Formation of Internal Micro-lens-like Structure for Organic Light-emitting Diodes

C. M. Hsu, Y. X. Zeng, B. T. Lin, W. M. Lin, and W. T. Wu
Department of Electro-Optical Engineering, Southern Taiwan University of Science and Technology
1, Nan-Tai St., Yung-Kang District, Tainan City 710, Taiwan, R.O.C.

Abstract— Micro-lens-like structures fabricated on indium tin oxide were employed to promote light extraction efficiency of an organic light-emitting diode (OLED). Four array patterns with coverage ratios of 7.9%, 14.1%, 20.9% and 27.7% were examined. The current efficiency of OLED was enhanced by 26.5% for the 14.1% recessed device (4.8 cd/A) compared with the planar device (3.8 cd/A). The improved current efficiency was attributed to the additional light-emitting area generated on the recess wall as well as the light scattering/deflection effects on the recessed surfaces. The current efficiency was found coverage-ratio independent suggesting that the light extraction is limited by the arrangement of the recesses.

1. INTRODUCTION

It is well known that the emitted light from the active layers of an organic light-emitting diode (OLED) is largely constrained in the refractive-index-mismatched structure, leading to low external quantum efficiency [1–3]. Two optical total reflections are responsible for light confinement in the refractive-index-mismatched structure. The total reflection at glass/air interface is called glass mode total reflection and that at indium tin oxide (ITO)/glass interface is called waveguide mode total reflection. Reduction of these two total reflections and thus to enhance light extraction efficiency of OLEDs has become a major research topic in recent years, particularly for lighting applications.

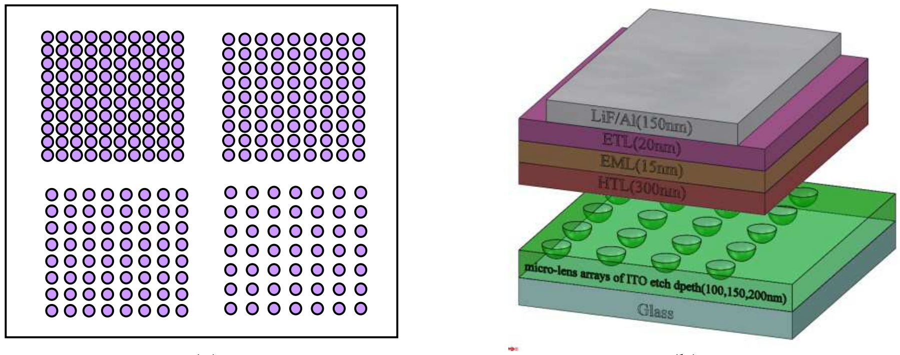
Reduction of glass mode total reflection by an external micro-lens film on glass has been demonstrated, and with which light extraction efficiency improved up to 70% has been reported [4, 5]. Attaching a porous film outside the glass can provide centers for light scattering and is also able to reduce glass mode total reflection [6]. On the other hand, surface-patterned structures such as photonic crystals and optical gratings have been introduced at glass/ITO or ITO/organic interfaces to minimize waveguide mode total reflection [7, 8]. The same effect can be achieved by internally embedding a scattering layer in a stacked OLED structure [9]. These approaches indeed have brought OLED lighting to become a practical stage.

This study reports the fabrication of micro-lens-like structure on ITO films and their application for OLED devices to enhance the external light extraction efficiency. Four arrays of recesses with various coverage ratios are created on an ITO film to form micro-lens-like internal structures in the OLED. The light extraction efficiency is expected to be enhanced by side wall effects of the recesses. These effects are discussed in detail.

2. EXPERIMENTAL DETAILS

To fabricate circular micro-lens-like internal structures, commercially available ITO films with a thickness of 250 nm deposited on glass were cleaned, patterned and etched to a depth of 200 nm. The circular patterns were designed to have two diameters of 4 μm and 6 μm with various pitches, yielding the recessed area a coverage ratio of 7.9%, 14.1%, 20.9% and 27.7%, as shown in Fig. 1(a). Morphology, optical, and electrical characteristics of the recessed ITO films were examined using atomic force microscope, ultraviolet-visible spectrophotometry, and 4-point prober, respectively.

Fabrication of OLED devices on the recessed ITO started with sequentially coating an organic hole transportation layer (PT-04, Lumitech Corp.), a light-emitting layer (PT-01/PT-86) and an electron transportation layer (PT-74) using thermal evaporation. Lithium fluoride (LiF) and aluminum (Al) cathode layers were then thermally evaporated. The complete OLED device comprised a glass/ITO(250 nm)/PT-04(30 nm)/PT-05+0.7%PT-01+2%PT-86(15 nm)/PT-74(20 nm)/LiF(0.5 nm)/Al(100 nm) structure, as shown in Fig. 1(b). The luminance-voltage (L-V) and current-voltage (I-V) characteristics of the OLED devices were measured using an I-V meter (model 237, Keithly Instruments Inc.) and an optical spectrometer (PR-650, PhotoResearch). The effects of recesses on light extraction are discussed.

