A universal approach for high-performance displays

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Integrating microlens arrays onto microcavity top-emitting organic light-emitting devices produces displays with an unparalleled combination of useful properties, including enhanced luminance and wide viewing angles.

Top-emitting organic light-emitting devices (OLEDs) possessing microcavity structures offer several significant benefits for OLED displays. Unlike standard bottom-emitting OLEDs, top-emitting OLEDs allow OLED displays to be fabricated on opaque substrates and permit the use of highly-functional pixel circuits. This produces a higher-quality display without sacrificing the aperture ratios of the pixels, meaning that the display still produces a good image when viewed from a wide range of angles.

In OLEDs with a microcavity structure, the light-emitting organic layer is placed between two mirrors, thereby narrowing the emission spectra (and thus improving color saturation for display applications) and enhancing the luminance. In some cases, the quantum efficiency of OLEDs can also be enhanced with carefully designed microcavities.

Unfortunately, all these useful properties do not usually occur in the same top-emitting/microcavity OLED design. Previous theoretical and experimental investigations of microcavity OLEDs have shown that this is mainly due to the microcavity resonant wavelength. Setting the normal-direction resonant wavelength to equal the peak wavelength of the OLED’s intrinsic emission usually produces the highest luminance enhancement along the normal direction and it results in negligible color shift as the viewing angle changes. However, it also generates lower external quantum efficiencies. Setting the normal-direction resonant wavelength to 20–40nm longer than the peak wavelength of the OLED’s intrinsic emission generates higher external quantum efficiencies, but at the expense of significant color shift as the viewing angle changes. These tradeoffs between different emission properties complicate the design of top-emitting/microcavity OLED devices for different applications.

Recently, we have shown that by integrating microlenses onto top-emitting/microcavity OLEDs, all the enhancements in efficiency and color performance (color saturation, small color shift with viewing angles) can be achieved simultaneously. In addition, the image blurring that usually occurs when microlens arrays are integrated onto OLEDs is also largely reduced. This combination of properties could make our OLED design a universal architecture for various applications.

Figure 1 shows the typical structure of a top-emitting microcavity OLED (green-emitting) without a microlens. Using room-temperature vapor phase deposition, the device is coated with a micrometer-thick parylene layer in order to make it unreactive. For the top-emitting OLED with integrated microlens, as shown in Figure 1(b), all the layer structures are the same except that a thin sheet (around 50µm thick) of polydimethylsiloxane (PDMS) is laminated on top of the parylene layer. This sheet contains a microlens array fabricated

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by micromolding with a silicon master mold.6 A conventional bottom-emitting OLED is also shown in Figure 1(c) for comparison.

Figure 2(a) shows a photo of a thin PDMS sheet with an integrated microlens array, while Figures 2(b) and 2(c) show scanning electron microscope images of the microlenses.

Figures 3(a) and 3(b) show the measured electroluminescence (EL) spectra for the top-emitting/microcavity OLEDs at various viewing angles, without and with microlenses. Both top-emitting microcavity devices show narrow EL spectra compared to the 0° EL spectrum of the conventional bottom-emitting device. For the top-emitting OLED without microlenses, however, the EL shows a significant shift to shorter wavelengths with changing viewing angles due to strong microcavity effects. (Incorporating microlenses into the OLED effectively eliminates this shift in the EL spectra.)

Laminating microlenses onto microcavity structures leads to the averaging of the EL over different angles, giving stable and saturated colors. Figures 4(a) and 4(b) compare the cd/A (candela per amp; a measure of the intensity of light emitted for a given electric current) and the external quantum efficiencies of the three devices. Compared to the conventional bottom-emitting OLED, the top-emitting microcavity OLED with microlenses shows significant enhancements in both external quantum efficiency (1.6×) and cd/A efficiency (3.0×).

Microlens arrays have also been used to enhance the efficiencies of conventional bottom-emitting OLEDs.7 However, as illustrated in Figure 5(a), serious image blurring can occur and pixels become hard to distinguish when conventional bottom-emitting OLEDs are laminated with microlenses. This problem is substantially reduced for top-emitting OLEDs laminated with microlenses, which exhibit a distinguishable pixel edge and clear enough pixel definition for display applications, as shown in Figure 5(b).

Figure 2. (a) Photo of the PDMS sheet with microlens arrays; (b) top-view scanning electron microscope (SEM) image of the microlenses; (c) oblique-view SEM image of the microlenses.

Figure 3. Relative intensities of electroluminescence (EL) spectra at viewing angles of 0°, 30°, and 60° for top-emitting device (a) without and (b) with microlenses. In (a) and (b), the EL spectrum of the conventional bottom-emitting OLED is shown for comparison.

Figure 4. (a) Candela per amp (cd/A) efficiencies and (b) quantum efficiencies of the three devices.

Microcavity and top-emitting OLEDs have proven useful at enhancing brightness, color saturation and aperture ratios of OLED displays. However, it has proven difficult to combine all

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of the desired properties into the same design, which has meant that OLED developers have had to accept some form of trade-off. We have overcome this problem by incorporating microlenses into microcavity top-emitting OLEDs, producing a universal approach. Since the microlenses can be fabricated separately and then laminated onto microcavity OLEDs, this method is simple, effective, and highly compatible.

**Figure 5.** Images of (a) the conventional bottom-emitting OLED laminated with microlenses and (b) the top-emitting OLED laminated with microlenses. Both images are taken near the edges of turned-on pixels.