Light extraction from organic light-emitting diodes for lighting applications by sand-blasting substrates

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Abstract: Light extraction from organic light-emitting diodes (OLEDs) by scattering the light is one of the effective methods for large-area lighting applications. In this paper, we present a very simple and cost-effective method to rough the substrates and hence to scatter the light. By simply sand-blasting the edges and back-side surface of the glass substrates, a 20% improvement of forward efficiency has been demonstrated. Moreover, due to scattering effect, a constant color over all viewing angles and uniform light pattern with Lambertian distribution has been obtained. This simple and cost-effective method may be suitable for mass production of large-area OLEDs for lighting applications.

OCIS codes: (230.3670) Light-emitting diodes; (160.4890) Organic materials.

References and links

1. K. Saxena, V. K. Jain, and D. S. Mehta, “A review on the light extraction techniques in organic electroluminescent devices,” Opt. Mater. **32**(1), 221–233 (2009).
2. C. F. Madigan, M.-H. Lu, and J. C. Sturm, “Improvement of output coupling efficiency of organic light-emitting diodes by backside substrate modification,” Appl. Phys. Lett. **76**(13), 1650–1652 (2000).
3. S. Möller, and S. R. Forrest, “Improved light out-coupling in organic light emitting diodes employing ordered microlens arrays,” J. Appl. Phys. **91**(5), 3324–3327 (2002).
4. P. Melpignano, V. Biondo, S. Sinesi, M. T. Gale, S. Westenhöfer, M. Murgia, S. Caria, and R. Zamboni, “Efficient light extraction and beam shaping from flexible optically integrated organic light-emitting diodes,” Appl. Phys. Lett. **88**(15), 153514 (2006).
5. H. J. Peng, 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. **96**(3), 1649–1654 (2004).
6. Y. H. Cheng, J. L. Wu, C. H. Cheng, K. C. Syao, and M. C. M. Lee, “Enhanced light outcoupling in a thin film by texturing meshed surfaces,” Appl. Phys. Lett. **90**(9), 091102 (2007).
7. Y. J. Lee, S. H. Kim, J. Hun, G. H. Kim, Y. H. Lee, S. H. Cho, Y. C. Kim, and Y. R. Do, “A high-extraction-efficiency nanopatterned organic light-emitting diode,” Appl. Phys. Lett. **82**(21), 3779–3781 (2003).
8. K. Ishihara, M. Fujita, I. Matsubara, T. Asano, S. Noda, H. Ohata, A. Hirasawa, H. Nakada, and N. Shimoji, “Organic light-emitting diodes with photonic crystals on glass substrate fabricated by nanoimprint lithography,” Appl. Phys. Lett. **90**(11), 111114 (2007).
9. M. H. Lu, and J. C. Sturm, “Optimization of external coupling and light emission in organic light-emitting devices: modeling and experiment,” J. Appl. Phys. **91**(2), 595–604 (2002).
10. M. H. Lu, C. F. Madigan and J. C. Sturm, “Improved external coupling efficiency in organic light-Emitting devices on high-index substrates,” Tech. Dig. - Int. Electron Devices Meet. 607–610 (2000).
11. A. Mikami and T. Koyanagi, “High efficiency 200-lm/W green light emitting organic devices prepared on high-index of refraction substrate,” SID 09 DIG. 907–910 (2009).
12. T. Tsutsui, M. Yahiro, H. Yokogawa, K. Kawano, and M. Yokoyama, “Doubling Coupling-Out Efficiency in Organic Light-Emitting Devices Using a Thin Silica Aerogel Layer,” Adv. Mater. **13**(15), 1149–1152 (2001).
13. T. Yamasaki, K. Sumioka, and T. Tsutsui, “Organic light-emitting device with an ordered monolayer of silica microspheres as a scattering medium,” Appl. Phys. Lett. **76**(10), 1243–1245 (2000).
14. J. J. Shiang, T. J. Faircloth, and A. R. Duggal, “Experimental demonstration of increased organic light emitting device output via volumetric light scattering,” J. Appl. Phys. **95**(5), 2889–2895 (2004).
15. R. Bathelt, D. Buchhauser, C. Gärditz, R. Paetzold, and P. Wellmann, “Light extraction from OLEDs for lighting applications through light scattering,” Org. Electron. **8**(4), 293–299 (2007).
16. C. L. Mulder, K. Celebi, and M. Baldo, “Organic light emitting devices,” US patent, Pub. No.: US 2008/0309217 A1 (2008).

