High Optical Density, High Efficiency Quantum Dot Photoresist for MicroLED Applications

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Abstract

Quantum dot color converters (QDCCs) are a leading technology for enhancing the gamut and efficiency of displays, notably in QD-OLED TVs and monitors. However, cadmium-free QDs require thick layers for effective color conversion. Our novel inorganic photoresist densely packs InP QDs, achieving over 60% PLQY and optical density of 1 at less than 10 µm thickness, advancing QDCCs for high-performance microLED displays. Patterning of 5 µm pixels with high fidelity is also demonstrated.

Keywords

quantum dot; microLED; quantum dot color converters; photoresist

1. Objective and Background

Quantum dot color converters (QDCCs) have emerged as a promising technology for enhancing the color gamut and efficiency of display applications, notably in quantum dot organic light emitting diode (QD-OLED) TVs and monitors. Moreover, they offer a potential solution for realizing full-color microLED displays, which are highly sought-after for their superior brightness, contrast, and energy efficiency, particularly in demanding applications like augmented reality (AR). However, the implementation of QDCCs in high-resolution AR displays faces a significant hurdle: the inherently low absorption cross-section of non-cadmium-containing quantum dots (QDs), such as InP. This limitation necessitates thick QDCC layers to achieve sufficient color conversion, which can lead to lower wall plug efficiencies and compromise the optical performance of the display. [1]

In this work, we demonstrate a novel approach to address this challenge by densely packing InP QDs while preserving their color conversion efficiency.

In contrast to traditional QD photoresists, direct optical lithography of functional inorganic nanomaterials (DOLFIN) enables direct photopatterning of optically dense QD films. [2]

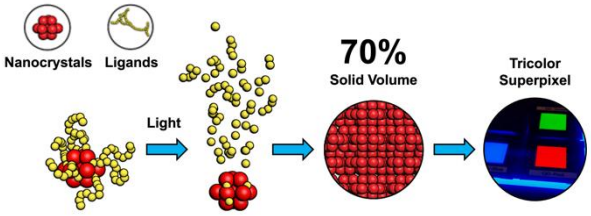

Figure 1. In the DOLFIN process, photosensitive ligands are used to create an inorganic photoresist. In this way a fully dense nanoparticle layer at up to 70% solid volume is formed.

In this process, a substrate is coated with an ink made of nanoparticles that are functionalized with a photosensitive ligand. As shown in Figures 1-2, the ink is then selectively modified via exposure to a patterned light source and the substrate is treated with a developer solution, which removes either material type, by which multilevel patterns may be formed.

We demonstrate red and green-emitting InP QDCCs with a photoluminescent quantum yield (PLQY) exceeding 60% and an optical density of 1 at a thickness of less than 8 µm. This achievement represents a significant advancement towards realizing high-performance, thin-film QDCCs for microLED displays.

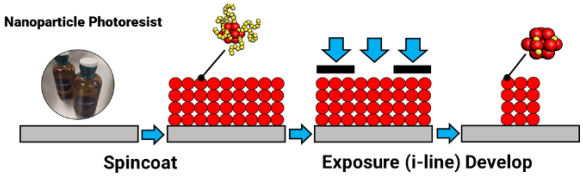

Figure 2. Method of patterning for our QD inorganic photoresist. The photoresist is coated onto a substrate and exposed to 365 nm light. This exposure alters the photoresist's solubility in a developer solvent, enabling the patterning of quantum dots into a dense layer.

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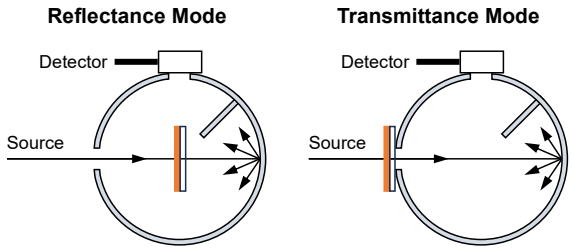

Figure 3. Schematic of integrating sphere setup: (a) Reflectance mode; (b) Transmittance mode.

