

Ester-Based Quantum Dot Ink for High-Performance Printed RGB Quantum Dot LED

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Abstract

An ester-based QD ink was developed for printed quantum dot LEDs. The uniformity of printed RGB layers were $\geq 85\%$, higher than that of reference inks. The corresponding QLEDs also showed improved current efficiencies (R/G/B: 60/150/12 cd/A) and T95@1,000 nit lifetimes (R/G/B: ~25,000/~15,000/~80 h). A 14-inch prototype display was fabricated to demonstrate the enhanced quality.

Author Keywords

Ester-Based QD Ink, Printed RGB QLED, Prototype Display.

1. Introduction

Inkjet printing, an additive manufacturing method, has become a suitable technique for producing low-cost and large-scale QLED displays. This mask-free approach demonstrates the merits of cost-effectiveness, material efficiency, and exceptional capability to precisely pattern quantum dot (QD) for high-definition pixels [1-4]. Nevertheless, advancements in the production of inkjet-printed QLEDs are still behind those of spincoated devices, especially regarding their efficiency and stability [5-7]. One important reason is that layer uniformity in a pixel of printed devices is lower than that to spincoated ones, especially the QD emission layer. Due to the capillary flow during solvent evaporation, QD layers prepared from typical linear alkane, cycloalkane, or benzene/naphthalene-derivative inks are concave (especially when they are thicker than 30 nm), that is, the center area is thin while the periphery is thick within each pixel. Such morphology induces inevitable emission inhomogeneity and other side effects.

In this work, we developed an ester-based QD ink. All printed RGB QD layers exhibited uniformity of at least 85% (uniformity will be defined below), which is higher than those of the RGB reference inks. The printed RGB QLED device exhibited current efficiencies of 60, 150, and 12 cd/A. The corresponding T95@1,000 nit lifetimes were ~25,000, ~15,000 and ~80 h, respectively. A 14-inch printed prototype display was also prepared to demonstrate the enhanced display quality.

2. Experiment and Method

QD was prepared according to a previously reported method [8]. The ester-based ink was prepared by dissolving QD in an ester and linear alkane mixture. The reference ink was adapted from reported formula [9]. Different solvent volume ratios, ink concentrations and vacuum-drying conditions were optimized not only for printability but to achieve the highest layer uniformity. Zinc oxide nanoparticles were prepared with similar method as the electron transport layer [10], and the ink was prepared by dissolving zinc oxide nanoparticle in high boiling point alcohol mixture. Poly(9,9-dioctylfluorene-alt-N-(4-sec-butylphenyl)-diphenylamine) (TFB) hole transport layer was printed as the substrate for QD layer. The 14-inch prototype display was

prepared by Kateeva G4.5 inkjet printing platform.

3. Result and discussion

Figure 1a demonstrates the contour profile of the printed QD layers on TFB using ester-based ink after optimization. Figure 1b-c exhibits the profiles of the reference ink after optimization. The uniformity is defined as the percentage of area with a thickness range (average thickness of $30 \times 30 \mu\text{m}$ in the pixel center $\pm 5 \text{ nm}$) to the entire pixel area. Higher uniformity indicates a more thickness-homogenous layer. The QD layer from the ester-based ink showed a substantially improved uniformity compared to the counterpart prepared from the reference ink, as can be seen from the fewer particle accumulation in the periphery. The improvement can be attributed to three proposed reasons. First, due to the appropriate surface tension difference between the two ink components, sufficient Marangoni flow was created and effectively weakened the capillary flow. Secondly, the ester-based ink has a higher viscosity (5.6 vs 2.8 cP), which simultaneously weakens both the capillary and the Marangoni flow, but in this case, inhibits the capillary flow more. These two factors balanced the capillary and the Marangoni flow, allowing QD particles to be evenly distributed above the TFB layer, as shown in Figure 1c. Third, non-ester solvents with similar surface tension and viscosity to those of the ester solvent, were also mixed with the same alkane as QD inks and printed. However, the uniformity of these inks was not as high as that of the ester-based ink. Ester-based inks have not been reported so far, and we consider that the layer-forming mechanism of the ester-based inks are different from typical alkane- or benzene/naphthalene-based QD inks. More investigations will be conducted in the future.

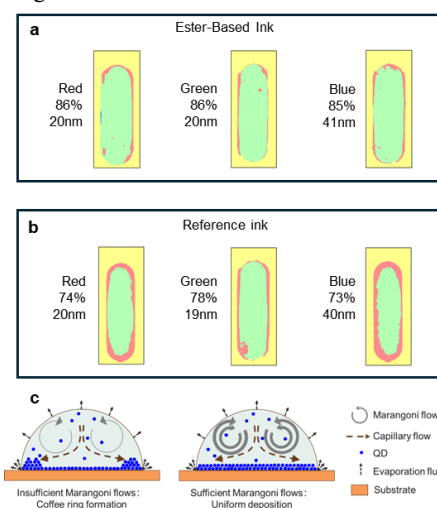


Figure 1. Contour profiles of RGB QD layers from (a) the ester-based ink and (b) the reference ink. The green part is the region whose thickness is within the range of center

area thickness ± 5 nm. The red part indicates the region whose thickness is beyond the $+5$ nm limit (much thicker than the center area). The values on the left of each profile are uniformity and thickness, respectively. (c) Scheme of the QD particle distribution upon solvent evaporation controlled by capillary and the Marangoni flow.

