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Organic light-emitting devices with double-block layer

Huishan Yang[a,b], Yi Zhao[a], Jingying Hou[a], Shiyong Liu[a,*]

[a]National Laboratory of Integrated Optoelectronics, Jilin University, Changchun 130012, People's Republic of China
[b]Department of Physics, Quanzhou Normal University, Quanzhou 362000, People's Republic of China

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Abstract

We report on the fabrication of organic light-emitting devices (OLEDs) using double-block layers on the electron transport layer and emitting layer. The current efficiency of the organic light-emitting diode is improved by 43% to 9.16 cd A^{-1} as compared to the device with a single host of Alq_3 as the electron transport layer. The maximum luminance is over 23 750 cd m^{-2} at the bias of 18 V and the current of 338.3 mA cm^{-2}, which is 33% higher than the single host Alq_3 device without block layer. Using a step-by-step procedure to smooth electron injection and transport, the energy levels introduced by the insertion layers are an effective method of improving the luminance characteristics.

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Keywords: Organic light-emitting diodes; Block layer; Vacuum deposition

1. Introduction

Organic light-emitting diodes (OLEDs) have attracted much attention because of their potential applications in next-generation flat-panel displays and large-area flexible displays [1–3]. OLEDs have emerged as excellent candidates for promising applications in the fabrication of full-color flat-panel displays with high brightnesses and high efficiencies because they have the unique advantages of a high-response velocity, a low-power consumption, and a wide-viewing angle [4,5]. However, since OLEDs have inherent problems due to limited self-luminescence [6–9], low efficiency [10], and short lifetime resulting from degradation [3,11,12], potential applications of OLEDs have driven extensive efforts to overcome these inherent problems, especially the low efficiency [13]. To improve carrier injection and balance, the charge transport, recombination, and luminescence processes in OLEDs occur in their organic thin layers [1], and the efficiencies of OLEDs can be improved by introducing various kinds of layers. For example, an insertion of a buffer layer between ITO and the hole transporting layer (HTL) can effectively improve the efficiency of OLEDs. An electron injection layer (EIL) and a hole injection layer (HIL) were introduced to enhance the injection of carriers [14–16], an electron transport layer (ETL) and a hole transport layer (HTL) were used to accelerate carrier transport, and a hole-blocking layer (HBL) and an electron-blocking layer (EBL) were interposed between the ETL and the emission layer (EML) or between the HTL and the EML to increase exciton recombination [17–19]. Among the several layers comprising the OLEDs, since the luminescence efficiencies of OLEDs are significantly affected by the existence of HBLs [20], systematic studies on the luminescence mechanism in OLEDs with HBLs are very important for improving their efficiencies and achieving high performance.

In this article, we use ITO/m-MTDATA (45 nm)/NPB (10 nm)/Alq_3 (5 nm)/QAD (0.1 nm)/Alq_3 (60 nm)/LiF (1 nm)/Al as the basic OLED. To improve the performance of the device, double-block layers (DHBL) were added between the EML and ETL. The structure, ITO/m-MTDATA (45 nm)/NPB (10 nm)/Alq_3 (5 nm)/QAD

*Corresponding author. Tel.: +86 431 517 0884; fax: +86 431 516 8278.
E-mail address: yanghuishan1697@163.com (S. Liu).

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(0.1 nm)/Alq_3 (10 nm)/HBL (16 nm)/Alq_3 (44 nm)/LiF (1 nm)/Al, greatly enhances the luminescent performance of the OLED.