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17. B. W. D'Andrade, and J. J. Brown, "Organic light-emitting device luminaire for illumination applications," Appl. Phys. Lett. **88**(19), 192908 (2006).
18. H. Peng, J. Sun, X. Zhu, X. Yu, M. Wong, and H. S. Kwok, "High-efficiency microcavity diodes using silver anode," Appl. Phys. Lett. **88**, 073517 (2006).

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1. Introduction

High efficiency organic light-emitting diodes (OLEDs) have been subjects of intensive research in recent years due to their potential applications in display and lighting [1–18]. Theoretically, the internal quantum efficiency of OLEDs can be achieved 100% by using phosphorescent emitters which harvest both of the singlet and triplet excitons emission, however, only ~20% of the internal emission can be out-coupled while the remaining ~80% of internal emission are lost mainly due to total internal reflection at ITO/glass, glass/air interface and surface plasmons at organic/metal interface [1]. Many approaches have been proposed such as employing micro-lens [2–4], texturing the substrate [5,6], using photonic crystal structure [7,8] to extract the substrate wave-guide light, and/or employing a high refractive-index substrate [9–11], inserting a low refractive-index silica aerogel between glass substrate and ITO [12] to extract the ITO/organic wave-guide light.

A significant improvement of efficiency by a factor of ~1.2-2 has been demonstrated by employing these methods, however, most reported methods require complex and expensive fabrication process like lithography to generate the micro/nano structures and hence they may be not a good choice for low-cost large-area lighting applications. Light extraction by employing scattering medium [13–16] is one of the effective choices for large-area lighting applications, since it offers inherent advantages, like constant color over all viewing angles, uniform light pattern with Lambertian distribution. However, most reports employed external scattering medium such as silica or polymer micro-sphere [13–15], diffuse thin film [16] to extract the light, which, though effective, increases the cost of OLEDs. Very few works have been presented on using glass substrate directly as scattering medium for OLEDs. Moreover, most reports focused on modifying the back-side surface of the glass substrates [1–16], and to the best of our knowledge, no works have been reported on modifying the edges of the glass substrates to further turn the useless edge emission into useful light emission. In this paper, we present a very simple and cost-effective method to rough the glass substrates and hence to scatter the light. By simply sand-blasting the edges and back-side surface of the glass substrates, a 20% improvement of the forward efficiency has been demonstrated. Moreover, due to scattering effect, a constant color over all viewing angles and uniform light pattern with Lambertian distribution has been obtained. This simple and cost-effective method may be suitable for mass production of large-area OLEDs for lighting applications.

2. Experimental results and discussion

Four kinds of devices were prepared on different glass substrates. The edges and back-side surface of the soda-lime glass substrates with thickness of 1.1 mm were roughed by sand-blasting. The untreated glass, edges sand-blasting glass, back-side surface sand-blasting glass and both edges and back-side surface sand-blasting glass were used as the substrates for device A, device B, device C and device D, respectively. All devices have identical structures, employing 80-nm-thick ITO as anodes, 60-nm-thick 4, 4'-bis [N-(1-naphthyl-1-)-N-phenyl-amino]-biphenyl (NPB) as hole-transporting layers, 60-nm-thick tris (8-hydroxyquinoline) aluminum (Alq_3) as electron-transporting and light-emitting layers and 1-nm-thick LiF capped with 100-nm-thick Al as cathodes. All organic layers in the devices were thermally evaporated in sequence in a multi-source vacuum chamber at a base pressure of around 5×10^{-7} Torr. The samples were then transferred to the metal chamber without breaking vacuum for cathode deposition. The current density-voltage characteristics of the devices were measured by the HP4145B semiconductor parameter analyzer. The forward direction photons emitted from the devices were detected by placing a calibrated UDT PIN-25D silicon photodiode very close onto the top of the devices. The luminance and external quantum efficiencies of the devices were inferred from the photocurrent of the photodiode. The

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electroluminescent (EL) spectra were obtained with the PR650 spectrophotometer. All measurements were carried out under ambient condition without device encapsulation.

