# Inkjet Printed Blue-to-Green Color Conversion Layer Formation by OTS Treatment for QD-OLED Fabrication

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## ABSTRACT

*Quantum dot (QD) color conversion layer needs to be few micrometers thickness to successfully block the blue light. We fabricated green QD color conversion layer with diverse thicknesses through inkjet printing by controlling surface wettability by octadecyltrichlorosilane (OTS) treatment.*

## 1 INTRODUCTION

### 1.1 Basic Operating Principle of QD-OLED

The blue light of Quantum Dot-Organic Light Emitting Diodes (QD-OLEDs) comes from the electroluminescence (EL) of the blue Organic Light Emitting Diodes (OLED), and the red and green lights come from the photoluminescence (PL) of the QD color conversion layers, which convert the blue light from the OLED to the green and red light of the QD.

### 1.2 Manufacturing Methods of QD Film

There are two frequently used methods for patterning the QD color conversion layer, conventional photolithography and inkjet printing [1]. Although photolithography has an advantage of its ability to make a small sized pattern, the manufacturing process is complicated, and wastes a large amount of material. However, inkjet-printing has advantages such as its manufacturing simplicity and great material usage efficiency compared to the photolithography.

### 1.3 Surface Wettability for Forming QD Film

To form few micrometers thick QD color conversion layers with inkjet printing, the shape of the printed droplet is important which depends on the wettability of the surface. On a hydrophilic surface, large droplets with low contact angle are usually produced, while on a hydrophobic surface small droplets with high contact angle are produced [2]. With large droplets with low contact angle, printed drops spread over the substrates and severe pile up occurs, making it difficult to form a uniform micrometer thick color conversion layer.

In this paper, by hydrophobic OTS treatment, we formed a uniform QD color conversion layers, besides, by changing the number of printed QD drops, we diversified thicknesses of QD color conversion layers and analyzed its effect on color conversion.

## 2 EXPERIMENT

### 2.1 Fabrication of Top Emitting Blue OLED

We fabricated a hybrid green QD-blue OLED. To fabricate the top emitting blue OLED, a glass substrate was cleaned by sonication in acetone for 40 minutes and in IPA for 40 minutes. The substrate was then treated by UV-ozone treatment for 20 minutes. Then all of the organic and metal layers were deposited by thermal evaporator under a vacuum atmosphere of 3x10-7 Torr. The blue OLED devices consisted of a stacked structure of aluminum (Al) (100 nm) as an anode, Molybdenum trioxide (MoO3) (5 nm) as a hole injection layer, N,N′-bis(naphthalen-1-yl)-N,N′-bis(phenyl)benzidine (NPB) (20 nm) as a hole injection layer, tris(4-carbazoyl-9-ylphenyl)amine (TCTA) (15 nm) as a hole transport layer, N,N’-dicarbazolyl-3,5-benzene (mCP) and 16 wt% bis[2-(4,6-difluorophenyl)pyridinato-C2,N](picolinato)iridium(III) (Firpic) as the host/dopant for the blue emitting layer (30 nm), 2,2′,2"-(1,3,5-benzinetriyl)-tris(1-phenyl-1-H-benzimidazole) (TPBi) (25 nm) as an electron transport layer, lithium fluoride (LiF) (1 nm) as an electron injection, aluminum (Al) (1 nm), silver (Ag) (15 nm) as a cathode electrode, and N,N′-bis(naphthalen-1-yl)-N,N′-bis(phenyl)benzidine (NPB) (60 nm) as the capping layer. An M6100 OLED I-V-L Test System (McScience Co., Korea) was used to measure the EL characteristics of the OLED.

### 2.2 Hydrophobic OTS Treatment

To control the wettability of the bank, a surface treatment was performed. Before the surface treatment, samples were cleaned by sonication in acetone for 15 minutes and in IPA for 30 minutes. The samples were then treated by UV-ozone treatment for 20 minutes. After the cleaning, the samples were put into a solution, which was 4% trichloro(octadecyl)silane diluted in toluene, and slowly stirred for 90 seconds.

### 2.3 Inkjet Printing QD Ink

We used a Dimatix DMP 2800 printer, and DMC-11610 cartridge (Fujifilm Co., Japan) for inkjet printing the QD ink.

## 3 RESULTS

### 3.1 Characteristics according to OTS Treatment

Before the surface treatment, inkjet printed QD drops spread over the substrates and severe pile up occurred as shown in the Fig.1 (b), (c). As a result, it can be seen from the thickness parameter of Fig. 1 (a), that color conversion layer was not uniformly formed in the bank. However, after the 90 seconds of OTS treatment, pile up did not occurred as seen in the Fig.1 (e), (f). Thickness of the color conversion layer increased to approximately 3 μm as seen in the Fig. 1 (d). Thus, with color conversion layer formed after the OTS treatment, QD film more efficiently cuts off blue light from OLED, and converts it to green light of QD as shown in Fig. 1 (g).

### 3.2 Characteristics according to Film Thickness

After the OTS treatment, thickness of QD color conversion layer was controllable by verifying the number of inkjet printed QD drops. We increased the number of QD drops from 12 to 20 and 28 drops. The thicknesses of each QD color conversion layers were approximately 1, 3 and 9 μm.

