Quantum Rods for Displays and LEDs: Full Visible Spectral Range, Less Cd and Higher Stability

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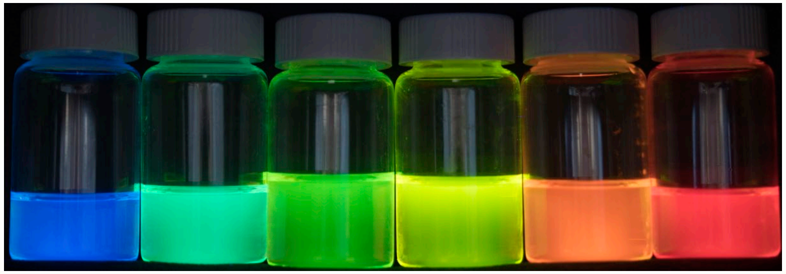


Displays Will Be Everywhere

Street displays

In-door and wall displays

Interactive windows

Problems and Trends

- Hi-resolution: 4k, 8K and 10K
- Bigger size: 55”, 65”, 85”, 100”
- The power consumption!
- The price!
- Image quality

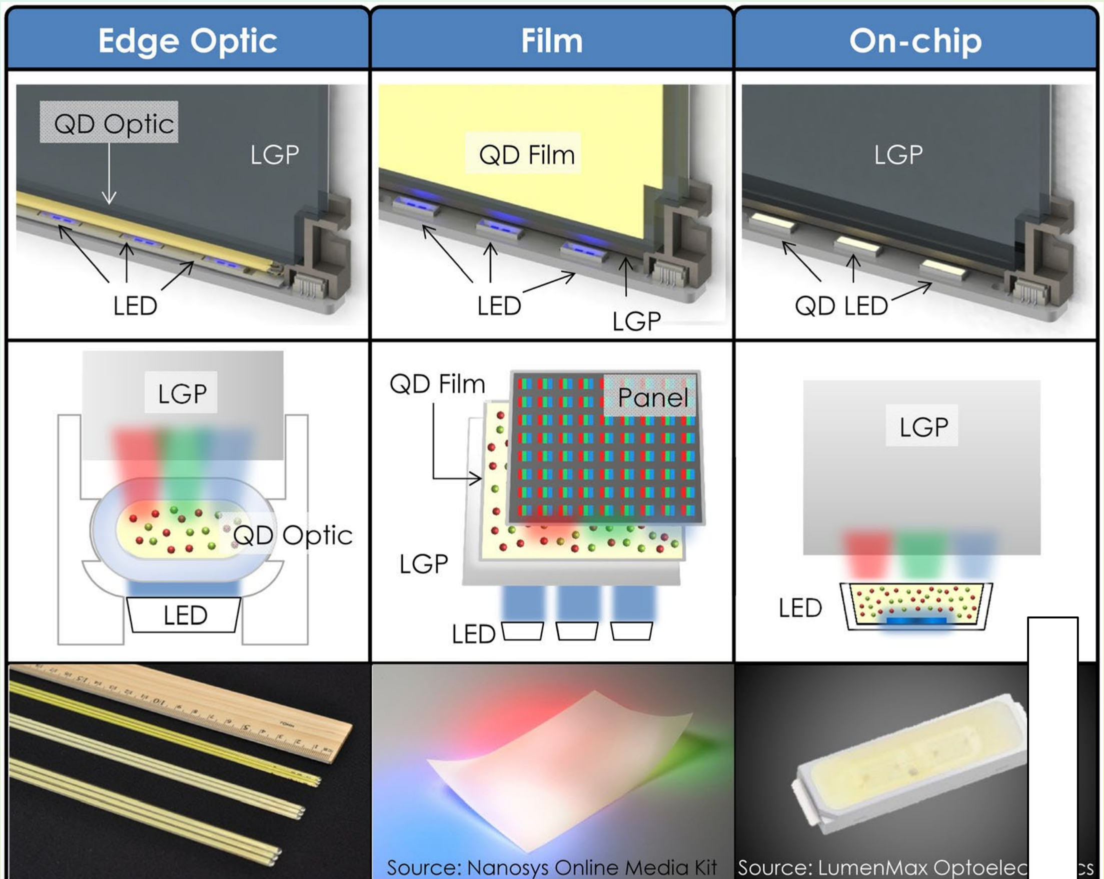
Medical augmented reality

Big data visualization

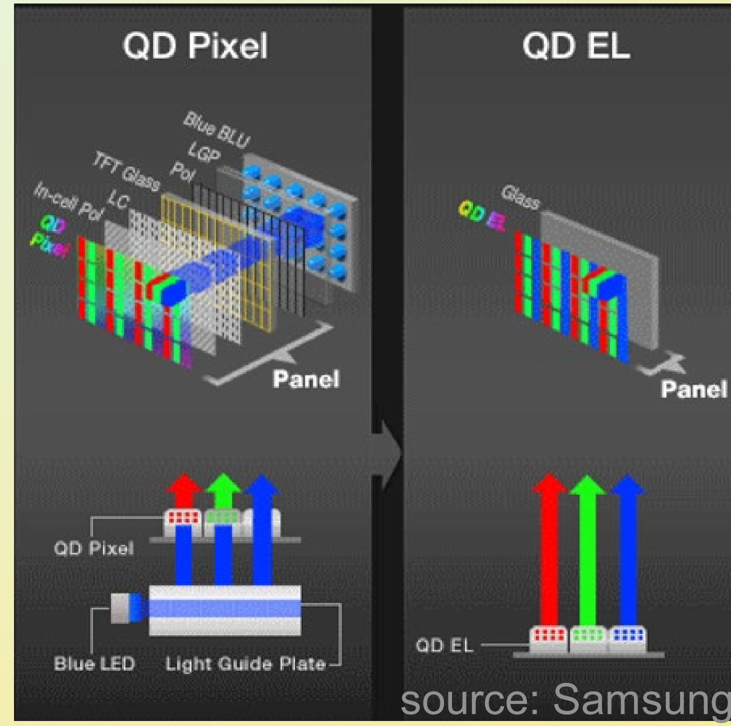
Flexible displays

QD Display Configurations

QD Vsion (Massachusetts) | **Nanosys (California)** | **LumenMax (Taiwan)**



Future emissive displays

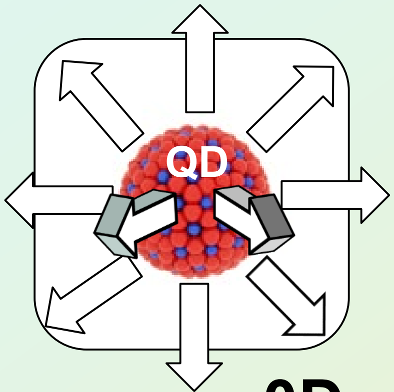


in the early phases of development

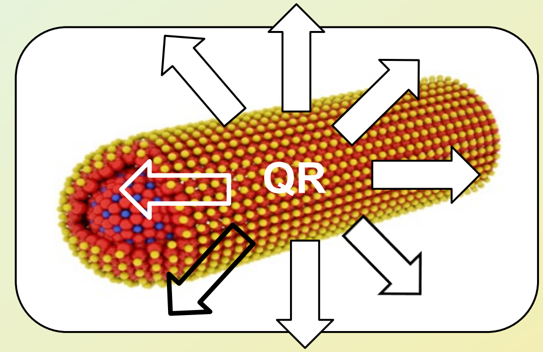
On-chip is a most desirable format because of higher efficiency, less material required, and ease of system integration

Thermal quenching problem limits application of QDs down converters!

