Analysis of Semi-Transparent Cathode Performance Based on Fabrication Methods

Haewon Kim[1], **Hai Xu**[1], **Xiaoning Liu**[1], **Wenbin Jia**[1], **Yuan Can**[1], **Huaiting Shih**[1]

[1]Hefei BOE Joint Technology Co., LTD, No.668 Longzihu Road, Anhui, China

Keywords: OLED, Top Emission, Semi-transparent Cathode.

ABSTRACT

By studying the transmittance rates and transmittance non-uniformity characteristics of various types of semi-transparent metal cathode within the visible light range and found that each performance varied according to the composition ratio, deposition rate and surface condition of alloy. These results suggest that the manufacturing method of semi-transparent metal cathode affects the performance and luminance imbalance of top emissive OLED TVs, and so on.

1 INTRODUCTION

AMOLED is in the spotlight for the optimal display because of its unique advantages such as fast response time, light weight, ultra-thin and low power consumption. In particular, AMOLED applications have been increasing rapidly on TVs as well as on mobile devices. Recently, there are many needs to develop transparent or top emissive OLEDs for high resolution and variety of applications that go beyond FHDs for 4K and 8K ultra-high definition (UHD). But so far, due to various technical difficulties, most of them still remain in the bottom emissive type. Therefore, studies on top emissive OLEDs to improve ultra-high definition, light efficiency, color purity and device lifetime are steadily underway, and as a part of that, many researchers are making their efforts to develop transparent cathode.

Current directions of developing transparent cathode can be divided into using TCOs and semi-transparent metal alloys. For TCOs, it is difficult to avoid sputtering damage when depositing directly on organic materials and additional damage protection layers would be needed. However, technologies that can replace traditional sputtering method is continuously being studied, but it has not yet to make progress to the stage of practical application. For semi-transparent metal alloys, it is not easy to apply to large panels due to lack of transmittance rate and high sheet resistance. However, it is expected that the use of appropriate auxiliary electrodes together will be a good alternative as transparent cathode without damaging the organic layers.

In this paper, the properties of semi-transparent metal alloys based on Mg:Ag are examined, and the research results of the most efficient composition of metal alloys are shown.

2 EXPERIMENT

The surface morphologies were measured by depositing Ag single films as thickness to identify the growth shapes of the metal thin film and the corresponding changes in characteristics. All experiments were conducted by depositing directly onto the cover glass and no medium was inserted between the glass and the metal film. The surface morphologies of the thin film were observed by SEM and the transmittance rates were measured by R1 angle-resolved spectroscopy system.

As is well known, metal thin film undergoes island growth (Volmer-Weber growth) in the early stage of formation, which in the early stage of metal growth resulted in the grain being small and clearly visible. However, as the thickness thickens, Ag's cluster grows and, at the same time, the combination with the surrounding clusters creates a relatively flat thin film that is not entirely continuous. And the same result was observed in this experiment as shown in Fig. 1.

Fig. 1 Surface status of Ag based on thickness measured by SEM

Prior to the experiment, the IR drop of 8K-based device was simulated. The simulation was performed based on 20 Ω/□ of cathode and the 0.03 Ω/□ of auxiliary electrode, and the result is as shown in Table 1. The result of 55" 8K device showed IR drop of up to 3.57V based on a brightness of 150nit and that of 65" resulted in IR drop of up to 5.94V under the same condition. It also showed an IR drop of up to 4.76V when the 65" device was simulated based on a brightness of 120nit. Some of the simulation results presented a little high values but study for improving these values is under way now.

Vss IR Drop (V)			
	55"_8K_150nit	65"_8K_150nit	65"_8K_120nit
Rs_Cathode	20		
Rs_SD	0.03		
10	0.015	0.024	0.019
100	0.16	0.27	0.22
1080	1.56	2.6	2.08
2160	2.68	4.46	3.57
4320	3.57	5.94	4.76

Table 1 Simulation results of IR drop

At first, the specifications were set that transmittance rate should be more than 60% and sheet resistance should be less than 20Ω/□. And then the transmittance rate by mixing ratio of Mg:Ag alloys was verified, which were widely used as semi-transparent cathode. When the thickness was fixed at 100Å, the result is the same as Table 2. It is generally known that Ag has high reflectance and low sheet resistance, while Mg has high absorption and high sheet resistance, it shows the optimum transmittance and sheet resistance at the appropriate mixing ratio. In this experiment, the result was best under the mixing ratio of 5:5. In case of this condition, the transmittance rate in the visible light range was 69.3% and the sheet resistance was 22.3Ω/□, and the transmittance non-uniformity for each color was ±3.5%.

