11.4: Coupling Efficiency Enhancement of Organic Light Emitting Devices with Refractive Microlens Array on High Index Glass Substrate

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Abstract

An approach to increase the coupling efficiency of organic light emitting diodes (OLEDs) is studied. Refractive microlens arrays are formed on the high refractive index glass substrate by etching the glass using reflowed photoresist as mask. Over 65% more light is extracted from the OLED on the microlens array substrate as compared with the conventional device, without affecting the electrical performance. No color variation is induced by the microlens array.

1. Introduction

High efficiency organic light emitting diodes (OLED) are required for display and solid state lighting applications [1]. Devices with nearly 100% internal quantum efficiency have been achieved by using phosphorescent emitting materials [2,3]. However, due to the mismatch of the refractive index between air and the organic light-emitting device, most of the generated light is lost through total internal reflection (TIR) into the waveguiding modes in glass substrate, ITO and organic layer, and self-absorption. The typical out-coupling efficiency is as low as ~20% [4]. This low coupling efficiency becomes the main limitation to high efficiency.

Various methods have been proposed to increase the coupling efficiency. They can be classified into four general schemes: (1) apply corrugated microstructure on the substrate to increase the coupling efficiency through Bragg-scattering the light bounded in lateral guided modes [5,6]; (2) modify the substrate surface to reduce the TIR loss at substrate/air interface, such as incorporation of monolayer of silica microsphere in the substrate [7], shaping of device into a mesa structure [8], patterning polymer microlens array [9], or directly placing a large size hemispherical lens directly on top of the substrate surface [10], (3) insert highly porous medium between ITO layer and supporting substrates to scatter the light out [11]; (4) make use of a microcavity structure [12,13]. Although these methods can increase the coupling efficiency, they also have drawbacks, such as strong angular dependent emission spectrum, changes in the electrical characteristics, or costly and complex processing.

In a conventional OLED fabricated on a glass substrate, 50%-80% of the light emission is lost to waveguiding modes in the glass, ITO and organic layers [14]. Although the loss in the ITO and organic layers can be reduced by thinning the layer thickness, the most effective and straightforward way is to fabricate the device on a high index glass substrate. In this paper, we proposed a simple method to improve the coupling efficiency. We employed the high refractive index glass as substrate to reduce the ITO/organic waveguide loss, and formed spherical microlenes pattern directly on backside of the substrate by conventional etching method to minimize the total internal reflection loss at substrate/air interface. An enhancement factor of 1.65 has been obtained in the preliminary experiment.

2. Experiment

The microlens array is fabricated using the melting photoresist technique with the process as shown in Fig 1(d). This technique use standard semiconductor equipment and process and

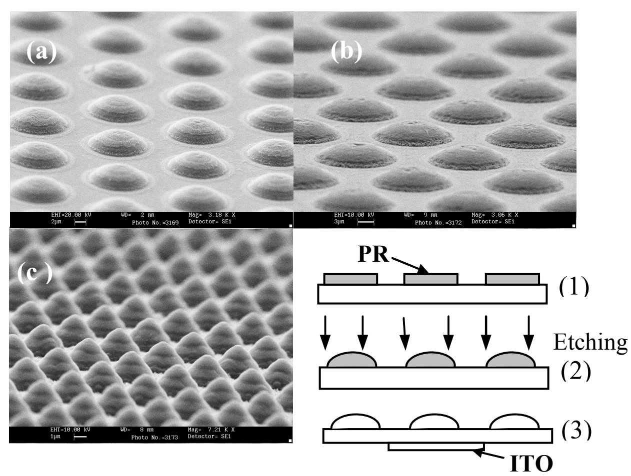

Figure 1. SEM images of the microlens arrays with diameter of 15μm(a), 20μm (b) and 5μm (c); and Schematic of the lens fabrication process (d)

allows to manufacture microlens array of good quality over the whole substrate (2.5 x 2.5 cm^2). A thin layer (1.5μm) of photoresist was coated on top of high index glass. An array of photoresist cylinders was then obtained by standard photolithography. After that, the resist cylinders were melted at temperature of 150°C by placing the substrate on a hot plate. A spherical curvature was formed due to photoresist surface tension, resulting microlens array. The photoresist microlenses were transferred in glass substrate by reactive ion etching (RIE) with the reflowed photoresist as etching mask. Atoms from the photoresist and substrate were simultaneously removed by energetic ions until the lens shape was completely etched into the

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substrate. The RIE parameters were carefully adjusted to obtain the appropriate selective ratio so that the spherical pattern of photoresist can be transferred to substrate with only slight deformation. The size and curvature of the microlens can be easily tuned by changing the photoresist cylinder thickness and diameter. In this experiment, microlens array of three different diameters, 5μm 15μm and 20μm were fabricated, with the same lens spacing of 1μm. Figure 1 shows scan electron micrograph (SEM) images of the formed microlens array.

