



Improvement in Power Efficiency in Organic Light Emitting Diodes Through Intermediate Mg:Ag Layer in LiF/Mg:Ag/Al Cathodes

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Effects of Mg:Ag interlayer between LiF and Al on electron injection and device performances of organic light-emitting diodes (OLEDs) were investigated. Thickness of Mg:Ag layer was changed from 0 to 10 nm and the relationship between interlayer thickness and device performances was studied. Current density of OLEDs was increased due to efficient electron injection from cathode to organic layer by Mg:Ag interlayer. In addition, power efficiency of OLEDs was improved by more than 50% due to low driving voltage and high recombination efficiency and it showed a maximum value at a Mg:Ag thickness of 1.0 nm. © 2007 The Electrochemical Society. [DOI: 10.1149/1.2756337] All rights reserved.

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Organic light-emitting diodes (OLEDs) have been developed for more than 20 years and have been used as displays for mobile phones, digital still cameras, and so on. However, lifetime and power consumption of OLEDs need to be improved further to expand their application to middle and large size displays.

Power consumption of OLEDs depends on light-emitting efficiency and driving voltage of OLEDs and low driving voltage is required to get low power consumption in OLEDs. There have been many studies to get low driving voltage in OLEDs and many studies focused on enhancing electron injection from electrodes to organic layer.¹⁻⁵ Hung et al. reported enhanced electron injection from cathode to tris(8-hydroxyquinoline) aluminium (Alq₃) by using LiF as an electron injection layer.¹ In other studies, it was found that electron injection barrier could be lowered by using Li₂O/Al as an electrode² and Mg:Ag was also effective to reduce driving voltage of OLEDs.³ LiF/Ca/Al cathode system also gave low driving voltage and CsF/Ca/Al was very effective as a cathode due to efficient dissociation of CsF.⁴ Recently, NaCl/Ca/Al was also used as a cathode for OLEDs and power efficiency could be improved by more than 30% compared with a common LiF/Al cathode.⁵ However, there was no systematic study about the effect of reactive metal thickness on device performance and no report about using Mg instead of Ca as an interlayer between LiF and Al.

In this work, a cathode system of LiF/Mg:Ag/Al was developed and its device performance was compared with that of conventional LiF/Al cathode. The thickness of Mg:Ag was controlled and device performances of LiF/Mg:Ag/Al devices were correlated with cathode structure. In particular, the effect of Mg thickness on device performance was studied in detail and electron injection mechanism of LiF/Mg:Ag/Al was discussed.

Experimental

A device configuration of indium tin oxide/*N,N'*-diphenyl-*N,N'*-bis-[4-(phenyl-*m*-totyl-amino)-phenyl]-biphenyl-4,4'-diamine(60 nm)/*N,N'*-di(1-naphthyl)-*N,N'*-diphenylbenzidine(30 nm)/Alq₃(50 nm)/LiF(1 nm)/Mg:Ag(*x* nm)/Al(100 nm) was used to study the effect of Mg:Ag thickness on device performances. The thickness of Mg:Ag was controlled from 0 to 10 nm to correlate Mg:Ag thickness with device performances. Electron only devices with a device configuration of Al/Alq₃(100 nm)/LiF/Mg:Ag(*x* nm)/Al were also fabricated to understand electron injection performances of LiF/Mg:Ag/Al compared with LiF/Al. Deposition rate of Mg:Ag was 0.2 Å/s and Al was evaporated at a depo-

sition rate of 2 Å/s. Current-voltage-luminance characteristics of electron only devices were measured with a Keithley 2400 and PR650 spectrophotometer (Photoresearch Inc.).

Results and Discussion

LiF/Al has been used as a conventional cathode for small molecule OLEDs, but its electron injection to organic layer has to be improved to get low driving voltage. Electron injection mechanism of LiF/Al cathode has not been clarified yet, but LiF dissociation and interface dipole formation are considered as dominant mechanisms for efficient electron injection.⁶ LiF dissociation by metal deposition is thermally activated and it was reported that reactive metals such as Ca could have high chemical reactivity with LiF, generating Li ion in organic layer.⁴ Therefore, thin Mg layer between LiF and Al can facilitate dissociation of LiF due to high chemical reactivity of Mg and chemical reaction of Mg with LiF can be activated by Al deposition. In this work, Mg:Ag was used as an interlayer instead of Mg because Mg cannot be effectively deposited on Alq₃.

