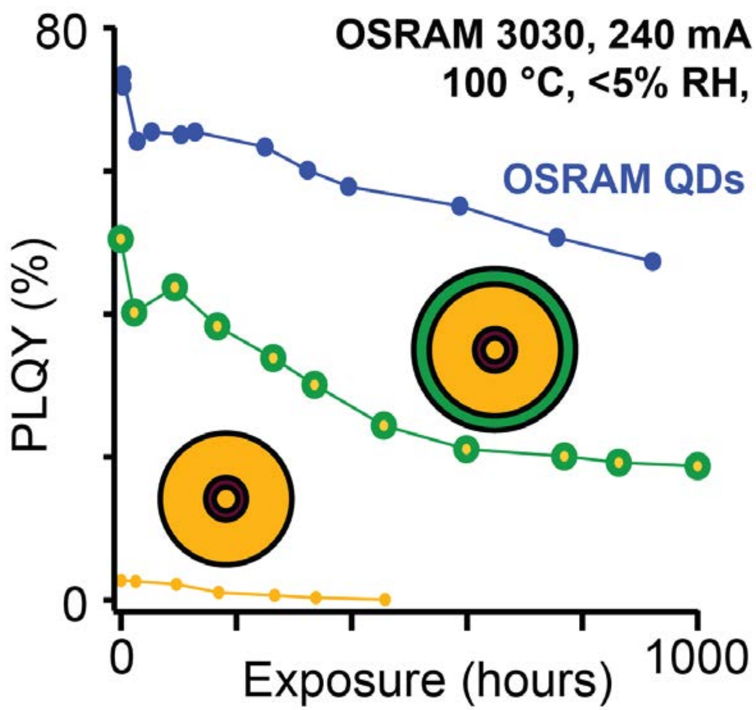


3) Reliability Testing

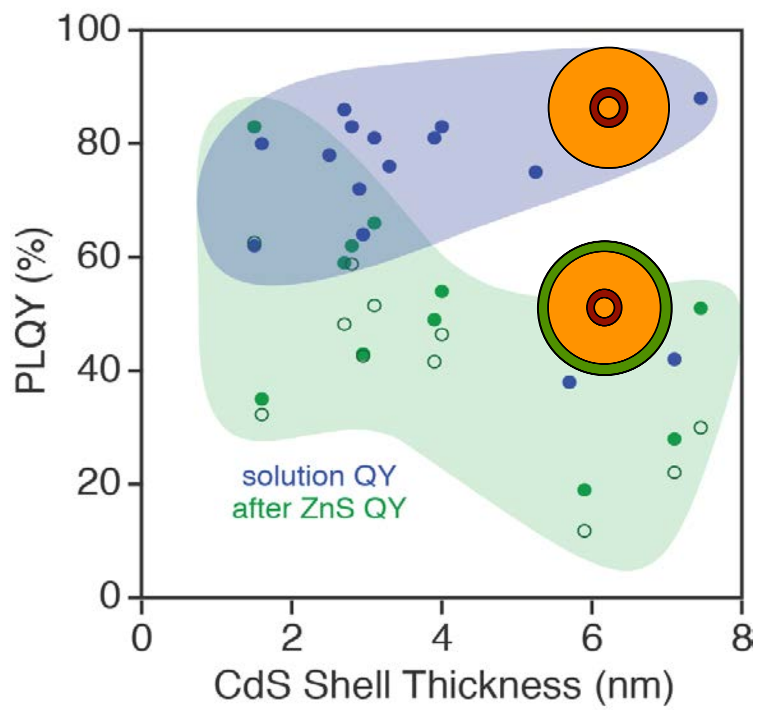
High temperature operating lifetime (HTOL)
100°C, <5% RH
240mA or 480 mA
LED Drive Current

Wet High temperature operating lifetime (WHTOL)
85°C, 85% RH
65mA LED Drive Current

ZnS Surface Layer Essential to Reliability but Reduces PLQY



Improved ZnS = Improved Reliability

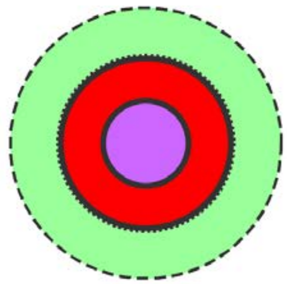


Objectives in 2019 – 2021 (DE-EE0008716)

