Low-voltage and high-efficiency stacked white organic light-emitting diodes

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We report a white stacked organic light-emitting device (SOLED) with high efficiency and low drive voltage by using Bphen:Li/WO_3 as the interconnecting layer. The SOLED have been fabricated by connecting two low-voltage driving white units with conductive transport layers. The stacked two-unit device produced two higher luminance efficiency than that expected of a single-unit device. A maximum efficiency of 17cd/A was achieved by the stacked device comprised of two white-fluorescent OLEDs. It is also found that the power efficiency of stacked white organic light-emitting device is enhanced by 53% as compared to the control device.

(Received April 28, 2010; accepted May 20, 2010)

Keywords: Organic emitting diode, Low-voltage, Stack, White EL devices

1. Introduction

White organic light emitting diodes (OLEDs) have attracted wide attention in view of practical applications for displays and lighting [1-4], since Kido et al. reported the white OLEDs in the year of 1995 [5]. Currently, one major obstacle confronted by the application of OLEDs is on how to enhance the efficiency of OLEDs. Except for novel material usage to improve the performance of OLEDs, the structure design of device is very vital in practice as well. Many researchers used new types of diode structure to improve the quality of OLEDs. Kido [6] and his Japanese colleagues proposed the concept of stacked OLEDs, that is, two or more vertically stacked light-emitting units can form a diode, in which different light-emitting units are connected by the charge generation layer. This layer, for satisfying the requirement of conductivity and transparency, is generally made of high-conductivity thin metal films, indium tin oxide (ITO) conductive films, or doped organic films. Using stacked structure to prepare the white OLEDs can have the benefits of high efficiency, high brightness, and prolonging the lifetime of the device. In particular, it has the potential to apply in full-color LED display and solid-state lighting [7,8]. Forrest et al[9] used the blue fluorescence, green and red phosphorescence as the emitter to generate high-efficiency white light, in which MoOx is served as the charge generation layer. Lee et al. [10] prepared the white stacked OLEDs by using Cs_2CO_3/MoO_3 as the charge generation layer, the current efficiency of which can reach a maximum of 17cd/A.

Stacked structure is a good way to generate highly efficient white-light emission. However, because of internal structure characteristics, the drive voltage is relatively high compared to other OLEDs, which limits the application of stacked technique to some extent. In the present study, firstly, we introduced the high-conductivity carrier transport layer to the white OLEDs and fabricated low-voltage driving white device. On such a basis, we stacked two low-voltage light-emitting units together to obtain the high-efficiency but low-voltage white emission.

2. Experiment design

The devices were fabricated on glass substrates precoated with indium tin oxide (ITO) with a sheet resistance of 20Ω/square. After routine chemical cleaning, ITO was further treated by oxygen plasma processes. The organic layers, charge generation layer and the cathode LiF/Al were sequentially deposited by conventional vacuum vapor deposition in the chamber without breaking the vacuum. The pressure of the chamber was kept at 8×10^{-4}Pa. The layer thickness and the deposition rate of organic and inorganic materials were monitored in situ by an oscillating quartz thickness monitor. The doped functional layers layer was coevaporated from separate heating sources. The electroluminescent (EL) spectrum and the Commission Internationale de I'Eclairage (CIE) coordinates were measured by PR650 Spectroscanner, the luminance–current-voltage (L–I–V) characteristics were measured by Keithley 2400 Source Meter. The molecular structures of the main organic materials and schematic structure of devices are shown in Fig. 1.