Mixing Ratio (Mg:Ag)	Overall (%)	Visible (%)	Blue / Green / Red 450nm / 520nm / 630nm	Sheet Resistance (□/Ω)
1:9	47.0	51.9	61.1 / 52.3 / 43.2	
2:8	48.0	53.9	63.6 / 56.2 / 45.8	16.6
5:5	60.2	69.3	71.2 / 70.2 / 66.4	22.3
8:2	40.9	44.0	54.7 / 48.6 / 41.2	78.1
9:1	42.8	46.2	57.2 / 51.7 / 43.2	

Table 2 Transmittance of Mg:Ag thin film as mixing ratio (100Å thickness)

In addition, the characteristic changes of Mg:Ag film were observed with the mixing ratio of 100 Å thickness and deposition rate. As shown in Table 3, it was found that the faster the deposition rate, the better the transmittance rate could be obtained regardless of the mixing ratio. In particular, if the deposition rate was increased by 2.5 times with the mixing ratio of Mg:Ag 5:5, the transmittance rate increased by an average 5.3% and 73% of transmittance rate was obtained in the visible light range. By excluding the effects of thin film improvement on the interface with EIL, this transmittance rate has been achieved and further improvement of transmittance due to improvement of early crystal growth of cathode is expected when appropriate EIL is applied in the future.

Mixing Ratio (Mg:Ag)	Reference		2.5 Times Rate	
	Overall (%)	Visible (%)	Overall (%)	Visible (%)
2:8	48.0	53.9	56.5	65.3
5:5	60.2	69.3	63.2	73.0
8:2	40.9	44.0	45.1	49.0

Table 3 Transmittance of Mg:Ag thin film as deposition rate and mixing ratio (100Å thickness)

As shown in Table 4, transmittance rates were measured at various thicknesses and mixing ratios and found that the transmittance rate decreased gradually as the thickness increased regardless of mixing ratio. The orders of transmittance rate by thicknesses and mixing ratios are as shown in Table 5. As shown in Fig. 2, in case of the 8:2 mixing ratio and 30Å of Mg:Ag thickness, even though the film thickness was too thin to measure the sheet resistance, it showed a high transmittance rate of 85% or more in the visible light range and was expected to be applicable with TCO for future improvements of work function and for barrier layer of sputtering.

Mixing Ratio (Mg:Ag)	30Å		100Å		120Å	
	Overall (%)	Visible (%)	Overall (%)	Visible (%)	Overall (%)	Visible (%)
2:8	58.1	63.6	56.5	65.3	53.3	61.1
5:5	65.7	74.3	63.2	73.0	53.9	61.7
8:2	74.9	86.3	45.1	49.0	38.6	41.1

Table 4 Transmittance of Mg:Ag thin film with 2.5 times deposition rate (various thickness)

Order	Trans. (%)	Unif. (%)	Recipe (Mg:Ag, Thickness)
1	85.7	±2.0	8:2, 30A
2	74.5	±0.7	5:5, 100A
3	68.4	±4.0	5:5, 120A
4	67.8	±8.1	2:8, 100A
5	65.5	±10.8	2:8, 120A

Table 5 Orders of transmittance (at B/G/R region) of Mg:Ag thin film with various conditions

