Inkjet-printed Quantum-dots Photopolymers for Full-color Micro-LED Displays

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Abstract: Quantum dots (QDs)-based color-conversion micro-LED displays require simple and cost-effective technology to remove blue excitation light. We demonstrate a simple process to remove the residual blue light from the color conversion layer by using QDs inkjet printing. It is found that the printed QDs films with the thickness of a few μm can effectively remove the blue excitation light as well as working as the color-conversion layer.

1. Introduction

Since light-emitting diodes (LEDs) appeared, it has been widely used in many fields, such as display, lighting, medical device, and so on [1]. To obtain high resolution and high contrast, the pixel size of LEDs needs to further decrease. The traditional size of LED chips is in the range of millimeters and these LEDs have been used to apply to large screen displays. However, the large size of LED chips cannot satisfy the requirement of high-resolution applications such as mobile phones, smart watches, AR/VR, and wearable devices [2]. In micro-LEDs technology, the pixel size is less than 100 micrometers, leading to a high resolution. Therefore, micro-LEDs have been proposed for use in optoelectronic devices requiring a high resolution [3]. Further, their high efficiency and low energy consumption make micro-LEDs the most promising platform for the next generation displays [4].

Despite of their superior features, there are still many technical challenges in the way of commercialization, like epitaxy and chip processing, mass transfer, and full-color technology. The realization of full-color is one of the toughest problems which should be solved. For full-color displays based on micro-LEDs, two major approaches have been developed: red-green-blue (RGB) micro-LEDs displays and color-conversion micro-LED displays [5].

The RGB method uses red, green and blue sub-pixel of micro-LEDs to realize full-color display. However, this method still suffers from several challenges. For example, in mass transfer technology, the traditional pick and place method is no longer suitable for micro-LEDs due to the need for precisely transferring millions of chips. Depending on different forces, many different methods were proposed, like laser, gravity, electrostatic, van der Waals and roll stamp [6]. However, placement accuracy is not good enough for display applications [7].

In the color conversion method, blue micro-LEDs and UV micro-LEDs are used to generate green and red colors with a color-converting layer. Common color-conversion materials are organic phosphors and quantum dots (QDs). QDs have excellent optical and physical properties such as high quantum yield, tunable emission wavelength, high absorption cross-section compared to organic phosphors [8]. They have been considered as the most promising color-conversion material for color-conversion based micro-LED displays. Many fabrication methods of QDs layers on the blue micro-LEDs have been developed such as spin coating, transfer printing, mist coating, inkjet printing and aerosol jet printing [9-11]. Among them, inkjet printing could be the most effective technique due to high accuracy, mask-free, material saving, simple and rapid fabrication, and cost effectiveness [12].

Effective removal of the residual excitation light (UV or blue light) and achieving high color purity are one of technical challenges in color-conversion micro-LED displays. At first, a distributed Bragg reflector (DBR) film on the top of device was used to remove the blue or UV-light [13]. However, it requires the addition of more processes in fabrication, leading to higher cost. Cost-effective and simpler techniques are required to be developed. One approach is to absorb the excitation light from LEDs by the QD themselves [14].

Here we report the preliminary results for effective removal of residual blue light from LEDs by QD layers fabricated by using inkjet printing, which can lead to a much simpler fabrication process. It is found that the optimized film thickness could significantly suppress the residual blue light by QDs.

2. Theoretical expectation

The required QDs film thickness for absorbing the blue excitation light can be estimated by using the optical characteristics of QD absorption. The relationship of the absorbance A and the transmittance T is defined as:

$$T = 10^{-A} \qquad (1)$$

The intrinsic absorption coefficient μ_i can describe the ability of absorb light and be defined as: [15-17]

$$\mu_i = \frac{Aln10}{fL} \quad (2)$$

where A and L are the absorbance and the thickness of the QDs film, and f is the volume fraction of the QDs solution. The intrinsic absorption coefficient of core/shell QDs in the frame of the Maxwell-Garnett effective medium theory, can be expressed by [18-20].