Quantum Dots VS Quantum Rods



0D



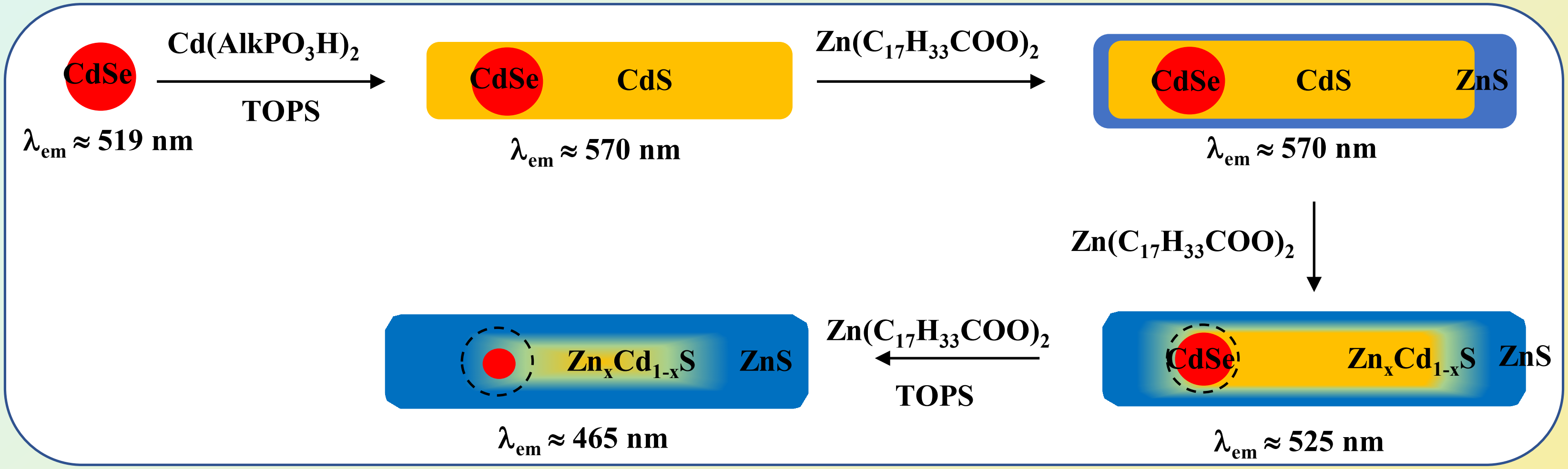
1D

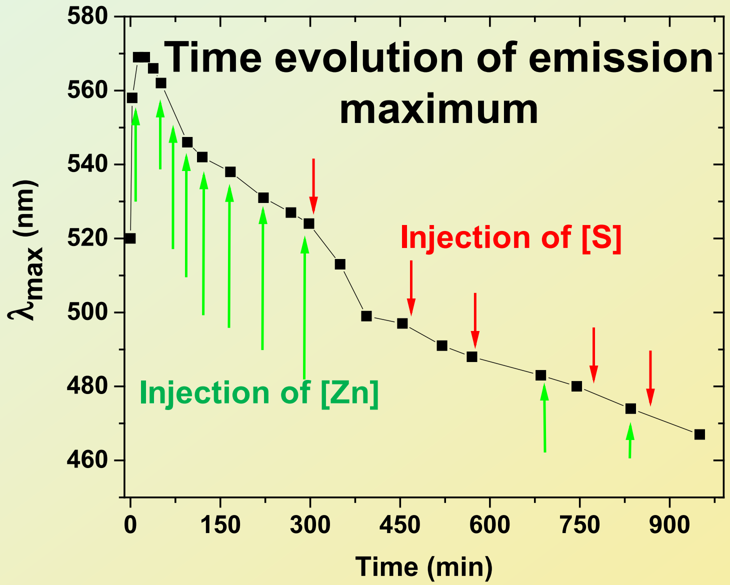
The shape matters

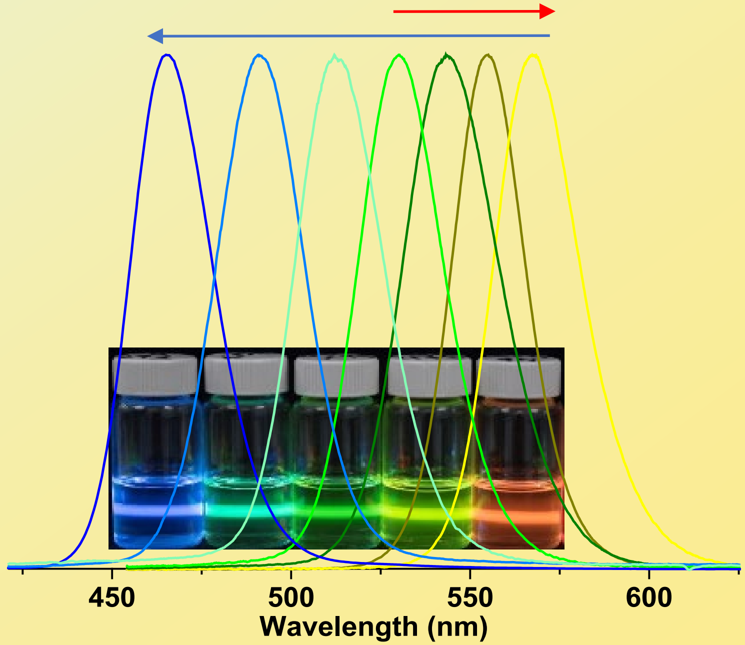
Properties	Quantum Dots	Quantum Rods	Remarks
Thermal quenching	+	+++	**Solved for QRs in this work**
Whole visible range tuneable emission	+++	+++	**Solved for QRs in this work**
Light extraction efficiency	–	++	41% vs 20% for QDs, twice less energy losses
Linearly polarized emission	–	++	Linearly polarized PL (max. DOP is around 0.87)
Narrow symmetric emission	+++	+++	FWHM can be less for QRs
Resistance to photobleaching	++	++	
Absorption cross-section	++	+++	Less material is required
PLQY in film	++	++	