After the microlens array formation on one side of the high index glass substrate, a layer of 40nm ITO film was sputtered on the other side of planar surface and then patterned using conventional photolithograph method. After ITO pretreatment by UV ozone, the substrates were put in a vacuum chamber. The constituent organic layers were next deposited using thermal vacuum evaporation of commercial grade organic powder. The functional organic layers were N,N'-diphenyl-N,N' bis(3-methylphenyl-1,1'-biphenyl-4,4'-diamine (TPD, 60 nm) as a hole-transport layer and tris-8-hydroxyquinoline aluminum (Alq_3, 50 nm) as an electron-transport and emitting layer. The base pressure in the evaporator was ~2 μTorr. The cathode consisted of sequential layers of 1 nm lithium fluoride (LiF) and 100 nm thick Al. The cathode structure was defined by a grid shadow mask with width of 6 mm during Al deposition. A reference device was also fabricated on the conventional glass substrate (n=1.5) without the microlens. Devices with 5 μm, 15 μm and 20 μm diameter microlens arrays are referred to as D5, D15, and D20 respectively. The diodes were characterized in room ambient and temperature without encapsulation. Electroluminescence intensity in the normal direction was measured using a PR650 SpectraScan spectrophotometer. Current-voltage (*IV*) characteristics were measured using an Advantest R6145 DC voltage-Current source and Fluke 45 Dual Display multi-meter.

3. Results and Discussion

The current density (J), voltage (V) and luminance (L) characteristics of the devices with the microlens arrays are compared with that of the standard reference in Fig. 2. The J-V curves for all four devices are identical, which indicates the microlens fabrication process have no effects on the electrical properties of the OLED. It is because the microlens array is fabricated on the opposite side of ITO, without any alternation of device configuration and interface design. The L-V curves indicates that under the same current density, the microlens device have higher luminance in the normal direction. At 50 mA/cm^2 the luminance is 1051 cd/m^2, 1164 cd/m^2, 1195 cd/m^2 and 1220 cd/m^2 for the reference device, D20, D15, and D5 respectively. This indicates a 20% enhancement of the luminance efficiency in the normal direction for the device D5. In order to find the total enhancement, the angular distributions of the devices have to be taken into account. The identity of the J-V curves shows evidence that the enhancement in luminance comes from the higher out-coupling efficiency.

To test the scattering effect of the microlens arrays, we observed the emitted light through a CCD camera and recorded the emission spectrum at different region. Fig. 3 shows the spectra of the light emitted of D5 measured at different angles. Inset is the photography viewed from front surface emissive side of device D5. For the microlens device, scattered light can be observed over the entire substrate surface and the light emission region looks

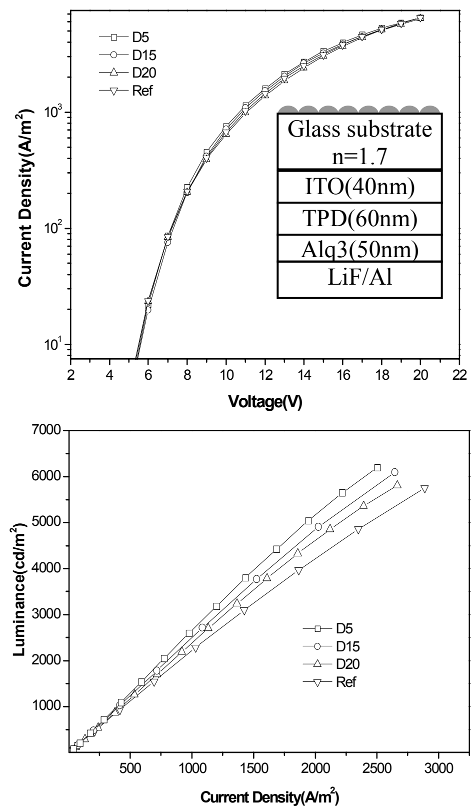

Figure 2. (a) Current density – Voltage (J-V) and (b) Luminance-Current density (L-J) characteristics of microlens devices compared with the reference device

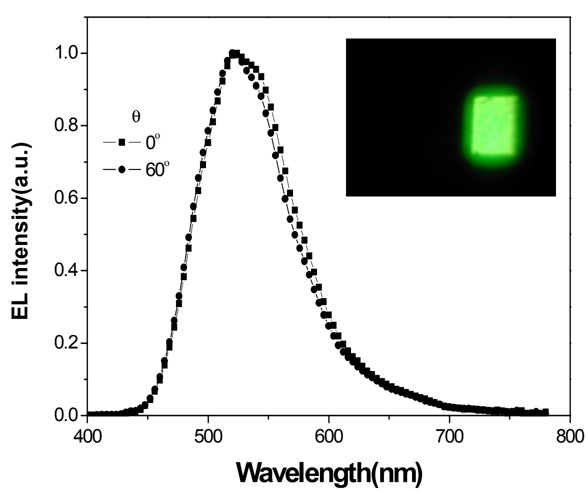

Figure 3. Emission spectra of microlens devices under viewing angle of 0° and 60°, (inset) photographs of front surface emission of microlens device

