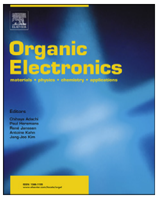
Organic Electronics 38 (2016) 121–129

Contents lists available at ScienceDirect

Organic Electronics

journal homepage: www.elsevier.com/locate/orgel



Effect of various microlens parameters on enhancement of light outcoupling efficiency of organic light emitting diode

Rahul K. Sharma [a, b, *], Deepak [a, b], Monica Katiyar [a, b]

[a] Department of Materials Science and Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India
[b] Samtel Centre for Display Technologies, Kanpur, Kanpur 208016, India

ARTICLE INFO

Article history:
Received 31 May 2016
Received in revised form
3 August 2016
Accepted 9 August 2016

Keywords:
Organic light emitting diode
Total internal reflection
Microlens array
Light outcoupling efficiency

ABSTRACT

Since organic light emitting diode (OLED) is a multilayer device where each layer has different refractive index, total internal reflection (TIR) plays an important role in limiting the efficiency of an OLED. Due to the presence of TIR, a major portion of light is trapped within the device in various wave guiding modes. Of the total light trapped in an OLED, we address only the part that is lost due to wave guiding mode arising from refractive index mismatch at the glass-air interface. Microlens array, to improve luminance, is a method that can be externally applied to the OLEDs without altering its electrical characteristics and is easy to use. Microlens arrays ranging from 10 to 40 μm have been fabricated using an organic elastomeric material polydimethylsiloxane (PDMS) by mold transfer technique. Maximum improvement of 25% in outcoupling efficiency for blue OLED is reported upon using the microlens array with diameter 10 μm. For a given diameter of microlens, out-coupling efficiency of OLED increases as height to diameter (H/D) ratio of microlens array approaches 0.5 (perfect hemisphere). It is also observed that outcoupling efficiency increases with the diameter of microlens for a given H/D ratio. The best luminescence improvement was observed for blue OLED, which can be explained by the higher refractive index of PDMS at lower wavelengths.

1. Introduction

Efficiency of an organic light emitting diode (OLED) is one of the parameters which is used to define the performance of OLED device. It can be divided into two parts, namely internal quantum efficiency (IQE) and external quantum efficiency (EQE). Internal quantum efficiency is the ratio of number of photons generated inside the device per electron-hole pair injected into the device, while external quantum efficiency is total number of photons emitted from the device in viewing direction per electron-hole pair injected. Mathematically, EQE can be represented as the product of IQE and outcoupling efficiency [1,2]. Hence, from the definition, outcoupling efficiency of an OLED is the fraction of light, which is coupled out from the device in the viewing direction. Various losses which occur within the device, limit the efficiency of OLED. The loss of light in OLED takes place mainly due to two reasons, first is total internal reflection (TIR) between different layers of OLED due to refractive index mismatch between layers and second is emission of the light from the edges of the device [3,4]. According to total internal reflection taking place in different layers, light loss can be classified into different modes such as substrate wave guiding mode and ITO/organic wave guiding mode. After the loss within different layers only ~20% of total generated light inside the device is collected as output light [5–7]. A number of techniques have been reported to enhance the light outcoupling efficiency of OLED. These techniques are categorized as internal substrate modification techniques [8–30] and external substrate modification techniques [3,6,31–61]. Since most of the light outcoupling techniques involve complicated fabrication process, modification in active layer, and insertion of additional layers, fabrication of microlens array and its integration on top of OLED seems to be easier and efficient method to extract the light from an OLED, without altering electrical properties of OLED.

The effect of microlens array on enhancement of outcoupling efficiency was first observed by Moller and Forrest [41]. They fabricated ordered array of microlenses with 10 μm diameter using PDMS. The lens shape was not hemispherical and square arrangement was used. They got improvement in outcoupling efficiency by

---

* Corresponding author. Department of Materials Science and Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India.
E-mail address: rahul.physics.iitd@gmail.com (R.K. Sharma).

http://dx.doi.org/10.1016/j.orgel.2016.08.010

a factor of 1.5 or improvement of 50% using microlens array on a 1 mm diameter OLED. It is important to note that in Moller and Forrest's work size of the microlens is 100 times smaller than the dimension of OLED light source. Lin et al. have shown that microlens arrays could lead to reduced light extraction if the area of emitting OLED is close to the dimensions of the lenses [42]. Alignment of microlens with the pixel is important in this scenario. Melpignano et al. have shown improvement of 70% by aligning microlens with each pixel [43]. Further, microlens with different shapes namely hemispherical [41–49], square shaped [50–52], cylindrical [53] and elliptical [54] have been tested.

In most studies, area faction (It is defined as the ratio of single microlens area to area of the geometry in which microlenses are arranged. In our case we have used hexagonally arranged microlens array) of microlens array has been kept constant. Wei et al. fabricated square shaped microlens array and demonstrated the effect of area coverage and base length size on improvement of luminance efficiency of OLEDs [50–52]. They have reported that the light outcoupling efficiency has linear dependence on base length of the square shaped microlens in the size range 100–190 μm. As the base length of microlens array decreases, luminance efficiency increases linearly. They observed maximum improvement of 56% on luminance efficiency. They also observed that the luminance efficiency of OLED increases with area fraction and edge length of microlens while CIE coordinates and emission spectrum do not change with microlens. The objective of their study was to experimentally obtain extraction efficiency as a function of lens size (constant area fraction) and area fraction of lens (constant size).