Synthesis of Truly Green and Blue Emitting Quantum Rods

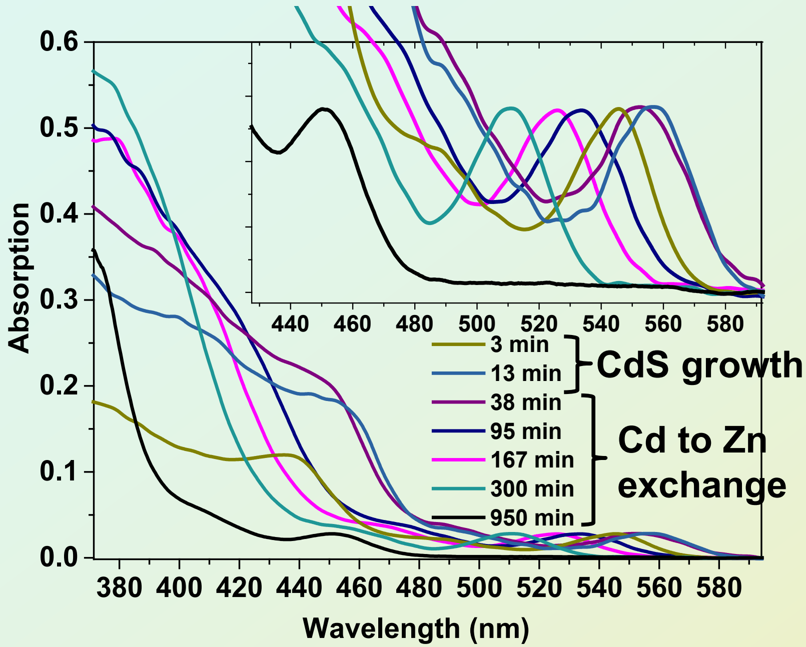
Previous works are mostly limited to red and green-yellow QRs ($\lambda_{em} \geq 550$ nm) because of very large red shift of emission during shell growth.
For Displays we need green with $\lambda_{em} \approx 520$ nm

