Electrode Thickness Optimization at Full Color OLED and Analysis of Power Consumption

Sung-Joon Park*, Ok-Tae Kim and Hee-Je Kim***

Abstract - The operating condition of the OLED (organic light-emitting diode) is very sensitive to electrode thickness properties. The electrode thickness is a significant issue in the construction of OLEDs because of its transparency, high conductivity and high efficiency as an injector into organic materials. We carried out a systematic study to optimize the electrode thickness conditions in Indium-tin oxide (ITO), Molybdenum (Mo) and Aluminum (Al). Further, we measured electrode thickness under standard conditions [ITO 1500Å, Mo 2600Å, Al 1500Å]. We also evaluated power consumption. In addition, we analyzed substrate uniformity with IVL measurement results. From these results, it is known that the electrode thickness should be optimized in order to accomplish optimal power efficiency.

Keywords: Electrode thickness, organic light-emitting diode, power consumption

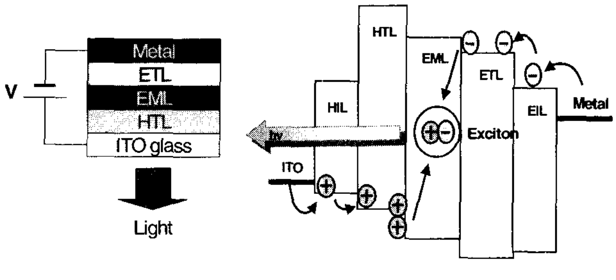
1. Introduction

Nowadays there is a great interest in OLEDs (organic light-emitting diode) since their performance has remarkably improved for application in flat panel display since 1987[1].

OLEDs have been shown to have sufficient brightness, range of color and operating lifetimes for use as a practical alternative technology to the LCD based full-color flat-panel display. Furthermore, OLEDs also have rapid response time, enabling the addressing of a simple matrix to be effectively used even for displaying fast moving pictures. Yet, each pixel current for driving and full-color problems still exist.

The ideal OLED must have lower power, higher uniformity and higher contrast ratio in order for the full color to be used effectively. The basic structure of the OLED, shown in Fig. 1, has not changed substantially since the initial demonstration of its high efficiency and low voltage electro-luminescence (EL) from an organic thin film.

A multi-layer structure consisting of a hole transport layer, emission layer and electron transport layer allows the achievement of bright electro-luminescent emission in the visible spectral region at low driving voltages. Fig. 2 describes the so-called barrier ribs in the panel structure [2]. Each layer was deposited by the vacuum evaporation method under a vacuum of < 10^{-5} Torr.



(a) (b)

Fig. 1 Typical device architecture of an OLED

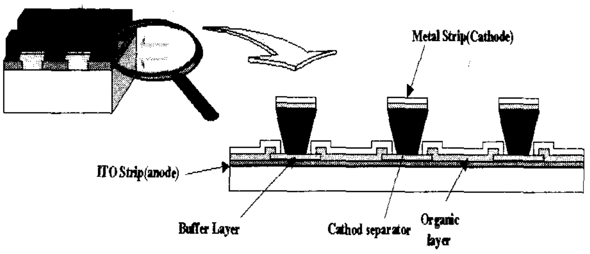


Fig. 2 Cross-sectional view of a passive OLED

The first layer consists of a hole transporting material such as N, N'-diphenyl-N, N-bis (3-methylphenyl)1-1'-biphenyl-4, 4'-diamine (TPD), and the second of a light-emitting, electron transporting material such as tris-(8-hydroxyquiniline) aluminum (Alq_3)[3].

The top electron-injecting electrode typically consists of Mg-Ag or Li-Al. The bottom hole-injecting electrode is typically composed of a thin film of transparent semiconductor indium tin oxide (ITO).

Light is emitted through this electrode when ITO is biased positive with respect to the top electrode. It was

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discovered that degradation of OLED's occurs in air on a time scale of a few hours. Charge conduction in these ostensibly insulating organic electro-luminescent materials requires electric fields typically in the range of active 2~5MV/cm. Such operating conditions, coupled with a reactive, low work function top electrode, which is required to ensure efficient injection of electrons into the organic, indicated that even simple encapsulation in an insert atmosphere using an epoxy-sealed glass package for example, can extend the useful device lifetime [4]. Also, remaining degradation modes after encapsulation include the formation and growth of non-emissive "dark spot defects." With small particles and scratches on the surface obtained through the sputtering process, the spikes and bulk bring about a significant decrease in resistance and in the path to leak current [5~6]. Also, the ITO film thickness on glass substrate is one of the important methods to build up reliability and performance of the panel. The electrode in OLEDs has been reported to be an important factor in influencing the electrical and luminescent properties.

