Electrochemical and Solid-State Letters, **10** (9) K39-K41 (2007)
1099-0062/2007/10(9)/K39/3/$20.00 © The Electrochemical Society

High-Efficiency Blue Organic Light-Emitting Diodes Using C_{60} as a Surface Modifier on Indium Tin Oxide

Sung Hyun Kim,[a] Jyongsik Jang,[a] Ji Hwan Yoon,[b] and Jun Yeob Lee[c,z]

[a] *School of Chemical and Biological Engineering, Seoul National University, Shinlim-dong, Kwanak-gu, Seoul 151-742. Korea*
[b] *Samsung SDI, AMOLED Business Team, contKiheung-gu, Yongin-si, Kyonggi-do 449-577, Korea*
[c] *Department of Polymer Science and Engineering, Dankook University, Hannam-dong, Yongsan-gu, Seoul 140-714, Korea*

C_{60} was introduced as a modifier on indium tin oxide (ITO) and the effect of C_{60} modification on light-emitting efficiency of blue organic light-emitting didoes was investigated. Device performances of C_{60} modified devices were greatly dependent on ITO surface properties and C_{60} thickness. Power efficiency of blue devices was improved by 80% by C_{60} buffer layer on ITO because of low driving voltage and balanced electron-hole recombination

---

Manuscript submitted April 8, 2007; revised manuscript received May 16, 2007. Available electronically June 19, 2007.

C_{60} is a molecule with 60 carbons on spherical surfaces and is well known as an electron acceptor in solar cells.[1,2] It can form a charge transfer complex with metals, organics and inorganics and interface dipole formation between C_{60} and other materials has been reported in other works.[3,4]

There have been several works about using C_{60} in organic light-emitting diodes (OLEDs).[3,5-7] C_{60} was used as an efficient electron transport material[6] and it was also effective as a buffer layer on Al.[5] The use of C_{60} as a buffer layer on Al reduced the interfacial energy barrier between Al and *N*,*N*′-di(1-naphthyl)-*N*,*N*′-diphenylbenzidine (NPB) from 1.2 to 0.3 eV. It was also used as a buffer layer on indium tin oxide (ITO) and low driving voltage was obtained after C_{60} modification on ITO due to the reduced energy barrier between ITO and NPB.[3] In our study, it was found that hole injection of C_{60} modified devices greatly depended on the surface treatment of ITO and O_2 plasma treatment was effective to get a high current density, while hole injection was not affected by C_{60} on untreated ITO.[8]

In this work, we studied device performances of blue OLEDs with C_{60} as a buffer layer on untreated ITO and O_2-plasma-treated ITO. The relationship between ITO surface treatment and device performances of C_{60} modified devices was investigated and the mechanism for efficiency enhancement in C_{60} modified devices was discussed.

Device configurations of ITO/C_{60} (x nm)/NPB (50 nm)/MADN (30 nm)/Alq_3 (20 nm)/LiF (1 nm)/Al (200 nm) were used to study the effect of C_{60} thickness on device performance. Two ITOs, untreated ITO and O_2-plasma-treated ITO, were used to obtain information about the relationship between surface properties of ITO and device performances. ITO glass substrates were cleaned with acetone and isopropyl alcohol in an ultrasonic bath for 15 min, respectively, and were dried at 120°C for 2 h before use. The ITO substrates were exposed to oxygen plasma at a radio-frequency (rf) power of 100 W with O_2 flow rate of 50 sccm. After O_2 plasma treatment, C_{60} was deposited at a deposition rate of 0.01 nm/s and other organic materials were evaporated at a rate of 0.1 nm/s. The thickness of C_{60} was controlled from 0 to 7 nm to correlate the C_{60} thickness with device performances. Al was evaporated at a deposition rate of 5 Å/s and the devices were encapsulated with a glass lid and calcium oxide getter. Current density-voltage-luminance characteristics of the devices were measured with Keithley 0253A source measurement unit and PR 650 spectrophotometer.

It was found in our previous work that surface dipole formation could be induced on O_2-plasma-treated ITO by C_{60} modification, leading to efficient hole injection and high current density, while no reduction of energy barrier was observed on untreated ITO without O_2 plasma treatment even after C_{60} modification.[8] It is well known that high power efficiency can be obtained in OLEDs by lowering a driving voltage and improving electron-hole balance in a light-emitting layer. C_{60} modification on ITO can give a low driving voltage due to the reduced energy barrier between ITO and NPB and it can also give high recombination efficiency due to reduced hole flow in the device depending on surface properties of ITO. Therefore, in this work, device performances of C_{60} modified devices were investigated according to surface properties of ITO and C_{60} thickness.

