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Organic Light-Emitting Diode with Patterned Inverted Conical Structure for Efficiency Enhancement

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Abstract: The Organic Light Emitting Diode(OLED) has become very popular in the recent times because of its astounding features that includes light weight, better efficiency than conventional displays, fast response time and low fabrication cost. The biggest impediment in the efficiency improvement of OLED is loss from Total Internal Reflection(TIR). So, it is imperative to enhance outcoupling without compromising with electrical properties. Besides, the flexible OLED is being built with Patterned Inverted Conical(PIC) substrate ,which can avoid the mirror reflection effect under the strong light for a better visual experience. This highly effective method is compatible with the current device fabrication process and is also applicable for full-color OLED display and lighting.

Index Terms: Nano Technology, Micro-optical devices, optoelectronics.

1. INTRODUCTION:

An organic light-emitting diode has emissive electro-luminescent layer, made of organic compound that emits light when supplied with electric current. Organic semiconductor has good charge carrier transport properties and it has high luminescence efficiencies of nearly 100 %. Alhough OLEDs have a score of advantages over conventional displays but the desired level have not been achieved so far.

A high optical device efficiency is still impeded by the total internal reflection (TIR) effect, resulting in the refractive index mismatch at the interface of various functional layers of OLED to achieve higher brightness [1]–[3]. The external quantum efficiency (ηEQE) of an organic optoelectronic device is generally determined by:

$$\eta EQE = X.\ \eta IQE \qquad \text{Eq. (1)}$$

Where, X is the light coupling efficiency and ηIQE is the internal quantum efficiency related to the probability of electron-photon conversion in the active region.

Nowadays, the internal quantum efficiency of OLEDs has been dramatic improved to nearly 100% by the use of phosphorescent dopant materials [4]. Conversely, the light-extraction efficiency is still limited to 20%, which is far below the desired level [5]. Hence, a great increase in the external quantum efficiency is essential to enhance the light out-coupling efficiency of electroluminescent devices.

Several techniques have been reported to enhance the light coupling efficiency from either the internal mechanism or the external construction on the back surface of substrate. Some of the techniques used for the outcoupling of glass modes are surface roughening of the substrate, use of micro – lens and shaped substrates [6-8]. Some of these techniques have been quite successful in enhancing the light outcoupling from the glass modes, especially the use of micro lens. By modifying the directions of light propagating and by adjusting the refractive index mismatch between the different functional layers, these approaches have shown the positive effect on the extraction of light out-coupling on glass substrate. However, flexibility is one of the most important advantages for OLED and for that purpose, there is a requirement to use the flexible plastic substrate instead of solid glass substrate, yet the features of plastic (such as much thinner than glass and non-high temperature resistance) and limited parts of the methods to be applied for flexible OLEDs. In this paper, we present a technique using patterned inverted conical (PIC) fabricated by a femtosecond laser to enhance the out-coupling efficiency of flexible OLEDs.

2. DEVICE OPERATION OF CONVENTIONAL OLED:

The principle of operation of organic light emitting diodes (OLEDs) and inorganic light emitting diodes (LEDs) are alike. Suppose that the device is forward biased. Thus, holes are injected from anode. Holes travel through HIL, HTL and EBL, and electron travel through EIL,ETL and HBL into emmisive layer. Here, they recombine resulting in formation of excitons. These excitons decay rediatively to emit light.

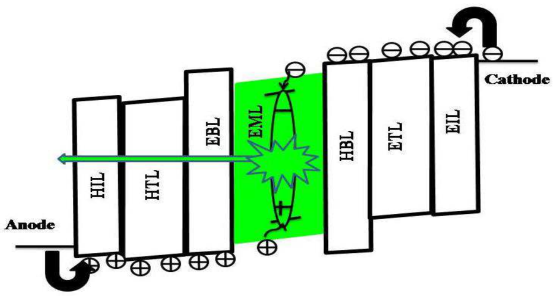

Fig. Schematic diagram of OLED

Where, HIL is Hole injection layer, HTL is Hole transport layer, HBL is Hole blocking layer, EIL is electron injection layer, ETL is electron transport layer and EBL is Electron blocking layer. Device efficiency depends upon the operating voltage, charge carrier balance inside the emissive layer, recombination efficiency and optical outcoupling efficiency and to have efficient device all these parameters must be optimized. Operating voltage depends upon the charge carrier injection and charge carrier transport [9]. The charge carrier balance is dependent on charge carrier injection as well as transport in organic layers. The third factor recombination efficiency depends upon the probability of radiative decay of exciton. The final factor is optical outcoupling efficiency which is described as the fraction of photons outcoupled from the device.

