Enhanced light outcoupling in a thin film by texturing meshed surfaces

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The authors demonstrate a method of texturing a meshed surface on a poly(dimethyl siloxane) (PDMS) film for improving light extraction. This meshed surface is fabricated through a casting process by using a self-organized porous film as a template. Experimental results show that the light outcoupling efficiency increases on the meshed surface of a freestanding PDMS film with large incident angles. The external quantum efficiency of an organic light-emitting diode with the textured PDMS film was also demonstrated to have an enhancement of 46%. © 2007 American Institute of Physics. [DOI: 10.1063/1.2709920]

Luminance of light-emitting devices (LEDs) such as semiconductor and organic light-emitting diodes (OLEDs) is usually limited by the fraction of spontaneous emission trapped inside the device. Due to this trapping effect, external quantum efficiencies are only 2% for ordinary LEDs (Ref. 1) and 20% for OLEDs (Ref. 2) although internal quantum yields can be more than 90%.3 The distribution of the trapped light is primarily determined by the index configuration of multiple thin-film layers. According to Snell’s law, high-index-contrast thin-film interfaces have small critical angles of total internal reflection (TIR), screening out most of light with large incident angles. This trapped light, furthermore, is reabsorbed in the device and could turn into heat that may impact the device performance.

Various attempts have been made to overcome this emission limitation. For the conventional OLEDs, the trapped light is mainly distributed in the transparent substrate such as glass and the electroluminescent (EL) layer. To reduce the light guided in the EL layer, optimizing the layer thickness4 or inserting photonic crystal structures5 at the interface between the EL layer and the substrate has been presented. On the other hand, texturing the substrate surface on the emission side is another approach to lessen the trapped light in the bulk substrate. Yamashiki et al.6 employed an ordered monolayer of silica microspheres on a substrate as a scattering medium. Moller and Forrest7 fabricated microlens arrays to direct emitted light. Tsutsui et al.8 applied low-index silica aerogel for replacing bulk glass substrate. Other techniques, such as adding a nanoporous film9 and a diffusive layer,10 have been reported to improve light emission in OLEDs.

In analyzing light extraction of these textured surfaces, the wavelength and angle dependencies are also important issues. Chaotic surface morphology could be possible to achieve a wide bandwidth and a wide emitting angle in that disordered structures barely scatter light coherently. Wide bandwidths and emitting angles are essential for lighting application such as white LEDs. In this letter, we examine the light outcoupling efficiency of a textured surface with disordered, meshed structures. Figure 1 illustrates the schematic diagram of optical ray trajectories in a thin film with and without a mesh on the surface. Without a meshed surface, the rays are trapped in the film in case the incident angle is larger than the critical angle. However, as optical rays invade on the textured surface, they are scattered by the mesh structure. Thus, the original trapped light in the film can escape.

The meshed surface was fabricated through a casting process of molding and demolding poly(dimethyl siloxane) (PDMS) into structures by using porous anodic aluminum oxide (AAO) as templates. PDMS has been shown to be with stable chemical properties and is easily synthesized. Additionally, it is transparent and the refractive index (1.45) is close to glass index (1.5). This closeness results in low Fresnel loss (about 0.0287%) as the light normally penetrates from glass to PDMS. AAO templates are self-organized porous films. The pore size typically ranges from tens of nanometers to 1 μm, controlled by programmable process conditions.11 The dimension of AAO templates can be ex-
tended to centimeters which is favorable for large-area lighting applications. The details of the fabrication process are described as follows. First, the precursors of PDMS were mixed and heated in 80 °C for 1 h to increase the viscosity. Before the cross-linking process completed, a commercial AAO template from Whatman International Ltd. with a diameter of 4.7 cm and a pore size of 200 nm was applied on the surface of the precursors. These liquid-phase precursors entered into the straight pores of AAO via capillary attraction. The heating process continued until the polymerization finished. The PDMS nanowires were formed and embedded inside the AAO pores. To remove the AAO template, the sample was immersed in NaOH solution for 2 h to etch the aluminum oxide. After rinsing in de-ionized water, the sample was dried in air. Figure 2 shows the fabricated meshed surface on PDMS. The meshed structure is composed of dense tangled microwires. The thickness of the mesh was measured to be about 20 μm. Although the PDMS was molded into nanowires by the AAO template, the linewidth of the mesh was actually in the micrometer scale. Figure 3 explains the possible transformation mechanism. As the AAO template was etched in strong alkali solution, water molecules could diffuse into the polymer chains of PDMS structures and the original nanowires expanded. Meanwhile, contiguous nanowires were further entangled to form many bundles. During the drying process, these bundles bent and interlaced to form a mesh. Some agglomeration was observed at the joints. It may have resulted from polymer reorganization as the water-soaked nanowires contacted each other. Via this developing process, the bottom of the mesh forms a columnlike structure that would guide incident light into the top mesh, which diffuses the light into air.