Figure 1 shows current density-voltage characteristics of C_{60} modified devices with and without O_2 plasma treatment according to C_{60} thickness. Current density of C_{60} modified devices with O_2 plasma treatment (Fig. 1b) showed a maximum value at a C_{60} thickness of 3 nm and then decreased. The high current density of C_{60} modified devices can be explained by a surface dipole formation on ITO as reported in previous work.[8] The surface dipole was induced between ITO and C_{60} by O_2 plasma treatment and the energy barrier between ITO and NPB was lowered from 0.94 to 0.54 eV by C_{60} modification, resulting in high current density in the devices. The decrease of current density at C_{60} thickness of 7 nm is due to low hole mobility and the highest occupied molecular orbital (HOMO) level of 6.2 eV of C_{60}. C_{60} is known to have a high electron mobility of 1 cm^2/V s,[9] while its hole mobility is only 1×10^{-4} cm^2/V s compared with NPB hole mobility of 3×10^{-3} cm^2/V s from our measurements. In addition, low-lying HOMO value (6.2 eV) of C_{60} limits hole injection because of large energy barrier between ITO and C_{60}. C_{60} acts as a separate layer at high thickness and it limits hole injection from ITO. Contrary to high current density of C_{60} modified devices with O_2-plasma-treated ITO, current density of C_{60} modified devices with untreated ITO was lowered by C_{60} modification. Current density was gradually decreased according to the thickness of C_{60}, indicating that hole injection of C_{60} modified devices was not facilitated by C_{60} on untreated ITO. There was no energy barrier reduction between ITO and NPB by C_{60} modification of untreated ITO and C_{60} acted just as a hole transport material with a low hole mobility and high energy barrier, resulting in low current density after C_{60} modification.

Figure 2 shows luminance-voltage curves of C_{60} devices with untreated ITO and O_2-plasma-treated ITO. Luminance was improved in O_2-plasma-treated devices, while it was decreased in the devices with untreated ITO except 1 nm C_{60} modified devices. The high luminance in O_2-plasma-treated devices is due to high current density in the devices which is induced by low hole injection barrier between ITO and NPB. However, the luminance was lowered at 7 nm thick C_{60} because of reduced current density as shown in Fig. 1. Compared with O_2-plasma-treated devices, C_{60} modified untreated ITO devices except for a device with 1 nm thick C_{60} showed lower luminance value than C_{60} free device as expected from current density data. The high luminance in 1 nm thick C_{60} modified de-

---

[z] E-mail: leej17@dankook.ac.kr

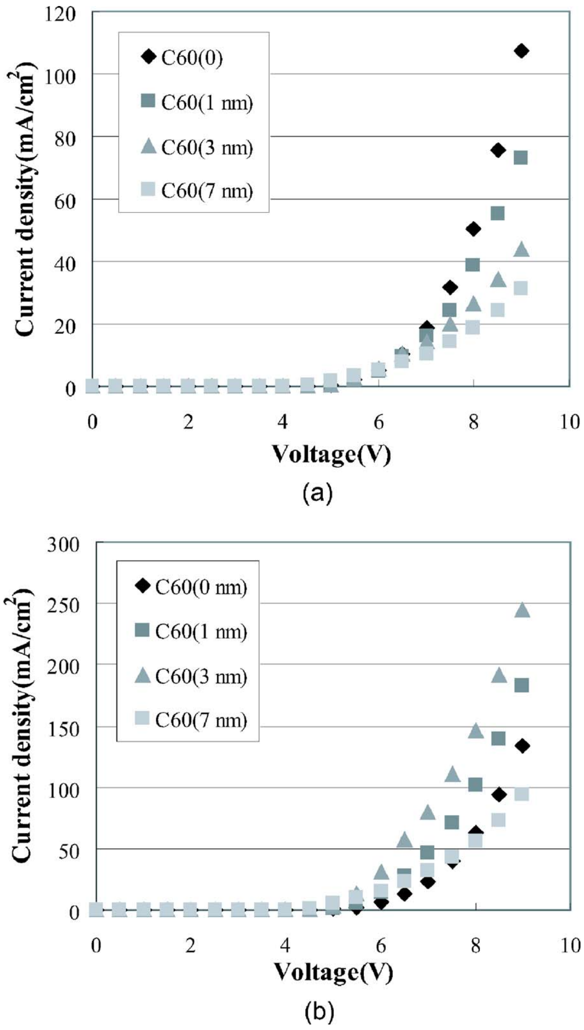

Figure 1. (Color online) Current density-voltage curves of C_{60} modified devices with and without O_2 plasma treatment. (a) C_{60} devices with untreated ITO. (b) C_{60} devices with O_2-plasma-treated ITO.

vices is due to efficient recombination of holes and electrons in the emission layer, which will be described in detail in current efficiency data.