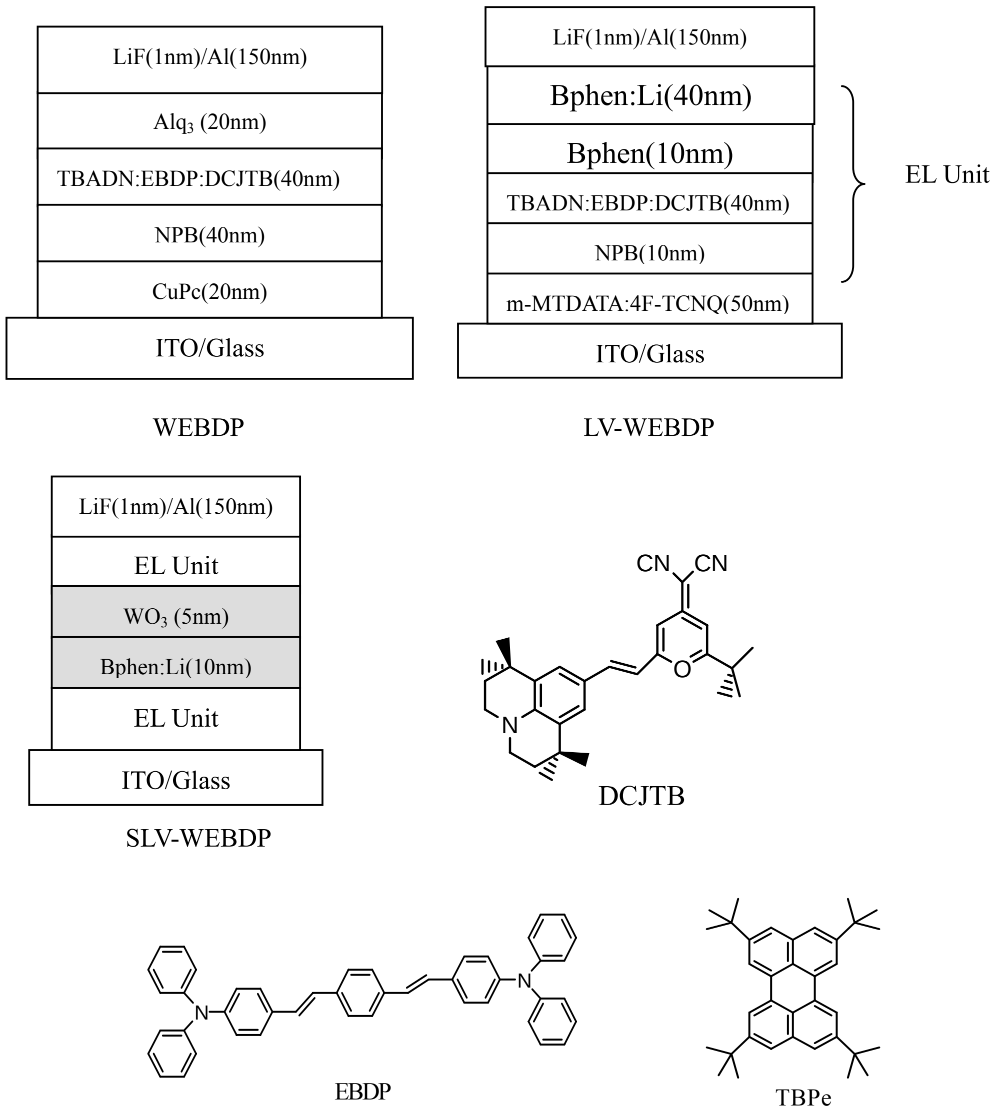

Fig. 1. Molecular structures of the organic materials and device configuration.

In the experimental period, a conventional white organic light-emitting device (WEBDP), a low-voltage white OLED (LV-WEBDP) and a stacked low-voltage white OLED (SLV-WEBDP) were prepared. The corresponding device structures are listed as follows:

WEBDP: ITO/CuPc/ NPB/ TBADN:EBDP:DCJTB/Alq_3/LiF/Al

LV-WEBDP:ITO/m-MTDATA:4F-TCNQ/NPB/TBADN:EBDP:DCJTB/Bpen/Bphen:Li/LiF/Al

SLV-WEBDP:ITO/m-MTDATA:4F-TCNQ/NPB/TBADN:EBDP:DCJTB/Bphen/Bphen:Li/WO_3/m-MTDATA:4F-TCNQ/NPB/TBADN:EBDP:DCJTB/Bpen/Bphen:Li/LiF/Al

Here, copper phthalocyanine(CuPc) is served as the buffer layer,N,N'-bis(1-naphthyl)-N,N'-diphenyl-1.1'-bipheny1-4-4'-diamine (NPB) is the hole transport layer, Alq_3 and Bphen are the electron transport layers. For reducing the drive voltage, the high-conductivity m-MTDATA:F4-TCNQ and Bphen:Li were inserted to serve as the hole and electron injection layer. The TBADN layer is simultaneously doped with blue dye EBDP and red dye DCJTB. White emission was obtained through an incomplete energy transfer of TBAND to EBDP and DCJTB in the same layer. The optimal dopant quality concentrations for EBDP and DCJTB were 3% and 1%, respectively. Bphen:Li /WO_3 was charge generation layer for the stacked devices. Here, the organic layers, between the ITO anode and LiF/Al cathode in the LV-WEBDP diode in Fig. 1, are defined as an electroluminescent (EL) unit.