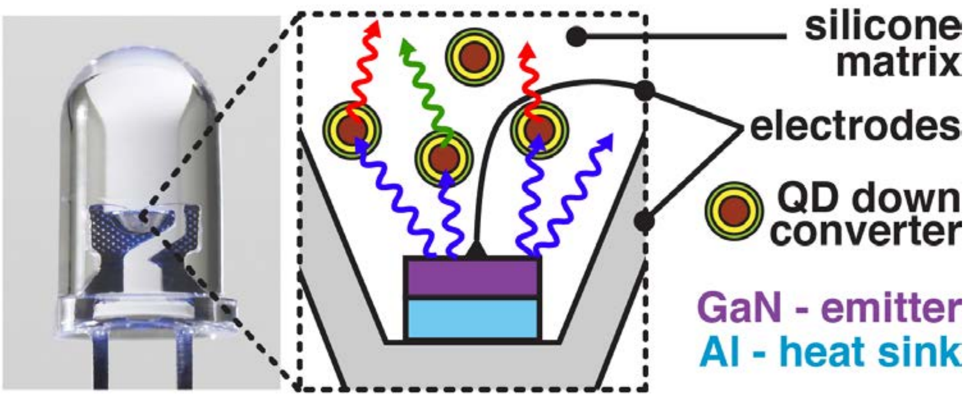
Task 1: InP

Task 2: ZnSe,S

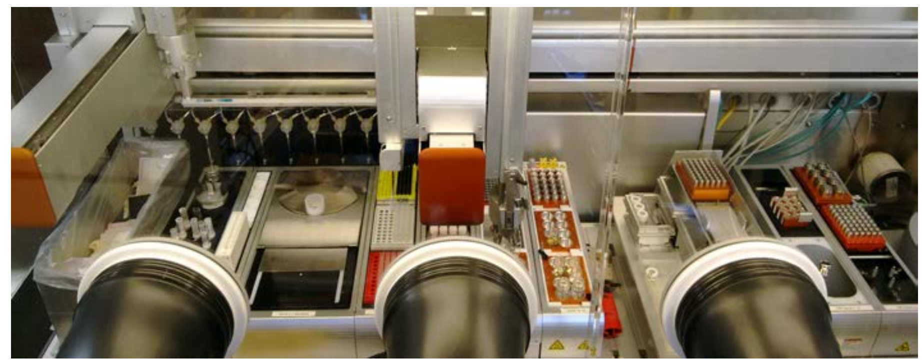
Tasks 3, 4: Silcone Encapsulation



Task 5: LED Performance Testing



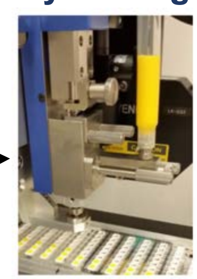
High Throughput QD Synthesis Robotics



Performance/Reliability Testing "On Chip"