To investigate the effect of thickness on color conversion efficiency (CCE), we extracted the intensity of blue OLED and green QD from the measured original EL spectra of blue OLED with different thicknesses of green QD color conversion layers as shown in the inset of Fig. 2 (d), (e), and (f). CCE was defined as the ratio between extracted green QD and the intensity of blue OLED without QD. The calculated CCE of the QD color conversion layers with 12, 20, and 28 drops were 6.81%, 8.15% and 7.17%, respectively.

Commission Internationale Ed l'eclairage (CIE) chromaticity is shown in Fig. 2 (g). As the thickness of green QD color conversion layer increases, the coordinates of the spectrum changed from blue OLED's (0,133, 0.307) to (0.173, 0.437), (0.257, 0.599), and (0.265, 0.648).

## 4 DISCUSSION

### 4.1 Analysis of Characteristics according to Film Thickness

Looking at CCE, CCE did not increase continuously as the thickness increase. When the thickness reached certain thickness, it decreased rather. This may due to the interactions of Forster type fluorescence resonance energy transfer (FRET) and increase of self-absorption between printed QDs [3].

However, in terms of color purity, as the thickness of QD color conversion layer increased, it moved from sky blue-green to nearly pure green which improved the color purity of the device.

Even though the decrease of the CCE, considering color purity, OLED with the thickness of 28 drops of green QD color conversion layer is most suitable when expressing green due to its high color purity.

## 5 CONCLUSIONS

In this study, hydrophobic OTS treatment was performed to form micrometer thick QD color conversion layer. The pile up and overflowed QD ink drops which were visible before the OTS treatment, noticeably disappeared after the OTS treatment. This made it possible to control the thickness of QD color conversion layer by changing the number of printed QD drops in a bank. As the number of printed QD drops increased from 12 to 20 and 28, thickness increased from 1 μm to 9 μm. CCE of the device was 6.81%, 8.15% and 7.17%, respectively. The CIE chromaticity coordinates of the spectrum changed from blue OLED's (0,133, 0.307) to (0.173, 0.437), (0.257, 0.599), and (0.265, 0.648), moving from sky blue-green to nearly pure green.

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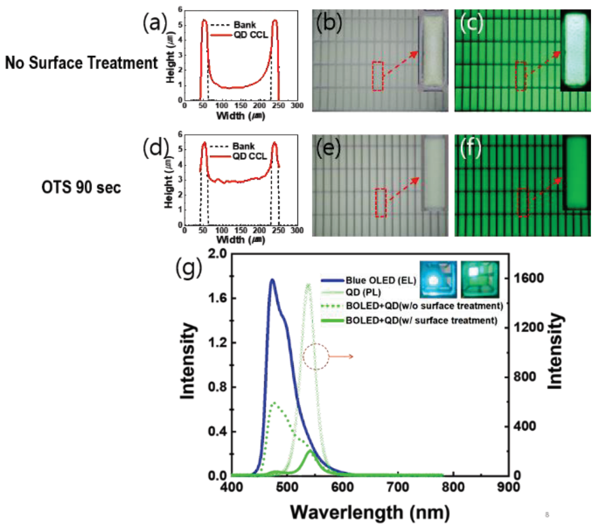


**Fig. 1 Thickness profile and optical microscope images of the printed QD films. QD films formed with 20 drops using a 10 pl nozzle with and without surface treatment. Without surface treatment (a), (b), (c) and 90 secs of OTS**

treatment (d), (e), (f). Here, (b), and (e) are optical microscope images without UV light, whereas (c), and (f) are optical microscope images with UV light. Photoluminescence (PL) spectrum of the green QD, electroluminescence (EL) spectrum of the blue OLED and the blue OLEDs with the inkjet printed green QD color conversion layers with and without surface treatment. Inset: EL images of the blue OLEDs with and without the green QD color conversion layer (g).

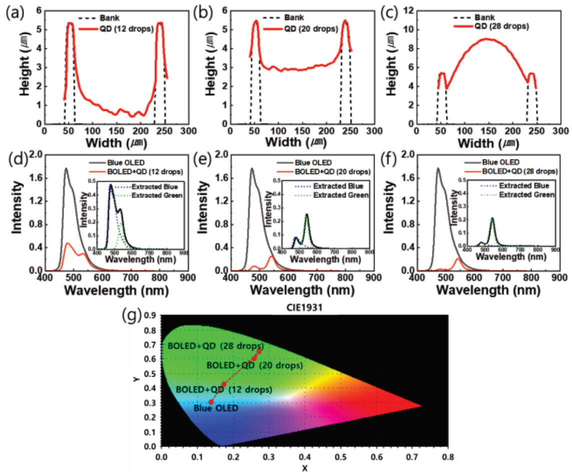


Fig. 2 Thicknesses of the QD color conversion layers with 12 (a), 20 (b) and 28 (c) drops of QDs, EL spectra of the top emitting blue OLEDs with and without the green QD color conversion layers of 12 (d), 20 (e) and 28 (f) drops of QD ink and the color gamut of the corresponding devices (g).The EL intensity was measured at the voltage of 9.5 V and each intensity was adjusted by matching the same current density due to the slight difference in current density of each devices. Also, inset figures of (d), (e), and (f) show the extracted intensity of blue OLED and QD from the original EL spectra of blue OLED with green QD, respectively.