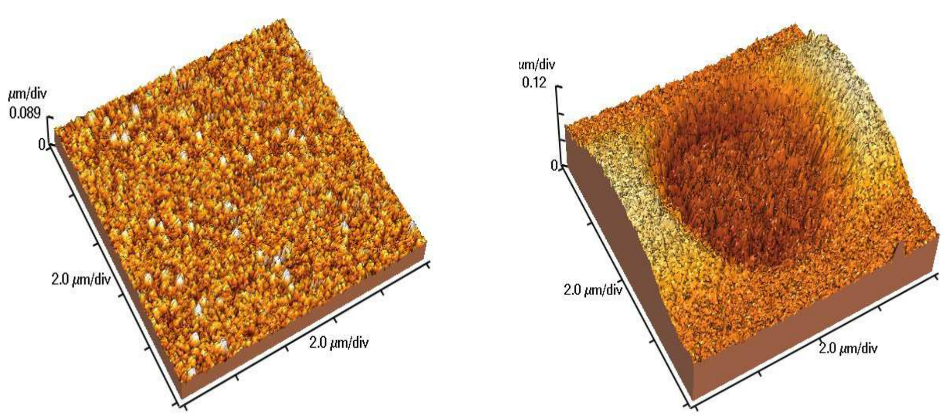


(a) (b)

Figure 1: (a) The four array patterns designed to generate various coverage ratios of the recesses. (b) The complete OLED structure with recessed ITO anodes.

3. RESULTS AND DISCUSSIONS

Figures 2(a) and (b) show the AFM surface profiles of the planar and recessed ITO films, respectively. The recess surface roughness (Ra) at depth of 200 nm was measured to be 53 nm, much rougher than that of the initial ITO film (Ra = 0.6 nm). A rough surface can cause a higher degree of light scattering and thus minimize the amount of light conducting total reflections at a refractive-index-mismatched interface. Fig. 3 shows the optical and electrical properties of 200-nm recessed ITO at various coverage ratios. The optical transmittance (averaged from 380–800 nm) dropped from 90.7% for the initial ITO to slightly below 90% for recessed ITO films. The haze ratio dramatically increases from 0.6% for the initial ITO to 6.7% and 21.4% for 7.9% and 14.1% recess ITO films, respectively. Haze ratio does not increase further for ITO with recess coverage ratio higher than 14.1%. This suggests that the scattering or deflection was more serious with increasing coverage ratio but limited by the recess wall density. The scattering and deflection at recesses causes the emitted light propagating differently from that in a planar OLED device, and this explains why the optical transmittance is low for recessed ITO films. The electrical sheet resistivity of ITO films linearly increases with recess coverage ratio. The ITO sheet resistivity is $1.4 \times 10^{-4}\,\Omega\text{cm}/\square$ with no recess and increases slightly to $39 \times 10^{-4}\,\Omega\text{cm}/\square$ for the 27.7% recessed ITO film. This is reasonable because interfacial carrier scattering is more serious and carrier concentration is less for ITO films with denser recesses. The increase in resistivity of an ITO anode would generally lead to a degraded I-V characteristics of an OLED. However, this was not observed in this study.



(a) (b)

Figure 2: (a) AFM images of planar and (b) recessed ITO surfaces.

Figure 4(a) shows the I-V characteristics of OLEDs. It can be seen that the current density of the planar device was higher than that of the recessed devices. The threshold voltage defined at $10\,\text{mA/cm}^2$ was however almost the same at $\sim 3.4\,\text{V}$ for all the devices. The higher current density for the planar device reflects that the electrical resistance of the planar ITO film is lower than

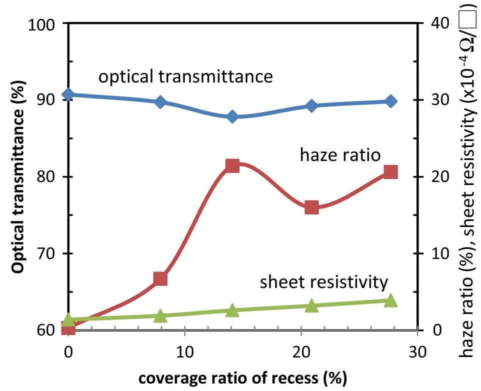
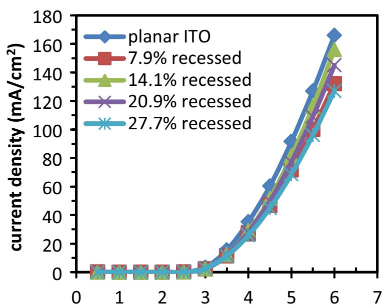
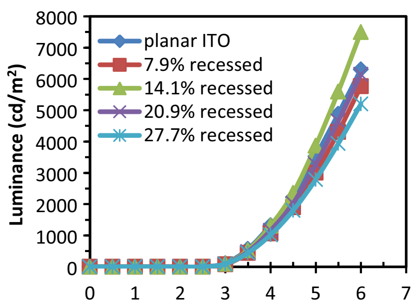


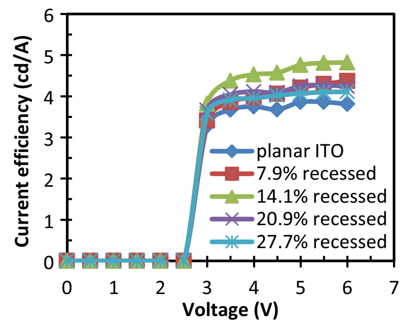
Figure 3: Optical transmittance, haze ratio and sheet resistivity of ITO films as a function of recess coverage ratio.



