Enhanced Brightness and Efficiency of Organic Light-Emitting Diodes With an LiF in the Alq_3

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***Abstract*—Highly efficient and bright organic light-emitting diodes have been realized by inserting a thin insulating lithium fluoride (LiF) layer in the tris-(8-hydroxyquinoline) aluminum (Alq_3) with conventional organic layers. By comparing the performances of newly devised devices as a function of the position of the LiF in the Alq_3 layer, the authors propose the optimal position of the LiF in the Alq_3 layer. Experimental results show that the efficiency and brightness of the newly devised device with LiF in the Alq_3 layer were seven times higher than that without LiF in the Alq_3 layer.**

***Index Terms*—Carrier injection, lithium fluoride (LiF), organic light-emitting diodes (OLEDs), recombination efficiency.**

I. Introduction

ORGANIC light-emitting diodes (OLEDs) have attracted considerable attention owing to their high brightness, high efficiency, and potential applications in mobile and full-color flat-panel displays [1]–[4]. It is necessary to enhance the efficiency and stability of the OLEDs for their applications. Usually, the hole mobility in the hole transport layer (HTL) is a few orders of magnitude higher than the electron mobility in the electron transport layer (ETL) [5], [6]. To achieve a high level of recombination efficiency, it is important to balance the number of holes and electrons injected from the electrodes into the emission layer (EML) [7], [8].

Recent investigations have been intensively focusing on the improvement of device performance by inserting the interlayer materials [7]–[12]. However, in Alq_3-based OLEDs, Alq_3 was usually used as EML and ETL at the same time, which led to the lowering of performance because the electron–hole recombination occurred randomly in the Alq_3. Therefore, Alq_3-based green light OLEDs required the effective emission region.

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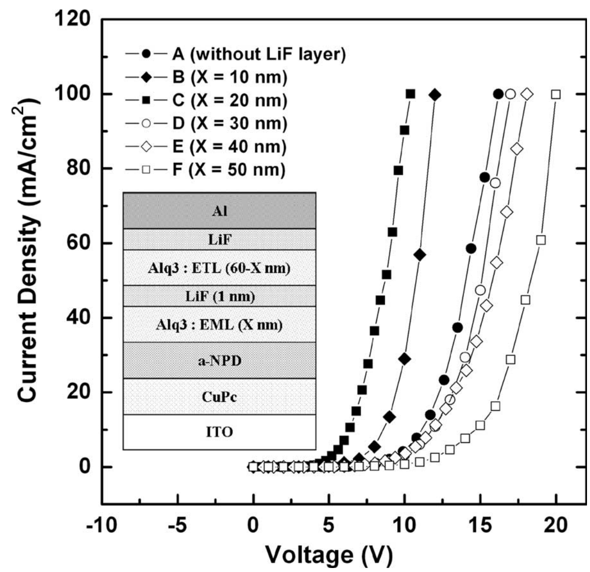

Fig. 1. Current density versus voltage (J–V) in OLEDs with a series of EMLs of various thicknesses by inserting a thin insulating LiF layer in the Alq_3 layer. The J–V characteristics are extremely sensitive to the position of a thin insulating LiF layer in the Alq_3. The inset shows the device structure.

In this letter, OLEDs with a thin insulating lithium fluoride (LiF) layer in tris-(8-hydroxyquinoline) aluminum (Alq_3) are fabricated to improve the recombination probability in the effective emission zone. Because the device performance depends on the position of a thin insulating LiF layer in the Alq_3, we investigated the optimal position of a thin insulating LiF layer in the Alq_3, i.e., the position that will best improve the electron injection, carrier balance, and recombination efficiency.

II. Fabrication

The device structure is detailed in the inset of Fig. 1. The structure of the test device consists of a 30-nm-thick copper phthalocyanine (CuPc) organic layer as a hole injection layer, a 30-nm-thick [N, N'-di(naphthalene-1-yl)-N, N'-diphenyl-benzidine] (α-NPD) organic layer as a hole transporting layer, and a Alq_3 organic layer as an ETL. Electroluminescence (EL) process occurs in the Alq_3 layer, which has no molecular doping. As an anode layer, we used an indium-tin-oxide layer with a thickness of 150 nm and a sheet resistance of $\sim 30\ \Omega/\square$, which was coated onto a glass substrate and had a photolithographically defined emission area of 10 mm $\times$ 10 mm. As a cathode layer, a 1-nm-thick LiF was deposited on top of the ETL. Finally, a 120-nm layer of Al electrode was deposited without breaking the vacuum. Thicknesses of organic layers