The improved film homogeneity enhanced the performance of printed QLED device. Figure 2a-c demonstrates the comparison of current density-voltage-luminance between the ester-based ink and the reference ink. RGB QLED devices using ester-based ink showed increased current density and luminance at the same voltage. The maximum current efficiencies of the RGB devices with the ester-based inks were 60, 150, and 12 cd/A, respectively, while the maximum current efficiencies from reference inks were 45, 120, and 10 cd/A, respectively. Current focusing on the thin region of a pixel not only leads to inhomogeneous emission but also reduces efficiency because a much higher current density than the measured value passes through the thin region (usually center part of a pixel). It is considered to increase the Auger recombination portion, which is related to high current density [11, 12]. The uniform QD emission layers from the ester-based ink alleviated current focusing, lowering the portion of Auger recombination and thus improving the luminance. Figure 2d-f display the RGB device luminance decay comparison. All RGB devices with both inks showed similar decays, which implies that the key factors to degradation are not strongly correlated with the layer uniformity. The initial increase of luminance was attributed to positive aging[13-15]. The starting point of the luminance for lifetime calculation was set to the time of luminance maximum. Due to higher luminance, the calculated device T95@1,000 nit values of the RGB ester-based ink were $\sim 25,000$, $\sim 15,000$ and 80 h, respectively, much higher than those of the RGB reference inks, $\sim 12,000$, $\sim 5,000$ and 40 h (using an acceleration factor of 1.7).

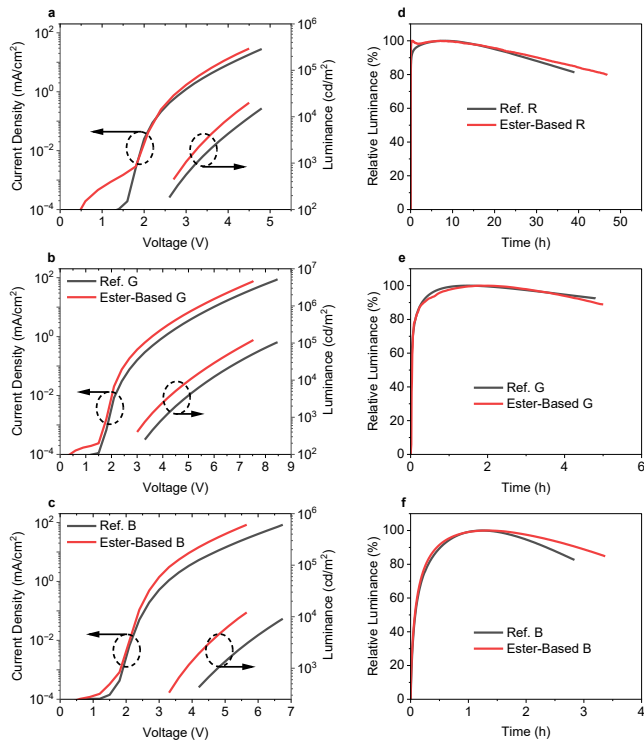


Figure 2. (a)-(c) Current density- voltage- luminance curves and (d)-(f) luminance decays of RGB devices using the ester-based and reference inks.

Finally, the ester-based ink was applied in the fabrication of the world's first 14-inch printed QLED laptop display prototype, as shown in Figure 3. The resolution of this prototype was as high as 240 PPI, which was a breakthrough in high-precision inkjet printing technology. The entire graph is clear and delicate, with vivid colors. By fully taking advantage of QD narrow emission the prototype color gamut reached $> 85\%$ BT.2020 without color filters. In addition, the prototype display adopted an optimized top-emitting QLED device structure. The efficient printed QLEDs substantially improved the display brightness up to 350 nit. Thanks to the 30-120 Hz VRR technology, the screen supported adaptive refresh, providing smooth and comfortable frames in terms of dynamic graphics. The panel specifications are listed in Table 1. These values are comparable to those of the top industrial products. The improved display quality and visual experience are attributed to the improved QD layer quality.



Figure 3. Photograph of a 14-inch laptop display prototype demonstrating colorful pictures.

Table 1. Specifications of the 14-inch prototype display

Resolution	2880 (H) \times RGB \times 1800 (V)
Frame rate	30~120 Hz
Brightness	350 nit
Color Gamut	BT.2020 $> 85\%$
Contrast Ratio	$> 1,000,000 : 1$

4. Conclusion

In summary, an ester-based QD ink was developed, and the uniformity of the printed RGB QD layer reached at least 85%. The printed RGB QLED devices exhibited current efficiencies of 60, 150, and 12 cd/A. The RGB device lifetimes reached $\sim 25,000$, $\sim 15,000$, and 80 h. The world's first 14-inch prototype display with 240 PPI resolution was fabricated to demonstrate the

enhanced color purity and brightness. This prototype fully exhibited the high quality printed RGB QLED using our ester-based QD ink. Further optimization can be performed to improve the layer uniformity for different esters and solvent ratios. Ester solvents allow more choices for QD ink development regarding surface tension, viscosity and density. We believe that our work sheds light on the development of novel QD inks for the commercialization of printed QLED displays.

5. Acknowledgements

All the research members are appreciated for their support and cooperation .

6. References

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