(a)



(b)



(c)

Figure 4: (a) I-V, (b) L-V, (c) η-V of OLEDs with various recess coverage ratios.

that of the recessed ITO film. Fig. 4(b) reveals the L-V characteristics of OLED devices. OLED with 14.1% recessed ITO anode apparently has better L-V characteristic than the planar device. Further examining the voltage dependent current efficiency (η) as shown in Fig. 4(c), one can see all recessed OLEDs performed improved current efficiency over the planar device. The 14.1% recessed device had the highest current efficiency of 4.8 cd/A at 6 V, which was 26.5% higher than that of the planar device (3.8 cd/A). The possible reasons are (1) the emitted light that generally trapped in a planar device now has a chance to reflect at the recess wall. The reflected light has a high possibility of escaping from the glass when moving in a direction almost normal to the glass; (2) the emitted light at recess bottom travels to a rougher ITO/organic interface and scatters more seriously. Part of the scattered light may be redirected in the normal direction of the glass and contribute to the total output optical density; (3) the emitted light in the recess wall area is an extra light source and has a large chance of escaping from the glass when moving upwards and downwards.

The degree of improvement in current efficiency is found not coverage-ratio dependent. The 14.1% recessed device has the highest, followed by the 7.9%, 20.9% and 27.7% recessed devices with current efficiency of 4.37, 4.24, and 4.11 cd/A at 6 V, respectively. The reasons for that are complicated since the light out-coupling involves the possible routes mentioned above. The recess covered area, the recess wall area and the pitches all can change the way the emitted light propagates in the recessed and stacked structure. In addition, the deteriorated electrical and optical properties of the recessed ITO anode are among other factors for this observation.

4. CONCLUSIONS

OLED devices with ITO anodes having circular micro-lens-like structures have been demonstrated to perform improved external current efficiency by up to 26.5%. The deflection effect at the recess wall and the scattering effect at the recess bottom enhanced out-coupling efficiency and led to the improved external current efficiency. The current efficiency is found coverage-ratio independent due to mixed optical and electrical effects at various recess patterns.

ACKNOWLEDGMENT

The authors would like to thank the National Science Council for financially supporting this work under contract grant NSC-101-2221-E218-042.

REFERENCES

1. Lin, C. L., T. Y. Cho, C. H. Chang, and C. C. Wu, "Enhancing light outcoupling of organic light-emitting devices by locating emitters around the second antinode of the reflective metal electrode," *Appl. Phys. Lett.*, Vol. 88, No. 8, 81114, 2006.
2. Meerheim, R., M. Furno, S. Hofmann, B. Lussem, and K. Leo, "Quantification of energy loss mechanisms in organic light-emitting diodes," *Appl. Phys. Lett.*, Vol. 97, No. 25, 253305, 2010.
3. Mladenovski, S., S. Hofmann, S. Reineke, L. Penninck, T. Verschueren, and K. Neyts, "Integrated optical model for organic light-emitting devices," *J. Appl. Phys.*, Vol. 109, No. 8, 083114, 2011.
4. Madigan, C., M. H. Lu, and J. Sturm, "Improvement of output coupling efficiency of organic light-emitting diodes by backside substrate modification," *Appl. Phys. Lett.*, Vol. 76, No. 13, 1650–1652, 2000.
5. Moller, S. and S. Forrest, "Improved light out-coupling in organic light emitting diodes employing ordered microlens arrays," *J. Appl. Phys.*, Vol. 91, No. 5, 3324–3327, 2002.
6. Peng, H. J., Y. L. Ho, X. J. Yu, and H. S. Kwok, "Enhanced coupling of light from organic light emitting diodes using nanoporous films," *J. Appl. Phys.*, Vol. 96, No. 3, 1649–1654, 2004.
7. Lee, Y., J. S. H. Kim, and J. Huh, "A high-extraction-efficiency nanopatterned organic light-emitting diode," *Appl. Phys. Lett.*, Vol. 82, No. 21, 3779–3781, 2003.
8. Do, Y. R., Y. C. Kim, and Y. M. Song, "Enhanced light extraction from organic light-emitting diodes with 2D $SiO_2/SiNx$ photonic crystals," *Adv. Mat.*, Vol. 15, No. 14, 1214–1218, 2003.
9. Chang, H. W., J. H. Lee, S. Hofmann, Y. H. Kim, L. Muller-Meskamp, B. Lussem, C. C. Wu, K. Leo, and M. Gather, "Nano-particle based scattering layers for optical efficiency enhancement of organic light-emitting diodes and organic solar cells," *J. Appl. Phys.*, Vol. 113, No. 20, 204502, 2013.