Invited - Quantum Dot Color Conversion for OLED and microLED Displays

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Abstract

Quantum dot color conversion (QDCC) can enable OLED-based displays with higher brightness and wider color gamut, and microLEDs with higher efficiencies and manufacturing scalability. Key to employing QDCC is the development of quantum dot (QD) materials with enhanced blue absorption, high quantum yield and narrow, tunable emission. Nanosys has developed new heavy metal-free QDs that meet all these requirements and enable the fabrication of patternable QDCC films with high (>38%) photon conversion efficiency and gamut coverage.

Author Keywords

Quantum dots; color conversion; QD-OLED; microLED; LCD; QD-photoresist; QD inkjet printing

1. Introduction

Quantum dot color conversion (QDCC) is the next step in the evolution of QD-based displays. QDCC replaces traditional pigment-based color filters with subpixels containing red or green QDs. In the color 'conversion' approach, white light is generated by absorbing blue light and reemitting red or green, which leads to higher efficiencies than the traditional color 'filtering' approach. Since QDCC can be applied to any type of display with a blue light source, the potential impact extends to a wide variety of applications such as televisions, monitors, mobile, AR/VR and digital signage.

Applying QDCC to blue OLEDs or microLEDs combines the deeper black levels achieved by those technologies with the higher brightness and wider color gamut (>90% BT.2020) that can be achieved through QDs.[1,2] Added benefits of applying QDCC to OLEDs and microLEDs include potentially lower implementation costs and simpler manufacturing processes.[3]

In order to achieve a wide color gamut, a key requirement is eliminating the emission overlap between the blue, green and red channels. While the importance of narrow emission linewidths for QDs is well understood, the significance of blue absorption has received relatively less attention.[3] The impact of blue light leakage on gamut coverage can be seen in Figure 1. As the blue leakage in the red and green channels increases from 0% to 1%, the gamut shrinks from 95.3% to 85.8% of BT.2020. The blue/green, blue/red and green/red emission overlaps can be minimized by applying additional color filters on top of the QDCC layer, but, this approach is inefficient because color filter materials are not fully transmissive in their targeted color. It is much more desirable to have high blue absorption and narrow green/red emission in the QDCC layer itself. Thus, the development of QDs with enhanced blue absorption is vital for advancing QDCC technology.

A further advantage from having highly blue-absorbing QDs is the flexibility this brings to the design of printable inks and formulations. A variety of manufacturing technologies are currently being explored for QDCC fabrication. Additive methods such as inkjet printing[5] are attractive due to lower material usage, while photolithography[6] and transfer printing[7] can leverage installed equipment in fabs around the world. In all cases, the deposited and patterned QDCC film must be very thin (5-10 µm). The printable inks or formulations used for fabricating these films must, therefore, rely on very high QD loadings to achieve high blue absorption. This presents a balancing act, since high QD loadings can lead to higher ink viscosity, which can make printing or patterning small features more difficult.

Herein, we present results from a new heavy metal-free green material that has been specifically developed for enhanced blue

