

Development of Functional Polymer Materials Based on Inkjet Printing for Next-Generation OLEDs

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Abstract

Studies on next-generation OLEDs are actively being conducted to achieve high-efficiency and high-resolution displays. In particular, the development of high-efficiency, long-lifetime blue materials and devices, as well as the development of functional polymer materials applied to panels, is necessary. We developed a low-viscosity quantum dot ink capable of high efficiency (PCE >40%) and high color purity (FWHM < 31 nm) by converting the color of blue backlight. Additionally, we developed a thermosetting material with a high refractive index (RI 1.60) for light extraction. Finally, we confirmed the commercial applicability by developing an inkjet polymer material with a low dielectric constant (Dk2.6) for device encapsulation.

Author Keywords

OLED; QD-OLED; Encapsulation; Filler

1. Introduction

The display industry is expanding applications, such as mobile, IT, TV, AR/VR, and flexible displays, based on organic light-emitting diode (OLED) displays. Recently, quantum dot (QD)-OLEDs, which apply the QD technology, have been developed as the next-generation displays. There is a need for developing materials considering mass production, processability, cost, and environmental friendliness.

Conventional OLED displays are manufactured based on vacuum deposition and photolithography processes, which allow for panel production with a high yield. However, these processes also have drawbacks, such as expensive equipment, high material consumption, complex procedures, and the need for masks. Therefore, production costs and efficiency have been recently improved through the use of eco-friendly and highly material-efficient inkjet printing processes.¹

For stable jetting during inkjet printing, controlling the viscosity and surface tension of the ink is crucial. If the viscosity is high, it can make ejection difficult, leading to changes in operating voltage, which can affect the stability and lifespan of the nozzle. Therefore, it is necessary to maintain a viscosity level of 10–30 cps.

Surface tension affects the shape of the drops ejected from the head. If the surface tension is high, a tail may form on the ink drop; if it is low, satellite drops may be generated. Additionally, it is desirable to have a surface tension of 20–40 N/m to ensure the straightness and surface uniformity of the printing surface.

This paper describes the development and performance of high-performance polymer materials that can be applied in the display industry using inkjet printing.

1. Development of low-viscosity, high-efficiency QD ink for monitors and TVs.
2. Development of low-viscosity/low-dielectric thin film encapsulation (TFE) ink.
3. Development of filler for improving the efficiency of OLED devices and for top/bottom junctions.

2. Results & Discussion

2.1 Development of QD ink

Recently, QD color conversion (QDCC) technology has been applied to QD-based displays. The color conversion method uses patterned subpixels of red or green QDs instead of pigment-based color filters to absorb blue light and re-emit red and green light. This provides higher efficiency than the color filtering method.² Moreover, various blue light sources, such as LCD, OLED, and Micro LED, can be used as backlights.³

To manufacture the color conversion layer of QDs, the following properties of the ink are essential. 1) It must have a low viscosity (10–30 cps) suitable for inkjet printing, 2) the dispersion stability of inorganic nanoparticles, such as QDs and light scattering agent (TiO₂), must be ensured, and 3) time and temperature stability must be ensured without viscosity changes. 4) Additionally, it must have the function of protecting the QDs from light, oxygen, and moisture after photopolymerization. We have developed a solvent-free type of high-performance QD ink that is resistant to light, oxygen, and moisture, while still being suitable for inkjet printing.

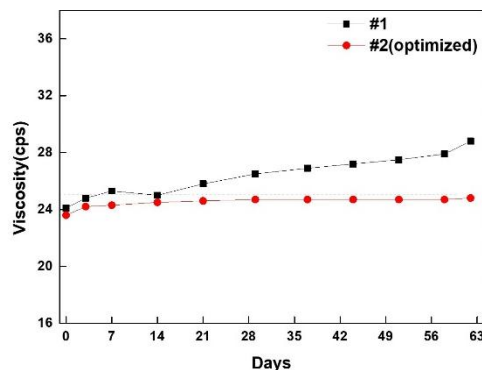


Figure 1. Storage stability at 25 °C

To develop QD ink with dispersion stability, it is critical to select the appropriate ligand and monomer for the QD surface. To ensure the dispersion stability of QD ink and the stability of the film after thin film formation, an aryl-alkyl acrylate monomer with a chemical structure similar to the ligand bound to the QD surface was applied. Furthermore, the surface of the QD was modified by adding a hetero alkyl polar moiety. Consequently, we secured the dispersion stability of QD nanoparticles at a viscosity of 25 cps or lower, and obtained ink with no viscosity change for over 60 d at 25 °C (see Figure 1).