In this study, we investigated the effect of OLED electrode thickness. We carried out an electrode thickness study to optimize the processing condition in OLEDs.

The optimal thickness of the various constituent OLED electrodes has been identified and discussed.

2. OLED's design

We developed a passive matrix of 1.98-in. Average brightness and resolution of the sample panel are 50cd/m^2 and 120×160, respectively, and it drives with PWM (Pulse-width-modulation) and PFM (Pulse-frequency-modulation). We developed a sample module that allows scanning duty-ratio to select freely. Average scanning duty is 1/60 cycle. A stack type column of anode pattern was formed in the active area by the conventional photo-lithography technique. Prior to the formation of cathode separators, a series of organic layers formed on the top of ITO by the vapor deposition in the vacuum. Eventually, the organic layers were thermally deposited on the substrate with ITO film. Glass size was 33.4x47.1mm. The deposed Al sealing line was 0.38mm. Dot pitch was 0.226x 0.255mm.

We fabricated a stack type panel under standard conditions [ITO 1500Å, Mo 2600Å, Al 1500Å]. We changed the standard conditions of electrode thickness.

3. Effects of Anode, Bus and Cathode Electrode Thickness

In order to precisely measure the electrode thickness, we used probe-station. Data-line resistance and scan-line resistance were measured by probe-station. The thickness of ITO, Al and Mo electrodes are summarized in Table 1. We fabricated two sample panels of each condition.

Table 1 Electrode thickness in samples measured by probe-station

condition	Test thickness			Thickness measured by SEM(ITO basis)			Data Resistance (kΩ)	Scan Resistance (Ω)	remark
	ITO(Å)	Mo(Å)	Al(Å)	ITO(Å)	Mo(Å)	Al(Å)			
1	1500	2600	1500	1500	2390	1740	66	159	Standard
2	1500	2600	1000	1500	2350	880	67	144	
3	1500	1500	1500	1500	1345	1590	11.52	184	
4	1500	700	1500	1500	765	1530	1235	270	Maximum Resistance
5	1000	1500	1000	1000	975	885	11.6	208	
6	1000	2600	1500	1000	2460	1465	7.1	159	

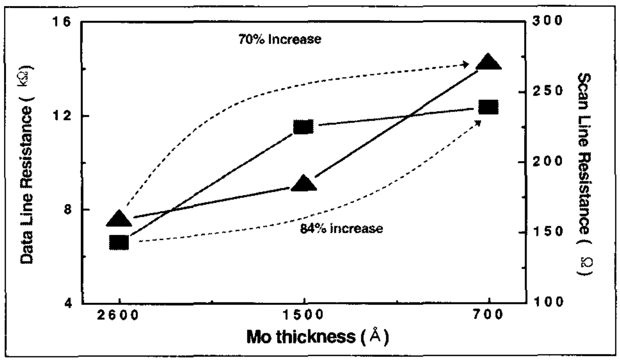


Fig. 3 Data-line resistance and scan-line resistance as a function of the Mo thickness

As shown in Table 1, the conditions for the electrode thickness measurement were as follows; [ITO: 1000 to 1500Å, Mo: 700 to 2600Å and Al; 1000 to 1500Å].

As demonstrated in Table 1, condition 1 is the standard condition. The highest resistance is obtained from condition 3. The dominant factor is the Mo thickness. Fig. 3 illustrates a contour plot of data and scan resistance value. As the Mo thickness was changed from 2600Å to 700Å, its resistance increased to 84%. The ITO thickness hardly has any effect on data-line resistance. When the ITO thickness has diminished from 1500Å to only 1000Å, data-line resistances have barely increased 6%.

As we examined so far, the Mo thickness is the main factor providing an effect to resistance not only in the case of data-line but also in scan-line. The same figure also demonstrates scan resistance characteristics when the Mo thickness decreased. In other words, data-resistance and scan-resistance depend on Mo thickness. On the other hand, the effect of ITO and Al are scarcely influenced by scan-line resistance of the OLED's panel.

4. Effects of Power Consumption

Table 2 demonstrates that as the thickness of the bus-line

(Mo) electrodes thinned, the power consumption increased. When one pixel current was flowing 250[μA], the maximum was 2057mW and the minimum was 23mW. The maximum increased by 150% from 23mW. Power consumption rate according to thickness of the bus-line electrode (Mo) is shown in Fig. 4.

