

## Improving performance of deep-blue OLED by inserting ultra-thin LiF between hole-blocking and electron-transporting layers

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### Abstract

Deep-blue organic light-emitting diodes (OLEDs) with/without ultra-thin LiF layer inserted at the interface between hole-blocking and electron-transporting layers have been fabricated and investigated. The fundamental structures of the OLEDs are ITO/m-MTDATA/NPB/BCP/LiF (with/without)/Alq<sub>3</sub>/LiF/Al. Deep blue light emission with CIE coordinate of (0.15, 0.11) has been achieved for all devices. Further, by inserting LiF with thickness of 1nm at the interface between BCP and Alq<sub>3</sub> layer, the luminous efficiency as well as the power efficiency is much improved compared to that without. The enhancement of electron injection due to insertion of LiF may account for this improvement.

### 1. Introduction

Organic light-emitting diodes (OLEDs) have attracted considerable attention due to their potential application in high brightness, high efficiency and full color flat-panel displays [1, 2]. Three primary color components red, green and blue (RGB) are required to obtain full color display. To date, especially with the discovery and improvement of phosphorescent materials, red and green emitters with high efficiency as well as color saturation become readily available [3-5]. However, the situation is not the same for blue emitters. Although UDC recently claimed the best triplet blue emitter with a luminous efficiency of 30 cd/A at 100 cd/m<sup>2</sup>, it is basically a sky-blue with the CIE coordinates of (0.16, 0.38) [6]. It seems always a tradeoff between high efficiency and saturated color at least now. Besides the sky-blue emitter, there remain high desires to develop OLEDs emitting in deep blue region normally with CIE<sub>y</sub> < 0.15 because that using such blue emission can reduce the power consumption of a full-color display and also it can be used to generate light of other colors by energy cascading to a suitable emissive dopant [7].

In this work, utilizing the similar structure with that reported by Y. Kijima et al [8], we fabricated the deep blue OLEDs based on the emission of hole-transporting emissive layer N,N'-di(naphthalen-1-yl)-N,N'-diphenyl-benzidine (NPB). With the fixed thicknesses of m-MTDATA and NPB and LiF inserted, we vary the thicknesses of BCP and Alq<sub>3</sub> from 10nm to 30nm. Table 1 shows the structures of the blue OLEDs fabricated in this paper. The electroluminescent (EL) performance of devices B are better than those of corresponding devices A. Undoubtedly, the improved performance is arise from the insertion of ultrathin LiF at the interface between BCP and Alq<sub>3</sub> no matter what thickness configuration of them. Detailed EL characteristics were compared between devices A and B. The possible mechanisms underlying are discussed as well.

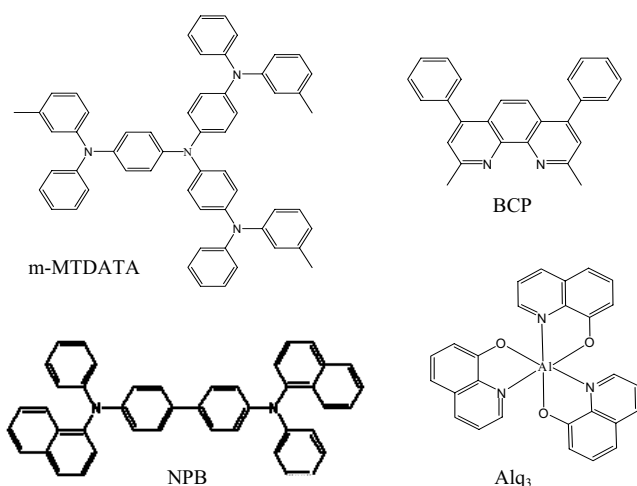
Table 1. The layer structures of devices A and B fabricated in this work (unit: nm)

Cell name	HIL/EML (m-MTDATA /NPB)	HBL (BCP)	LiF	ETL (Alq <sub>3</sub> )	Cathode (LiF/Al)
A1	25/30	10	0	30	1/120
A2	25/30	20	0	20	1/120
A3	25/30	30	0	10	1/120
B1	25/30	10	1	30	1/120
B2	25/30	20	1	20	1/120
B3	25/30	30	1	10	1/120