3. Results and discussion

The electroluminescence(EL) spectra of devices is shown in Fig. 2. It is seen that the shape of the EL spectra of these devices is quite similar, and spectral peaks of all the three ones appeared at 460nm, 490nm and 560nm. At current density of 20mA/cm^2, the coordinates of CIE chromaticity diagram for all the diodes were consistently at (0.33, 0.42), exhibiting stable white color. There is practically no EL color shift with varying drive currents of the devices.

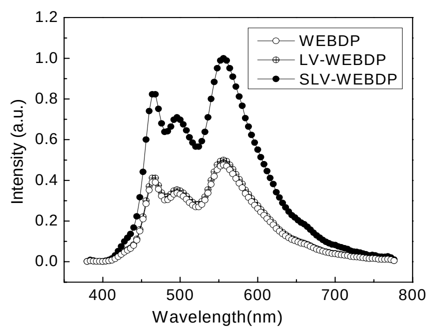

Fig. 2. EL spectra of devices.

Typical luminance-voltage characteristics of the devices are plotted in Fig. 3. It is shown that device LV-WEBDP has much superior characteristics than WEBDP. The insertion of high-conductivity m-MTDATA:4F-TCNQ and Bphen:Li can remarkably reduce the drive voltage of LV-WEBDP. At a luminance of 16000cd/m^2, the drive voltage of diode LV-WEBDP is 9.6V, which has been reduced by 36% compared to that of diode WEBDP. Owing to the inherit characteristics of the stacked structure, i.e., two embedded EL units in a tandem structure, the drive voltage of stacked diode SLV-WEBDP is remarkably increased compared to WEBDP. At a luminance of 16000cd/m^2, the voltage for SLV-WEBDP is 14.2V. The turn-on voltages for WEBDP, LV-WEBDP and SLV-WEBDP were 4.3V, 3.2V and 5.5V respectively. Therefore, it can reduce the drive voltage and turn-on voltage through the way of adding high-conductivity carrier injection and transport layers, followed by accelerating the injection and transport rates.

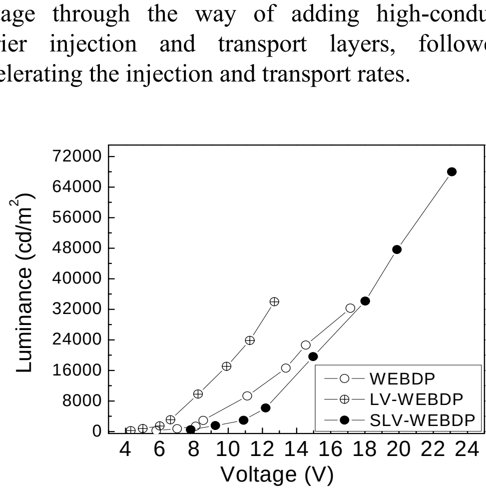

Fig. 3. Luminance variation with voltage of devices.

Fig. 4 was the current density and voltage relation curves for the diodes. It is clearly seen that the drive voltage for LV-WEBDP is remarkably reduced by the insertion of high-conductivity m-MTDATA:4F-TCNQ and Bphen:Li. At current density of 200mA/cm^2, the drive voltage for LV-WEBDP is 9.9V, reduced by 35% compared to that of WEBDP. As expected, the drive voltage of stacked device SLV-WEBDP is much higher than that of the control device due to the large vertical stack structure. At the current density of 200mA/cm^2, the drive voltages for the LV-WEBDP and SLV-WEBDP were 5.9V and 10.8V, respectively. As shown in relation curve of the luminance and current density (Fig. 5), the luminance for stacked diode SLV-WEBDP is remarkably enhanced than those of WEBDP and LV-WEBDP. At the current density of 20mA/cm^2, the luminance for SLV-WEBDP was 2975cd/m^2, while the luminance for WEBDP and LV-WEBDP were 1413 cd/m^2 and 1487cd/m^2, respectively.

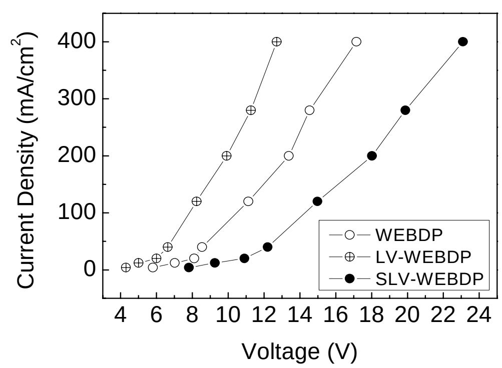

Fig. 4. Current density variation with voltage of devices.