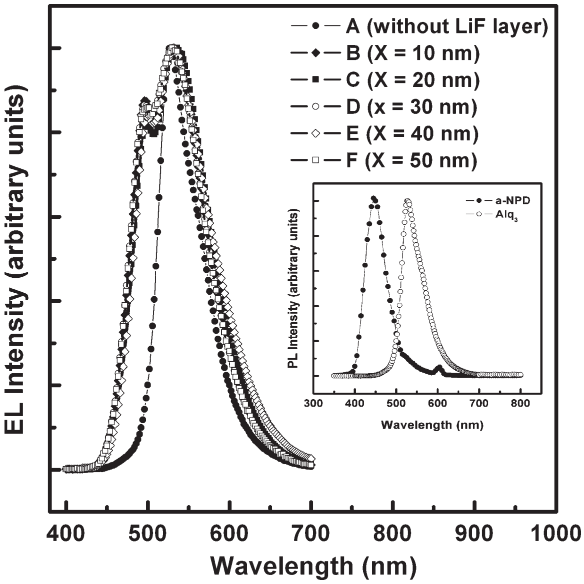

Fig. 2. EL emission spectra of devices with and without a thin insulating LiF layer in the Alq_3 at a current density of 20 mA/cm^2. In addition, full-width at half-maximums (FWHMs) of devices C and A are 102 and 59 nm, respectively. The EL emission wavelengths of devices with an LiF in the Alq_3 get broader toward the blue side than device A. The inset shows the PL spectra of α-NPD and Alq_3.

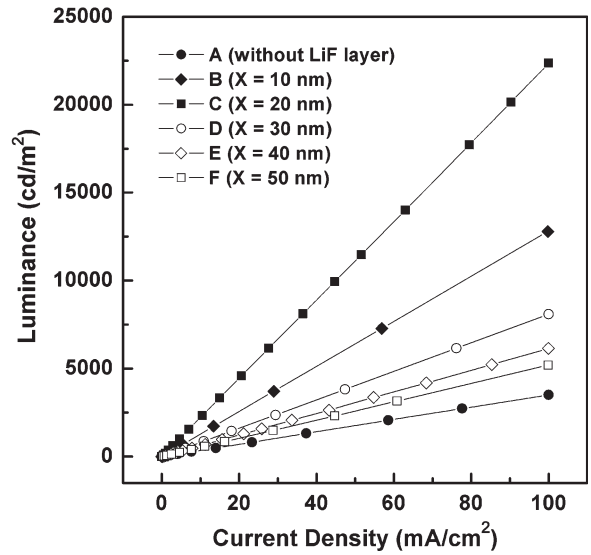

Fig. 3. Luminance versus current density L–J in the OLEDs with a series of EMLs of thicknesses varying from 10 to 50 nm. The devices with a thin insulating LiF layer in the Alq_3 had better luminance characteristics than device A without a thin insulating LiF layer in the Alq_3.

and metal layer were controlled by a programmable SID-242 thin-film codeposition controller (Sigma Instruments, Berlin, Germany).

The total thickness of the Alq_3 was 60 nm, and a thin insulating LiF layer was inserted in the Alq_3 layer to control the effective EML thickness, which varied from 10 to 50 nm. The current density versus voltage measurement was performed using a Keithley 237 source measure unit, and EL properties were obtained using Minolta LS-110 luminance meter and Oriel MS125 Spectrograph.

III. Results and Discussion

The typical current density–voltage (J–V) characteristics of conventional and proposed OLEDs are plotted in Fig. 1. The J–V characteristics of the proposed device with an EML thickness of less than 30 nm show a much higher current at a lower voltage. However, as the EML thickness increases, the driving voltage becomes much higher than that of control device A at the same current level. Device C, in particular, required a driving voltage of $\sim$ 10 V to generate a current density of 100 mA/cm^2 and had a turn-on voltage of $\sim$ 2 V at 1 cd/m^2.

For devices with an LiF layer in the Alq_3, we interpreted the J–V characteristics as follows. Photoemission measurements show that the energy bands of the Alq_3 layer were bent downward when the Alq_3 surface was in contact with the LiF, which led to the lowering in the electronic barrier height of the Alq_3–thin insulating LiF layer interfaces [9], [10]. Therefore, the electrons in the EML were highly mobile and conductive, and so the electron injection of the devices was improved. However, the conductivity of the EML diminished as the thin insulating LiF layer was positioned closer to the metal cathode.

Fig. 2 shows the EL spectra of devices at a current density of 20 mA/cm^2. A shoulder peak of devices with a thin insulating LiF layer in the Alq_3 could be seen at around 490 nm. It is due to the shift of the effective emission area from the bulk area of Alq_3 to the interface of α-NPD and Alq_3 by inserting an LiF in the Alq_3 [10]. The inset in Fig. 2 shows the photoluminescence (PL) spectra of α-NPD and Alq_3.

Fig. 3 shows that the luminances of all devices increase linearly as the current density increases. When the EML thickness increased from 10 to 50 nm at 100 mA/cm^2, the luminances for control devices A to F were 3500, 12 790, 22 350, 8090, 6140, and 5190 cd/m^2, respectively. Device C obtained a brightness of 1000 cd/m^2 but only at a current density of 5 mA/cm^2.