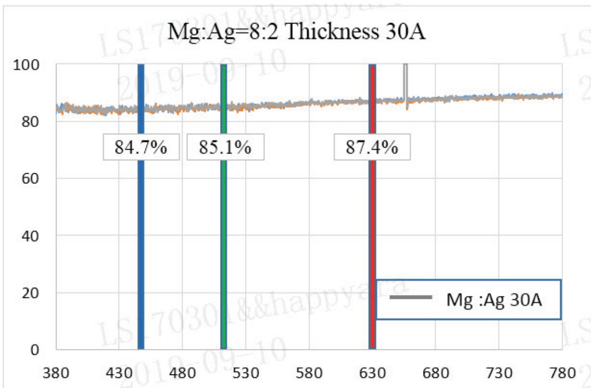

Fig. 2 Transmittance @ Mg:Ag 8:2, 30A

The surface of the Mg:Ag film was studied according to the surface treatment of substrate and deposition conditions. The results of the experiment showed that the morphology of the thin film improved when plasma was treated on the substrate as shown in Fig. 3. In addition, the faster the deposition rate and the higher the Mg mixing ratio, the better the morphology of the thin film as well. This is because the better the wettability of the substrate, the faster the deposition rate, the more diffusion of the metal particles occurred on the surface of substrate, thereby inter-particle clumps on the surface of the substrate are mitigated. And it is thought that the relatively small Mg particles compared to Ag could fill the space between the Ag particles, and the more the Mg particles are making it easier to create a denser and smoother thin film.

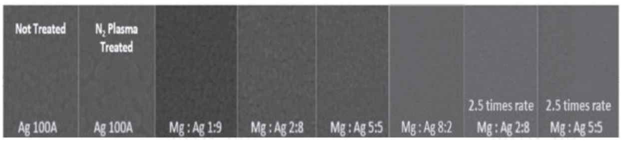

Fig. 3 Surface status of Mg:Ag based on deposition conditions measured by SEM

OLED is basically a device that implements the screen using a combination of light form B/G/R and since each color has different lifetime, the color of the whole screen tends to redshift as time goes by. Therefore, better transmittance non-uniformity among wavelengths of each color is required, and experiment on this was carried out and the results were obtained as shown in Table 6. Experiments were conducted in various conditions by mixing ratio, deposition rate and thickness. In this paper, only the results of the actual applicable thickness considering the sheet resistance were shown. The best condition in the experiment was Mg:Ag mixing ratio of 5:5 with thickness of 100Å, and the transmittance rates for each wavelength were 74%@450nm, 75%@520nm and 74.5%630nm as shown in Table 7 and Fig. 4. Through this experiment, ±0.67% of transmittance non-uniformity for each color was achieved. In this condition, the sheet resistance was less than 20Ω/□ and was expected to be applicable when using with a suitable auxiliary electrode.

Order	Trans. (%)	Unif. (%)	Recipe (Mg:Ag, Thickness)
1	74.5	±0.7	5:5, 100A
2	68.4	±4.0	5:5, 120A
3	67.8	±8.1	2:8, 100A
4	65.5	±10.8	2:8, 120A

Table 6 Transmittance non-uniformity (at B/G/R region) of Mg:Ag thin film with various conditions

Mg:Ag 100A Transmittance (%)				
	450nm	520nm	630nm	Dev.
Reference Rate	71.2	70.2	66.4	±3.49%
2.5 Times Rate	74.0	75.0	74.5	±0.67%

Table 7 Transmittance of Mg:Ag at each color region with 5:5 mixing ratio and 100Å thickness

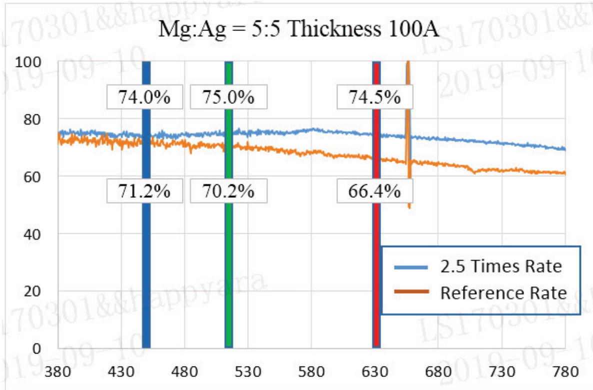

Fig. 4 Transmittance based on deposition rate

According to the above test results, lifetime test cells (LTCs) for each condition were made to compare their performance. The device structure is ITO (reflective Al embedded) / HIL / HTL / EML / EIL / cathode / CPL as shown in Fig. 5. Anode and organic layers were fixed under the same conditions and all organic layers are formed by inkjet printing method. The cathodes were divided by the mixing ratio of Mg:Ag into 5:5 and 2:8, and the thicknesses of each device was also 100A, 120A and 150A respectively.