Table 2 Power consumption caused by bus-line resistance

<table>
<tr><th rowspan="2">condition</th><th colspan="3">Test thickness</th><th colspan="2">Resistance increased in standard basis</th><th colspan="2">Power increasement (mW)</th><th colspan="4">Power consumption</th></tr>
<tr><th>ITO(Å)</th><th>Mo(Å)</th><th>Al(Å)</th><th>Data resistance (kΩ)</th><th>Scan resistance (Ω)</th><th>50μA basis</th><th>250μA basis</th><th colspan="2" rowspan="2">Mode A (mW)</th><th colspan="2" rowspan="2">Mode B (mW)</th></tr>
<tr><td>2</td><td>1500</td><td>2600</td><td>1000</td><td>0.1</td><td>-15</td><td></td><td></td></tr>
<tr><td>3</td><td>1500</td><td>1500</td><td>1500</td><td>4.92</td><td>25</td><td>25</td><td>626</td><td>Designed value</td><td>Observed value</td><td>Designed value</td><td>Observed value</td></tr>
<tr><td>4</td><td>1500</td><td>700</td><td>1500</td><td>5.75</td><td>111</td><td>82</td><td>2057</td><td rowspan="3">220</td><td rowspan="3">340</td><td rowspan="3">1300</td><td rowspan="3">-</td></tr>
<tr><td>5</td><td>1000</td><td>1500</td><td>1000</td><td>5</td><td>44</td><td>38</td><td>938</td></tr>
<tr><td>6</td><td>1000</td><td>2600</td><td>1500</td><td>0.5</td><td>0</td><td>1</td><td>23</td></tr>
</table>

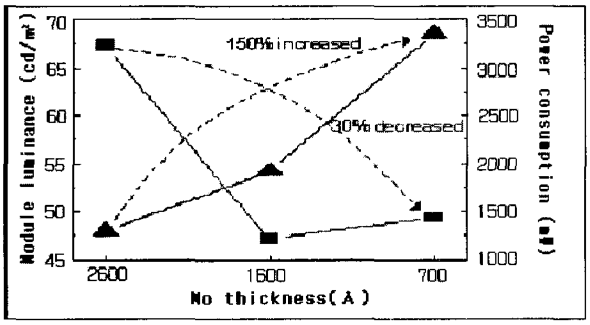


Fig. 4 Module brightness and power consumption as a function of Mo thickness

That is a major factor in optimizing line current toward column direction during driving. We also calculated the voltage drop.

We obtained (condition 4),

data line - Red: $250[\mu A]\times10^{-6}\times5.75[k\Omega]\times10^{3} = 1.44[V]$

Green: $250[\mu A]\times10^{-6}\times5.75[k\Omega]\times10^{3} = 1.44[V]$

Blue: $250[\mu A]\times10^{-6}\times5.75[k\Omega]\times10^{3} = 1.44[V]$

scan line - $(250+250+250)[\mu A]\times120\times10^{-6}10^{-6}\times111[\Omega] = 10[V]$

Also, maximal power amplification is,

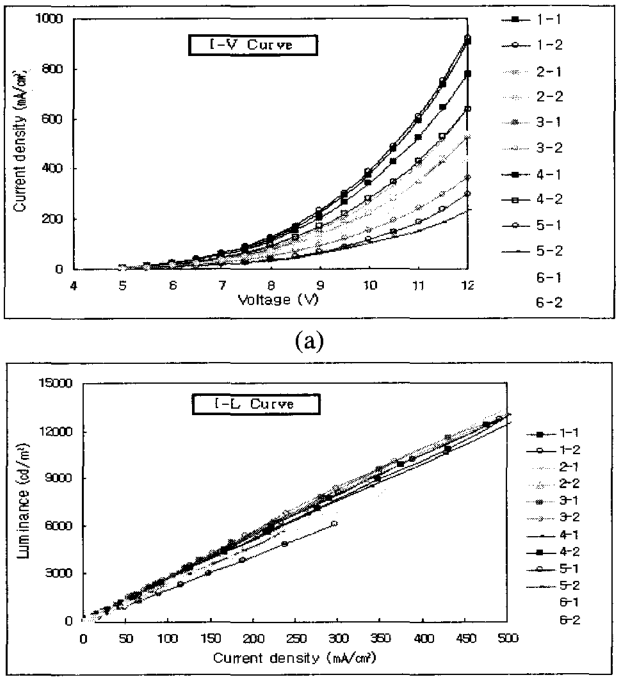
$\{(250\times1.44+250\times1.44+250\times1.44)[\mu A]\times10^{-6}\times120\times2\}$(data-line)+$\{(250+250+250)[\mu A]\times10^{-6}\times120\times2\times10[V]$(scan-line) = 2057[mW]

As we can see, in condition 2, the panel scan-resistance is observed to reduce the resistance of the scan-electrode once the thickness of the Al electrode is reduced, because Mo and Al electrodes improve contact resistance. Therefore, the scan-line resistance is diminished. When reducing Mo thickness, the rate of power consumption increases rapidly. Due to the increased power consumption, it is too difficult to apply mobile applications. This is applied to home appliances such as refrigerators, air-conditioners and washing machines.