2. Experimental details

The chemical structures of organic materials, the device structure and energy-level diagrams of OLEDs used in this work are shown in Fig. 1. 4, 4′, 4″-tris (3-methylphenyl-phenylamino)—triphenylamine (m-MTDATA), *N*, *N*′-bis-(1-naphthyl)-*N*,*N*′-diphenyl-1,1′-biph-enyl-4,4′-diamine (NPB), and tris-(8-hydroxyquinoline) aluminum (Alq_3) were used as the hole injection, hole transporting, and emission/electron-transporting layers, respectively. In device B, double-block layer aluminum (III) bis(2-methyl-8-quinolinato)4-phenylphenolato (BAlq)/4,7-diphenyl-1, 10-phenanthroline (BPhen) was fabricated. To make a comparison, device A with the structure of ITO/m-MTDATA/NPB/Alq_3/QAD/Alq_3/LiF/Al and devices C and D, BAlq and BPhen was used as the hole-blocking layer, respectively, were also fabricated. The OLEDs were prepared in an organic vapour-phase deposition system. The ITO glasses were cleaned by scrubbing and sonication and were rinsed in DI water and thermally dried. Organic layers were deposited by high-vacuum (10^{-6} Torr) thermal evaporation onto a cleaned indium tin oxide (ITO) -coated glass substrate. The layer thickness of the deposited material was monitored using an oscillating quartz thickness monitor. EL spectra and CIE coordination of the devices were measured by PR650 spectra scan spectrometer and the current–voltage–brightness characteristics were simultaneously measured by a Keithley 2400