### 2. Experimental details

Devices A and B were fabricated in the same run in order to eliminate different operation errors. ITO coated glass with a sheet resistance of 25Ω/□ are used as the starting substrates. The substrates were first soaked in ultra-sonic detergent for 30mins, then spray cleaned with de-ionized (DI) water for 10mins. They were then soaked in ultra-sonic DI water again for 30mins and oven bake dried for 1hr. Organic materials including m-MTDATA, NPB, BCP and Alq<sub>3</sub> were all used as received without further purification. The molecular structures of them are shown in Fig. 1. All the films were prepared in a high

vacuum chamber with a base pressure of less than  $1 \times 10^{-6}$  Torr. The evaporation rate was typically 1-2 Å/s, 0.2-0.3 Å/s and 3-4 Å/s for organic materials, LiF and Al, respectively. A quartz crystal monitor was used for determining the thickness of films *in situ*.



**Figure 1. The molecular structure of organic materials used for the blue devices**

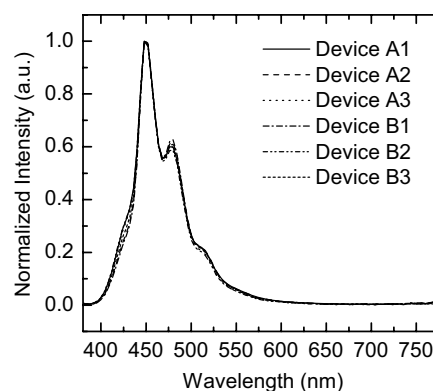
The luminance-current density-voltage (L-J-V) characteristics of the devices were recorded simultaneously by a semiconductor parameter analyzer (HP4145B) combined with a calibrated silicon photodiode. The electroluminescence (EL) spectra were obtained from the PhotoResearch PR650 spectrometer. All measurements were carried out under ambient atmosphere without any encapsulation.

### 3. Results and discussion

With a high ionization potential, BCP is a very effective material for hole-blocking layer [8]. As a result, we can get blue EL emission from NPB for devices A and B. The normalized EL spectra of devices A and B are similar to each other as shown in Fig. 2. These phenomena can be understood by two facts. On one hand, when biasing the OLED the electrons injected from the cathode and the holes injected from the anode move into NPB layer, the holes can not move over the band gap between NPB and BCP due to the superior hole-blocking ability of BCP. The recombination zone will be fixed near the interface of NPB/BCP no matter 10nm, 20nm or 30nm BCP used in our experiments. On the other hand, due to the ultra thin of LiF (1nm) is so transparent that there is little change of optical

property of total device after its insertion and therefore minor alternating the out-coupling spectra caused by interference effect.

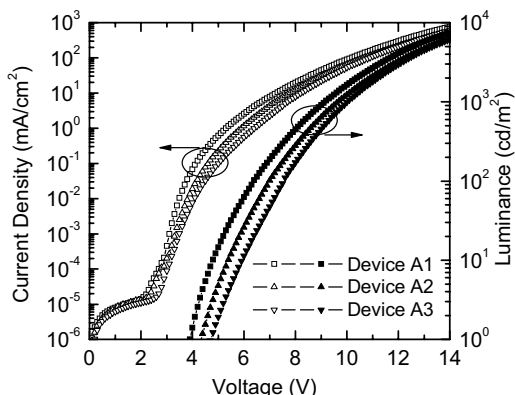
For devices A and B, the Alq<sub>3</sub> emission (peak at ~520nm) almost has no contribution to the total spectra. It can be observed from the comparison of EL spectra between device A/B and another blue emission device without Alq<sub>3</sub>, consisting of ITO/m-MTDATA/NPB/BCP/LiF/Al, there is no intensity difference especially around 520nm between them (not shown here). However, the latter device without using Alq<sub>3</sub> as electron injection layer exhibit relatively poor efficiency, e.g., the maximum external quantum efficiency (EQE) is only 1.12 %. On the contrary, devices A and B showed improved performance over it, e.g., device B3 showed maximum EQE of ~2.5%.



