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Enhanced Brightness and Efficiency in Organic Light-Emitting Devices Using an LiF-Doped Electron-injecting Layer with Aluminium Cathode *

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Organic light-emitting devices (OLEDs) with enhanced brightness and efficiency were developed using an LiF-doped organic layer as an electron-injecting layer besides the aluminium cathode. The typical device structure is glass substrate/indium-tin-oxide/N, N′-bis (3-methyphenyl)-N, N′-diphenylbenzidize/8-tris-hydroxyquinoline aluminium (Alq_3) /LiF-doped Alq_3/Al. An optimized device with an LiF-doped Alq_3 layer showed brightness over 15300 cd/m^2, while the device without the LiF-doped Alq_3 layer exhibited only 3200 cd/m^2, also, the luminance efficiency of the former was 4−5 times as that of the latter. This is another way to improve the OLEDs performance, especially in applications of OLEDs with a large active area.

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Since the discovery of efficient organic light-emitting devices (OLEDs),[1] there has been considerable interest in developing OLEDs with high brightness, high efficiency and long lifetime,[2−6] due to their potential applications in the multicolour flat-panel displays. The brightness and efficiency of OLEDs depend on the number of excitons formed in the emission layer, and also on the balanced injection of carriers into organic materials from the anode and cathode. In addition, the barrier between the indium-tin-oxide (ITO) anode and the hole-transport layer is lower, and the barrier between the metal cathode and the electron-transport layer is higher. Therefore, increasing the electron injection is critical for bright and efficient OLEDs. It was found that the use of low work function metals such as lithium, calcium and magnesium can improve electron injection from the cathode to the 8-tris-hydroxyquinoline aluminium (Alq_3) layer, resulting in higher brightness and efficiency of the devices.[7−9] However, OLEDs with this kind of cathode typically exhibit poor reliability due to the reactive nature of these metals. It is important to use a relatively stable metal cathode, such as aluminium, but the high work function precludes the application of such a metal, because OLEDs based on that kind of cathode are not as bright or efficient as the similar devices with an Li, Ca or Mg cathode. In order to achieve stability better and to retain good performance, insertion of an ultra-thin film of an insulator material, such as LiF, MgO, Al_2O_3, CsF etc., has been made between the organic layer and the aluminium cathode in OLED fabrication.[10−15] Unfortunately, in the fabrication process of the OLEDs with a large active area, it is difficult to achieve an ultra-thin and uniform insulating layer, and the performance of this type of device is very sensitive to thickness variations.

In this letter, using an LiF-doped organic layer between the organic emitting layer and the Al cathode, we fabricated an OLED with enhanced efficiency and brightness. This structure is achieved by co-deposition of the inorganic insulator LiF and the organic material. The use of an LiF-doped organic/cathode structure avoids the difficulty of fabricating an ultra-thin uniform insulating layer in OLEDs with a large active area.

In this study, Alq_3 was the emissive as well as the electron-transport layer, and N, N′-bis (3-methyphenyl)-N, N′-diphenylbenzidize (TPD) is the hole-transport layer. From that, the following structure devices were made: ITO/TPD (60 nm)/Alq_3 (60 nm)/Al (100 nm), ITO/TPD (60 nm)/ Alq_3/Alq_3:LiF/Al (100 nm), where the total thickness of the Alq_3 layer and the Alq_3:LiF layer was kept to 60 nm. The thickness of each layer was measured *in situ* by a quartz oscillating thickness monitor (Model IL-400). Fig. 1 shows the molecular structures of the used organic materials and the configurations of OLEDs. Glass substrates coated with an ITO film (60 Ω/sq) were cleaned by scrabbling and in an ultrasonic bath with toluene, acetone and alcohol, respectively. Then they were rinsed in the deionized water, and finally treated by oxygen plasma.[16] The devices were fabricated by the multiple source organic molecular beam deposition system. The chamber pressure was under 1×10^{-6} Torr. The deposition rates are 0.1−0.2 nm/s for the organic materials, 1−5 nm/min for LiF, and 0.8−1 nm/s for the aluminium cathode. The emitting area was 2×2 mm. The brightness was measured with a 1980A Spectra Pritchard photometer. All measurements were carried out at room temperature under ambient atmosphere.

The doping concentrations of LiF are varied from 2.5 to 50 wt.% in order to investigate the effect of the LiF concentrations on the device performance. The thickness of the LiF-doped Alq_3 layer is 2 nm.