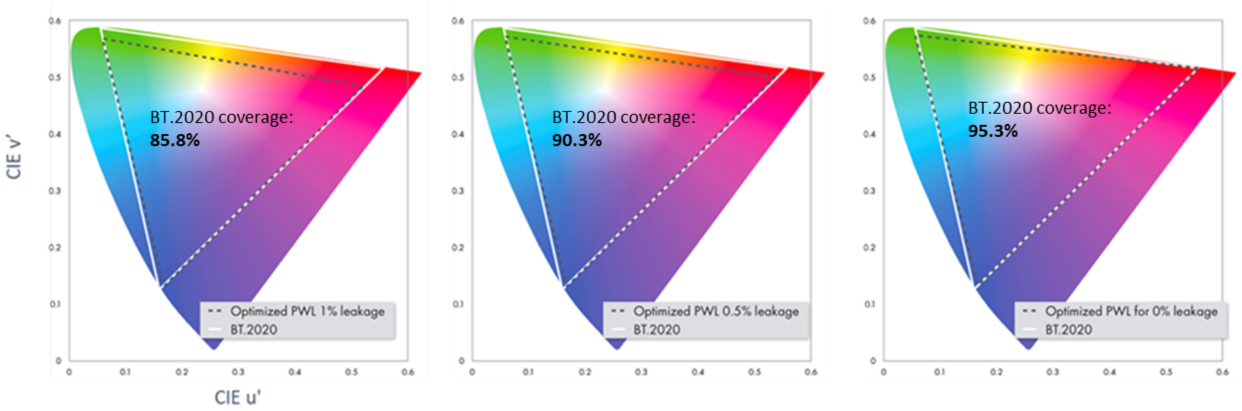


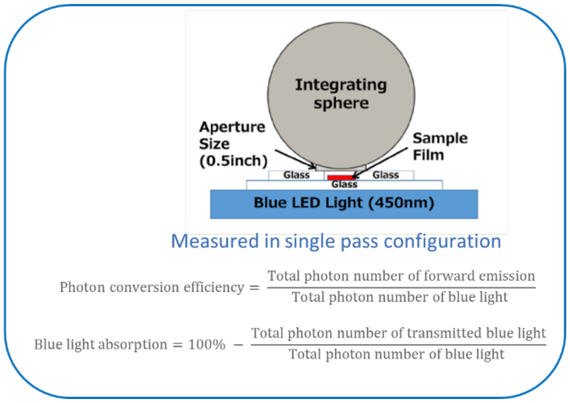
Figure 1. Impact of blue leakage in the green and red channels on the gamut coverage. As blue leakage increases from 0% to 0.5% and 1%, the gamut coverage decreases from 95.3% to 90.3% and 85.8%

absorption. The higher blue absorption, narrow emission, and wavelength tunability of this material enable the fabrication of QDCC displays with much wider gamut coverage than can be achieved with current Cd-free QDs. Careful design of the QD and ligand structure enables quantum yields (QY) higher than 90%, which translates into photon conversion efficiencies (PCE) of >38%. Furthermore, the high blue absorption efficiency of this material lends greater flexibility in terms of ink and formulation design, which may enable deposition and patterning in a wider variety of form factors.

2. Ink preparation and film characterization:

To study the effect of blue absorption on gamut coverage, we made films with three different types of heavy metal free QDs – InP-green, InP-red and a new composition green QD. First, the ligands on as-synthesized QDs were exchanged with hydrophilic ligands that enable good dispersion of the QDs in UV-curable monomers. The QDs were then mixed into an ink formulation containing monomer(s), scattering media and a photoinitiator. Typical QD loadings in the ink are 25-30% w/w, but can be as low as 10% for the new composition green QDs.

The inks thus prepared were spin-coated onto glass substrates at different spin-speeds, then cured by UV irradiation. Optionally, the films were further cured by baking on a 180°C hotplate in a N_2 environment. The fully cured films were then encapsulated using a glass slide and an optically transparent adhesive.



$$\text{Photon conversion efficiency} = \frac{\text{Total photon number of forward emission}}{\text{Total photon number of blue light}}$$

$$\text{Blue light absorption} = 100\% - \frac{\text{Total photon number of transmitted blue light}}{\text{Total photon number of blue light}}$$

Figure 2. Geometry of QDCC film measurement, and definitions of blue absorption and photon conversion efficiency.

The films were then measured using a custom-built optical measurement setup, as shown in Figure 2. The films were placed on a blue light (~450 nm) emission source, and the resulting emission spectra were captured in a one-pass geometry using an integrating sphere connected to a spectrophotometer. The blue absorption and photon conversion efficiency (PCE) were measured using the formulae in Figure 2.