Figure 1 shows *I-V* curves of LiF/Mg:Ag/Al cathodes according to Mg:Ag thicknesses. Mg:Ag thickness was controlled from 0 to 10 nm to investigate the relationship between Mg:Ag thickness and device performances of LiF/Mg:Ag/Al devices. LiF/Mg:Ag/Al devices showed the highest current density value at Mg:Ag thickness of 0.5 nm and it was decreased at Mg:Ag thickness over 3 nm even though the current density of all LiF/Mg:Ag/Al devices was higher than that of LiF/Al devices. The current density of

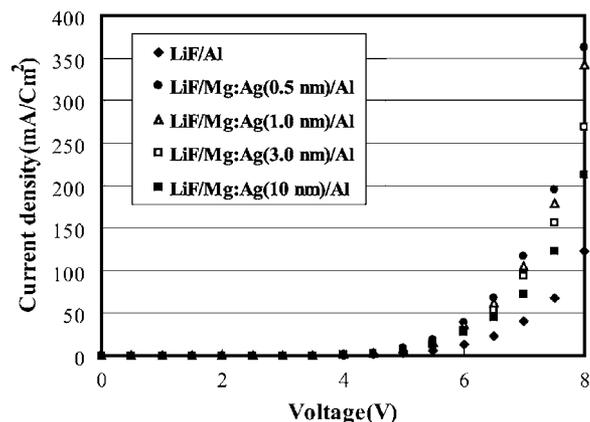


Figure 1. Current density-voltage curves of LiF/Mg:Ag/Al devices according to Mg:Ag thickness.

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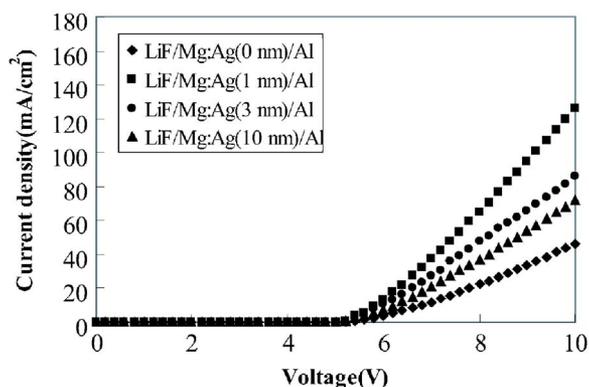
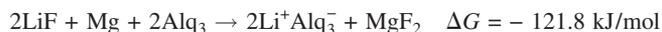
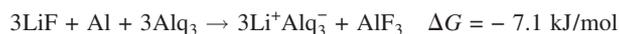


Figure 2. Current density-voltage curves of electron only devices of LiF/Mg:Ag/Al.

LiF/Mg:Ag/Al with 0.5 nm Mg:Ag interlayer at 6 V was higher than that of LiF/Al by three times. The high current density in LiF/Mg:Ag/Al devices can be explained by high chemical reactivity of Mg:Ag with LiF compared with chemical reactivity of Al with LiF. Alkaline earth metals are known to have high chemical reactivity with alkaline halide and Mg can facilitate the dissociation of LiF, resulting in efficient electron injection from cathode to Alq₃. Assuming LiF dissociation by cathode metals, Gibbs free energy of formation for the LiF-Al and LiF-Mg can be calculated based on the reaction mechanism below⁷



Negative Gibbs free energy for the reaction between LiF and Mg indicates that LiF is more reactive toward Mg rather than toward Al and Li formation can be effective in LiF/Mg:Ag, explaining high current density in LiF/Mg:Ag/Al devices. However, the increase of current density in the device with 0.5 nm thick Mg interlayer cannot be explained by just chemical reactivity of Mg or dipole effect. LiF dissociation by highly reactive Mg may be the same considering only chemical reactivity of Mg with LiF and interface dipole also will not be affected by Mg thickness because the interface dipole is influenced by the chemical nature of metal fluoride. However, in case of LiF and MgF₂, its contribution to the interface dipole will not be affected by Mg thickness. One factor which can affect the chemical reaction between Mg and LiF in LiF/Mg:Ag/Al is a thermal energy from Al deposition. There was a previous report that the current density of the LiF/Al system depended greatly on temperature and high temperature was beneficial to liberate more Li by effective dissociation of LiF.⁸ In LiF/Mg:Ag/Al devices, chemical reaction between Mg and LiF can be facilitated by thermal energy supplied from Al deposition because thermal energy has an effect of providing energy to overcome activation energy of the reaction. At low Mg:Ag thickness (0.5 nm), Mg cannot form a continuous film and both LiF and Mg are exposed to Al deposition. Therefore, LiF dissociation by chemical reaction of LiF and Mg can be activated by Al deposition. However, at high Mg:Ag thickness (>3 nm), most of LiF would be covered with Mg:Ag film and interfacial chemical reaction between LiF and Mg is difficult to be activated by Al deposition because Al cannot penetrate into the interfacial region. This is in agreement with the data that the current density of LiF/Mg:Ag/Al device is saturated at a Mg thickness over 3 nm.