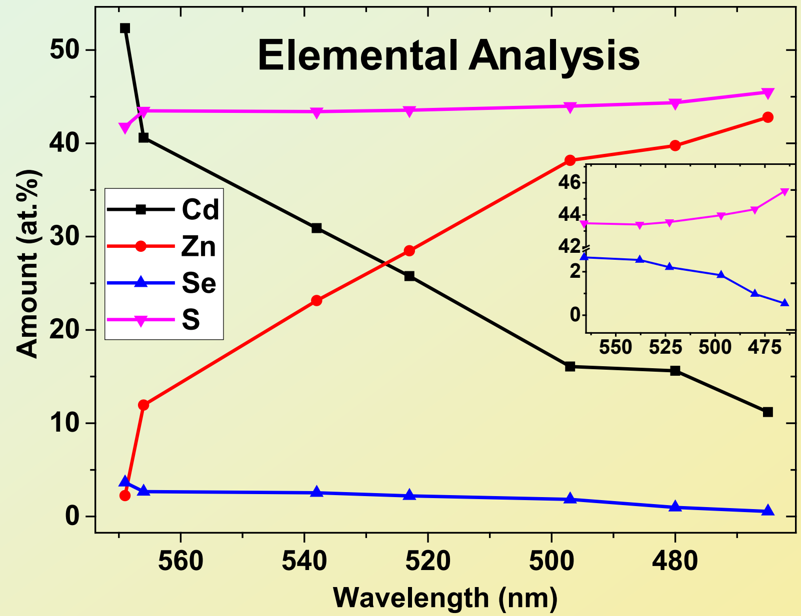


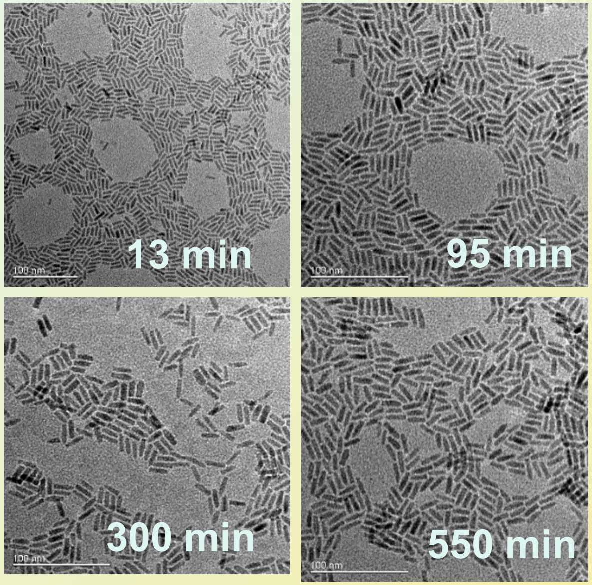


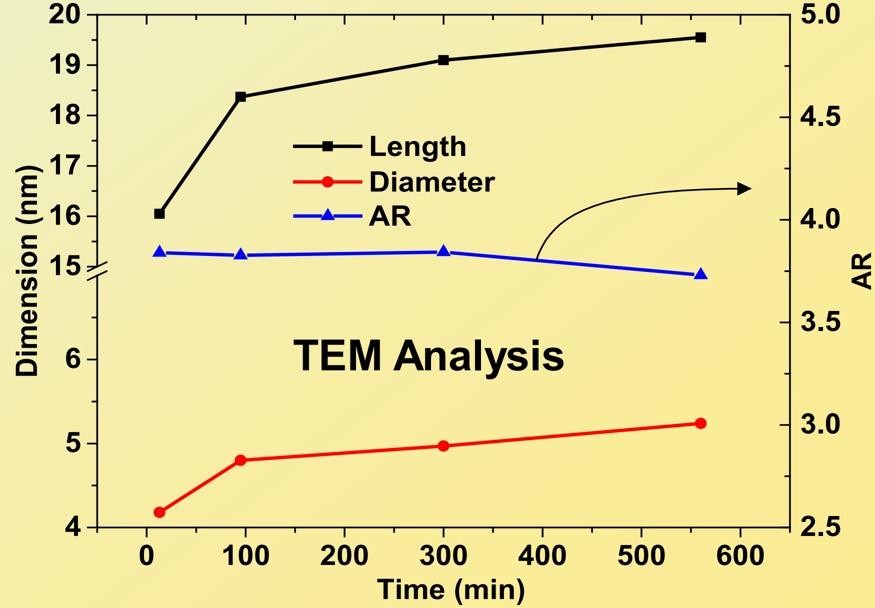


Characterization

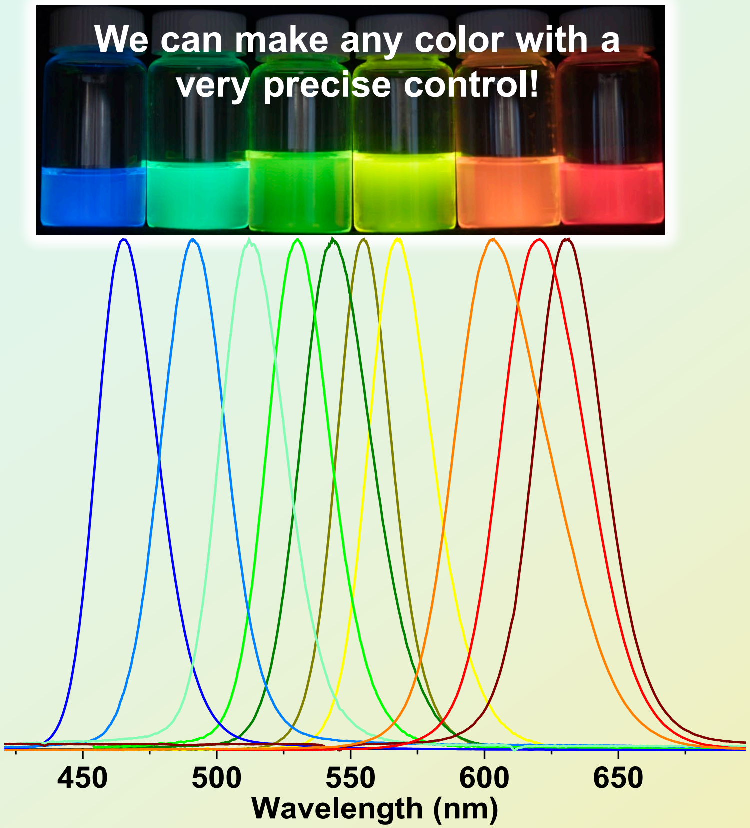


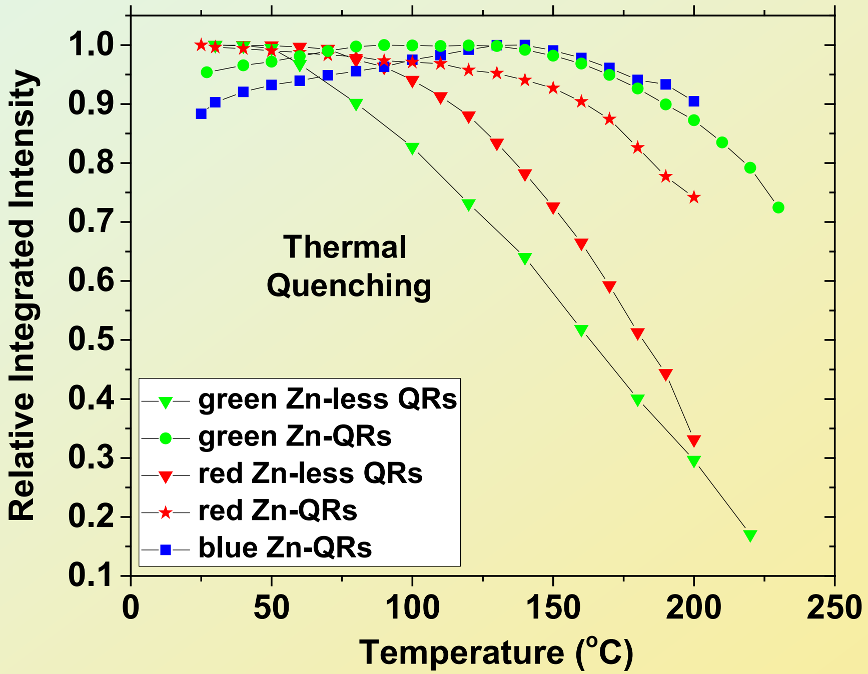


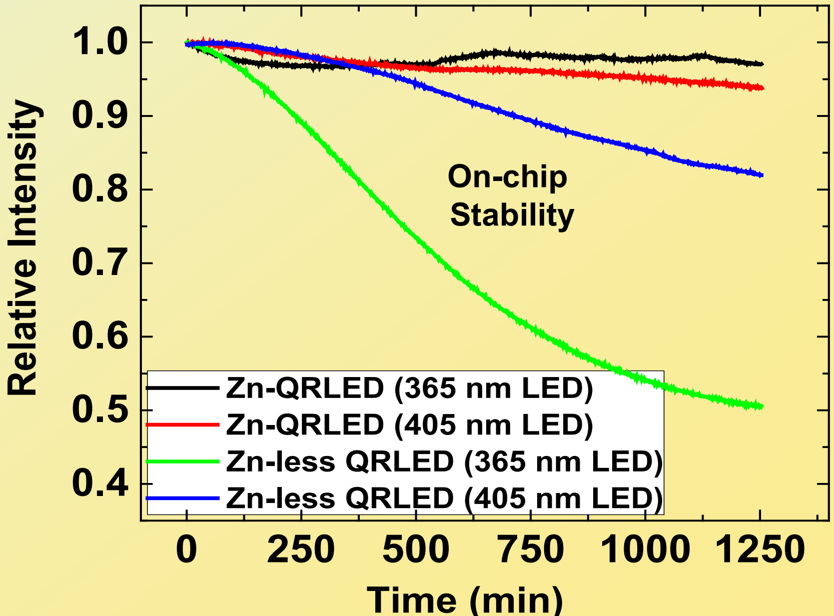




Zn-modified Quantum Rods Are More Stable





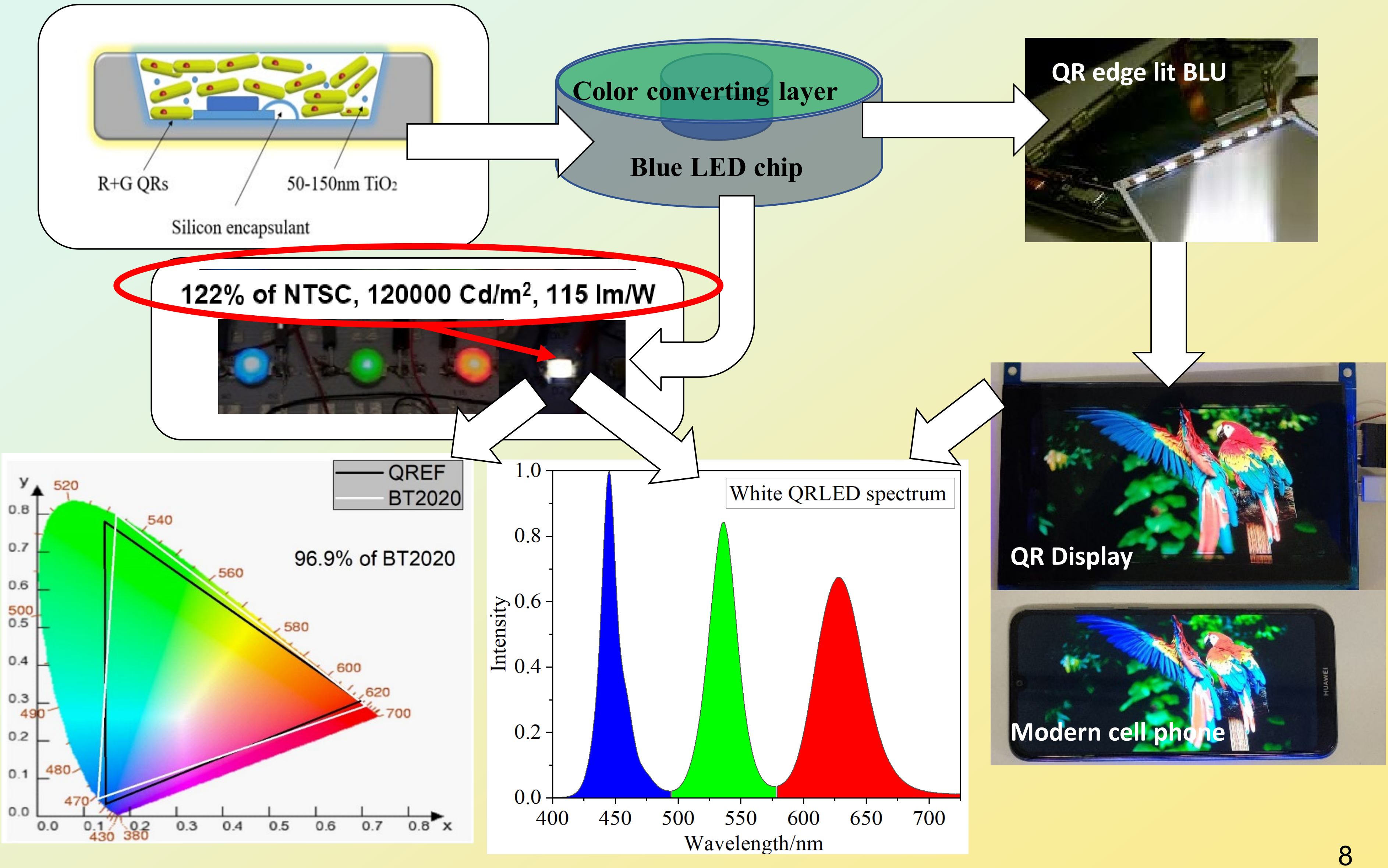


Our QR material

- ✓ possesses unique thermal stability of luminescence
- ✓ can emit in any range of visible spectrum with a narrow bandwidth
