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The effect of various electrodes on the properties of electroluminescent devices with potassium chloride inside tris (8-hydroxyquinoline) aluminum

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ABSTRACT

The performance of organic light-emitting diodes (OLED), based on NPB/Alq_3/KCl/Alq_3 active regions, with various anode (i.e. ITO and ITO/MoO_3) and cathode (i.e. Al and LiF/Al) structures is compared. NPB, Alq_3, KCl, ITO, MoO_3, Al and LiF are N,N′-bis-(1-naphthl)-diphenyl-1,1′-biphenyl-4,4′-diamine, tris (8-hydroxyquinoline) aluminum, potassium chloride, indium-tin oxide, molybdenum trioxide, aluminum and lithium fluoride, respectively. When bare Al is used as a cathode, both luminance and efficiency are improved by the insertion of KCl inside Alq_3 (**anode**/NPB/Alq_3/KCl/Alq_3/Al), compared to a control device (**anode**/NPB/Alq_3/Al). This is attributed to trap sites induced by KCl layer, which give a better recombination in the devices. However, if the cathode is LiF/Al, the performance of control device (**anode**/NPB/Alq_3/LiF/Al) is superior to that of devices with KCl inside Alq_3 (**anode**/NPB/Alq_3/KCl/Alq_3/LiF/Al), which is attributed that the probability of electron injection from cathode is decreased.

1. Introduction

In the last decade, tremendous progress has been made in the science and technology of organic light-emitting diodes (OLEDs) [1–4]. OLEDs have attracted considerable attention due to its extensive commercial applications [5], and in fact, OLED displays are now a commercial reality. Intense academic and industrial interest has resulted in a vast number of publications and patents in the area.

In previous works [6,7], we reported the efficiency and EL intensity improvements of OLEDs with potassium chloride (KCl) inserted inside tris (8-hydroxyquinoline) aluminum (Alq_3) layer. The structure of devices was ITO/NPB/Alq_3/KCl/Alq_3/Al in the literature, where ITO (indium-tin oxide) and Al (aluminum) are used as anode and cathode, respectively, and NPB is N, N′-bis-(1-naphthl)-diphenyl-1,1′-biphenyl-4,4′-diamine. As we all know, the electron injection between Alq_3 and Al is very poor. Such devices have given poor light output and low electroluminescent (EL) efficiency. By inserting a thin buffer layer of lithium fluoride (LiF) between Alq_3 and Al, the EL performance of OLEDs was greatly enhanced [8]. And, recently, molybdenum trioxide (MoO_3) as an anode buffer layer significantly reduces the operational voltage and improves the efficiency and lifetime of OLEDs [9–14], owing to the enhancement of hole injection.

In this study, a series of devices with an "active region" of NPB/Alq_3/KCl/Alq_3, combined with a variety of anode and cathode structures, were fabricated. With the difference in performance due to the anode and cathode structures, this comprehensive comparative study can give some insight into the impact of each of the various electrodes on the device performance and the mechanism for performance enhancement. We demonstrate that the cathode has a great influence on the improving properties of KCl inside Alq_3. Yet, the enhancing properties of KCl in OLEDs are hardly susceptible to the anodes. The results show that the insertion of KCl inside Alq_3 improves the performance of OLEDs with bare Al cathode but not if LiF/Al cathode is employed.

2. Experiment

Indium-tin oxide (ITO) coated glass sheets were used as substrates for the devices. The substrates were cleaned by routine procedure included sonication in detergent, de-ionized water, acetone and alcohol, and finally irradiated in an UV–ozone chamber. The procedure of device fabrication can be found in our previous work [6].

Four groups (groups A–D) of EL devices with various electrode structures were fabricated in the experiment. The device configuration is **anode**/NPB(40 nm)/Alq_3(60-*d* nm)/KCl(1 nm)/Alq_3(*d* nm)/**cathode**, where *d* = 10, 20 and 30. A control device without KCl inside Alq_3 was fabricated as a reference in each group.