**Figure 2. Normalized EL spectra of blue devices fabricated in this work**

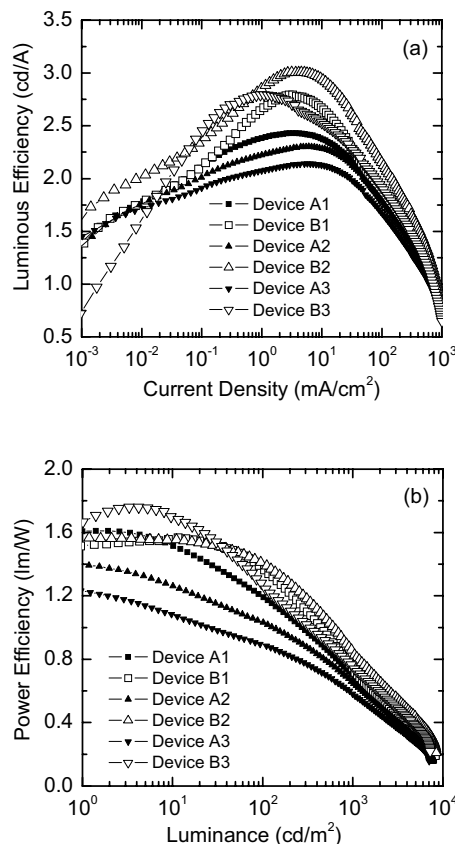
Fig. 3 shows the L-J-V characteristics of devices A. These three blue OLED turn on (to achieve  $1 \text{ cd/m}^2$ ) at 3.9V, 4.5V, 4.7V for A1, A2, and A3, respectively. Device A1 shows lowest voltage to achieve current density of  $20 \text{ mA/cm}^2$  among them due to the thinnest BCP used. As we know, the BCP has lower electron transport property than that of Alq<sub>3</sub> [9]. Assuming the same electron injection for device A1, A2, and A3, the electron transport in BCP+Alq<sub>3</sub> will most influence the total current flowing in the devices. Obviously, the electron conductivity of BCP+Alq<sub>3</sub> bilayer will be different for three thickness configuration above. Consequently, device A1 having less BCP and more Alq<sub>3</sub> will be most electron-conductive among them and have largest current flowing. Additionally, these differences are also responding to the difference of EL efficiency. Device

A1 has the largest efficiency among them because of more electrons can move into NPB layer to recombine with holes and most excitons formed thereafter (data will be shown later). Even though, the luminous efficiency of device A1 is not high enough and only  $\sim 2.26\text{cd/A}$  at  $20\text{mA/cm}^2$ .



**Figure 3. J-V-L characteristics comparison between devices A1, A2 and A3**

Motivated by the usefulness of LiF interposed between a light emitting layer and an Al cathode to enhance electron injection and therefore to raise the quantum efficiency [10], we further insert LiF with thickness fixed on 1nm at the interface between BCP and Alq<sub>3</sub> of devices A to form devices B. Fortunately, the luminous efficiency as well as power efficiency of devices B was better than their corresponding devices A. Fig. 4 shows the efficiency comparison of devices A and B. It is noteworthy that the extents of efficiency improvement of devices B comparing with devices A are differing from what BCP and Alq<sub>3</sub> thickness configuration used.



**Figure 4. Luminous efficiency Vs current density curves (a) and Power efficiency Vs luminance curves (b) of blue devices fabricated in this work**

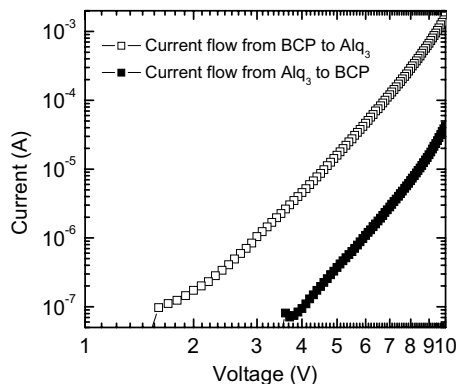
Table 2 summarizes the key EL characteristics of devices A and B. Interestingly, for device B1 and B2, the turn-on voltages show a little bit higher compared with that of A1 and A2, however, that of device B3 was decreased by 0.6V with respect to device A3.