To examine the capability of extracting light from the meshed surface, we launched a laser beam with various incident angles and measured the optical transmission. The PDMS sample was intentionally shaped into a half cylinder, as illustrated in Fig. 4(a). The flat side was imprinted with meshed structures at the center. The curved side was prepared with a smooth surface. The laser beam entered the sample on the curved side in a normal incident angle and aimed at the meshed surface. Therefore, the beam was not deflected by the surface and the Fresnel loss can be minimized and fixed without varying with angles. We launched the laser beam and observed the luminance on the surfaces. As the incident angle is larger than the critical angle of TIR, the meshed surface is obviously much brighter than the flat surface.
surface. The experimental images are shown in Figs. 4(b) and 4(c).

To quantitatively analyze the outcoupling efficiency, we varied the incident angle of the laser beam and measured the transmitted power emitted from the meshed surface. Since the laser beam could be scattered into various angles by the surface, an integrating sphere connected with a power meter was used for collecting total radiation. The measured optical transmission is plotted in Fig. 5. Two wavelengths of 532 nm (green) and 650 nm (red) were used in this experiment, and the result shows that only slight differences are observed on the transmission curves of these two wavelengths. Thus, the outcoupling efficiency is insensitive to optical wavelength. In addition, because small reflection (∼3.37%) occurs on the curved side, the optical transmission can be considered a result of single incident. The optical transmission only maintains a high level for small incident angles on the flat surface but abruptly decreases as the angle becomes larger than 43.26°, which is the critical angle of TIR for PDMS. On the contrary, the transmission gradually decays with incident angles on the meshed surface although the transmission is relatively lower for normal incident. It may result from the textured surface that induces more backscattering in the normal direction.

In order to investigate the light-extraction efficiency on a real device, two OLEDs with layers of indium tin oxide (100 nm)/Alq3(50 nm)/N,N’-bis-(1-naphthyl)-N,N’-diphenyl-1,1’-biphenyl-4,4’-diamine(NPB)(40 nm)/CuPc(15 nm)/Mg:Ag(200 nm) were simultaneously fabricated on a glass substrate. One OLED was glued to a thin PDMS sheet with meshed surface on the back side via epoxy with refraction index of 1.4–1.7, while the other was not. The diameter of each OLED is 0.5 cm and the thickness of the PDMS film is 1 mm. These two OLEDs can be individually lit by applying a voltage of 15 V. Figure 6 shows images of the two lit OLEDs. The lighting area of the OLED with the meshed surface slightly expands, in agreement with the fact that the waveguide mode can escape from the glass as well as the PDMS substrate. The factor of outcoupling enhancement is defined by

$$g = \frac{L_{\text{meshed}} - L_{\text{plate}}}{L_{\text{plate}}} \times 100\%,$$ (1)

where \(L_{\text{meshed}}\) and \(L_{\text{plate}}\) are the total luminescences of meshed-surface and plate-glass OLEDs. The outcoupling enhancement was calculated to be 46.09% ± 8.85% according to Eq. (1). Because emitted light has to go through the epoxy film between the glass and the PDMS, extra Fresnel losses between glass/epoxy and epoxy/PDMS interfaces were also included in the measurement.

In conclusion, we have demonstrated the light-extraction enhancement of meshed surfaces fabricated on a PDMS substrate. The outcoupling coefficient of OLEDs with this meshed structure enhances up to 46%. In addition, the experimental result shows that the outcoupling efficiency is insensitive to optical wavelength. This property is beneficial to preserve the color spectrum of light-emitting devices. A salient feature of this technology is that PDMS meshed surfaces can be fabricated separately and laminated on the large-area glass substrate of organic electroluminescent devices.

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