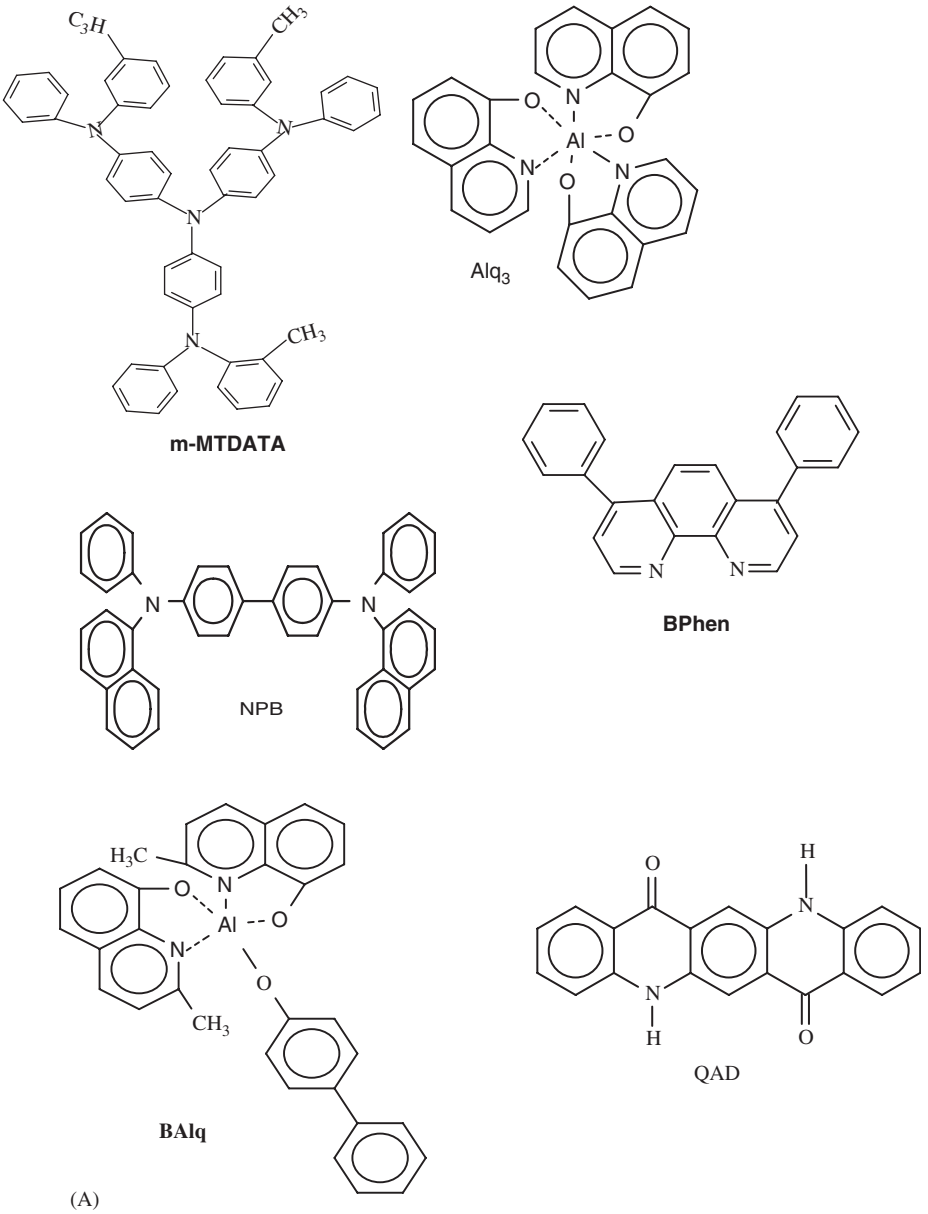

Fig. 1. (A,B) The chemical structure of organic materials, the device structure of the OLEDs and schematic energy band diagram of devices.

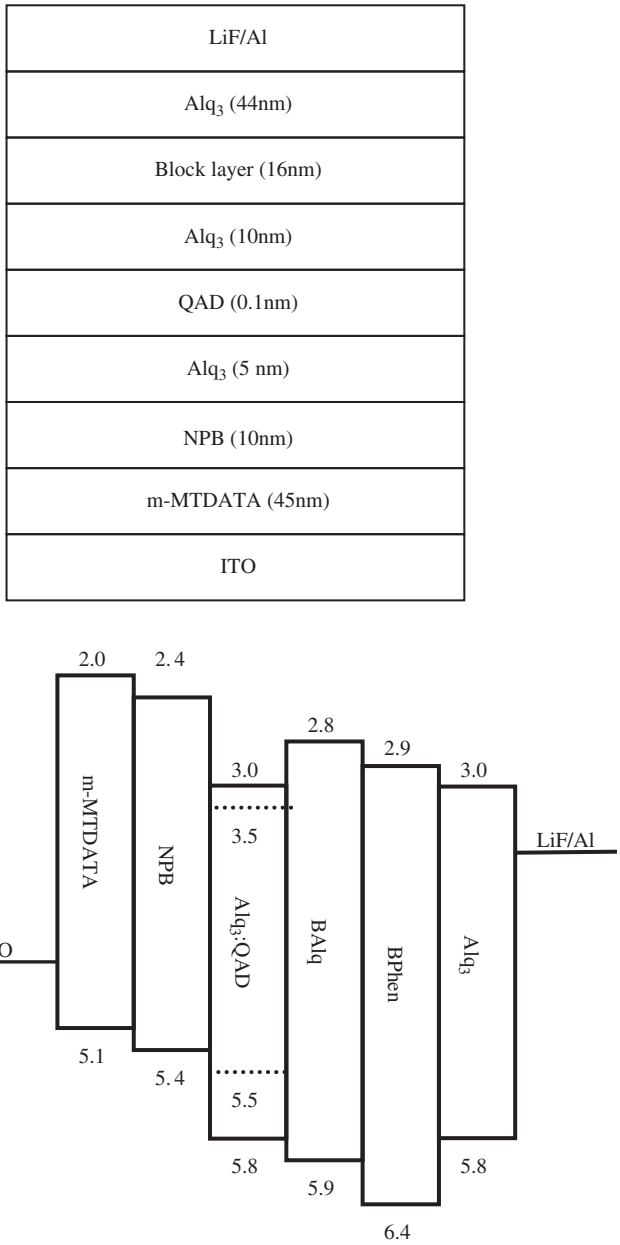

Fig. 1. (*Continued*)

programmable voltage–current source. All measurements were carried out at room temperature under ambient conditions.

3. Results and discussion

Fig. 2 shows the normalized EL intensity of the devices with and without HBL at 8 V. It can be seen that the devices A, B and C have the same EL spectra and the green emission from QAD with the peaks at 540 nm were observed, device B has a little emission from BAlq. It indicated that all the emissions of the four devices are almost coming from the efficient QAD that emission almost without Alq_3 spectrum was realized. It showed that the energy transfer from Alq_3 to QAD sub-monolayer became almost complete.