**Table 2. The key EL characteristics of devices A and B**

Cell name	Turn-on voltage (V)	Luminance at 100mA/cm <sup>2</sup> (cd/m <sup>2</sup> )	Max luminous efficiency (cd/A)	Luminous efficiency at 20mA/cm <sup>2</sup> (cd/A)	Power efficiency at 100cd/m <sup>2</sup> (lm/W)
A1	3.9	1773	2.43	2.26	1.19
A2	4.4	1799	2.3	2.21	1.03
A3	4.7	1668	2.14	2.07	0.89
B1	4.15	1844	2.79	2.47	1.38
B2	4.45	2151	3.0	2.78	1.4
B3	4.1	1914	2.79	2.4	1.26

The efficiency improvement of device B in comparison with device A can be attributed to the enhancement of electron injection from Alq<sub>3</sub> to BCP. From the estimated energy diagrams reported in ref. 8, we can clearly see that there is a little electron injection barrier from Alq<sub>3</sub> to BCP. To further investigate electron transport across the BCP/Alq<sub>3</sub> interface, a multilayer structure was employed with a configuration of Al/LiF/BCP/Alq<sub>3</sub>/LiF/Al.

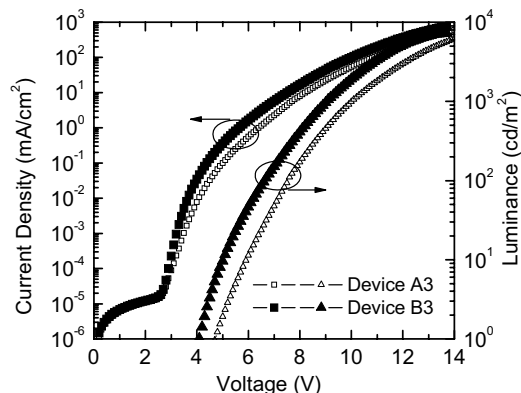
In this structure, the carriers were almost exclusively electrons due to the large offset between the work function of Al/LiF bi-layer and the ionization energy of Alq<sub>3</sub> and BCP. It was found that the current flow from the Alq<sub>3</sub> to BCP required a higher threshold voltage than that from the BCP to Alq<sub>3</sub>, and its current density was about 50 times less than that from the BCP to Alq<sub>3</sub>. These results are shown in Fig. 5. The addition of LiF at the interface of BCP/Alq<sub>3</sub> is believed to cause the band bending of BCP and therefore lowering the electron injection barrier. The balance of carrier injection will definitely result in the improvement of light emission efficiency.



**Figure 5. I-V curves of electron-only device with structure of Al/LiF/BCP/Alq<sub>3</sub>/LiF/Al at two-direction biasing**

Apart from this, for device B3, the current density was also increased due to the insertion of LiF. Fig. 6 shows the J-V-L characteristics comparison between devices A3 and B3. The current density of device B3 is much increased compared to A3. We infer that the LiF diffusing into BCP will increase its conductivity. For different thickness of BCP deposited, there will be different ways of packing of molecules [11]. We think that most diffusion of LiF into BCP happened on device B3 instead of B1 and B2. Therefore, not

only efficiency but also the J-V characteristics are improved for device B3. Of course, exact reasons underlying need deeply investigated.



**Figure 6. J-V-L characteristics comparison between devices A3 and B3**

#### 4. Conclusion

In conclusion, we have demonstrated the better luminous efficiency as well as the power efficiency of the deep blue OLED having CIE coordinate of (0.15, 0.11) can be achieved by insertion of LiF with thickness of 1nm at the interface between BCP and Alq<sub>3</sub>. It is suggested that the increase of efficiency of the OLED with insertion of LiF at BCP/Alq<sub>3</sub> is attributed to the improving of electron injection due to lowering barrier at this interface. Devices with three thickness configuration of BCP and Alq<sub>3</sub> all showed improved efficiency after addition of LiF, however, the J-V characteristics was enhanced only happened on the device with BCP and Alq<sub>3</sub> thickness of 30nm and 10nm, respectively. This may be caused by the different packing way of BCP at different thickness which will influence the diffusion of LiF into it and therefore adjust its conductivity thereof. This method of improving EL performance of deep blue OLED can be utilized to other devices involving BCP/Alq<sub>3</sub> interface as well.

#### 5. Acknowledgements

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