- ✓ has improve light extraction efficiency!

Direct on-chip application (QRLED)

Outstanding color gamut and luminous efficiency



Comparison with reported wide color gamut WLED

Green emitting material	Red emitting material	Color gamut (% NTSC)	Luminous efficacy (lm W^{-1})	I_{150} [a)] (%)	CCT (K)	Refs.
Phosphors						
$RbLi(Li_3SiO_4)_2:Eu^{2+}$	$K_2SiF_6:Mn^{4+}$	107	97.28	103	6221	1
$CsPbBr_3$ QDs	$Na_2WO_2F_4:Mn^{4+}$	107.1	–	2	12 123	2
$Ba_{0.75}Al_{11}O_{17.25}:Mn^{2+}$	$K_2SiF_6:Mn^{4+}$	107.3	–	32	6645	3
$MgAl_2O_4:Mn^{2+}$	$K_2SiF_6:Mn^{4+}$	116	56	105	10 342	4
b-Sialon:Eu^{2+}	$K_2SiF_6:Mn^{4+}$	96	136	86	11770	5
g-AlON:Mn^{2+}	$K_2SiF_6:Mn^{4+}$	102	38	–	10611	6
$RbNa(Li_3SiO_4)_2:Eu^{2+}$	$K_2SiF_6:Mn^{4+}$	113	111	102	5196	7
$Cs_3Mn_{0.96}Zn_{0.04}Br_5$	$K_2SiF_6:Mn^{4+}$	101	107.76	87	7732	8
$Sr_2MgAl_{22}O_{36}:Mn^{2+}$	$K_2SiF_6:Mn^{4+}$	127	70.58	86	–	9
						10
Quantum Dots						
$CsPbBr_3$ QDs	$K_2SiF_6:Mn^{4+}$	124	62	–	–	11
$CsPbBr_3$ QDs@glass	$Cs_2SiF_6:Mn^{4+}$	125	–	5	–	12
$CsPbBr_3$ QDs@SDDA	$K_2SiF_6:Mn^{4+}$	102	–	<60[b)]	–	13
$CsPbBr_3$ QDs	$CsPb(I_{0.6}Br_{0.4})_3$ QDs	113	30	<40[b)]	–	14
$CsPbBr_3$(QDs)@ α-ZrP	$K_2SiF_6:Mn^{4+}$	125	–	<20[b)]	–	15
$CsPbBr_3$(QDs)/SiO_2	–	126.8	58.9	<40[b)]	5829	16
CdSe// ZnS/CdSZnS QDs	CdSe/CdS/ZnS/CdSZnS QDs	100	41	–	10000	17
CdSe/ZnS QDs	CdSe/ZnS QDs	122	–	–	2763	18
CdSe/CdZnS QDs	CdSe/CdZnS QDs	116	–	–	5410	19
Quantum Rods						
CdSe@CdZnS QRs	**CdSe@CdZnS QRs**	**122**	**115**	**106**	**8909**	**This Work**