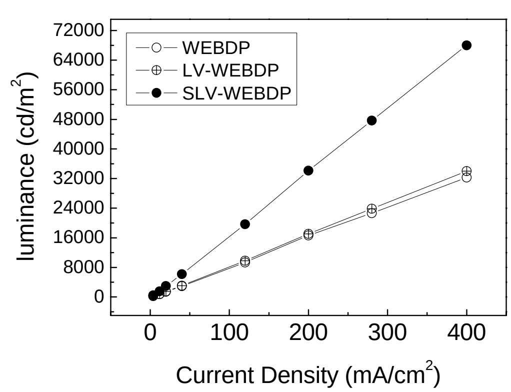

Fig. 5. Luminance variation with drive current density of devices.

Fig. 6 is the current efficiency-current density relation plot, while Fig. 7 is the power efficiency- current density relation curve. It is clearly seen that stacked structure also substantially increased the efficiency of the diodes. At the current density of 20mA/cm^2, the current efficiency for the white stacked diode SLV-WEBDP was 14.9cd/A, while the efficiency for not-stacked diodes WEBDP and LV-WEBDP were 7cd/A and 7.4cd/A. The stacked diode SLV-WEBDP reached the maximal current efficiency of 17cd/A. At the same current density, the current efficiency of the stacked diode is 2.3 times over those for conventional not-stacked diodes. All the three devices have the same chromaticity (0.33, 0.42), indicating a relatively high color purity. As showed in Fig. 7, the power efficiency for diodes LV-WEBDP and SLV-WEBDP is significantly higher than that of WEBDP. When the current density is at 20mA/cm^2, the power efficiency for the diodes SLV-WEBDP, LV-WEBDP, and WEBDP were 4.3lm/W, 3.9lm/W, and 2.8lm/W respectively. The efficiency for SLV-WEBDP increased by 53% compared to that of WEBDP.

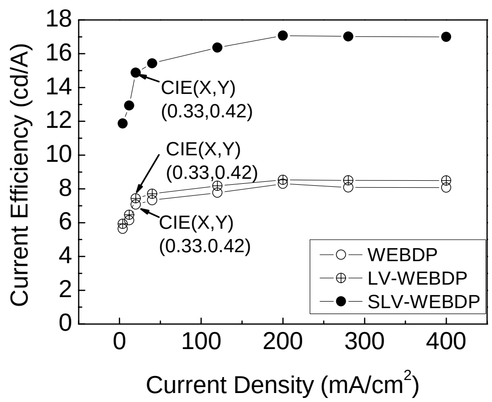

Fig. 6. The luminance efficiency–current density characteristics of devices.

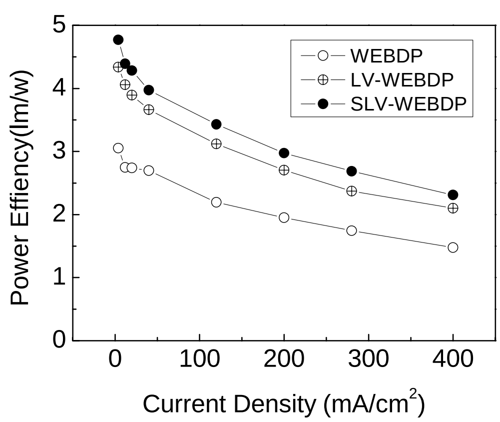

Fig. 7. Power efficiency–current density characteristics of devices.

4. Conclusions

The white organic light-emitting device with high efficiency and low drive voltage was fabricated by introducing the high-mobility carrier injection and transport layers into the stacked diodes. The stacked two-unit device produced two higher luminance efficiency than that expected of a single-unit device. A maximum efficiency of 17cd/A was achieved by the stacked device comprised of two white-fluorescent OLEDs. It is also found that the power efficiency of stacked white organic light-emitting device is enhanced by 53% as compared to the control device. The operational lifetime of the tandem OLEDs may also be substantially improved because of high brightness and high EL efficiency at low current density. The kind of structure should be an effective and promising way to generate high-efficiency white light emission.

Acknowledgements

This work was supported by the National Natural Science Foundation of China [No.90202034] and Youth Foundation of China University of Mining and Technology (2007A051).

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