As the Mo thickness was reduced from 2600Å to 700 Å, the power consumption was changed from 1990[mW] to 3000[mW]

5. IVL Characteristics Results

Current-voltage (I-V) and luminance-voltage (L-V) characteristics were measured with Keithley source-measurement unit 236 and Yokokawa electronics illuminance-Meter 3298. We observed voltage (V) and current density (J) characteristics of the OLED device, which are summarized in Fig. 5 (a). And, Fig. 5 (b) shows the plots of the luminance versus current-density. In this study, the 1-1 (see Fig. 5) curve of the peak demonstrates that standard condition is only composed of ITO, Mo and Al electrode.



(a)

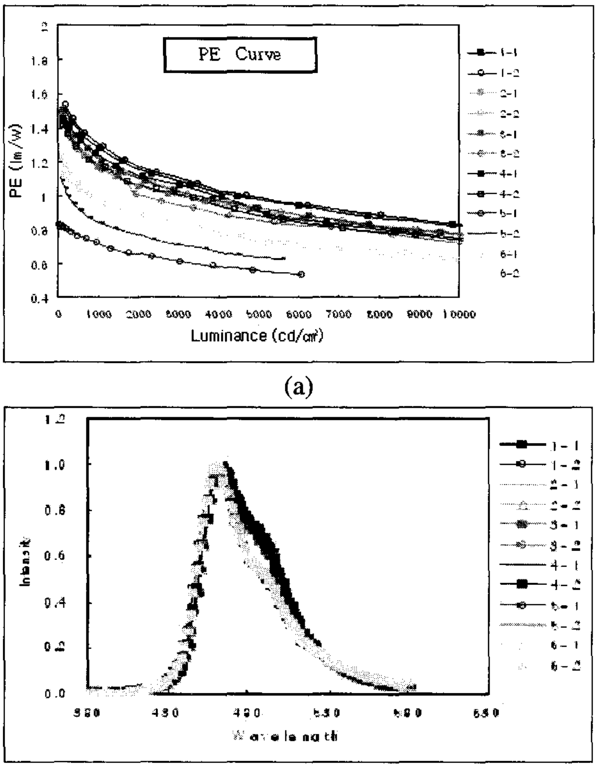
(b)

Fig. 5 (a) Current density-voltage characteristics of samples
(b) Dependence of OLED luminance-voltage characteristics of samples

The relative luminescence and photo-efficiency of the sample panel is indicated in Fig. 6 (a).

The output spectrum of OLED with each sample, measured from the substrate surface, is shown in Fig. 6 (b). The emission spectra from the surfaces are similar to conventional ones.

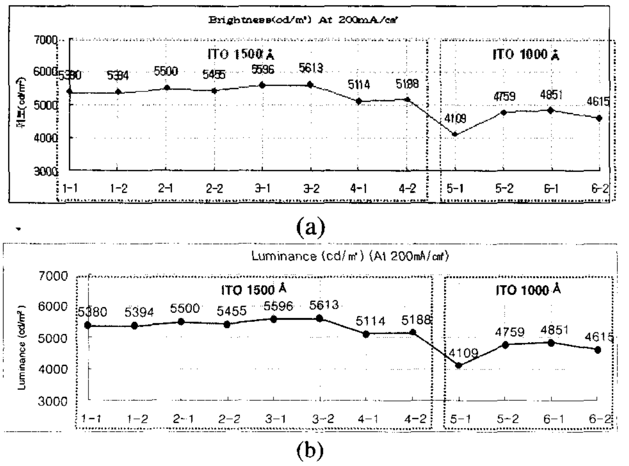
However, there is a slight curve at 510nm due to differences in the transparency by ITO thickness. The 1-1 sample (standard panel) quantum efficiency is higher than the others. A function of current-density of the OLED with each electrode thickness is displayed in Fig. 7 (a). The more the resistance of a panel's electrode is increased, the worse the I-V characteristic is. A luminescence characteristics of the OLED compared with that of a thick ITO electrode are shown in Fig. 7 (b), indicating that there is a dependency on ITO thickness. Also, it is relatively independent of bus-line resistance.