$$\mu_i = \frac{2\pi}{\lambda n_S} Im(3\epsilon_c\beta) \text{ with } \beta = \frac{\epsilon_{sh}\epsilon_a - \epsilon_s\epsilon_b}{\epsilon_{sh}\epsilon_a + 2\epsilon_s\epsilon_b} \quad (3)$$

$$\epsilon_a = \epsilon_c\left(3 - 2\frac{V_{sh}}{V_{QD}}\right) + 2\epsilon_{sh}\frac{V_{sh}}{V_{QD}},$$

$$\epsilon_b = \epsilon_c\frac{V_{sh}}{V_{QD}} + \epsilon_{sh}\left(3 - \frac{V_{sh}}{V_{QD}}\right) \quad (4)$$

Where λ, n_s, ϵ_c, ϵ_{sh}, ϵ_s, V_{sh}, V_{QD} are the incident wavelength, the refractive index of solution, the dielectric function of the QDs core, the dielectric function of the shell, the dielectric function of solution, the shell volume of the core/shell QDs and the total volume of the core/shell QDs, respectively. By using Eq. (1 – 4), the transmittance of blue light passing through CdSe/ZnS QDs film are calculated with different thickness. The calculated results are displayed in Figure 1. The calculated intrinsic absorption coefficient μ_i is 7.62 × 10^4 cm^{-1}. As we expected, the transmittance decreased with increasing film thickness and it can be reduced to 0.1% with about 9.5 μm thickness. With this expectation, the QDs films with different thickness are fabricated by inkjet printing, and the blue light is measured.

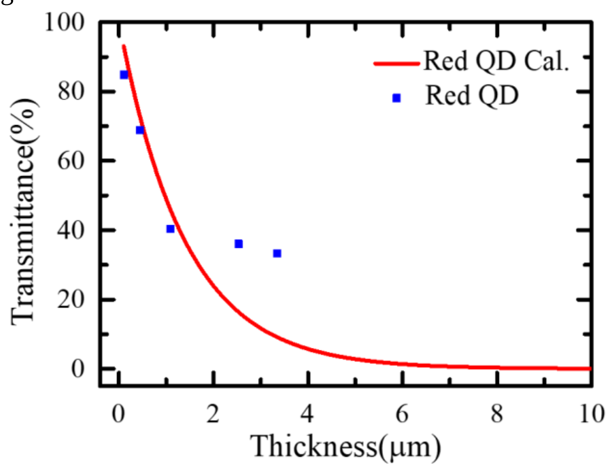

Figure 1. Transmittance (solid red line) of residual blue light with the wavelength of 450 nm. The blue squares represent the experimental values.

3. Results and discussion

Commercial core/shell CdSe/ZnS QDs in MMA are used in this work. The absorption and emission spectra of QDs in toluene are displayed in Figure 2. The exciton peak in the absorption spectrum and emission peak are located at 621 nm and 630 nm, respectively. The viscosity of QD-photopolymer solution is adjusted as 1000cps. QDs polymer is printed by using a super inkjet printer (S050, SIJ technology) on glass substrate patterned with 180μm width, 60μm length, 3μm deep banks surrounded by a blocking polymer as seen in Figure 3(a). The designed bank size is selected carefully from typical chip size of micro-LEDs

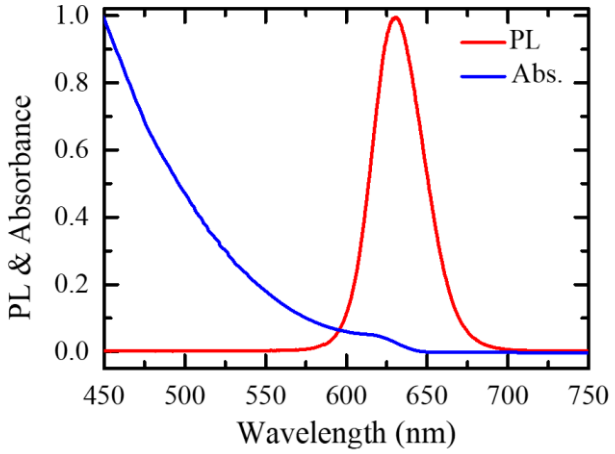

Figure 2. Absorption spectrum of the QDs-polymer and photoluminescence spectrum of the QDs-polymer under the excitation of 405 nm Laser.

The thickness of the printed QDs film is controlled by repeated printing. After printing, the QDs-polymer films were cured using an UV light. Finally, the color conversion layer was made as shown in Figure 3(b).