Figure 3 shows absorption spectra for the three QD materials in this study, as well as the blue absorption achieved in films of different thicknesses under the same formulation conditions. The absorption curve for InP-green QDs features a valley around 450 nm. Consequently, films containing InP green QDs have a lower blue absorption at a given thickness than films with InP red QDs. The new green QD material has been specifically designed for enhanced blue absorption, and can achieve much higher absorption at a given thickness than either of the InP-based QDs. Alternatively, much lower loadings of the new green QDs can be used in inks to reach a desired blue absorption. This flexibility is particularly attractive for devices such as microLEDs, where the requirement for well-defined, high resolution structures presents unique challenges for ink design.

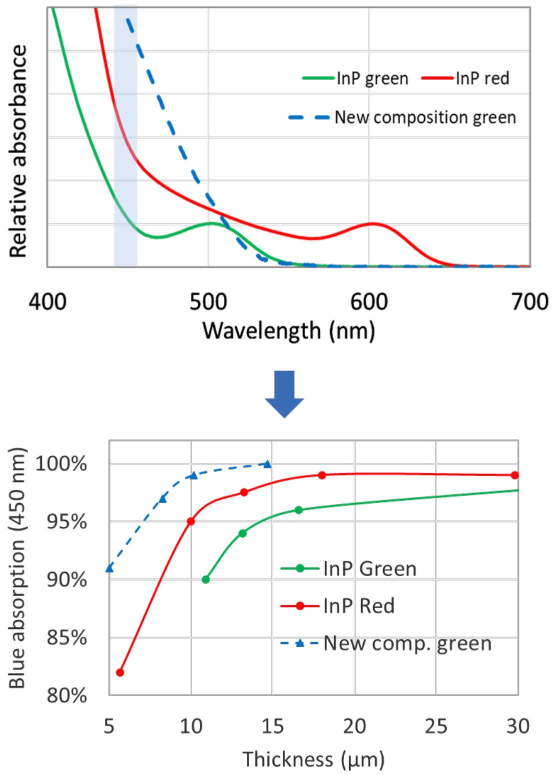


Figure 3. Absorption spectra for InP-green, InP-red and new composition green QDs in solution (*top*), and films of different thicknesses (*bottom*)

Table 1 shows typical optical emission properties for 10 µm thick films made with the three QD types. Through careful design of the QD structure, capping ligands and ink formulation, we can achieve photon conversion efficiencies (PCE) of >38% for fully cured and thermally processed films containing the new composition green QDs. The new QDs also offer narrower emission (full width at half maximum, or FWHM), and greater wavelength tunability in a regime that is relevant to the BT.2020 color gamut.

Table 1. Typical properties of 10µm thick QDCC films

QD type	Optical properties of 10 µm thick films			
	Blue absorption	**PCE**	**Wavelength**	**FWHM**
InP-green	<90%	>35%	535-545 nm	37 nm
InP-red	95%	>38%	635-640 nm	37 nm
New comp. green	98%	>38%	525-540 nm	30 nm

Examples of emission spectra for the three QD types can be seen in Figure 4. Since InP green is a poorer absorber of blue light, films made with InP green QDs show substantial leakage at 450 nm (green curve). Films containing InP-red and the new composition green QDs absorb blue light much more efficiently, and therefore show very little leakage at 450 nm (red and dashed-blue curves). The new composition green can also achieve narrower and brighter emission at lower wavelengths, compared to InP green.

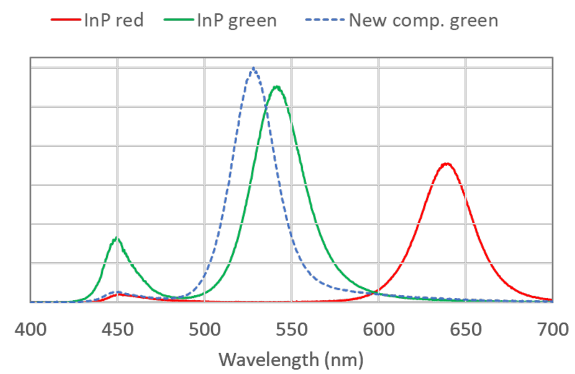


Figure 4. Emission spectra of ~10 µm thick QDCC films made with InP red, InP green and a new composition green QD .