(a)

(b)

Fig. 6 (a) Dependence of the Efficiency (E)-Current density (J) Characteristics on the thickness of electrode
(b) Spectra of the light from a full color OLED through the top electrode and the glass substrate



(a)

(b)

Fig. 7 (a) Current density and (b) brightness characteristic

The luminance of this sample device is 13,000 cd/m² at 10.8V with 481 mA/cm². In our IVL plots, it was confirmed that this is the best characteristic of the sample's standard condition [No. 1].

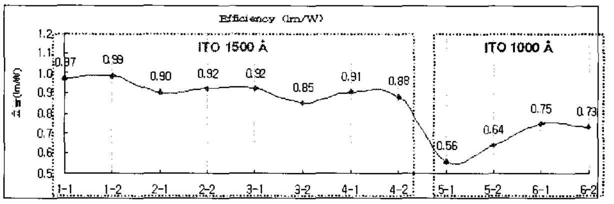


Fig. 8 Efficiency characteristic of OLED samples

The reason why both I-V and L-V characteristics are simultaneously increased after optimizing is thought to be that the electrode thickness is very optimistic. From the efficiency characteristic of the OLED sample, it can be seen that the relative power efficiency in Fig. 8 shows the expected stable flatness with increasing ITO thickness.

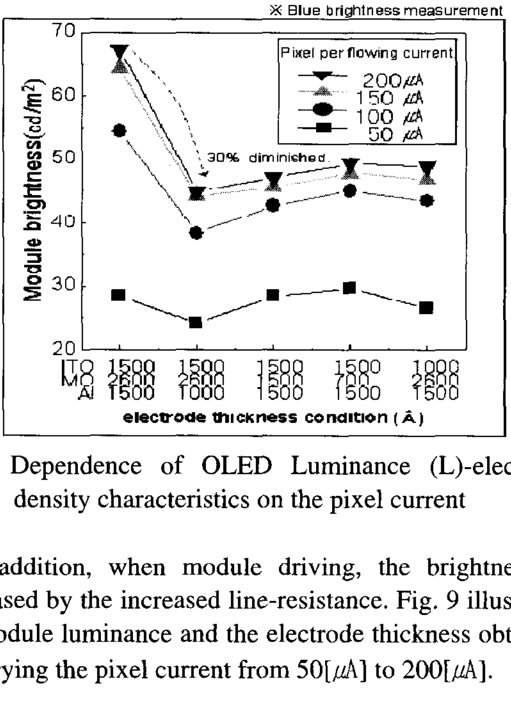


Fig. 9 Dependence of OLED Luminance (L)-electrode density characteristics on the pixel current

In addition, when module driving, the brightness is decreased by the increased line-resistance. Fig. 9 illustrates the module luminance and the electrode thickness obtained by varying the pixel current from 50[㎂] to 200[㎂].

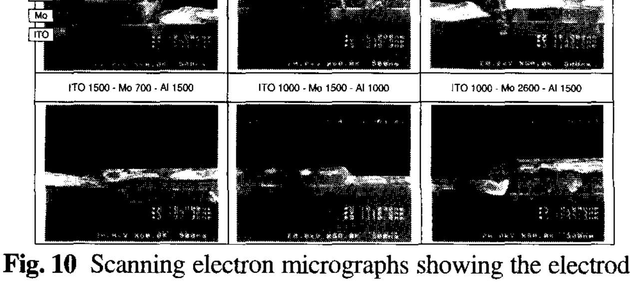


Fig. 10 Scanning electron micrographs showing the electrode.

The electrode surface samples were examined by SEM. Fig. 10 shows SEM images of ITO, Mo, and Al. These results suggest that the data resistance and scan resistance are determined by Mo thickness. We have taken the view that ITO and Al thickness are irrelevant.

6. Results and Discussion

We have shown that it was possible to improve the operating conditions of the OLED through appropriate electrode thickness. Furthermore, we have proposed optimistic electrode thickness in 1.8" passive mobile applications. We've determined that the most significant factor is Mo's thickness.

As a result, if there is any problem with the thickness reduction of Mo, it is impossible to apply mobile applications because of higher power consumption. However, it is applied to digital appliances such as air-conditioners, refrigerators, microwaves and so on.

For optimal power efficiency and brightness, the thickness of ITO, Mo, and Al are 1500Å, 2600Å, and 1500Å, respectively. At these optimal configurations, a luminance of 13,000 cd/m^2 is obtained at a current density of 481 mA/cm^2.

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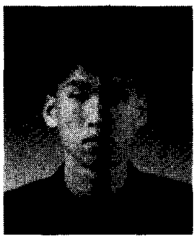

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