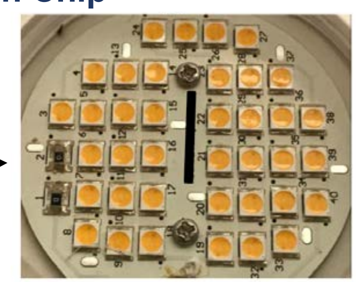
Silicone/QD Slurry

→



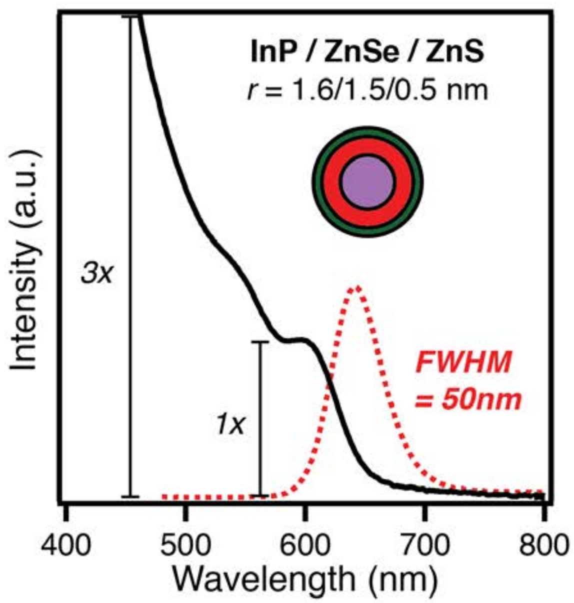
Deposit

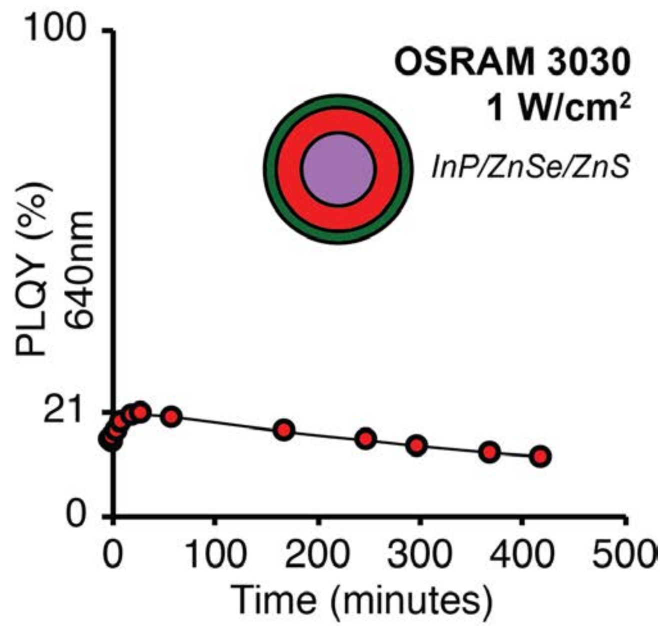
→



Environmental Reliability Testing

Low Reliability of InP/ZnSe/ZnS QDs on LED Packages

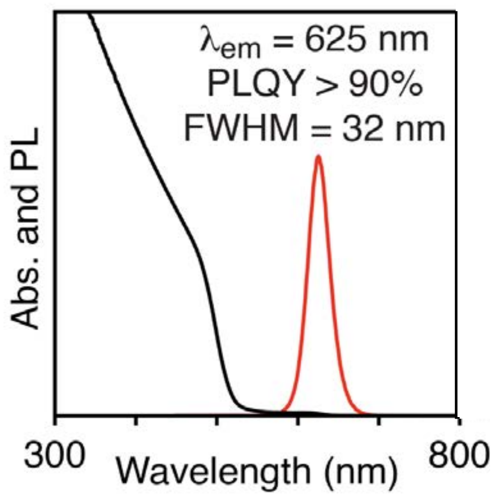


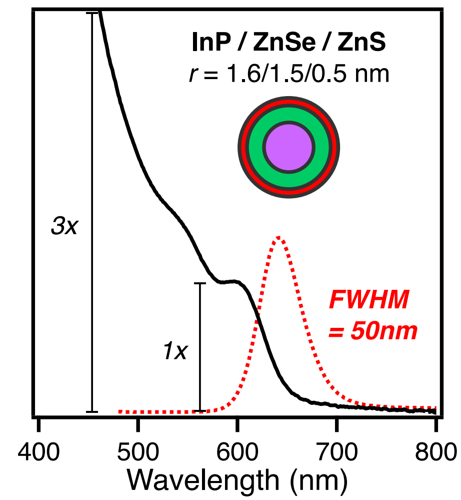


Lower chemical instability thought to arise from the junction of ZnSe/InP.

Growing GaP shell can increase PLQY and stability.

“Cd Free” III-V Nanocrystals Have Poor Absorptivity at λ = 450nm





CdS shell layer provides absorptivity at 450nm (95:5 S:Se shown above).