Table 2 shows the gamut coverage that can be achieved using the emission spectra in Figure 4. When InP-green films are paired with InP-red, the BT.2020 gamut coverage is relatively low (67%), mainly due to the blue leakage through the green channel and the non-optimized InP green wavelength. Pairing the new composition green QDs with InP red enables a significant expansion in gamut coverage (to 78%) due to a more favorable green wavelength and lower blue leakage in both the green and red channels.

Table 2. BT.2020 gamut coverage for the films from Figure 4, with InP-red paired with either InP or new composition green.

	Wavelengths	**Blue OD in G/R channels**	**BT.2020 coverage**	
			QD layer only	**With additional CF**
All-InP QDCC films	450/542/ 640	1.0/1.6	67%	85%
InP-R + new comp. green	450/528/ 640	1.6/1.6	78%	93%
With optimized wavelengths	462/524/ 646	>2 / >2		97%

In both cases, the gamut coverage can be improved further (to 85% or 93%) by applying additional color filters to eliminate the small amount of blue leakage, as well as the green/red tails. Table 2 also shows an ideal but realistic case, where up to 97% BT.2020 coverage can be achieved by optimizing all three wavelengths, including blue used for excitation, and eliminating leakage in all channels.

3. Impact of Your Research

The development of heavy metal free QDs with enhanced blue absorption, tunable wavelength and efficient green emission has huge implications for the design of QDCC-based devices, as well as the printable inks and formulations used for fabricating the QDCC layer. High PCE in the green layer is critical for achieving high device brightness. High blue absorption in the green channel can reduce the blue filtering requirements, leading to further improvements in device brightness and a greater variety of device form factors. Wavelength tunability, together with high blue absorption, will lead to wider color gamut coverage.

The combination of these features with the deeper black levels and wide viewing angles of OLED and microLED displays will usher in a new generation of bright, efficient, high-contrast, wide color gamut displays.

4. References

1. Luo, Z., Yurek, J. "Quantum dots: The technology platform for all future displays", Proc. SPIE 10940, Light-Emitting Devices, Materials, and Applications, 1094010 (1 March 2019)
2. DSCC/OLED-A Quarterly OLED Material Report
3. B. Boerger, N. van Wyck, 2017. "Rapid Assembly of Quantum Dots for MicroLED Micro-Displays." www.ledinside.com/knowledge/2017/11/rapid_assembly_of_quantum_dots_for_microled_micro_displays.
4. Osinski, J. and Palomaki, P. (2019), 4-5: Quantum Dot Design Criteria for Color Conversion in MicroLED Displays. SID Symposium Digest of Technical Papers, 50: 34-37
5. Aya Ishizuka, Eiji Otsuki, Takeo Kizaki, Takayuki Miki, Sunao Yoshihara, Ikuro Kiyoto, Ernest Lee, Ravi Tangirala, Charlie Hotz, Heejae Kim, Meeting 5-1: Invited Paper, Cadmium-free Quantum Dot Inkjet Inks for Color Conversion Devices, IDW'18, Dec 2018, Japan.
6. E. Lee, S. Kan, C. Hotz, J. Yurek, Z. Luo, J. Yamanaga, A. Carpenter. 2017. "Ambient Processing of Quantum Dot Photoresist for Emissive Displays." SID Symposium Digest of Technical Papers. Volume 44, Issue 1, pages 984-987.
7. T.-H. Kim, K. -S. Cho, E. K. Lee, S. J. Lee, J. Chae, J. W Kim, D. H. Kim, et al., "Full-colour quantum dot displays fabricated by transfer printing", Nat. Photon. 5, p. 176-182, 2011