Figure 1 shows the optical microscope images of the glass substrates after sand-blasting. A random distributed grain with grain size of ~100 microns, corresponding to the diameter of the sand particles used to blast the substrates, can be clearly observed, resulting in a uniform rough surface with average roughness of ~100 microns. These random distributed grains can scatter the substrate wave-guide light effectively and thus an increased external efficiency can be expected.

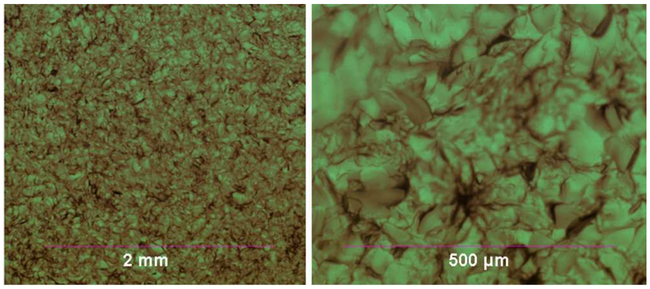


Fig. 1. Optical microscope images of the glass substrates after sand-blasting.

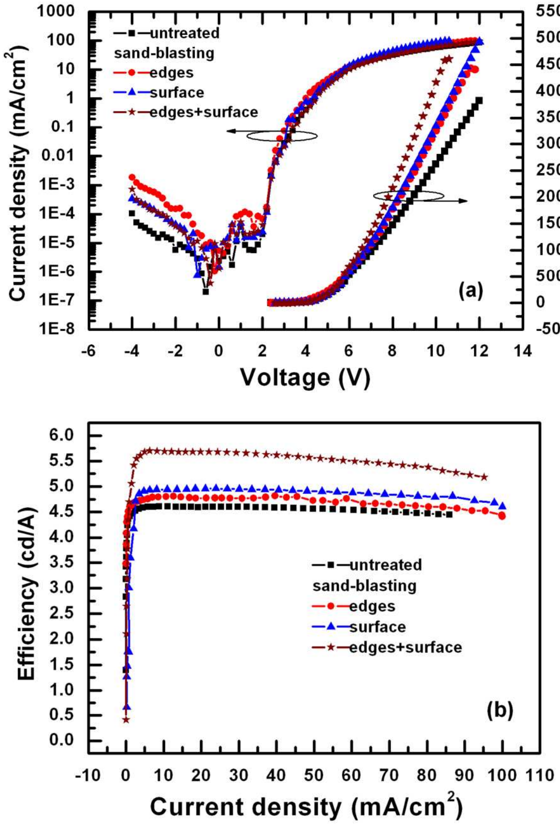
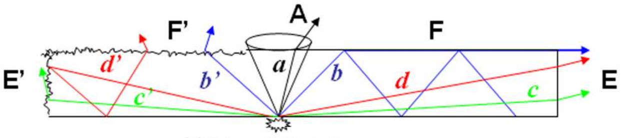
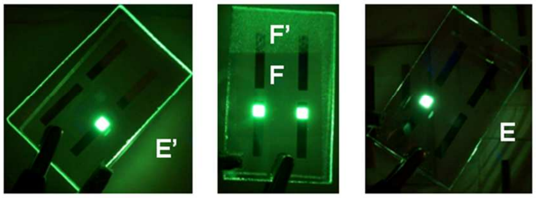


Fig. 2. (a) Current density – forward luminance - voltage and (b) EL efficiency - current density characteristics of the devices.

Figure 2(a) compares the typical current density-forward luminance-voltage characteristics of the devices, which were fabricated on 20 × 20 mm^2 glass substrates with light-emitting area of 10 × 10 mm^2. It should be noted that the active surface area of the photodiode was 613 mm^2, which was sufficiently large to detect all of forward surface and edge emission of the devices. It is obvious that all devices studied here show similar current density-voltage characteristics due to their identical structures. However, the luminance characteristics are quite divergent. All devices employing sand-blasting glass substrates exhibit substantially higher luminance than that of the devices employing untreated glass substrates. For example, at a current density of 50 mA/cm^2, device B with edges sand-blasting substrates, device C with back-side surface sand-blasting substrates and device D with both edges and surface san-blasting substrates exhibit a luminance of 2347 cd/m^2, 2464 cd/m^2 and 2864 cd/m^2, respectively, significantly higher than that of 2269 cd/m^2 for the device A with untreated glass substrates. As a result, the current efficiency of device B, device C and device D is 4.7 cd/A, 4.9 cd/A and 5.5 cd/A, respectively, exhibiting an improvement of ~5%, ~10% and ~20%, respectively, compared to that of 4.5 cd/A for the device A, as shown in Fig. 2(b).