3. DESIGN PRINCIPLE AND FABRICATION PROCESS

3.1 Extraction Principle

Light trapping is a critical problem that limits the performance of electroluminescent devices. The light extraction from the organic emission layer in conventional OLEDs is limited owing to the waveguide in the multilayered sandwich structures and plasmonic quenching at the metallic cathode. The light-energy proportion in each mode can be approximately calculated by Snell's law with optics modeling according to the refractive indices of the organic emitting layer (*n~1.71)*, PET substrate *(n~1.5)*, and external ambient condition *(n~1)*. Only about 18.8% of light can be directly coupled out into the air, nearly 31.3% of the light is trapped as substrate mode, and approximately 45.9% is dissipated in the ITO/organic layers as a waveguide mode, followed by the total internal reflection (TIR) limitation. Since that extracting light from PET(polyehylene terephthalate) substrate is much easier than that from ITO layer, we will be focussing on PET substrate [10]. Reason is that in conventional OLEDs, by using high refractive index material, ITO*(n~1.9)* , as anode, a large proportion of lights (46%) were trapped in ITO/organic layers but not in substrate. In order to increasing the proportion of trapped lights in substrate, index matched material should be used as anode, according to the classical electromagnetic theory [10]. PEDOT: PSS *(n~* 1:53) is a good candidate as its index is well matched with PET substrate *(n*~1:6). Combined PEDOT: PSS with PET substrate, the proportion of light trapping in PET substrate was increased from 31.3% to 54.8% with a factor of 1.75 [11]. The out-coupling efficiency can be increased by a factor of 3.9 in theoretically. To extract energy from PET substrate, a patterned inverted conical (PIC) structure was produced, as shown in Fig. 1. In conventional flexible OLEDs, a part of light could be out-coupled [e.g., Ray A in Fig. 1(a)] and rest of them are trapped by the TIR which normally occurred on the interface of PET/air [e.g., Ray B in Fig. 1(a)]. The PIC was able to change the optical path of the light propagating in the substrate, break the TIR limitation via multiple refraction and increase the out-coupling efficiency, as schematically illustrated in Fig. 1(b) (e.g., Ray C).

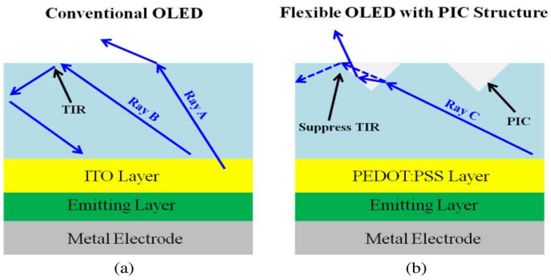

Fig. 1. Schematic of the mechanism for the outcoupling efficiency enhancement. (a) Conventional flexible OLED structure and (b) proposed method with PIC structure.

3.2 PIC Fabrication

The PIC was fabricated by a femtosecond laser on a motorized x-y-z micro-positioning stage, as shown in Fig. 2. This stage has a 0.01-mm-step motor for precise positioning of the fabricated pattern (pre-design specifications). A laser beam propagated through the substrate in a perpendicular direction and converged on the PET substrate by a focal lens. The inverted conical structures were formed by melting the PET with laser radiation. The inverted conical is about 30 µm-diameter, several micrometers-depth and 150 µm-pitch.

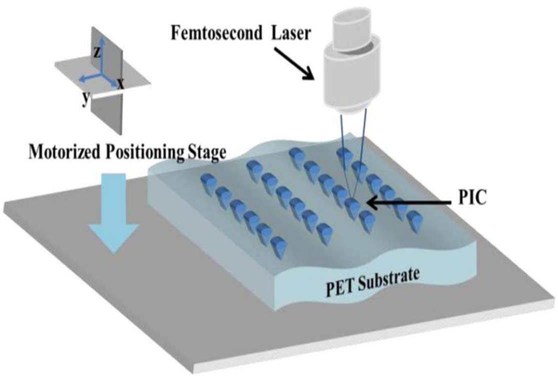

Fig. 2. Fabrication process of a predesigned PIC structure.