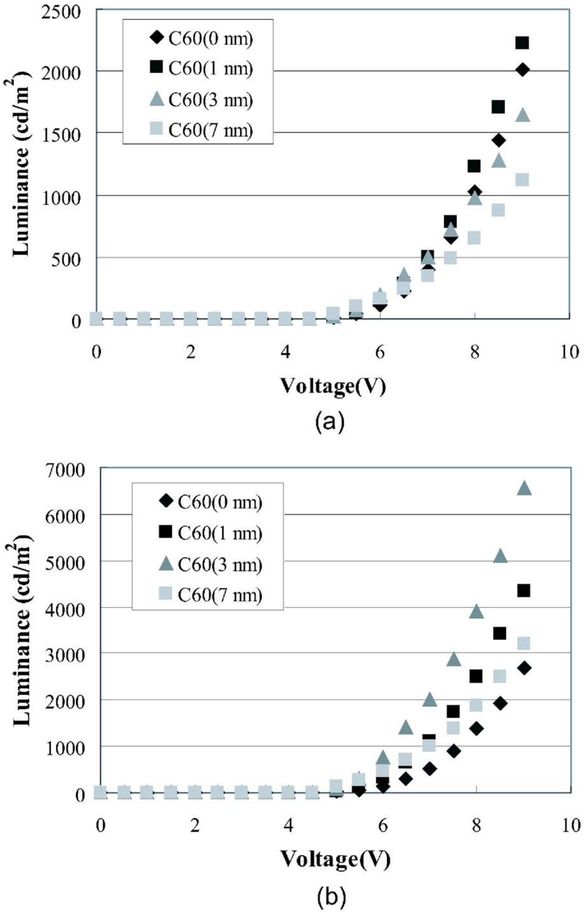

Figure 2. (Color online) Luminance-voltage curves of C_{60} modified devices with and without O_2 plasma treatment. (a) C_{60} devices with untreated ITO. (b) C_{60} devices with O_2-plasma-treated ITO.

Based on the current density and luminance of C_{60} modified devices, current efficiency was calculated and was plotted against C_{60} thicknesses (Fig. 3). Current efficiency of blue devices was almost constant at low C_{60} thickness and then increased at a thickness of 7 nm after O_2 plasma treatment, while it showed a maximum value at 3 nm and was saturated without O_2 plasma treatment. High efficiency of 3.7 cd/A at 1000 cd/m^2 could be obtained in blue devices with 3 nm C_{60} buffer layer on untreated ITO. 80% improvement of current efficiency was observed by C_{60} modification on untreated ITO. The high efficiency of C_{60} modified devices can be explained by efficient hole-electron recombination in the emitting layer.[10,11] In general, hole injection is more efficient than electron injection in OLEDs and hole is the dominant charge carrier in the devices.[11] Therefore, less hole flow in the device can improve hole-electron balance in the device, enhancing recombination efficiency. In spite of high driving voltage, the hole and electron charge balance improved current efficiency of C_{60} modified device with untreated ITO. A decrease of current efficiency at 7 nm C_{60} modification on untreated ITO indicates that electron-hole balance is optimized at 3 nm C_{60} thickness. Similar results could be obtained in blue devices with O_2-plasma-treated ITO. High efficiency of 3.1 cd/A could be observed in C_{60} devices with O_2 plasma treated ITO at a C_{60} thickness of 7 nm, which is also due to improved hole-electron balance in the device caused by less hole flow in the device. Current efficiency was not increased at low C_{60} thickness because hole injection was efficient due to the low energy barrier in

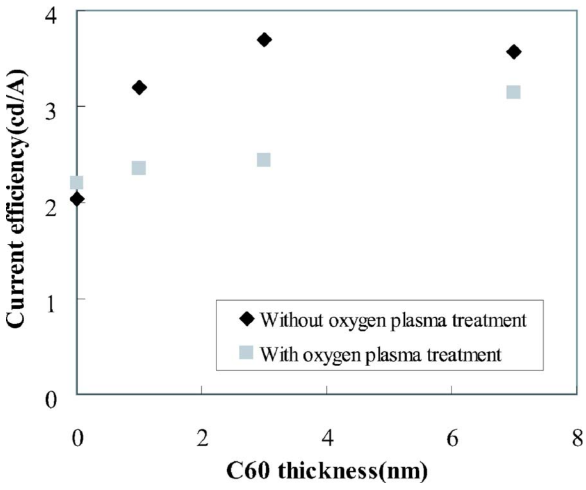

Figure 3. (Color online) Current efficiency of C_{60} devices according to C_{60} thickness.