a) Intensity at 150 °C relatively to r.t. emission

[i] Zhao, M. et al. Next-generation narrow-band green-emitting $RbLi(Li_3SiO_4)_2$:Eu_2 phosphor for backlight display application. Adv Mater 30, 1802489 (2018).
[ii] Hu, T. et al. A highly-distorted octahedron with a C2v group symmetry inducing an ultra-intense zero phonon line in Mn 4 -activated oxyfluoride $Na_2WO_2F_4$. Journal of Materials Chemistry C 5, 10524-10532 (2017).
[iii] Hu, J. et al. Non-stoichiometric defect-controlled reduction toward mixed-valence Mn-doped hexaaluminates and their optical applications. Journal of Materials Chemistry C 7, 5716-5723 (2019).
[iv] Song, E. H. et al. A thermally stable narrow-band green-emitting phosphor $MgAl_2O_4$:Mn_2 for wide color gamut backlight display application. Journal of Materials Chemistry C 7, 8192-8198 (2019).
[v] Li, S. et al. Achieving high quantum efficiency narrow-band β-sialon: Eu_2 phosphors for high-brightness LCD backlights by reducing the Eu3 luminescence killer. Chemistry of Materials 30, 494-505 (2018).
[vi] Yoshimura, K. et al. Achieving superwide-color-gamut display by using narrow-band green-emitting γ-AlON: Mn, Mg phosphor. Japanese Journal of Applied Physics 56, 041701 (2017).
[vii] Liao, H. et al. Polyhedron Transformation toward Stable Narrow-Band Green Phosphors for Wide-Color-Gamut Liquid Crystal Display. Advanced Functional Materials 29, 1901988 (2019).
[viii] Su, B., Molokeev, M. S. & Xia, Z. Mn 2 -Based narrow-band green-emitting Cs_3 $MnBr_5$ phosphor and the performance optimization by Zn 2 alloying. Journal of Materials Chemistry C 7, 11220-11226 (2019).
[ix] Zhu, Y., Liang, Y., Liu, S., Li, H. & Chen, J. Narrow-Band Green-Emitting $Sr_2MgAl_{22}O_{36}$: Mn_2 Phosphors with Superior Thermal Stability and Wide Color Gamut for Backlighting Display Applications. Advanced Optical Materials 7, 1801419 (2019).
[x] Dave, K. et al. Improvement in quantum yield by suppression of trions in room temperature synthesized CsPbBr 3 perovskite quantum dots for backlight displays. Nanoscale 12, 3820-3826 (2020).
[xi] Pang, X. et al. Precipitating $CsPbBr_3$ quantum dots in boro-germanate glass with a dense structure and inert environment toward highly stable and efficient narrow-band green emitters for wide-color-gamut liquid crystal displays. Journal of Materials Chemistry C 7, 13139-13148 (2019).
[xii] Zhang, X. et al. Robust and stable narrow-band green emitter: an option for advanced wide-color-gamut backlight display. Chemistry of Materials 28, 8493-8497 (2016).
[xiii] Wang, H. et al. Mesoporous silica particles integrated with all-inorganic $CsPbBr_3$ perovskite quantum-dot nanocomposites (MP-PQDs) with high stability and wide color gamut used for backlight display. Angewandte Chemie International Edition 55, 7924-7929 (2016).
[xiv] Li, Y. et al. Stabilizing CsPbBr3 perovskite quantum dots on zirconium phosphate nanosheets through an ion exchange/surface adsorption strategy. Chem. Eng. J. 381, 122735 (2020).
[xv] Cao, P., Yang, B., Zheng, F., Wang, L. & Zou, J. High stability of silica-wrapped $CsPbBr_3$ perovskite quantum dots for light emitting application. Ceram. Int. 46, 3882-3888 (2020).
[xvi] Jang, E. et al. White-light-emitting diodes with quantum dot color converters for display backlights. Adv Mater 22, 3076-3080 (2010).
[xvii] Altintas, Y., Genc, S., Talpur, M. Y. & Mutlugun, E. CdSe/ZnS quantum dot films for high performance flexible lighting and display applications. Nanotechnology 27, 295604 (2016).
[xviii] Jang, J. et al. Exceptionally stable quantum dot/siloxane hybrid encapsulation material for white light-emitting diodes with a wide color gamut. Nanoscale 11, 14887-14895 (2019).