Lee et al. fabricated cylindrical microlens array using PDMS on PET film with refractive index matching Si oil. They found improvement in luminous current efficiency and luminous power efficiency by 45% and 38%, respectively [53]. Similar to cylindrical microlens array, Yang et al. fabricated elliptical microlens array on polycarbonate film (PC) by roll to roll mold transfer process and achieved 60% (or 1.6 times) improvement in light out coupling efficiency [54]. Peng et al. [44,45] and Sun [55] have reported that the maximum enhancement in light outcoupling efficiency can be obtained with hemispherical shape of microlens array. But, they have not explained whether this improvement is due to height to diameter (H/D) effect or size effect.

The combined effect of size of microlens array and high refractive index glass substrate on outcoupling efficiency of an OLED has been reported by Peng et al. High refractive index substrate was used in order to rule out the loss in ITO/organic wave guided mode. They obtained maximum improvement of a factor of 1.65, 1.46 and 1.39 in outcoupling efficiency for microlens array with diameter of 5 μm, 15 μm and 20 μm, respectively. It is reported that smaller size (5 μm) microlenses are giving the best enhancement. The conclusions may be erroneous as shape is not kept constant in these experiments [44]. In another report, larger size (10 μm) microlens array provides best enhancement and it also has most hemispherical shape [45]. In both these reports, effect of size and shape could not be decoupled. This is the reason for contradictory results.

This paper focuses on detailed study of the effects of various microlens parameters such as diameter (D), height to diameter (H/D) ratio, area fraction and emission wavelength on light outcoupling efficiency of OLEDs.

2. Experimental section

2.1. Materials

In this study all the devices were fabricated on glass substrates pre-coated with indium tin oxide (ITO), which acts as an anode. ITO coated substrates were then cleaned with soap solution, thoroughly rinsed in de-ionized water and acetone, respectively. For removal of organic and inorganic contaminants cleaning of the substrates was done with the well known RCA (Radio Corporatio of America) solution. Prior to deposition of organic layers these cleaned ITO substrates were treated with oxygen-argon plasma. After plasma treatment, organic layers were deposited using thermal evaporator under ultra high vacuum of the order of 10^{-8} Torr at room temperature. The organic materials which were used for OLED fabrication are DS 205, *N*,*N*′- Di(1-naphthyl)-*N*,*N*′-diphenyl-(1,1′-biphenyl)-4,4′-diamine (NPB), and Tris-(8-hydroxyquinoline) aluminum (Alq_3) as hole injection layer (HIL), hole transport layer (HTL) and electron transport layer (ETL) respectively for all of devices. The stacks for all red, green and blue OLEDs, which were used in out coupling efficiency enhancement are given as follows:

ITO/DS 205 (1000 Å)/NPB (200 Å)/Red Host Alq_3 (198 Å)/Red Cohost Rubrene EY51 (132 Å)/Red Dopant TC1712 (5.5 Å)/Alq_3 (300 Å)/LiF (8 Å)/Al (1500 Å)/NPB (500 Å)
ITO/DS 205 (1000 Å)/NPB (200 Å)/Green Host DS 522 (300 Å)/Green Dopant DS 501 (9 Å)/Alq_3 (300 Å)/LiF (8 Å)/Al (1500 Å)/NPB (500 Å)
ITO/DS 205 (1000 Å)/NPB (200 Å)/Blue Host DSH 43 (300 Å)/Blue Dopant DS 405 (30 Å)/Alq_3 (300 Å)/LiF (8 Å)/Al (1500 Å)/NPB (500 Å)

All of the HIL, HTL, ETL were deposited at the rate of 1 Å/s. Green host and green dopant were deposited with rates 1 Å/s and 0.05 Å/s, respectively. The HIL, HTL and ETL are from Doosan Electronics, South Korea, Sensient Technologies, USA and others from e-Ray Optoelectronics Technology Company Ltd, Taiwan. Electroluminance spectra (EL) and luminance curve are shown as Fig. S1 in electronic supplementary information (ESI). The film thicknesses of the organic layers for all the colors have been optimized thoroughly in order to get highest efficiency device.

2.2. Microlens fabrication process

For the fabrication of microlens array, silicon mold was made using conventional photolithography process. For Si mold fabrication a highly As doped n-type Si wafer with SiO_2 coating on it (Si/SiO_2) was purchased from Silicon Quest International, Inc. Thickness, orientation and resistivity of this As doped n-type Si wafer were 525 ± 25 μm, ⟨100⟩ and <0.005 Ω-cm, respectively. Thickness of SiO_2 on top of this Si wafer was 200 nm. Si/SiO_2 substrates were cleaned by the standard RCA cleaning process (NH_4OH:-H_2O_2:H_2O::1:1:5). Finally, dehydration baking of Si substrates was done inside the oven at 150 °C for 15 min. Then Si mold was fabricated by wet processing using buffered HF solution for SiO_2 etching and HNO_3: HF: CH_3COOH (5:1:1) for Si etching. For fabrication of polymeric microlens, a polymer is chosen such that it has refractive index same as that of glass [62,63]. PDMS with curing agent in ratio of 1:10 was used for this purpose. From the above process, microlens array with different diameter ranging from 10 μm to 41 μm were fabricated. The shape and size of microlens array can be controlled by changing the etching time for Si etching and SiO_2 etching. The microlens diameter was measured using optical microscope. Thickness of PDMS film and height of the microlens were measured using Bruker Dektak XT thickness profilometer. Microlens array were applied on top of an OLED pixel (4 mm × 4 mm) because fabricated PDMS films had good adhesive property due to the elastomeric nature of PDMS polymer. The luminance measurement of OLED was done with and without applying microlens array, with the help of Konica Minolta CS 1000 spectroradiometer.