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High performance fully transparent OLED encapsulated using a novel permeation barrier by ALD

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1. Introduction

The organic light emitting diode (OLED) has been considered as the next generation display because of its potential advantages include high pixel resolution, high efficiency and low fabricating cost [1]. However, a long life OLED device bears much higher limitations include water vapor transmission rate (WVTR) of 10^{-6}g/m^2/day and the O_2 transmission rate (OTR) of 10^{-3}cm^3/m^2/day [2]. The main factors degrading the performance of OLED are the oxidation and delamination of the cathode [3] and the formation of the dark spots in the active area [4]. The main reason causing these mechanisms is the permeation of oxygen and moisture. Therefore, to make an effective encapsulation to prolong the life time is an urgent need. On the other hand, although the conventional glass or metal-lid encapsulation provides very good barrier property [5], they are not fit for ultra thin and full transparent applications; hence it is necessary to develop the technique of thin film encapsulation. In this study, the atomic layer deposition (ALD), which is considered as a promising method to deposit a smooth, conformal, pinhole free and densely packed film [6], was performed for a full transparent OLED (FTOLED) encapsulation. A novel barrier material, laminated Al_2O_3/HfO_2 multilayer depositing in one ALD process, was used. Although the Al_2O_3 is accepted as one of the most widely studied materials grown by ALD [7], the single Al_2O_3 layer can not extend the lifetime very well because of its easily hydrolyzed property. On the contrary, HfO_2, which is a hydrophobic material [8], can offset the deficiency of Al_2O_3. The electrical and optical properties, luminance, efficiency and lifetime were studied. The results are competitive to those of the glass-encapsulated device.

2. Experiment

A FTOLED device was fabricated with the structure of ITO coated glass /PEDOT: PSS /PFO /LiF /Ag /IZO. The details of the fabrication process have been described in our previous work. [9] After these procedures, ALD process was then carried out using trimethylaluminum (TMA), tetradimethylamino hafnium (TDMAHf) and H_2O as precursors and the N_2 as the purge gas. The sequence of the pulse for one cycle deposition of Al_2O_3 and HfO_2 were TMA /N_2 /H_2O /N_2 and TDMAHf /N_2 /H_2O /N_2. The ALD system is Cambridge NanoTech Savannah 100, and the N_2 pressure was kept in ~0.1Torr in the chamber. The ALD conditions were listed in Table 1. It is noticeable that the first nucleation layer with exposure time of 25sec is to enhance the absorption possibility of the precursors and improve the adhesion of the film with the substrate. The total film thickness was 600Å with the alternate deposition of Al_2O_3 2Å/ HfO_2 3Å repeating 120 times. The optical transmittance was studied as a function of the wavelength from 400 to 700nm using UV-visible-near IR spectrometer. The water vapor transmission rate (WVTR) was measured at 27°C in 100% relative moisture on MOCON 221 for 60h, whereas the oxygen transmission rate (OTR) was characterized at 27°C in pure O_2 using MOCON 398 for 60h. The current density-voltage (J-V) characteristics were examined using Keithley 2400, while the luminance-current (L-J) of and current efficiency were investigated using CS-100. The luminance was the top-side measurements. Finally, the lifetime was measured using LS-100.

Table 1 The Parameters of ALD.

	Precursor	Plus (s)	Exposure (s)	Purge (s)	T (℃)
Nucleation layer	TMA	0.05	25	25	90
	H_2O	0.05	25	25	
Al_2O_3	TMA	0.03	0	5	90
	H_2O	0.03	0	5	
HfO_2	TDMAHf	0.1	0	5	90
	H_2O	0.03	0	5	

3. Result and discussion

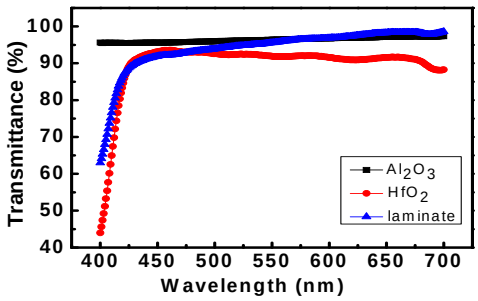

Fig. 1 The optical transmittance spectra of the ALD layers.

The optical transmittance spectra of single Al_2O_3, HfO_2 layer and laminated Al_2O_3/HfO_2 multilayer are shown in Fig. 1. The average transmittance of these layers was 95%, 89% and 92% in turn. HfO_2 showed less transparency than Al_2O_3 and resulted in a poor transmittance of Al_2O_3/HfO_2 multilayer, which slightly reduced the light output through the encapsulation layer. Furthermore, The WVTR and OTR of the Al_2O_3/HfO_2 multilayer were >10^{-4}g/m^2/day (over the

detect limit of MOCON) and ~0.02cm^3/m^2/day. According to these results, the laminated Al_2O_3/HfO_2 multilayer showed not only high optical transmittance but also excellent barrier property for water and O_2, and it was very fit for OLED encapsulation.