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Table 1
The structures and labels of EL devices in the experiment. **Anode**/NPB(40 nm)/Alq_3(60-*d* nm)/KCl(1 nm)/Alq_3(*d* nm)/**cathode**, where *d* = 10, 20 and 30 (group A: ITO anode and Al cathode; group B: ITO/MoO_3 anode and Al cathode; group C: ITO anode and LiF/Al cathode; group D: ITO/MoO_3 anode and LiF/Al cathode). A control device without KCl inside Alq_3 was fabricated as a reference in each group.

Groups	Devices			
Group A (ITO anode and Al cathode)	A0 NPB/ Alq_3	A1 (*d* = 10 nm) NPB/Alq_3(50 nm)/KCl/ Alq_3(10 nm)	A2 (*d* = 20 nm) NPB/Alq_3(40 nm)/KCl/Alq_3(20 nm)	A3 (*d* = 30 nm) NPB/Alq_3(30 nm)/KCl/ Alq_3(30 nm)
Group B (ITO/MoO_3 anode and Al cathode)	B0 NPB/ Alq_3	B1 (*d* = 10 nm) NPB/Alq_3(50 nm)/KCl/Alq_3 (10 nm)	B2 (*d* = 20 nm) NPB/Alq_3(40 nm)/KCl/Alq_3(20 nm)	B3 (*d* = 30 nm) NPB/Alq_3(30 nm)/KCl/ Alq_3(30 nm)
Group C (ITO anode and LiF/Al cathode)	C0 NPB/ Alq_3	C1 (*d* = 10 nm) NPB/Alq_3 (50 nm)/KCl/ Alq_3(10 nm)	C2 (*d* = 20 nm) NPB/Alq_3(40 nm)/KCl/Alq_3(20 nm)/ Al	C3 (*d* = 30 nm) NPB/Alq_3(30 nm)/KCl/ Alq_3(30 nm)
Group D (ITO/MoO_3 anode and LiF/Al cathode)	D0 NPB/ Alq_3	D1 (*d* = 10 nm) NPB/Alq_3(50 nm)/KCl/ Alq_3(10 nm)	D2 (*d* = 20 nm) NPB/Alq_3(40 nm)/KCl/Alq_3(20 nm)	D3 (*d* = 30 nm) NPB/Alq_3(30 nm)/KCl/ Alq_3(30 nm)

The labels of EL devices (groups A–D) are summarized in Table 1 and the configuration of EL devices is illustrated in Fig. 1a.

In group A, the anode and cathode are ITO and Al, respectively.
For group B, ITO/MoO_3 (3 nm) is used as an anode and the cathode is Al.
And in group C, the anode and cathode are ITO and LiF (0.5 nm)/Al, respectively.
Further, in group D, the anode is ITO/MoO_3 (3 nm) and the cathode is LiF (0.5 nm)/Al.

To further investigate the functionality of KCl layer in OLEDs, other two groups of electron-only devices with different cathodes (groups E and F) were prepared as follows:

Group E: ITO/BCP(15 nm)/Alq_3(60-*d* nm)/KCl(1 nm)/Alq_3(*d* nm)/Al (*d* = 10, 20 and 30 labeled as E1–E3, respectively) and ITO/BCP (15 nm)/Alq_3(60 nm)/Al (E0) as a control device;
Group F: ITO/BCP(15 nm)/Alq_3(60-*d* nm)/KCl(1 nm)/Alq_3(*d* nm)/LiF(0.5 nm)/Al (*d* = 10, 20 and 30 labeled as F1–F3, respectively) and ITO/BCP(15 nm)/Alq_3(60 nm)/LiF(0.5 nm)/Al (F0) as a control device.

And the labels and configuration of electron-only devices (groups E and F) are shown in Table 2 and Fig. 1b, respectively.