(a) Schematic illustration



(b) Edges sand-blasting (c) Surface sand-blasting (d) Untreated

Fig. 3. (a) Schematic illustration of light propagation inside the devices; photos of devices fabricated on (b) edges sand-blasting substrates, (c) partial surface sand-blasting substrates and (d) untreated substrates.

Such efficiency improvement mainly is due to the strong scattering effect of the sand-blasting glass substrates, which extract the substrate wave-guide light effectively. To give a clear explanation, the schematic illustration of light propagation inside the device is shown in Fig. 3(a). For comparison, photos taken from devices with light-emitting area of 2 × 2 mm^2 fabricated on 25 × 40 mm^2 edges sand-blasting substrates, partial surface sand-blasting substrates and untreated substrates are shown in Fig. 3(b), (c) and (d), respectively. The rays can be classified into three categories according to their incident angles (the angle between the normal of substrate surface and ray), i.e, ray *a* with incident angle θ smaller than the critical angle θ_c at glass/air interface ($\theta_c = \arcsin(1/1.52) = 42°$), ray *b* with $\theta > \theta_c$, and ray *c* with $\theta >> \theta_c$. Ray *a* can emit to the forward surface directly, while ray *b, c*, instead of being out-coupled to the forward surface directly, they are wave-guided by the glass due to total internal reflection. The wave-guided ray *b* undergoing many times reflection/absorption, has limited opportunities to escape from the edges or surface of substrate, and finally disappear due to absorption, leading to a dark region F, as shown in Fig. 3(a), (c). In contrast to ray *b*, ray *c* with $\theta >> \theta_c$ may find opportunities to escape from the edges of substrate, resulting in an edge emission with light propagation direction nearly parallel to the surface. Due to its directionality, this edge emission leads to a stripe illumination region E, as shown in Fig. 3(a), (d). It should be noted that, this quasi-parallel propagated edge emission cannot be employed as useful light for lighting, since for general lighting applications, the light are required to shine on the ground instead on the ceiling. In other words, the light should be directed to a forward propagation direction. Although adding a luminaire can address this problem [17], it destroys the simplicity concept of OLED lamp and absorbs large amount of light. Hence, the

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substrate wave-guide rays *b, c* which take up ~30% of the internal emission are totally lost if without employing any extraction techniques.

By sand-blasting the edges of substrates, the original quasi-parallel propagated edge emission are random scattered, resulting in a bright, uniform emission surrounding the edges, as shown in Fig. 3(a), (b) (region E'). Compared to the dark edges of the devices with untreated substrates (Fig. 3(d)), this bright, beautiful edge emission not only increases the forward efficiency by an improvement of 5%, as shown in Fig. 2, but also can be utilized as decoration for the OLED lamp. To further clarify the scattering effect due to sand-blasting, part of the back-side surface of the substrates was sand-blasted (region F') while other regions remain untreated (region F), as shown in Fig. 3(c). It is obvious that due to scattering effect, the original non-emissive regions F due to total internal reflection exhibit bright emission, resulting in a 10% improvement of forward efficiency. Therefore, with edges and back-side surface sand-blasting, the original lost substrate wave-guide light such as rays *b, c* can be out-coupled as useful light for lighting. Intuitively, a summation of 15% improvement of forward efficiency would be expected by sand-blasting the edges and back-side surface of the glass substrates. However, as shown in Fig. 2(b), a 20% improvement of forward efficiency has been achieved by sand-blasting the edges and back-side surface of the glass substrates, substantially higher than the expected value of 15%. This may imply that with the help of back-side surface sand-blasting, the edges sand-blasting work more effectively to extract the light than that without the help of back-side surface sand-blasting, hence resulting in an additional 5% improvement of forward efficiency. As shown in Fig. 3(a), ray *d'* is scattered back to the glass substrate, and it may find opportunities to escape from the back-side surface due to scattering effect. However, if the bask-side surface is untreated, ray *d'* after scattering back may be wave-guided by the substrate and thus it has limited opportunities to escape from the back-side surface. To further test this assumption, a 100-nm-thick Al was deposited on the edges of device B (edges sand-blasting) and device D (edges + back-side surface sand-blasting), and hence the edges of device B and device D serve as diffuse reflectors. By doing so, almost no improvement of forward efficiency has been observed in device B. However, device D shows an improvement of ~21% of forward efficiency (data not shown here); on subtracting the 10% improvement due to back-side surface sand-blasting, a 11% improvement due to edges sand-blasting was achieved, clearly demonstrating that the edges sand-blasting work more effectively with the help of back-side surface sand-blasting.