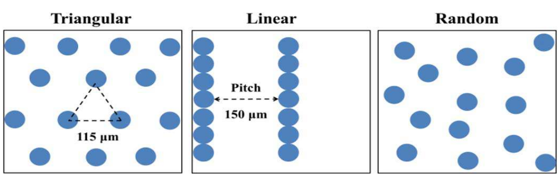

Fig. 3. Different arrangements for PIC

3. SIMULATION RESULTS AND ANALYSIS DISCUSSION:

In order to monitor the external coupling efficiency of the PIC structure, the 3-D geometric model of the OLED was built by the ray tracing software Light tools 7.2, which employs the Monte Carlo method [12]. Three main parameters are taken into consideration—arrangement of PIC, the refractive index of the anode, and the density of PIC. These are the parameters for the enhancement in the out-coupling efficiency. The factors related to the increase in the optical efficiency were simulated and are summarized in Tables 1–3..All the simulation results were only based on ray-optic modeling (excluding the surface plasmonic, interference and micro-cavity effect). Besides, in order to keep the simulation as close as possible to the experiment, the depth-to-width ratio of PIC was fixed as 2:1 when calculating the optical efficiency in the simulation. The different arrangements with a density of approximately 16.7% for the PIC are shown in Fig. 3. In order to maintain a similar density, the lengths of the regular triangle and pitch of linear are kept as 115 µm and 150 µm, respectively. As summarized in Table 1, PICs with different arrangements leads to a similar increase in the optical efficiency by a factor of 2.33, 2.35, and 2.34, compared with the reference device. It shows that the optical efficiency can be enhanced effectively by the PIC, but it is alomost insensitive to the specific arrangement. As summarized in Table 2, more light was coupled to the substrate from the waveguide mode as the refractive index of the anode well matched with the substrate, leading to the enhancement of optical efficiency by factors ranging from 1.82 to 2.35. This implies that Combination of a matched-refractive-index anode with the PIC substrate can enhance the optical efficiency. As summarized in Table 3, the optical efficiencies were improved by factors of 2.34, 2.74, and 3.65 as the PIC density increased from 16.7% to 66.8%. A larger amount of emitted light can be effectively out-coupled by breaking the TIR limitation (occuring because of multiple refraction) by increasing the density of the PIC. As the density of PIC reaches 66.8%, the factor of increase of 3.65 in the optical efficiency, which is very close to that of the maximum value given in theory (3.9).

This implies that all of the light trapped in substrate is mostly out-coupled. The 66.8% density of the PIC is an optimal value for optical efficiency enhancement.

TABLE 1
Factor of increase in optical efficiency for different arrangements of PIC

Arrangement of PIC	Triangular	Linear	Random
Increase factor	2.33	2.35	2.34

With a R.I of 1.53 for PDOT:PSS and 16.7% density of PIC.

TABLE 2
Factor of increase in the optical efficiency for different anode refractive indices

Refractive Index(R.I)	1,9(ITO)	1,53(PDOT:PSS)
Increase Factor	1.82	2.35

With a linear arrangement of PIC and 16.7% density of PIC.

TABLE 3
Factor of increase in the optical efficiency for different densities of PIC

Densities of PIC(%)	16.7	33.4	66.8
Increase factor	2.34	2.74	3.65

With a linear arrangement of PIC and with a R.I of 1.53 for PDOT:PSS

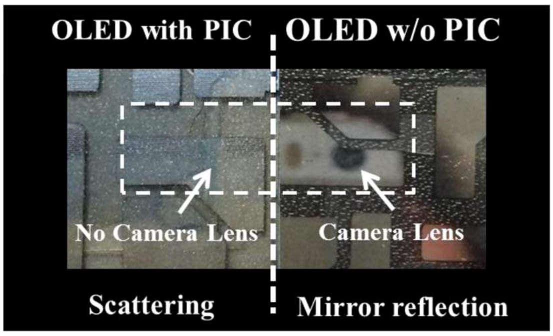

Fig. 4. Reflectivity comparison between OLEDs with PIC and without PIC substrate.

5. CONCLUSION

Exposition of a PIC structure in a glass substrate fabricated by a femtosecond laser was given to enhance the optical out-coupling efficiency for electroluminescent devices without sacrificing its electrical property. Compared to a conventional flexible OLED, the flexible OLEDs with PIC structure exhibited a maximum enhancement of current efficiency without any emission spectrum altered. The light distribution can be modulated by different depth-to-width ratio of PIC structure to satisfy various needs. Besides, the flexible OLED with PIC substrate can avoid the mirror reflection effect under the strong ambient light. The proposed method, which is very compatible with current fabrication processes, effectively increases optical out-coupling efficiency and shows great potential for next-generation displays and solid-state lighting.

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