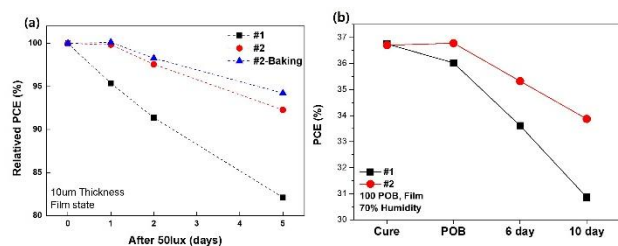


Figure 2. (a) Yellow light stability of QD film (10 μm).
(b) Film stability at humidity 70%

Using ink with secured dispersion stability, a 10 μm film was produced after photopolymerization. QD films may experience surface oxidation when exposed to oxygen, moisture, or light, leading to a decrease in photoconversion efficiency. To address this issue, we adjusted the intramolecular interaction, polarity, and acrylate monomer chain length, and increased the density of the film to inhibit the detachment of ligands from the QD surface. Consequently, the photostability was improved when exposed to yellow light (100 lux) in the air compared with the film (#1) using a typical alkyl chain acrylate (see Figure 2a). Additionally, by reducing moisture penetration in the thin film state, the decrease in photoconversion efficiency at 70% humidity was minimized (see Figure 2b).

In this study, we developed a QD ink with dispersion stability at a low viscosity of 25 cps by applying QDs, a ligand, and an acryl monomer with similar chemical structures, while simultaneously delaying moisture penetration to inhibit the oxidation of the QD surface.

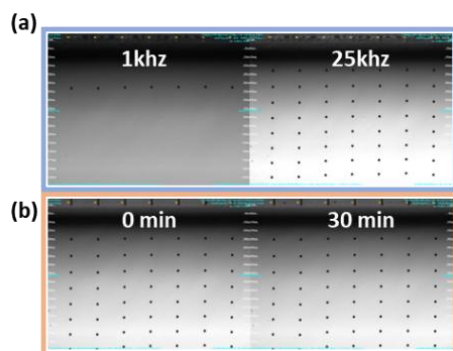


Figure 3. (a) Inkjet test of frequency.
(b) Continuous inkjet evaluation

The QD ink was evaluated for ink jetting using the KM1024 head. We examined stable jetting characteristics without satellites in the frequency range of 1 kHz to 25 kHz during a 30-min continuous inkjet evaluation (see Figure 3).

2.2 Development of TFE ink

TFE suppresses oxygen/moisture penetration, and the technology for implementing capacitive touch sensors on TFE (TOE) is expanding. The TOE technology enables the thinning of displays, and the positioning of the polarizing film beneath the cover glass allows for improved display quality (see Figure 4).⁴

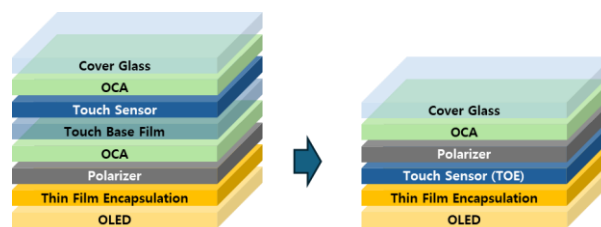


Figure 4. Structure of TOE (touch sensor on TFE)

The typical TFE structure with the encapsulation layer is shown in Figure 5.⁵ If the dielectric constant of the TFE layer is high, the thickness of the product may increase. In this study, we developed a low-dielectric TFE ink capable of high-quality touch performance and thin-film application.

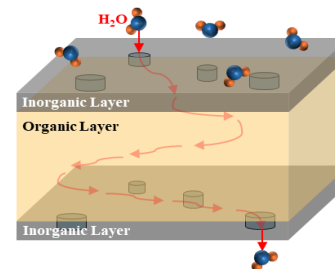


Figure 5. Structure of TFE

To ensure viscosity and surface tension suitable for inkjet processes and storage stability, a monomer with high steric hindrance and a monomer incorporating an aliphatic long chain structure to achieve low dielectric properties were applied. The aliphatic structure is composed solely of nonpolar alkyl moieties, resulting in low polarizability, and the long chain structure, with its low density, increases free volume, thereby reducing the dielectric constant while simultaneously decreasing the rate of moisture movement within the TFE owing to its hydrophobic properties.⁶

However, when a thin film is formed solely with an alkyl moiety, the dielectric constant can be reduced, but owing to weak intermolecular interactions, the mechanical properties are lowered, which can increase the surface roughness and haze during inorganic material deposition. To address this issue, a rigid structure monomer was applied to the aliphatic long chain backbone to secure low dielectric properties. Additionally, by introducing a bulky-rigid structure that can increase the low free rotation and porosity, the surface uniformity and permeability of the cured TFE were ensured (Table 1).

Table 1. Physical properties of the TFE organic film

Properties	TFE	Low-Dk TFE
Viscosity (cps)	22	20
Surface tension (N/m)	34	28
Dielectric constant	3.30	2.58
Transmittance (%)	98.9	99.5

Finally, we evaluated the discharge stability and coating uniformity of a low-Dk TFE ink using an inkjet device equipped with a KM1024 head. Good characteristics were confirmed by verifying the ejection characteristics of 1024 nozzles at a

frequency of 20 kHz (see Figure 6a). After UV curing the 10 μm coated thin film under these conditions, the production of a thin film with uniform thickness was confirmed through surface analysis with an alpha step (see Figure 6b).