Figure 4 shows the EL spectra of device A and device D. A slightly blue-shift spectrum with increasing viewing angles is observed in device A with untreated substrates due to the weak micro-cavity effect. However, with sand-blasting substrates, the spectra and brightness are almost unchanged by changing the viewing angles. Thus a high quality light source can be obtained by applying this method since the resulting OLEDs exhibit constant color over all viewing angles and uniform light pattern with Lambertian distribution. It should be pointed out that the micro-cavity OLEDs with their light-emission colors depend on viewing angles, can be fabricated on sand-blasting substrates to further enhance the light extraction efficiency [18], generate constant color and offer Lambertian light pattern.

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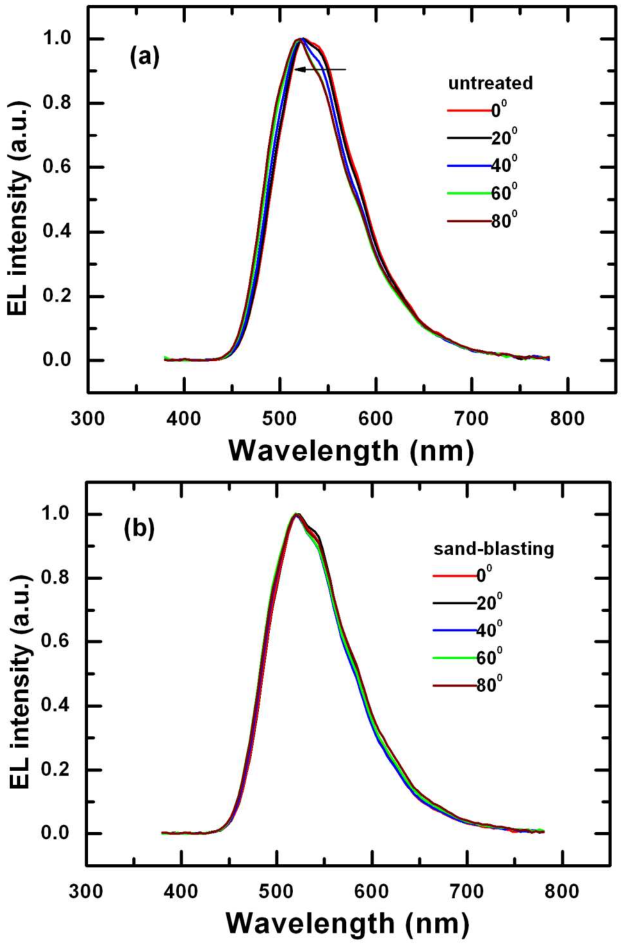

Fig. 4. EL spectra of the devices fabricated on (a) untreated substrates and (b) sand-blasting substrates.

3. Conclusion

In conclusion, a 20% improvement of forward efficiency has been achieved by sand-blasting the edges and back-side surface of the substrates. This preliminary result can be further boosted by using smaller size sand particles to blast the substrates, so that a smaller grain size can be obtained to further increase the scattering probability. Due to scattering effect, a constant color over all viewing angles and Lambertian distribution of light has been obtained. This simple and cost-effective method may be suitable for mass production of large area OLEDs for lighting applications.

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