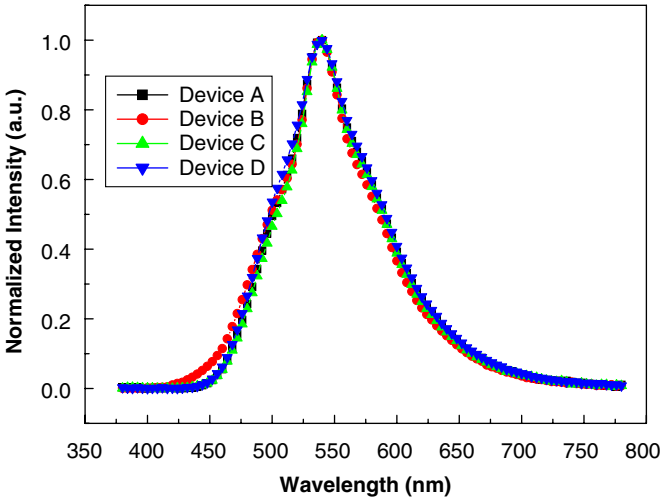

Fig. 2. Normalized EL intensity of devices A–D at 8 V.

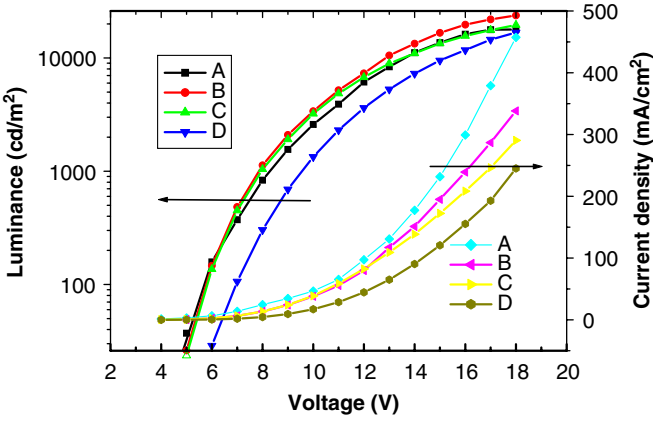

Fig. 3. The current density–voltage and the luminance–voltage characteristics of devices A–D.

Fig. 3 shows the current density–voltage–luminance characteristics of OLEDs with and without hole-blocking layers. As is expected, the current density decreases with hole-blocking layer. This suggests that the present of the HBL can block the holes from EML to ETL effectively. It shows that the EL intensity is dependent on the HBL and the device B has higher luminance with the same voltage.

Fig. 4 illustrates the current efficiency-current density and power efficiency-current density characteristics of devices A–D. It is obvious that the devices B–D with HBL has higher EL efficiency and power efficiency, among them with BAlq/BPhen as double-block layer has the highest current efficiency that is improved by 43% to 9.16 cd A^{-1} as compared to the device with a single host of Alq_3 as the electron transport layer (6.39 cd A^{-1}), and the power efficiency reach 3.39 lm W^{-1} which is almost 1.9 times higher than that of the device without HBL.

Table 1 lists the performance of the devices A–D. The maximum power efficiencies of devices A–D are 1.75, 3.39, 3.14 and 2.64 lm W^{-1}, respectively. The maximum current efficiency of devices A–D are 6.39, 9.16, 8.24 and