To prove efficient electron injection by the Mg:Ag interlayer, electron only devices were prepared and electron injection from cathode to Alq₃ was compared. Figure 2 is a current density-voltage curve of electron only devices with LiF/Mg:Ag/Al cathodes. Current density was high in electron only device with 1.0 nm Mg:Ag interlayer, agreeing with the current density-voltage data of

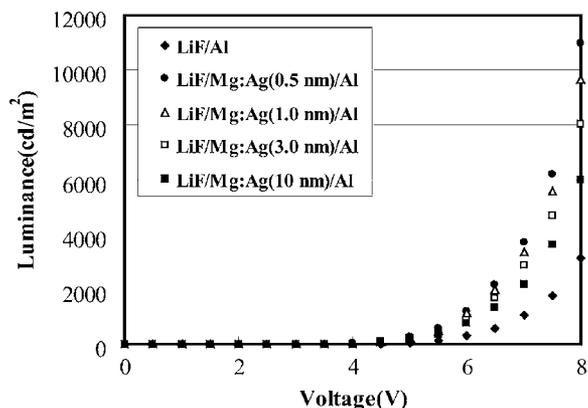


Figure 3. Luminance-voltage curves of LiF/Mg:Ag/Al devices according to Mg:Ag thickness.

LiF/Mg:Ag/Al devices. This result indicates that the increase of current density in OLEDs with Mg:Ag interlayer is due to enhanced electron injection from cathodes.

Luminance of LiF/Mg:Ag/Al devices is shown in Fig. 3. As expected from current density-voltage curves, luminance of LiF/Mg:Ag/Al devices was higher than that of LiF/Al. The luminance showed the same tendency as current density.

From the current density, voltage and luminance data of LiF/Mg:Ag/Al devices, current efficiency and power efficiency of the devices were plotted against Mg:Ag thickness (Fig. 4). There was 50% improvement of power efficiency and power efficiency of LiF/Mg:Ag/Al device with 1.0 nm Mg:Ag layer was 1.7 lm/W compared with 1.1 lm/W of LiF/Al device. In general, power efficiency is determined by driving voltage and current efficiency of devices. In the LiF/Mg:Ag/Al case, driving voltage was lowered by 1 V and current efficiency was enhanced from 2.6 to 3.2 cd/A, resulting in high power efficiency. The high current efficiency in LiF/Mg:Ag/Al cathode system is due to efficient hole and electron recombination in the emitting layer. Efficient electron injection from cathode to emitting layer improves hole and electron balance because hole is the majority carrier in our device structure. The efficiency value was even higher than that of efficiency value reported in other work.⁹

Conclusion

Power efficiency of LiF/Mg:Ag/Al devices was improved by 50% due to low driving voltage and high current efficiency. Electron injection from cathode to Alq₃ layer was enhanced by Mg:Ag interlayer and current injection was maximized at a Mg:Ag thickness of 1 nm.

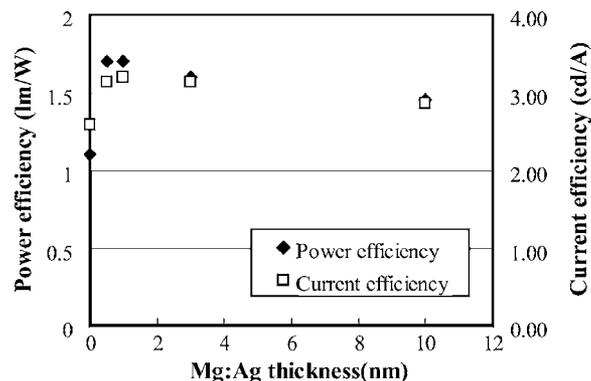


Figure 4. Current efficiency and power efficiency of LiF/Mg:Ag/Al devices according to Mg:Ag thickness.

References

1. L. S. Hung, C. W. Tang, and M. G. Manson, *Appl. Phys. Lett.*, **70**, 152 (1997).
2. T. Wakimoto, Y. Fukuda, K. Nagayama, A. Yokoi, H. Nakada, and M. Tschuida, *IEEE Trans. Electron Devices*, **44**, 1245 (1997).
3. C. O. Poon, F. L. Wong, S. W. Tong, R. Q. Zhang, C. S. Lee, and S. T. Lee, *Appl. Phys. Lett.*, **83**, 1038 (2003).
4. T. M. Brown, R. H. Friend, I. S. Millard, D. J. Lacey, T. Butler, J. H. Burroughes, and F. Cacialli, *J. Appl. Phys.*, **93**, 6159 (2003).
5. S. Shi and D. Ma, *Appl. Surf. Sci.*, **252**, 6337 (2006).
6. H. Heil, J. Steiger, S. Karg, M. Gastel, H. Ortner, H. von Seggern, and M. Stoßel, *J. Appl. Phys.*, **89**, 420 (2001).
7. M. G. Mason, C. W. Tang, L.-S. Hung, P. Raychaudhuri, J. Madathil, D. J. Giesen, L. Yan, Q. T. Le, Y. Gao, S.-T. Lee, et al., *J. Appl. Phys.*, **89**, 2756 (2001).
8. S. D. Wang, M. K. Fung, S. L. Lai, S. W. Tong, C. S. Lee, S. T. Lee, H. J. Zhang, and S. N. Bao, *J. Appl. Phys.*, **94**, 169 (2003).
9. J. Lee, Y. Park, D. Y. Kim, H. Y. Chu, H. Lee, and L.-M. Do, *Appl. Phys. Lett.*, **82**, 173 (2003).