2. Methods and Results

Optical Properties: The photoluminescent quantum yield (PLQY), photon conversion efficiency (PCE), and optical density (OD) of our dense nanoparticle films have been measured under excitation with blue light at 455 nm wavelength. Films of InP QDCCs from Nanosys Shoei were blade coated onto glass substrates before and after formulating into our photoresist. The PLQY was measured in reflectance mode (Figure 3) by placing the coated glass slide inside an integrating sphere, exciting with blue light from a 455 nm light emitting diode, and measuring the percentage of absorbed blue photons converted into red or green photons. Spectra were captured with an Ocean Insight OCEAN-HDX-UV-VIS spectrometer.

While the solution PLQY of InP QDCC can be typically higher than 90%,[4] after coating into dense films the quantum yield drops to around 50%. This drop is typically attributed to Forster resonant energy transfer (FRET) between proximate quantum dots leading to an increase in nonradiative recombination rates. This mechanism is commonly used as a feature in biomedical assays, [3] however in display applications, the transfer of electrons between neighboring QDs leads to a decrease in efficiency. Through formulation improvements, we have been able to improve the PLQY of dense nanoparticle films to >60% for red InP films and >70% for green InP films as shown in Table 1.

To measure the optical density, coated films of varying thickness were placed on the outside of the sphere as shown in Figure 3(b). An uncoated glass slide was used to measure the reference incident blue light intensity and the coated slides were used to measure the extinction of the blue light as a function of film thickness. The optical density is plotted in Figure 4.

Table 1. Photoluminescent quantum yield (PLQY) of dense quantum dot films before and after formulation

	Red (635-640 nm)	**Green (535-545 nm)**
As received QD film	51%	54%
Formulated QD film	62%	73%

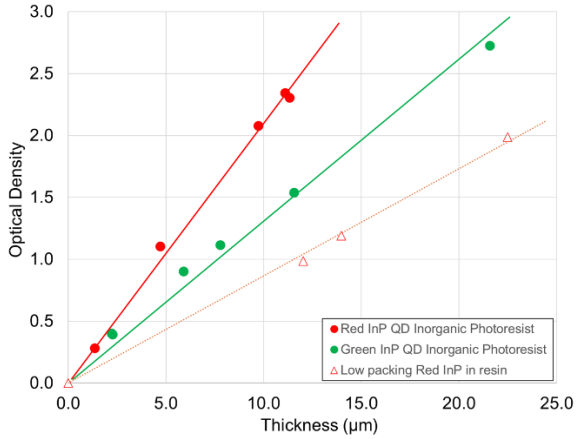

Figure 4. Optical density vs thickness of red and green InP QD inorganic photoresist as compared to traditional QD Photoresist made from suspending quantum dots in resin.

The red quantum dot films achieve an OD of 1 in under 5 μm thickness and OD of 2 in under 10 μm of thickness. This is less than half of the thickness required for the same blue light extinction in a conventional quantum dot photoresist material. As expected, due to the weaker absorption strength of green quantum dots compared to red quantum dots, the green quantum dot films show a shallower slope of optical density with thickness, achieving an OD of 2 in just under 16 μm film thickness.

Looking at the effect of the PLQY and the optical density together, we can plot the PCE versus thickness, which plots the number of converted photons per incident blue photon, as seen in Figure 5 for both reflectance and transmittance configurations. The PCE is roughly half in transmittance mode because the photons that emit in the backward direction, outside of the optical sphere, are not measured. For both red and green films, the maximum PCE is met

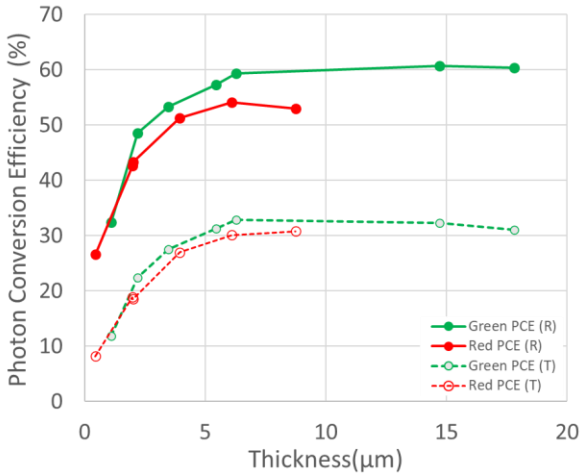

Figure 5. PCE of red and green InP inorganic photoresist in reflectance (solid lines) and transmittance (dashed lines) configurations.