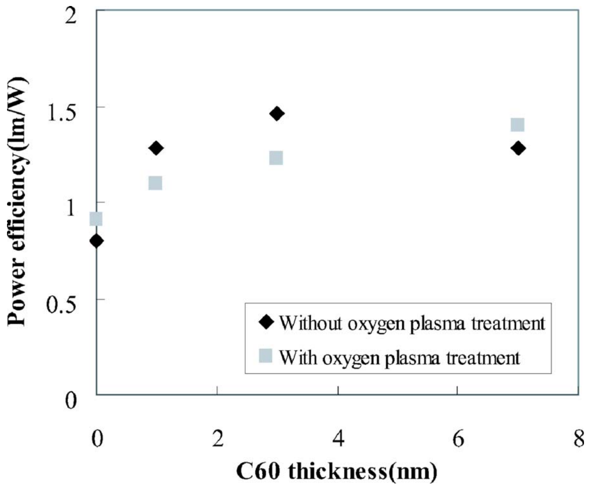

Figure 4. (Color online) Power efficiency of C_{60} devices according to C_{60} thickness.

O_2-plasma-treated devices. Hole-electron charge balance was not improved at low C_{60} thickness even though driving voltage was lowered by C_{60} modification.

Figure 4 shows the power efficiency of C_{60} modified devices according to C_{60} thickness. As can be expected from the current efficiency of C_{60} devices, power efficiency of C_{60} devices was greatly enhanced by C_{60} modification. Power efficiency as high as 1.5 lm/W could be obtained in C_{60} devices with 3 nm C_{60} on untreated ITO, while C_{60} devices with 3 nm C_{60} on O_2-plasma-treated ITO showed only 1.2 lm/W at 1000 cd/m^2. Even though the driving voltage of C_{60} devices was reduced by O_2 plasma treatment, the power efficiency was not improved remarkably due to moderate current efficiency of O_2-plasma-treated C_{60} devices. O_2-plasma-treated C_{60} devices showed a maximum power efficiency value of 1.4 lm/W at a C_{60} thickness of 7 nm because of the high current efficiency at high C_{60} thickness in spite of similar driving voltage with devices without C_{60}. On the other hand, power efficiency of C_{60} devices with untreated ITO was decreased at high C_{60} thickness due to the high driving voltage in spite of high current efficiency. In short, power efficiency was high at low C_{60} thickness because of moderate driving voltage and high current efficiency in C_{60} modified devices with untreated ITO, while power efficiency was rather low at high C_{60} thickness because of high driving voltage in spite of high current efficiency. In the case of C_{60} modification on O_2-plasma-treated ITO, power efficiency was high at high C_{60} thickness due to high current efficiency even though the driving voltage was similar to that of C_{60} free devices, while it was not improved greatly at low C_{60} thickness due to rather low current efficiency in spite of low driving voltage.

In summary, current efficiency and power efficiency of C_{60} devices were greatly improved by C_{60} modification of ITO. C_{60} retarded hole flow in C_{60} devices with untreated ITO, while it facilitated hole injection in O_2-plasma-treated devices. 80% improvement of current and power efficiency was observed in C_{60} devices and the use of C_{60} as a buffer layer on ITO can freely control device performances of OLED by combined management of ITO surface properties and C_{60} thicknesses.

Dankook University assisted in meeting the publication costs of this article.

References

1. N. Sariciftci, D. Braun, C. Zhang, V. Srdranov, A. J. Heeger, G. Stucky, and F. Wudl, *Appl. Phys. Lett.*, **62**, 585 (1993).
2. S. E. Shaheen, C. J. Brabec, N. S. Sariciftci, F. Padinger, T. Fromherz, and J. C. Hummelen, *Appl. Phys. Lett.*, **78**, 841 (2001).
3. I. Hong, M. Lee, Y. Koo, H. Jeong, T. Kim, and O. Song, *Appl. Phys. Lett.*, **87**, 063502 (2005).
4. N. Hayashi, H. Ishii, Y. Ouchi, and K. Seki, *J. Appl. Phys.*, **92**, 3284 (2002).
5. J. Y. Lee, *Appl. Phys. Lett.*, **88**, 073512 (2006)
6. Y. Y. Yuan, S. Han, D. Grozea, and Z. H. Lu, *Appl. Phys. Lett.*, **88**, 093503 (2006).
7. J. Y. Lee and J. H. Kwon, *Appl. Phys. Lett.*, **86**, 063514 (2005).
8. S. H. Kim, J. Jang, and J. Y. Lee, *Appl. Phys. Lett.*, **89**, 253501 (2006).
9. G. Priebe, B. Pietzak, and R. Konenkamp, *Appl. Phys. Lett.*, **71**, 2160 (1997).
10. S. W. Forsythe, M. A. Abkowitz, and Y. Gao, *J. Phys. Chem.*, **104**, 3948 (2000).
11. H. Aziz, Z. D. Popovic, N. Hu, A. Hor, and G. Xu, *Science*, **283**, 1990 (1999).