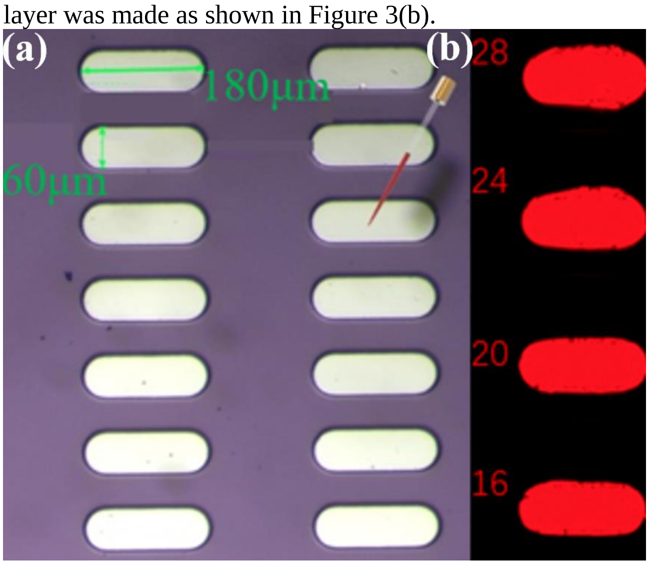

Figure 3. (a) Schematic of inkjet printing of QDs-polymers on a pre-patterned substrate. (b) Different times of printing QDs-polymer films under the fluorescence microscope.

An upright microscope with Xe-lamp is used to investigate the thickness-dependent intensity of the residual blue light. The transmitted light from Xe-lamp passing through the printed QD film in the bank are measured for different QD thickness as seen in Figure 4. Transmittance of the light from Xe-lamp decreases with increasing thickness due to more printing. In general, QD-based color-conversion displays use the wavelength of 450 nm for excitation and blue color. Therefore, transmittance at 450 nm (blue squared) are extracted and are plotted in Figure 1. The film thickness is estimated by using profilometer. The thickness of QD film by one printing is about 110 nm and the transmittance is 84.84% at 450 nm. The measured transmittance agrees very well with the calculated values until the film thickness of about 1 µm. However, beyond 1 um, the measured values are larger than the calculated values. At this point, we do not have any explanation about the bigger experimental values. Further study is in progress. However, our results exhibit that thicker film could remove large amounts of blue excitation light by QDs themselves. One challenging work is fabricating thick film with ≥ 5µm by inkjet printing. For thick film, the high viscosity QD polymer solution (1000 cps) is designed and used, but it is not good enough to fabricate the film with thickness of ≥ 5µm. More printing can fabricate thicker film, but more than 30 printing leads to the high surface roughness and bad thickness uniformity of the printed film.

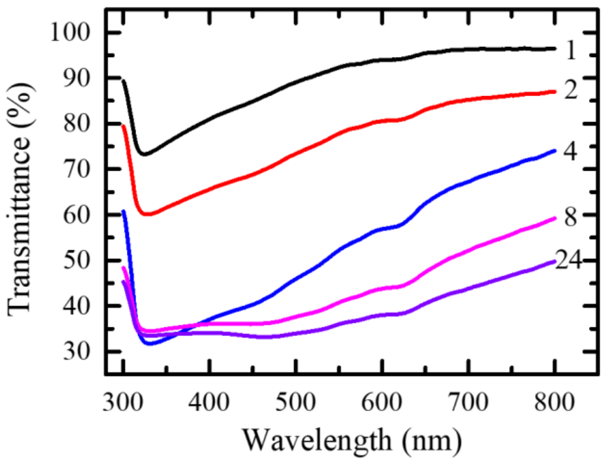

Figure 4. The transmittance spectra of different thickness films and background. The numbers in legend represent the printing times.

4. Conclusion

QD-based color-conversion micro-LEDs by inkjet printing can be the most cost-effective and simplest way to achieve full-color micro-LED displays. Our results show that the blue excitation light can be effectively reduced or removed by absorbing it by the QDs themselves without adding more complex fabrication steps. Thus, our approach can open a cost-effective route to realize full-color micro-LED displays.

5. Acknowledgment

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