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Study on the influences of quantum well structure on the performance of organic light emitting devices

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ABSTRACT

In this paper, six organic light emitting devices with different quantum well cycles and different position of well structures have been demonstrated. These well structures were composed by N,N′-diphenyl-N,N′-bis(1-napthyl)-1,1′-biphenyl-4,4′-diamine and tris-(8-hydroxyquinoline) aluminum, or tris-(8-hydroxyquinoline) aluminum and 2,9-dimethyl-4,7-diphenyl-1,10-phenanthroline. The device with one cycles well structure as electron transporting layer exhibits the highest brightness 3354 cd/m^2 and current efficiency of 3.46 cd/A. The current efficiency improved owing to carrier confinement and higher exciton formation probability in the well layer. Results illustrated that using proper period of well structure could improve the current efficiency of organic light emitting device and using well structure as electron transporting layer are better than as hole-transporting layer.

1. Introduction

Quantum well structure (QWS) devices have been studied in inorganic area for many years. It plays a very important role in improving the performance of semiconductor optoelectronic devices. The studies of organic quantum well structure devices began in 1989, So et al. [1,2] firstly reported organic multiple quantum well structures (OMQWs) using composition of 3,4,9,10-perylenetetracarboxylic dianhydride (PTCDA) and 3,4,7,8-naphthalenetetracarboxylic dianhydride (NTCDA). The exciton confinement effect has been obtained similar to inorganic semiconductors. OMQWs were recognized to conduce to the enhancement of the performance of organic light-emitting diodes (OLEDs) [3–12]. Qiu et al. introduced an effective method to reduce the hole mobility by using an organic multiple QWS as the hole-transporting layer, which corresponded to type-I QWS [13,14]. Yang et al. [15] have reported a quantum-well-like structure device, and illustrate that the QWS could increase the carrier trapping and recombination probabilities, as a result, a lower current density and higher luminance intensity were achieved.

In this paper, the properties of organic devices with multi-period QWS, which consisted of alternate N,N′-diphenyl-N,N′-bis(1-napthyl)-1,1′-biphenyl-4,4′-diamine (NPB) and tris-(8-hydroxyquinoline) aluminum (Alq_3) as hole-transporting layer (HTL), or Alq_3 and 2,9-dimethyl-4,7-diphenyl-1,10-phenanthroline (BCP) as electron transporting layer (ETL), were investigated. The electroluminescent characteristics of these devices have been studied. Improved brightness and current efficiency was obtained in QWS devices compare with the conventional three-layer device. Under our experimental conditions, the device with one cycles QWS as ETL got the optimal efficiency. The results indicated that using appropriate period QWS could effectively enhancing the current efficiency of OLEDs, and it is better using QWS as ETL than as HTL.

2. Experimental details

To fabricate the OLEDs, an indium tin oxide (ITO) glass with a resistivity of 60 Ω/□ was used as the substrate. The ITO surface was cleaned followed by in acetone, ethanol and deionized water using an ultrasonic bath, and was then dried using nitrogen gas. Organic layers were sequentially deposited in vacuum, at a base pressure of 5×10^{-5} Pa. The chemical structures of the organic materials are shown in Fig. 1. The powders of NPB, Alq_3 and BCP were loaded to separate Knudsen cell. The cells were subsequently heated up to sublimate at a growth rate of about 0.03–0.06 nm/s, which was determined by an oscillating quartz thickness monitor located close to the substrates. Al cathode was prepared in another vacuum chamber with atmospheric pressure of 8×10^{-4} Pa, the evaporation rate is 1 nm/s. The thickness of Al cathode was about 100 nm. The active area was about 9 mm^2. Measurements of current–voltage characteristics were made with a Keithley Source Meter (Model 2410). EL spectra were measured with CCD. All the measurements were performed in air at room temperature.

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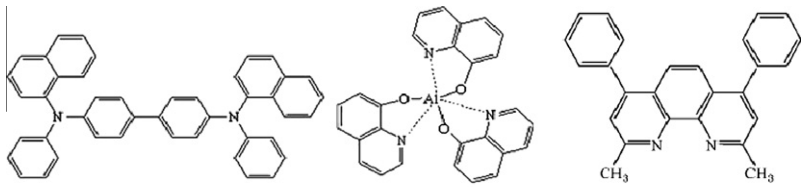

NPB Alq3 BCP

Fig. 1. Chemical structures of the organic materials.

3. Results and discussion

For comparing the performance of organic light emitting devices with QWS as HTL, including current density, brightness and current efficiency, the ITO/$(NPB/Alq_3)_x$/NPB/Alq_3/BCP/Al structure devices have been fabricated. Here the x is the well cycles of HTL varying from 0 to 3, and we named these devices as device A, B, C and D. All the structures of devices have been fabricated in our studies were shown in Table 1. Improved efficiency has been obtained because of the introduction of QWS as HTL.

The highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) levels of NPB are −5.5 and −2.3 eV, and those of Alq_3 are −5.8 and −3.0 eV, respectively. From the energy diagram of the organic QWS shown in Fig. 2, we know that the Alq_3 layer acts as potential well layer and NPB as potential barrier layer of electrons. Device A is a traditional three-layer device. Device B, C and D are the devices with one, two and three cycles QWS as HTL, respectively. The current density–voltage characteristic curves of these four devices were shown in Fig. 3. From this figure, one can see that the current density is decreasing as the period number of QWS becomes larger under a constant voltage. The reason is that device B, C, and D are QWS devices according to their energy level structures shown in Fig. 2a. Some of the holes would be limited at the NPB/Alq_3 interface because of the energy barrier when the devices working, and the limit effect would enhance as the cycle of well become larger. We know that the current density is the total of hole current density and electron current density. Therefore, current density decreases as the cycle of well structure increasing under the same driving voltage. Fig. 4a and b shows the brightness and current efficiency vs. current density properties of these four devices. When the cycle is smaller than 3, the brightness and current efficiency increases when the cycle of well changing from 0 to 3 under the same current density. The maximum brightness and current efficiency of the traditional device (device A) are 1140 cd/m^2 and 1.38 cd/A. We got the maximum brightness 1575 cd/m^2 and current efficiency 2.41 cd/A of all these four devices from device C with 2-periodic well structure as HTL. We knew that the mobility of holes in NPB is much larger than the mobility of electrons in Alq_3 in traditional three-layer device. Holes are the majority carriers. Thus the holes and electrons are not balance in the emitting zone. In the devices with QWS as HTL, the well structure could effectively limit holes (majority carrier) transport because of the existence of the energy barrier at the interface of NPB/Alq_3 when the device is working. Therefore, the current of the electrons and holes will be more balance. This limit effect could enhance when the cycle of QWS increasing. Thus the

Table 1
The structures of all the devices have been fabricated in this research.

x	Device structures
A	ITO/NPB(40 nm)/Alq_3(30 nm)/BCP(15 nm)/Al
B	ITO/NPB(40 nm)/Alq_3(3 nm)/NPB(5 nm)/Alq_3(27 nm)/BCP(15 nm)/Al
C	ITO/NPB(40 nm)/$[Alq_3(3\ nm)/NPB(5\ nm)]_2$/$Alq_3$(24 nm)/BCP(15 nm)/Al
D	ITO/NPB(40 nm)/$[Alq_3(3\ nm)/NPB(5\ nm)]_3$/$Alq_3$(21 nm)/BCP(15 nm)/Al
E	ITO/NPB(40 nm)/Alq_3(15 nm)/BCP(7.5 nm)/Alq_3(15 nm)/BCP(7.5 nm)Al
F	ITO/NPB(40 nm)/Alq_3(10 nm)/BCP(5 nm)/$[Alq_3(10\ nm)/BCP(5\ nm)]_2$/Al

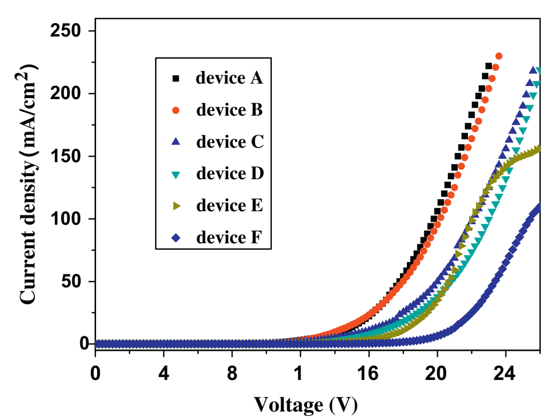

Fig. 3. The current density–voltage properties of all the six devices.

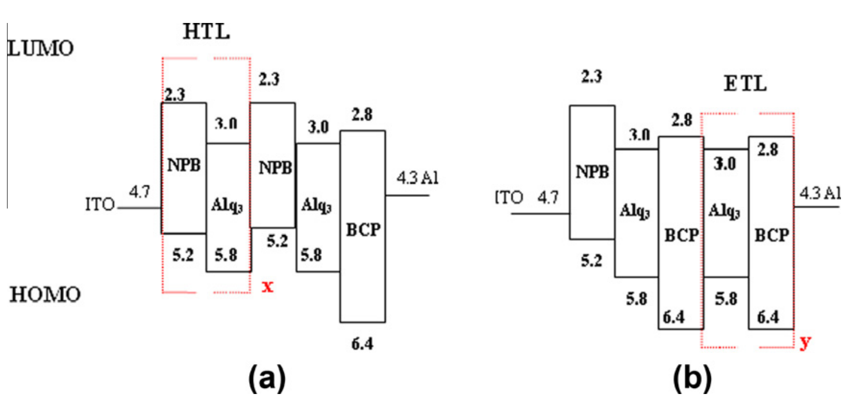

Fig. 2. The energy diagram of device A, B, C and D with the value of x is 0, 1, 2 and 3 (a); device E, F with the value of y is 1 and 2 (b).