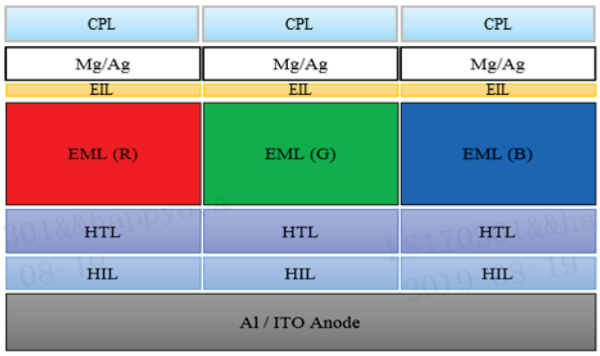

Fig. 5 Structure of LTC

Based on the Mg:Ag ratio of 2:8 and thickness of 150A device which is commonly used cathode condition for reference, each performance was compared as shown in Table 8. For a cathode of 100A with an Mg:Ag ratio of 5:5, the current efficiency was better than other devices at the all color regions. And it was shown that y-coordinate in blue color of Mg:Ag 5:5 and 100A device was slightly high but it is expected to be improved by tuning device structure.

There were some errors during the test so the efficiency of blue color of reference LTC could not be measured. However, the blue color is also expected to perform a little poorly, given the differences in the characteristics of the different color under each condition.

In the future, various conditions of devices will be tested to analyze each characteristic in more detail.

Color	Mg:Ag	Thickness (Å)	CE (cd/A)	CIEx	CIEy
Red	Reference		22.2	0.657	0.342
	5:5	120	13.4	0.659	0.340
	5:5	100	21.0	0.665	0.335
Green	Reference		36.1	0.282	0.658
	5:5	120	45.5	0.286	0.657
	5:5	100	49.4	0.290	0.653
Blue	Reference		-	0.140	0.087
	5:5	120	5.4	0.142	0.090
	5:5	100	5.8	0.139	0.105

Table 8 Performance comparison of each condition

3 RESULTS

The changes in characteristics of Mg:Ag semi-transparent metal alloy were studied according to various conditions and verified the method of improving the transmittance non-uniformity of each color, and as a result, the transmittance rate of 74.5% and transmittance non-uniformity of ±0.67% in the B/G/R light region could be achieved.

In addition, we produced lifetime test cells (LTCs) and analyzed their performances and found that the device with a cathode of Mg:Ag 5:5, 100A showed the outstanding performance.

In this paper, the properties of semi-transparent metal alloys based on Mg:Ag are examined, and the research results of the most efficient composition of metal alloys are shown.

4 CONCLUSIONS

The results in this paper are expected to be applied to improve the luminance and lifetime of top emissive OLEDs, and in particular, more stable devices can be produced by implementing uniform transmittance rate by color.

REFERENCES

[1] C. C. Wu, et al. "Light Out-Coupling of OLEDs: the Transparent Electrode Effects", 24-3 SID Symposium Digest 2016

[2] Z. Jiao, et al. "Weakening Micro-Cavity Effects in White Top-Emitting WOLEDs with Semitransparent Metal Top Electrode", 61-2 SID Symposium Digest 2018

[3] S.Y. Kim, et al. "Electrical and Optical Properties of Red Phosphorescent Top Emission OLEDs with Transparent Metal Cathodes", Journal of the Korean institute of electronic material engineers V20 no.9, 2007

[4] C. Han, et al. "3 Stack-3 Color White OLEDs for 4K Premium OLED TV", 3-1 SID Symposium Digest 2017

[5] K. Hong, et al. "Optical Properties of WO3/Ag/ WO3 Multilayer as Transparent Cathode in Top-Emitting Organic Light Emitting Diodes", J. Phys. Chem. C, 115(8), 3453–3459, 2011

[6] J. Hou, et al. "Efficient top-emitting organic light-emitting diodes with Sm/Ag bilayer cathode", Thin Solid Films. 519 2011

[7] D. S. Ghosh, et al. ""Widely transparent electrodes based on ultrathin metals", Optics Letters 34 no.3, 2009

[8] J. H. Im, et al. "Bulk-like Al/Ag bilayer film due to suppression of surface plasmon resonance for high transparent organic light emitting diodes", Org. Electron. 2016

[9] M. H. Lu, et al. "High-efficiency top emitting organic light-emitting devices" Applied Physics Letter 81, 2002