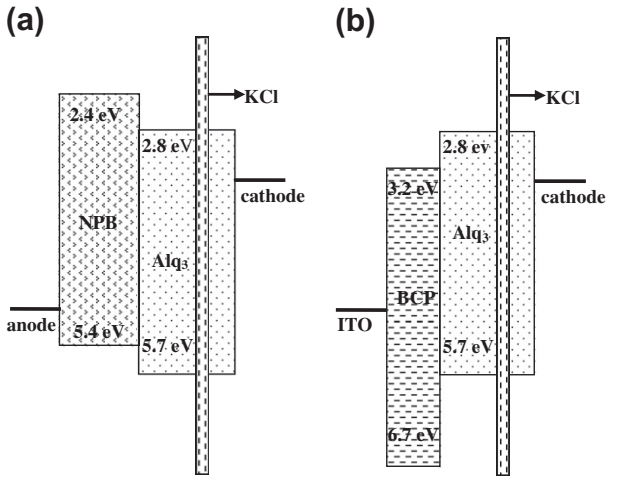

Fig. 1. The configurations and the energy level diagram of devices in the experiment. (a) EL devices: **anode**/NPB(40 nm)/Alq_3(60-*d* nm)/KCl(1 nm)/Alq_3(*d* nm)/**cathode**. (b) Electron-only devices: ITO/BCP(15 nm)/Alq_3(60-*d* nm)/KCl(1 nm)/Alq_3(*d* nm)/**cathode**. Herein, *d* = 10, 20 and 30.

Table 2
The structures and labels of electron-only devices in the experiment. ITO/BCP(15 nm)/Alq_3(60-*d* nm)/KCl(1 nm)/Alq_3(*d* nm)/**cathode**, where *d* = 10, 20 and 30 (the cathodes of groups E and F are Al and LiF/Al electrode, respectively). A control device without KCl inside Alq_3 was fabricated as a reference in each group.

Groups	Devices			
Group E (Al cathode)	E0 BCP/ Alq_3	E1 (*d* = 10 nm) BCP/ Alq_3(50 nm)/ KCl/ Alq_3(10 nm)	E2 (*d* = 20 nm) BCP/ Alq_3(40 nm)/ KCl/Alq_3(20 nm)	E3 (*d* = 30 nm) BCP/ Alq_3(30 nm)/ KCl/ Alq_3(30 nm)
Group F (LiF/Al cathode)	F0 BCP/ Alq_3	F1 (*d* = 10 nm) BCP/ Alq_3(50 nm)/ KCl/ Alq_3(10 nm)	F2 (*d* = 20 nm) BCP/Alq_3 (40 nm)/KCl/ Alq_3(20 nm)	F3 (*d* = 30 nm) BCP/ Alq_3(30 nm)/ KCl/ Alq_3(30 nm)

In all devices of groups A–F, *d* is the distance of KCl interlayer away from the cathode and designed as 10, 20 and 30 in nanometers, respectively.

The overlap between anode and cathode was 3×3 mm^2 as the emissive area of devices. Current–voltage–luminance characteristics were recorded by using a Keithley source measurement unit (Keithley 2410) with a silicon photodiode (Newport Optical Power Meter Model 1830-C) calibrated by PR-650 spectrometer. All the measurements were carried out under ambient atmosphere at room temperature.

3. Results and discussion

The structures of group A are ITO/NPB(40 nm)/Alq_3(60-*d* nm)/KCl(1 nm)/Alq_3(*d* nm)/Al, where *d* = 10, 20 and 30, labeled as A1–A3, respectively, and ITO/NPB(40 nm)/Alq_3(60 nm)/Al (A0) as reference. The labels are shown in Table 1. In the Ref. [6], we have discussed the device properties of group A and given a suggested explanation for the effect of KCl inside OLEDs in detail. In this report, the current density–luminance–voltage and current efficiency–current density characteristics (refer to the Ref. [6]) are not shown. Yet, the performance of devices in group A is summarized in Table 3. As can be seen from Table 3, the current density at a voltage of 12 V is decreased by inserting KCl inside Alq_3 and the turn-on voltage (i.e. the voltage required for the luminance of 1 cd/m^2) is a little increased. It is attributed that the trap sites, induced by KCl interlayer inside Alq_3, trap holes which are leakage to the cathode. The holes leakage to the cathode form the hole leakage current. If some of them are trapped by the KCl trap sites