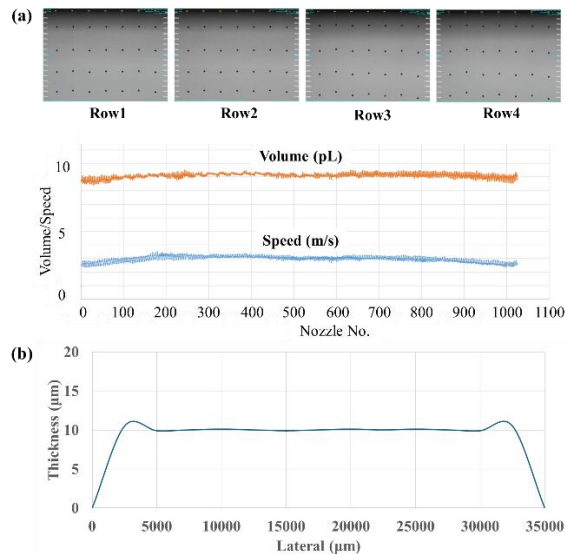


Figure 6. Ink jetting properties. (a) Ink droplet stability of etch nozzle. (b) Coating film thickness uniformity

2.3 Development of filler

The light generated in the panel, while passing through the interface between the light-emitting layer and the layer with a different refractive index, is a major factor in the reduction of optical efficiency owing to reflection or refraction.⁷

Filler is a material that is filled between the OLED blue panel and the color conversion device, requiring high adhesion and low shrinkage for the interfacial bonding of the two different materials (Figure 7).

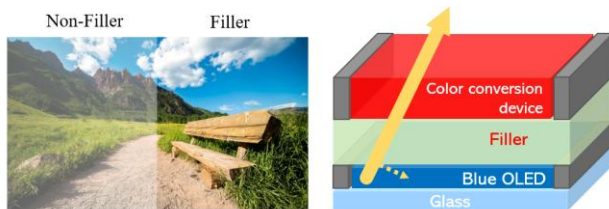


Figure 7. Structure of QD OLED TV panel

The high-refractive-index monomer of the conventional filler is either solid or has high viscosity, making jetting difficult. Additionally, its low adhesion can cause delamination between the panel and the color conversion device, potentially leading to moisture and oxygen permeation.

Furthermore, high-refractive-index monomers containing an aromatic ring have a high polarizability, which lowers the Abbe number and improves the refractive index. However, their adhesion is reduced, limiting the use of high-refractive-index monomers, making it difficult to achieve a refractive index above 1.6.⁸

In this study, we improved the optical extraction characteristics by developing a filler with high refractive index and adhesion between the backlight and the color filter.

We applied two or more high-refractive-index monomers containing aromatic rings and used oligomers with symmetrical phenolic rings to enhance adhesion, thereby improving high-temperature stability and mechanical properties.⁹ Moreover, to minimize shrinkage and ensure viscosity, a low-viscosity monomer of rigid structure with a cycloaliphatic type was applied.

Table 2. Physical properties of fillers

Properties	Filler	HR-Filler
Refractive Index (film)	1.60	≥ 1.65
Adhesion Strength (kgf/cm^2)	7.0	≥ 10.0
Shrinkage (%)	4.0	≤ 2.5
Transmittance (%)	98.7	≥ 99.4

Consequently, it was possible to reduce light scattering and loss and achieve clear image quality by applying a filler with a refractive index of 1.65, adhesion strength greater than 10 kg/cm^2 , and a shrinkage of 2.5% or less between the panel and the color conversion device (Table 2).

3.1 Fabrication of conversion device

The QD, TFE, filler, and fluorescence blue OLED device used as a backlight were utilized to fabricate the optical switching device with the structure shown in Figure 8(a). The emission wavelength of the blue backlight is 459 nm, and after manufacturing the QD film with a thickness of 10 μm , it was encapsulated with the TFE. Subsequently, the conversion spectrum analysis and light extraction effect were confirmed by using the filler to bond with the backlight device. By applying the HR filler between the blue backlight and the QD layer, the blue light conversion efficiency increased by more than 10% compared with the conventional filler (Figure 8(b)).

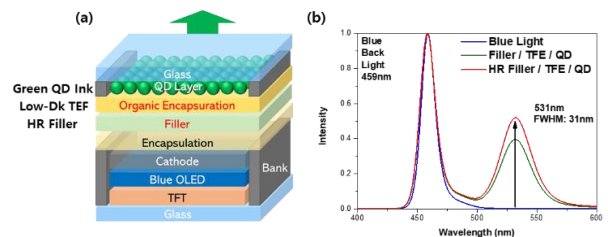


Figure 8. (a) Color conversion device, (b) Color conversion spectra

3. Impact of Research

Our study developed a low-viscosity QD ink, low-dielectric TE, and high-refractive filler applicable to QDCC through the development of high-performance polymers applicable to next-generation large-area displays. Thus, we have secured the commercialization potential of functional polymer materials that can be widely applied to next-generation display applications.

4. References

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