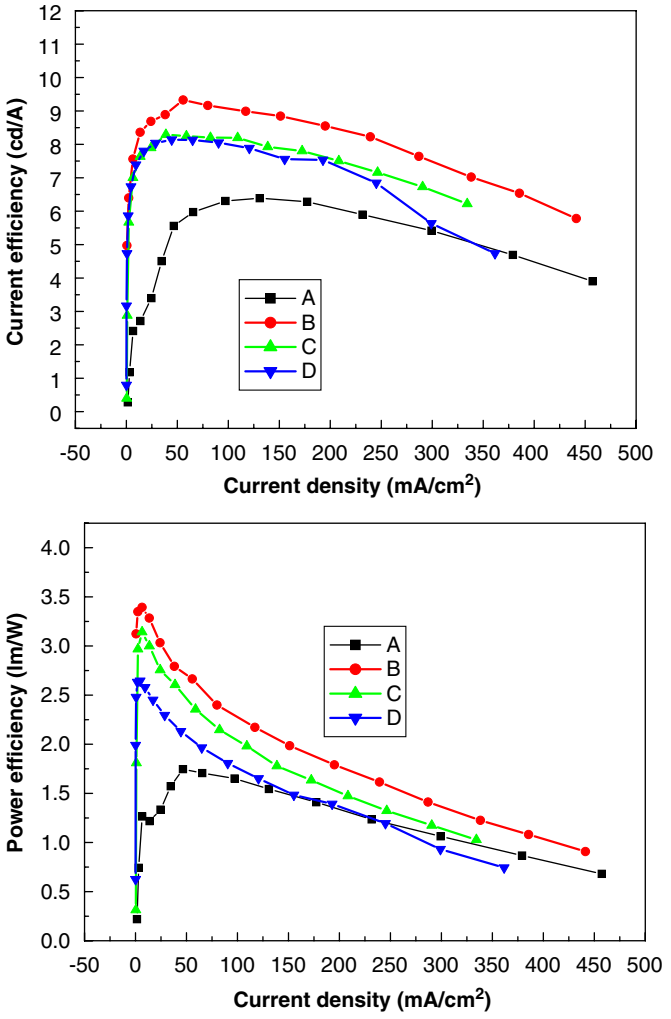

Fig. 4. The current efficiency–voltage and power efficiency–voltage characteristics of devices A–D.

Table 1
OLED parameters of devices A–D

Device	Max power efficiency ($lm\,W^{-1}$)	Max current efficiency ($cd\,A^{-1}$)	Max luminance ($cd\,m^{-2}$) at 18 V	Current density at 1000 cdm^{-2} ($mA\,cm^{-2}$)
A	1.75 at 10 V	6.39	17 840	26.3
B	3.39 at 9 V	9.16	23 750	11.6
C	3.14 at 7 V	8.24	19 550	13.3
D	2.64 at 8 V	8.14	16 780	12.5

8.14 $cd\,A^{-1}$, respectively. We can see that at luminance of 1000 $cd\,m^{-2}$, the device with DHBL shows the minimum current density (11.6 $mA\,cm^{-2}$). It indicated that the injection efficiency of holes and electrons is more balanceable in the OLED with DHBL than in another three devices. Our results suggest that DHTL can block the hole injected and improve the balance of hole and electron injections resulting in the improvement of the efficiency, which can be discussed by using the simplified energy band model. Fig. 1 shows the proposed energy level diagram of the device structure studied, with the relative alignment of the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) levels of each layer. We can see that the HOMO level of BAlq or BPhen is −6.4 or −5.9 eV, which is lower than that of Alq (−5.8 eV). The LUMO level of BAlq and BPhen is −2.8 and −2.9 eV, respectively, which is higher than that of Alq (−3.0 eV). DHBL has a ladder effect makes electron injection into the organic layer easier and leads to increase in the current density compare with single HBL. And as a result, the current density of device B is higher than that of device C or D. The inserted HBL at the EML/ETL interface suppressed the holes injection and equalized the number of injected holes and electrons at the emission layer, resulting in the efficient excitons formation. The significant rise in the efficiency of devices B–D is attributed to the formation of a narrow recombination zone and the efficient prevention of leakage of hole from the emission layer into the Alq_3 layer and increasing the probability of QAD exciton formation, in which both charge carriers and excitons are confined. Moreover, the electron mobility of BAlq and BPhen is much higher than that of Alq_3 and HBL which will increase the injection of electrons, especially at the high electric field as reported in the literature [21]. The holes which accumulate at the Alq_3/HBL interface will increase the electric field in the HBL which will further assist the electron injection. Introduction of DHBL as the hole-blocking layer in device B not only increases hole concentrations but also increases the electron injection in the emitting zone, and as a result, the efficiency of the device will increase because of the increase of the charge balance. It has therefore been suggested that the resulting staircase arrangement of electron-transporting molecular levels must improve charge transport.

4. Conclusion

In summary, organic light-emitting devices with a narrow recombination zone confined by an organic double-block layer structure were reported. The device using BAlq/BPhen as the hole-blocking/electron-transporting layer shows superior performance, the maximum efficiency and luminance of the device are 9.16 $cd\,A^{-1}$ and 23 750 $cd\,m^{-2}$, respectively.

Acknowledgments

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