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Fabrication Process of Organic and Quantum Dot-Based Light-Emitting Diodes for Full-Color Display

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ABSTRACT

Fabrication processes for organic and quantum dot (QD) light-emitting diodes for realizing full-color displays is demonstrated, one is an inkjet printing of the QD layer and another is a common layer structure. With the methods, device performances were also improved.

1 Introduction

Since the first quantum dot (QD)-based light-emitting diodes (QLEDs) have been introduced, the performances, such as efficiency, color purity, and lifetime, have been improved to date.[1–5] Recently, Cd-free QLEDs showing high performances which are comparable to those of organic light-emitting diodes were introduced based on multilateral efforts, including material design and synthesis and device structure optimization.[4,5] However, inevitable solution-based processes of QD deposition make it difficult to commercialize QLED displays. Among various full-color QD patterning techniques, inkjet printing is considered the most promising candidate for large-sized displays due to the high speed, low QD usage, and proper accuracy. But controlling the morphology of QD films and forming a thin QD film uniformly is challenging. There is few research on controlling the film morphology of QDs, except for tuning the solvent properties. Also, the processes need to be compatible with small- to mid-sized displays, such as mobile phones and augmented reality (AR)/virtual reality (VR) devices, it is requited to develop advanced patterning technologies for enhancing the resolution.

Here, we introduce some strategies on fabrication processes for realizing full-color displays, one is inkjet printed QLEDs and the other is organic and QD based hybrid LEDs based on a common layer structure. We believe that both fabrication processes introduced here are highly compatible and applicable for mass-production of full-color QLEDs.

2 Results and Discussion

The most widely used fabrication process for sub-pixels is an inkjet-printing method. With this process, one can directly form a fine pattern in a several-micrometer scale in a solution process with low material usage. On the other hand, there also exist drawbacks in inkjet printing, for instance, low uniformity due to the coffee ring effect, mis-alignment to a sub-pixel, and a damage to underlying functional layers. Nevertheless, the inkjet-printing method is considered the most practical and feasible technique especially for QD deposition. Recently, we demonstrated that improved film morphology of inkjet-printed QD films and high device performances in QLEDs using them, by incorporating a small amount of polymeric additive into the QD solution.[6]

In order to further improve the morphology of QD films, the surface energy of the underlying layer as well as the side-wall of the pixel-defining layer (i.e., the bank). In general, the bank structure is made from hydrophobic polymers, such as polyimide (PI). To compare the surface properties, we measured contact angles of each surfaces where the QDs are intimately connected to; that are, the PI bank and the spin-coated ZnO nanoparticles film. As shown in Table 1, the contact angles for the surfaces of PI and ZnO nanoparticles are largely different from each other. As a result, the QD ink droplets form a curvy surface inside the pixel, which lead to form a poor film morphology. To overcome this issue, we adopted a few atomic layers of ZnO deposited by atomic layer deposition (ALD) over the entire device having a bank structure. Owing to the good step coverage of the ALD process, we thought that a thin ZnO ALD layer can reduce the surface energy difference between the underlying electron transport layer and the side-wall of the bank, even with little effect on the electron transport properties in QLEDs. As shown in Table 1, the ALD-deposited ZnO surface exhibited smaller difference in its contact angle than the ZnO nanoparticles layer.

Table 1. Contact angles at various surfaces using DI water and diiodomethane.

Surface	Contact angle (degree)	
	DI	diiodomethane
PI bank	62.9	22.7
ZnO (spin-coated)	32.5	19.1
ZnO (ALD)	51.7	20.8

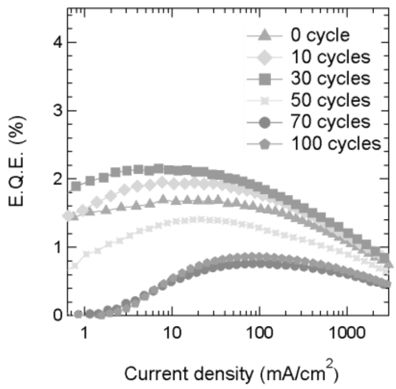

Fig. 1. EQE of the inkjet-printed QLEDs with varying the number of ALD cycles.

Furthermore, the smaller contact angle difference enabled to form much smoother morphology of the inkjet-printed QD films inside the PI bank structure. As a result of the good QD morphology, we could improve the maximum external quantum efficiency (EQE) of the QLEDs with the ALD ZnO layer up to 27% and the maximum luminance up to 17%, in comparison with the control device. Using the electron-only and hole-only devices, we found that the deposition of the thin ALD ZnO also improved the charge balance in the QLEDs. In addition to this, the ALD ZnO-incorporated QLEDs showed improved lifetime than the control device. We optimized the device performances with varying the number of ALD cycles, from 10 cycles to 100 cycles of deposition.

As another strategy to fabricate a full-color display, we suggest a blue common layer (BCL) structure for organic–QD hybrid LEDs. The BCL consists of a host–guest system, which is commonly used for the blue-emitting layer in organic light-emitting diodes (OLEDs). Using this structure, one can reduce a single patterning step for the blue sub-pixel. In this device architecture, the red- and green-emitting sub-pixels are based on QLEDs. In the red and green sub-pixels, blue emission is negligible despite of the direct contact between the red- and green-emitting QDs and the blue-emitting common layer. Based on optimization, we could demonstrate that the electroluminescence (EL) spectra were changed little when the BCL was introduced and color coordinates of the red- and green-emitting QLEDs showed small shifts from (0.69, 0.31) to (0.67, 0.30) and (0.17, 0.77) to (0.16, 0.77), respectively. Furthermore, the BCL-adopted QLEDs exhibited improved performances compared to the QLEDs without the BCL. For example, the maximum EQE of the red-emitting QLED was enhanced from 7.7% to 8.6% and that of the green-emitting QLED was enhanced from 9.9% to 13.7%, which were originated from the improved charge balance and Förster resonance energy transfer from the BCL to QDs.

Finally, we demonstrated a QLED pixel being operated with a thin-film transistor based on a two-dimensional nanosheet of $MoTe_2$ as the active layer, which has a low light-induced effect.[7]

3 Summary

In summary, we introduce fabrication processes of organic and QD based light-emitting diodes, using inkjet printing and a common layer device structure. First, we improved jettability of QDs inside sub-pixels by enhancing the surface property using atomic layers of ZnO. Second, a common layer structure was adopted to reduce one fine metal mask step with improved QLED performances. We thus believe that both performances are practically applicable for mass-production of full-color QLEDs.

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