Improved performance of organic light-emitting diodes with dual electron transporting layers*

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In this study the performance of organic light-emitting diodes (OLEDs) are enhanced significantly, which is based on dual electron transporting layers (Bphen/CuPc). By adjusting the thicknesses of Bphen and CuPc, the maximal luminescence, the maximal current efficiency, and the maximal power efficiency of the device reach 17570 cd/m^2 at 11 V, and 5.39 cd/A and 3.39 lm/W at 3.37 mA/cm^2 respectively, which are enhanced approximately by 33.4%, 39.3%, and 68.9%, respectively, compared with those of the device using Bphen only for an electron transporting layer. These results may provide some valuable references for improving the electron injection and the transportation of OLED.

Keywords: organic light-emitting diodes, dual electron transporting layers, CuPc

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1. Introduction

Organic light-emitting diodes (OLEDs) have attracted extensive attention because of their potential applications in solid-state lighting and large flat panel displays. Commercial application of OLEDs requires high brightness, efficiency, and an extended lifetime. Consequently it is very necessary for the light emission to run at a low driving voltage, since a high driving voltage will reduce the lifetime of the device due to thermal aging and impurity diffusion problems.[1−3] Due to the fact that the electron mobility in electron-transport materials (ETMs) is much lower than the hole mobility in typical hole-transport materials (HTMs),[4] studying the enhancement of electron injection, which is crucial for the efficiency of the device would be quite meaningful and practical. Copper phthalocyanine (CuPc) is a well-known organic semiconductor, which is widely used as a hole injection layer (HIL) in OLEDs.[5,6] Also, it was reported to have been used as a buffer layer in preventing sputter damage of a transparent cathode to the OLED layer structure.[7−9] However, its highest occupied molecular orbital (HOMO) is only 5.3 eV which does not seem to be suitable for an electron transporting layer.

In this study, we use both CuPc and Bphen as dual electron transporting layers to improve the ability of electron injection and transportation. By adjusting their thicknesses, the luminescence and the current efficiency are enhanced significantly. The improved performance is further explained by the step barrier provided by the intermediate energy level and the good electron mobility of the CuPc layer.

2. Experiment

The OLEDs were fabricated on indium–tin–oxide (ITO) coated glass substrates with the following device structures:

Device A: ITO/MoO_3 (5 nm)/NPB (30 nm)/ADN (30 nm)/Bphen (40 nm)/LiF (0.8 nm)/Al (120 nm);

Device B: ITO/MoO_3 (5 nm)/NPB (30 nm)/ADN

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(30 nm)/Bphen (30 nm)/CuPc (10 nm)/LiF (0.8 nm)/Al (120 nm);

Device C: ITO/MoO_3 (5 nm)/NPB (30 nm)/ADN (30 nm)/Bphen (20 nm)/CuPc (20 nm)/LiF (0.8 nm)/Al (120 nm);

Device D: ITO/MoO_3 (5 nm)/NPB (30 nm)/ADN (30 nm)/Bphen (10 nm)/CuPc (30 nm)/LiF (0.8 nm)/Al (120 nm).

All the organic layers as well as LiF and Al were deposited onto a pre-cleaned ITO glass substrate with a sheet resistance of 20 Ω/sq, by a thermal evaporation coating system at a pressure of about 2×10^{-4} Pa. The deposition rates and thicknesses of the various layers were monitored using a quartz crystal oscillator. The evaporation rates were 0.1 nm/s–0.3 nm/s, 0.05 nm/s, and 1 nm/s for each organic layer, LiF layer, and Al cathode, respectively. The current density (J)–voltage (V)–luminance (L) and electroluminescence (EL) characteristics of the devices were measured by the Keithley model 2400 programmable voltage–current source and the PR 650 spectra scan spectrometer. And all of the records were carried out at room temperature in air without encapsulation.

3. Results and discussion

ADN was used as the blue emitter in the device tested in this study. ADN is a usual blue host material because of its good electron mobility.[10] It can be clearly seen in Fig. 1 that the current density of the device with dual electron transporting layers is improved compared with that of the device with a single electron transporting layer. At a fixed bias of 8 V, the current densities of devices A, B, C, and D are 32.62 mA/cm^2, 74.47 mA/cm^2, 105.31 mA/cm^2, and 237.42 mA/cm^2, respectively. With a decrease of Bphen thickness and an increase of CuPc thickness, the current density of the device increases gradually. The lowest unoccupied molecular orbital (LUMO) of CuPc is 3.6 eV,[11] which is a beneficial barrier step for the injection of electrons from cathode (4.3 eV) to the LUMO (2.9 eV) of Bphen (Fig. 2). Because of its lower LUMO and good electron mobility, as the thickness of CuPc increases, more electrons will accumulate at the interface between CuPc and Bphen and then reach the LUMO of Bphen, leading to the improved current density.

What is more, the enhancing of the luminescence could be found to be the same as the current density after incorporating dual electron transporting layers in Fig. 1. The values of luminescence at the fixed bias of 8 V are 1141 cd/m^2, 2831 cd/m^2, 4357 cd/m^2, and 6339 cd/m^2 for device A, B, C, and D, respectively. This could be explained by the easier electron injection from cathode to CuPc, thereby increasing the number of electrons reaching the emitting layer (EML). Also, the HOMO of Bphen is 6.4 eV which could effectively prevent holes from transporting towards the cathode. Consequently, the recombination rate of holes and electrons would be enhanced and more excitons would be created, resulting in the higher luminescence of the device.