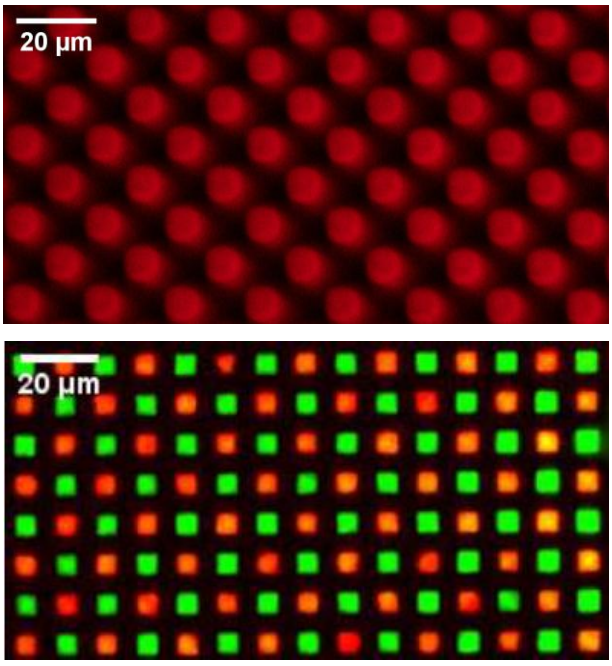

Figure 6. Fluorescence microscope images of 5 µm pixels of red and green QD inorganic photoresist patterned with 5 µm spacing on a silicon substrate. Top: after first layer of red QDs is patterned into alternating wells. Bottom: final pattern after green QD layer is coated onto the red QD pattern, exposed, and developed.

at around 5 µm film thickness. Beyond this film thickness, which corresponds to about 90% blue light absorption, additional thickness results in more self-absorption of the converted photons than further blue light conversion. This results in flattening the PCE curve, and even a slight decrease in PCE for very thick films. As a result, the maximum PCE is around 55% for red and 60% for green films.

Patterning: While achieving high optical density and PLQY is crucial for efficient color conversion, practical implementation in microLED displays also requires precise spatial patterning of QD films at the microscale. To demonstrate the compatibility of our QD photoresist with high-resolution microfabrication, we patterned red and green QD layers into a checkerboard structure, simulating the pixel arrangement needed for full-color microLED displays.

To validate the patterning properties of the red and green InP QD inorganic photoresist measured in figures 4 and 5, a checkerboard array was patterned onto a silicon substrate. The silicon substrate was first patterned with an array of 5 µm x 5 µm wells with a depth of approximately 2 µm and 5 µm spacing between wells. This structured surface was fabricated to simulate the optical isolation structure that would be needed in a microLED substrate to block excitation of the red pixels by adjacent green pixels. Next, a red QD inorganic photoresist layer was coated and patterned with a checkerboard structure such that every other well contains red QD film (Figure 6 top).

After patterning the red layer, the green layer is coated, exposed, and developed into a checkerboard red and green pattern (Figure 6 bottom). Both red and green InP QD inorganic resist films retain their patterns and luminescence after development, as demonstrated by the fluorescence microscope images taken under 460 nm light excitation shown in Figure 6.

3. Impact

The InP inorganic QD photoresist demonstrated in this study addresses a key requirement for facile fabrication of full color microLED displays by use of QD downconverters to address the cost and yield issues associated with fabricating microLED displays from separate red, green, and blue LED wafers.[5] The optical performance and patterning resolution meeting industry requirements is demonstrated down to 5 um pixel sizes, enabling QD downconverters to be utilized for applications with >1,000 ppi requirements such as AR/VR.

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5. References

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