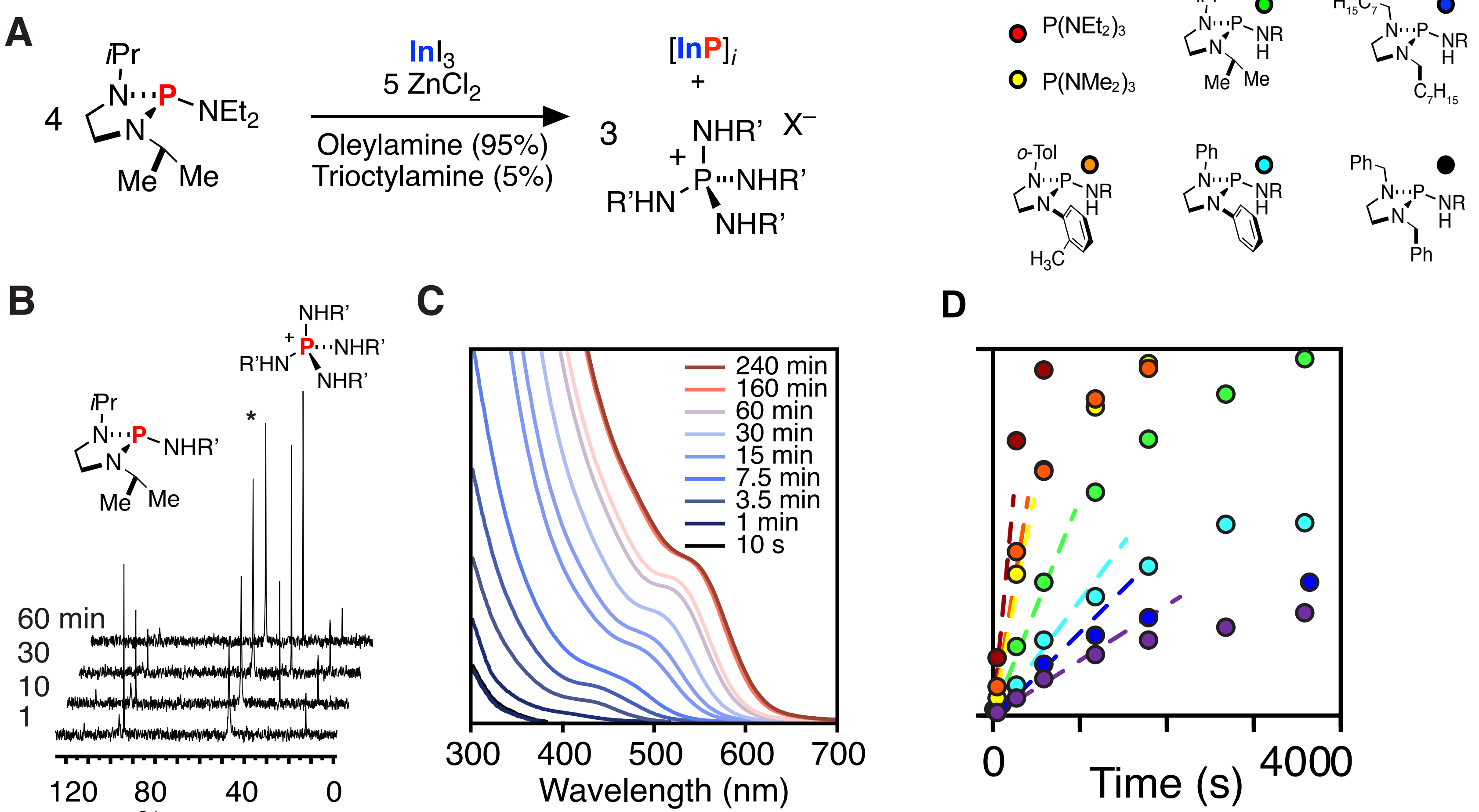
Shell thickness increases chemical robustness, reduces Auger recombination, and lengthens luminescence lifetime.

Poor absorptivity and reabsorption of red and of green is a major drawback.

GaP layers would increase absorption at 450 nm, and better passivate InP layer.

Fundamentally new synthetic methods to grade InP/GaP interfaces are needed.

Reaction Kinetics of Aminophosphine Conversion to InP



McMurtry, *et al. Sumitted.*

Conclusions

(1) Precursor reactivity can be used to control particle size and composition.

(2) Characterization of microstructure with higher than 5 nm spatial resolution is challenging.

(3) ZnS surface layers are essential to long-term stability and photoluminescence quantum yield.

(4) Quantum dots remain promising candidates for deep red emission on LED packages.

Acknowledgements

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