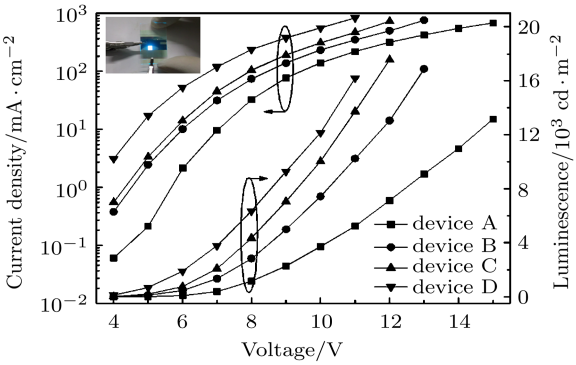


Fig. 1. (colour online) Dependences of current density and luminescence on voltage characteristics for the devices.

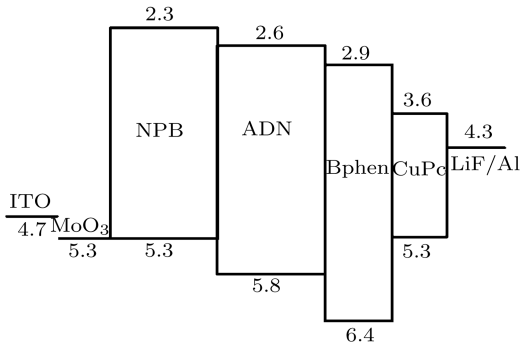


Fig. 2. Energy level diagram of the devices.

The balance between holes and electrons in the recombination zone is a crucial factor for the high efficiency of the device. The dependence of current efficiency on current density is shown in Fig. 3. The maximal current efficiencies are 3.87 cd/A, 4.44 cd/A, 5.39 cd/A, and 4.07 cd/A for devices A, B, C, and D, respectively. For device A, its electron transporting layer is just a single Bphen layer, consequently the number of holes in the recombination zone is more than that of electrons, due to the fact that the mobility of hole transport material is much greater than that of electron transport material for general organic material, which almost exits in all simple ordinary

devices,[12] resulting in the low current efficiency. But when inserting a CuPc layer between Bphen and the cathode, the current density increases immediately, which indicates that more electrons could be injected into the recombination zone easily. So the balance between holes and electrons would be improved gradually while the thickness of CuPc increases and that of Bphen decreases. When the thicknesses of Bphen and CuPc are adjusted to 10 nm and 20 nm, the current efficiency and the power efficiency reach the highest values of 5.39 cd/A and 3.39 lm/W respectively, which implies that the balance between holes and electrons in device C is best. However, the current efficiency of device D decreases, which is because the number of electrons is more than that of holes in the recombination zone and a new imbalance is created again.

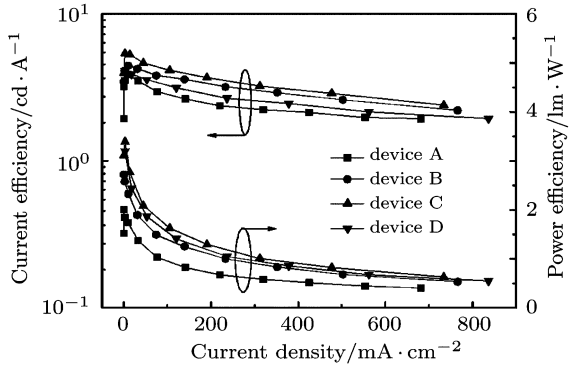


Fig. 3. Dependences of current efficiency on current density characteristic for the devices.

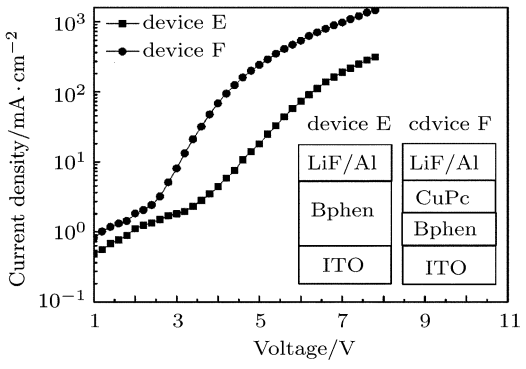


Fig. 4. Dependences of current density on voltage and the structure (inset) of the electron-only devices.

To further clarify the effect of the dual electron transporting layer, the electron-only devices with the structures of ITO/Bphen (40 nm)/LiF (0.8 nm)/Al (120 nm) (Device E) and ITO/Bphen (20 nm)/CuPc (20 nm)/LiF (0.8 nm)/Al (120 nm) (device F) are designed and their dependences of current density on voltage are shown in Fig. 4, in which it could be clearly found that the current density of device F is indeed higher than that of device E. Hence, the higher current density should be induced by the insertion of a CuPc electron transporting layer. This indicates that dual electron transporting layers are more beneficial for the injection and transportation of electrons.

4. Conclusions

In this paper, a simple blue organic light-emitting diode is fabricated based on dual electron transporting layers. Compared with the performance of the ordinary device with a single Bphen electron transporting layer, the performance of the device in this study was improved significantly. With the optimal thicknesses of Bphen and CuPc, the maximal luminescence, maximal current efficiency and maximal power efficiency of the device reach 17570 cd/m^2 at 11 V, 5.39 cd/A and 3.39 lm/W at 3.37 mA/cm^2, respectively, which indicates that this work may provide some valuable references for improving the injection and the transportation of electrons in OLEDs.

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