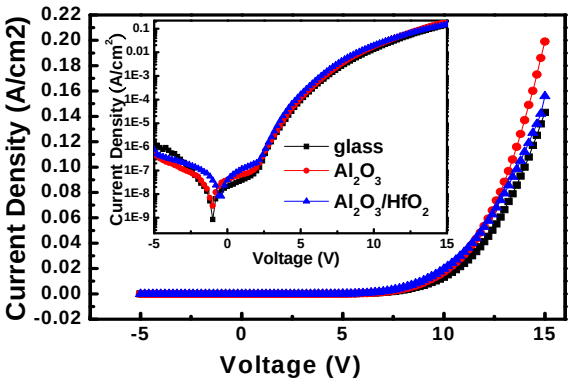

Fig. 2 The J-V curve of the FTOLED device with various encapsulation layers: glass, single Al_2O_3 and Al_2O_3/ HfO_2 layer.

Fig. 2 is the J-V curve of the OLED devices with various encapsulation materials including glass lid, Al_2O_3 single layer and the Al_2O_3/HfO_2 multilayer. The turn on voltage in sequence were 7V, 6.8V and 6.4V, whereas the leakage current were 1.47×10^{-6}A/cm^2, 6.56×10^{-7}A/cm^2 and 7.1×10^{-7}A/cm^2, which were quite low. ALD encapsulated devices exhibited lower turn on voltage and leakage current than glass lid encapsulated device.

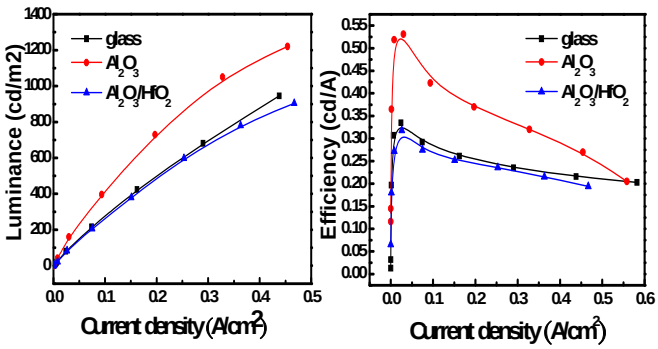

Fig. 3 The J-V, L-I curve and current efficiency of the FTOLEDs with various encapsulation layers: glass, single Al_2O_3 and Al_2O_3/ HfO_2 layer.

Fig. 3 is the J-V, L-I curve and current efficiency of the FTOLED devices encapsulated with glass-lid, Al_2O_3 and Al_2O_3/ HfO_2 multilayer. The luminance of top side respectively was 945cd/m^2, 1220cd/m^2 and 904cd/m^2, whereas the current efficiency was 0.335cd/A, 0.531cd/A and 0.318cd/A. The Al_2O_3 encapsulated device exhibited the best performance, and the Al_2O_3/HfO_2 encapsulated device showed a similar performance to the glass-lid one. However, due to its easily hydrolyzed property, the Al_2O_3 single layer can't prolong the lifetime effectively, which will be shown later. Therefore, Al_2O_3 single layer was not the best choice for OLED encapsulation.

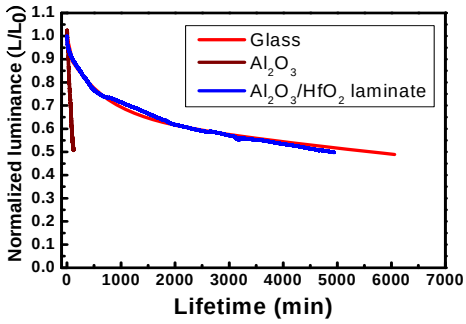

Fig. 4 The comparison of the lifetime of FTOLEDs encapsulated with various materials: glass, single Al_2O_3 and Al_2O_3/HfO_2 layer.

Fig.4 is the comparison of the lifetime of the FTOLED devices with various encapsulation layers: glass, single Al_2O_3 and Al_2O_3/HfO_2 multilayer. The lifetime of the glass-lid encapsulated device was 5600minutes and it was the best one. The Al_2O_3/HfO_2 multilayer encapsulated device extended the lifetime unto 4900minutes, and this was only inferior to the glass-lid one. However, the lifetime of the single Al_2O_3 encapsulated device was only 120minutes, which was quite short. The reason is the easily hydrolyzed property of Al_2O_3.

4. Conclusion

A FTOLED encapsulated with Al_2O_3/HfO_2 multilayer grown by ALD in one process was successfully fabricated. The turn on voltage was 6.4V, the luminance was 904cd/m^2 and the current efficiency was 0.318cd/A. It was noticeable that the lifetime of the device extended to 4900minutes. According to the results of these experiments, ALD Al_2O_3/HfO_2 could be considered as a good encapsulation material for ultra thin FTOLED applications.

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