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Their current density–voltage and brightness–voltage characteristics are shown in Figs. 2 and 3, respectively. Green electroluminescence from the Alq_3 layer is observed through the glass substrate when the Al cathode is biased negatively and the ITO anode positively. As is clearly seen from these figures, their performance depended on the doping concentrations. The device with 25 wt.% LiF doped in Alq_3 exhibited the highest current density and brightness, with a lower driving voltage and higher luminance efficiency. This device has a maximum brightness over 15300 cd/m^2 and a maximum luminance efficiency of 1.52 lm/W. However, the device without the LiF-doped organic layer only shows a light output of 3200 cd/m^2, and a maximum luminance efficiency of 0.33 lm/W. The efficiency of the former was 4–5 times as that of the latter. This indicates an improved balance of the hole and electron injections by using an LiF-doped Alq_3/Al cathode structure in OLEDs. Table 1 summarizes the performance comparisons of the device with an LiF-doped Alq_3/Al cathode structure on various doping concentrations and the device without, including the driving voltage at 100 cd/m^2, maximum brightness and maximum luminance efficiency.

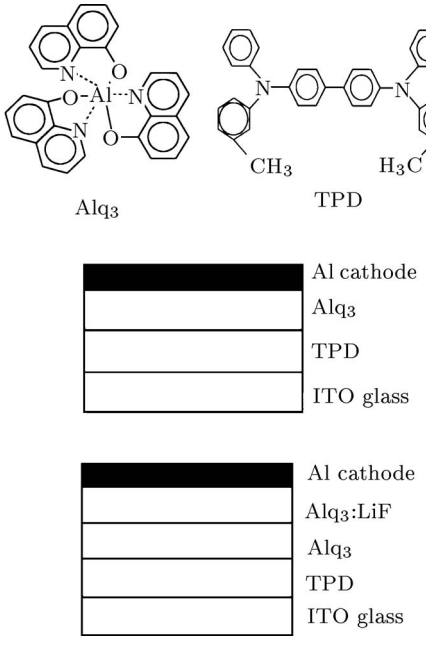

Fig. 1. Molecular structures of the used organic materials and the configurations of OLEDs.

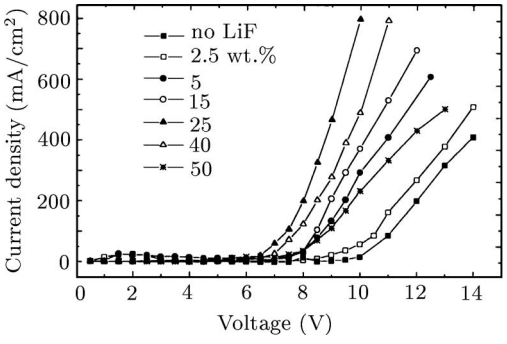

Fig. 2. Current density–voltage characteristics of OLEDs with various LiF-doping concentrations (2.5, 5, 15, 25, 40, and 50 wt.%) without the LiF-doped Alq_3 layer.

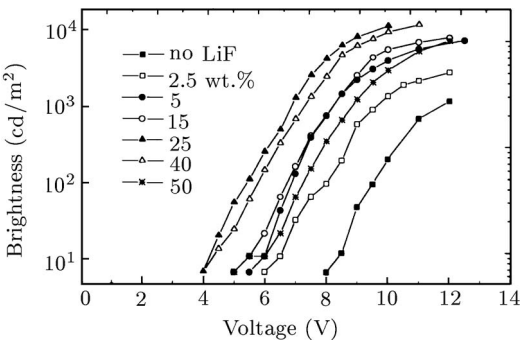

Fig. 3. Brightness–voltage characteristics of OLEDs with various LiF-doping concentrations (2.5, 5, 15, 25, 40 and 50 wt.%)without the LiF-doped Alq_3 layer.

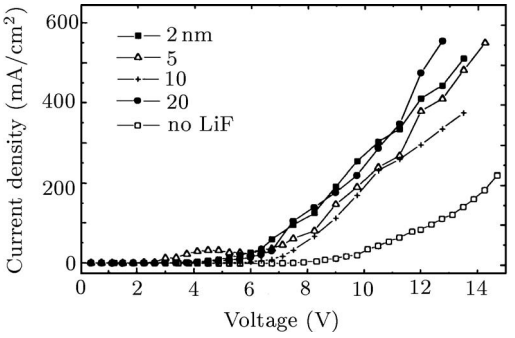

Fig. 4. Current density–voltage characteristics of OLEDs with various LiF-doped thickness (2, 5, 10 and 20 nm) and the device without the LiF-doped Alq_3 layer.