Fig. 4 shows the luminance and power efficiency–current density characteristics of the device with a thin insulating LiF layer in Alq_3 and control device A. By comparing the results of devices A and C, we found that the insertion of a thin insulating LiF layer into the Alq_3 resulted in an increase of luminance efficiency by 22 cd/A. The luminance efficiencies for control devices A to F at a current density of 20 mA/cm^2 are 3.5, 12.8, 22.4, 8.1, 6.2, and 5.2 cd/A, respectively. Furthermore, the power efficiency of device C was the highest of all the devices, as shown in Fig. 4.

The results show that the electron injection, carrier balance, and recombination efficiency of the devices decreased when the effective EML thickness increased by more than 30 nm, although devices D, E, and F were more efficient than device A. The lower efficiency was probably due to the EL quenching with increasing thickness of an EML by inserting an LiF layer. This phenomenon is thought to be due to an increase in resistance according to an increase in the effective emission area and the degradation by joule heating from a high driving voltage. Another reason is that the effective conductivity and density of LiF may vary according to the position of LiF in Alq_3. The diffusion length of LiF and the conductivity in the

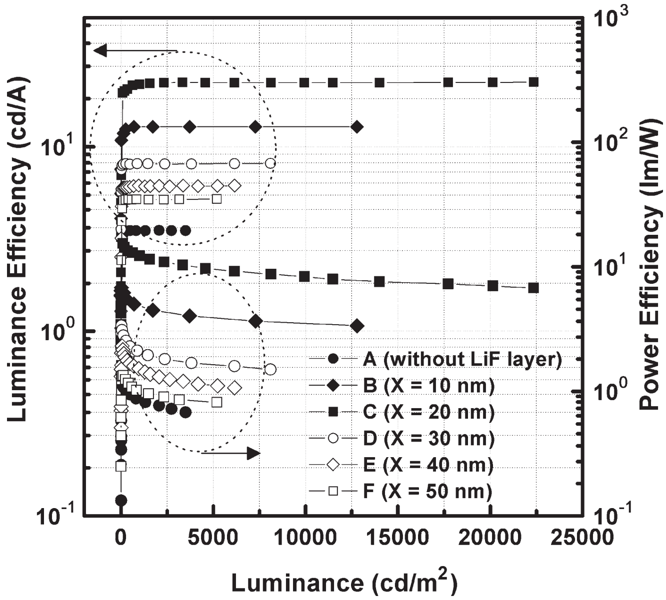

Fig. 4. Luminance efficiency–luminance and power efficiency–luminance characteristics with a series of EMLs of thicknesses varying from 10 to 50 nm.

organic bulk layer are varied by the thickness of the organic layer [13]. As the thickness of the organic layer becomes thicker than the diffusion length of LiF, the high local field generated by accumulated space charges exists around the cathode side. Therefore, the recombination zone shift to metallic electrodes and the position of LiF in the Alq_3 may affect the device performance and quench the excitons [14]. However, as the most investigated buffer in OLEDs, LiF shows quite different optimal thickness at different interfaces [9]–[16], the range of which varies from several angstroms to several nanometers.

The mechanism to improve the device performance is based on the theory that the highest occupied molecular orbital (HOMO) level can be lowered by band bending, and that band bending is induced by the different functions of the Alq_3 layer and the LiF layer, which leads to the lowering of the lowest unoccupied molecular orbital (LUMO) level [9]. The lowering LUMO level infers a shift of the Fermi level toward the Alq_3 LUMO that is indicative of an increase in the carrier density in the bulk [13]. For a α-NPD/Alq_3 bilayer device, it is well known that the α-NPD/Alq_3 interface possesses an electron injection barrier of about 0.6 eV from Alq_3 to α-NPD and a hole injection barrier of about 0.3 eV from α-NPD to Alq_3 [14]. Lowering the LUMO and HOMO levels improves the electron injection into EML and accumulates a hole at an interface between α-NPD and Alq_3. Thus, the high local charge density at an interface between α-NPD and Alq_3 increases the recombination probability of the electrons and holes.

In this letter, device C exhibited the highest luminance efficiency in all the devices. Thus, the optimum thickness is 20 nm for EML and 40 nm for ETL.

IV. Conclusion

We have demonstrated the high efficiency and brightness characteristics of OLEDs by inserting a thin insulating LiF layer at the optimal position in the Alq_3 of conventional structure. OLED performance with optimal thicknesses of EML and ETL by inserting a thin insulating LiF layer was enhanced in terms of electron injection, carrier balance, and recombination efficiency within the emission zone. Finally, very efficient and bright OLEDs can be fabricated simply by using an excellent thin insulating LiF layer instead of using functional organic layers.

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