expanded. This shows that large amounts of light trapped in the glass substrate are effectively scattered out from the lens array surface. Similar scattering effect has also been reported using silica microspheres as scattering medium on the substrate [7]. However, strong color variation with viewing angle was observed in that method because of pronounced diffraction effect. In our experiment, no emission color variation is observed by comparing the emission spectra measured at different viewing angles, indicating the microlens array does not induce any color shift to the OLED. It is not surprising because the size of the microlens is quite a bit larger than the light wavelength and therefore refractive rather than diffractive effect is dominant.

To measure the total coupling efficiency enhancement, we employ the integrating sphere to obtain the total flux of the light emitted from device front side. The device was attached to the 0.5inch detector port of a 2inch diameter sphere (IS-020, Labsphere Inc.), which was connected to a spectrometer (PC2000, Ocean Optics Inc.) with an optical fiber. Fig. 4 shows the electroluminescence (EL) spectra of various devices under the identical injection current density of 25 mA/cm^2. The absolute EL can be extrapolated as product of the measured spectra with a constant determined in terms of the Labsphere feature. Thus the coupling efficiency enhancement can be extracted by directly comparing the EL spectra. Total coupling enhancement is calculated by comparing the spectrally integrated EL signals. The experimental results indicate that the total enhancement factor is 1.65, 1.46, and 1.39, for devices D5, D15 and D20, respectively. Meanwhile, the emission spectra measured are almost the same for the mocrolens devices and the conventional device, suggesting that scattering by microlens array does not induce emission color change.

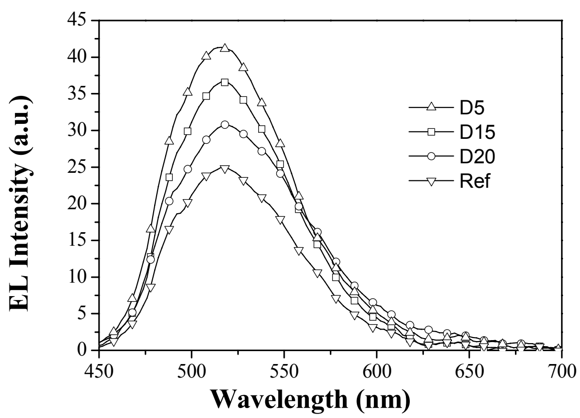

Figure 4. Integrating spectra indicating the total emission enhancement from microlens devices

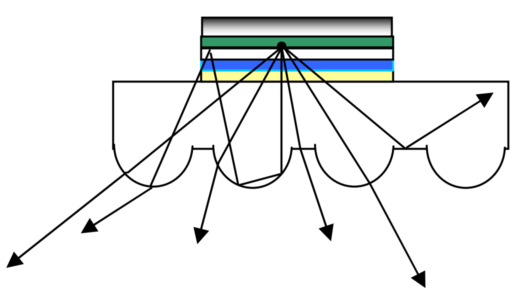

Figure 5. Schematic explanation for the mechanism of outcoupling enhancement with microlens array on high index glass substrate

Figure 5 shows the schematic explanation for the enhancement of devices with microlens array on high index glass substrate. Light is generated in the active emitting layer. Because index of the substrate is close the organic material, all the emitting light could enter the substrate without loss in ITO/organic waveguiding mode. With microlens array modification of the glass-air interface, the light emitting at large angle can be extracted out because the incident angle at the interface becomes less than the critical angle. A portion of the light still reflects at the interface and enters back to the organic layer. However, with little loss by absorption, that portion will reflect at the metal-organic interface and reach the glass-air interface again. The second incidence has a high chance to transmit through the interface. Therefore, more light is extracted out due to scattering effect of the microlens array. We believe the scattering effect strongly depends on geometric structure and fill factor of the lens array. The relation between the enhancement factor and the microlens array parameters will be investigated in future work.

4. Conclusion

In conclusion, we have demonstrated that refractive microlens arrays on high index glass substrate can enhance the coupling efficiency of OLEDs. The enhancement effect strongly depends on the aperture ratio and curvature ratio of microlens array. Experimentally, a high enhancement factor over 1.65 was obtained for the total emissive flux. The results also indicate that perhaps smaller microlenses may produce beven more enhancement in the coupling efficiency. Without any detrimental effect to the electrical and optical performance of the OLED, this coupling efficiency enhancement method can be combined with high internal quantum efficiency electrophosphorescent OLEDs to fabricate super-high efficiency devices.

5. Acknowledgement

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