In order to investigate the effect of the thickness of the LiF-doped layer on the device characteristics, the devices with different thicknesses (2, 5, 10, 20 nm) of the LiF-doped layer are fabricated. The total thickness of the undoped Alq_3 layer and the LiF-doped Alq_3 layer is kept to 60 nm, and the doping concentration is the same (25 wt.%). Their current density–voltage and brightness–voltage characteristics are shown in Figs. 4 and 5, respectively. Apparently, they all show enhanced performance as compared to the undoped ones. We also find that the performance of OLEDs depends slightly on the increased thickness of the LiF-doped Alq_3 layer. Considering the contingent factors in the fabrication process, we think that the increased thickness of the LiF-doped Alq_3 layer does not affect the device performance. The LiF-doped electron-injecting layer besides the Al cathode is the dominant factor of the OLED performance improvement. The mechanism of the enhanced performance using an LiF-doped Alq_3/Al cathode structure is not completely clear. In contrast to the previous OLEDs[11–14] using an ultra-thin insulating film between the Al cathode and their organic layer, the increased electron injection in these devices with an LiF-doped Alq_3/Al cathode structure cannot be explained using the tunnelling-through-an-insulator argument. Also, we cannot attribute it to the lowered work function of the cathode.[15] Hung *et al.*[10] reported

Table 1. Performance comparisons of devices with an LiF-doped Alq_3/Al structure and the device without an LiF-doped structure.

Doping concentration (wt.%)	no LiF	2.5	5	15	25	40	50
Driving voltage at 100 cd/m^2 (V)	9.7	7.8	6.5	6.2	5.2	5.4	7.2
Maximum brightness (cd/m^2)	3200	4000	9800	11900	15300	13400	10700
Driving voltage (V)	18	15	16	15	15	16	16
Maximum luminance efficiency (lm/W)	0.33	0.65	0.93	0.96	1.52	1.45	0.8
Driving voltage (V)	9.5	8.5	7.5	8	5	6	9

that LiF lowered the energy levels of Alq_3 and the improvements using an LiF/Al cathode were attributed to band bending of the organic layer in contact with the insulators. In our experiment, it seems that the presence of LiF-doped in Alq_3 perhaps lowers the energy levels of Alq_3 besides the Al cathode, and thus lowers the barrier to electron injection. In addition, we suspect that the existence of LiF in Alq_3, especially near the Alq_3/Al interface, removes parts of the quenching centres[12,13,17,18] which is one of the important reasons why OLEDs with an Al cathode show poor performance.

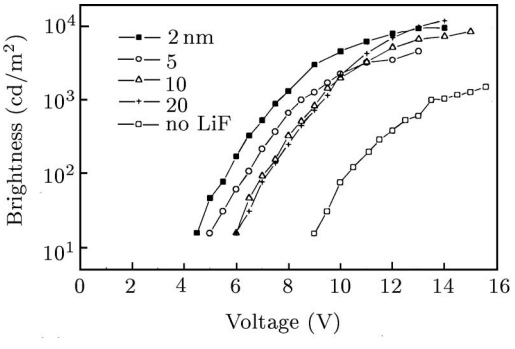

Fig. 5. Brightness–voltage characteristics of OLEDs with various LiF-doped thicknesses (2, 5, 10 and 20 nm) and the device without the LiF-doped Alq_3 layer.

In summary, by using an LiF-doped Alq_3/aluminium cathode structure, we fabricated an OLED with enhanced brightness and efficiency. When the doping concentration of LiF is 25 wt.%, the OLEDs showed the best performance. This device showed a maximum luminance efficiency of 1.52 lm/W and a brightness over 15300 cd/m^2. Also, the OLED performance is independent of the thickness of the LiF-doped organic layer when it is thicker than 2 nm. The LiF-doped Alq_3 layer at the cathode interface is the dominant factor to enhance the performance of this type device. This is another method to enhance OLED performance, especially in the application of OLEDs with a large active area; it is helpful to achieve a well-distributed luminance in the whole active area as this method has avoided the difficulty of fabricating a large area uniform ultra-thin insulating layer.

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